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BOX 11 FOLDER 5

HEPAP correspondence

1970

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

OFFICE OF THE CHAIRMAN

December 31, 1970

Dear Viki:

Many thanks for your note of December 21, 1970. His name has come up on several previous occasions, and he has felt that he wouldn't be interested. However, I shall certainly bear your suggestion in mind.

With best regards,

Cordially,

Glenn T. Seaborg

Professor Victor F. Weisskopf
Head, Department of Physics
Massachusetts Institute of Technology
Cambridge, Mass. 02139

Finally, there is the political aspect that a collaboration in high energy physics between differing continents and power blocks has general human appeal in addition to the scientific value, which will make it easier to obtain funds for it than just by reasoning purely about the scientific importance.

Because of this, I think there should be a forum where these questions are regularly discussed and the outcome of other contacts on private or official levels become public.

Since the last meeting took place in the Soviet Union, I would propose to hold the next one in 1971 after the Accelerator Conference at CERN. The exact dates would be 26th and 27th September 1971 and the place Morges, near Lausanne, in Switzerland. It should have about an equal number of participants of the highest level from the United States, Europe and the USSR, but otherwise the informal structure should be kept.

Specifically I propose the following draft programme for the next meeting: the first day should contain review talks on the status of the projects under way in the three continents and of the plans for the immediate future. Of course, these review talks should be limited and directed specifically to those aspects of the projects which are of interest to international collaboration. The second day could be first a review of the art of accelerator construction in the light of the Accelerator Conference, and, finally, a general discussion on the possibilities of further collaboration in the exploitation of existing facilities and the construction of new ones.

With my best regards,

Yours sincerely,

Bernard P. Gregory

Bernard P. Gregory
Director-General

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF PHYSICS
CAMBRIDGE. MASSACHUSETTS 02139

December 15, 1970

Dear Friends:

I have received the enclosed letter from Bernard Gregory which is, to a great extent, self-explanatory.

Having been present at most of the previous meetings, I would suggest taking the request very seriously. We have a number of international projects going on, such as the Drickey experiment at Serpukhov, several at the ISR in Geneva, and probably some experiments at NAL. I believe that it is in the interest of high energy physics and of the general idea of international science to support and enlarge those cooperative ventures. The previous conferences of this kind were not very well organized. Unfortunately, most of the talks were repetitions of some talks which most of the audience had heard on other occasions. I know that Gregory is very much aware of this point, and he intends to organize the next conference much more rationally, and he wants to discuss only the on-going and future collaborative efforts of high energy physics.

Very sincerely yours,

Viki

Victor F. Weisskopf

VFW:gpm
Enclosure

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

1211 GENÈVE 23, Suisse

Weisskopf
Bogolubov
R.R. Wilson
Ed McMillan

LE DIRECTEUR GÉNÉRAL

Professor Victor F. Weisskopf,
Department of Physics,
M.I.T.,
CAMBRIDGE,
MA 02139,

Etats-Unis.

REF.: CERN/13.917

Genève, 2nd December, 1970

Dear Viki,

I have been asked by Bogolubov about the sequel of the meetings at Riga, Semmering and Tbilisi. You will remember that these meetings between Europe and the USSR, with the participation of the United States, had primarily the purpose of informing people concerned with the planning of high energy physics. I personally see very strong reasons for a continuation of these talks and a broadening of the scope, and I should like to have your views on the following proposal.

First of all, it seems clear to me that, as the financial needs of high energy physics increase and the funds available remain constant or go down, a coordination on an international level will become very important. This may help to avoid unnecessary duplication, and an exchange of experience will prevent previous errors being repeated. All parties involved in the big accelerator business, in particular the United States, USSR and Europe should take part in these meetings.

Secondly, the meetings have been and will be useful for exploring the maximum ground of possible collaboration. Already the collaboration of the various continents has played an important part in high energy physics and will continue to do so even more in the future. In particular the CERN-Serpukhov collaboration is turning out to be very fruitful and has proved the feasibility of such endeavours, whilst the more unofficial USA-Serpukhov collaboration has made a promising start. Further, since it will be impossible to have all types of instruments in all continents, collaboration will be the only way in which certain facilities such as Serpukhov, the ISR at CERN, Batavia and the electron storage rings in Novosibirsk, DESY and the USA can be made available to the whole high energy physics community.

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Téléphone : (022) 41 98 11 Télégramme : CERNLAB-GENÈVE Télex : GENÈVE - 22548

December 3, 1970

Professor Surja N. Gupta
Distinguished Professor of Physics
Wayne State University
Detroit, Michigan 48202

Dear Professor Gupta:

I have received your letter of November 23. I am going to study carefully the papers which you included.

I should tell you, however, that the High Energy Physics Advisory Panel of the AEC of which I am Chairman does not deal with the question of grants to individuals. The problems which this Committee deals with are problems of general financial support and long-rang planning. The distribution of funds among individuals is left to the appropriate selection committees. I shall, nevertheless, aquaint the members of the Committee with your complaints.

Sincerely,

Victor F. Weisskopf

VFW:gpm

cc Wallenmeyer

WAYNE STATE UNIVERSITY
COLLEGE OF LIBERAL ARTS DETROIT, MICHIGAN 48202

DEPARTMENT OF PHYSICS

November 23, 1970

Professor Victor S. Weisskopf
Chairman, Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Professor Weisskopf:

I am writing this letter to you, because you are a theoretical physicist and Chairman of the AEC's High Energy Physics Advisory Panel, and I am having some difficulty with the AEC regarding my research proposal on problems in theoretical high-energy physics. Although you have needlessly shown considerable rudeness to me in the past, I shall try to be as objective as possible.

I am enclosing for your consideration a list of my recent publications, and I am sure you will agree that most individuals, who are currently receiving the AEC research support, cannot match my publication record in the Physical Review during 1969 and 1970. I would further like to comment specifically on three of these papers to give the AEC some idea of the extraordinary quality of my research contributions.

1. "Relativistic Hadron Model with Intrinsic Mass Splittings." Most theoreticians, including yourself, have repeatedly expressed strong disbelief in the existence of quarks not only because they have not been observed but also because of purely theoretical reasons. At the same time the quark model is found to give reasonable results for many phenomena. This situation has puzzled every high-energy physicist, it has been the subject of much discussion at scientific conferences, and it has been referred to as a "paradox." (Physics Today, April 1969, p. 21.) My paper has basically resolved this paradox by showing that it is possible to develop a formalism that yields the results of the quark model without requiring the existence of physical quarks. Moreover, this paper for the first time provides a derivation of the hadron mass formulae that is free from objectionable features.

2. "Nonlinear Hadron Couplings from Divergence Conditions. I. Pions and Nucleons." Chiral dynamics is one of the "hottest" areas of research in high-energy physics, and many physicists, including those at MIT, have published a vast amount of literature on this subject. However, it is also recognized that chiral symmetry is a broken symmetry, which raises the fundamental question of why this symmetry is broken. It has been suggested in this connection that the pseudoscalar mesons intrinsically have vanishing masses, but they acquire their finite masses due to some

symmetry-breaking mechanism. Obviously, this suggestion is not only vague but naive in view of the large observed masses of some of the pseudoscalar mesons. I hope you will read my paper carefully, because it is one of the most beautiful papers published in recent times. I might also add that I am about to submit a second paper on this subject to the Physical Review, which also deals with the controversy regarding the existence of the axial-vector mesons.

3. "Quantization of the Charged Spin-3/2 Field." For a long time physicists have been under the impression that there might be theoretical reasons for excluding the existence of elementary particles of spins higher than one. For instance, Schwinger, whom you greatly admire, has indicated in his Nobel Prize address that it may not be possible to construct a consistent theory of the charged spin-3/2 field. This problem has acquired great significance in recent times because of the discovery of the high-spin resonances. In my paper the electromagnetic interaction of the spin-3/2 field has been thoroughly investigated, and it is shown that it is possible to develop a consistent formalism. Incidentally, the difficulties encountered by earlier authors arose because of the extremely complicated nature of the mathematical manipulations.

I am enclosing the reprints of the above three papers for your convenience. If you feel that I have exaggerated the importance of my work, please do not hesitate to say so, because I am not reluctant to invite an open discussion of the scientific merits of my papers.

There is of course the usual excuse of shortage of research funds. It is, however, a matter of public record that the AEC approved the proposals of G. Domokos and T. T. Wu at a time when it was unable to support my proposal. I do not wish to seem unkind, but the work of these theoretical physicists cannot be put in the same class as mine by any stretch of imagination. Incidentally, Wu has essentially carried out lengthy calculations by employing a device originated by me to deal with multiple photon production in quantum electrodynamics. [Gupta, Phys. Rev. 98, 1502 (1955).]

I have also examined the latest issue, dated 15 October 1970, of Physical Review D to see what kind of papers are currently being supported by the AEC. The first such paper by R. E. Cutkowsky (p. 1386) is devoted to the discussion of lack of causality in somebody else's paper, the second paper by K. G. Wilson (p. 1438) deals with nonphysical "scalar pions", and there are many other routine papers on pp. 1473, 1478, 1511, 1519, 1535, 1541, 1577, 1586, 1621, 1630, 1640, 1649, 1657, 1680, and 1724. If, however, you disagree with my appraisal, I hope you will let me know what is so remarkable about these AEC-supported papers.

I fully realize that these are difficult times for the professors in general and the scientists in particular. I have always felt a special obligation to the scientific community, and I have tried to defend my colleagues as far as possible. I have, for instance, pointed out to many critical politicians and civic leaders that if an average physicist

earned as much as an average physician or surgeon, the APS would be as conservative as the AMA.

I do hope you will give serious thought to this letter in the interest of fair play.

Sincerely,

Suraj N. Gupta

Suraj N. Gupta
Distinguished Professor
of Physics

Copy: Dr. Glenn T. Seaborg
Dr. Paul W. McDaniel
Dr. Bernard Hildebrand

1969 Publications

1. "Quantization of the Charged Spin-3/2 Field," S. N. Gupta and W. W. Repko, Phys. Rev. 177, 1921 (1969).

2. "Comment on Quantum Electrodynamics," S. N. Gupta, Phys. Rev. 180, 1601 (1969).

3. "Gauge Conditions in Gravitational Interactions," B. M. Barker, M. S. Bhatia, and S. N. Gupta, Phys. Rev. 182, 1387 (1969).

4. "Graviton Bremsstrahlung and Infrared Divergence," B. M. Barker, S. N. Gupta, and J. Kaskas, Phys. Rev. 182, 1391 (1969).

5. "Relativistic Hadron Model with Intrinsic Mass Splittings," S. N. Gupta, Phys. Rev. 187, 1984 (1969).

1970 Publications

1. "Deviations from Charge Independence in Nuclear Forces," S. S. El-Ghabaty, S. N. Gupta, and J. Kaskas, Phys. Rev. D. 1, 249 (1970).

2. "Symmetry-Breaking Mechanism in Strong Interactions," S. N. Gupta, in Symmetries and Quark Models (Gordon and Breach, New York, 1970), p. 51.

3. "Nonlinear Hadron Couplings from Divergence Conditions. I. Pions and Nucleons," S. N. Gupta and W. H. Weihofen, Phys. Rev. D 2, 1123 (1970).

4. "Nonlinear Lagrangian Transformations," S. S. El-Ghabaty, S. N. Gupta, and W. H. Weihofen, Phys. Rev. D. 2, 1130 (1970).

5. "Higher Symmetries and Nuclear Forces," S. S. El-Ghabaty, S. N. Gupta, and W. H. Weihofen, Phys. Rev. D (accepted for publication).

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Relativistic Hadron Model with Intrinsic Mass Splittings*

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(Received 16 June 1969)

A simple mechanism for the $SU(3)$-symmetry breaking in strong interactions is introduced by using the formalism of the multispinor field equations, which avoids the use of physical quarks but has resemblance to the quark model. The resulting treatment leads to the Gell-Mann–Okubo mass formula for baryons, but not for mesons. It yields approximate values of $-19.5°$ and $33°$ for the η-η' and ϕ-ω mixing angles, respectively, and also provides a reasonable explanation for the intermultiplet meson mass formula $m_K{}^2-m_\pi{}^2=m_{K^*}{}^2-m_\rho{}^2$.

1. INTRODUCTION

IT has been suggested[1,2] that baryons and mesons might be composed of three elementary particles called quarks, and it is further believed that the $SU(3)$-symmetry breaking in strong interactions is at least partly due to the difference in the quark masses.[3] The quark model has proved valuable for a dynamical understanding of hadron physics.[4] However, the quarks have quite unusual properties, because they have fractional charges, fractional hypercharges, and a fractional baryon number.[5] Moreover, so far all attempts to observe quarks experimentally have led to negative results.[6]

In view of the uncertainty about the existence of quarks, we shall follow an alternative approach, based on the use of the multispinor field equations.[7] Such an approach does not require the existence of quarks but has resemblance to the quark model. We are not particularly interested in the group-theoretical aspects of the multispinor formalism, but rather consider it as a means of combining the baryon octet of spin $\frac{1}{2}$ with the baryon decuplet of spin $\frac{3}{2}$ and the pseudoscalar-meson nonet with the vector-meson nonet in an elegant manner. We regard all these baryons and mesons as elementary particles, but we shall keep open the possibility that some of the other hadron "resonances" might not represent elementary particles.

It has not been possible so far to provide a satisfactory explanation for the mass splittings of hadrons in the multispinor formalism, but we shall suggest a simple mechanism for the $SU(3)$-symmetry breaking in analogy with the quark model. We postulate that in the multispinor field equations for baryons and mesons the mass parameter m must be replaced by the mass matrix

$$m_i{}^j=\begin{pmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m+\Delta \end{pmatrix}, \tag{1}$$

where i and j are $SU(3)$ indices. We regard the $SU(3)$-symmetry breaking as entirely due to the intrinsic-mass-splitting parameter Δ, and assume that the hadron couplings are $SU(3)$-invariant. As we shall see, it is then possible to find a satisfactory explanation for the mass splittings of hadrons *by combining the intrinsic mass splittings and the self-energy effects.*

Apart from avoiding the use of physical quarks, the present approach has the following advantages: (a) Since in our formalism the major portion of the mass splittings within $SU(3)$ multiplets is due to differences in the intrinsic masses, our approach avoids the difficulties that appear when the entire mass splittings within $SU(3)$ multiplets are regarded as due to self-eneriges.[8] (b) Our symmetry-breaking mechanism leads to η-η' and ϕ-ω mixings in a natural way and enables us to determine the mixing angles. (c) Since at very high energies the intrinsic mass splittings become unimportant, our formalism conforms to the ideas of the asymptotic $SU(3)$ symmetry,[9] while on the other hand, if we regard the mass splittings as due to some $SU(3)$-violating medium-strong interaction, it is not clear why such an interaction should vanish at very high energies.

We shall denote the space-time coordinates as $x_\mu=(x_i,ix_0)$, and take the γ_μ as Hermitian matrices. An asterisk will be used to denote the complex conjugate of a number or the Hermitian conjugate of an operator.

2. SYMMETRY-BREAKING FORMALISM

Let us consider the $SU(3)$-invariant multispinor field equations for baryons and mesons

* Supported in part by the National Science Foundation.

[1] M. Gell-Mann, Phys. Letters **8**, 214 (1964).

[2] G. Zweig, CERN Report, 1964 (unpublished).

[3] G. Zweig, in *Symmetries in Elementary Particle Physics*, edited by A. Zichichi (Academic Press Inc., New York, 1965), p. 192.

[4] R. H. Dalitz, in *Proceedings of the Thirteenth International Conference on High-Energy Physics, Berkeley, California*, edited by M. Alston-Garnjost (University of California Press, Berkeley, 1967), p. 215.

[5] A number of proposals have been made to modify some of the unusual properties of the quarks. See, e.g., H. Bacry, J. Nuyts, and L. Van Hove, Phys. Letters **9**, 279 (1964); F. Gürsey, T. D. Lee, and M. Nauenberg, Phys. Rev. **135**, 467 (1964).

[6] L. Lederman, Comments Nucl. Particle Phys. **1**, 155 (1967). A more recent attempt has been described by Y. Fukushima *et al.*, Phys. Rev. **178**, 2058 (1969).

[7] V. Bargmann and E. P. Wigner, Proc. Natl. Acad. Sci. U. S. **34**, 211 (1948); A. Salam, R. Delbourgo, and J. Strathdee, Proc. Roy. Soc. (London) **A284**, 146 (1965); B. Sakita and K. C. Wali, Phys. Rev. Letters **14**, 404 (1965); Phys. Rev. **139**, B1355 (1965).

[8] R. L. Anderson and S. N. Gupta, Nucl. Phys. **60**, 518 (1964); A. R. Swift, Phys. Rev. **156**, 1729 (1967).

[9] S. Weinberg, Phys. Rev. Letters **18**, 507 (1967); T. Das, V. S. Mathur, and S. Okubo, *ibid.* **18**, 761 (1967).

$$(\gamma\cdot\partial)_\alpha{}^{\alpha'}\Psi_{\alpha' p,\beta q,\gamma r}=(\gamma\cdot\partial)_\beta{}^{\beta'}\Psi_{\alpha p,\beta' q,\gamma r}=(\gamma\cdot\partial)_\gamma{}^{\gamma'}\Psi_{\alpha p,\beta q,\gamma' r}=-3m\Psi_{\alpha p,\beta q,\gamma r}, \quad (2)$$

$$(\gamma\cdot\partial)_\alpha{}^{\alpha'}\Phi_{\alpha' p}{}^{\beta q}=-(\gamma\cdot\partial)_{\beta'}{}^{\beta}\Phi_{\alpha p}{}^{\beta' q}=-2m\Phi_{\alpha p}{}^{\beta q}, \quad (3)$$

where the multispinor $\Psi_{\alpha p,\beta q,\gamma r}$ is totally symmetrical with respect to the exchange of the pairs of indices αp, βq, and γr, and a multispinor of rank n describes particles of mass nm.

According to our symmetry-breaking mechanism, the mass m appearing in the above field equations should be replaced by the mass matrix $m_i{}^j$, given by (1). Thus, (2) and (3) are replaced by

$$\begin{aligned}&(\gamma\cdot\partial)_\alpha{}^{\alpha'}\Psi_{\alpha' p,\beta q,\gamma r}\\&=(\gamma\cdot\partial)_\beta{}^{\beta'}\Psi_{\alpha p,\beta' q,\gamma r}=(\gamma\cdot\partial)_\gamma{}^{\gamma'}\Psi_{\alpha p,\beta q,\gamma' r}\\&=-(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'}\\&\qquad+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'})\Psi_{\alpha p',\beta q',\gamma r'}, \quad (4)\\&(\gamma\cdot\partial)_\alpha{}^{\alpha'}\Phi_{\alpha' p}{}^{\beta q}\\&=-(\gamma\cdot\partial)_{\beta'}{}^{\beta}\Phi_{\alpha p}{}^{\beta' q}\\&=-(m_p{}^{p'}\delta_q{}^{q'}+\delta_p{}^{p'}m_q{}^{q'})\Phi_{\alpha p'}{}^{\beta q'}, \quad (5)\end{aligned}$$

where it is necessary to introduce the mass matrix in a symmetrical form with respect to various indices to ensure that

$$\begin{aligned}&(\gamma\cdot\partial)_\alpha{}^{\alpha'}\Psi_{\alpha' p,\beta q,\gamma r}=(\gamma\cdot\partial)_\beta{}^{\beta'}\Psi_{\alpha p,\beta' q,\gamma r}\\&\qquad=(\gamma\cdot\partial)_\gamma{}^{\gamma'}\Psi_{\alpha p,\beta q,\gamma' r},\\&(\gamma\cdot\partial)_\alpha{}^{\alpha'}\Phi_{\alpha' p}{}^{\beta q}=-(\gamma\cdot\partial)_{\beta'}{}^{\beta}\Phi_{\alpha p}{}^{\beta' q}.\end{aligned}$$

Also observe that (1) is the simplest mass matrix that breaks $SU(3)$ symmetry but preserves $SU(2)$ symmetry.

As shown in Appendix A, the resulting field equations for the octet of spin-$\frac{1}{2}$ baryons, the decuplet of spin-$\frac{3}{2}$ baryons, the nonet of pseudoscalar mesons, and the nonet of vector mesons are given by

$$\gamma\cdot\partial B_r{}^s+(m_r{}^{r'}\delta_{s'}{}^s-\delta_r{}^{r'}m_{s'}{}^s+m_p{}^p\delta_r{}^{r'}\delta_{s'}{}^s)B_{r'}{}^{s'}=0, \quad (6)$$

$$\gamma\cdot\partial D_{\mu,(pqr)}+(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'})D_{\mu,(p'q'r')}=0, \quad (7)$$

$$\Box^2P_p{}^q-(m_p{}^rm_r{}^{p'}\delta_{q'}{}^q+2m_p{}^{p'}m_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^rm_r{}^q)P_{p'}{}^{q'}=0, \quad (8)$$

$$\partial_\nu(\partial_\nu V_{\mu,p}{}^q-\partial_\mu V_{\nu,p}{}^q)-(m_p{}^rm_r{}^{p'}\delta_{q'}{}^q+2m_p{}^{p'}m_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^rm_r{}^q)V_{\mu,p'}{}^{q'}=0, \quad (9)$$

respectively, where we have ignored those relations that merely define auxiliary fields. The symmetry-breaking terms in the field equations can be separated by putting

$$m_i{}^j=m\delta_i{}^j+\Delta\lambda_i{}^j, \quad \lambda_i{}^j\equiv\begin{pmatrix}0&0&0\\0&0&0\\0&0&1\end{pmatrix}. \quad (10)$$

The contractions for the field operators $B_r{}^s$, $D_{\mu,(pqr)}$, $P_p{}^q$, and $V_{\mu,p}{}^q$ are derived in Appendix B and are given by (B11), (B12), (B14), and (B15) up to terms of the first order in Δ. These contractions have the remarkable property that their $SU(3)$-invariant parts involve the usual Feynman's singular functions Δ_F, S_F, ..., while their $SU(3)$-dependent parts involve $\partial\Delta_F/\partial m$, $\partial S_F/\partial m$, ...

Since the precise form of the strong-interaction couplings is not known, we shall only assume that these couplings are Lorentz-invariant as well as $SU(3)$-invariant.[10] Nevertheless, the self-energies of hadrons will contain $SU(3)$-invariant as well as $SU(3)$-dependent parts because of the presence of the $SU(3)$-symmetry-breaking terms in the contractions of the field operators. Let W denote the self-energy of a hadron multiplet up to all orders in the coupling constant, and let us express W as

$$W=W_0+W_1, \quad (11)$$

where W_0 is $SU(3)$-invariant, W_1 is of the first order in Δ, and we have ignored terms of higher order in Δ. By applying the perturbation theory up to any order, it can be seen that W_1 can be obtained from W_0 by replacing in the self-energy integrals one of the singular functions Δ_F, S_F ... by $\partial\Delta_F/\partial m$, $\partial S_F/\partial m$, ..., with appropriate factors. Since differentiation with respect to m tends to reduce the singularities of Δ_F, S_F, etc., it is reasonable to conclude that W_0 represents the dominant self-energy contribution, while W_1 is small compared with W_0. An extension of this argument also justifies the dropping of terms of higher order in Δ in (11) as a reasonable approximation.

The above conclusion essentially means that although the hadron self-energies are large, they are not rapidly varying functions of the hadron masses. Consequently, it is reasonable to include the self-energy contributions up to all orders in the coupling constant, but up to the lowest order in Δ. Moreover, the Δ-dependent part of the self-energy is small compared with the $SU(3)$-invariant part, even if Δ is not too small compared with m.

3. BARYON MASS FORMULAS

We first consider the spin-$\frac{1}{2}$ baryon octet for which the Lagrangian density, corresponding to the field equation (6), is given by

$$L_0=-\bar B_s{}^r\gamma\cdot\partial B_r{}^s-\bar B_s{}^r(m_r{}^{r'}\delta_{s'}{}^s-\delta_r{}^{r'}m_{s'}{}^s+m_p{}^p\delta_r{}^{r'}\delta_{s'}{}^s)B_{r'}{}^{s'}. \quad (12)$$

As explained in Sec. 2, the effect of the self-energy will be to introduce in (12) additional terms of the form

$$L_{\rm self}=-a_0\bar B_s{}^rB_r{}^s-b\bar B_s{}^r\lambda_r{}^{r'}B_{r'}{}^s-c\bar B_s{}^rB_r{}^{s'}\lambda_{s'}{}^s, \quad (13)$$

where a_0 represents the effect of the $SU(3)$-invariant self-energy, while b and c represent the effect of the $SU(3)$-dependent self-energy to the lowest order in Δ. Note that the subscript 0 indicates an $SU(3)$-invariant self-energy parameter.

[10] Our use of the multispinor free-field equations does not imply that we accept the $U(6,6)$ coupling as the fundamental baryon-meson coupling. The strong-interaction couplings, when finally determined, will presumably contain some features of the $SU(6)$ symmetry and chiral dynamics.

With the usual identification of the components of $B_r{}^s$ as

$$B_r{}^s=\begin{bmatrix}\Sigma^0/\sqrt2+\Lambda/\sqrt6 & \Sigma^+ & p\\ \Sigma^- & -\Sigma^0/\sqrt2+\Lambda/\sqrt6 & n\\ \Xi^- & \Xi^0 & -2\Lambda/\sqrt6\end{bmatrix}, \quad (14)$$

the sum of (12) and (13) is expressible as

$$L=-\bar N(\gamma\cdot\partial+m_N)N-\bar\Xi(\gamma\cdot\partial+m_\Xi)\Xi-\bar\Sigma_i(\gamma\cdot\partial+m_\Sigma)\Sigma_i-\bar\Lambda(\gamma\cdot\partial+m_\Lambda)\Lambda, \quad (15)$$

with

$$\begin{aligned}&m_N=(3m+a_0)+c, \quad m_\Xi=(3m+a_0)+2\Delta+b,\\&m_\Sigma=(3m+a_0)+\Delta, \quad m_\Lambda=(3m+a_0)+\Delta+\tfrac{2}{3}b+\tfrac{2}{3}c.\end{aligned} \quad (16)$$

The above masses evidently satisfy the Gell-Mann–Okubo formula

$$\tfrac{1}{2}(m_N+m_\Xi)=\tfrac{1}{4}(3m_\Lambda+m_\Sigma). \quad (17)$$

For the spin-$\frac{3}{2}$ baryon decuplet, the Lagrangian density is

$$\begin{aligned}L_0'=&-\bar D_\mu{}^{(pqr)}[\gamma\cdot\partial\delta_{\mu\nu}-(\gamma_\mu\partial_\nu+\gamma_\nu\partial_\mu)+\gamma_\mu\gamma\cdot\partial\gamma_\nu]D_{\nu,(pqr)}\\&-\bar D_\mu{}^{(pqr)}[(\delta_{\mu\nu}-\gamma_\mu\gamma_\nu)(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'}\\&+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'})]D_{\nu,(p'q'r')}, \quad (18)\end{aligned}$$

which yields not only the field equation (7) but also the necessary relation

$$\gamma_\mu D_{\mu,(pqr)}=0. \quad (19)$$

The modification of the above Lagrangian density due to self-energy must be carried out in an appropriate manner. According to the present approach, the effective interaction energy density due to the self-energy of the baryon decuplet will be of the form

$$\begin{aligned}H'_{\rm self}=&a_0'\bar D_\mu{}^{(pqr)}D_{\mu,(pqr)}\\&+b'\bar D_\mu{}^{(pqr)}(\lambda_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\lambda_q{}^{q'}\delta_r{}^{r'}\\&+\delta_p{}^{p'}\delta_q{}^{q'}\lambda_r{}^{r'})D_{\mu,(p'q'r')}, \quad (20)\end{aligned}$$

which includes $SU(3)$-dependent self-energy terms to the lowest order in Δ. But, in view of (19), it is possible to express (20) as

$$\begin{aligned}H'_{\rm self}=&a_0'\bar D_\mu{}^{(pqr)}(\delta_{\mu\nu}-\gamma_\mu\gamma_\nu)D_{\nu,(pqr)}\\&+b'\bar D_\mu{}^{(pqr)}[(\delta_{\mu\nu}-\gamma_\mu\gamma_\nu)(\lambda_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\lambda_q{}^{q'}\delta_r{}^{r'}\\&+\delta_p{}^{p'}\delta_q{}^{q'}\lambda_r{}^{r'})]D_{\nu,(p'q'r')}, \quad (21)\end{aligned}$$

and thus the effect of self-energy is to introduce in the Lagrangian density additional terms given by

$$\begin{aligned}L'_{\rm self}=&-a_0'\bar D_\mu{}^{(pqr)}(\delta_{\mu\nu}-\gamma_\mu\gamma_\nu)D_{\nu,(pqr)}\\&-b'\bar D_\mu{}^{(pqr)}[(\delta_{\mu\nu}-\gamma_\mu\gamma_\nu)(\lambda_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\lambda_q{}^{q'}\delta_r{}^{r'}\\&+\delta_p{}^{p'}\delta_q{}^{q'}\lambda_r{}^{r'})]D_{\nu,(p'q'r')}, \quad (22)\end{aligned}$$

which ensures that the relation (19) follows from the resulting Lagrangian density.

On using the identification

$$\begin{aligned}&D_{\mu,111}=N_\mu{}^{*++}, \quad D_{\mu,112}=N_\mu{}^{*+}/\sqrt3,\\&D_{\mu,122}=N_\mu{}^{*0}/\sqrt3, \quad D_{\mu,222}=N_\mu{}^{*-},\\&D_{\mu,113}=Y_{1\mu}{}^{*+}/\sqrt3, \quad D_{\mu,123}=Y_{1\mu}{}^{*0}/\sqrt6,\\&D_{\mu,223}=Y_{1\mu}{}^{*-}/\sqrt3, \quad D_{\mu,133}=\Xi_\mu{}^{*0}/\sqrt3,\\&D_{\mu,233}=\Xi_\mu{}^{*-}/\sqrt3, \quad D_{\mu,333}=\Omega_\mu{}^-,\end{aligned} \quad (23)$$

the sum of (18) and (22) gives for the masses of the various members of the decuplet

$$\begin{aligned}&m_{N^*}=(3m+a_0'),\\&m_{Y_1{}^*}=(3m+a_0')+(\Delta+b'),\\&m_{\Xi^*}=(3m+a_0')+2(\Delta+b'),\\&m_{\Omega^-}=(3m+a_0')+3(\Delta+b'),\end{aligned} \quad (24)$$

which again satisfy the Gell-Mann–Okubo formula

$$m_{Y_1{}^*}-m_{N^*}=m_{\Xi^*}-m_{Y_1{}^*}=m_{\Omega^-}-m_{\Xi^*}. \quad (25)$$

4. MESON MASS FORMULAS

The pseudoscalar and vector mesons can be treated in the same way as the baryons. The Lagrangian density for the pseudoscalar-meson nonet, described by the field equation (8), is given by

$$\begin{aligned}L_0=&-\tfrac{1}{2}(\partial_\mu P_q{}^p)(\partial_\mu P_p{}^q)-\tfrac{1}{2}P_q{}^p(m_p{}^rm_r{}^{p'}\delta_{q'}{}^q\\&+2m_p{}^{p'}m_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^rm_r{}^q)P_{p'}{}^{q'}. \quad (26)\end{aligned}$$

The effect of the self-energy will be to introduce in (26) additional terms of the form

$$\begin{aligned}L_{\rm self}=&-\tfrac{1}{2}d_0P_q{}^pP_p{}^q-\tfrac{1}{2}e_0P_p{}^pP_q{}^q\\&-\tfrac{1}{2}fP_q{}^p\lambda_p{}^{p'}P_{p'}{}^q-\tfrac{1}{2}gP_p{}^pP_q{}^q\lambda_{q'}{}^q, \quad (27)\end{aligned}$$

where d_0 and e_0 represent the effect of the $SU(3)$-invariant self-energy, while f and g represent the effect of the $SU(3)$-dependent self-energy to the lowest order in Δ.

On putting

$$P_p{}^q=\begin{bmatrix}\pi^0/\sqrt2+\eta_8/\sqrt6+\eta_1/\sqrt3 & \pi^+ & K^+\\ \pi^- & -\pi^0/\sqrt2+\eta_8/\sqrt6+\eta_1/\sqrt3 & K^0\\ K^- & \bar K^0 & -2\eta_8/\sqrt6+\eta_1/\sqrt3\end{bmatrix}, \quad (28)$$

the sum of (26) and (27) takes the form

$$L=-\tfrac{1}{2}[(\partial_\mu\pi_i)^2+m_\pi{}^2\pi_i{}^2]-[(\partial_\mu K^*)(\partial_\mu K)+m_K{}^2K^*K]-\tfrac{1}{2}[(\partial_\mu\eta_8)^2+m_{\eta_8}{}^2\eta_8{}^2]-\tfrac{1}{2}[(\partial_\mu\eta_1)^2+m_{\eta_1}{}^2\eta_1{}^2]-\tfrac{1}{2}\mu^2\eta_8\eta_1, \quad (29)$$

with

$$\begin{aligned}
&m_\pi{}^2=(4m^2+d_0)\,,\\
&m_K{}^2=(4m^2+d_0)+\Delta^2+\tfrac{1}{2}(8m\Delta+f)\,,\\
&m_{\eta_8}{}^2=(4m^2+d_0)+(8/3)\Delta^2+\tfrac{2}{3}(8m\Delta+f)\,,\\
&m_{\eta_1}{}^2=(4m^2+d_0)+\tfrac{4}{3}\Delta^2+\tfrac{1}{3}(8m\Delta+f)+3e_0+g\,,\\
&\mu^2=-\sqrt{2}[(8/3)\Delta^2+\tfrac{2}{3}(8m\Delta+f)+g]\,,
\end{aligned}\tag{30}$$

where μ^2 is the $\eta_8-\eta_1$ mixing parameter. The above relations do not yield the Gell-Mann–Okubo formula for the K, π, and η_8 masses, but instead we find

$$m_K{}^2=\tfrac{1}{4}(3m_{\eta_8}{}^2+m_\pi{}^2)-\Delta^2.\tag{31}$$

Similarly, the Lagrangian density for the vector-meson nonet, described by the field equation (9), is

$$\begin{aligned}
L_0'=&-\tfrac{1}{4}(\partial_\mu V_{\nu,q}{}^p-\partial_\nu V_{\mu,q}{}^p)(\partial_\mu V_{\nu,p}{}^q-\partial_\nu V_{\mu,p}{}^q)\\
&-\tfrac{1}{2}V_{\mu,q}{}^p(m_p{}^r m_r{}^{p'}\delta_{q',}{}^q+2m_p{}^{p'}m_{q',}{}^q\\
&+\delta_p{}^{p'}m_{q',}{}^r m_r{}^q)V_{\mu,p'}{}^{q'}\,,
\end{aligned}\tag{32}$$

and the effect of the self-energy is to introduce additional terms of the form

$$\begin{aligned}
L'_{\rm self}=&-\tfrac{1}{2}d_0'V_{\mu,q}{}^pV_{\mu,p}{}^q-\tfrac{1}{2}e_0'V_{\mu,p}{}^pV_{\mu,q}{}^q\\
&-\tfrac{1}{2}f'V_{\mu,q}{}^p\lambda_p{}^{p'}V_{\mu,p'}{}^q-\tfrac{1}{2}g'V_{\mu,p}{}^pV_{\mu,q}{}^{q'}\lambda_{q'}{}^q.
\end{aligned}\tag{33}$$

By proceeding in the same way as in the case of the pseudoscalar mesons, we now have

$$\begin{aligned}
&m_\rho{}^2=(4m^2+d_0')\,,\\
&m_{K^*}{}^2=(4m^2+d_0')+\Delta^2+\tfrac{1}{2}(8m\Delta+f')\,,\\
&m_{\omega_8}{}^2=(4m^2+d_0')+(8/3)\Delta^2+\tfrac{2}{3}(8m\Delta+f')\,,\\
&m_{\omega_1}{}^2=(4m^2+d_0')+\tfrac{4}{3}\Delta^2+\tfrac{1}{3}(8m\Delta+f')+3e_0'+g'\,,\\
&\mu'^2=-\sqrt{2}[(8/3)\Delta^2+\tfrac{2}{3}(8m\Delta+f')+g']\,,
\end{aligned}\tag{34}$$

where the role of π, K, η_8, and η_1 has been replaced by ρ, K^*, ω_8, and ω_1, respectively, and μ'^2 is the $\omega_8-\omega_1$ mixing parameter. The relationship between the K^*, ρ, and ω_8 masses is

$$m_{K^*}{}^2=\tfrac{1}{4}(3m_{\omega_8}{}^2+m_\rho{}^2)-\Delta^2.\tag{35}$$

5. MIXING ANGLES AND INTERMULTIPLET MASS FORMULA

The present approach demands that *the $SU(3)$-dependent self-energy parameters be small, while neither the $SU(3)$-invariant self-energy parameters nor the intrinsic-mass-splitting parameter Δ is required to be small.* This enables us to arrive at some interesting conclusions.

By equating the baryon masses, given by (16) and (24), to their experimental values, it is possible to determine $\Delta+b$, $\Delta-c$, and $\Delta+b'$. Moreover, in order that the major portion of the $SU(3)$ mass splittings be accounted for by the intrinsic mass splittings, it would be reasonable to choose Δ in such a way that the magnitudes of the $SU(3)$-dependent self-energy parameters b, c, and b' are as small as possible, which gives

$$\Delta\approx 190\text{ MeV},\tag{36}$$

with

$$b\approx c\approx -65\text{ MeV},\quad b'\approx -45\text{ MeV}.\tag{37}$$

Now, with the substitution of the relations

$$\begin{aligned}
\eta&=\cos\theta_P\,\eta_8-\sin\theta_P\,\eta_1\,,\\
\eta'&=\sin\theta_P\,\eta_8+\cos\theta_P\,\eta_1
\end{aligned}\tag{38}$$

into

$$m_\eta{}^2\eta^2+m_{\eta'}{}^2\eta'^2=m_{\eta_8}{}^2\eta_8{}^2+m_{\eta_1}{}^2\eta_1{}^2+\mu^2\eta_8\eta_1\,,\tag{39}$$

the mixing angle θ_P is expressible as

$$\sin^2\theta_P=(m_{\eta_8}{}^2-m_\eta{}^2)/(m_{\eta'}{}^2-m_\eta{}^2)\,,\tag{40}$$

$$\sin 2\theta_P=\mu^2/(m_{\eta'}{}^2-m_\eta{}^2)\,.\tag{41}$$

By using the theoretical value (36) of Δ and the experimental values of m_K and m_π, we can find m_{η_8} from (31), and by using this value of m_{η_8} along with the experimental values of m_η and $m_{\eta'}$, we can determine the magnitude of θ_P from (40). Moreover, since μ^2, given by (30), is negative and $m_{\eta'}>m_\eta$, it is evident from (41) that θ_P is negative. We thus arrive at the $\eta-\eta'$ mixing angle

$$\theta_P=-19.5^\circ\,,\tag{42}$$

which is considerably larger than the value[11] obtained by using the quadratic Gell-Mann–Okubo mass formula and seems to be in better agreement with some recent results,[12] although the experimental situation is not entirely clear. Indeed, the failure of the experimental results to decide between the two values of θ_P obtained from the quadratic and linear Gell-Mann–Okubo formulas might be due to the fact that our value of θ_P lies between these two values.

Similarly, on replacing the role of η and η' by ϕ and ω, respectively, we obtain for the $\phi-\omega$ mixing angle,

$$\sin^2\theta_V=(m_{\omega_8}{}^2-m_\phi{}^2)/(m_\omega{}^2-m_\phi{}^2)\,,\tag{43}$$

$$\sin 2\theta_V=\mu'^2/(m_\omega{}^2-m_\phi{}^2)\,,\tag{44}$$

which give, on using (35), (36), and the experimental values of m_{K^*}, m_ρ, m_ϕ, and m_ω,

$$\theta_V=32.7^\circ\,,\tag{45}$$

where the positive sign of θ_V results from the fact that μ'^2, given by (34), is negative and $m_\omega<m_\phi$. The above value of θ_V, which is fairly close to the ideal mixing angle $\theta=35.3^\circ$ corresponding to $\tan\theta=1/\sqrt{2}$, agrees with the experimental findings.[13]

It is further possible to find approximate intermultiplet relations from our treatment of the pseudoscalar and vector mesons, for, according to (30) and (34),

$$m_K{}^2-m_\pi{}^2=(\Delta^2+4m\Delta)+\tfrac{1}{2}f\,,\tag{46}$$

$$m_{K^*}{}^2-m_\rho{}^2=(\Delta^2+4m\Delta)+\tfrac{1}{2}f'.\tag{47}$$

Thus, the success of the approximate-mass relation[14]

$$m_K{}^2-m_\pi{}^2=m_{K^*}{}^2-m_\rho{}^2\tag{48}$$

is merely a manifestation of the fact that the $SU(3)$-dependent self-energy contributions $\frac{1}{2}f$ and $\frac{1}{2}f'$ in (46) and (47) are small compared with the intrinsic mass-splitting contribution $\Delta^2+4m\Delta$. Moreover, by assuming that the $SU(3)$-dependent self-energy parameters f, f', g, and g' are all small compared with $2\Delta^2+4m\Delta$, we obtain from (30) and (34) that $\mu^2\approx\mu'^2$, and, consequently, in view of (41) and (44), that

$$\sin 2\theta_P/\sin 2\theta_V=(m_\omega{}^2-m_\phi{}^2)/(m_{\eta'}{}^2-m_\eta{}^2)\,,\tag{49}$$

which is satisfied fairly well by our values of θ_P and θ_V, given by (42) and (45).

The above results show that the present formalism provides a self-consistent model of the baryon and meson mass splittings.

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APPENDIX A: DECOMPSOITION OF THE MULTISPINOR FIELD EQUATIONS

The decomposition of the multispinor field equations (4) and (5) can be carried out in the usual way with appropriate changes because of the presence of the mass-splitting terms.

We put

$$\begin{aligned}
\Psi_{\alpha p,\beta q,\gamma r}=&D_{(\alpha\beta\gamma),(pqr)}\\
&+\tfrac{1}{3}[B_{[\alpha\beta]\gamma,[pq]r}+B_{[\beta\gamma]\alpha,[qr]p}+B_{[\gamma\alpha]\beta,[rp]q}]\\
&+(1/\sqrt{6})A_{[\alpha\beta\gamma]}\epsilon_{pqr}\,,
\end{aligned}\tag{A1}$$

where parentheses denote symmetrical indices, square brackets denote antisymmetrical indices, $B_{[\alpha\beta]\gamma,[pq]r}$ satisfies the relations

$$\begin{aligned}
&B_{[\alpha\beta]\gamma,[pq]r}+B_{[\alpha\beta]\gamma,[qr]p}+B_{[\alpha\beta]\gamma,[rp]q}=0\,,\\
&B_{[\alpha\beta]\gamma,[pq]r}+B_{[\beta\gamma]\alpha,[pq]r}+B_{[\gamma\alpha]\beta,[pq]r}=0\,,
\end{aligned}\tag{A2}$$

and ϵ_{pqr} is the totally antisymmetrical unit tensor. By substituting (A1) into (4) and multiplying by the decuplet projection operator

$$\begin{aligned}
(P_D)_{pqr}{}^{p'q'r'}=&\tfrac{1}{6}(\delta_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{q'}\delta_q{}^{r'}\delta_r{}^{p'}+\delta_p{}^{r'}\delta_q{}^{p'}\delta_r{}^{q'}\\
&+\delta_p{}^{r'}\delta_q{}^{q'}\delta_r{}^{p'}+\delta_p{}^{q'}\delta_q{}^{p'}\delta_r{}^{r'}+\delta_p{}^{p'}\delta_q{}^{r'}\delta_r{}^{q'})\,,
\end{aligned}\tag{A3}$$

we find that terms involving fields other than $D_{(\alpha\beta\gamma),(pqr)}$ vanish because of their symmetry properties. Similarly, the use of the singlet projection operator

$$(P_S)_{pqr}{}^{p'q'r'}=\tfrac{1}{6}\epsilon_{pqr}\epsilon^{p'q'r'}\tag{A4}$$

gives the result that $A_{[\alpha\beta\gamma]}\epsilon_{pqr}$ satisfies (4). It follows that the combination

$$B_{[\alpha\beta]\gamma,[pq]r}+B_{[\beta\gamma]\alpha,[qr]p}+B_{[\gamma\alpha]\beta,[rp]q}$$

also satisfies (4), whence we can show, by multiplying by

$$(\delta_p{}^{p'}\delta_q{}^{q'}-\delta_p{}^{q'}\delta_q{}^{p'})\delta_r{}^{r'}\,,$$

that $B_{[\alpha\beta]\gamma,[pq]r}$ itself satisfies (4). Hence, each of the $SU(3)$ multiplets comprising $\Psi_{\alpha p,\beta q,\gamma r}$ satisfies the field equations (4).

When the multiplet $B_{[\alpha\beta]\gamma,[pq]r}$ is expressed as

$$B_{[\alpha\beta]\gamma,[pq]r}=B_{[\alpha\beta]\gamma,r}{}^s\epsilon_{pqs}\,,\tag{A5}$$

where, in view of (A2),

$$\begin{aligned}
&B_{[\alpha\beta]\gamma,r}{}^r=0\,,\\
&B_{[\alpha\beta]\gamma,r}{}^s+B_{[\beta\gamma]\alpha,r}{}^s+B_{[\gamma\alpha]\beta,r}{}^s=0\,,
\end{aligned}\tag{A6}$$

the field equations take the form

$$\begin{aligned}
&(\gamma\cdot\partial)_\alpha{}^{\alpha'}B_{[\alpha'\beta]\gamma,r}{}^s\\
&\quad=-(m_r{}^{r'}\delta_{s'}{}^s-\delta_r{}^{r'}m_{s'}{}^s+m_p{}^p\delta_r{}^{r'}\delta_{s'}{}^s)B_{[\alpha\beta]\gamma,r'}{}^{s'}\,,\\
&(\gamma\cdot\partial)_\beta{}^{\beta'}B_{[\alpha\beta']\gamma,r}{}^s\\
&\quad=-(m_r{}^{r'}\delta_{s'}{}^s-\delta_r{}^{r'}m_{s'}{}^s+m_p{}^p\delta_r{}^{r'}\delta_{s'}{}^s)B_{[\alpha\beta]\gamma,r'}{}^{s'}\,,\\
&(\gamma\cdot\partial)_\gamma{}^{\gamma'}B_{[\alpha\beta]\gamma',r}{}^s\\
&\quad=-(m_r{}^{r'}\delta_{s'}{}^s-\delta_r{}^{r'}m_{s'}{}^s+m_p{}^p\delta_r{}^{r'}\delta_{s'}{}^s)B_{[\alpha\beta]\gamma,r'}{}^{s'}\,.
\end{aligned}\tag{A7}$$

Keeping in mind the symmetry properties of $B_{[\alpha\beta]\gamma,r}{}^s$, we can also carry out the spinor-tensor decomposition[15]

$$\begin{aligned}
B_{[\alpha\beta]\gamma,r}{}^s=&(C)_{\alpha\beta}(\gamma_5B_r{}^s-i\gamma_5\gamma_\nu B_{\nu,r}{}^s)_\gamma\\
&+i(\gamma_\nu\gamma_5C)_{\alpha\beta}(B_{\nu,r}{}^s)_\gamma+(\gamma_5C)_{\alpha\beta}(B_r{}^s)_\gamma\,,
\end{aligned}\tag{A8}$$

with

$$B_r{}^r=B_{\nu,r}{}^r=0.\tag{A9}$$

By substituting (A8) into the first and the last relations in (A7) and multiplying them by $i(C^{-1}\gamma_\mu\gamma_5)^{\beta\alpha}$ and $(C^{-1}\gamma_5)^{\beta\alpha}$, respectively, we obtain

$$\begin{aligned}
&i\partial_\mu B_r{}^s-(m_r{}^{r'}\delta_{s'}{}^s-\delta_r{}^{r'}m_{s'}{}^s+m_p{}^p\delta_r{}^{r'}\delta_{s'}{}^s)B_{\mu,r'}{}^{s'}=0\,,\\
&\gamma\cdot\partial B_r{}^s+(m_r{}^{r'}\delta_{s'}{}^s-\delta_r{}^{r'}m_{s'}{}^s+m_p{}^p\delta_r{}^{r'}\delta_{s'}{}^s)B_{r'}{}^{s'}=0\,.
\end{aligned}\tag{A10}$$

Similarly, the field equations for $D_{(\alpha\beta\gamma),(pqr)}$, given by

$$\begin{aligned}
&(\gamma\cdot\partial)_\alpha{}^{\alpha'}D_{(\alpha'\beta\gamma),(pqr)}\\
&\quad=-(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'})\\
&\qquad\times D_{(\alpha\beta\gamma),(p'q'r')}\,,\\
&(\gamma\cdot\partial)_\beta{}^{\beta'}D_{(\alpha\beta'\gamma),(pqr)}\\
&\quad=-(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'})\\
&\qquad\times D_{(\alpha\beta\gamma),(p'q'r')}\,,\\
&(\gamma\cdot\partial)_\gamma{}^{\gamma'}D_{(\alpha\beta\gamma'),(pqr)}\\
&\quad=-(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'})\\
&\qquad\times D_{(\alpha\beta\gamma),(p'q'r')}\,,
\end{aligned}\tag{A11}$$

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[13] S. C. C. Ting, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna*, edited by J. Prentki and J. Steinberger (CERN, Geneva, 1968), p. 54.

[14] S. Coleman and S. L. Glashow, Phys. Rev. **134**, B671 (1964).

[15] With the present notation, the antisymmetrical matrix C satisfies the relations $C^{-1}=C^*$, and $C^{-1}\gamma_\mu C=-\gamma_\mu{}^T$.

can be expressed in the spinor-tensor form by putting

$$D_{(\alpha\beta\gamma),(pqr)}=(\gamma_\mu C)_{\alpha\beta}(D_{\mu,(pqr)})_\gamma +\tfrac{1}{2}(\sigma_{\mu\nu}C)_{\alpha\beta}(D_{\mu\nu,(pqr)})_\gamma, \quad \text{(A12)}$$

with

$$\gamma_\mu D_{\mu,(pqr)}=0, \quad D_{\mu,(pqr)}=i\gamma_\nu D_{\mu\nu,(pqr)}. \quad \text{(A13)}$$

Thus, by substituting (A12) into the first and the last relations in (A11) and multiplying them by $(C^{-1}\sigma_{\mu\nu})^{\beta\alpha}$ and $(C^{-1}\gamma_\nu)^{\beta\alpha}$, respectively, we find

$$\begin{aligned} &i(\partial_\mu D_{\nu,(pqr)}-\partial_\nu D_{\mu,(pqr)}) \\ &\quad+(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'}) \\ &\qquad\times D_{\mu\nu,(p'q'r')}=0, \\ &\gamma\cdot\partial D_{\mu,(pqr)}+(m_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}+\delta_p{}^{p'}m_q{}^{q'}\delta_r{}^{r'} \\ &\qquad+\delta_p{}^{p'}\delta_q{}^{q'}m_r{}^{r'})D_{\mu,(p'q'r')}=0. \end{aligned} \quad \text{(A14)}$$

Finally, the field equations for $A_{[\alpha\beta\gamma]}\epsilon_{pqr}$ can be easily simplified to yield

$$\begin{aligned}(\gamma\cdot\partial)_\alpha{}^{\alpha'}A_{[\alpha'\beta\gamma]}&=(\gamma\cdot\partial)_\beta{}^{\beta'}A_{[\alpha\beta'\gamma]}=(\gamma\cdot\partial)_\gamma{}^{\gamma'}A_{[\alpha\beta\gamma']}\\ &=-m_p{}^pA_{[\alpha\beta\gamma]}, \end{aligned} \quad \text{(A15)}$$

which cannot be satisfied by the totally antisymmetrical $A_{[\alpha\beta\gamma]}$ unless

$$A_{[\alpha\beta\gamma]}=0. \quad \text{(A16)}$$

We next carry out the decomposition of (5) by expressing it in the form

$$\tfrac{1}{2}[(\gamma\cdot\partial)_\alpha{}^{\alpha'}\delta_\beta{}^{\beta'}-\delta_\alpha{}^{\alpha'}(\gamma\cdot\partial)_\beta{}^{\beta'}]\Phi_{\alpha'p}{}^{\beta'q} +(m_p{}^{p'}\delta_q{}^{q'}+\delta_p{}^{p'}m_q{}^{q'})\Phi_{\alpha p'}{}^{\beta q'}=0, \quad \text{(A17)}$$

and then putting

$$\Phi_{\alpha p}{}^{\beta q}=\delta_\alpha{}^\beta S_p{}^q+i(\gamma_\mu)_\alpha{}^\beta V_{\mu,p}{}^q+\tfrac{1}{2}(\sigma_{\mu\nu})_\alpha{}^\beta V_{\mu\nu,p}{}^q +i(\gamma_\mu\gamma_5)_\alpha{}^\beta P_{\mu,p}{}^q+i(\gamma_5)_\alpha{}^\beta P_p{}^q, \quad \text{(A18)}$$

which, when substituted into (A17), gives

$$\begin{aligned} &i\gamma_\mu\partial_\nu V_{\mu\nu,p}{}^q-\tfrac{1}{2}\sigma_{\mu\nu}(\partial_\mu V_{\nu,p}{}^q-\partial_\nu V_{\mu,p}{}^q)+i\gamma_\mu\gamma_5\partial_\mu P_p{}^q \\ &\quad+i\gamma_5\partial_\mu P_{\mu,p}{}^q+(m_p{}^{p'}\delta_q{}^{q'}+\delta_p{}^{p'}m_q{}^{q'})(S_{p'}{}^{q'}+i\gamma_\mu V_{\mu,p'}{}^{q'} \\ &\quad+\tfrac{1}{2}\sigma_{\mu\nu}V_{\mu\nu,p'}{}^{q'}+i\gamma_\mu\gamma_5P_{\mu,p'}{}^{q'}+i\gamma_5P_{p'}{}^{q'})=0. \end{aligned} \quad \text{(A19)}$$

The left side of the above equation involves 16 linearly independent matrices $i\gamma_5$, $i\gamma_\mu\gamma_5$, $i\gamma_\mu$, $\frac{1}{2}\sigma_{\mu\nu}$, and 1, whose coefficients must vanish separately. Thus, the meson field equations in the tensor form are

$$\begin{aligned} \partial_\mu P_{\mu,p}{}^q+(m_p{}^{p'}\delta_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^q)P_{p'}{}^{q'}&=0,\\ \partial_\mu P_p{}^q+(m_p{}^{p'}\delta_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^q)P_{\mu,p'}{}^{q'}&=0,\\ \partial_\nu V_{\mu\nu,p}{}^q+(m_p{}^{p'}\delta_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^q)V_{\mu,p'}{}^{q'}&=0,\\ -(\partial_\mu V_{\nu,p}{}^q-\partial_\nu V_{\mu,p}{}^q)+(m_p{}^{p'}\delta_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^q)V_{\mu\nu,p'}{}^{q'}&=0,\\ (m_p{}^{p'}\delta_{q'}{}^q+\delta_p{}^{p'}m_{q'}{}^q)S_{p'}{}^{q'}&=0, \end{aligned} \quad \text{(A20)}$$

and consequently,

$$\Box^2P_p{}^q-(m_p{}^rm_r{}^{p'}\delta_{q'}{}^q+2m_p{}^{p'}m_{q'}{}^r +\delta_p{}^{p'}m_{q'}{}^rm_r{}^q)P_{p'}{}^{q'}=0, \quad \text{(A21)}$$

$$\partial_\nu(\partial_\nu V_{\mu,p}{}^q-\partial_\mu V_{\nu,p}{}^q)-(m_p{}^rm_r{}^{p'}\delta_{q'}{}^q+2m_p{}^{p'}m_{q'}{}^q +\delta_p{}^{p'}m_{q'}{}^rm_r{}^q)V_{\mu,p'}{}^{q'}=0, \quad \text{(A22)}$$

$$S_p{}^q=0. \quad \text{(A23)}$$

APPENDIX B: CONTRACTIONS WITH INTRINSIC MASS SPLITTINGS

In order to determine the effect of the intrinsic mass splittings on the contractions of field operators, consider the case of the spin-$\frac{1}{2}$ baryons, which satisfy the free-field equation

$$(F_{pq'p'q}+\Delta_{pq'p'q})B_{p'}{}^{q'}=0, \quad \text{(B1)}$$

with

$$F_{pq'p'q}=(\gamma\cdot\partial+3m)\delta_p{}^{p'}\delta_{q'}{}^q,$$
$$\Delta_{pq'p'q}=\Delta(\delta_p{}^{p'}\delta_{q'}{}^q+\lambda_p{}^{p'}\delta_{q'}{}^q-\delta_p{}^{p'}\lambda_{q'}{}^q), \quad \text{(B2)}$$

where $\lambda_p{}^q$ is given by (10). Equation (B1) can be decomposed into eight separate equations for the various independent components of $B_p{}^q$, and the corresponding contractions are then uniquely defined. We are, however, interested in how the self-energy integrals for the entire spin-$\frac{1}{2}$ multiplet are affected by the intrinsic mass splitting, so that we seek an expression for the contraction that will exhibit the Δ dependence explicitly.

For this, we first ignore the mass-splitting term $\Delta_{pq'p'q}$ in (B1), which then leads in the usual way to the contraction

$$[B_p{}^q(x)]_\alpha\cdot[\bar B_s{}^r(x')]_\beta=i(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r) \times[S_F(x-x';3m)]_{\alpha\beta}, \quad \text{(B3)}$$

with

$$S_F(x;m)=(\gamma\cdot\partial-m)\Delta_F(x;m), \quad \text{(B4)}$$

where we observe that the above contraction satisfies the relation

$$F_{pq'p'q}[(\delta_{p'}{}^r\delta_s{}^{q'}-\tfrac{1}{3}\delta_{p'}{}^{q'}\delta_s{}^r)S_F(x;3m)] =-(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r)\delta(x). \quad \text{(B5)}$$

The presence of the mass-splitting term in (B1) will change the contraction (B3) into a relation of the form

$$[B_p{}^q(x)]_\alpha\cdot[\bar B_s{}^r(x')]_\beta=i(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r) \times[S_F(x-x';3m)]_{\alpha\beta}+i[T_{ps}{}^{qr}(x-x')]_{\alpha\beta}, \quad \text{(B6)}$$

where, corresponding to (B5), we must now have

$$(F_{pq'p'q}+\Delta_{pq'p'q})[(\delta_{p'}{}^r\delta_s{}^{q'}-\tfrac{1}{3}\delta_{p'}{}^{q'}\delta_s{}^r)S_F(x;3m) +T_{p's}{}^{q'r}(x)]=-(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r)\delta(x), \quad \text{(B7)}$$

which gives

$$(\gamma\cdot\partial+3m)T_{ps}{}^{qr}(x)=-\Delta(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r +\lambda_p{}^r\delta_s{}^q-\delta_p{}^r\lambda_s{}^q)S_F(x;3m)+O(\Delta^2). \quad \text{(B8)}$$

But, by differentiating

$$(\gamma\cdot\partial+3m)S_F(x;3m)=-\delta(x)$$

with respect to m, we have

$$S_F(x;3m)=-\tfrac{1}{3}(\gamma\cdot\partial+3m)(\partial/\partial m)[S_F(x;3m)], \quad \text{(B9)}$$

which enables us to infer from (B8) that

$$T_{ps}{}^{qr}(x)=\tfrac{1}{3}\Delta(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r+\lambda_p{}^r\delta_s{}^q-\delta_p{}^r\lambda_s{}^q) \times(\partial/\partial m)[S_F(x;3m)]+O(\Delta^2). \quad \text{(B10)}$$

Hence, the contraction for the spin-$\frac{1}{2}$ baryon octet with intrinsic mass splitting can be expressed as

$$\begin{aligned}[B_p{}^q(x)]_\alpha\cdot[\bar B_s{}^r(x')]_\beta&=i(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r)[S_F(x-x')]_{\alpha\beta}\\ &+i\tfrac{1}{3}\Delta(\delta_p{}^r\delta_s{}^q-\tfrac{1}{3}\delta_p{}^q\delta_s{}^r+\lambda_p{}^r\delta_s{}^q-\delta_p{}^r\lambda_s{}^q)(\partial/\partial m)\\ &\times[S_F(x-x';3m)]_{\alpha\beta}+O(\Delta^2). \end{aligned} \quad \text{(B11)}$$

Similarly, for the spin-$\frac{3}{2}$ baryon decuplet we obtain[16]

$$\begin{aligned}[D_{\mu,(pqr)}(x)]_\alpha\cdot[\bar D_\nu{}^{(lmn)}(x')]_\beta&\cdot\\ =i(P_D)_{pqr}{}^{lmn}[S_{\mu\nu,F}(x-x')]_{\alpha\beta}&+i\tfrac{1}{3}\Delta(\lambda_p{}^{p'}\delta_q{}^{q'}\delta_r{}^{r'}\\ +\delta_p{}^{p'}\lambda_q{}^{q'}\delta_r{}^{r'}&+\delta_p{}^{p'}\delta_q{}^{q'}\lambda_r{}^{r'})(P_D)_{p'q'r'}{}^{lmn}\\ \times(\partial/\partial m)[S_{\mu\nu,F}(x-x';3m)]_{\alpha\beta}&+O(\Delta^2), \end{aligned} \quad \text{(B12)}$$

[16] Strictly speaking, (B12) gives the *effective* contraction. See S. N. Gupta and W. W. Repko, Phys. Rev. **177**, 1921 (1969).

where P_D is given by (A3), and $S_{\mu\nu,F}$ by

$$S_{\mu\nu,F}(x;m)=(\gamma\cdot\partial-m)[\delta_{\mu\nu}-\tfrac{1}{3}\gamma_\mu\gamma_\nu+\tfrac{1}{3}m^{-1}(\gamma_\mu\partial_\nu-\gamma_\nu\partial_\mu) -\tfrac{2}{3}m^{-2}\partial_\mu\partial_\nu]\Delta_F(x;m), \quad \text{(B13)}$$

while for the pseudoscalar and vector meson nonets we have

$$\begin{aligned}[P_p{}^q(x)]\cdot[P_s{}^r(x')]&\cdot\\ =-i\delta_p{}^r\delta_s{}^q\Delta_F(x-x';2m)&-i\tfrac{1}{2}\Delta(\lambda_p{}^r\delta_s{}^q+\delta_p{}^r\lambda_s{}^q)\\ \times(\partial/\partial m)[\Delta_F(x-x';2m)]&+O(\Delta^2), \end{aligned} \quad \text{(B14)}$$

$$\begin{aligned}[V_{\mu,p}{}^q(x)]\cdot[V_{\nu,s}{}^r(x')]&\cdot\\ =-i\delta_p{}^r\delta_s{}^q(\delta_{\mu\nu}-\tfrac{1}{4}m^{-2}\partial_\mu\partial_\nu)\Delta_F(x-x';2m)&\\ -i\tfrac{1}{2}\Delta(\lambda_p{}^r\delta_s{}^q+\delta_p{}^r\lambda_s{}^q)(\partial/\partial m)[(\delta_{\mu\nu}-\tfrac{1}{4}m^{-2}\partial_\mu\partial_\nu)&\\ \times\Delta_F(x-x';2m)]+O(\Delta^2). \end{aligned} \quad \text{(B15)}$$

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Nonlinear Hadron Couplings from Divergence Conditions. I. Pions and Nucleons

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It is shown that chiral-dynamical models for the pion-nucleon system can be obtained simply by requiring that the source function in the pion field equation be expressible as a complete divergence. Both nonderivative and derivative pion-nucleon couplings are considered. The nonderivative-coupling case yields models with one coupling constant, while the derivative-coupling case leads to models involving two coupling constants. Since our approach avoids the use of chiral symmetry, it does not raise the problems associated with a broken symmetry. It is also suggested that the nonlinear pion-nucleon coupling, arising from the divergence condition, might very well represent a fundamental coupling rather than merely an effective coupling.

I. INTRODUCTION

WHEN confronted with phenomena whose basic nature is unknown, it is often helpful to search for analogies with other phenomena that are better understood. The theories of electromagnetic and gravitational interactions have been developed to the extent where they are considered to be in the latter category, and are found to have significant similarities.[1] The fundamental basis of strong and weak interactions, on the other hand, is not well known. The purpose of this investigation is to explore the theory of strong interactions by emphasizing an analogy between the meson field equations and the electromagnetic and gravitational field equations. We shall confine ourselves to the interaction of pions and nucleons in this paper, while other mesons and baryons will be included in subsequent papers.

Since the source functions in the electromagnetic and gravitational field equations represent the current four-vector and the total energy-momentum tensor, they satisfy the condition of vanishing divergence, and it seems reasonable to look for appropriate divergence conditions for the source functions in the meson field equations. However, the source function in the pion field equation does not carry any tensor index, and we cannot demand that its divergence vanish. We shall, instead, impose the requirement that for the pion-nucleon system this source function be expressible as a complete divergence, and thus the pion field equation should be of the form

$$(\Box^2-m^2)\boldsymbol{\pi}=\partial_\mu \mathbf{J}_{\mu 5}. \tag{1.1}$$

It is also natural to assume that the Lagrangian density, which yields (1.1), should involve derivatives of the lowest possible order.

In recent years Weinberg,[2] Schwinger,[3] and others[4] have proposed Lagrangian schemes with broken chiral symmetry, which seem promising in the light of experimental results. We shall show that all the chiral-symmetry results together with the symmetry-breaking terms for the pion-nucleon system can be obtained simply as a consequence of requiring that the pion field equation be expressible in the form (1.1). Evidently, the field equation (1.1) can be written

$$\partial_\mu(\mathbf{J}_{\mu 5}-\partial_\mu\boldsymbol{\pi})=-m^2\boldsymbol{\pi}, \tag{1.2}$$

which can be interpreted as the well-known condition[5,6] for the partially conserved axial-vector current (PCAC), if we regard $\mathbf{J}_{\mu 5}-\partial_\mu\boldsymbol{\pi}$ with appropriate normalization as the PCAC current. *Thus, in the present treatment we regard the PCAC condition as fundamental but completely avoid the use of chiral symmetry.*[7]

Apart from its basic simplicity, our formulation has the following conceptual advantages.

(1) The analogy between the pion field equation and the electromagnetic and gravitational field equations suggests that the nonlinear pion-nucleon couplings resulting from our treatment might represent fundamental couplings and not merely effective couplings.

(2) Since we do not make use of the broken chiral symmetry, we are not faced with the question of why and how this symmetry is broken.

(3) There is no temptation here to introduce the scalar σ meson.

We shall first consider the case of the nonderivative pion-nucleon coupling in Secs. II and III, then consider the case of the derivative pion-nucleon coupling in Secs. IV and V, and subsequently establish the relationship between them in Sec. VI, where the role of the chiral symmetry will also be briefly discussed.

We shall take $c=\hbar=1$, denote the space-time coordinates as $x_\mu=(x_1,x_2,x_3,ix_0)$. treat the γ_μ as Hermitian matrices, and use boldface letters to denote isovectors.

[1] S. N. Gupta, Phys. Rev. **96**, 1683 (1954).
[2] S. Weinberg, Phys. Rev. Letters **18**, 188 (1967).
[3] J. Schwinger, Phys. Letters **24B**, 473 (1967).
[4] For a review of Lagrangian schemes with chiral symmetry, see S. Gasiorowicz and D. A. Geffen, Rev. Mod. Phys. **41**, 531 (1969).
[5] M. Gell-Mann and M. Lévy, Nuovo Cimento **16**, 705 (1960).
[6] Y. Nambu, Phys. Rev. Letters **4**, 380 (1960).
[7] The fundamental role of the PCAC condition in the derivation of Lagrangian schemes for the pion-nucleon system has also been recognized by other authors. See, e.g., D. B. Fairlie and K. Yoshida, Phys. Rev. **174**, 1816 (1968); R. Dashen and M. Weinstein, *ibid.* **183**, 1261 (1969).

An asterisk will be used to denote the complex conjugate of a number or the Hermitian conjugate of an operator.

II. LAGRANGIAN FORMALISM WITH NONDERIVATIVE PION-NUCLEON COUPLING

In order to examine the restrictions imposed on the Lagrangian density for a pion-nucleon system by the divergence condition, we begin by considering the general nonlinear form[8]

$$L=L_{0\pi}+L_{0N}+L_{\pi\pi}+L_{\pi N}, \tag{2.1}$$

where

$$L_{0\pi}=-\tfrac{1}{2}(\partial_\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}+m^2\boldsymbol{\pi}\cdot\boldsymbol{\pi}), \tag{2.2}$$

$$L_{0N}=-\bar{N}(\gamma\cdot\partial+M)N, \tag{2.3}$$

$$L_{\pi\pi}=a(\boldsymbol{\pi}^2)+b(\boldsymbol{\pi}^2)\partial_\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}+c(\boldsymbol{\pi}^2)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2, \tag{2.4}$$

$$L_{\pi N}=-M\bar{N}\alpha(i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi})N. \tag{2.5}$$

Since $(\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi})^2=\boldsymbol{\pi}^2$, the function α can be expressed as

$$\alpha(i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi})=s(\boldsymbol{\pi}^2)+2it(\boldsymbol{\pi}^2)\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}, \tag{2.6}$$

and thus L involves the five unknown Hermitian functions $a(\boldsymbol{\pi}^2)$, $b(\boldsymbol{\pi}^2)$, $c(\boldsymbol{\pi}^2)$, $s(\boldsymbol{\pi}^2)$, and $t(\boldsymbol{\pi}^2)$. It is the most general isospin-invariant Lagrangian density with nonlinearity in the pion field such that $L_{\pi\pi}$ is at most bilinear in the derivative of the pion field, and $L_{\pi N}$ contains no derivative coupling. Because L must reduce to the free Lagrangian density $L_{0\pi}+L_{0N}$ in the absence of interaction, it is required that

$$a(0)=a'(0)=b(0)=s(0)=0, \tag{2.7}$$

where a prime denotes differentiation with respect to the argument, which is $\boldsymbol{\pi}^2$.

The above Lagrangian density yields the nucleon field equations

$$\begin{aligned}&\partial_\mu\bar{N}\gamma_\mu=M\bar{N}(1+s+2it\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}),\\ &\gamma_\mu\partial_\mu N=-M(1+s+2it\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi})N,\end{aligned} \tag{2.8}$$

and the pion field equation

$$\begin{aligned}(\Box^2-m^2)\boldsymbol{\pi}=&2Ms'\bar{N}N\boldsymbol{\pi}+4Mt'(\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\ &+2Mt\bar{N}i\gamma_5\boldsymbol{\tau}N-2a'\boldsymbol{\pi}+2c'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}\\ &+4b'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}+2(c-b')\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\ &+2b'(\boldsymbol{\pi}\cdot\Box^2\boldsymbol{\pi})\boldsymbol{\pi}+2b\Box^2\boldsymbol{\pi}.\end{aligned} \tag{2.9}$$

In order that (2.9) be expressible in the form (1.1), $\mathbf{J}_{\mu5}$ must evidently be of the form

$$\mathbf{J}_{\mu5}=\beta\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N+d(\boldsymbol{\pi}^2)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}+e(\boldsymbol{\pi}^2)\partial_\mu\boldsymbol{\pi}, \tag{2.10}$$

with

$$\beta=\text{const}, \quad e(0)=0, \tag{2.11}$$

[8] It is understood that the Lagrangian density consists of ordered products of field operators, although for simplicity we have omitted the ordered-product notation. See S. N. Gupta, Phys. Rev. **107**, 1722 (1957).

where β is required to be a constant rather than a function of $\boldsymbol{\pi}^2$ because the terms bilinear in the nucleon field in (2.9) do not involve any derivative of the pion field. Substitution of (2.10) into (1.1) gives

$$\begin{aligned}(\Box^2-m^2)\boldsymbol{\pi}=&\beta(\partial_\mu\bar{N})i\gamma_\mu\gamma_5\boldsymbol{\tau}N+\beta\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\partial_\mu N\\ &+2d'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}+d\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\ &+(d+2e')(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}+e\Box^2\boldsymbol{\pi},\end{aligned} \tag{2.12}$$

so that, on simplification with the help of (2.8),

$$\begin{aligned}(1-e)\Box^2\boldsymbol{\pi}=&2M\beta(1+s)\bar{N}i\gamma_5\boldsymbol{\tau}N-4M\beta t\bar{N}N\boldsymbol{\pi}\\ &+2d'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}+d\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\ &+(d+2e')(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}+m^2\boldsymbol{\pi}.\end{aligned} \tag{2.13}$$

By obtaining the value of $\Box^2\boldsymbol{\pi}$ from (2.13) and substituting it into (2.9), we obtain

$$\begin{aligned}&2[s'(1-e)+2(1-2b-2b'\boldsymbol{\pi}^2)t\beta]M\bar{N}N\boldsymbol{\pi}\\ &+2[t(1-e)+(2b-1)(1+s)\beta]M\bar{N}i\gamma_5\boldsymbol{\tau}N\\ &+4[t'(1-e)+b'(1+s)\beta]M(\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\ &+[2a'(e-1)+(2b-e)m^2+2b'm^2\boldsymbol{\pi}^2]\boldsymbol{\pi}\\ &+[4b'(1-e)+(2b-1)(d+2e')](\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}\\ &+[2(c-b')(1-e)+(2b-1)d+2b'd\boldsymbol{\pi}^2]\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\ &+2[c'(1-e)+(2b-1)d'+b'(d+2e')+2b'd'\boldsymbol{\pi}^2]\\ &\times(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}=0.\end{aligned} \tag{2.14}$$

The above equation can be satisfied only if the coefficients of the terms involving $\bar{N}N\boldsymbol{\pi}$, $\bar{N}i\gamma_5\boldsymbol{\tau}N$, $(\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}$, $\boldsymbol{\pi}$, $(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}$, $\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}$, and $(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}$ vanish separately. The solution of the resulting differential equations leads, as shown in Appendix A, to the following relationships.

Let us put

$$t(0)=f, \tag{2.15}$$

so that f can be interpreted as a coupling constant that specifies the first-order pion-nucleon coupling in (2.5). The constant β is then given by

$$\beta=f. \tag{2.16}$$

The functions s and t are not determined uniquely, but they satisfy the relation

$$(1+s)^2+4t^2\boldsymbol{\pi}^2=1, \tag{2.17}$$

while the functions a, b, c, d, and e can be expressed in terms of f, s, and t as

$$1-2a'/m^2=-s'/2ft, \tag{2.18}$$

$$1-2b=t^2/f^2, \tag{2.19}$$

$$c=(t^4-\tfrac{1}{4}s'^2)/2f^2t^2\boldsymbol{\pi}^2, \tag{2.20}$$

$$d=(2/f)[ts'-t'(1+s)], \tag{2.21}$$

$$e=1-(t/f)(1+s). \tag{2.22}$$

III. SPECIAL NONDERIVATIVE-COUPLING MODELS

The divergence condition provides the four relations (2.17), (2.18), (2.19), and (2.20), which are to be satisfied by the five functions a, b, c, s, and t appearing in the Lagrangian density. Therefore, all these functions can be determined only by choosing one of them in some appropriate manner. We shall now discuss three special models such that in each model one of the functions a, b, and c vanishes. This simple procedure, as we shall see, yields all the models considered by Chang and Gürsey.[9]

Model A

We first consider the model obtained by putting

$$a\equiv0. \tag{3.1}$$

Then, according to (2.18),

$$-s'/2ft=1$$

or, on using (2.17),

$$[1-(1+s)^2]^{-1/2}s'=-(1/\sqrt{\boldsymbol{\pi}^2})f,$$

which gives, in view of the condition (2.7),

$$s=\cos(2f\sqrt{\boldsymbol{\pi}^2})-1, \tag{3.2}$$

and, on using (2.17) again,

$$t=(1/2\sqrt{\boldsymbol{\pi}^2})\sin(2f\sqrt{\boldsymbol{\pi}^2}). \tag{3.3}$$

Substitution of (3.2) and (3.3) into (2.19)–(2.22) gives all the functions appearing in $L_{\pi N}$, $L_{\pi\pi}$, and $\mathbf{J}_{\mu5}$, and thus

$$\begin{aligned}L_{\pi N}=&-M[\cos(2f\sqrt{\boldsymbol{\pi}^2})-1]\bar{N}N\\ &-M(1/\sqrt{\boldsymbol{\pi}^2})\sin(2f\sqrt{\boldsymbol{\pi}^2})\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N,\end{aligned} \tag{3.4}$$

$$\begin{aligned}L_{\pi\pi}=&\tfrac{1}{2}[1-(1/4f^2\boldsymbol{\pi}^2)\sin^2(2f\sqrt{\boldsymbol{\pi}^2})]\\ &\times[\partial_\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}-(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2/\boldsymbol{\pi}^2],\end{aligned} \tag{3.5}$$

$$\begin{aligned}\mathbf{J}_{\mu5}=&f\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N+(1/\boldsymbol{\pi}^2)[1-(1/4f\sqrt{\boldsymbol{\pi}^2})\\ &\times\sin(4f\sqrt{\boldsymbol{\pi}^2})][\boldsymbol{\pi}^2\partial_\mu\boldsymbol{\pi}-(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}].\end{aligned} \tag{3.6}$$

Model B

To obtain another model we require that

$$b\equiv0, \tag{3.7}$$

so that (2.19), together with (2.15), yields

$$t=f, \tag{3.8}$$

and, on using (2.17),

$$s=(1-4f^2\boldsymbol{\pi}^2)^{1/2}-1. \tag{3.9}$$

Again, the above values of s and t enable us to determine all the required functions, and lead to the results

$$\begin{aligned}L_{\pi N}=&-M[(1-4f^2\boldsymbol{\pi}^2)^{1/2}-1]\bar{N}N\\ &-2fM\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N,\end{aligned} \tag{3.10}$$

$$\begin{aligned}L_{\pi\pi}=&(m^2/4f^2)[(1-4f^2\boldsymbol{\pi}^2)^{1/2}-1+2f^2\boldsymbol{\pi}^2]\\ &-2f^2(1-4f^2\boldsymbol{\pi}^2)^{-1}(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2,\end{aligned} \tag{3.11}$$

$$\begin{aligned}\mathbf{J}_{\mu5}=&f\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N-4f^2(1-4f^2\boldsymbol{\pi}^2)^{-1/2}(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\ &+[1-(1-4f^2\boldsymbol{\pi}^2)^{1/2}]\partial_\mu\boldsymbol{\pi}.\end{aligned} \tag{3.12}$$

This model was suggested by Gell-Mann and Lévy,[5] and further developed by Weinberg[2] and by Brown.[10]

Model C

If we put

$$c\equiv0, \tag{3.13}$$

it follows from (2.20) that

$$\tfrac{1}{4}s'^2=t^4 \quad \text{or} \quad -\tfrac{1}{2}s'=t^2,$$

where, in addition to $t(0)=f$ we have used the condition $s'(0)=-2f^2$, which is obtained by differentiating (2.17) with respect to $\boldsymbol{\pi}^2$ and then putting $\boldsymbol{\pi}^2=0$. The above relation becomes, on using (2.17),

$$[1-(1+s)^2]^{-1}s'=-(1/2\boldsymbol{\pi}^2),$$

which gives, when integrated with the condition (2.7),

$$s=-2f^2\boldsymbol{\pi}^2(1+f^2\boldsymbol{\pi}^2)^{-1}, \tag{3.14}$$

and, on using (2.17) again,

$$t=f(1+f^2\boldsymbol{\pi}^2)^{-1}. \tag{3.15}$$

After determining the required functions with the help of (3.14) and (3.15), we obtain

$$\begin{aligned}L_{\pi N}=&2Mf^2\boldsymbol{\pi}^2(1+f^2\boldsymbol{\pi}^2)^{-1}\bar{N}N-2Mf(1+f^2\boldsymbol{\pi}^2)^{-1}\\ &\times\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N,\end{aligned} \tag{3.16}$$

$$\begin{aligned}L_{\pi\pi}=&\tfrac{1}{2}m^2[\boldsymbol{\pi}^2-(1/f^2)\ln(1+f^2\boldsymbol{\pi}^2)]\\ &+\tfrac{1}{2}[1-(1+f^2\boldsymbol{\pi}^2)^{-2}](\partial_\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}),\end{aligned} \tag{3.17}$$

$$\begin{aligned}\mathbf{J}_{\mu5}=&f\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N-2f^2(1+f^2\boldsymbol{\pi}^2)^{-2}(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\ &+[1-(1-f^2\boldsymbol{\pi}^2)(1+f^2\boldsymbol{\pi}^2)^{-2}]\partial_\mu\boldsymbol{\pi}.\end{aligned} \tag{3.18}$$

This model is related to the work of Schwinger discussed in Sec. V.

Besides the above three models, we have been able to find two other reasonably simple models corresponding to $d=0$ and $s'=\text{const}$, respectively. The values of s and t for these models are

$$s=(1+4f^2\boldsymbol{\pi}^2)^{-1/2}-1, \quad t=f(1+4f^2\boldsymbol{\pi}^2)^{-1/2}$$

for $d=0$, and

$$s=-2f^2\boldsymbol{\pi}^2, \quad t=f(1-f^2\boldsymbol{\pi}^2)^{1/2}$$

for $s'=\text{const}$. The derivation of $L_{\pi N}$, $L_{\pi\pi}$, and $\mathbf{J}_{\mu5}$ from the above values of s and t is quite straightforward.

[9] P. Chang and F. Gürsey, Phys. Rev. **164**, 1752 (1967).

[10] L. S. Brown, Phys. Rev. **163**, 1802 (1967).

IV. LAGRANGIAN FORMALISM WITH DERIVATIVE PION-NUCLEON COUPLING

We shall now reinvestigate the Lagrangian formalism of Sec. II by giving up the condition that $L_{\pi N}$ contains no derivative coupling and assuming instead that $L_{\pi N}$ contains a single derivative of the pion field. Thus, we retain the Lagrangian density of Sec. II except that $L_{\pi N}$, given by (2.5), is replaced by

$$L_{\pi N}=\alpha_1(\pi^2)\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N+\alpha_2(\pi^2)\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N +\alpha_3(\pi^2)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N, \quad (4.1)$$

with α_1, α_2, and α_3 unknown Hermitian functions of π^2. In addition, we must now include analogous terms in the general form of $\mathbf{J}_{\mu 5}$, which becomes

$$\mathbf{J}_{\mu 5}=\beta_1(\pi^2)\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N+\beta_2(\pi^2)\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N +\beta_3(\pi^2)(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi} +d(\pi^2)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}+e(\pi^2)\partial_\mu\boldsymbol{\pi}. \quad (4.2)$$

The Lagrangian formalism yields the nucleon field equations

$$\begin{aligned}\partial_\mu\bar{N}\gamma_\mu&=\bar{N}[M-\alpha_1 i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}-\alpha_2 i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}\\&\qquad-\alpha_3(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}],\\ \gamma_\mu\partial_\mu N&=-[M-\alpha_1 i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}-\alpha_2 i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}\\&\qquad-\alpha_3(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}]N,\end{aligned} \quad (4.3)$$

and the pion field equation

$$\begin{aligned}&(\Box^2-m^2)\boldsymbol{\pi}\\&=\partial_\mu[\alpha_1\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N+\alpha_2\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N\\&\quad+\alpha_3\boldsymbol{\pi}(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)]-2\alpha\boldsymbol{\pi}[a_1'\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N\\&\quad+\alpha_2'\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N+\alpha_3'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N]\\&\quad+\alpha_2\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\partial_\mu\boldsymbol{\pi}N-\alpha_3\bar{N}i\gamma_\mu\gamma_5(\boldsymbol{\tau}\cdot\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}N\\&\quad-\alpha_3\bar{N}i\gamma_\mu\gamma_5(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\tau}N\\&\quad-2a'\boldsymbol{\pi}+2c'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}+4b'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}\\&\quad+2(c-b')\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}+2b'(\boldsymbol{\pi}\cdot\Box^2\boldsymbol{\pi})\boldsymbol{\pi}\\&\qquad+2b\Box^2\boldsymbol{\pi}.\end{aligned} \quad (4.4)$$

On the other hand, substitution of (4.2) into the divergence condition (1.1) gives

$$\begin{aligned}&(\Box^2-m^2)\boldsymbol{\pi}=\partial_\mu[\beta_1\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N+\beta_2\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N\\&\quad+\beta_3\boldsymbol{\pi}(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)]+2d'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}\\&\quad+d\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}+(d+2e')(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}+e\Box^2\boldsymbol{\pi}.\end{aligned} \quad (4.5)$$

The total divergence terms appearing in (4.4) and (4.5) have the same structure, and they can be simplified by using the nucleon field equations (4.3) and the commutation property of the isospin matrices

$$[\boldsymbol{\tau}\cdot\mathbf{A},\boldsymbol{\tau}]=2i\boldsymbol{\tau}\times\mathbf{A}, \quad (4.6)$$

along with the standard vector identities such as

$$\begin{aligned}&\boldsymbol{\tau}\times(\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi})=(\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}-(\boldsymbol{\tau}\cdot\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi},\\&(\boldsymbol{\tau}\cdot\boldsymbol{\pi})\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}=(\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\&\qquad-(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\tau}\times\boldsymbol{\pi}+\pi^2\boldsymbol{\tau}\times\partial_\mu\boldsymbol{\pi}.\end{aligned} \quad (4.7)$$

Thus, it is possible to express (4.4) as

$$\begin{aligned}&(\Box^2-m^2)\boldsymbol{\pi}=2M\alpha_1\bar{N}i\gamma_5\boldsymbol{\tau}N+2M\alpha_3(\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+(2\alpha_1'-\alpha_3-2\alpha_1\alpha_2-2\alpha_2\alpha_3\pi^2)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N\\&\quad-(2\alpha_1'-\alpha_3-2\alpha_1\alpha_2-2\alpha_2\alpha_3\pi^2)(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad-2(\alpha_2'-\alpha_2^2+\alpha_1\alpha_3)(\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+2(\alpha_2'-\alpha_2^2+\alpha_1\alpha_3)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N\\&\quad+2(\alpha_2+\alpha_1{}^2+\alpha_2{}^2\pi^2)\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\partial_\mu\boldsymbol{\pi}N\\&\quad-2\alpha'\boldsymbol{\pi}+2c'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}+4b'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}\\&\quad+2(c-b')\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}+2b'(\boldsymbol{\pi}\cdot\Box^2\boldsymbol{\pi})\boldsymbol{\pi}+2b\Box^2\boldsymbol{\pi},\end{aligned} \quad (4.8)$$

and (4.5) as

$$\begin{aligned}&(1-e)\Box^2\boldsymbol{\pi}=2M\beta_1\bar{N}i\gamma_5\boldsymbol{\tau}N+2M\beta_3(\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+2(\beta_1'-\alpha_1\beta_2-\alpha_3\beta_2\pi^2)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N\\&\quad+2(\beta_3'-\alpha_2\beta_3+\alpha_3\beta_2)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+(\beta_3+2\alpha_2\beta_1+2\alpha_2\beta_3\pi^2)(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+2(\alpha_2\beta_2-\alpha_1\beta_3)(\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+(\beta_3+2\alpha_1\beta_2-2\alpha_2\beta_1)(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\partial_\mu\boldsymbol{\pi}\\&\quad+2(\beta_2'-\alpha_2\beta_2+\alpha_3\beta_1)(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N\\&\quad+(\beta_2+2\alpha_1\beta_1+2\alpha_2\beta_2\pi^2)\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\partial_\mu\boldsymbol{\pi}N\\&\quad+2d'(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}+d\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\&\qquad+(d+2e')(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}+m^2\boldsymbol{\pi}.\end{aligned} \quad (4.9)$$

By obtaining the value of $\Box^2\boldsymbol{\pi}$ from (4.9) and substituting it into (4.8), we find

$$\begin{aligned}&[2M\beta_1(1-2b)-2M\alpha_1(1-e)](\bar{N}i\gamma_5\boldsymbol{\tau}N)+[2M\beta_3(1-2b)-4Mb'(\beta_1+\beta_3\pi^2)-2M\alpha_3(1-e)](\bar{N}i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+[2(\beta_1'-\alpha_1\beta_2-\alpha_3\beta_2\pi^2)(1-2b)-(2\alpha_1'-\alpha_3-2\alpha_1\alpha_2-2\alpha_2\alpha_3\pi^2)(1-e)](\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N)\\&\quad+[2(\beta_3'-\alpha_2\beta_3+\alpha_3\beta_2)(1-2b)-2b'(2\beta_1'+\beta_3-2\alpha_2\beta_1+2\beta_3'\pi^2-2\alpha_2\beta_3\pi^2)](\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad+[(\beta_3+2\alpha_2\beta_1+2\alpha_2\beta_3\pi^2)(1-2b)-2b'\pi^2(\beta_3+2\alpha_2\beta_1+2\alpha_2\beta_3\pi^2)+(2\alpha_1'-\alpha_3-2\alpha_1\alpha_2-2\alpha_2\alpha_3\pi^2)(1-e)]\\&\quad\times(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N)\boldsymbol{\pi}+[2(\alpha_2\beta_2-\alpha_1\beta_3)(1-2b)+2b'(\beta_2+2\alpha_1\beta_1+2\alpha_1\beta_3\pi^2)-2(\alpha_2^2-\alpha_2'-\alpha_1\alpha_3)(1-e)]\\&\quad\times(\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N)\boldsymbol{\pi}+[(\beta_3+2\alpha_1\beta_2-2\alpha_2\beta_1)(1-2b)](\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\partial_\mu\boldsymbol{\pi}\\&\quad+[2(\beta_2'-\alpha_2\beta_2+\alpha_3\beta_1)(1-2b)+2(\alpha_2^2-\alpha_2'-\alpha_1\alpha_3)(1-e)](\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})(\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N)\\&\quad+[(\beta_2+2\alpha_1\beta_1+2\alpha_2\beta_2\pi^2)(1-2b)-2(\alpha_1{}^2+\alpha_2+\alpha_2{}^2\pi^2)(1-e)](\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\partial_\mu\boldsymbol{\pi}N)-[2a'(e-1)+(2b-e)m^2+2b'm^2\pi^2]\boldsymbol{\pi}\\&\quad-[4b'(1-e)+(2b-1)(d+2e')](\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\partial_\mu\boldsymbol{\pi}-[2(c-b')(1-e)+(2b-1)d+2b'd\pi^2]\partial_\mu(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\&\qquad-2[c'(1-e)+(2b-1)d'+b'(d+2e')+2b'd'\pi^2](\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2\boldsymbol{\pi}=0.\end{aligned} \quad (4.10)$$

Again, as in Sec. II, the coefficients of all the terms on the left-hand side of (4.10) must vanish separately. Then, after solving the differential equations, as shown in Appendix B, we arrive at the following results.

By introducing two functions $s(\pi^2)$ and $t(\pi^2)$ such that

$$(1+s)^2+4t^2\pi^2=1, \quad (4.11)$$

with

$$s(0)=0, \quad t(0)=f, \quad (4.12)$$

it is possible to express the functions a, b, c, d, and e again in terms of f, s, and t by means of the relations (2.18) to (2.22). We also put

$$\alpha_1(0)=g, \quad (4.13)$$

so that g can be interpreted as a coupling constant that specifies the first-order pion-nucleon coupling in (4.1). We are then able to express the functions α_1, α_2, and α_3 in terms of g, f, s, and t as

$$\begin{aligned}\alpha_1&=gt/f,\\ \alpha_2&=s/2\pi^2,\\ \alpha_3&=(2g/f)[(1+s)t'-s't+st/2\pi^2],\end{aligned} \quad (4.14)$$

and the functions β_1, β_2, and β_3 as

$$\begin{aligned}\beta_1&=g(1+s),\\ \beta_2&=-2ft,\\ \beta_3&=-gs/\pi^2.\end{aligned} \quad (4.15)$$

Note the appearance of two independent coupling constants f and g in the above relations.

V. SPECIAL DERIVATIVE-COUPLING MODELS

It is possible to obtain derivative-coupling models corresponding to those described in Sec. III. However, $L_{\pi N}$ and $\mathbf{J}_{\mu 5}$ now acquire a more complicated form, although $L_{\pi\pi}$ remains the same. The first two models described below have not been derived before with two coupling constants, while the third model has been given by Schwinger.

Model A′

When $a=0$, the functions b, c, d, e, s, and t have the same values as in Model A of Sec. III. Moreover, the functions α_1, α_2, α_3, β_1, β_2, and β_3 can be determined by substituting the values of s and t, given by (3.2) and (3.3), into (4.14) and (4.15). We thus obtain

$$\begin{aligned}L_{\pi N}&=(g/2f\sqrt{\pi^2})\sin(2f\sqrt{\pi^2})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N\\&\quad-(1/\pi^2)\sin^2(f\sqrt{\pi^2})\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N\\&\quad+(g/\pi^2)[1-(1/2f\sqrt{\pi^2})\sin(2f\sqrt{\pi^2})]\\&\qquad\times(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N,\end{aligned} \quad (5.1)$$

$$\begin{aligned}\mathbf{J}_{\mu 5}&=g\cos(2f\sqrt{\pi^2})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N-(f/\sqrt{\pi^2})\sin(2f\sqrt{\pi^2})\\&\quad\times\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N+(g/\pi^2)[1-\cos(2f\sqrt{\pi^2})]\\&\quad\times(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}+(1/\pi^2)[1-(1/4f\sqrt{\pi^2})\\&\qquad\times\sin(4f\sqrt{\pi^2})][\pi^2\partial_\mu\boldsymbol{\pi}-(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}].\end{aligned} \quad (5.2)$$

Model B′

This model, for which $b=0$, corresponds to Model B of Sec. III. By following the same procedure as described above for Model A′, we find

$$\begin{aligned}L_{\pi N}&=g\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N-(1/2\pi^2)[1-(1-4f^2\pi^2)^{1/2}]\\&\quad\times\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N-(g/\pi^2)[1-(1-4f^2\pi^2)^{-1/2}]\\&\qquad\times(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N,\end{aligned} \quad (5.3)$$

$$\begin{aligned}\mathbf{J}_{\mu 5}&=g(1-4f^2\pi^2)^{1/2}\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N-2f^2\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N\\&\quad+(g/\pi^2)[1-(1-4f^2\pi^2)^{1/2}](\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad-4f^2(1-4f^2\pi^2)^{-1/2}(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\&\qquad+[1-(1-4f^2\pi^2)^{1/2}]\partial_\mu\boldsymbol{\pi}.\end{aligned} \quad (5.4)$$

Model C′

The model, obtained by taking $c=0$, corresponds to Model C of Sec. III, and gives

$$\begin{aligned}L_{\pi N}&=g(1+f^2\pi^2)^{-1}\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N\\&\qquad-f^2(1+f^2\pi^2)^{-1}\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N,\end{aligned} \quad (5.5)$$

$$\begin{aligned}\mathbf{J}_{\mu 5}&=g(1-f^2\pi^2)(1+f^2\pi^2)^{-1}\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}N\\&\quad-2f^2(1+f^2\pi^2)^{-1}\bar{N}i\gamma_\mu\boldsymbol{\tau}\times\boldsymbol{\pi}N\\&\quad+2gf^2(1+f^2\pi^2)^{-1}(\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N)\boldsymbol{\pi}\\&\quad-2f^2(1+f^2\pi^2)^{-2}(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\boldsymbol{\pi}\\&\qquad+[1-(1-f^2\pi^2)(1+f^2\pi^2)^{-2}]\partial_\mu\boldsymbol{\pi},\end{aligned} \quad (5.6)$$

in agreement with Schwinger's results.[3]

It is, of course, possible to obtain additional derivative-coupling models as indicated in Sec. III.

The constants g and f appearing in the above models remain unrelated unless additional considerations are introduced into the formalism.[11] Moreover, since $L_{\pi N}$ can be expanded in powers of f^2, it is sufficient to require that g and f^2 be real to ensure that $L_{\pi N}$ is Hermitian. We shall, however, for simplicity take f itself to be real.

VI. CHIRAL SYMMETRY AND TRANSFORMATION OF PION-NUCLEON COUPLING

Let us define a function $U(i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi})$ as

$$U=1+s+2it\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi} \quad (6.1)$$

in terms of the functions $s(\pi^2)$ and $t(\pi^2)$ of Secs. II or IV which satisfy the relation

$$(1+s)^2+4t^2\pi^2=1. \quad (6.2)$$

Then,

$$U^*U=(1+s)^2+4t^2\pi^2=1,$$

so that U is unitary and

$$U^{-1}=U^*=1+s-2it\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}. \quad (6.3)$$

[11] Such considerations have been advanced, e.g., by J. Schwinger, Phys. Rev. Letters **18**, 923 (1967).

It can also be established, with the help of (6.2), that

$$U^{\pm 1/2}=(1+\tfrac{1}{2}s)^{1/2}\pm i(1+\tfrac{1}{2}s)^{-1/2}t\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}, \quad (6.4)$$

which implies that

$$(U^{\pm 1/2})^*=U^{\mp 1/2}, \quad \gamma_\mu U^{\pm 1/2}=U^{\mp 1/2}\gamma_\mu. \quad (6.5)$$

Evidently, in the nonderivative-coupling case the sum of (2.3) and (2.5) takes the form

$$L_{0N}+L_{\pi N}=-\bar{N}(\gamma\cdot\partial+MU)N. \quad (6.6)$$

We also find that

$$\mathrm{Tr}(\partial_\mu U\partial_\mu U^{-1})=8[t^2\partial_\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}+(s'^2+4t'^2\boldsymbol{\pi}^2+4tt')(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2],$$

where Tr denotes the trace of the products of isospin matrices, and consequently, by virtue of (2.19), (2.20), and (6.2),

$$-(1/16f^2)\,\mathrm{Tr}(\partial_\mu U\partial_\mu U^{-1})=-\tfrac{1}{2}(1-2b)\partial_\mu\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi}+c(\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})^2. \quad (6.7)$$

Thus, the sum of (2.2) and (2.4) can be expressed as

$$L_{0\pi}+L_{\pi\pi}=-(1/16f^2)\,\mathrm{Tr}(\partial_\mu U\partial_\mu U^{-1})+L', \quad (6.8)$$

where

$$L'=-\tfrac{1}{2}m^2\boldsymbol{\pi}^2+a=-\tfrac{1}{2}m^2\int_0^{\boldsymbol{\pi}^2}\left(1-\frac{2a'}{m^2}\right)d(\boldsymbol{\pi}^2)$$

or, in view of (2.18),

$$L'=\frac{m^2}{4f}\int_0^{\boldsymbol{\pi}^2}\frac{s'}{t}\,d(\boldsymbol{\pi}^2). \quad (6.9)$$

In the derivative-coupling case, the sum of L_{0N} and $L_{\pi N}$ becomes, on the substitution of (4.14) into (4.1),

$$L_{0N}+L_{\pi N}=-\bar{N}(\gamma\cdot\partial+M)N+(g/f)t\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\partial_\mu\boldsymbol{\pi}N+(s/2\boldsymbol{\pi}^2)\bar{N}i\gamma_\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\times\partial_\mu\boldsymbol{\pi}N+(g/f)[2(1+s)t'-2s't+st/\boldsymbol{\pi}^2](\boldsymbol{\pi}\cdot\partial_\mu\boldsymbol{\pi})\bar{N}i\gamma_\mu\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}N, \quad (6.10)$$

and it can be verified by direct calculation that (6.10) can be put in the form

$$L_{0N}+L_{\pi N}=-\bar{N}(\gamma\cdot\partial+M)N-[(f+g)/2f]\bar{N}\gamma_\mu(U^{1/2}\partial_\mu U^{-1/2})N-[(f-g)/2f]\bar{N}\gamma_\mu(U^{-1/2}\partial_\mu U^{1/2})N, \quad (6.11)$$

while $L_{0\pi}+L_{\pi\pi}$ is again given by (6.8).

The relations (6.6), (6.11), and (6.8) exhibit chiral symmetry except for the symmetry-breaking term L', which disappears only if the pion mass is unrealistically assumed to vanish.[12]

[12] Properties of the Lagrangian-density terms of the form (6.6), (6.11), and (6.8) under chiral transformations have been discussed in Ref. 9. Also note that these authors use chiral symmetry for the determination of the symmetry-preserving terms and the PCAC condition for the determination of the symmetry-breaking terms.

By putting[13]

$$N=U^{-1/2}N', \quad \bar{N}=\bar{N}'U^{-1/2}, \quad (6.12)$$

where the second relation follows from the first one by virtue of (6.5), it is possible to transform (6.6) into the form

$$L_{0N}+L_{\pi N}=-\bar{N}'(\gamma\cdot\partial+M)N'-\bar{N}'\gamma_\mu(U^{1/2}\partial_\mu U^{-1/2})N', \quad (6.13)$$

which shows that the nonderivative pion-nucleon coupling is equivalent to a special case of the derivative coupling (6.11) corresponding to $g=f$. We have also investigated the Lagrangian formalism by taking a mixture of the nonderivative and derivative pion-nucleon couplings, and verified that the nonderivative coupling can again be eliminated by a unitary transformation so that the total pion-nucleon coupling is of the form (6.11).

We conclude that (6.11) together with (6.8) provides the most general form of the Lagrangian density for the pion-nucleon system that satisfies the divergence condition (1.1). However, the choice among the various models discussed in Sec. V must await further theoretical and experimental developments.

APPENDIX A: SOLUTION OF EQUATIONS FOR NONDERIVATIVE-COUPLING CASE

The vanishing of the coefficient of each of the seven terms in (2.14) yields the differential equations

$$s'(1-e)=-2(1-2b-2b'\boldsymbol{\pi}^2)t\beta, \quad (A1)$$

$$t(1-e)=(1-2b)(1+s)\beta, \quad (A2)$$

$$t'(1-e)=-b'(1+s)\beta, \quad (A3)$$

$$1-2a'/m^2=(1-2b-2b'\boldsymbol{\pi}^2)/(1-e), \quad (A4)$$

$$d=4b'(1-e)/(1-2b)-2e', \quad (A5)$$

$$c=b'+\tfrac{1}{2}d(1-2b-2b'\boldsymbol{\pi}^2)/(1-e), \quad (A6)$$

$$c'(1-e)=(1-2b-2b'\boldsymbol{\pi}^2)d'-b'(d+2e'). \quad (A7)$$

By putting $\boldsymbol{\pi}^2=0$ in (A2), we find, in view of (2.7) and (2.11),

$$\beta=t(0)\equiv f. \quad (A8)$$

It also follows from (A1)–(A3) that

$$2(1+s)s'=-4(t^2+2tt'\boldsymbol{\pi}^2), \quad (A9)$$

which gives

$$(1+s)^2+4t^2\boldsymbol{\pi}^2=1, \quad (A10)$$

where the constant of integration is determined by the condition that $s=0$ for $\boldsymbol{\pi}^2=0$.

According to (A2) and (A3), we have

$$t'/t=-b'/(1-2b)$$

[13] According to Ref. 2, the above transformation can be interpreted as a redefinition of the nucleon field operator.

or

$$\ln t=\tfrac{1}{2}\ln(1-2b)+\ln f,$$

where we have used the condition that $b=0$ and $t=f$ for $\boldsymbol{\pi}^2=0$, and thus

$$1-2b=t^2/f^2. \quad (A11)$$

On using (A8) and (A11), we also obtain from (A2)

$$e=1-(t/f)(1+s). \quad (A12)$$

The relation (A4) becomes, by virtue of (A1) and (A8),

$$1-2a'/m^2=-s'/2ft, \quad (A13)$$

while (A5) gives, with the help of (A11) and (A12),

$$d=(2/f)[ts'-t'(1+s)]. \quad (A14)$$

By using (A11), (A12), and (A14), and simplifying by means of (A9) and (A10), it is possible to express (A6) as

$$c=-(2/f^2)(\tfrac{1}{4}s'^2+tt'+t'^2\boldsymbol{\pi}^2) \quad (A15)$$

or

$$c=(t^4-\tfrac{1}{4}s'^2)/2f^2t^2\boldsymbol{\pi}^2. \quad (A16)$$

It can also be verified that (A7) is indeed satisfied by b, e, d, and c, given by (A11), (A12), (A14), and (A15).

APPENDIX B: SOLUTION OF EQUATIONS FOR DERIVATIVE-COUPLING CASE

The differential equations resulting from the vanishing of the coefficients of all the terms in (4.10) are given by

$$\beta_1(1-2b)=\alpha_1(1-e), \quad (B1)$$

$$\beta_3(1-2b)-2b'(\beta_1+\beta_3\boldsymbol{\pi}^2)=\alpha_3(1-e), \quad (B2)$$

$$2[\beta_1'-\beta_2(\alpha_1+\alpha_3\boldsymbol{\pi}^2)](1-2b)=[2\alpha_1'-\alpha_3-2\alpha_2(\alpha_1+\alpha_3\boldsymbol{\pi}^2)](1-e), \quad (B3)$$

$$(\beta_3'-\alpha_2\beta_3+\alpha_3\beta_2)(1-2b)-b'[\beta_3+2\beta_1'+2\beta_3'\boldsymbol{\pi}^2-2\alpha_2(\beta_1+\beta_3\boldsymbol{\pi}^2)]=0, \quad (B4)$$

$$[\beta_3+2\alpha_2(\beta_1+\beta_3\boldsymbol{\pi}^2)](1-2b)-2b'\boldsymbol{\pi}^2[\beta_3+2\alpha_2(\beta_1+\beta_3\boldsymbol{\pi}^2)]=-[2\alpha_1'-\alpha_3-2\alpha_2(\alpha_1+\alpha_3\boldsymbol{\pi}^2)](1-e), \quad (B5)$$

$$(\alpha_2\beta_2-\alpha_1\beta_3)(1-2b)+b'[\beta_2+2\alpha_1(\beta_1+\beta_3\boldsymbol{\pi}^2)]=(\alpha_2^2-\alpha_2'-\alpha_1\alpha_3)(1-e), \quad (B6)$$

$$(\beta_3+2\alpha_1\beta_2-2\alpha_2\beta_1)(1-2b)=0, \quad (B7)$$

$$(\beta_2'-\alpha_2\beta_2+\alpha_3\beta_1)(1-2b)=-(\alpha_2^2-\alpha_2'-\alpha_1\alpha_3)(1-e), \quad (B8)$$

$$(\beta_2+2\alpha_1\beta_1+2\alpha_2\beta_2\boldsymbol{\pi}^2)(1-2b)=2(\alpha_1^2+\alpha_2+\alpha_2^2\boldsymbol{\pi}^2)(1-e), \quad (B9)$$

together with the relations (A4)–(A7).

By subtracting $2\alpha_2$ times (B1) and $(2\alpha_2\boldsymbol{\pi}^2+1)$ times (B2) from (B5), we obtain the simple relation

$$\beta_1b'=-\alpha_1'(1-e)$$

or, on using (B1),

$$\alpha_1'/\alpha_1=-b'/(1-2b),$$

which has the solution

$$\alpha_1=g(1-2b)^{1/2}, \quad \alpha_1(0)\equiv g. \quad (B10)$$

It then also follows from (B1) that

$$\beta_1=g(1-e)(1-2b)^{-1/2}, \quad \beta_1(0)=g. \quad (B11)$$

By adding (B3), (B5), (B7), and $2\boldsymbol{\pi}^2$ times (B4), we find

$$(\beta_1'+\beta_3+\beta_3'\boldsymbol{\pi}^2)(1-2b-2b'\boldsymbol{\pi}^2)=0$$

or, $(1-2b-2b'\boldsymbol{\pi}^2)$ being nonzero because it obviously cannot vanish for $\boldsymbol{\pi}^2=0$,

$$\beta_1'+\beta_3+\beta_3'\boldsymbol{\pi}^2=0,$$

which can be integrated immediately to yield

$$\beta_1+\beta_3\boldsymbol{\pi}^2=g, \quad (B12)$$

where the constant of integration is determined by the condition $\beta_1(0)=g$, obtained above. Substitution of (B11) into (B12) gives

$$\beta_3=(g/\boldsymbol{\pi}^2)[1-(1-e)(1-2b)^{-1/2}], \quad (B13)$$

and a further substitution of (B12) and (B13) into (B2) gives

$$\alpha_3=(g/\boldsymbol{\pi}^2)[(1-2b-2b'\boldsymbol{\pi}^2)/(1-e)-(1-2b)^{1/2}]. \quad (B14)$$

According to (B7),

$$\beta_3+2\alpha_1\beta_2-2\alpha_2\beta_1=0, \quad (B15)$$

while (B9) can be reduced, with the help of (B1), to the form

$$\alpha_1\beta_2-2\alpha_2\beta_1+2\alpha_2\boldsymbol{\pi}^2(\alpha_1\beta_2-\alpha_2\beta_1)=0$$

or, in view of (B15),

$$\beta_3+2\alpha_2(\beta_1+\beta_3\boldsymbol{\pi}^2)=0. \quad (B16)$$

By substituting the earlier results into (B15) and (B16), we can express α_2 and β_2 in terms of b and e as

$$\alpha_2=(1/2\boldsymbol{\pi}^2)[(1-e)(1-2b)^{-1/2}-1], \quad (B17)$$

$$\beta_2=(1/2\boldsymbol{\pi}^2)[(1-e)^2/(1-2b)-1](1-2b)^{-1/2}. \quad (B18)$$

We have now found all of the nucleon functions in terms of b and e. However, we have used only six of our nine equations, because only a linear combination of (B3) and (B4) has been used, while (B6) and (B8) have not been used at all. When the results for the nucleon functions are substituted into (B3), (B4), (B6), and (B8), we obtain in each case the same relationship between b and e, given by

$$\left[\frac{1-(1-e)^2/(1-2b)}{(1-2b)\boldsymbol{\pi}^2}\right]'=0,$$

which yields

$$(1-e)^2/(1-2b)+\lambda(1-2b)\pi^2=1, \qquad \text{(B19)}$$

where λ is the constant of integration. It is convenient to introduce f, s, and t, defined as

$$4f^2=\lambda, \quad 1+s=(1-e)/(1-2b)^{1/2}, \quad t=f(1-2b)^{1/2}, \qquad \text{(B20)}$$

so that (B19) can be expressed in the form

$$(1+s)^2+4t^2\pi^2=1. \qquad \text{(B21)}$$

By using (B20) and (B21) and remembering that the relations (A4) to (A7) also hold in the present case, the functions a, b, c, d, and e can be expressed in terms of s and t in the same form as in Appendix A. Moreover, the functions α_1, α_2, α_3, β_1, β_2, and β_3, when expressed in terms of s and t, give the relations (4.14) and (4.15).

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Quantization of the Charged Spin-$\frac{3}{2}$ Field*

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The canonical quantization of the spin-$\frac{3}{2}$ field is carried out in the presence of electromagnetic interaction by a suitable choice of canonical variables, which satisfy the usual commutation relations as well as Heisenberg's equations of motion. The present investigation shows that the canonical formalism can be developed consistently for the charged spin-$\frac{3}{2}$ field despite the enormous mathematical complications which appear in the treatment of high-spin fields.

1. INTRODUCTION

THE canonical quantization of the spin-$\frac{3}{2}$ field in the presence of electromagnetic interaction seems to involve serious difficulties, which have been discussed by several authors.[1,2] We shall, however, show that, although the charged spin-$\frac{3}{2}$ field cannot be treated as simply as the lower-spin fields, it is possible to find suitable canonical variables for this field in the presence of interaction such that they satisfy the canonical commutation relations and Heisenberg's equations of motion. This then enables us to carry out the quantization consistently in the Heisenberg picture, pass over to the interaction picture, and derive the scattering matrix elements in a covariant form without encountering any unusual difficulty. The present approach involves a good deal of complicated mathematical manipulations, and it is quite necessary for this purpose to use the quantum field theory in terms of ordered products.[3]

We shall denote the space-time coordinates as $x_\mu=(x_1,x_2,x_3,it)$, take $c=\hbar=1$, and treat the γ_μ as Hermitian matrices. An asterisk will be used to denote the complex conjugate of a number or the Hermitian conjugate of an operator.

2. CANONICAL FORMALISM FOR THE FREE FIELD

The field with spin $\frac{3}{2}$ can be described most conveniently by means of the Rarita-Schwinger[4] spinor-tensor field equation

$$(\gamma\partial+m)\psi_\mu=0, \tag{1}$$

with

$$\gamma_\mu\psi_\mu=0, \tag{2}$$

which can be obtained from the Lagrangian density[5]

$$L=-:[\bar\psi_\mu(\gamma\partial+m)\psi_\mu+A\bar\psi_\mu(\gamma_\mu\partial_\nu+\partial_\mu\gamma_\nu)\psi_\nu +\tfrac{1}{2}(3A^2+2A+1)\bar\psi_\mu\gamma_\mu\gamma\partial\gamma_\nu\psi_\nu -(3A^2+3A+1)m\bar\psi_\mu\gamma_\mu\gamma_\nu\psi_\nu]:, \tag{3}$$

where $A\neq-\frac{1}{2}$. As pointed out by Fradkin,[6] under the linear transformation

$$\psi_\mu\rightarrow\psi_\mu+\frac{(A'-A)}{2(2A+1)}\gamma_\mu\gamma_\nu\psi_\nu, \tag{4}$$

the Lagrangian density (3) retains its form except that A is replaced by A'. Thus, the parameter A can be chosen according to convenience, and we shall take $A=-1$, so that

$$L=-:\bar\psi_\mu[(\gamma\partial+m)\delta_{\mu\nu}-(\gamma_\mu\partial_\nu+\partial_\mu\gamma_\nu) +\gamma_\mu(\gamma\partial-m)\gamma_\nu]\psi_\nu:. \tag{5}$$

The field equation obtained from (5) is evidently

$$-(\gamma\partial+m)\psi_\mu+(\partial_\mu\gamma_\nu+\gamma_\mu\partial_\nu)\psi_\nu-\gamma_\mu(\gamma\partial-m)\gamma_\nu\psi_\nu=0, \tag{6}$$

which yields (1) and (2), and further, on putting $\mu=4$ in (6), we find

$$\partial_k\psi_k+(m-\gamma_i\partial_i)\gamma_k\psi_k=0. \tag{7}$$

The interdependence relations (2) and (7), which do not involve time derivatives, reduce the number of independent components of ψ_μ to eight as required for the field with spin $\frac{3}{2}$.

Because of the complicated interdependence between the components of ψ_μ, the usual method of introducing the canonical variables is no longer adequate.[7] We shall, therefore, choose the canonical variables ϕ_k and π_k by making use of the following requirements:

(a) The charge Q of the system should be expressible in terms of the canonical variables as

$$Q=e\int:\pi_k\phi_k:d\tau. \tag{8}$$

(b) The canonical variables should obey Heisenberg's equations of motion

$$\partial_\mu\phi_k=i[\phi_k,\mathcal{G}_\mu], \quad \partial_\mu\pi_k=i[\pi_k,\mathcal{G}_\mu], \tag{9}$$

where $\mathcal{G}_\mu$ is the energy-momentum four-vector of the system.

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[7] For the general conditions under which the usual canonical formalism is applicable, see Ref. 3.

It is convenient to introduce the operator

$$P_{jk}=\delta_{jk}-\tfrac{1}{3}\gamma_j\gamma_k \tag{10}$$

with the properties

$$\gamma_jP_{jk}=P_{jk}\gamma_k=0\,,\quad P_{jk}P_{kl}=P_{jl}\,,\quad P_{jk}{}^*=P_{kj}\,, \tag{11}$$

and, by defining ϕ_j as

$$\phi_j\equiv P_{jk}\psi_k\,, \tag{12}$$

we have

$$\gamma_j\phi_j=0\,,\quad P_{jk}\phi_k=\phi_j\,. \tag{13}$$

Then, the interdependence relation (7) takes the form

$$(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)\phi=-\tfrac{3}{2}\partial_k\phi_k \tag{14}$$

or

$$\phi=-\tfrac{3}{2}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_k\phi_k\,, \tag{15}$$

where

$$\phi\equiv\gamma_k\psi_k\,, \tag{16}$$

and the field equation for ϕ_j is found to be

$$\partial_4\phi_j=-\gamma_4P_{jk}[(\boldsymbol{\gamma}\cdot\nabla+m)\delta_{kl}-\partial_k(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_l]\phi_l\,. \tag{17}$$

Now, the current density four-vector j_μ, obtained from (5), is given by

$$j_\mu=ie:(\bar\psi_\lambda\gamma_\mu\psi_\lambda-\bar\psi_\lambda\gamma_\lambda\psi_\mu-\bar\psi_\mu\gamma_\lambda\psi_\lambda+\bar\psi_\lambda\gamma_\lambda\gamma_\mu\gamma_\rho\psi_\rho):\,, \tag{18}$$

so that the charge density $\rho=-ij_4$ is

$$\rho=e:(\bar\psi_k\gamma_4\psi_k+\bar\psi_j\gamma_j\gamma_4\gamma_k\psi_k):\,,$$

which can be expressed in terms of ϕ_k and ϕ as

$$\rho=e:(\phi_k{}^*\phi_k-\tfrac{2}{3}\phi^*\phi):\,. \tag{19}$$

Thus, in view of the relation (15), the total charge Q is expressible as

$$Q=e\int:\{\phi_k{}^*\phi_k-\tfrac{3}{2}[(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_k\phi_k]^*\times[(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_l\phi_l]\}:d\tau\,,$$

which may be integrated by parts to yield

$$Q=e\int:\{\phi_k{}^*\phi_k+\tfrac{3}{2}[\partial_l(9m^2/4-\nabla^2)^{-1}\partial_k\phi_k]^*\phi_l\}:d\tau$$

or

$$Q=e\int:\pi_j\phi_j:d\tau\,, \tag{20}$$

where

$$\pi_j=\{[\delta_{jl}+\tfrac{3}{2}P_{jk}\partial_k(9m^2/4-\nabla^2)^{-1}\partial_l]\phi_l\}^*\,, \tag{21}$$

and

$$\pi_j\gamma_j=0\,,\quad \pi_jP_{jk}=\pi_k\,. \tag{22}$$

Similarly, the energy-momentum four-vector $\mathcal{G}_\mu$ is expressible as

$$\mathcal{G}_\mu=-i\int:(\phi_k{}^*\partial_\mu\phi_k-\tfrac{2}{3}\phi^*\partial_\mu\phi):d\tau\,, \tag{23}$$

which can be put in the form

$$\mathcal{G}_\mu=-i\int:\pi_j\partial_\mu\phi_j:d\tau\,. \tag{24}$$

Then, by imposing the canonical commutation relations

$$\{[\phi_j(\mathbf{r},t)]_\alpha,[\pi_k(\mathbf{r}',t)]_\beta\}=[P_{jk}]_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}')\,, \tag{25}$$

it is easily verified that the Heisenberg equations (9) are satisfied. Indeed, the first relation in (9) follows from (24) and (25) by remembering that, in view of (17), ϕ_k not only anticommutes with $\partial_i\phi_j$ but also with $\partial_4\phi_j$. The second relation in (9) follows from the first one by making use of (21).

It should be observed that the appearance of the operator P_{jk} in (25) is necessary to ensure the compatibility of the commutation relations with (13) and (22). By putting

$$\eta=-(\sqrt{\tfrac{3}{2}})\gamma_3\phi_3\,,\quad \zeta=(\sqrt{\tfrac{1}{2}})(\gamma_1\phi_1-\gamma_2\phi_2)\,,$$
$$\pi_\eta=-(\sqrt{\tfrac{3}{2}})\pi_3\gamma_3\,,\quad \pi_\zeta=(\sqrt{\tfrac{1}{2}})(\pi_1\gamma_1-\pi_2\gamma_2)\,,$$

where η, ζ, π_η, and π_ζ are linearly independent and satisfy

$$\pi_j\phi_j=\pi_\eta\eta+\pi_\zeta\zeta\,,$$

the canonical commutation relations (25) can also be expressed in the more familiar form

$$\{[\eta(\mathbf{r},t)]_\alpha,[\pi_\eta(\mathbf{r}',t)]_\beta\}=\delta_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}')\,,$$
$$\{[\zeta(\mathbf{r},t)]_\alpha,[\pi_\zeta(\mathbf{r}',t)]_\beta\}=\delta_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}')\,.$$

3. CANONICAL VARIABLES IN THE PRESENCE OF INTERACTION

The Lagrangian density for the spin-$\frac{3}{2}$ field interacting with the electromagnetic field is given by[5,8]

$$L=-:\bar\psi_\mu[(\gamma D+m)\delta_{\mu\nu}-(\gamma_\mu D_\nu+D_\mu\gamma_\nu)+\gamma_\mu(\gamma D-m)\gamma_\nu]\psi_\nu:-\tfrac{1}{2}:(\partial_\nu A_\mu)(\partial_\nu A_\mu):\,, \tag{26}$$

where the first term is obtained from (5) by replacing ∂_μ by $D_\mu=\partial_\mu-ieA_\mu$. The resulting field equation for the spin-$\frac{3}{2}$ field is

$$(\gamma D+m)\psi_\mu-(\gamma_\mu D_\nu+D_\mu\gamma_\nu)\psi_\nu+\gamma_\mu(\gamma D-m)\gamma_\nu\psi_\nu=0\,, \tag{27}$$

and the interdependence relations take the form

$$\gamma_\mu\psi_\mu=-(e/3m^2)(2i\gamma_\nu F_{\mu\nu}-\sigma_{\lambda\rho}F_{\lambda\rho}\gamma_\mu)\psi_\mu\,, \tag{28}$$

$$(m-\boldsymbol{\gamma}\cdot\mathbf{D})\gamma_k\psi_k+D_k\psi_k=0\,. \tag{29}$$

We can again define ϕ_k and ϕ by (12) and (16), which are now related as

$$(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\mathbf{D})\phi=-\tfrac{3}{2}D_k\phi_k \tag{30}$$

or

$$\phi=-\tfrac{3}{2}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\mathbf{D})^{-1}D_k\phi_k\,. \tag{31}$$

[8] S. N. Gupta and W. W. Repko, Phys. Rev. **165**, 1415 (1968).

Also, the charge Q and the momentum-energy four-vector $\mathcal{G}_\mu$ are expressible as

$$Q=e\int:(\phi_k{}^*\phi_k-\tfrac{2}{3}\phi^*\phi):d\tau\,, \tag{32}$$

$$\mathcal{G}_\mu=-i\int:(\phi_k{}^*\partial_\mu\phi_k-\tfrac{2}{3}\phi^*\partial_\mu\phi):d\tau+\tilde{\mathcal{G}}_\mu\,, \tag{33}$$

where

$$\tilde{\mathcal{G}}_\mu=-i\int:[(\partial_4A_\lambda)(\partial_\mu A_\lambda)-\tfrac{1}{2}\delta_{\mu4}(\partial_\lambda A_\rho)(\partial_\lambda A_\rho)]:d\tau\,. \tag{34}$$

It is tempting to define the canonical variables as ϕ_j and

$$\pi_j=\{[\delta_{jl}+\tfrac{3}{2}P_{jk}D_k(9m^2/4+e\boldsymbol{\sigma}\cdot\mathbf{H}-\mathbf{D}^2)^{-1}D_l]\phi_l\}^*\,, \tag{35}$$

since this choice enables us to express the charge Q as

$$Q=e\int:\pi_j\phi_j:d\tau \tag{36}$$

in a manner quite analogous to the treatment of the free field in Sec. 2. However, according to (30),

$$(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\mathbf{D})\partial_\mu\phi=-\tfrac{3}{2}D_k\partial_\mu\phi_k+\tfrac{3}{2}ie(\phi_k-\tfrac{2}{3}\gamma_k\phi)\partial_\mu A_k\,,$$

which enables us to express (33) as

$$\mathcal{G}_\mu=-i\int:\{\phi_k{}^*\partial_\mu\phi_k-\tfrac{3}{2}[(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\mathbf{D})^{-1}D_l\phi_l]^*\times(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\mathbf{D})^{-1}D_k\partial_\mu\phi_k\}:d\tau$$
$$+\tfrac{3}{2}e\int:\{[(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\mathbf{D})^{-1}D_l\phi_l]^*\times(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\mathbf{D})^{-1}(\phi_k-\tfrac{2}{3}\gamma_k\phi)\partial_\mu A_k\}:d\tau+\tilde{\mathcal{G}}_\mu\,,$$

or, after integration by parts,

$$\mathcal{G}_\mu=-i\int:\pi_k\partial_\mu\phi_k:d\tau+\tfrac{3}{2}e\int:\{[(9m^2/4+e\boldsymbol{\sigma}\cdot\mathbf{H}-\mathbf{D}^2)^{-1}D_l\phi_l]^*\times(\phi_k-\tfrac{2}{3}\gamma_k\phi)\partial_\mu A_k\}:d\tau+\tilde{\mathcal{G}}_\mu\,.$$

Moreover, with the help of the relation

$$P_{jk}D_jD_k=\tfrac{2}{3}\mathbf{D}^2+\tfrac{1}{3}e\boldsymbol{\sigma}\cdot\mathbf{H}\,,$$

it can be verified that

$$[(9m^2/4+e\boldsymbol{\sigma}\cdot\mathbf{H}-\mathbf{D}^2)^{-1}D_l\phi_l]^*=\tfrac{2}{3}(D_l{}^*\pi_l)(\tfrac{3}{2}m^2+e\boldsymbol{\sigma}\cdot\mathbf{H})^{-1}\,,$$

and thus $\mathcal{G}_\mu$ becomes

$$\mathcal{G}_\mu=-i\int:\pi_k\partial_\mu\phi_k:d\tau+e\int:(D_l{}^*\pi_l)(\tfrac{3}{2}m^2+e\boldsymbol{\sigma}\cdot\mathbf{H})^{-1}\times(\phi_k-\tfrac{2}{3}\gamma_k\phi)\partial_\mu A_k:d\tau+\tilde{\mathcal{G}}_\mu\,. \tag{37}$$

Because of the presence of the second term on the right-hand side of (37), the commutation relations

$$\{[\phi_j(\mathbf{r},t)]_\alpha,[\pi_k(\mathbf{r}',t)]_\beta\}=[P_{jk}]_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}')$$

do not lead to Heisenberg's equations for ϕ_j and π_j, which shows that ϕ_j and π_j cannot be regarded as the canonical variables, and the above commutation relations are inconsistent.[9] This difficulty cannot be avoided by manipulating the definition of the photon canonical variables, because the unwanted term in (37) is non-Hermitian.

In order to find the appropriate canonical variables for a consistent scheme of quantization, we shall modify ϕ_j and π_j so as to try to remove the second term on the right-hand side of (37) but preserve the relations (13), (22), and (20). This will be achieved by expanding (37) in powers of e as

$$\mathcal{G}_\mu=-i\int:\pi_j\partial_\mu\phi_j:d\tau-\tfrac{2}{3}\left(\frac{e}{m^2}\right)\int:\pi_j[\partial_\mu,\partial_jA_k\mu_{kl}]\phi_l:d\tau$$
$$+\tfrac{2}{3}i\left(\frac{e^2}{m^2}\right)\int:\pi_j[A_j(\partial_\mu A_k)-\tfrac{2}{3}im^{-2}\partial_j\boldsymbol{\sigma}\cdot\mathbf{H}(\partial_\mu A_k)$$
$$+\partial_j(\partial_\mu\boldsymbol{\gamma}\cdot\mathbf{A})(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_k]u_{kl}\phi_l:d\tau+\tilde{\mathcal{G}}_\mu+O(e^3)\,, \tag{38}$$

with

$$u_{kl}=\delta_{kl}+\gamma_k(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_l\,, \tag{39}$$

and then eliminating the unwanted terms of various orders in (38) by successive transformations. As we shall see, these transformations are not unitary but they preserve the relations (13), (22), and (20).

We first introduce a set of variables ϕ_j' and π_j' as

$$\phi_j'=\phi_j+eT_{jk}\phi_k+(1/2!)e^2T_{jk}T_{kl}\phi_l+\cdots\,,$$
$$\pi_j'=\pi_j-e(\bar T_{jk}\pi_k{}^*)^*+(1/2!)e^2(\bar T_{jk}\bar T_{kl}\pi_l{}^*)^*-\cdots\,, \tag{40}$$

which may be inverted to give

$$\phi_j=\phi_j'-eT_{jk}\phi_k'+(1/2!)e^2T_{jk}T_{kl}\phi_l'-\cdots\,,$$
$$\pi_j=\pi_j'+e(\bar T_{jk}\pi_k'{}^*)^*+(1/2!)e^2(\bar T_{jk}\bar T_{kl}\pi_l'{}^*)^*+\cdots\,, \tag{41}$$

where T_{jk} and $\bar T_{jk}$ are such that

$$\gamma_jT_{jk}=\gamma_j\bar T_{jk}=0\,, \tag{42}$$

and, for arbitrary field operators $f(x)$ and $g(x)$,

$$\int gT_{jk}fd\tau=\int(\bar T_{kj}g^*)^*fd\tau\,. \tag{43}$$

[9] These commutation relations can be expressed in terms of ϕ_j and $\phi_k{}^*$ by using the identity

$$[\delta_{jl}-P_{jk}D_k(\tfrac{3}{2}m^2+e\boldsymbol{\sigma}\cdot\mathbf{H})^{-1}D_l]\times[\delta_{ln}+\tfrac{3}{2}P_{lm}D_m(9m^2/4+e\boldsymbol{\sigma}\cdot\mathbf{H}-\mathbf{D}^2)^{-1}D_n]=\delta_{jn}\,,$$

and they are then identical to those given in Ref. 1. We, therefore, agree with Johnson and Sudarshan that the simplest choice of the canonical variables in the presence of interaction leads to inconsistency.

The above relations ensure that

$$\gamma_j\phi_j'=0\,,\quad \pi_j'\gamma_j=0\,, \tag{44}$$

$$Q=e\int:\pi_j'\phi_j':d\tau\,, \tag{45}$$

and (38) can be transformed, with the help of (41), as

$$\begin{aligned}\mathcal{G}_\mu=&-i\int:\pi_j'\partial_\mu\phi_j':d\tau\\&-\tfrac{1}{2}ie^2\int:\pi_j'\{T_{jk}[\partial_\mu,T_{kl}]-[\partial_\mu,T_{jk}]T_{kl}\}\phi_l':d\tau\\&+\tfrac{2}{3}i(e^2/m^2)\int:\pi_j'[A_j(\partial_\mu A_k)-\tfrac{2}{3}im^{-2}\partial_j\boldsymbol{\sigma}\cdot\mathbf{H}(\partial_\mu A_k)\\&+\partial_j(\partial_\mu\boldsymbol{\gamma}\cdot\mathbf{A})(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_k]u_{kl}\phi_l':d\tau\\&+\bar{\mathcal{G}}_\mu+O(e^3)\,,\end{aligned} \tag{46}$$

where the first-order unwanted term has been eliminated by taking

$$T_{jk}=-\tfrac{2}{3}im^{-2}P_{jl}\partial_l A_m u_{mk}\,. \tag{47}$$

From the definition of T_{jk} we find, after some manipulations with the help of the relation

$$u_{kl}P_{lm}\partial_m=(\partial_k-\gamma_k\boldsymbol{\gamma}\cdot\nabla-m\gamma_k)+\tfrac{3}{2}m^2\gamma_k(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\,,$$

that

$$\begin{aligned}&\pi_j'T_{jk}[\partial_\mu,T_{kl}]\phi_l'\\&\quad=-\tfrac{2}{3}m^{-2}\pi_j'v_{jk}A_k(\partial_\mu A_l)u_{lm}\phi_m'\\&\qquad+\tfrac{2}{3}m^{-2}\pi_j'A_j(\partial_\mu A_k)u_{kl}\phi_l'\\&\qquad-(4/9)im^{-4}\pi_j'\partial_j\boldsymbol{\sigma}\cdot\mathbf{H}(\partial_\mu A_k)u_{kl}\phi_l'\\&\qquad-\tfrac{2}{3}m^{-2}\pi_j'\partial_j\boldsymbol{\gamma}\cdot\mathbf{A}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}(\partial_\mu A_k)u_{kl}\phi_l'\,,\end{aligned} \tag{48}$$

$$\begin{aligned}&\pi_j'[\partial_\mu,T_{jk}]T_{kl}\phi_l'\\&\quad=-\tfrac{2}{3}m^{-2}\pi_j'v_{jk}(\partial_\mu A_k)A_l u_{lm}\phi_m'\\&\qquad+\tfrac{2}{3}m^{-2}\pi_j'(\partial_\mu A_j)A_k u_{kl}\phi_l'\\&\qquad-(4/9)im^{-4}\pi_j'\partial_j(\partial_\mu\boldsymbol{\sigma}\cdot\mathbf{H})A_k u_{kl}\phi_l'\\&\qquad-\tfrac{2}{3}m^{-2}\pi_j'\partial_j(\partial_\mu\boldsymbol{\gamma}\cdot\mathbf{A})(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_k u_{kl}\phi_l'\,,\end{aligned} \tag{49}$$

where

$$v_{jk}=\delta_{jk}+\tfrac{2}{3}m^{-2}\partial_j(\partial_k-\gamma_k\boldsymbol{\gamma}\cdot\nabla-m\gamma_k)\,. \tag{50}$$

It is also convenient to put

$$\xi_j'=u_{jk}\phi_k'\,, \tag{51}$$

and thus, within the present approximation,

$$\xi_j'=\bar{v}_{jk}\pi_k'^*\,, \tag{52}$$

where $\bar{v}_{jk}$ denotes the transformation of v_{kj} by a relation of the form (43). The relations (48), (49), (51), and (52) enable us to express (46) as

$$\begin{aligned}\mathcal{G}_\mu=&-i\int:\pi_j'\partial_\mu\phi_j':d\tau+\tfrac{1}{3}i\Big(\frac{e^2}{m^2}\Big)\int:\pi_j'[\partial_\mu,A_jA_k\\&+\partial_j\boldsymbol{\gamma}\cdot\mathbf{A}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_k-\tfrac{2}{3}im^{-2}\partial_j\boldsymbol{\sigma}\cdot\mathbf{H}A_k]u_{kl}\phi_l':d\tau\\&+\tfrac{1}{3}i\Big(\frac{e^2}{m^2}\Big)\int:\xi_j'^*[A_j(\partial_\mu A_k)-(\partial_\mu A_j)A_k]\xi_k':d\tau\\&+\bar{\mathcal{G}}_\mu+O(e^3)\,.\end{aligned} \tag{53}$$

The second term on the right-hand side of (53) can be eliminated by the transformation

$$\begin{aligned}\phi_j'&=\phi_j''-e^2T_{jk}'\phi_k''+\cdots\,,\\\pi_j'&=\pi_j''+e^2(\bar{T}_{jk}'\pi_k''^*)^*+\cdots\,,\end{aligned} \tag{54}$$

where

$$\begin{aligned}T_{jk}'=&-\tfrac{1}{3}m^{-2}P_{jl}[A_lA_m+\partial_l\boldsymbol{\gamma}\cdot\mathbf{A}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_m\\&-\tfrac{2}{3}im^{-2}\partial_l\boldsymbol{\sigma}\cdot\mathbf{H}A_m]u_{mk}\,,\end{aligned} \tag{55}$$

and $\bar{T}_{jk}'$ is related to T_{jk}' as

$$\int gT_{jk}'f\,d\tau=\int(\bar{T}_{kj}'g^*)^*f\,d\tau \tag{56}$$

for arbitrary field operators $f(x)$ and $g(x)$. This transformation ensures that

$$\gamma_j\phi_j''=0\,,\quad \pi_j''\gamma_j=0\,, \tag{57}$$

and

$$Q=e\int:\pi_j''\phi_j'':d\tau\,, \tag{58}$$

while $\mathcal{G}_\mu$ takes the form

$$\begin{aligned}\mathcal{G}_\mu=&-i\int:\pi_j''\partial_\mu\phi_j'':d\tau+\tfrac{1}{3}i(e^2/m^2)\\&\times\int:\xi_j''^*[A_j(\partial_\mu A_k)-(\partial_\mu A_j)A_k]\xi_k'':d\tau\\&+\bar{\mathcal{G}}_\mu+O(e^3)\,,\end{aligned} \tag{59}$$

where

$$\xi_k''=u_{kl}\phi_l''=\bar{v}_{kl}\pi_l''^*\,. \tag{60}$$

The remaining second-order term in (59), which is Hermitian, can be eliminated only by a suitable choice of the canonical variables of the photon field. Indeed,

by taking these canonical variables as A_μ and Π_μ, where

$$\begin{aligned}\Pi_k&=i\partial_4A_k-\tfrac{1}{3}i(e^2/m^2):(\xi_j''^*A_j\xi_k''-\xi_k''^*A_j\xi_j''):\,,\\\Pi_4&=i\partial_4A_4\,,\end{aligned} \tag{61}$$

we find

$$\begin{aligned}\mathcal{G}_\mu=&-i\int:\pi_j''\partial_\mu\phi_j'':d\tau+\int:[-\Pi_\lambda(\partial_kA_\lambda)\delta_{\mu k}\\&+\tfrac{1}{2}i\Pi_\lambda\Pi_\lambda\delta_{\mu4}+\tfrac{1}{2}i(\partial_kA_\lambda)(\partial_kA_\lambda)\delta_{\mu4}]:d\tau+O(e^3)\,,\end{aligned} \tag{62}$$

and we have thus obtained the desired canonical variables ϕ_j'', π_j'', A_λ, and Π_λ up to second order in e.

4. COMMUTATION RELATIONS IN THE PRESENCE OF INTERACTION

We now choose the canonical commutation relations

$$\begin{aligned}\{[\phi_j''(\mathbf{r},t)]_\alpha,[\pi_k''(\mathbf{r}',t)]_\beta\}&=[P_{jk}]_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}')\,,\\[A_\mu(\mathbf{r},t),\Pi_\nu(\mathbf{r}',t)]&=i\delta_{\mu\nu}(\mathbf{r}-\mathbf{r}')\,,\end{aligned} \tag{63}$$

where it can be verified, with the help of (41) and (54), that the first relation in (63) is not equivalent to the commutation relation obtained by treating ϕ_j and π_k as canonical variables. The difference consists in terms involving the derivatives of $\delta(\mathbf{r}-\mathbf{r}')$. We shall show that the commutation relations (63) lead to Heisenberg's equations of motion for the canonical variables, and thus establish the consistency of our quantization procedure.

For this purpose it is necessary to express $\partial_4\phi_j''$ in terms of the canonical variables and their space derivatives. Therefore, by putting $\mu=k$ in the field equation (27), multiplying by P_{jk}, and using (28) and (29), we obtain

$$\begin{aligned}\partial_4\phi_j=&-\gamma_4(\boldsymbol{\gamma}\cdot\mathbf{D}+m)\phi_j+\tfrac{2}{3}\gamma_4(D_j+\gamma_j\boldsymbol{\gamma}\cdot\mathbf{D}-m\gamma_j)\phi\\&-\gamma_4P_{jk}D_k\phi+ieA_4\phi_j-\tfrac{2}{3}e\gamma_4P_{jl}D_l(\tfrac{3}{2}m^2+e\boldsymbol{\sigma}\cdot\mathbf{H})^{-1}\\&\times(\tfrac{3}{2}i\gamma_\nu F_{k\nu}\phi_k-\boldsymbol{\sigma}\cdot\mathbf{H}\phi+i\gamma_4\gamma_kF_{4k}\phi)\,,\end{aligned} \tag{64}$$

where, according to (31),

$$\begin{aligned}\phi=&-\tfrac{3}{2}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_k\phi_k+\tfrac{3}{2}ie(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_lu_{lk}\phi_k\\&+\tfrac{3}{2}e^2(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\boldsymbol{\gamma}\cdot\mathbf{A}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\\&\times A_lu_{lk}\phi_k+O(e^3)\,.\end{aligned} \tag{65}$$

After substituting (65) into (64), and expanding in powers of e, we find

$$\partial_4\phi_j=E_{jk}{}^{(0)}\phi_k+eE_{jk}{}^{(1)}\phi_k+e^2E_{jk}{}^{(2)}\phi_k+O(e^3)\,, \tag{66}$$

where

$$E_{jk}{}^{(0)}=-\gamma_4P_{jl}[(\boldsymbol{\gamma}\cdot\nabla+m)\delta_{lk}-\partial_l(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_k]\,, \tag{67}$$

$$\begin{aligned}E_{jk}{}^{(1)}=&i\gamma_4P_{jl}[\delta_{lk}\gamma A-A_l(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_k\\&+\tfrac{2}{3}m^{-2}\partial_l(\tfrac{3}{2}\gamma_mF_{mk}-\tfrac{1}{2}\gamma_mF_{mn}u_{nk}\\&+\gamma_4F_{4m}u_{mk})]\,,\end{aligned} \tag{68}$$

$$\begin{aligned}E_{jk}{}^{(2)}=&-\gamma_4P_{jl}[\partial_l(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\boldsymbol{\gamma}\cdot\mathbf{A}(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_mu_{mk}\\&-\tfrac{2}{3}m^{-2}A_l(\tfrac{3}{2}\gamma_mF_{mk}-\tfrac{1}{2}\gamma_mF_{mn}u_{nk}+\gamma_4F_{4m}u_{mk})\\&+(4/9)im^{-4}\partial_l\boldsymbol{\sigma}\cdot\mathbf{H}(\tfrac{3}{2}\gamma_mF_{mk}-\tfrac{1}{2}\gamma_mF_{mn}u_{nk}+\gamma_4F_{4m}u_{mk})\\&+\tfrac{2}{3}m^{-2}\partial_l(\tfrac{1}{2}\gamma_m\gamma_nF_{mn}-\gamma_4\gamma_nF_{4n})\\&\times(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}A_ru_{rk}]\,.\end{aligned} \tag{69}$$

Further, by recalling

$$\phi_j=\phi_j''-eT_{jk}\phi_k''+e^2(\tfrac{1}{2}T_{jk}T_{kl}-T_{jl}')\phi_l''+O(e^3)\,,$$

the relation (66) can be expressed in terms of ϕ_j'' as

$$\begin{aligned}\partial_4\phi_j''=&E_{jk}{}^{(0)}\phi_k''+eT_{jk}E_{kl}{}^{(0)}\phi_l''-eE_{jk}{}^{(0)}T_{kl}\phi_l''\\&+eE_{jk}{}^{(1)}\phi_k''+e[\partial_4,T_{jk}]\phi_k''-e^2[(\tfrac{1}{2}T_{jk}T_{kl}-T_{jl}')E_{lm}{}^{(0)}\\&-E_{jk}{}^{(0)}(\tfrac{1}{2}T_{kl}T_{lm}-T_{km}')]\phi_m''-e^2E_{jk}{}^{(1)}T_{kl}\phi_l''\\&+e^2E_{jk}{}^{(2)}\phi_k''+e^2T_{jk}\{T_{kl}E_{lm}{}^{(0)}\phi_m''\\&-E_{kl}{}^{(0)}T_{lm}\phi_m''+E_{kl}{}^{(1)}\phi_l''+[\partial_4,T_{kl}]\phi_l''\}\\&-e^2[\partial_4,(\tfrac{1}{2}T_{jk}T_{kl}-T_{jl}')]\phi_l''+O(e^3)\,.\end{aligned} \tag{70}$$

The right-hand side of (70) involves the field operators ϕ_k'', A_μ, ∂_4A_μ, and their space derivatives. However, since all the terms involving ∂_4A_μ are of first or second order in e, it is possible to replace ∂_4A_μ by $-i\Pi_\mu$ everywhere within the present approximation. This replacement enables (70) to express $\partial_4\phi_k''$ in terms of ϕ_k'', A_μ, Π_μ, and their space derivatives.

In order to derive Heisenberg's equations of motion, we first observe that (62) and (63) easily yield the relations

$$\partial_4\phi_k''=i[\phi_k'',\mathcal{G}_4]\,,\quad \partial_4A_\mu=i[A_\mu,\mathcal{G}_4]\,. \tag{71}$$

We have also found above that $\partial_4\phi_k''$ can be expressed in terms of ϕ_k'', A_μ, Π_μ, and their space derivatives, which shows that ϕ_k'' anticommutes with $\partial_4\phi_k''$, and therefore from (62) and (63) we get

$$\partial_4\phi_k''=i[\phi_k'',\mathcal{G}_4]\,. \tag{72}$$

Further, let

$$\begin{aligned}\mathcal{G}_4{}^{(1)}&=\tfrac{1}{2}i\int:[\Pi_\lambda\Pi_\lambda+(\partial_kA_\lambda)(\partial_kA_\lambda)]:d\tau\,,\\\mathcal{G}_4{}^{(2)}&=-i\int:\pi_j''\partial_4\phi_j'':d\tau\,,\end{aligned} \tag{73}$$

so that, according to (63),

$$i[A_\mu,\mathcal{G}_4{}^{(1)}]=-i\Pi_\mu\,, \tag{74}$$

and

$$\begin{aligned}i[A_\mu,\mathcal{G}_4{}^{(2)}]&=\int:\pi_j''(\mathbf{r}',t)[A_\mu(\mathbf{r},t),\partial_4\phi_j''(\mathbf{r}',t)]:d\tau'\\&=-\int:\pi_j''(\mathbf{r}',t)[\partial_4A_\mu(\mathbf{r},t),\phi_j''(\mathbf{r}',t)]:d\tau'\,,\end{aligned}$$

which gives, on substituting for ∂_4A_μ from (61), and then

evaluating the commutator,

$$i[A_\mu,\mathcal{G}_4^{(2)}]=\tfrac{1}{3}(e^2/m^2) \times:(\xi_j''^*A_j\delta_{\mu k}\xi_k''-\xi_k''^*\delta_{\mu k}A_j\xi_j''):. \quad (75)$$

By adding (74) and (75), we obtain

$$i[A_\mu,\mathcal{G}_4]=\partial_4 A_\mu, \quad (76)$$

and thus (71), (72), and (76) give us Heisenberg's equations of motion

$$\partial_\mu\phi_k''=i[\phi_k'',\mathcal{G}_\mu], \quad \partial_\mu A_\nu=i[A_\nu,\mathcal{G}_\mu]. \quad (77)$$

It, of course, follows from (77) that ϕ_k'', $\phi_k''^*$, A_μ, and their successive space-time derivatives also satisfy Heisenberg's equations of motion, and hence

$$\partial_\mu\pi_k''=i[\pi_k'',\mathcal{G}_\mu], \quad \partial_\mu\Pi_\nu=i[\Pi_\nu,\mathcal{G}_\mu]. \quad (78)$$

5. INTERACTION ENERGY IN THE INTERACTION PICTURE

According to (62), the total energy $\mathcal{H}=-i\mathcal{G}_4$ is given by

$$\mathcal{H}=-\int:\pi_j''\partial_4\phi_j'':d\tau +\tfrac{1}{2}\int:[\Pi_\lambda\Pi_\lambda+(\partial_k A_\lambda)(\partial_k A_\lambda)]:d\tau, \quad (79)$$

which can be put in the canonical form by using (70). Then, by separating the interaction part, and passing over to the interaction picture by replacing all the Heisenberg canonical variables by the corresponding canonical variables for free fields, we find that the interaction energy in the interaction picture is

$$\begin{aligned}\mathcal{H}_{\rm int}=&-ie\int:\{\pi_j(\delta_{jk}-\tfrac{2}{3}m^{-2}P_{lk}\partial_l\partial_j)\gamma_4\gamma_\lambda A\phi_k-\tfrac{1}{3}\pi_j(\delta_{jk}-\tfrac{2}{3}m^{-2}P_{lk}\partial_l\partial_j)\gamma_4 A_k\gamma_m u_{mn}\phi_n-(4/9)m^{-2}\pi_j\partial_j(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)\gamma_4 A_k\phi_k\\ &-(10/27)m^{-2}\pi_j\partial_j(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)\gamma_4\boldsymbol{\gamma}\cdot\mathbf{A}\gamma_k u_{km}\phi_m+(2/9)m^{-2}\pi_j\partial_j(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)A_4\gamma_k u_{km}\phi_m\}:d\tau\\ &+e^2\int:\{\tfrac{2}{3}m^{-1}\pi_j v_{jk}\gamma_4 A_k A_l u_{lm}\phi_m+\tfrac{2}{3}m^{-2}\pi_j v_{jk}\gamma_4[A_k(\partial_l\gamma A)-(\partial_k\gamma A)A_l]u_{lm}\phi_m\\ &+\tfrac{1}{3}m^{-2}\pi_j v_{jk}\gamma_4[(\gamma\partial A_k)A_l-A_k(\gamma\partial A_l)]u_{lm}\phi_m-(8/27)m^{-4}\pi_j v_{jk}\gamma_4 A_k(\partial_l-\boldsymbol{\gamma}\cdot\nabla\gamma_l-m\gamma_l)A_l\gamma_m u_{mn}\phi_n\\ &+(4/27)m^{-4}\pi_j v_{jk}\gamma_4 A_k A_l(\partial_l-\boldsymbol{\gamma}\cdot\nabla\gamma_l-m\gamma_l)\gamma_m u_{mn}\phi_n+(8/9)m^{-4}\pi_j\partial_j(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)\gamma_4 A_k(\partial_k-\boldsymbol{\gamma}\cdot\nabla\gamma_k+m\gamma_k)A_l u_{lm}\phi_m\\ &-(4/9)m^{-4}\pi_j\partial_j(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)(\partial_k-\boldsymbol{\gamma}\cdot\nabla\gamma_k-m\gamma_k)\gamma_4 A_k A_l u_{lm}\phi_m\}:d\tau+O(e^3), \end{aligned} \quad (80)$$

where all operators refer to the interaction picture, so that π_l and ϕ_l are related as in Sec. 2. In the derivation of the above result we have made use of (67)–(69), (47), and the relation

$$\tfrac{1}{2}T_{jl}T_{ln}-T_{jn}'=\tfrac{2}{3}m^{-2}P_{jk}A_k A_l u_{ln}-(4/9)im^{-4}P_{jk}\partial_k\boldsymbol{\sigma}\cdot\mathbf{H}A_l u_{ln}-\tfrac{1}{3}m^{-2}P_{jk}v_{kl}A_l A_m u_{mn}. \quad (81)$$

We have also carried out extensive manipulations of the various terms to remove the inverse differential operator $(\frac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}$ from everywhere except when it occurs in the operator u_{kl} operating on ϕ_l.

With the help of the relations

$$\begin{aligned}&\phi_j=\psi_j-\tfrac{1}{3}\gamma_j\gamma_k\psi_k, \quad u_{jk}\phi_k=\bar v_{jk}\pi_k^*=\psi_j-\gamma_j\gamma_k\psi_k,\\ &(\delta_{jl}-\tfrac{2}{3}m^{-2}P_{jk}\partial_k\partial_l)\pi_l^*=\psi_j-\tfrac{1}{3}\gamma_j\gamma_k\psi_k, \quad m^{-2}(\tfrac{3}{2}m+\boldsymbol{\gamma}\cdot\nabla)\partial_j\pi_j^*=-\tfrac{3}{2}\gamma_j\psi_j,\end{aligned} \quad (82)$$

where ψ_μ satisfies the field equations (1) and (2), the interaction energy (80) is expressible as

$$\mathcal{H}_{\rm int}=\int H_{\rm int}d\tau, \quad (83)$$

where

$$\begin{aligned}H_{\rm int}=&-ie:A_\mu(\bar\psi_\lambda\gamma_\mu\psi_\lambda-\bar\psi_\lambda\gamma_\lambda\psi_\mu-\bar\psi_\mu\gamma_\lambda\psi_\lambda+\bar\psi_\lambda\gamma_\lambda\gamma_\mu\gamma_\rho\psi_\rho):+\tfrac{2}{3}(e^2/m):[2A_\mu^2\bar\psi_4\psi_4-A_\mu A_\nu(\bar\psi_\mu\gamma_4\gamma_\nu\psi_4+\bar\psi_4\gamma_\nu\gamma_4\psi_\mu)]:\\ &-\tfrac{1}{3}(e^2/m^2):[\bar\psi_4\gamma_\mu A_\mu\gamma_\lambda\partial_\lambda\gamma_\nu A_\nu\psi_4-(\partial_\lambda\bar\psi_4\gamma_\mu A_\mu)\gamma_\lambda\gamma_\nu A_\nu\psi_4]:-\tfrac{2}{3}(e^2/m^2):[\bar\psi_4\gamma_\mu A_\mu\gamma_4\partial_k\gamma_\nu A_\nu\psi_k-(\partial_k\bar\psi_k\gamma_\mu A_\mu)\gamma_4\gamma_\nu A_\nu\psi_4]:\\ &-\tfrac{1}{3}(e^2/m^2):[\bar\psi_\mu A_\mu\gamma_\lambda\partial_\lambda A_\nu\psi_\nu-(\partial_\lambda\bar\psi_\mu A_\mu)\gamma_\lambda A_\nu\psi_\nu]:+\tfrac{1}{3}(e^2/m^2):[\bar\psi_\mu A_\mu\partial_\lambda\gamma_\nu A_\nu\psi_\lambda-(\partial_\lambda\bar\psi_\lambda\gamma_\nu A_\nu)A_\mu\psi_\mu]:\\ &+\tfrac{1}{3}(e^2/m^2):[\bar\psi_\lambda\gamma_\mu A_\mu\partial_\lambda A_\nu\psi_\nu-(\partial_\lambda\bar\psi_\nu A_\nu)\gamma_\mu A_\mu\psi_\lambda]:+0(e^3). \end{aligned} \quad (84)$$

The first-order term in $H_{\rm int}$ has the usual form $-A_\mu j_\mu$, but in addition we obtain higher-order terms, whose significance will be discussed in Sec. 7.

6. COVARIANT COMMUTATION RELATIONS AND CONTRACTIONS

The covariant commutation relations in the interaction picture can be obtained from (25) with the help of the identity

$$[\delta_{jl}-\tfrac{2}{3}m^{-2}P_{jk}\partial_k\partial_l] \times[\delta_{ln}+\tfrac{3}{2}P_{lm}\partial_m(9m^2/4-\nabla^2)^{-1}\partial_n]=\delta_{jn}. \quad (85)$$

The Hermitian conjugate of (25) is

$$\{[\pi_l^*(\mathbf{r},t)]_{\alpha'},[\phi_k^*(\mathbf{r}',t)]_\beta\}=[P_{lk}]_{\alpha'\beta}\delta(\mathbf{r}-\mathbf{r}'),$$

which, when multiplied by $[\delta_{jl}-\frac{2}{3}m^{-2}P_{jm}\partial_m\partial_l]_{\alpha\alpha'}$, becomes

$$\{[\phi_j(\mathbf{r},t)]_\alpha,[\phi_k^*(\mathbf{r}',t)]_\beta\} =[(\delta_{jl}-\tfrac{2}{3}m^{-2}P_{jm}\partial_m\partial_l)P_{lk}]_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}'). \quad (86)$$

By using the relation

$$\psi_j=[\delta_{jk}-\tfrac{1}{2}\gamma_j(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_k]\phi_k,$$

and observing that

$$(\tfrac{3}{2}m-\boldsymbol{\gamma}\cdot\nabla)^{-1}\partial_j(\delta_{jl}-\tfrac{2}{3}m^{-2}P_{jm}\partial_m\partial_l) =(4/9)m^{-2}(\tfrac{3}{2}m+\boldsymbol{\gamma}\cdot\nabla)\partial_l,$$

we can express (86) in terms of ψ_j as

$$\{[\psi_j(\mathbf{r},t)]_\alpha,[\psi_k^*(\mathbf{r}',t)]_\beta\}=[\delta_{jk}-\tfrac{1}{3}\gamma_j\gamma_k -\tfrac{1}{3}m^{-1}(\gamma_j\partial_k-\gamma_k\partial_j)-\tfrac{2}{3}m^{-2}\partial_j\partial_k]_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}')$$

or

$$\{[\psi_j(\mathbf{r},t)]_\alpha,[\bar\psi_k(\mathbf{r}',t)]_\beta\}=\{\gamma_4[\delta_{jk}-\tfrac{1}{3}\gamma_j\gamma_k +\tfrac{1}{3}m^{-1}(\gamma_j\partial_k-\gamma_k\partial_j)-\tfrac{2}{3}m^{-2}\partial_j\partial_k]\}_{\alpha\beta}\delta(\mathbf{r}-\mathbf{r}'). \quad (87)$$

The above equal-time commutation relations are equivalent to the covariant commutation relations

$$\{[\psi_\mu(x)]_\alpha,[\bar\psi_\nu(x')]_\beta\}=-i[S_{\mu\nu}(x-x')]_{\alpha\beta}, \quad (88)$$

where

$$S_{\mu\nu}(x)=S_{\mu\nu}(\partial)\Delta(x), \quad (89)$$

$$S_{\mu\nu}(\partial)=(\gamma\partial-m)[\delta_{\mu\nu}-\tfrac{1}{3}\gamma_\mu\gamma_\nu +\tfrac{1}{3}m^{-1}(\gamma_\mu\partial_\nu-\gamma_\nu\partial_\mu)-\tfrac{2}{3}m^{-2}\partial_\mu\partial_\nu], \quad (90)$$

and

$$[\Delta(x-x')]_{t'=t}=0, \quad [\partial_4\Delta(x-x')]_{t'=t}=i\delta(\mathbf{r}-\mathbf{r}'). \quad (91)$$

Now, the contraction of any two Fermi operators $U(x)$ and $V(x')$ can be expressed as

$$U^\cdot(x)V^\cdot(x')\equiv\tfrac{1}{2}[1+\epsilon(t-t')]\{U^+(x),V^-(x')\} -\tfrac{1}{2}[1-\epsilon(t-t')]\{U^-(x),V^+(x')\}, \quad (92)$$

where the superscripts + and − refer to the positive- and negative-frequency parts, and

$$\begin{aligned}\epsilon(t-t')&=1, \quad \text{for} \quad t>t'\\ &=-1, \quad \text{for} \quad t<t'.\end{aligned} \quad (93)$$

Therefore, according to (88),

$$[\psi_\mu^\cdot(x)]_\alpha[\bar\psi_\nu^\cdot(x')]_\beta=i[S_{\mu\nu}(\partial)]_{\alpha\beta}\Delta_F(x-x') -\tfrac{1}{2}i[\epsilon(t-t'),\{S_{\mu\nu}(\partial)\}_{\alpha\beta}]\Delta(x-x'), \quad (94)$$

where

$$\Delta_F(x)=-\tfrac{1}{2}[\Delta^+(x)-\Delta^-(x)]-\tfrac{1}{2}\epsilon(t)\Delta(x). \quad (95)$$

The second term in (94) can be evaluated by using the relations

$$\begin{aligned}&[\epsilon(t),\partial_\mu]\Delta(x)=0,\\ &[\epsilon(t),\partial_\mu\partial_\nu]\Delta(x)=-2\delta_{\mu4}\delta_{\nu4}\delta(x),\\ &[\epsilon(t),\partial_\mu\partial_\nu\partial_\lambda]\Delta(x)=-2\delta_{\mu4}\delta_{\nu4}\partial_\lambda\delta(x) -2(\delta_{\mu4}\delta_{\nu k}\delta_{\lambda4}+\delta_{\mu k}\delta_{\nu4}\delta_{\lambda4})\partial_k\delta(x),\end{aligned} \quad (96)$$

and thus the contraction takes the form

$$[\psi_\mu^\cdot(x)]_\alpha[\bar\psi_\nu^\cdot(x')]_\beta=i[S_{\mu\nu,F}(x-x')]_{\alpha\beta} +i[S_{\mu\nu}']_{\alpha\beta}\delta(x-x'), \quad (97)$$

where

$$S_{\mu\nu,F}(x)=S_{\mu\nu}(\partial)\Delta_F(x), \quad (98)$$

while the noncovariant operator $S_{\mu\nu}'$ is given by

$$S_{\mu\nu}'=\tfrac{1}{3}m^{-1}(4\delta_{\mu4}\delta_{\nu4}-\gamma_\mu\gamma_4\delta_{\nu4}-\delta_{\mu4}\gamma_4\gamma_\nu)-\tfrac{2}{3}m^{-2}\delta_{\mu4}\delta_{\nu4}\gamma_4\partial -\tfrac{2}{3}m^{-2}\gamma_4(\delta_{\mu4}\delta_{\nu k}+\delta_{\mu k}\delta_{\nu4})\partial_k. \quad (99)$$

7. LORENTZ INVARIANCE OF THE SCATTERING OPERATOR

We shall finally establish the Lorentz invariance of the scattering operator by applying Matthews's argument[10] to the present formalism.

Let us consider the second-order scattering matrix element due to the first order interaction term in (84), and let us carry out the contraction of a pair of Fermi field operators, which gives us

$$\begin{aligned}S_2=&e^2\int dx\int dx':A_\mu(x)A_\nu(x')\\ &\times[\bar\psi_\alpha(x)\gamma_\mu-\delta_{\mu\alpha}\bar\psi_\lambda(x)\gamma_\lambda-\bar\psi_\mu(x)\gamma_\alpha+\bar\psi_\lambda(x)\gamma_\lambda\gamma_\mu\gamma_\alpha]\\ &\times\psi_\alpha^\cdot(x)\bar\psi_\beta^\cdot(x')[\gamma_\nu\psi_\beta(x')-\gamma_\beta\psi_\nu(x') -\delta_{\beta\nu}\gamma_\rho\psi_\rho(x')+\gamma_\beta\gamma_\nu\gamma_\rho\psi_\rho(x')]:. \end{aligned} \quad (100)$$

If we substitute the noncovariant part of the contraction (97) into (100), we find after some simplification

$$\begin{aligned}S_2'=ie^2\int dx:[&\bar\psi_\alpha\gamma_A S_{\alpha\beta}'\gamma_A\psi_\beta-\bar\psi_\alpha\gamma_A S_{\alpha\beta}'\gamma_\beta A_\nu\psi_\nu\\ &-\bar\psi_\mu A_\mu\gamma_\alpha S_{\alpha\beta}'\gamma_A\psi_\beta+\bar\psi_\mu A_\mu\gamma_\alpha S_{\alpha\beta}'\gamma_\beta A_\nu\psi_\nu]:. \end{aligned}$$

By using (99) and the relations

$$\gamma_\mu S_{\mu\nu}'=S_{\nu\mu}'\gamma_\mu=-\tfrac{1}{3}m^{-1}\gamma_\nu-\tfrac{2}{3}m^{-2}\partial_\nu,$$

[10] P. T. Matthews, Phys. Rev. **76**, 684 (1949).

it is possible to express S_2' as

$$S_2'=\tfrac{2}{3}i\left(\frac{e^2}{m}\right)\int dx:[2A_\mu{}^2\bar{\psi}_4\psi_4-A_\mu A_\nu(\bar{\psi}_\mu\gamma_4\gamma_\nu\psi_4+\bar{\psi}_4\gamma_\nu\gamma_4\psi_\mu)]:$$
$$-\tfrac{2}{3}i\left(\frac{e^2}{m^2}\right)\int dx:[\bar{\psi}_4\gamma A\gamma_\mu\partial_\mu\gamma A\psi_4+\bar{\psi}_4\gamma A\gamma_4\partial_k\gamma A\psi_k+\bar{\psi}_k\gamma A\gamma_4\partial_k\gamma A\psi_4]:$$
$$+\tfrac{2}{3}i\left(\frac{e^2}{m^2}\right)\int dx:[\bar{\psi}_\mu\gamma A\partial_\mu A_\nu\psi_\nu+\bar{\psi}_\nu A_\nu\partial_\mu\gamma A\psi_\mu-\bar{\psi}_\mu A_\mu\gamma\partial A_\nu\psi_\nu]:, \quad (101)$$

which exactly cancels[11] the first-order scattering matrix element due to the second-order interaction terms in (84).

Thus, for practical purposes we can use the *effective interaction*

$$H_{\rm int}=-ie:A_\mu\bar{\psi}_\lambda(\delta_{\lambda\rho}\gamma_\mu-\delta_{\mu\rho}\gamma_\lambda-\delta_{\mu\lambda}\gamma_\rho+\gamma_\lambda\gamma_\mu\gamma_\rho)\psi_\rho:, \quad (102)$$

together with the *effective contraction*

$$[\psi_\mu\cdot(x)]_\alpha[\bar{\psi}_\nu\cdot(x')]_\beta=i[S_{\mu\nu,F}(x-x')]_{\alpha\beta}, \quad (103)$$

to obtain the scattering matrix elements.

We conclude that, although the canonical quantization of the charged spin-$\frac{3}{2}$ field creates enormous mathematical complications, it does not appear to involve any fundamental difficulty or inconsistency.

APPENDIX

If we ignore the canonical formalism, the rules for writing down the scattering matrix elements for the charged spin-$\frac{3}{2}$ field can be obtained in an intuitive manner by comparing its field equations in the presence of electromagnetic interaction with those of quantum electrodynamics.

In quantum electrodynamics the field equations are

$$D(\partial)\psi=ieA_\mu\gamma_\mu\psi, \quad D(\partial)\equiv\gamma\partial+m, \quad (A1)$$
$$\Box^2A_\mu=-ie:\bar{\psi}\gamma_\mu\psi:, \quad (A2)$$

and any scattering matrix element can be expressed in terms of ψ, $\bar{\psi}$, γ_μ, A_μ, S_F, and D_F. The function S_F is given by

$$S_F(x)=S(\partial)\Delta_F(x), \quad S(\partial)\equiv\gamma\partial-m, \quad (A3)$$

where $S(\partial)$ is obtainable from the relation

$$D(\partial)S(\partial)=\Box^2-m^2, \quad (A4)$$

so that S_F and D_F are essentially Green's functions[12] defined by the equations

$$D(\partial)S_F(x)=-\delta(x), \quad \Box^2D_F(x)=-\delta(x), \quad (A5)$$

with the appropriate boundary conditions.

The field equations in the present case are of the form

$$D_{\alpha\beta}(\partial)\psi_\beta=ieA_\mu\Gamma_{\mu,\alpha\beta}\psi_\beta, \quad (A6)$$
$$\Box^2A_\mu=-ie:\bar{\psi}_\alpha\Gamma_{\mu,\alpha\beta}\psi_\beta:, \quad (A7)$$

where

$$D_{\alpha\beta}(\partial)\equiv(\gamma\partial+m)\delta_{\alpha\beta}-\gamma_\alpha\partial_\beta-\partial_\alpha\gamma_\beta+\gamma_\alpha(\gamma\partial-m)\gamma_\beta, \quad (A8)$$
$$\Gamma_{\mu,\alpha\beta}\equiv\gamma_\mu\delta_{\alpha\beta}-\delta_{\mu\beta}\gamma_\alpha-\delta_{\mu\alpha}\gamma_\beta+\gamma_\alpha\gamma_\mu\gamma_\beta. \quad (A9)$$

The Green's function $S_{\beta\gamma,F}$ can be obtained by taking

$$S_{\beta\gamma,F}(x)=S_{\beta\gamma}(\partial)\Delta_F(x), \quad (A10)$$

where

$$D_{\alpha\beta}(\partial)S_{\beta\gamma}(\partial)=\delta_{\alpha\gamma}(\Box^2-m^2), \quad (A11)$$

which implies that

$$D_{\alpha\beta}(\partial)S_{\beta\gamma,F}(x)=-\delta_{\alpha\gamma}\delta(x). \quad (A12)$$

We then find that $S_{\beta\gamma}(\partial)$, obtained from (A11), agrees with Eq. (90) of Sec. 6, so that the above Green's function agrees with Eq. (98).

The above results suggest that the rules for writing down the scattering matrix elements for the electromagnetic interaction of spin-$\frac{3}{2}$ particles can be obtained from those of quantum electrodynamics by replacing $\bar{\psi}$, ψ, γ_μ, and S_F by $\bar{\psi}_\alpha$, ψ_β, $\Gamma_{\mu,\alpha\beta}$, and $S_{\beta\gamma,F}$, respectively.

[11] It should be noted that if we take the first-order interaction term in (84) simply as $-ie:A_\mu\bar{\psi}_\lambda\gamma_\mu\psi_\lambda:$, the above cancellation does not occur. The resulting formalism is quite correct, but it is less convenient.

[12] The Green's-function approach in various forms has been used by many authors. For the earliest papers, see R. P. Feynman, Phys. Rev. **76**, 749 (1949); **76**, 769 (1949); C. N. Yang and D. Feldman, *ibid.* **79**, 972 (1950); J. Schwinger, Proc. Natl. Acad. Sci. U. S. **37**, 452 (1951); **37**, 455 (1951).

HEPAP

NATIONAL SCIENCE FOUNDATION
OFFICE OF THE DIRECTOR
WASHINGTON, D.C. 20550

DEC 1 1970

Dr. Victor F. Weisskopf
Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Dr. Weisskopf:

I am delighted to see National Science Foundation activities included within the purview of the High Energy Physics Advisory Panel. This is valuable input for the Foundation and I hope you will continue to include this work in your deliberations.

I expect to discuss in the near future the special needs of the Cornell Accelerator with Ed Creutz and other members of the staff to determine what possible response the Foundation will be able to make in the light of our existing commitments and limitations on funding.

Thank you for your help.

Sincerely yours,

W. D. McElroy

W. D. McElroy
Director

COPY

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D. C. 20550

DEC 1 1970

Dr. Victor F. Weisskopf
Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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Thank you for your help.

Sincerely yours,

/s/ W. D. McElroy

W. D. McElroy
Director

THE UNIVERSITY OF CHICAGO
CHICAGO · ILLINOIS 60637
THE ENRICO FERMI INSTITUTE
5630 ELLIS AVENUE
AREA CODE 312, 667-4700

Office of the Director

November 11, 1970

Professor Victor F. Weisskopf
Massachusetts Institute of Technology
Department of Physics
Cambridge, Massachusetts 02139

Dear Viki:

I am writing to confirm our telephone conversation in regard to your letter of November 3 in which you invited me to serve as a temporary member of HEPAP. As I said then, I am working under severe pressure to try to get the panel report put together for the Bromley Committee. However, if we can minimize the amount of time it will take, I shall accede to your request. As I indicated to you in our conversation, I shall only be able to come to the next meeting, which I believe occurs on December 4 and 5, if my participation is limited to the early part of Friday, December 4. I must be back in Chicago in the early evening.

I certainly appreciate your interest in our efforts in behalf of the Panel on Elementary Particle Physics and look forward to getting substantial help from HEPAP in regard to some of the serious decisions we must make in formulating our report.

I am looking forward to hearing your further comments about our report on the status of elementary particle physics. The draft is being rewritten largely by Jim Bjorken but I believe the amount of rewriting will not be great unless I hear more severe criticism than I have so far. Since it is such an extensive job, it may be desirable to separate it from the main body of our report. I was hoping to get some reaction from the Physics Survey Committee itself on that score.

I look forward to seeing you in Washington.

Sincerely,

Bob

Robert G. Sachs
Director

RGS/dg

October 16, 1970

Dr. William A. Wallenmeyer
Research Division
U. S. Atomic Energy Commission
Washington, D. C. 20545

Dear Bill:

I have studied the budget figures again and would like to express one worry in respect to CEA. Essentially, the latest FY 71 figures are identical with the OMB FY 72 figures. The additional $2 million which goes to NAL are taken from the vanishing budget for PPA. This is certainly a reasonable procedure. However, I find it not easy to understand why CEA should be cut by over 15%. After all, we have decided that CEA should concentrate on the bypass and we have cut the budget appreciably by eliminating all other work. We should not then punish them excessively when they successfully work on the bypass. A cut of 15% is very serious for them as it would mean at least a 20% reduction in personnel, a grave blow at a time when they are in the midst of the most important part of their work. If further cuts are necessary they should probably come later when research is taking place, but not now when they are about to finish the gadget. A cut of $350,000 distributed over all other institutions is an imperceptible loss, whereas such a cut at CEA would hurt considerably.

I am always worried when I have to bring forward arguments in behalf of CEA. This is shy I prefer to bring the argument directly to you. I believe that the above reasoning has its validity above any local interests.

Best regards,

Victor F. Weisskopf

VFW:gpm

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF PHYSICS
CAMBRIDGE. MASSACHUSETTS 02139

October 15, 1970

To All Members of HEPAP

Dear Friends:

Enclosed is the draft of a letter to Ed Creutz. Please compare it with the letter we wrote before, a copy of which is also enclosed. Some of you may think a reiteration of our previous statement is not called for. I do, however, believe that this reiteration may strengthen the case.

We will again follow the usual procedure. After having the text viewed by you the letter will go to Paul McDaniel, and he will transmit it to the NSF. I need your reaction by October 22. No letter from you will be interpreted as an agreement.

Sincerely,

Viki

Victor F. Weisskopf

VFW:gpm
Enclosures

The Honorable Dr.

D R A F T

William D. McElroy

Dear Ed: ~~McElroy~~

At its last meeting on October 11, the High Energy Physics Advisory Panel again discussed the plans of the Cornell Electron Accelerator Laboratory to increase its energy and to add to its experimental and computational facilities.

Recent experimental results obtained with electron accelerators, such as the SLAC studies of the deep inelastic electron scattering, have confirmed the panel's views as expressed in my letter to you of July 14, 1970. High energy electron beams are a most important tool for the exploration of the subnuclear world. In view of the reduction in the research activities at CEA in Cambridge, the Cornell Laboratory provides the only opportunity in the United States for electron experiments with long-duty cycles. It is therefore of utmost importance that this facility is available to serve the national community. The present small experimental area is insufficient for this purpose and must be enlarged in order to enable the physicists to perform the fundamental experiments which are definitely needed.

Furthermore, many of these experiments require a maximum possible beam energy. It would be most deplorable if the planned increase of energy to 15 GeV would have to be postponed because of lack of funds. This increase can be obtained by a relatively modest amount of money. It would make the Cornell Accelerator a unique tool in the whole world; of great importance for the exploration of the inner structure of the proton.

DRAFT (2)

Therefore, we again urge the Nat'l Science Foundation to give high priority to the proposals of the Cornell Accelerator Laboratory. The scientific value gained is unusually high in view of the relatively moderate costs of the proposals.

Enclosure was a copy of correspondence of July 14 to Ed Creutz

UNIVERSITIES RESEARCH ASSOCIATION, INC.

2100 Pennsylvania Avenue, N.W. / Washington, D.C. 20037 / Area Code 202 293-1382

October 13, 1970

Professor Victor F. Weisskopf
Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Viki:

Yesterday at NAL I had occasion to mention my recent correspondence with Jerry Tape which was related to the tempest in a teapot crisis of several years ago with the AEC on Bob Wilson's selection of the cover for the NAL Design Study. Last evening at the Smiths' I also mentioned the draft letter of Bob Wilson on his plan for handling student activists.

I hope you can see from the enclosed letters that Bob and I work very seriously on all problems pertaining to NAL.

Both Bob and I were delighted to have you and your Committee visit NAL. For all of our sakes I hope the work of HEPAP goes well.

Sincerely,

Norman

Norman F. Ramsey
President

NFR:bls

Encl.

PLEASE READ AND INITIAL
NFR ELB
BFB RAW
MNH BLS

copy:
BS
H. Kinsey
J. Seaborg
R Wilson

UNIVERSITIES RESEARCH ASSOCIATION, INC.

2100 Pennsylvania Avenue, N.W. / Washington, D.C. 20037 / Area Code 202 293-1382

September 9, 1970

UNIVERSITIES RESEARCH ASSN, INC.
SEP 23 1970
WASHINGTON, D. C.

Dr. Paul W. McDaniel
United States Atomic Energy Commission
Washington, D. C. 20545

Dear Paul:

I have just received the enclosed letter from Gerry Tape. I am glad to see that former AEC Commissioners can have sufficient time to keep so well informed.

It seems to me that the low level states on the diagram obscure some important facts. I hope that the difference between this illustration and the NAL design study does not indicate a basic disagreement on vital matters of structure between the physicists and the U. S. Public Health Service. I am also somewhat concerned that the AEC/Division of Technical Information may be somewhat misinformed.

The illustration may indicate the cause of the serious difficulty NAL is having in its ecology effort to repopulate the midwest with herds of roaming buffalo starting with one bull and five cows. Either the bull is constructed in accordance with the Public Health and AEC Information Division specifications or he thinks he is.

Sincerely yours,

NFR:aec
enclosure

Norman F. Ramsey
President

PLEASE READ AND INITIAL
NFR
BFB
MNH
RAW
BLS copy BS

UNIVERSITIES RESEARCH ASSOCIATION, INC.

2100 Pennsylvania Avenue, N.W. / Washington, D.C. 20037 / Area Code 202 293-1382

UNIVERSITIES RESEARCH ASSN, INC.
SEP 23 1970
WASHINGTON, D. C.

September 9, 1970

Dr. Gerald F. Tape, President
Associated Universities, Inc.
1717 Massachusetts Avenue, N. W.
Washington, D. C. 20036

Dear Gerry:

Thanks very much for your letter of August 24, 1970, and its enclosure showing some confusing low-level states. I hope that the comparison between this illustration and that in the NAL Report does not indicate a basic disagreement on vital matters of structure between the physicists and the U. S. Public Health Services.

The illustration may indicate the cause of the serious difficulty NAL is having in its ecological effort to repopulate the midwest with herds of roaming buffalo, starting with one bull and five cows. Either the bull is constructed in accordance with the Public Health and AEC Information Division specifications or he thinks he is. NAL, as a single purpose laboratory, may have to call on BNL as a versatile multipurpose lab for help in this difficult problem.

Sincerely yours,

NFR:aec

Norman F. Ramsey
President

PLEASE READ AND INITIAL
MFR
BFB
RAW
PLS

ASSOCIATED UNIVERSITIES, INC.
SUITE 603
1717 MASSACHUSETTS AVENUE, N. W.
WASHINGTON, D. C. 20036
462-1676

OFFICE OF THE PRESIDENT

CABLES: UNIVASSOC

UNIVERSITIES RESEARCH ASSN. INC.
AUG 25 1970
WASHINGTON, D. C.

copy RS
P Mokamel
H Finney
Seaborg
G. Wilson

August 24, 1970

Dear Norman,

It is obvious that URA and NAL did much to point the way!

Sincerely,

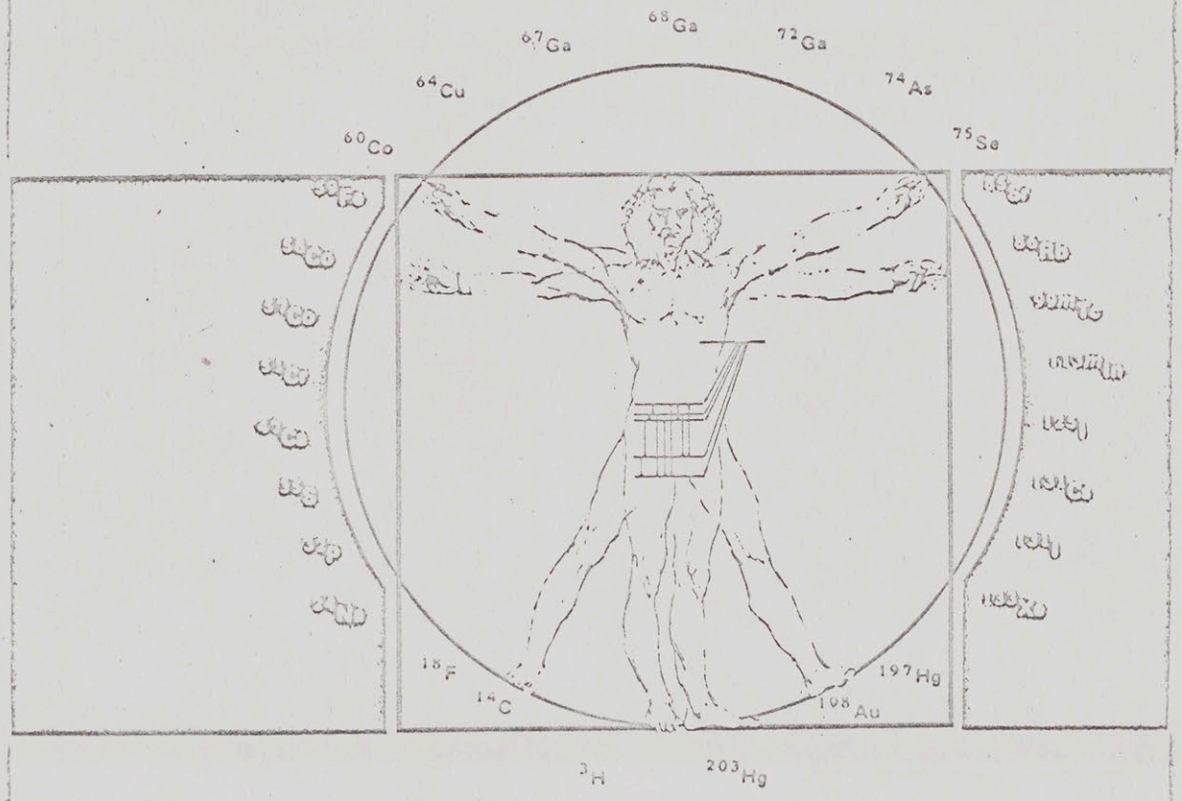
Jerry

Dr. Norman F. Ramsey
President
Universities Research Association, Inc.
2100 Pennsylvania Ave., N. W.
Washington, D. C. 20037

AEC Symposium Series 20

copy:
B L
P McDaniel
N Kinney
G. Hastings
R Wilson

MEDICAL RADIONUCLIDES: RADIATION DOSE AND EFFECTS



U. S. PUBLIC HEALTH SERVICE/Bureau of Radiological Health
U. S. ATOMIC ENERGY COMMISSION/Division of Technical Information

DRAFT

5/27/70

Daar Mr. Brooks

AEC-Washington has requested my plan for handling the student activists when they come to destroy the National Accelerator Laboratory. It is as follows:

First may I modestly point out that the project is fortunate to have a Director with long experience in confrontations with students - on their own ground, right at the university.

I propose to face the attacking hordes of students quite alone, as has been my custom, but armed with the most potent student-stopper yet devised -- a lecture on physics. I have found that, when exposed to such verbal radiations, strong men waiver, brave men weep. A touch of Newton or a dose of quantum mechanics causes the eyes to glaze over, unconsciousness to set in. The fact is, I rather hesitate to use this weapon of overkill for any but the most vicious of attacks because of the inevitable soporific pollution it engenders. Who knows, maybe the solution at Kent was more humane.

You may assure the people in Washington to rest easy - we await the impending attack with confidence. Not one bludgeoning word till I see the whites of their eyes.

Sincerely,

Robert the Wrathful

Robert Rathbun Wilson

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

SEP 17 1970

Professor Victor F. Weisskopf
Head, Department of Physics
Massachusetts Institute of
Technology
Cambridge, Massachusetts 02139

Dear Viki:

Thank you very much for your letter of September 9, 1970, and the enclosed letter relating to the CERN computer. I provided a copy to Jim Kratz who will see to it that the people concerned with the subject are informed. He was very pleased with the letter and said it should excellently serve the purpose of dispelling any rumors which remain.

The Commission has approved the appointment of Burt Richter to membership on HEPAP, and a letter of invitation has been sent to him which, however, since he will not be back from Europe until September 25 he is not yet aware of.

Looking forward with anticipation to seeing you next month at NAL and hearing the latest news on your summer at CERN.

With warm regards.

Sincerely,

Bill

William A. Wallenmeyer
Assistant Director for High
Energy Physics Program
Division of Research

SEP 1 5 1970

Dr. Burton Richter
Stanford Linear Accelerator Center
Stanford University
P. O. Box 4349
Stanford, California 94305

Dear Dr. Richter:

We have considered the composition of the High Energy Physics Advisory Panel (HEPAP) for Fiscal Year 1971 and invite you to serve as a member. This Panel was established in January 1967 as a standing committee, with membership selected from qualified leaders of the scientific community, to provide valuable advice and guidance on major problems affecting the research program in high energy physics. The recommendations of the Panel have been most helpful and the need for its continuation is clear in view of the importance and complexity of the problems affecting this area of physical research. A copy of the HEPAP Charter is enclosed for your information.

Dr. V. F. Weisskopf, who was appointed first Chairman of the Panel in 1967, has agreed to serve another year in that capacity. In addition, eight current members are requested to continue on HEPAP and five new members are being appointed. A list of the planned membership for FY 1971 is enclosed for your information. In the selection of members we endeavor to achieve a balance of broad geographic location and professional capabilities. However, each individual is requested to serve in the national interest of the high energy physics program and not as a representative of his institution or geographic region.

We would like to have your services on HEPAP made available through the AEC contract with Stanford University for operation of the Stanford Linear Accelerator Center. If this arrangement meets with approval, your time and cost of travel to meetings of HEPAP will be provided through this contract.

You are well aware of the current problems facing basic science and we believe that it will be most helpful to the AEC to have the benefit of your keen perception and counsel on important matters relating to the nation's high energy physics program. We hope you will accept the appointment to the Advisory Panel and that you will plan to attend the next meeting to be held October 11-12, 1970, at NAL.

Sincerely,

Paul W. McDaniel, Director
Division of Research

Enclosures:
As stated

cc: SAM
W. K. H. Panofsky, SLAC

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

1211 GENÈVE 23
SUISSE / SWITZERLAND

Téléphone: (022) 41 98 11
Telex: GENÈVE - 2 36 98
Télégramme: CERNLAB-GENÈVE

Votre référence
Your reference

Notre référence
Our reference JBA/pd

A rappeler dans la réponse
Please quote in your reply

To Committee of Council Members
& Department Directors

cc: Prof. V. Weisskopf
(for information)

Genève, le 14 August, 1970

I was asked at the June Council to write a new brochure on the 300 GeV Programme to replace the original 'Red Book'. The difficulty in such an assignment is to avoid on the one hand oversimplification and error and on the other hand incomprehensible technical phraseology.

Before getting this new brochure printed therefore, I am sending copies of the text to the CERN Directors and to Members of the Committee of Council hoping that, if it is acceptable to them, it will gain general approval. I would very much appreciate your comments as soon as possible so that the brochure can be issued for the October meeting of Council.

Yours sincerely,

John Adams.

J.B. Adams.

Encl.

Draft August 1970

THE EUROPEAN 300 GeV ACCELERATOR PROGRAMME

Introduction

In 1966 a brochure was produced by CERN on the status of the European 300 GeV proton synchrotron, the purpose of which was to present in summary form the work which had been carried out on this project over the preceding three years. This brochure was widely distributed and enabled many people, unfamiliar with this field of research and the purpose of CERN, to understand the reasons for putting forward such a large new project in Europe. It was expected at that time that the 300 GeV Programme would be started at the beginning of 1968 but events proved otherwise and the brochure is now 4 years out of date. Now that the Council of CERN is again considering the European 300 GeV Programme it has been suggested that the original brochure be revised to take into account all the developments that have occurred since 1966. Rather than add sections to the original brochure it seemed more appropriate for a variety of reasons to rewrite it completely.

In the first place the expansion of basic scientific research which started in the mid-1940's and which was still in full swing in the mid-1960's has now slowed down so that for the 1970's it is predictable that basic science budgets, including those for nuclear particle physics, will level off at figures not much greater than they are today. Hence a programme being put forward in 1970 is launched against a very different background than one put forward in the mid-1960's. In the second place, experience

with central research laboratories and the role of CERN in Europe have matured considerably in the last few years. In the mid-1960's the CERN proton synchrotron was only a few years old and the laboratory had much to learn in providing at one place in Europe the most advanced research facilities for the universities of a whole continent. The methods of operating the CERN-Meyrin laboratory, which were only being established in the mid-1960's, have changed considerably in recent years and should be reflected in any new presentation of the 300 GeV Programme. Lastly the equipment itself has evolved as developments have occurred and new technologies have emerged and the designs now being proposed are different in many ways from those put forward in the original brochure.

This new brochure starts by outlining the role of nuclear particle physics in European science and education because unless this is clearly explained there is no firm basis for the 300 GeV Programme. It must be admitted with regret that one reason for the declining interest of governments in basic science in recent years is the failure of research scientists to relate their work to public affairs and interests. Too often, the only clear message which reaches both governments and the general public from scientists working on the frontiers of knowledge is a demand for more money. All the excitement and interest which scientists feel for their research is hardly communicated at all and the public, which can neither understand the esoteric jargon of science nor appreciate the significance of the research results is left to wonder only at the financial demands of these modern frontiermen and to worry anxiously what returns will ever result from these heavy investments of public money.

The second chapter attempts to foresee the kind of research which the 300 GeV facilities will make possible in the future. As nuclear particle physicists know only too well, trying to foresee the course of research so many years ahead is a very hazardous business. When the 25 GeV CERN accelerator was planned in 1953 bubble chambers had not been invented and computers were scientific toys used by a few specialists. The importance of the role which these two instruments have played in the research carried out with the 25 GeV accelerator, which was not and could not be foreseen, should humble the most ardent research forecasters. The course of research is not a smooth function which can be extrapolated with confidence into the future but is subject to sudden discontinuities, brilliant insights and breakthroughs. All that can be predicted now is the research which would be important and significant if the new facilities existed today. Perhaps for the non-scientist a close analogy would be the purchase of a new telescope. A scientist can explain what he expects to see with the new instrument which he cannot see or only dimly see with his present one, but very often what turns out to be most important is what he never expected to see. Yet this kind of argument is hardly convincing to governments who are being asked to contribute large sums of money for the new instrument. This chapter should therefore be interpreted, with all its limitations, as what might be observed with the 300 GeV machine. What will be observed may be quite different and much more important.

The third chapter describes the facilities themselves; the 300 GeV machine, its experimental equipment and its laboratory. The designs for

these facilities have changed considerably in the last few years as different ideas have emerged. Two versions of the 300 GeV Programme are presented and these are related to the original CERN 1964 design and that described in the ECFA report of 1967. The first of these two versions, called Project A, was developed towards the end of 1969 and incorporates a machine which initially would operate at 250 GeV eight years after the start of the Programme but later could be developed to operate at 500 GeV. Such a machine, 3 km in diameter, and its laboratory could be built on any of the five sites offered by the six Member States of CERN who intended to participate in this Programme. The second version, called Project B, was developed during the first half of 1970 and describes a machine which could operate at 300 GeV six years after the start of the Programme. Such a machine, 2 km in diameter, can be built on a site adjacent to and north of the present CERN laboratories and Project B is only relevant to this site because it makes use of major capital facilities of the present laboratory as an integral part of the 300 GeV Programme. Both the Project A and Project B machines could be further developed in output energy by the use of superconducting magnets if they become practical and economic in the next few years. The Project A machine could then reach about 1300 GeV energy and the Project B machine 800 GeV. The cost of the Project A version of the 300 GeV Programme is 1431 MSF and that of the Project B version is 1110 MSF. For comparison, the cost of the machine and laboratory described in the ECFA report of 1967 would now be 1900 MSF.

Annexed to this brochure is a short history of the European 300 GeV Programme which includes references to all the main CERN documents concerning this Programme. This annex is included not only for the sake of completeness but also to illustrate all the long-term planning which has been carried out over the last six or seven years in order to establish the next stage of experimental facilities for nuclear particle physics in Europe.

It would be too much to expect that this brochure will satisfy everyone. The nuclear particle physicists and the accelerator builders may find it rather trivial. Other scientists may find some of the jargon unfamiliar. The non-scientist may find parts of it difficult to follow. All that can be hoped is that everyone will find something in it which is interesting and which will encourage him to support the Programme.

Chapter 1

The role of nuclear particle physics in European science and education

Nuclear particle physics is one of the basic sciences which has enjoyed a continuously evolving history in Europe ever since the discovery by Rutherford in 1917 that one of the components of the atomic nucleous was the proton and the discovery by Chadwick in 1932 that another component was the neutron. It is, however, only the most recent phase of the search for the fundamental constituents of matter and the laws governing their interactions. The original enquiry can be said to have started in ancient Greece, with Democritus, who postulated that atoms formed the building blocks of all material objects. Thus Europe not only was the craddle of this fundamental enquiry, but has supported its growth and development over many centuries and today continues to support those of its scientists who work on this basic research in its latest form.

As the frontiers of this research have advanced decade by decade there has been left in their wake a vast knowledge of the material world which has illuminated other sciences, notably chemistry, metallurgy and other solid state sciences. The application of this knowledge has moulded the form of modern civilization and has helped man to live at ease with his environment. It has also given man great power over the physical world which has transferred his fears away from a seemingly capricious and hostile environment back to himself, his social problems and the deterious effect he is now having on the environment he once feared.

As the research has pushed forward in the last three or four decades the research tools have grown larger and more costly and this has changed the character of the work though not its method. Like other basic sciences progress in understanding depends on the interplay of theory and experiment. Without experiments, theories remain unchecked; without theories, experiments lack generalized explanation. The essential experimental tools are nuclear particle accelerators which generate beams of high energy particles and these beams of particles, impinging on target nuclei, are used to create new entities whose interactions are the purpose of the research. As the research has progressed, more and more new particles and resonant states have been discovered and their place in the scheme of nature partially unravelled. But instead of getting simpler as the research has progressed the nucleon world has proved to be more and more complicated and as the complications have been uncovered the need for more and more energetic beams of particles has steadily increased. To create beams of particles with more energy requires larger particle accelerators and larger accelerators cost more money.

In the early 1950's the size and cost of accelerators had grown sufficiently large that the States of Europe decided to join together to build a European laboratory which would house a very large particle accelerator. In this way research facilities for nuclear particle physics were provided for all the European universities at a cost which was acceptable to the European States. Thus CERN was founded near Geneva in 1953 and the accelerator, a 25 GeV proton synchrotron, first came into operation at the end of 1959. A method had been found to continue the

research in Europe for at least the next two decades and at the same time an experiment had been carried out in European cooperation which was to prove useful as a basis of more extensive collaboration in other fields later on. The foundation of CERN and the concept of joint European research illustrates the relationships of nuclear particle physics to European science and education which is the subject of this chapter.

The 1950's and early 1960's were the period of the great national technological projects sponsored by governments; military projects, national prestige projects and projects aimed at improved material wellbeing. In all these projects science was seen as the key to success and since they required a great number of scientists, the university system, particularly the science departments, were rapidly expanded to meet the needs. The teaching staff at the universities expanded with the increasing output and, since it was considered essential to carry out research in order to be able to teach at the university level, the support for research increased accordingly. Also, basic research was seen to be essential as the source of new ideas and new knowledge for the national projects so as they increased in size and number they invested more of their budgets in basic research.

During the whole of this period therefore basic science in the universities and elsewhere increased rapidly in volume and those basic sciences which most closely related to the national technological projects increased the fastest. Nuclear physics and nuclear particle physics

related strongly to many of the projects; to military nuclear projects and civil nuclear energy projects in particular. Also as sometimes happens in scientific research the subject was ready to respond to this social pressure since the techniques were available and the scientific concepts sufficiently well developed. This coincidence of popular demand and an ability to respond led to an extraordinary growth of the nuclear sciences in Western Europa, America and Russia. All growth, however, is limited; in a finite system the parts can only grow to a certain size; inevitably in time a plateau is reached. The first signs of growth limitation in nuclear particle physics were evident in the mid-1960's first in Britain and then, soon afterwards, in America. It can be traced primarily to a certain disenchantment of the public with the national technological projects and to a growing preoccupation of the governments with national economic affairs. The application of cost/benefit analysis to government investments became popular and as benefit was usually equated with economic benefit some of the national projects were found unsatisfactory. As the budgets for these projects levelled off so did the support for the basic sciences which related most closely to the projects. Also the basic sciences were examined in their own right and since it is difficult to prove economic benefit from investment in basic research, at least on the time scales of government activities, the purpose of the basic sciences in the universities and elsewhere was questioned closely. These two effects combined in the late 1960's to cause a general levelling off of the investment by governments in basic science and the growth rate at present, at the beginning of the 1970's, are very much

smaller than those of the early 1960's. It is against this background that the future support for nuclear particle physics in Europe must be examined and the new 300 GeV Programme justified.

As far as the research itself is concerned there is little doubt of its growth potential or what the next step should be. This question has been discussed and debated for many years and the answer has always emerged that a larger particle accelerator, of an anergy about 300 GeV, is required if the research is to continue to progress in Europe during the 1980's and 1990's. Such a machine could only be built nowadays in Europe by collaboration between the Member States of CERN using the Organization which they have built up over the past 17 years and when it comes into operation it will serve as the principal research tool for all the universities in Europe engaged in nuclear particle physics for many decades ahead, probably to the end of this century.

The questions which arise therefore concern not so much the kind of new facilities required, or the growth potential of the subject, or the methods by which it should be achieved, but rather the support which this particular basic science will enjoy in Europe in the future and its relationship to European affairs and interests. It now seems clear that the special relationship which nuclear particle physics experienced with some of the national technological projects no longer exists or exists only indirectly through the higher education system and therefore it is the relationship between nuclear particle physics and higher education,

particularly the university system, which should be examined and where the main justification must lie. This is not to say that no further technological advances will arise from this research in the future. On the contrary, unless there is a sharp break with the past, new technologies and even new industries, as yet unknown, can be predicted with some confidence. It is rather that the original demands of national technological projects are no longer pressing nuclear particle physics as they did in the past and therefore this stimulus cannot easily be used to justify further expansion in the investment in this research.

If the demand for more university type education, particularly in the sciences, continues to grow in the next decade, as seems likely, it might be expected that basic scientific research will again grow with the output of the universities. Several factors could, however, intervene to moderate the future growth of nuclear particle research. In the first place the money allocated to the basic sciences by governments may not simply increase with a further increase in university education. In the second place, within whatever allocation is made to the basic sciences, nuclear particle physics may not grow at the same rate as other basic sciences. Thirdly, within whatever growth rate nuclear particle physics enjoys in the future it may not be possible to afford the heavy capital expenditure necessary to build the very large nuclear particle accelerators essential for carrying the research forward. These factors therefore need to be examined.

If university education in science expands in the future without an increase in financial support for the basic sciences it will be necessary to review the premise that research activity is essential to teaching at the university level. This premise is a very old one and is based on the notion that the function of a university is to create knowledge, to preserve knowledge and to teach knowledge. However, other forms of higher education exist in Europe and could be expanded, although it may be questioned whether the quality of the teaching and hence the quality of the output of these alternative systems is sufficient for a modern society which is steadily becoming more and more science based.

Within whatever growth rate is decided in the next decade for the totality of the basic sciences as a component of higher education in the university system, nuclear particle physics could be allocated a lesser growth rate if it was concluded that other basic sciences gave a more appropriate training than nuclear particle physics for future generations of skilled manpower emerging from the university system. For example, it might be concluded that a higher proportion of biologists will be required in the future than at present and the basic science budgets modified to produce this change in the output of the university system. It can be argued, however, that the mixture of scientific skills acquired by undergraduates and graduates through the study of nuclear particle physics is suited to a wide range of future employments and also that some knowledge of such a fundamental science as nuclear particle physics is indispensable to any new generations of university science graduates.

It seems therefore that some growth rate of nuclear particle physics as a component of university scientific education is likely in the next decade but, in the absence of clearly defined plans for university science expansion in the different disciplines, it is difficult to predict what that growth rate will be in the various countries of Europe. A guess might be that it will lie in the range of 3 - 6% per annum bracketing a predicted growth rate of the overall European economy of 4 - 4½% per annum during the decade 1970-1980.

It remains to discuss whether, with an annual growth rate of this size, the 300 GeV Programme could be afforded on a European basis. The Project A version of the 300 GeV Programme would require a growth rate in the international part of nuclear particle physics expenditure of about 9½% per annum over a period of eight years. The Project B version would require about 6½% per annum. The ratio between the national and international expenditures on nuclear particles physics varies widely amongst the Member States of CERN. In some of the larger countries the ratio is two to one, in others expenditures are equally divided between the national and international components. In the latter case, for example, the Project B version of the 300 GeV Programme could be afforded within a total growth rate for nuclear particle physics expenditure of about 3% per annum over the next decade if the national expenditure is held at about a constant level during this period.

Thus in each Member State of CERN the financial impact of the 300 GeV Programme in the next decade is different and dependent on

national science and education policies. Overall, however, it seems that the Project B version of the 300 GeV Programme, at least, would not unduly distort the orderly development of the basic sciences in the next decade and could be contained within the likely growth rates without depending on any special relationship between nuclear particle physics and national technological projects, nor on enhanced growth rates of the national university systems in Europe in the future.

The relationship between nuclear particle physics and the European science and education system has been explored in some detail in this chapter and indeed this seems the principal way in which this basic science relates to European affairs. There is, however, another relationship which should not be ignored which is the wholly beneficial effect CERN has had on European collaboration in science. Amongst the many European scientific organizations set up since 1950 it may be claimed that CERN still maintains its leading place as the example of effective and successful collaboration in Europe. This has not been at all an inward looking collaboration, content only to satisfy European needs, but has successfully pioneered collaborative programmes with America, with Eastern European countries, with the Soviet Union, and with the Middle-Eastern and Eastern countries. It would be impossible to put an economic value on all these collaborative efforts which sprang from the ideas and ideals of those statesment and scientists who first founded the Organization but in the years to come it may well be concluded that whatever the importance of CERN has been for European science its effect

on European collaboration both internal and external is of no less importance. The future progress and success of the Organization now depends on starting the 300 GeV Programme for without it it is difficult to look with confidence on the future of nuclear particle physics in Europe. And if the Organization withers away in the future Europe will lose its principal example of successful collaboration.

Chapter 2

Research at the 300 GeV energy level

Research at the 300 GeV energy level can only start in Europe in eight years' time if Project A is approved, or in six years' time if Project B is approved. Nuclear particle physics is developing at such a rate that it is difficult to predict what will be the important experiments in six or eight years' time. Furthermore, the American machine at NAL, Batavia and the ISR machine at CERN will be operating in one or two years' time and the physics results obtained with these machines will undoubtedly affect experiments planned for the 300 GeV machine. Therefore all that can be predicted now are the kind of experiments which an energy of 300 GeV would make possible and which at this time seem important.

A simple list of experiments, however significant to nuclear particle physicists, is hardly likely to enlighten other scientists and would probably bore most non-scientists. Some background is therefore required which will enable everyone to appreciate why it is that experiments at the 300 GeV energy level are so extraordinarily interesting and how they will add to the present knowledge of the internal structure of the nucleon. In one chapter of a brochure such as this it would hardly be possible to sketch the whole history of nuclear particle physics. The difficulty, therefore, is to know where to start.

Everyone knows that matter consists of atoms, that atoms arrange themselves into molecules and that the arrangements of molecules give the familiar materials of this world. Most people know that atoms consist of a nucleous around which orbit electrons and that it is the interaction of the orbiting electrons of one atom with those of another which determine the way atoms arrange themselves into molecules and molecules into materials. Some people know that the nuclei of atoms consist of protons and neutrons and that the different nuclei are characterized by the number of protons and neutrons they contain. A few people know that the protons and neutrons, called collectively the nucleons, themselves have an internal structure and that it is this minute world smaller than a molecule, smaller than an atom and smaller than a nuclei that is the present interest and occupation of those scientists who call themselves nuclear particle physicists. They got to this minute world via the molecules, the atoms and the nuclei about 30 years ago and ever since then have been trying to understand its strange inhabitants and their peculiar behaviour.

Some idea can be obtained of the size of the world of the nucleon by noting that diameter of the proton is of the order of 10^{-13} cm. Clearly to examine such a small object it is desirable to have tools which are smaller than the object itself. But the only tools available, anywhere near this size, are the nuclear particles themselves. Fortunately these can effectively be made smaller by accelerating them to very high velocities, near the velocity of light.

It is well known that when looking at an object under a microscope the amount of detail that can be seen depends on the wavelength of the light used. Objects separated by distances much less than a wavelength cannot be resolved distinctly. The concepts of wave mechanics enable an effective wavelength to be assigned to a beam of particles. Thus the effective wavelength of the beam of particles produced by the present 30 GeV proton synchrotrons is 1.6×10^{-14} cm, which, although smaller than the nucleon, is still rather a blunt instrument for precision measurement. A 300 GeV proton synchrotron on the other hand would give beams of particles with an effective wavelength of 5×10^{-15} cm, which is a factor of 3 smaller still and therefore, using the analogy of the microscope, should allow much more detail to be seen.

This analogy with a microscope, however, does not illustrate the full potential of an accelerator. A microscope is a detector of light which is reflected from some source by the object being viewed. The light source, which is the equivalent of the accelerator, usually does not affect the object itself. A beam of fast protons, on the other hand, impinging on nucleons at rest in a target, certainly does affect the target and what is seen by the detectors (bubble chambers, counters, etc.) is not an image of the target but new objects created by interactions in the target. These new objects or particles are of intense interest to the nuclear particle physicists and the higher the energy of the beam of particles the larger the number of new types of particles which can be observed. Furthermore, the higher the intensity of the beam of particles

from the accelerator the greater the number of these new particles is produced so that the experimentation gets easier the higher the intensity of the proton beam and the results, which depend on statistical information, become more certain.

Thus the trend of development of particle accelerators since the first machines were built in the 1930's has always been towards higher energies and higher intensities. As the energies and intensities have increased the complicated world of the nucleon has gradually been unfolded, and what has been found is not only new but largely unexpected. A remarkable number of new particles have been discovered whose significance is barely understood and a whole new spectroscopy has been revealed so that, in analogy with atomic spectra, there is now a nucleon spectroscopy with resonant states and new quantum numbers.

The interest of the nuclear particle physicist is directed not only towards the discovery and listing of new particles but also to studying the way they interact together. Ever since Newton, physicists have described interactions between bodies by means of 'fields of force'. For example, the attraction of the earth by the sun is described as the earth moving in the gravitational field of the sun. In the same way nuclear particles interact by way of fields of force, although in their case the gravitational force is far too weak to be significant in the interactions. One such interaction is due to the well known electric force between charged particles and is described by the electric field

surrounding electric charges. Another is the strong interaction between protons and neutrons which keeps them tightly bound together in the atomic nucleous. It has been found that protons and neutrons are members of a much wider class of particles - the baryons, which have masses equal to or greater than a proton - all of which interact through the strong nuclear interaction. As its name implies, the strong nuclear force is much stronger than the electric force but it extends only to very small distances from the baryon particles - distances of the order of 10^{-13} cm - whereas the electric field extends indefinitely.

Fields of force have the property of being able to propagate freely in space in the form of waves. The electric field propagates in the form of electromagnetic waves of which light waves are the easiest to observe; the gravitational field propagates in the form of gravitational waves, which, so it is claimed, have recently been observed by very delicate apparatus; the strong nuclear field has also wave propagation characteristics. In modern quantum physics any wave propagation is equivalent to the emission of a stream of particles or field-quanta. Electromagnetic waves correspond to light quanta or photons, gravitational waves to gravitons (not yet detected) and the quanta of the strong nuclear field are the group of particles called the mesons of which there are many members, some only discovered very recently. Most of the baryons and mesons, however, have a very ephemeral existence, breaking up spontaneously into lighter and more stable baryons and mesons in the remarkably short time of 10^{-22} s. They are therefore thought of more as resonant or excited states of the lighter and more stable particles rather than as particles in their own right.

In addition to many different kinds of baryons and mesons there is also another group of particles in the nucleon world called the leptons of which the electron is the best known member. This group also includes the heavy electron or muon and several kinds of neutrinos. The leptons seem quite impervious to the strong nuclear field but those of this group which are electrically charged - the electrons and muons - interact through the electric field. Members of the lepton group of particles, however, are subject to yet another interaction, called the weak interaction. Thus in nature there seem to be four forces which in order of their strength are the gravitational force, the weak nuclear force, the electromagnetic force and the strong nuclear force. The weak nuclear interaction seems to be a most peculiar one and its characteristics are by no means understood. Although it acts between all the known particles, the baryons, mesons and leptons, its corresponding field is not known, nor are the particles or quanta which correspond to this field. However, it seems certain that, whatever the field quanta are, they disintegrate always into a pair of leptons (a lepton and an anti-lepton). For example, the neutron decays by the weak interaction into an electron and anti-neutrino pair. These disintegrations can be thought of as the emission of a quantum of the weak interaction which subsequently transforms itself into a pair of leptons. But what particle corresponds to the quantum of the weak interaction remains a mystery. It has been called the W-particle (official name - the intermediate vector boson) and the reason it has not yet been found could either be that it does not exist, which would be very interesting indeed, or that it is

too heavy to be created by the present 30 GeV accelerators. A 300 GeV accelerator could create particles 3 times as heavy, so the search for the W-particle will figure strongly on the list of experiments with the new machine when it is ready.

One of the methods used by nuclear particle physicists to put some order into all these new particles is to invent theoretical models which group together particles having properties in common. Some of these models have lifetimes not much longer than those of the particles themselves but others linger on until dismissed by a well chosen experiment. One such ordering system has recently been successful in predicting a new particle, the Ω^-, which was subsequently found by experiment and it has therefore gained great respect. This system, which was developed by applying Lie's algebra to the particles and resonances, is known as SU3 (transformation by unitary matrices in 3 dimensions) and it groups the physical entities into sets of three, eight, ten or twenty-seven particles of similar properties. The new particle just mentioned was in fact the missing element in a set of ten in which nine meson-baryon resonances were already known.

However successful this classification of particles into sets, or multiplets as they are called, maybe it is only a first step in real understanding and physicists have naturally wondered what lies behind this particular system. Why this system and not any other? It has been suggested that the SU3 classification would follow if all known particles

were built up from three basic particles, called somewhat whimsically "quarks". The baryons would be composed of three quarks and the mesons of a quark and an anti-quark. If this idea turns out to be correct it really would be a very important step forward in nuclear particle physics. It would then be established that the basic building blocks of nature are not the multitudinous array of baryons, mesons and leptons but only a trinity of quarks which can combine in different ways to make up the particles we observed today. However, if they exist, the quarks are expected to be rather heavy with masses much greater than those of the baryons and mesons. So far no quarks have been definitely found and again this may be because the existing accelerators are not energetic enough to create them. So hunting for quarks will be another experimental activity with the 300 GeV machine.

Yet another particle which physicists would dearly like to discover is the magnetic-monopole. There is an odd asymmetry in nature whereby isolated electric charges exist but magnetic poles are always found in pairs (north pole and south pole). The electromagnetic interactions of such a magnetic monopole would be enormously stronger than those of an electron. In passing through matter it would ionize atoms at 10^8 times the rate of an electron of the same velocity. But despite diligent searches no magnetic monopole has yet been found. Once again it could be that its mass is too great for existing accelerators and, if so, the 300 GeV accelerator may be energetic enough to create it.

New fundamental particles are always interesting to find but they are by no means the only task of a higher energy accelerator. Other problems are just as fundamental and just as important. For example, there is the question of what a proton really looks like when illuminated by very fast particles which because of their short wavelength would be able to show up fine detail. Does it look like a very small ball with a sharply defined boundary or like a soft cloud with a minute hard core? Does it look the same at 300 GeV as at 30 GeV; does it look different when probed by neutrinos than when probed by electrons? The neutrino fluxes and energies generated by the 300 GeV accelerator would greatly extend the rather inconclusive results of present experiments and give more meaningful answers to this question. Another surprising feature of high energy interactions has been the rarity of collisions in which a large transfer of momentum takes place. If it could be shown that there is an upper limit to the amount of momentum that can be transferred this would effectively determine the "hardness" of an elementary particle. It could also be interpreted that no distance smaller than a certain minimum has any meaning, and, if this is so, then space as well as time may be quantised and both have a granular structure. The 300 GeV accelerator would extend these kind of experiments to much higher energies.

As was mentioned at the beginning of this chapter it is only possible at this time to indicate the kind of experiments which would be significant and important to do if the 300 GeV machine existed now. The ones mentioned above do not by any means exhaust the list. However, future events could

make any such list obsolete in a few years' time. For example, the intervention of new theories and insights could make the present ones untenable or new experiments with the existing machines could unceremoniously dismiss many of the present theories. Also the initial experiments using the NAL machine and the CERN ISR machine will certainly throw new light on many of the questions mentioned above.

It may be thought that the new American machine will make the European one unnecessary, but this would be to misunderstand the whole nature of scientific research. Undoubtedly it is always a great advantage to be first in a new energy field and to have a few years to look around for interesting objects. Finding a new particle is rather like finding a unicorn in a forest which no one has ever explored and sometimes it is almost as unexpected. But finding a unicorn is one thing; explaining how it came to be there and how it related to animal kingdom is another. The first is headline news; the second is scientific research. Every nuclear particle physicist would like to bask in the glory of discovering a new particle but that pleasure, in so far as it depends on getting first into the 300 GeV energy field, has now been denied European physicists. The unicorn analogy may therefore taste a little of sour grapes but it is nevertheless true. The complexity of the nucleon world will not all be solved in the next few years nor in the next decade. It will need the inspiration and inventiveness of theoreticians and experimenters of the whole world for several decades to resolve and two 300 or 400 GeV accelerators will hardly provide enough experimental facilities. If

experiments predictable as significant today are all done before the European 300 GeV machine comes into operation, which is not very likely, there will be just as significant experiments to do later; indeed the list will be even longer. In any case Europe will have the Intersecting Storage Ring machine operating in these intervening years giving equivalent primary beam energies of 1500 GeV whose resolution, to use again the microscope analogy, is far greater than either the NAL 400 GeV machine or the European 300 GeV machine and although the experiments possible with the ISR machine may be rather limited in scope they certainly will enable a first look to be taken into the region of the very high energies.

Chapter 3

The experimental facilities of the 300 GeV Programme

The first detailed studies for a 300 GeV accelerator and its laboratory were carried out at CERN in 1963-64 by a design group led by Prof. K. Johnsen. The machine design proposed by this group followed closely the successful designs used for the CERN 25 GeV proton synchrotron and its sister machine, the Brookhaven 30 GeV proton synchrotron. A combined-function lattice was adopted (focusing and bending of the protons in the same magnet unit) and a C type yoke was chosen for the magnets. The machine diameter was 2.4 km and, at a peak magnetic field of 12 kG, the machine was designed to give 300 GeV peak energy. The design of machine remained essentially unaltered until mid-1969 when another design group was set up at CERN to look again into these matters. At this time, six of the Member States of CERN had declared their intention to join the 300 GeV Programme and it was thought that a decision to start the Programme would be made at the end of 1969. The task of the 1969 design group was to study developments in accelerator design which had taken place since the 1964 study and to prepare a revised design for the machine, ready for a start on construction early in 1970.

The 1964 design for the new laboratory was modelled rather closely on the CERN-Meyrin laboratory but scaled up to be capable of operating at the 300 GeV energy level. When the new laboratory came into operation it was thought that the importance of the present one would gradually decline as the role of Europe's central laboratory for nuclear particle physics

was taken over by the new laboratory. Consequently the new laboratory was designed so that it could operate independently of the present one. The 1964 machine design was arranged so that the machine could operate efficiently and economically at 300 GeV energy in rather the same way as the 25 GeV machine was being operated at CERN-Meyrin. The cost of the 300 GeV machine and its laboratory was estimated to be 1556 MSF which at 1969 prices would be 1900 MSF. When it became apparent that only six of the twelve Member States of CERN intended to join the 300 GeV Programme some reductions had to be made to the Programme in order to reduce its cost to about 1400 MSF which was the figure the six participating Member States were prepared to contribute. These reductions were made simply by leaving out parts of the original Programme but it was arranged that the parts left out could be added later if and when extra money became available. Thus it was proposed to reduce the machine energy to about 200 GeV by leaving out part of the magnet power supplies and to reduce its intensity by leaving out parts of other machine components. However, most of the difference betweeen the capital estimate of 1900 MSF and the intended contribution level of 1400 MSF was achieved by leaving out, or rather delaying, the construction of a considerable part of the experimental facilities of the new laboratory, on the grounds that these could be gradually added later during the operating period of the laboratory. In this way most of the essential features of the 1964 design were preserved intact through until 1969.

The 1969 design study started out not only with the 1964 CERN design as a basis, but also with two other major studies, one carried out in 1965 at the Lawrence Radiation Laboratory, Berkeley, California, and the other at the new National Accelerator Laboratory, Batavia, Illinois in 1967-68. The LRL, Berkeley study had put forward the idea of an extendible energy machine, that is a machine which can start operation at an initial energy level and then, in the same machine building or ring tunnel, can be increased in energy in successive stages over a period of years. Up to this time a substantial energy increase usually meant building a new machine and often a new laboratory. This idea was particularly attractive for the new CERN Laboratory since it enabled the capital expenditure to be spread over many years, starting with a lower initial capital expenditure than would be required to complete the programme up to the required energy of 300 GeV.

The way in which this seeming miraculous energy escalation can be achieved is very simple. At the initial construction phase only part of the machine magnets are installed and the machine is aligned accordingly. In other words, at this phase of construction, only a fraction of the ring tunnel, which houses the machine and its magnets, is occupied by equipment - the rest is left empty. Later, in successive steps, more and more magnets are added, the machine realigned at each step and its maximum energy increased. The limit is reached when the ring tunnel is full of magnets and therefore the final energy of the machine is set, as usual, by the diameter of the ring tunnel which, of course, must be fixed right

at the start of the programme. Since ring tunnels are relatively cheap compared with magnets it pays to start with as large a ring tunnel as possible.

This idea was taken up and developed during the 1969 study and it came to be called the Missing-Magnet design. Apart from spreading out the capital cost and making possible a final machine energy about twice as great as could be afforded initially it has the extra advantage that new magnet technologies can be incorporated into the machine development programme. The new technology which is of most interest at this time is superconducting windings for magnets in place of the usual copper or aluminium windings since these offer the prospect of being able to operate the magnet of an accelerator economically at magnet fields of 40-60 kG instead of 12-20 kG as at present. Combining superconducting magnet technology with the Missing-Magnet machine design would enable a machine to reach about five times its initial energy in successive stages, all within the same ring tunnel and on the same laboratory site.

Since superconducting technology is a rather recent development it is worth recalling why it is now possible to consider using it in such a large device as the 300 GeV accelerator. Superconducting coils for magnets which run at a steady magnet field were developed some time ago and are currently used for large bubble chamber magnets and beam transport systems. The problem was to develop a superconducting wire which would operate under the pulsed field conditions of the synchrotron magnets. The breakthrough came with the invention in Britain of a wire which is

composed of hundreds of fine filaments of superconducting material, about 10 microns in diameter, imbedded in a matrix of copper to make a wire about 0.2 mm diameter. The internal losses of such an extraordinary conductor due to the varying magnetic field can be reduced to a level which allows economic operation of a synchrotron magnet. Wires of this type, which are now produced commercially, have been wound into coils both in Europe and in America to make experimental dipole magnets which operate under pulsed conditions in the magnetic field range of 40-60 kG. There are yet many problems to be solved before superconducting magnet technology can be incorporated with confidence in a large proton synchrotron. For example solutions have yet to be tried out to transfer the electromagnetic energy fed into these magnets into an external store and back again into the magnets, and the effect of intense radiation fields on the superconducting materials is as yet unknown. All this development work will take a few more years to complete but if it is successful this new technology will certainly open up great possibilities for accelerating machines. Furthermore, the development of pulsed superconducting magnets, which at present is being carried out in Europe at three of the National Laboratories, Rutherford, Karlsruhe and Saclay, is a great challenge to European industry and there may be many applications for it outside the field of nuclear particle physics.

By the end of 1969 it was possible to put together all the work of the study and to design a machine which would satisfy the requirements of the 300 GeV Programme. The overall requirement was that the machine and

its laboratory should cost no more than 1431 MSF at its initial stage of construction. In addition, the initial energy of machine should be as near 300 GeV as this money would allow and it should be possible to build it on any of the five sites then offered by the six Member States intending to support the Programme.

The design put forward, afterwards called Project A, incorporated a proton synchrotron with the following operating energy levels.

Project A

Machine diameter	3 km
Initial operating energy (with a half-set of iron-cored bending magnets)	250 GeV
Final operating energy (with a full set of iron-cored bending magnets)	500 GeV
Alternative operating energy - 1 (with a half-set of superconducting bending magnets)	650 GeV
Alternative operating energy - 2 (with a full set of superconducting bending magnets)	1300 GeV

The machine design used a separated-function lattice, that is a magnet system in which the bending and focusing functions are carried out in different magnet units. This system was adopted because it is no less economic than a combined-function lattice and it is more flexible. The initial stage of construction of the machine included a half-set of bending magnets which would allow an energy of 250 GeV to be reached and

at this construction stage the total project cost, for the machine, its laboratory and its experimental facilities was 1431 MSF. The duration of the initial construction period and hence the duration of the commitment of the participating Member States was eight years. After the initial construction period, if and when more money became available, the machine could be developed in several different ways. By adding the second half-set of iron-cored bending magnets the energy could be raised to 500 GeV. If, however, superconducting magnets were shown to be practical and economic by this time, instead of adding a second half-set of iron-cored bending magnets, a half-set of superconducting magnets could be added and the energy raised to about 650 GeV. Later on still, if the superconducting magnets proved satisfactory, the original half-set of iron-cored bending magnets could be removed and another half-set of superconducting magnets put in their place to raise the energy to about 1300 GeV. Thus stage by stage over many years the energy of the machine could be raised from 250 GeV to 500 GeV or even to 1300 GeV if superconducting magnets proved practical and economic.

The Project A version of the 300 GeV Programme also proposed a different scheme for the experimental areas of the machine. In the 1964 design study it was thought that, following the experience of the 25 GeV CERn machine, several beam ejection systems would be installed feeding experimental areas radiating out tangentially from the circumference of the machine. The 1969 study proposed only one ejection system and one

external proton beam line from which would be branched several experimental areas. Thus in the new scheme all the experimental areas would be grouped together along a single proton beam line, an arrangement which is more economic in its use of the site area and costs less money.

It was this version of the 300 GeV Programme which was discussed by the Scientific Policy Committee towards the end of 1969 and which was the basis of the Council decision expected at the December 1969 session of the Council. However, difficulties arose in choosing a site for the new laboratory amongst the five then offered and no decision was taken at that time. Faced with further delays of the 300 GeV Programme of unknown duration the 1969 Study was extended into 1970 and at the June 1970 session of Council a second proposal for the 300 GeV Programme was presented.

This second proposal, which came to be called Project B, is not fundamentally different from Project A but follows logically the thinking which lay behind the first proposal. The original requirement of the Programme was a machine which would operate at a maximum energy of 300 GeV. Instead of trying to get as near to this energy as possible at the initial stage of construction, it was arranged to reach it at the second stage with all the iron-cored magnets installed. Clearly this allows the machine diameter to be reduced from 3 km to about 2 km. A machine of this size using the new scheme for its experimental areas could then be located on a site adjacent to and north of the present CERN laboratory at Meyrin. Furthermore, the machine could be located in such a way that the

25 GeV machine already existing at CERN could be used as its injector and the West Hall area of the present site could be used as its initial experimental area. The cost estimates for a 300 GeV machine of 2 km diameter built next to CERN-Meyrin and using some of its major equipment showed that the Programme cost could be reduced to 1110 MSF. Within this cost is included the main experimental area which will be built north of the machine and will extend some 4 km from the beam ejection region of the machine. The duration of the Programme is eight years but research can start in the West Hall area during the sixth year of the Programme.

Thus the idea of continuously developing a laboratory over many years so that the energy level at which research can be carried out steadily increases with time, which had been the theme of the 1969 studies, was in 1970 applied to the present CERN laboratory which would not be replaced by the new 300 GeV laboratory but absorbed by it.

Following the scheme of energy development used for the Project A version of the 300 GeV Programme and using essentially the same machine design the energy steps for the Project B version work out as follows:-

Project B

Machine diameter	∿ 2 km
Operating energy (with a full set of iron-cored bending magnets)	300 GeV
Alternative operating energy - 1 (with a half-set of superconducting bending magnets)	400 GeV
Alternative operating energy - 2 (with a full set of superconducting bending magnets)	800 GeV

At the beginning of the Programme it is proposed to order only a half-set of iron-cored bending magnets. About 3 years afterwards it will be necessary to decide whether to order the other half-set and so allow the machine to be completed to the 300 GeV level with iron-cored magnets or to order a half-set of superconducting magnets and so allow an energy of 400 GeV to be reached. If the latter course is adopted then later on still the original iron-cored bending magnets could be replaced by superconducting magnets and the energy raised to 800 GeV. The decision which course to follow does not have to be taken at the start of the Programme and many factors are involved. Obviously it must be demonstrated by the time the decision must be taken that superconducting magnets are practical and economic, but also the needs of the research programme must be considered. If it is decided that superconducting magnets will be used then, while these are being ordered, manufactured and assembled, the machine can be operated at the 150 GeV energy level using the West Hall as the experimental area. If the superconducting magnets are installed by the end of the Programme then research can begin in the North

experimental area about eight years after the start of the Programme at an energy level of about 400 GeV. Thus the problem will be whether it is better to go as quickly as possible to the 300 GeV energy level or to operate at the 150 GeV energy level for a few years and then go to 400 GeV with the prospect of reaching 800 GeV later on. It is a fortunate start of the programme but can be left until some research results are available at these high energies from the NAL machine at Batavia and the ISR machine at CERN.

The 1969 and 1970 design studies have thus produced two versions of the 300 GeV Programme both of which are extremely interesting and each of which in its different way satisfies the requirements of the Programme. The following table summarizes the main features of these two versions and for comparison purposes include those of the version produced by the 1964 study. (Table on Page 36.)

The advantages and disadvantages of the Project A and B versions of the 300 GeV Programme are clearly shown in this table. The Project A version is larger, offers higher energy levels for research at each stage but costs more than the Project B version. The Project B version is cheaper. and offers the possibility of starting research at a somewhat higher energy level than Project A three years earlier. What is not shown in this table, however, is that the combined cost of operating the CERN-Meyrin laboratory and the 300 GeV Programme would rise to a level of over 600 MSF per annum with Project A and probably continue at this level thereafter whereas with Project B it rises to 470 MSF per annum and would continue thereafter at about the 500 MSF per annum level.

Comparisons of different versions of the 300 GeV Programme

	Proposed starting date of Programme	Energy level (GeV)	Completion date	Cost (MSF)	Future development in energy (GeV)
1. 1964 Study revised by ECFA in 1967	1968	300	1976	1900	-
2. Project A	1971	250	1978	1431	500 (iron-cored magnets) 1300 (superconducting magnets)
3. Project B	1971	300 or 150 (West Area) 300 (North Area)	1976 1978	1110	800 (superconducting magnets)

Project B also provides at one place in Europe a remarkable complex of experimental apparatus for nuclear particle physics. In the first place there would be the 25 GeV proton synchrotron which, using the South and East experimental areas, can offer a continuing programme of research at the 25 GeV energy level as long as this is relevant. In the second place the ISR machine will offer next year exciting research programmes at an equivalent primary beam energy level of 1500 GeV. In the third place the 300 GeV machine will make possible from 1976 onwards research programmes at the 300 GeV energy level and possibly later on at energy levels approaching 1000 GeV. Such a complex should be sufficient for the needs of nuclear particle physics in Europe until the end of the century.

Figure 1 shows the layout of the Project B machine on the proposed site and the connections between the 300 GeV machine, the 25 GeV machine and the West Experimental Area. The North Experimental Area is also shown. The whole of the site area is required to be reserved for the 300 GeV Programme but not much of the surface of this area will be built upon. When the Programme is completed the area will look as shown in Figure 2, which is a retouched aerial photograph. Very little appears on the surface because the machine will be built underground in tunnels bored in the underlying rock. Only the laboratory buildings and the North Experimental Area are noticeable in Figure 2. Thus the character of the region, which at present is used for farming and forestry, will be perpetuated in the future.

ANNEX

The History of the 300 GeV Programme and Documentation

The history of the CERN 300 GeV Programme is a remarkable record of endeavour by both research physicists and accelerator designers to establish the next stage of experimental facilities for nuclear particle physics research in order to ensure the continuation of this research in Europe.

The present laboratory of CERN at Meyrin was conceived in the early 1950's and its principal experimental facility, the CERN 28 GeV Proton Synchrotron, took advantage of the important invention of alternating gradient focusing (Christofilos, 1950; Courant, Livingston and Snyder, 1952). Even before the CERN P.S. and its twin sister, the Brookhaven A.G.S., were finished, discussions were going on amongst accelerator designers about the possibility of building much higher energy machines employing the same A.G. focusing principle but using the experience gained in building the 30 GeV machines to reduce further the costs per GeV. In 1959 the CERN P.S. came into operation followed shortly afterwards by the Brookhaven A.G.S. Both machines were extraordinarily succesful, if not beyond the dreams of their designers at least beyond reasonable expectation, and they have proved not only dependable and intense sources of high-energy particles, but immensely flexible research tools capable of extensive development. Thus, both machines, which started with beam intensities of about 10^{10} protons/pulse are now operating at intensities

of 10^{12} protons/pulse; two orders of magnitude higher than originally intended. Of equal importance has been the flexibility of these machines in providing many output particle beams, often simultaneously, to a wide variety of experimenters so that it has been possible to build up many large experimental areas around the machines in place of the one experimental hall originally provided. However, the successful operation and exploitation of these machines has brought its own problems. Because it has been possible for CERN, for example, to offer to European research physicists a far greater range of facilities and a far greater use of these facilities than was imagined possible when the CERN P.S. was designed, the annual cost of running the CERN-Meyrin laboratory, for research work and for developing the CERN P.S. machine and its experimental facilities, has turned out to be much greater than was ever foreseen. However, although the potential for reliable operation, subsequent development and intensive exploitation should be essential features of any new and larger accelerator, the degree of exploitation is something which depends not only on the scientific interest in the field when the machine comes into use but also on the economic situation of the Member States financing the laboratory at that time. It does not follow that a new and larger accelerator must be exploited as much as the CERN P.S. has been the last few years.

In the Accelerator Research Division of CERN, a special Study Group was set up, with the authorization of the Council, at the beginning of 1962 under the direction of Prof. K. Johnsen to look into the feasibility

of a 300 GeV proton synchrotron and to arrive at realistic parameters and reliable estimates of cost, manpower and time schedules. In January 1963, the Director-General of CERN, with the agreement and help of the Scientific Policy Committee, invited representatives of the European community of nuclear particle research physicists to meet at CERN to form the European Committee on Future Accelerators (ECFA). ECFA immediately set up a working party under the chairmanship of Prof. E. Amaldi which submitted in June 1963 a report on the European High-Energy Accelerator Programme (Report FA/WP/23/Rev. 3) and this report, the conclusions of which were endorsed by ECFA and the Scientific Policy Committee, was submitted to the Council at its June 1963 session (CERN/505) as the basis for future accelerator planning in Europe. The conclusions of the "Amaldi Report" as far as European joint action was concerned were twofold. At the highest energy levels the programme should include the construction of intersecting storage rings (I.S.R.) in association with the CERN P.S. machine and the construction of a new proton accelerator for an energy of about 300 GeV. The Council authorized a supplementary programme and budget for the preparation of detailed designs for what came to be called the two "summit projects"; the I.S.R. and the 300 GeV P.S. The special Study Group in the Accelerator Research Division of CERN, which had helped the Amaldi Working Party to prepare its report to ECFA and the Council, was temporarily enlarged and augmented by accelerator experts from laboratories in the Member States and from the U.S.A. and U.S.S.R. and in November 1964 produced a report in two volumes on the Design Study of a 300 GeV Proton Synchrotron which

was submitted to the Council at its December 1964 session (CERN/563). A companion report on the ISR Project was presented to the Council in June 1964.

The Scientific Policy Committee presented its recommendations to the Council for a future programme for CERN at the June 1964 session (CERN/546) and subsequently presented a supplementary paper (CERN/562) at the December 1964 session of Council. Essentially, the Scientific Policy Committee recommended to the Council a single coherent programme in three parts. The first part was improvements to the existing facilities of CERN-Meyrin including increasing the intensity of the CERN P.S., extensions to experimental areas and new experimental equipment. The second part was the addition of intersecting storage rings to the CERN P.S. and the third part was the creation of a new laboratory containing a 300 GeV accelerator.

Between the first report of the Scientific Policy Committee in June 1964 and its second report to the Council in December 1964 a meeting took place in Vienna between representatives of Western Europe, the U.S.A. and the U.S.S.R. to consider intercontinental collaboration in nuclear particle physics and future accelerator building. The conclusions of that meeting were that at the level of 200-500 GeV energy, machines could still be built on a continental basis but, at the 1000 GeV level and above, it would probably be necessary to consider an intercontinental machine. As a result the Scientific Policy Committee was able in its

second document (CERN/562) to report unanimity amongst the European nuclear particle physicists on the necessity of constructing a 300 GeV machine in Europe as an essential part of the European nuclear particle physics programme.

In 1965, at its December session, the Council approved the first and second parts of the European programme recommended to it by the Scientific Policy Committee, namely the CERN P.S. improvement programme and the ISR project, and both these programmes are now well under way. The third part of the programme, the 300 GeV laboratory, to which the Scientific Policy Committee gave a priority equal to the other two parts of the programme and many European nuclear particle physicists considered of overriding importance for the long-term future of this research, has been under discussion ever since.

In 1966 the European Committee on Future Accelerators was convened again to consider the European nuclear particle physics situation as it had developed since the "Amaldi Report" was issued (FA/WP/23/Rev. 3, 1963). Two plenary sessions took place in the spring and summer of 1966. Working Parties studied once again the component parts of the European programme. As far as the 300 GeV part of the original programme was concerned, ECFA reaffirmed its previous conclusion that "the 300 GeV project remains the primary objective of the international high-energy programme in Europe". They further recommended that the main characteristics of the accelerator should correspond to the CERN Design Study and ECFA recommendations of

1963/64 and "urged Member States to authorize the project at the earliest possible date" (Resolution by ECFA to the June 1966 Council, CERN/ECFA 66/4 Rev. 3). About a year later, in May 1967, ECFA issued a full report on its studies during 1966/67 which was submitted to the Council at its June 1967 session (CERN/700). In this report ECFA again recommended, "the building of a large proton accelerator in Europe with the least possible delay. This is essential if European scientists are to continue to contribute to the advances of high-energy physics into the 1980's". The design of the accelerator, its cost and laboratory manpower requirements were reviewed and some changes and additions proposed to the original specifications of 1963/64 but substantially the concepts of the original propositions of CERN and ECFA were upheld.

After the intensive work carried out by the CERN Study Group in 1962/63 culminating in the two-volume Design Study of a 300 GeV Proton Synchrotron submitted to Council at its December 1964 session (CERN/563) most of the CERN staff involved in the studies returned to their original jobs and to the two programmes which had been approved namely, the CERN P.S. improvement programme and the ISR project. However, some work continued at CERN on the 300 GeV Programme financed by a supplementary programme of CERN. This work included technological problems such as the linac and injection system of the 300 GeV machine and the R.F. acceleration system, and also very extensive investigations into possible sites in Europe for the 300 GeV laboratory. In June 1964 the Council had invited Member States to make proposals for possible sites for the new

laboratory and as a result some twenty-two 'official' sites were offered to CERN out of an initial list of about a hundred sites. The investigations on these sites were carried out by CERN staff and by experts and authorities in the Member States themselves and they were finally brought together in a two-volume report "Sites for the proposed CERN 300 GeV Proton Synchrotron" issued in May 1967 and submitted to Council (CERN/644/Rev. Vol. I and II). The studies showed that there was no shortage of suitable sites for the new laboratory in the Member States and, although some sites were better than others, sufficient were available to enable a good choice to be made by the Governments of the Member States when the time came to launch the new programme. The work carried out all over Europe on these site investigations is itself a remarkable story of European cooperation involving quite different people from those usually associated with the activities of CERN. Most of the national geological and survey organizations of the Member States were concerned in the work and most of the national nuclear physics laboratories. That so many suitable sites for the 300 GeV accelerator and its laboratory were discovered in Europe and investigated in such depth and extent is a great tribute to all those who took part in the work including the local administrative authorities who, after their initial surprise at finding such unforeseen virtues in the familiar soils and rocks of their regions, joined enthusiastically in the investigations.

In parallel with the continuing technological studies at CERN and the site investigations, the Committee of Council and the CERN

Administration actively pursued the formal steps necessary to set up a new Laboratory. It was at the June 1966 meeting of the Council that the President was authorized to place the 300 GeV Programme formally before the Governments of the Member States for discussion and decision. As a summary of the project up to that time, a special brochure entitled "Status of the project for a European 300 GeV proton synchrotron, July 1966", was written by CERN and issued to the Delegates to the Council. In the Foreword to that report the Director-General of CERN wrote, "I should point out one difference between high-energy physics and many other branches of science; the unavoidable large size of the equipment forces us to make plans for fifteen years ahead, involving physicists of a whole continent. Delays in decision can therefore have a catastrophic effect on the whole future of (this) fundamental physics in Europe, and for this reason Governments have been requested to decide on this new Laboratory as soon as possible. Five years of study will have gone into preparing the decisions and ten more years will pass before the new Laboratory can start to operate. By then CERN will have been running for nearly twenty years. The time to take the next step forward is now". The two essential documents which must be formally agreed by the Member States before the 300 GeV Programme can be started are a new Convention, which allows the setting up of a new Laboratory, and a document defining its Programme. Work on the new CERN Convention was started in March 1966, reached an agreed form in December 1967, and was submitted to Member States for ratification in January 1968 (CERN/716/Rev. 5). At the time of writing this brochure ten Member States have announced their

ratification of the new Convention but all must ratify before it can come into force. Work on a Programme Definition document was started soon after the work on the new Convention and a version suitable for the Project A 300 GeV Programme was submitted to Council at its December 1969 session (CERN/873). Another version suitable for the Project B 300 GeV Programme will be submitted to Council at its October 1970 session.

In 1969, in anticipation of a favourable decision by the Council on the 300 GeV Programme a new committee was set up, again under the chairmanship of Prof. E. Amaldi, to advance the study of various technological problems associated with the 300 GeV accelerator. This "300 GeV Steering Group" set up a number of Working Groups composed partly of CERN staff but mainly of staff of the national accelerator laboratories to study different aspects of the accelerator. The report of this Steering Group and its Working Groups was submitted to the Council at its December 1969 session (CERN/870).

The Committee of Council decided in 1969 to visit the sites proposed for the new 300 GeV Laboratory by those Member States who had indicated their intention to join the Programme. Accordingly five sites, Göpfritz (Austria), Le Luc (France), Doberdò (Italy), Drensteinfurt (F.R. of Germany and Focant (Belgium) were visited by Members of the Committee of Council together with CERN Directors and site experts from the Member States. The timing of this visit, arranged to give Members of the Committee of Council a thorough understanding of the qualities and

potentialities of the proposed sites before the June 1969 Council meeting, proved very opportune since on each of the sites visited it was possible, by virtue of the shafts and galleries driven into the bedrock, to inspect the actual rock in which the machine would be founded.

It was expected at the December 1969 session of Council that a decision would be reached to start the 300 GeV Programme. Six Member States had announced their intention to join the Programme, five sites were available for the new laboratory and all the necessary documentation was prepared and presented to Council. However, difficulties arose in choosing one site out of the five offered and no decision was taken. Instead a meeting at Ministerial level was arranged for the end of January 1970 to discuss the problems but it did not take place.

Faced with delays of unknown duration the small group at CERN began once again in early 1970 to review the Programme, this time from an entirely different starting point. Project A, which was the basis of the 300 GeV Programme submitted to Council in 1969, started with the notion of a fixed sum of money and five sites and described a machine and a laboratory which could be built for that sum of money on any of the five sites. The sum of money, 1431 MSF, had been agreed by the six Member States intending to join the Programme and, for this money, it was planned that the machine, at its first stage of construction, would run at an energy of 250 GeV eight years after the start of the Programme. Later on the energy could be raised to 500 GeV if and when additional money became available.

Project B, which emerged from the 1970 studies, started with the original ECFA recommendations for a machine of 300 GeV energy and incorporated a machine which would reach that energy if completed with iron-cored magnets. The machine diameter was consequently smaller than that of Project A, 2 km as against 3 km, and it was found that a machine of such a size and its laboratory could be located on a site next to and north of the present CERN Laboratory at Meyrin. It then became possible to consider using major installations at the present laboratory as an integral part of the new laboratory which both reduced the cost of the 300 GeV Programme and shortened the time between the start of the Programme and the first research operation. The cost of the Project B 300 GeV Programme is estimated at 1110 MSF and research could start at the 300 GeV energy level six years after the start of the Programme.

This second version of the 300 GeV Programme took shape as a result of many discussions in the Committee of Council, in the Scientific Policy Committee, in ECFA and, of course, in the 300 GeV Machine Committee, which was set up to design the machine in the second half of 1969. Project B was first presented to Council at its June 1970 session (CERN/943) where it gained a wide measure of support and the Council at that meeting unanimously authorized further studies of the Project so that it could be presented in the same detail as Project A towards the end of 1970.

These studies are now underway and it is hoped to submit Project B formally to Council at its October 1970 session together with the relevant

documentation so that Council may reach a decision at its December 1970 session.

If indeed a decision is taken in favour of Project B at that time, the 300 GeV Programme could start at the beginning of 1971 and research could start in 1976 at the 300 GeV energy level in Europe. Curiously enough this is the same date as well as the same energy that ECFA recommended as long ago as 1963 and if it is achieved the essential experimental needs of nuclear particle physics in Europe should be satisfied for the next two or three decades.

Box 002 - D

STANFORD UNIVERSITY

STANFORD LINEAR ACCELERATOR CENTER

Mail Address
SLAC, P. O. Box 4349
Stanford, California 94305

August 4, 1970

Professor V. F. Weisskopf
CERN
1211 Geneva 23
Switzerland

Dear Viki:

This is a follow-up on our telephone conversation. When I finally turned down both yours and Paul McDaniel's invitation to serve on HEPAP, I had spoken to both of you very highly recommending Ballam as an excellent candidate, with Richter as an alternate. Recently I heard that the HEPAP high command was going for a theorist instead. Since I interpreted this as meaning that SLAC would be unrepresented, which I thought would be very bad, I phoned to express my views to you. Now that I learn you are combining SLAC and Theory in the person of BJ I feel much better.

I can think of no one better than BJ for looking carefully at, and keeping his eye on, important problems and directions of physics. From a selfish SLAC point of view, someone like Joe Ballam, who has many broad virtues and in addition is so very well informed on the real problems of life at SLAC, would, of course, be a stronger member. I say this because the crucial recommendations of HEPAP are going to involve what will happen to us when we lose, say, a couple of hundred thousand dollars in our budget, one way or another. And no one has a better feel for this as well as its physics impact than Joe who is also an excellent physicist. It is all a matter of weighting the importance of familiarity with real facts of life at a major lab, factors from which BJ has so far been pretty well shielded but which are vital for HEPAP. Maybe he'll have to learn them now, however.

I look forward to seeing you in the fall. Have a good summer.

Best regards,

Sid

Sidney D. Drell

P. S. - I am enclosing a copy of "Policy on SLAC Participation in Work at the National Accelerator Laboratory" which Pief wanted forwarded to you before the next HEPAP meeting.

Enclosure

AEC

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

July 24, 1970

Professor Victor F. Weisskopf
European Organization for Nuclear
Research - CERN
1211 Geneva 23, Switzerland

Dear Vicki:

I would like to thank you very much for your thoughtful letter of June 25, 1970, discussing the justification for and problems of the AEC-supported research programs in low and medium energy physics.

I found your letter most helpful and the information provided is already being put to good use. Thanks again for the imposition on your time.

Sincerely,

George

George A. Kolstad
Assistant Director (for Physics
and Mathematics Programs)
Division of Research

July 18, 1970

Dr. Paul W. McDaniel, Director
Division of Research
U.S. Atomic Energy Commission
Washington, D.C. 20545

Dear Paul:

As you know the High Energy Advisory Panel has discussed future plans for the PPA on a number of occasions. Earlier this year when we were advised of the drastic budgetary situation for FY 1971 and the absence of prospects for a significantly improved situation for FY 1972, we concluded that it would be impossible to operate all of the accelerators which were supporting the research programs. This point of view was arrived at because of the absolute necessity to provide funds for the maintenance of research efforts at the more advanced laboratories having higher energy beams and greater capabilities. As a consequence it was concluded that the PPA should be phased out. This was a painful recommendation since the PPA is still a viable laboratory with a large number of university users producing results of significant value.

We believe that the situation has changed since the original decision was made. Dr. White has proposed a limited operating program over the next few years, drawing heavily on utilization of the facilities which now exist. This would avoid a precipitous shut down and permit the completion of important research projects. Further, there are interesting possibilities for utilization of the machine in areas such as nuclear structure physics and high energy-ion research, which should be investigated. A heavy ion capability may be of special interest to the NASA. We, therefore, urge that the federal government continue support of the PPA high energy physics program in FY 1972 at a minimal level. If another mission is to be accomplished by the PPA, the possibility of federal support on an incremental basis for a modest but significant high energy program in the future should be considered.

Sincerely,

Victor F. Weisskopf

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF PHYSICS
CAMBRIDGE. MASSACHUSETTS 02139

Off. Letter

14 July 1970

Dr. Edward Creutz
National Science Foundation
Washington, D.C. 20550

Dear Ed:

At its meeting on May 24-25, 1970, the High Energy Physics Advisory Panel had a presentation of the plans to increase the utility of the NSF supported electron accelerator at Cornell by raising the energy to over 15 BeV, by extending the experimental area, and by increasing the associated computer facilities. We believe that all aspects of the proposal are well thought out and would help substantially and in a relatively inexpensive way improve the research capability of this accelerator.

The Cornell accelerator laboratory is a very important element in the complement of high energy facilities of the United States. It has acquired recently even more significance by the fact that the research activities at the Cambridge Electron Accelerator (CEA) have been sharply reduced in order to meet financial stringencies. Since CEA most probably will concentrate exclusively on the exploitation of the so-called "by-pass", producing clashing electron-positron beams, the research activities with several BeV electron beams of large duty cycle will be performed in the U.S. exclusively at Cornell. Among these are inelastic electron scattering with identified final states, exploration of photo-produced reactions with multiple final states, etc. which the Cornell accelerator would have to perform. These experiments require instrumentation, floor space and computer capacity which is generally in excess of that now available. We feel that the addition of floor space and computer capacity is essential to have the Cornell machine make use of its unique characteristics. In addition, the proposed increase in energy will make this instrument as a long-duty cycle electron accelerator unique not only for the U.S. but for the whole world, since the only two competitors in Germany and Russia do not go higher than 7 BeV.

The addition of the experimental area and of the computer facility are not only desirable at the present energy but are even more important for the exploitation of the higher energy beams.

By funding these efforts, the National Science Foundation can play a most important role in helping to keep elementary particle physics research in the United States on a high level. We very much hope that the proposed improvements can be realized. We consider the Cornell facility to be one of those laboratories of which we can be truly proud.

Very truly yours,

Victor F. Weisskopf

Victor F. Weisskopf
Chairman
High Energy Physics
Advisory Panel
A.E.C.

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

JUL 6 1970

Professor V. F. Weisskopf
CERN
1211 Geneva 23
Switzerland

Dear Professor Weisskopf:

My purpose in writing is to express my deep appreciation for the excellent and devoted service you have given to the Atomic Energy Commission as Chairman of the High Energy Physics Advisory Panel. Under your leadership the Panel has applied their expert knowledge of the field of research to many complex problems and has given us the benefit of their well considered assessment and recommendations. Your important role has been especially effective and your untiring and effective leadership is much appreciated.

Letters were sent out a few days ago to five new members and to the eight continuing members of the Panel. A list of the membership for FY 1971 is enclosed for your information. We believe this list, approved by the Commission in advance of dispatching the letters, provides the desirable balance as to specialization, geographic location, and type of institutional affiliation. Each new and continuing member was reminded that HEPAP members serve on the Panel in the interest of the national program and not as representatives of their respective institutions or geographic locations. A copy of the Charter was sent to the new members.

We are gratified that you are willing to continue as Chairman of HEPAP for one more year and we look forward to continuing this pleasant association. We have scheduled the meeting of July 17-18, 1970 at the H Street Building, Washington, D. C. and we shall be pleased to see you at that time.

I hope you are enjoying a productive and pleasant summer at CERN.

Sincerely,

Paul W. McDaniel

Paul W. McDaniel, Director
Division of Research

Enclosure:
As stated

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Dr. Gerald F. Tape, President
Associated Universities, Inc.
1717 Massachusetts Avenue, N. W.
Washington, D. C. 20036
202-462-1676

Professor Kent M. Terwilliger
Department of Physics
University of Michigan
Ann Arbor, Michigan 48104
313-764-4445

Professor Sam B. Treiman
Palmer Physical Laboratory
Princeton University
Princeton, New Jersey 08540
609-452-4350

Dr. William A. Wenzel
Lawrence Radiation Laboratory
University of California
Berkeley, California 94720
415-843-2740 Ext. 5501

Professor William J. Willis
Sloane Physics Laboratory
Yale University
New Haven, Connecticut 06520
203-436-1580

6/24/70

corr-P

STANFORD UNIVERSITY

STANFORD LINEAR ACCELERATOR CENTER

Mail Address
SLAC, P. O. Box 4349
Stanford, California 94305

June 29, 1970

Professor V. F. Weisskopf
CERN
2511 Geneva 23
Switzerland

Dear Viki:

I got your June 23 letter and I tried to persuade Sidney to serve on HEPAP but, as you can tell from his letter of June 26, I failed. I agree with him that it would be unwise for him to become the chairman; this is a job which I believe should go to a non-big laboratory man and I hoped to be able to persuade him to serve provided the chairmanship was barred. However he is really incredibly harassed at the present moment. Although he has been off PSAC he still is involved with one of its major panels which is right in the middle of ongoing battles in Washington. In addition both of us are heavily drawn into the ABM and other debates in the Congress, and are also getting involved in the total student-university problem, which is now aggravated by Pitzer's abrupt resignation. Sid just does not want to get involved with anything more now.

To some extent the total amount of HEPAP-associated work which Sid has seen on my side has scared him a little bit, although I assured him that something like the effort involved in writing our report would be very unlikely to be repeated next year. Anyhow this is it and we have to make the best of it. I agree with your general complaint that the total HEPAP membership is being downgraded in prominence, although I do not believe in vitality. We have to embark on a major educational process on the AEC that they are good people. I think either Ballam or Richter would be very good. Richter is more vocal and more thoughtful but he may have antagonized some people at some time in the past. Ballam is very well regarded by the Users because he has put the bubble chamber operation at SLAC into the most productive source of pictures of which only well under 20% are being used in-house. In addition he serves on the Stanford Academic Senate and therefore knows a lot about university-laboratory interactions. He is, however, relatively quiet and probably would not engage in vigorous dialogues with the Ledermans, et al.

I am sorry I could not do better.

Regards,

Pief

W. K. H. Panofsky

Correspondence - D

STANFORD UNIVERSITY

STANFORD LINEAR ACCELERATOR CENTER

Mail Address
SLAC, P. O. Box 4349
Stanford, California 94305

June 26, 1970

Professor V. F. Weisskopf
CERN
1211 Geneve 23
Switzerland

Dear Viki:

I am finally responding to your letter of June 1 after mulling it over in Israel for the last few weeks. It is very difficult for me to turn down your appeal but I am afraid I will and for several reasons:

1. I still have just too much work and too many commitments in Washington and I don't really see them tapering off, especially during the height of the SALT sessions.

2. I think you are being a little harsh on Ballam or Richter regarding this committee; I think that the working people in the AEC should be more responsive to a man's knowledge in the field and his willingness to argue his views in a vigorous and forthright way rather than being responsive to his titles or very irrelevant paraphernalia of rank.

3. In any case I think it would be inappropriate to groom someone from a national laboratory for chairmanship of that committee, as you suggested in a phone call to me. Certainly the chairman should be a university person.

It really pains me to reject your persuasive request but I fundamentally feel that these other people not only can but will do a first-rate job to continue the fine precedent you have set so far with HEPAP.

Dan and I had a marvelous trip in Israel and I was pleased to see that Nechama is in good shape and has resumed her career vigorously. We are trying very hard now to bring her and the boys to Stanford next summer. Why don't you and Ellen join us?

Best wishes,

Sid

Sidney D. Drell

general

PHYSICS TODAY

Published by The American Institute of Physics 335 East 45 Street New York, N.Y. 10017
(212) MU 5-1940

24 June 1970

Professor Victor F. Weisskopf
Massachusetts Institute of Technology
Department of Physics
Cambridge, Massachusetts 02139

Dear Professor Weisskopf:

For your information, here is the item on the subpanels of the High Energy Physics Advisory Panel, which is scheduled to appear in the August issue of PHYSICS TODAY.

Sincerely,

Theodora Johnides

(Miss) Theodora Johnides
Assistant Editor

TJ:lmg

MEMBER SOCIETIES:
American Physical Society/Optical Society of America/Acoustical Society of America/Society of Rheology
American Association of Physics Teachers/American Crystallographic Association/American Astronomical Society

Sandweiss and Cork Head AEC

High-Energy Physics Subpanels

Two subpanels have been added to the High-Energy Physics Advisory Panel of the Atomic Energy Commission, which is headed by Victor F. Weisskopf of MIT. The subpanel on future patterns of high-energy physics research is headed by Jack Sandweiss of Yale University and is studying the changing character of particle physics in view of the advent of large-scale accelerators and in view of prospects for limited financial support. Bruce Cork of Argonne National Laboratory is chairman of the subpanel on accelerator technology. This subpanel plans to advise the AEC division of research on multi-GeV accelerator developments that should be more fully supported and to study the cost and time scale of the next generation of high-energy accelerators. Both chairmen would welcome the advice and the opinion of anyone who has an interest in these problems.

HEPAP

FYI - from Wallenmeyer

THE UNIVERSITY OF ROCHESTER
RIVER CAMPUS STATION
ROCHESTER, NEW YORK 14627

DEPARTMENT OF PHYSICS
AND ASTRONOMY

June 23, 1970

Dr. Glenn T. Seaborg
Chairman
Atomic Energy Commission
Washington, D. C. 20545

Dear Glenn,

In common with scientific groups throughout the country, the Division of Particles and Fields of the American Physical Society became concerned about the employment situation in particle physics. In particular, it was decided to make a rather thorough study of the situation in theoretical particle physics. In my capacity as Chairman of this division, I appointed a "select" committee of the two most recent Dannie Heineman prize winners (Profs. Y. Nambu and A. Wightman) to gather the basic data. A special (and rather sensitive) feature of this survey was the attempt to obtain a rough qualitative evaluation of the applicants for postdoctoral positions, in addition to distinguishing between U. S. and non- U. S. citizens. I am enclosing a copy of the interim report which Profs. Nambu and Wightman have submitted to the Executive Committee of the Division of Particles and Fields. This interim report already emphasizes the gravity of the situation since it indicates that approximately one half of the American applicants ranked A have not succeeded in obtaining positions in the approximately fifty leading theoretical particle physics centers.

The DPF Executive Committee has accepted the recommendations of the select committee and letters have gone out to the institutions (recommendation B) and the American applicants (recommendation C) in order to complete the study. When the study is completed in early Fall, the DPF Executive Committee will attempt to forward to you specific recommendations. Meanwhile, it seems to me that the preliminary report of Profs. Nambu and Wightman may be helpful to you in proposing solutions to the present unemployment problem for young Ph.D's in most scientific disciplines.

Best greetings.

Sincerely yours,

R. E. Marshak, Chairman
Division of Particles and Fields

REM:eh
encls.
cc: Dr. W. Wallenmeyer ✓

03020

June 4, 1970

TO: R. Marshak

FROM: Y. Nambu and A. Wightman

SUBJECT: Report on Manpower Situation in Theoretical Particle Physics

In response to the request contained in your letter of February 10, 1970, we have written a letter soliciting information about the employment of physicists working in theoretical particle physics who are in their first three or four years after the doctorate.

Our letter went to individuals at the 59 institutions on a list provided by you (See Appendix I). The text of the letter is Appendix II. It asked for a list of the applicants for post-doctoral positions for 1970-71, ranked in three categories:

A - Outstanding.
B - Competent, but not very exciting
C - Mediocre to Incompetent.

We received replies from 49 institutions, giving us altogether the names of about 600 applicants. Of these 82-85 had been hired or would be hired.

Before we describe in more detail the breakdown of these figures, we want to emphasize that many of our informants expressed their opinion that the assignment of A, B, C categories was quite unreliable. This was also clear from the internal consistency of the ratings. (How should we list a man who received five A's, three B's and four C's?) In the end, recognizing that much more effort was likely to have been spent distinguishing A's from B's, and noticing that almost all the applicants got some B's, we lumped the B and C categories.

A man is counted as Class A if he is so classified by two institutions. A man is also in Class A if he is so classified by just one institution, unless in our judgment we regarded the rating as out of line (institution did not get many good applicants or gave a high percentage of A's, or the candidate was given a low rating by many other institutions). The number of these doubtful cases was about 5% of the Class A total.

The results are these:

1. The number of applicants is about 628. The total number of applications was about 5000, because average applicant wrote to many institutions.

2. About 140 applicants were ranked A.

3. It is estimated that about 50% of all applicants are U.S. citizens.

03020

4. It is estimated that about 50% of all A applicants are U.S. citizens.

5. Of the 82-85 applicants who got (or would get) the jobs, it is estimated that 70 are A class and 15 are B class.

6. Among those who got jobs, about a third are U.S. citizens, a third are not, and another third do not have their citizenship listed.

7. Since our table contains the date of Ph.D. we can give a rough answer to the question: Does a considerable fraction of the job seekers represent people who are seeking a second post-doctoral position? The answer seems to be yes. Crudely put, several years' production of Ph.D. people seems to be stuck in the pipeline.

8. The comments we solicited pointed a clear picture of contracting budgets and tight job markets, with the smaller institutions hit somewhat harder than the larger. A selection of the remarks which we regarded as of special interest is included in Appendix III.

We have three recommendations:

A. That copies of the final version of this report be sent to all institutions which supplied information.

B. That a letter be addressed to the applicants asking them to provide information on their employment, as well as any comments they may have on the job situation. Since this involves the use of the names supplied to us in confidence by the institutions listed in Appendix I, we believe that the institutions should be given a chance to object to this procedure, if they wish. The simplest method would be to include a copy of the proposed letter to applicants along with the report to be sent, according to recommendation A.

C. Since it seems likely that many of the applicants will end up doing something other than research on particle physics at one of the centers, an effort should be made to find out what kind of jobs they do get, in order that next year's crop can be given realistic advice, and something can be done about the unemployed among this year's crop.

APPENDIX I

Institutions to which the survey letter was sent.

Amherst, Boston, Massachusetts
Argonne National Laboratory, Argonne, Illinois
Boston University, Boston, Massachusetts
Brandeis University, Waltham, Massachusetts 02154
Brookhaven National Laboratory, Upton, L.I., New York 11973
Brown University, Providence, Rhode Island 02912
California Institute of Technology, Pasadena, California 91109
California, University of, Berkeley, California 94720
California, University of, San Diego, La Jolla, California 92037
California, University of, Irvine, California
California, University of, Santa Barbara, California 93106.
California, University of, Los Angeles, California 90024
California, University of, Santa Cruz , California 95060
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
Chicago, University of, Chicago, Illinois 60637
Colorado, University of, Boulder, Colorado 80302
Columbia University, New York, New York 10027
Cornell University, Ithaca, New York 14850
Duke University, Durham, North Carolina 27706
Harvard University, Cambridge, Massachusetts 02138
Hawaii, University of, Honolulu, Hawaii 96822
Illinois, University of, Urbana, Illinois 61801
Indiana University, Bloomington, Indiana 47401
Iowa, University of, Iowa City, Iowa 52240
Iowa State University, Ames, Iowa 50010
Johns Hopkins University, Baltimore, Maryland 21218
Maryland, University of, College Park, Maryland 20742
Massachusetts Institute of Technology, Cambridge, Mass. 02139
University of Massachusetts, Boton, Massachusetts
Miami, University of, Coral Gables, Florida 33124
Michigan, University of, Ann Arbor, Michigan 48104
Minnesota, University of, Minneapolis, Minnesota 55455
Michigan State University, Lansing, Michigan
National Accelerator Laboratory, P. O. Box 500, Batavia, Ill. 60510

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University of Nebraska, Lincoln, Nebraska
New Mexico State University
New York University, Washington, Square, New York, 10003
Northeastern University, Boston, Massachusetts 02115
Northwestern University, Evanston, Illinois 60201
Notre Dame University, Notre Dame, Indiana 46556
Ohio State University, Columbus, Ohio 43210
University of Oregon, Eugene, Oregon 97403
University of Pennsylvania, Philadelphia, Pennsylvania 19104
University of Pittsburgh, Pittsburgh, Pennsylvania 15213
Princeton University, Princeton, New Jersey 08540
Purdue University, Lafayette, Indiana 47907
University of Rochester, Rochester, New York 14627
Rockefeller University, New York, New York 10021
Rutgers University
New Brunswick, New Jersey 08903
Stanford University, Stanford, California 94305
State University of New York, Stony Brook, L.I., New York 11790
Syracuse University, Syracuse, New York 13210
The University of Texas, Austin, Texas 78712
University of Utah
Tufts University, Medford, Massachusetts 02155
Washington University, St. Louis , Missouri 63130
University of Washington, Seattle, Washington 98105
University of Wisconsin, Madison, Wisconsin 53706
University of Wisconsin, Milwaukee, Wisconsin 53201
Yale University, New Haven, Connecticut 06520
Yeshiva University, New York, New York 10033

Appendix II

THE UNIVERSITY OF CHICAGO
THE ENRICO FERMI INSTITUTE
5630 ELLIS AVENUE
CHICAGO • ILLINOIS 60637
AREA CODE 312-667-4700

March 11, 1970

The purpose of this letter is to ask your cooperation in a manpower survey. Robert Marshak, as Chairman of the Division of Particles and Fields of the American Physical Society, has asked us to find out how many theoretical physicists, working in particle physics and allied areas at the post-doctoral level, are having employment difficulties. At the moment, there is a general impression that an employment crisis exists for post-doctorals. The Executive Committee of the Division wants to know to what extent multiple applications for positions have created an impression that there are many more candidates for post-doctoral positions than available positions. The Executive Committee would like the survey to distinguish those individuals who may be expected to be real contributors to physics from those who are merely competent. If it turns out that there will be a substantial number of the first category unemployed, it is expected that the Executive Committee will attempt to bring the situation to the attention of the Government.

We have been given a list of approximately 50 institutions which are generally regarded as centers for work in particle physics. At each we have selected an individual who, we hope, can help us get the needed information. If it turns out that you are unable to do this job, we hope that you will be able to enlist some other colleague to do it.

We are asking for some information which obviously should be kept confidential; for example, your rating of the quality of the candidates. In particular, our report to the Executive Committee will include no names of individual candidates but only statistical information (e.g. the number of applicants in the A, B, C categories described below).

Please return the questionnaire to A. Wightman by April 15 (Address: Physics Department, Princeton University, Princeton, New Jersey 08540). This will give us time to prepare the report to the Executive Committee for its meeting of April 29.

We are sorry to have to ask you to perform this onerous task, but we think that it is very important that the Executive Committee base its action on solid facts.

Sincerely,

Y. Nambu A. S. Wightman

Y. Nambu A. S. Wightman

P.S. Please do not hesitate to phone one of us if you have any questions.
Y. Nambu: 312-667-4700, ext. 8608 A. Wightmann: 609-452-3000
(After April 3, Phys. Dept., Univ. of Texas, 512-471-5206)

03020

EMPLOYMENT SURVEY FOR POST DOCTORAL THEORETICAL PHYSICISTS WORKING IN PARTICLE PHYSICS OR ALLIED FIELDS

1. Please list the names of your applicants for post-doctoral positions, their current institutional affiliation, and the year in which they received their Ph.D. Also indicate their citizenship, if it is known.

2. Label the candidates A, B, C:

   A: Outstanding, likely to make significant contributions to physics.
   B: Competent, but not very exciting, probably will do useful work.
   C: Mediocre to incompetent.

3. Please describe the post-doctoral positions available at your institution and how you have filled, or expect to fill, them. Include both research associateships, part or full-time instructorships, and first-term assistant professorships.

4. Please add any comments you would like the Executive Committee to have (on the seriousness of the situation, comparisons with other years, trends, etc.).

What we will do with the data:

a) Eliminate overlaps from the lists.

b) Estimate the unemployment rate.

c) Transmit the number of applicants in each category and the number of available positions of each type.

In addition, a summary of the comments will be sent to the Executive Committee.

Otherwise all data will be treated as confidential.

Appendix III

APPENDIX III A Selection of Comments

"I would advise against special pleading for particle physics. The crisis is in science education, as I see it. We have probably overdone it in the past, and are being cut back. The complaint should be about the rate of cutting back which puts almost the entire burden on new graduates. I would like to be sure our field was in special trouble before making a special case."

F. Low, M.I.T.

"The only constructive comment I could make is that the AIP or AAPT should try to transmit to the very large number of small colleges the fact that an opportunity exists for getting good Ph.D.'s It may be that small colleges, surviving on gifts and tuition, are also saturated. Some however, are used to seeing only the most discontented Ph.D.'s (researchers manqués), and this may be why placing Ph.D.'s now may be difficult. We have two post-docs. who have only looked at small colleges and the response to ~200 letters has been zero."

S. Gasiorowicz, Minnesota

"There is the feeling that the present situation is the inevitable result of a chaotic overproduction in high energy theory coupled with the marked diminution of openings at this level in the last few years."

R. Rockmore, Rutgers

"The number and the quality of applicants has been fairly constant here over the past five years. This is not a particularly outstanding year. My own experience in obtaining jobs for my students and other Ph.D.'s in particle physics this year has been that it is exceedingly tough to find good jobs, or in fact any opeinings at all. I have three students at the post-doctoral level in particle physics and all three do, however, have jobs for next year.

In my opinion there is no reason to suppose that it will be any easier to find jobs next year. In fact, I think it will be tougher, because many groups (such as our own) will be in the position of having their contracts end, and having to find new sources of support."

D. Walecka, Stanford

" In my view the current job situation for theoretical physicists has become nearly 50 per cent worse in each of the last three or four years and is now extremely serious - not only for the physics profession, but for the nation as a whole."

E. Shrauner, Washington U. at St. Louis

conn - general

GEORGE P. MILLER, CALIF., CHAIRMAN

OLIN E. TEAGUE, TEX.
JOSEPH E. KARTH, MINN.
KEN HECHLER, W. VA.
EMILIO Q. DADDARIO, CONN.
JOHN W. DAVIS, GA.
THOMAS N. DOWNING, VA.
JOE D. WAGGONNER, JR., LA.
DON FUQUA, FLA.
GEORGE E. BROWN, JR., CALIF.
EARLE CABELL, TEX.
BERTRAM L. PODELL, N.Y.
WAYNE N. ASPINALL, COLO.
ROY A. TAYLOR, N.C.
HENRY HELSTOSKI, N.J.
MARIO BIAGGI, N.Y.
JAMES W. SYMINGTON, MO.
EDWARD I. KOCH, N.Y.

JAMES G. FULTON, PA.
CHARLES A. MOSHER, OHIO
RICHARD L. ROUDEBUSH, IND.
ALPHONZO BELL, CALIF.
THOMAS M. PELLY, WASH.
JOHN W. WYDLER, N.Y.
GUY VANDER JAGT, MICH.
LARRY WINN, JR., KANS.
JERRY L. PETTIS, CALIF.
D. E. (BUZ) LUKENS, OHIO
ROBERT PRICE, TEX.
LOWELL P. WEICKER, JR., CONN.
LOUIS FREY, JR., FLA.
BARRY M. GOLDWATER, JR., CALIF.

COMMITTEE ON SCIENCE AND ASTRONAUTICS
HOUSE OF REPRESENTATIVES
SUITE 2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, D.C. 20515

June 11, 1970

CHARLES F. DUCANDER
EXECUTIVE DIRECTOR AND
CHIEF COUNSEL

JOHN A. CARSTARPHEN, JR.
PHILIP B. YEAGER
FRANK R. HAMMILL, JR.
W. H. BOONE
JAMES E. WILSON
RICHARD P. HINES
HAROLD A. GOULD
J. THOMAS RATCHFORD
PHILIP P. DICKINSON
WILLIAM G. WELLS, JR.
K. GUILD NICHOLS, JR.
ELIZABETH S. KERNAN
FRANK J. GIROUX
DENIS C. QUIGLEY
RICHARD K. SHULLAW

JAMES A. ROSE, JR.
MINORITY STAFF

Prof. Victor F. Weisskopf
Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Professor Weisskopf:

I would like to extend a special invitation for you to submit a statement to this Committee in regard to the possible establishment of a National Science Policy. I am attaching a memorandum which sets forth in some detail the reasons for this request and what we hope to accomplish by our inquiry into the subject.

I sincerely hope you will find it possible to make your views known to us on this extremely important matter. If you have any questions, please do not hesitate to contact me or the staff of the Committee.

Sincerely yours,

Emilio Q. Daddario

EMILIO Q. DADDARIO
Chairman, Subcommittee on
Science, Research and
Development

Enclosure

COMMITTEE ON SCIENCE AND ASTRONAUTICS
HOUSE OF REPRESENTATIVES
WASHINGTON, D. C.

June 10, 1970

Memorandum

To: Participants in a Symposium of Views on National Science Policy

From: Mr. Daddario

Subject: Scope of Papers

1. The Subcommittee on Science, Research and Development has scheduled hearings in July and August, 1970, with regard to a National Science Policy. In conjunction with these hearings, the Subcommittee is also requesting written views from selected individuals to be incorporated into the printed record.

The reason for these activities is two-fold. First, upon a careful perusal of the Congressional scene we find that no committee of the Congress has ever inquired precisely into this subject. Second, the nation has clearly arrived at a point where the government-science relationship which has been in existence since World War II is either at a close or is being radically altered. Under these circumstances, it is our intent to obtain the advice of a broad spectrum of experts as to whether or not a future structured national science policy is desirable and, if so, what the constituent elements of that policy ought to be.

2. It is not the intent of the committee or myself to limit or direct the content of any paper. Each contributor is free to organize his thoughts without any restrictions or guidance other than that set out in the foregoing paragraph.

3. As we have proceeded with the organization of this inquiry, we have had considerable discussions with competent observers who are not themselves a direct part of the scientific community. This includes Don Price of Harvard and Hunter Dupree of Brown. From these discussions we have identified a few sub-topics which certainly will be of interest to the subcommittee. They are as follows:

4. Can we make a determination as to whether and how government science support can be carried on if there is a broad shift away from traditional military research? How far should government support the joining of research with higher education? How can support for basic research be integrated with applied research and made an integral part of policy decision-making? To what extent can NSF shoulder the additional burden for basic research as military support lessens, as the rise of social sciences increases, as environmental problems become greater and the need for multidisciplinary research accelerates? How do we fulfill DoD's continuing need for research which bears on its critical mission? How can we supply proper mechanisms for technology assessment? How can we synthesize knowledge gained from the space program with the contemporary social needs? Must there be a redefinition of the mission of American universities during the 1970's? Should there be new organization and administration of the Federal science activities in the Executive branch?

5. The contributions may be as concise or as comprehensive as the contributor cares to make them. It is requested, however, that they be typed, double-spaced, and that they be forwarded to Mr. Philip Yeager, in 2321 Rayburn House Office Building, not later than August 15, 1970. It is further requested that a brief biographical sketch of the contributor accompany his paper.

Basic Science / {Research + Teaching (together) Science = State of mind successful

need: undergr. education → {More Sc. educ. people in public affairs

Science employment. / Grad. ed → see editorial

Diversion to new projects / over emph. on applied dangerous / {new ideas : methods : phenomena

VS leading: Europe 5-6%! / (1) NSF mainly basic

2) NSF should not have monopoly.

applied should be supported by other agencies HUD, AEC D.T.

UNITED STATES
ATOMIC ENERGY COMMISSION
DIVISION OF RESEARCH
WASHINGTON, D.C. 20545

TO: V. Weisskopf

FROM: W. A. Wallenmeyer

For your information.

7/1/70

HEP

THE UNIVERSITY OF ROCHESTER
RIVER CAMPUS STATION
ROCHESTER, NEW YORK 14627

PARTMENT OF PHYSICS
AND ASTRONOMY

June 23, 1970

Dr. Glenn T. Seaborg
Chairman
Atomic Energy Commission
Washington, D. C. 20545

Dear Glenn,

In common with scientific groups throughout the country, the Division of Particles and Fields of the American Physical Society became concerned about the employment situation in particle physics. In particular, it was decided to make a rather thorough study of the situation in theoretical particle physics. In my capacity as Chairman of this division, I appointed a "select" committee of the two most recent Dannie Heineman prize winners (Profs. Y. Nambu and A. Wightman) to gather the basic data. A special (and rather sensitive) feature of this survey was the attempt to obtain a rough qualitative evaluation of the applicants for postdoctoral positions, in addition to distinguishing between U. S. and non- U. S. citizens. I am enclosing a copy of the interim report which Profs. Nambu and Wightman have submitted to the Executive Committee of the Division of Particles and Fields. This interim report already emphasizes the gravity of the situation since it indicates that approximately one half of the American applicants ranked A have not succeeded in obtaining positions in the approximately fifty leading theoretical particle physics centers.

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Best greetings.

Sincerely yours,

R. E. Marshak, Chairman
Division of Particles and Fields

REM:eh
encls.
cc: Dr. W. Wallenmeyer ✓

03020

June 4, 1970

TO: R. Marshak

FROM: Y. Nambu and A. Wightman

SUBJECT: Report on Manpower Situation in Theoretical Particle Physics

In response to the request contained in your letter of February 10, 1970, we have written a letter soliciting information about the employment of physicists working in theoretical particle physics who are in their first three or four years after the doctorate.

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A man is counted as Class A if he is so classified by two institutions. A man is also in Class A if he is so classified by just one institution, unless in our judgment we regarded the rating as out of line (institution did not get many good applicants or gave a high percentage of A's, or the candidate was given a low rating by many other institutions). The number of these doubtful cases was about 5% of the Class A total.

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4. It is estimated that about 50% of all A applicants are U.S. citizens.

5. Of the 82-85 applicants who got (or would get) the jobs, it is estimated that 70 are A class and 15 are B class.

6. Among those who got jobs, about a third are U.S. citizens, a third are not, and another third do not have their citizenship listed.

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We have three recommendations:

A. That copies of the final version of this report be sent to all institutions which supplied information.

B. That a letter be addressed to the applicants asking them to provide information on their employment, as well as any comments they may have on the job situation. Since this involves the use of the names supplied to us in confidence by the institutions listed in Appendix I, we believe that the institutions should be given a chance to object to this procedure, if they wish. The simplest method would be to include a copy of the proposed letter to applicants along with the report to be sent, according to recommendation A.

C. Since it seems likely that many of the applicants will end up doing something other than research on particle physics at one of the centers, an effort should be made to find out what kind of jobs they do get, in order that next year's crop can be given realistic advice, and something can be done about the unemployed among this year's crop.

APPENDIX I

Institutions to which the survey letter was sent.

Amherst, Boston, Massachusetts
Argonne National Laboratory, Argonne, Illinois
Boston University, Boston, Massachusetts
Brandeis University, Waltham, Massachusetts 02154
Brookhaven National Laboratory, Upton, L.I., New York 11973
Brown University, Providence, Rhode Island 02912
California Institute of Technology, Pasadena, California 91109
California, University of, Berkeley, California 94720
California, University of, San Diego, La Jolla, California 92037
California, University of, Irvine, California
California, University of, Santa Barbara, California 93106.
California, University of, Los Angeles, California 90024
California, University of, Santa Cruz , California 95060
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
Chicago, University of, Chicago, Illinois 60637
Colorado, University of, Boulder, Colorado 80302
Columbia University, New York, New York 10027
Cornell University, Ithaca, New York 14850
Duke University, Durham, North Carolina 27706
Harvard University, Cambridge, Massachusetts 02138
Hawaii, University of, Honolulu, Hawaii 96822
Illinois, University of, Urbana, Illinois 61801
Indiana University, Bloomington, Indiana 47401
Iowa, University of, Iowa City, Iowa 52240
Iowa State University, Ames, Iowa 50010
Johns Hopkins University, Baltimore, Maryland 21218
Maryland, University of, College Park, Maryland 20742
Massachusetts Institute of Technology, Cambridge, Mass. 02139
University of Massachusetts, Boton, Massachusetts
Miami, University of, Coral Gables, Florida 33124
Michigan, University of, Ann Arbor, Michigan 48104
Minnesota, University of, Minneapolis, Minnesota 55455
Michigan State University, Lansing, Michigan
National Accelerator Laboratory, P. O. Box 500, Batavia, Ill. 60510

03020

University of Nebraska, Lincoln, Nebraska
New Mexico State University
New York University, Washington, Square, New York, 10003
Northeastern University, Boston, Massachusetts 02115
Northwestern University, Evanston, Illinois 60201
Notre Dame University, Notre Dame, Indiana 46556
Ohio State University, Columbus, Ohio 43210
University of Oregon, Eugene, Oregon 97403
University of Pennsylvania, Philadelphia, Pennsylvania 19104
University of Pittsburgh, Pittsburgh, Pennsylvania 15213
Princeton University, Princeton, New Jersey 08540
Purdue University, Lafayette, Indiana 47907
University of Rochester, Rochester, New York 14627
Rockefeller University, New York, New York 10021
Rutgers University
New Brunswick, New Jersey 08903
Stanford University, Stanford, California 94305
State University of New York, Stony Brook, L.I., New York 11790
Syracuse University, Syracuse, New York 13210
The University of Texas, Austin, Texas 78712
University of Utah
Tufts University, Medford, Massachusetts 02155
Washington University, St. Louis , Missouri 63130
University of Washington, Seattle, Washington 98105
University of Wisconsin, Madison, Wisconsin 53706
University of Wisconsin, Milwaukee, Wisconsin 53201
Yale University, New Haven, Connecticut 06520
Yeshiva University, New York, New York 10033

Appendix II

THE UNIVERSITY OF CHICAGO
THE ENRICO FERMI INSTITUTE
5630 ELLIS AVENUE
CHICAGO • ILLINOIS 60637
AREA CODE 312-667-4700

March 11, 1970

The purpose of this letter is to ask your cooperation in a manpower survey. Robert Marshak, as Chairman of the Division of Particles and Fields of the American Physical Society, has asked us to find out how many theoretical physicists, working in particle physics and allied areas at the post-doctoral level, are having employment difficulties. At the moment, there is a general impression that an employment crisis exists for post-doctorals. The Executive Committee of the Division wants to know to what extent multiple applications for positions have created an impression that there are many more candidates for post-doctoral positions than available positions. The Executive Committee would like the survey to distinguish those individuals who may be expected to be real contributors to physics from those who are merely competent. If it turns out that there will be a substantial number of the first category unemployed, it is expected that the Executive Committee will attempt to bring the situation to the attention of the Government.

We have been given a list of approximately 50 institutions which are generally regarded as centers for work in particle physics. At each we have selected an individual who, we hope, can help us get the needed information. If it turns out that you are unable to do this job, we hope that you will be able to enlist some other colleague to do it.

We are asking for some information which obviously should be kept confidential; for example, your rating of the quality of the candidates. In particular, our report to the Executive Committee will include no names of individual candidates but only statistical information (e.g. the number of applicants in the A, B, C categories described below).

Please return the questionnaire to A. Wightman by April 15 (Address: Physics Department, Princeton University, Princeton, New Jersey 08540). This will give us time to prepare the report to the Executive Committee for its meeting of April 29.

We are sorry to have to ask you to perform this onerous task, but we think that it is very important that the Executive Committee base its action on solid facts.

Sincerely,

Y. Nambu A. S. Wightman

Y. Nambu A. S. Wightman

P.S. Please do not hesitate to phone one of us if you have any questions.
Y. Nambu: 312-667-4700, ext. 8608 A. Wightmann: 609-452-3000
(After April 3, Phys. Dept., Univ. of Texas, 512-471-5206)

03020

EMPLOYMENT SURVEY FOR POST DOCTORAL THEORETICAL PHYSICISTS WORKING IN PARTICLE PHYSICS OR ALLIED FIELDS

1. Please list the names of your applicants for post-doctoral positions, their current institutional affiliation, and the year in which they received their Ph.D. Also indicate their citizenship, if it is known.

2. Label the candidates A, B, C:

   A: Outstanding, likely to make significant contributions to physics.
   B: Competent, but not very exciting, probably will do useful work.
   C: Mediocre to incompetent.

3. Please describe the post-doctoral positions available at your institution and how you have filled, or expect to fill, them. Include both research associateships, part or full-time instructorships, and first-term assistant professorships.

4. Please add any comments you would like the Executive Committee to have (on the seriousness of the situation, comparisons with other years, trends, etc.).

What we will do with the data:

a) Eliminate overlaps from the lists.

b) Estimate the unemployment rate.

c) Transmit the number of applicants in each category and the number of available positions of each type.

In addition, a summary of the comments will be sent to the Executive Committee.

Otherwise all data will be treated as confidential.

Appendix III

APPENDIX III A Selection of Comments

"I would advise against special pleading for particle physics. The crisis is in science education, as I see it. We have probably overdone it in the past, and are being cut back. The complaint should be about the rate of cutting back which puts almost the entire burden on new graduates. I would like to be sure our field was in special trouble before making a special case."

F. Low, M.I.T.

"The only constructive comment I could make is that the AIP or AAPT should try to transmit to the very large number of small colleges the fact that an opportunity exists for getting good Ph.D.'s It may be that small colleges, surviving on gifts and tuition, are also saturated. Some however, are used to seeing only the most discontented Ph.D.'s (researchers manqués), and this may be why placing Ph.D.'s now may be difficult. We have two post-docs. who have only looked at small colleges and the response to ~200 letters has been zero."

S. Gasiorowicz,Minnesota

"There is the feeling that the present situation is the inevitable result of a chaotic overproduction in high energy theory coupled with the marked diminution of openings at this level in the last few years."

R. Rockmore, Rutgers

"The number and the quality of applicants has been fairly constant here over the past five years. This is not a particularly outstanding year. My own experience in obtaining jobs for my students and other Ph.D.'s in particle physics this year has been that it is exceedingly tough to find good jobs, or in fact any opeinings at all. I have three students at the post-doctoral level in particle physics and all three do, however, have jobs for next year.

In my opinion there is no reason to suppose that it will be any easier to find jobs next year. In fact, I think it will be tougher, because many groups (such as our own) will be in the position of having their contracts end, and having to find new sources of support."

D. Walecka, Stanford

" In my view the current job situation for theoretical physicists has become nearly 50 per cent worse in each of the last three or four years and is now extremely serious - not only for the physics profession, but for the nation as a whole."

E. Shrauner, Washington U.
at St. Louis

UNITED STATES
ATOMIC ENERGY COMMISSION
DIVISION OF RESEARCH
WASHINGTON, D.C. 20545

5/26

Dear Vicki:

The enclosed has been reproduced for mailing this week.

The mailing list of the NAL users organization is fairly complete and NAL has an automated envelope addressing system which can be used for other

purposes also in the future. We plan to work up a graduate student mailing list here at the DEC.

I shall work up a combined announcement (Cork + Sandwiss panels) and phone you

Bennett

May 25, 1970

Memorandum to Experimental Physicists and Graduate Students in High Energy Physics

At the request of the high energy physics advisory panel of the AEC (HEPAP), I have agreed to chair a subcommittee to study and recommend with respect to "future patterns of HEP research". The principle motivation for launching this activity at this time is of course the prospect of limited financial support combined with the advent of a major new HEP resource, the NAL accelerator.

We shall try to see whether or not new methods of organizing and/or funding research efforts will be desirable. Obviously, this is an extremely broad subject which touches many aspects of our work, both as research physicists and as members of our home institutions.

The purpose of this memorandum is to inform you and to ask for your advice and opinions. Please write to me or to any other member of the committee.

Sincerely,

Jack Sandweiss

Jack Sandweiss

JS:jlj

Addendum: Committee Members

Martin Deutsch - Mass. Inst. of Tech., Cambridge 02139

Myron L. Good - SUNY at Stony Brook, Stony Brook 11790

Richard A. Lundy - Argonne Nat. Lab., High Energy Facilities, 9700 South Cass Avenue, Argonne, Ill. 60439

Richard J. Plano - Rutgers University, New Brunswick, New Jersey 08903

James R. Sanford - Nat. Accelerator Lab., P. O. Box 500, Batavia, Ill. 60510

Melvin Schwartz - Stanford University, Stanford, Calif. 94305

M. Lynn Stevenson - Univ. of California, Berkeley 94720

Chairman - Jack Sandweiss, Yale University, New Haven, Conn. 06520

UNIVERSITY OF CALIFORNIA

LAWRENCE RADIATION LABORATORY
BERKELEY, CALIFORNIA 94720
TELEPHONE (415) 843-2740

TELEX 335313 LAWRADLAB BERK
TWX 910-366-7172 LAW RAD LAB
CABLE UCLRL BERKELEY

May 20, 1970

Professor Victor F. Weisskopf
Physics Department
Room 6-303
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Weisskopf:

When you visited here I commented on the insufficient analysis of the cost of experiments compared with the scientific importance of the results obtainable, a common evil to all laboratories.

A member of the Scheduling Committee says that they try hard to do the best they can in making a critical appraisal of the physics and techniques involved in the experiments. As support he has pointed out that last year experiments 108 to 139 have been proposed of which 12 have been rejected, that is 12 in 31. Some came back later in an improved form and were accepted but about 8 did not return.

Selectivity has been improved during the past two years.

Sincerely yours,

Emilio Segrè

ES/rmf

PRINCETON-PENNSYLVANIA ACCELERATOR
PRINCETON UNIVERSITY
JAMES FORRESTAL CAMPUS
PRINCETON, N.J.

MAIL ADDRESS
ACCELERATOR, P.O. BOX 682
PRINCETON, N.J. 08540

TELEPHONE
PRINCETON, N.J.
609-452-3000

May 19, 1970

Prof. Victor Weisskopf
Physics Department
MIT
Cambridge, Massachusetts 02139

Dear Vicki,

By now you will have received my most recent communication with HEPAP in which I summarize, very briefly, some of the experiments already proposed by PPA Users for the next couple of years. Actually, if all the proposed experiments were mounted we would have over three years' work ahead of us just based on today's proposals. Obviously, new proposals will continue to come in, and some of the present ones will be withdrawn or not scheduled. Taking all this into account, it is clear that there will be a continuing strong demand for the PPA into the foreseeable future.

I believe you will agree that many of the proposed experiments are very interesting and possibly will make a substantial contribution to our understanding of elementary particles and nuclear matter. Perhaps there is no single great experiment here, but I am sure you will be among the first to assert that great break-throughs are made possible by first establishing a firm foundation on which to stand. Also, I always enjoy observing that many of the great discoveries have come out of simple experiments performed by smart people with very modest goals - and a bit of luck!

If we can agree that the demand for the PPA, the quality of the proposed experiments, and the experimental and theoretical skills of the Users strongly argue for an indefinite continuation of the PPA at a low, but viable level, then how can this be accomplished in the light of history and today's budgeting and political turmoil?

May I suggest that the following course of action by HEPAP would be most helpful. HEPAP could recommend, in strong terms, that the AEC plan to continue operating the PPA, indefinitely, at a low level and that all steps to terminate operations be dropped immediately. The level I suggest is $1.2 million in FY'72 and that subsequent years be at approximately the same level of activity, which implies escalation to meet rising costs. Further, HEPAP could recommend that, in the event the AEC can not support the PPA in FY'72, or thereafter, that it take active and timely steps to transfer support to the NSF if that agency is willing to support the PPA.

In order for HEPAP's position to be clearly understood by other agencies, particularly by OST and the Bureau of the Budget, I would urge that a written recommendation be made to the AEC. Copies can, somehow, be gotten

to these and other agencies. I am sure you appreciate that I am as concerned as you are about the terrible things that are happening to our country. As the lights of reason go out, one by one, I feel it to be all the more important for small candles to be left burning wherever there exists the will to shelter them. I hope you will understand my reasons for believing that the PPA can serve as one such candle.

Vicki, I would like to talk with you more about this and will phone you in a day or two about getting together before your HEPAP meeting on Sunday.

With best personal regards.

Milt

Milton White

MW:elap
Enclosure

P.S.

I enclose a recent letter by Bob Wilson.

NATIONAL ACCELERATOR LABORATORY

P.O. BOX 500
BATAVIA, ILLINOIS 60510
TELEPHONE 312 231-6600
DIRECTORS OFFICE

April 29, 1970

Professor Milton White
Princeton-Pennsylvania Accelerator
P O Box 682
Princeton, New Jersey 08540

Dear Milt:

Somehow your letter of March 26 containing your eloquent appeal to Mr. Hollifield came while I was away or was just leaving. I did not read the enclosure to Mr. Hollifield until today. I see that it concerns NAL and does require a reply however belated -- my sincere apologies.

You most certainly have made a very strong case for supporting basic elementary particle research and in particular for continuing a strong university involvement by the support of university-oriented accelerators. I cannot disagree with you on any point. Furthermore, I am aghast that the National Accelerator Laboratory, which was supposed to be added to the present foundation of work going on, appears to be siphoning badly needed funds from that kind of research.

I don't know what to say. This was not the idea when we started. We are, of course, operated by and for universities, and here at NAL, we are dedicated to the idea that our work be completely oriented in that direction. We too are getting by on a severely cut budget compared to our originally expected needs. I do not believe it is for us to renounce funds, for it is not obvious that they would go to university research.

In view of the severe funding restrictions which are affecting the plans of our entire high energy physics program, indeed of all scientific research, we are doing everything possible to hold down the size of our staff and to maximize our capabilities at the reduced rate of funding that is being provided. We are also taking special care to keep the Atomic Energy Commission and the physics community informed in detail about our problems, progress, and changing potentialities so that they may reach their own judgments about the balance of the overall program.

Well, congratulations on the strength of your appeal, and good luck. I do hope to see you at the Lab here in Batavia soon.

Sincerely,

Robert Rathbun Wilson

May 18, 1970

Dr. Paul McDaniel
Director
Division of Research
U. S. Atomic Energy Commission
Washington, D. C. 20545

Dear Paul:

I would like to transmit to you the deep concern and dismay of the High Energy Physics Advisory Panel in regard to the budget figures which are considered for FY '72. An operational budget of 122 Million for high energy physics is totally inadequate for the prosecution of our programs. It would represent a further decrease in real value from the FY '71 figure of 119 Million in view of the inflationary price developments. We would be faced with this decrease at a time when the improvement program at BNL will be completed and the NAL accelerator nearing completion. Funds will be needed to exploit these new facilities, one being an investment of 40 Million, the other of 250 Million. The must rudimentary and minimal preparations for the exploitation of these new facilities require funds which, if taken from the proposed budget, would seriously jeopardize the activities at the other existing national laboratories and at the universities, by reducing them below a reasonable minimum. We are aware that the exploitation of new modern facilities must be accompanied by a reduction of other activities in the field, But we find it most dangerous for the survival of the art, if this exploitation is to be financed within a shrinking total budget. The abnormally low equipment budget adds to the difficulties because of the importance of up-to-date equipment, not only in our new facilities, but also in carrying out successful research at the other laboratories.

We urge the Commission to reconsider the situation in FY '72. The financial stringencies of the last three years have already weakened our laboratories--both the national ones and those at universities--to such an extent that further major reductions may leave us with the second-rate research establishments; a poor return for our past investments. It is great to have the highest energy beam and the highest beam intensity available in the United States, but without a viable scientific community we won't be able to exploit it.

Sincerely yours,

Victor F. Weisskopf
Chairman
High Energy Physics Advisory Panel

VFW:p

Columbia University
DEPARTMENT OF PHYSICS
NEVIS LABORATORIES
P.O. Box 137
Irvington, N.Y. 10533
914 LY 1-8100

May 4, 1970

Dr. Bernard Hildebrand
U.S. Atomic Energy Commission
Physics
Washington, D.C.

Dear Bernie:

If we are to do anything useful in our next meeting, we need some data.

1. National Labs: We need to know the apportionment of funds in the lab for various functions:
   a. Operation of the accelerator
   b. Advance studies, improvement research, etc.
   c. Instrumentation
   d. Administration
   e. On-site groups research programs
   f. Plans of present lab groups to use NAL.

2. University Groups:
   a. Total budgets (including "equipment", computers, etc.) for last ?? years (4 or 5?)
   b. Publication lists
   c. Number of i) senior physicsts, ii) Ph.D.'s, iii) graduate students.

Aside from petitioning Nixon for more money, if we are to make hard decisions, we need this data base.

Sincerely,

Leon

Leon M. Lederman

at
cc: V. Weisskopf

copy sent BH 5/13.

April 13, 1970

Dr. Gerald F. Tape
President
Associated Universities, Inc.
1717 Massachusetts Avenue, N. W.
Washington, D. C. 20036

Dear Gerry:

I hope very much that you will be at our HEPAP meeting in Berkeley because it will be one of the most difficult ones, and I need your help. Also, I have had a very bad case of the 'flu and I am still rather weak and may not be able to hold out through all meetings. I would be very glad if you could temporarily replace me as chairman if this turns out to be necessary.

First of all, we are going to face a wave of complaints from the PPA and CEA, some of which will be justified, and some of which will be difficult to counter because one important underlying reason of our position was, that the physics produced by those two institutions was not quite up to standards. This argument cannot easily be used in facing the people themselves.

We also have another important problem in the CEA situation. It was our position that the CEA should continue vigorously with development of the by-path. We consider this as their strongest project and rightly so. (A few days ago they succeeded in introducing a positron and electron beam through the ring!) Here is our problem: If we want them to continue on this project it will be necessary to guarantee them support for the by-path budget for at least three years in order to finish it and to exploit it. Anything less than that would undermine the morale and destroy the project. If we give that guarantee--and I am in favor of it--we have implicitly made the following decision: The next victim in our efforts to provide enough money for NAL must be the bevatron or the ZGS (by the way it should be the bevatron). In other words, if further cuts are necessary we must leave CEA alone in order to finish the by-path and make the cut somewhere else.

This is an important and very far-reaching decision to be made. I am not sure whether HEPAP will make it. It may also reverse its positive position toward the by-path. However, the latter cut would ruin the by-path completely. This would not only

be inhumanly cruel, but also intellectually incorrect. I feel that the bevatron must be the next victim. However, the present composition of the HEPAP membership will make it difficult to come to such a conclusion.

I am writing this to you to elicit your criticism and/or your help. I will try to call you Wednesday, and I repeat my fervent hope that you will be at the Berkeley meeting.

With best regards.

Sincerely yours,

Victor F. Weisskopf

VFW:p

UNIVERSITY OF CALIFORNIA

LAWRENCE RADIATION LABORATORY
BERKELEY, CALIFORNIA 94720

9 April 1970

Distribution by National Laboratory of Particle Experiments resulting in recent publications.

Andy Sessler asked me if the Particle Data Group could provide any data on the following two questions: "For experimental results published recently...

I. At which accelerators were they run?

II. If published by research groups at National Labs, then at which labs?"

We have tried to answer this question using the following data base:

1. To emphasize quality, Phys. Rev. Letters, from 1969 and 68 (221 letters)

2. To increase the statistics we added Phys. Rev. 1969, which in fact covers the same time scale as the two years of Letters, and got 60 more papers.

The results are shown in the attached histograms. The two 1969 sources are cross hatched -- if you want to emphasize "recent" look at the cross hatched pattern. The Letters are the top two bands -- to emphasize "quality" ignore the bottom band. As far as we can see, all three bands tell about the same story.

A few warnings:

1. The top set of histograms (the answers to question II) depend on the style of whether a group calls itself by the name of the National Laboratory or not. For instance I know of no group which calls itself a CEA or PPA group.

2. Five of the publications were collaborations between ~~National~~ groups at <u>two</u> National Labs, all involving SLAC(4 with LRL, 1 with BNL). We have included these in both the SLAC histogram and the histogram of the other lab.

3. These histograms reflect not the current situation, but rather work that averages two years old. These experiments were published on

the average a year ago, with another half year delay since submission to a journal. The taking of the data was of course even earlier. For example I think it interesting that of the 62 LRL experiments in the sample, 30 were done using the 72" HBC, which pulsed its last in December 1966.

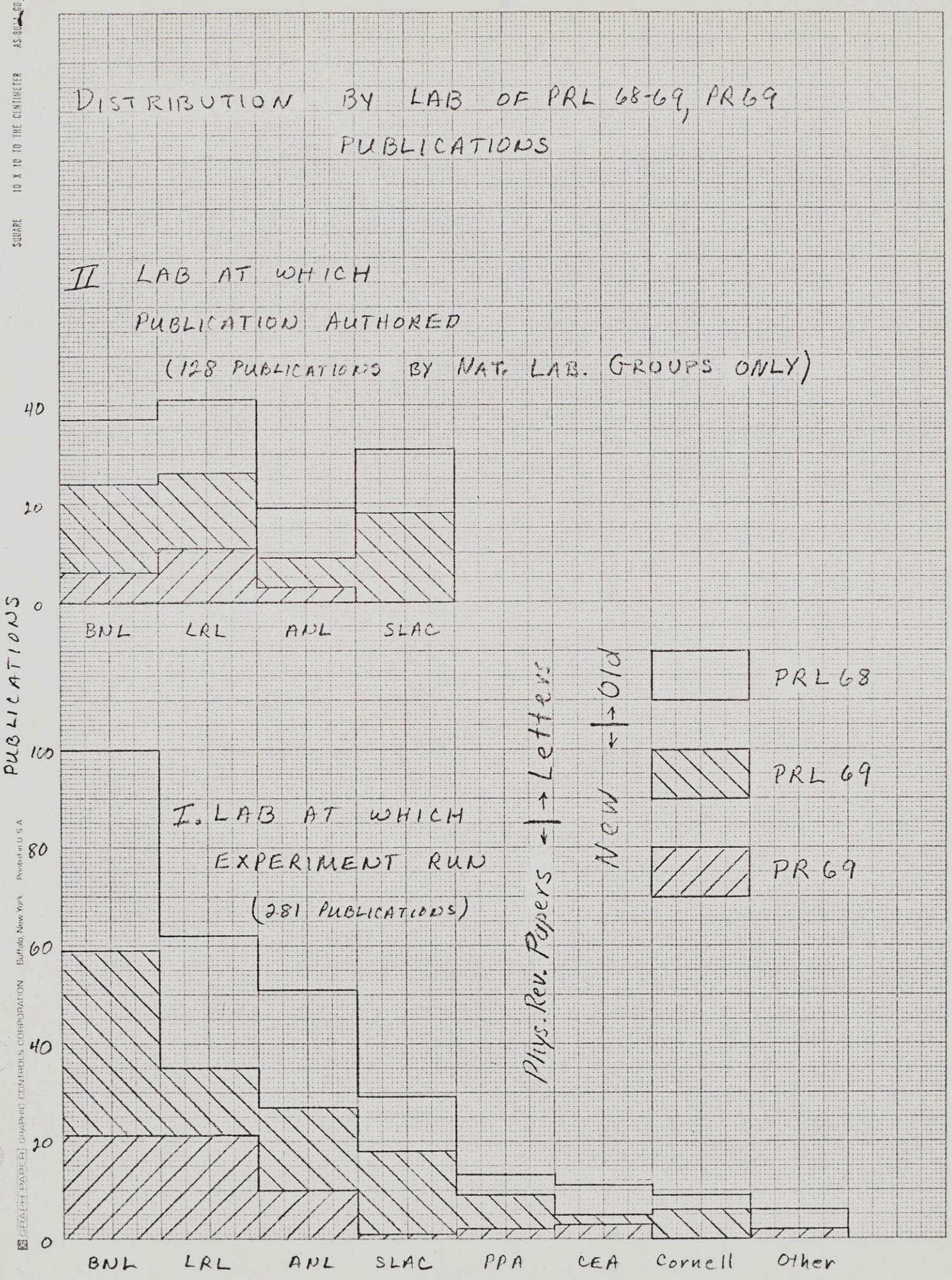
Art

A.H. Rosenfeld

AHR:ek

9 April 1970

DISTRIBUTION BY LAB OF PRL 68-69, PR 69 PUBLICATIONS



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THE UNIVERSITY OF MICHIGAN
ANN ARBOR

THE HARRISON M. RANDALL LABORATORY
OF PHYSICS

TEL. NO. 313-764-4437

April 13, 1970

To: HEPAP Members

From: Kent Terwilliger

Enclosed are Bill Fowler's letter on the NAL bubble chamber program, and our bubble chamber subpanel's final draft on cost savings.

Concerning the NAL 15' vs. the ANL 12' chamber question, Fowler discusses the magnetic field requirements, and the backgrounds for ν experiments for the two chambers, and finds an edge for the NAL chamber, although it is apparent that the ANL 12' cannot be ruled out on either ground. The cost for the NAL 15' is as before: $7 million, of which $2 million is labor, $5 million construction and equipment. They intend to finance the construction portion out of the authorized lab construction funds.

It is clear, both from the tone of the letter and statements at the NAL Users meeting April 10-11, that NAL is committed to a rapid construction program for their own 15' chamber. Approval of that program would be consistent with our subpanel's previous recommendations and certainly HEPAP's least painful course of action.

NATIONAL ACCELERATOR LABORATORY

P.O. BOX 500
BATAVIA, ILLINOIS 60510
TELEPHONE 312 231-6600
DIRECTORS OFFICE

April 11, 1970

Professor Kent Terwilliger
Physics Department
University of Michigan
Ann Arbor, Michigan 48104

Dear Kent:

Since our letter of January 7, 1970, concerning the NAL plan for bubble chambers, we have made progress and it seems appropriate to bring you up-to-date. In particular, this letter provides more information on the physics capability of the NAL approximate 15-foot chamber, justification arguments for the 30 kilogauss magnetic field, an evaluation of the background problem, i.e., cosmic-ray and muons from neutrino interactions in the filter and in material close to the chamber, and, finally, suitability of the Argonne 12-foot chamber as a chamber for NAL.

There is general agreement that by the time NAL starts operation of its chamber, several tens-of-thousands of neutrino events should have been recorded at other labs. These events will predominantly be in the 1 BeV energy region. The data should give considerable insight towards the determination of elastic form factors, N^* behavior and a preliminary look at hyperon production. The NAL neutrino experiments will add about an order of magnitude to the total events of the above studies while extending the data to higher energies. Most importantly the NAL exposures will give unique data on high energy neutrino interactions with large momentum transfers, i.e., from the presently available $\sim 1(\mathrm{GeV})^2$ to up to 30 $(\mathrm{GeV})^2$ in some cases.

To illustrate neutrino experiments in the 15-foot bubble chamber, four possible neutrino experiments were considered. These include the so-called elastic scattering ($\nu + n \rightarrow \mu^- + p$) important at high q^2, inelastic neutrino scattering to look for intermediate boson production, a search for events demonstrating $\Delta S = \Delta Q = -1$, and a study of the four fermion interaction. Quantitative estimates have been made of the number of events per energy interval for each of these processes in a million picture experiment. The number of events ranges from several hundred thousand at low energy to tens of events at high energies. These statistics appear adequate for the study of neutrino processes over a large range of available neutrino energies at NAL.

We have reviewed the use of the NAL chamber for hadron physics studies, particularly in the light of the measurement accuracy reported by BNL in their

October 1969 test run of the 7-foot chamber. In the summer studies Derrick[1] and others calculated the capability of the 25-foot and the ANL 12-foot to do experiments in the 50-100 BeV region using a number of assumptions concerning measurement accuracy. Our conclusion is that if in routine operation the 15-foot maintains the measurement accuracy that has been observed on cosmic ray tracks obtained in the Brookhaven test, i.e., ~100μ, then the chamber dimensions and 30 kG magnetic field are well matched for strong interaction studies up to at least 100 GeV/c incident momentum. This feature should allow a substantial research program to be carried out by providing early in the chamber operating period an initial set of exposures for 10 to 20 research groups. Each of these runs would be of ~100,000 pictures. This would allow for a rapid survey of hadron physics in a new energy region.

Starting from the work of Slattery[2] and Ascoli[3], during the Aspen Summer Study of 1969, we have reviewed the factors which enter into the choice of a design magnetic field for hadron physics. For strong interaction studies a magnetic field of at least 20 kilogauss is needed to keep the accuracy of missing mass determinations to desired values. However, higher fields would result in substantially reducing the missing mass errors. Roe and Stevenson[4] pointed out that for high energy neutrino physics the role of the magnetic field is different. Unlike strong interactions, where the incident hadron momentum usually is known to high precision, the incident energy in neutrino interactions is an important parameter to be determined from the measurements. For events where all of the neutrals are converted, the neutrino energy is determined by summing the energy of all the outgoing particles and subtracting the target mass. For high momentum particles, the error in this energy sum depends directly on the error of the curvature measurement and this in turn is inversely proportional to the magnetic field. The angles are important in deciding whether all neutrals are converted. For good detection efficiency for neutrals, mixtures with a high percentage of neon will be used when operating with tract sensitive targets and the 30 kilogauss field will be required to maintain accuracy sufficient to determine the neutrino energy. Other arguments used by Roe and Stevenson for a high magnetic field included particle trapping and reduction of γ-ray ambiguities.

The availability of Nb-Ti superconductor whose properties are well known and where information on the cost of large quantities is available, also suggests a design value of 30 kG for the 30,000ℓ chamber. Higher fields are possible only by inclusion of much larger amounts of superconductor and at correspondingly much higher cost.

---

1 Aspen Summer Study 1968, A-1-68-35, 89
2 Aspen Summer Study 1969, SS-141
3 Ibid, SS-103
4 Ibid, SS-106

Background tracks in the bubble chamber stem from a number of sources. The largest backgrounds are due to tracks of muons from cosmic rays and muons generated by neutrino interactions in the iron shield. Calculations have been made corresponding to the present design of the chamber, and agree with the results of summer study calculations for the 25-foot chamber, after making corrections for volume differences.

The cosmic ray muon flux in the 15-foot chamber is calculated to be about 1500 muons/sec. Assuming a sensitive time of 5 millisec, this will give 5-10 visible tracks. Drawings have been generated that simulate the appearance of a chamber picture. The tracks will cause no major problem with scanning or measuring. The number of hadron interactions from cosmic ray protons and neutrons is negligible.

The neutrino-induced muon background is a more severe problem. These arise from neutrino interactions near the end of the shield. Fortunately, most of these muons are low energy and can be deflected from the detector by magnetizing some of the iron shield. Without deflection the number of muons in the chamber would be 75 muons/pulse.

The average muon momentum is 7 GeV, and can be swept away by the magnetized shield. The muons produced in the chamber walls and coils cannot be removed. Using the neutrino spectrum calculated by F. Nezrick, one calculates that 10 muons/pulse will be generated in the walls and coils of the chamber. Many of the low-energy muons will not get far into the chamber. Hadrons from inelastic neutrino interactions in the walls and coils will add about five charged particles to the picture. Consequently the number of background tracks of all energies produced in the near vicinity of the chamber is about 20.

A comparison of the background in the 15-foot compared to that in the ANL 12-foot shows that they are nearly similar. The number of neutrino induced muons in the ANL 12-foot is calculated to be twice that in the NAL 15-foot. This means that there would be about 40 tracks in the Argonne chamber per pulse. This is tolerable, but the lower background provided by the design of the NAL 15-foot chamber is desirable.

In summary, it is true that the previously proposed 25-foot-100 cubic meter chamber would have been more productive than the 15-foot-30 cubic meter chamber. The smaller chamber will need longer exposures, higher accelerator intensity or will be used for studying processes with more favorable cross sections. However, many neutrino event rates in the 30,000 liter chamber are satisfactory for a large range of neutrino studies. In addition, the hadron physics possibilities from

this chamber are substantial. We conclude that the physics capability justifies the construction of a 30-cubic meter chamber. On this basis and the fact that the NAL Accelerator is well on its way towards meeting the target date of July 1972 for experimental use of the accelerator, NAL has decided to initiate construction of a 30,000 liter hydrogen bubble chamber that could be ready for use with the accelerator at the earliest possible date, - on or before January 1973.

This goal can be achieved by treating the conventional part of the construction as within the scope of our existing laboratory construction authorization, and supplementing these funds by purchasing capital equipment and procuring technical components from our annual equipment budget. A listing of costs associated with major systems is given in Table I. The total facility cost of the project apart from manpower cost is estimated to be about $5 million.

The schedule for chamber construction provides that the chamber should be ready for experiments at the same time as Experimental Area 1 is turned on in late '72 or early '73. In the last few weeks, the NAL staff has been examining the possibility of earlier turn-on dates for the accelerator and its experimental areas. The bubble chamber schedule is being reviewed to see if it also can be shortened.

In conclusion, the present NAL plan is to provide a bubble chamber that can accomplish the objectives stated in the recent HEPAP report:

> "Detailed technical studies have demonstrated the bubble chambers unique value as a tool for both qualitative and quantitative research in neutrino interactions. There is little doubt that the study of neutrino interactions at high energy and large momentum transfer will be a major research field at NAL. Moreover the bubble chamber is an instrument particularly suitable for the exploration of strong interactions in a new domain of energy."

Sincerely yours,

William B. Fowler

William B. Fowler

TABLE I

30,000 ℓ Bubble Chamber Costs

System	NAL Estimate 4/7/70
Chamber, Vacuum, Expansion	1,000,000
Cryogenic Equipment	1,200,000
Optics	460,000
Magnet	1,300,000
Instrumentation	290,000
Conventional Facilities	500,000
Miscellaneous	250,000
	$5,000,000

DRAFT

Possible Cost Savings in the Bubble Chamber Program
High Energy Physics Advisory Panel

March 10, 1970

Due to financial restrictions a number of bubble chambers are being run at less than their maximum picture producing capacity. Since chambers have some fixed operating expenses, the cost per picture in this situation is higher than if the chambers were run at the maximum rate. It is reasonable to believe that cost saving might be effected, with substantially the same physics output, by turning off some chambers completely, running the remainder at full capacity. With the present tight budget situation, it would seem wise to consider seriously such cost savings possibilities.

To study this question, HEPAP has collected data on operating costs and present and planned particle beam coverage for the running bubble chambers (82" and under). A set of possible options in the bubble chamber program, with the consequent operating cost savings, is presented here:

Bubble Chamber Program Options	Operating Savings Over Planned Program ($ Millions)
1. Present actual program	-0.8
2. Planned program of laboratories:	
BNL 31" off, BNL 30" stand by	0
Change planned program by:	
3. LRL 25" off	0.17
4. LRL 25", SLAC 40" off	0.46
5. LRL 25", ANL 30" off	0.65
6. LRL 25", ANL 30", SLAC 40" off	1.04
7. LRL 25", ANL 30", BNL 80" off (if 7' can handle load)	1.43
Turning off ANL 40" heavy liquid chamber would save an additional	0.84

The figures are purely chamber operating costs, and do not include chamber development, beam transport costs, or laboratory overhead. The addition of these items could well increase the indicated savings by 50 to 100%. The total picture output for the country's set of ≤82" hydrogen chambers has been held ~ constant for the various options at ~ 15 million/year. However, options which run the larger chambers more heavily will increase the event production rate, up to a factor of two from the present program; the 7-12' chambers coming into operation also will lead to an increased output. The operating cost savings are given with respect to a program which is the laboratories' stated future plans: the Brookhaven chambers have been moved to their new area, the 31" BNL chamber is shut off, the 30" BNL chamber placed on stand by, and the SLAC chambers have been converted to a new cheaper film format. The figures are for equilibrium conditions, immediate savings of this magnitude should not be expected.

Details of the pictures and operating costs assumed for the chambers and comments on the beam coverage for each of the options are given in Table I. The track length figures are based on chamber fiducial volume and estimates of the optimum number of tracks per picture (range 10-15). The operating cost numbers provided by the laboratories are presented in Tables II and III. Table II gives the figures for past and present operation, Table III the expected incremental costs for the additional pictures to go to full operation. The incremental costs of

~ 10¢/picture are well under the 20¢-35¢/picture cost for present partial operation. A chart showing present and planned beam coverage for the different chambers is presented in Fig. 1.

It is clear from examination of the above options that significant cost savings are possible in principle with only minimal coverage loss and at least an equivalent event output rate. Achieving this requires of course that the remaining chambers run with few problems, although an event output safety factor of two is available.

Table I

BUBBLE CHAMBER OPTIONS

OPTIONS	PICTURES x 10^6	TRACK LENGTH ft. x 10^6	COST x 10^6	SAVINGS OVER PLANNED PROGRAM x 10^6	COVERAGE
1. Present (1969)					
25" LRL	2.1	38	.472		
30" BNL) 31" BNL)	2.8	84	.673		
30" ANL	2.0	60	.706		Complete
40" SLAC	1.76	79	.596	-.787	
82" SLAC	3.24	290	1.097		
80" BNL	1.4	126	1.123		
	13.3	677	4.667		
2. Planned					
25" LRL	2.1	38	.472		Complete
30" BNL (stand by)	-		-		
30" ANL	2.0	60	.706		
40" SLAC	1.74	78	.587	0	
82" SLAC	3.26	290	.915		
80" BNL	5.0	450	1.200		
	14.1	916 +270 from 12'	3.880		
3.					
30" BNL	-		-		
30" ANL	5.0	150	1.006		
40" SLAC	1.74	78	.587		
82" SLAC	3.26	290	.915	.172	
80" BNL	5.0	450	1.200		
	15.0	968 +270 from 12'	3.708		

0.9-2.5 GeV/c $K^{\pm}$ missing. Could be partially filled with a new D.C. separated beam at 40" SLAC or at BNL 80" for under ~$1.5M, less if equipment is transferred. Fluxes at SLAC determine the low energy cut off which conceivably might approach 2 GeV/c.

Table I (Cont.)

BUBBLE CHAMBER OPTIONS

	OPTION	PICTURES	TRACK LENGTH	COST	SAVINGS	COVERAGE
4.	30" BNL	-		-		0.9-2.5 GeV/c $K^{\pm}$ missing. Could be filled at BNL 80" as in 3 for <$1.5M. See Note 1 for qualitative comments.
	30" ANL	5.	150	1.006		
	82" SLAC	5	450	1.211	.463	
	80" BNL	5	450	1.200		
		15	1050	3.417		
			+ 270 from 12'			
5.	30" BNL	-		-		0.9-3.0 GeV/c $K^{\pm}$ missing. Could be filled at SLAC 40" or BNL 80" as in 3 with capital expenditures. Also 1-2 BeV $\bar{p}$ missing. Could be filled at 80" but not 40".
	40" SLAC	4.24	190	.825		
	82" SLAC	5.76	520	1.207	.648	
	80" BNL	5.	450	1.200		
		15.	1160	3.232		
			+ 270 from 12'			
6.	30" BNL	-		-		Gaps as in 5. Could be filled with BNL 80". See note.
	82" SLAC	10	900	1.645	1.035	
	80" BNL	5	450	1.2		
		15	1350	2.845		
			+ 270 from 12'			
7.	30" BNL	-		-		Gaps as in 5 plus 12-20 GeV/c $K^{\pm}$, 16-25 GeV/c $\pi^{\pm}$, 1-20 GeV/c $\bar{p}$ all missing. Gaps could be filled with BNL 7'.
	40" SLAC	5	225	.874	1.430	
	82" SLAC	10	900	1.576		
		15	1125	2.450		
			+ 270 from 12'			

Note 1. i) The ANL and SLAC 40" are the only chambers with thin windows allowing triggering and study of hybrid devices.

ii) γ-rays, polarized backscattered laser gammas, timed K_2 beams, etc., are uniquely available at SLAC.

iii) Consideration in Plan 6 must be given as to whether the chambers can be operated that hard, especially if the 82" is to handle the physics mentioned in ii.

Table II

Cost Table - Past Costs and Output - No Overhead Included

(Per Year)

	LRL	SLAC		BNL		ANL
	25"	40"	82"	30"&31"	82"	30"
Manpower	252,400	288,000	472,000	363,000	577,000	386,000
Supplies	24,700	174,000	134,000	89,000	280,000	100,000
Film	115,000	122,000	466,000	140,000	140,000	80,000
Magnet Power	80,000	12,000	25,000	81,000	126,000	140,000
Total	472,100	596,000	1,097,000	673,000	1,123,000	706,000
Pics	2.13×10^6	1.74×10^6	3.26×10^6	2.8×10^6	1.4×10^6	2.0×10^6
Cost/Pic	$ 0.22	$ 0.34	$ 0.34	$ 0.24	$ 0.80	$ 0.35

NOTES:

1. No overhead has been put in. Also, beam costs were not added in.
2. The bases used to calculate average pictures per year are as follows:
   - LRL 25" - Output 5/68 to 9/69
   - SLAC - FY 69
   - BNL - FY 68, FY 69
   - ANL - FY 70. Budget assuming .02/pic. for 35 mm, .10/pic for 70 mm and about $.5 \times 10^6$ 70 mm pics. scheduled.
3. Film and processing costs for BNL were roughly calculated from given data at .05/pic. for 30", 31" and .10/pic. for 80".

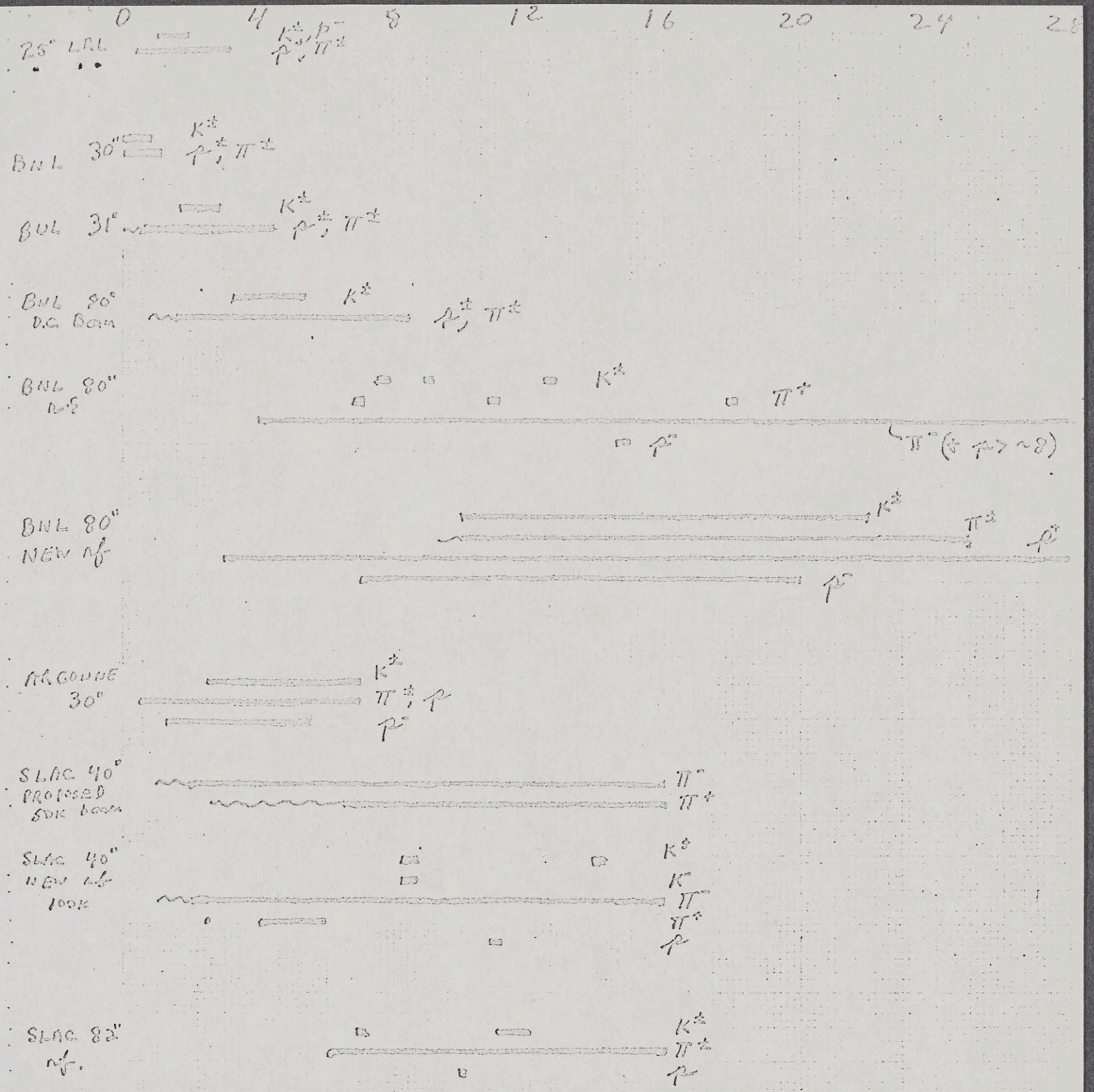
Table III

Full Operation Estimates

	LRL	SLAC	BNL		ANL
	25"	40" & 82"	30" & 31"	82"	
Recent Photo Output	2.1×10^6	5×10^6	2.8×10^6	1.4×10^6	2.5×10^6
Possible Photo Output	$3\text{-}4 \times 10^{6**}$	$\sim 10 \times 10^6$	$\sim 6 \times 10^6$	$\sim 5 \times 10^6$	$\sim 5.0 \times 10^6$
Differential Cost to increase output	~0.06/pic	~0.20/pic*	~0.06/pic	~.10/pic	~.10/pic
		~0.13/pic (after format change)			
Estimated Cost for full operation $= \frac{(\text{full costs})}{(\text{full pictures})}$	~.16/pic	~0.26/pic*	~0.13/pic	~.24/pic	~.20/pic
		~0.20/pic (after format change)			

* This figure will be substantially reduced by film format changes presently planned - to 35 mm (82"), 46 mm (40")

** Triple pulsing - no change in Bevatron shut down schedule



BEAM COVERAGE

Fig. 1

29.3.70

Notes on K. Strauch's Memo on HEP Funding (19.3.70)

(M. Hynes)

A. There are some particular criticisms which could be made to Strauch's memo, without denying the proposal that the alternatives need more study.

1. Par.2. Is a "constant budget" constant "total" or constant "operating" funds?

2. Par.9. The comparison between CEA and DESY is one between U.S. and German physicists as well as between large and small budget labs - what would the results have been if DESY had been at Harvard?

3. Par.10. A more valid comparison would be between the minimal cost of a small lab and the non-fixed cost of the larger one.

4. Pars. 11,12. No one would contend that most of the good ideas will come from university laboratories where most of the physicists are. It is not so clear that even in the past the physicists who produced specially good ideas did so preferentially at local machines. It is also even less clear that they will do so in the future, when the technical requirements of most experiments (higher energy and intensities) will be increasingly in favor of the bigger machines.

5. Par.12. The danger of Ph.D.'s becoming data analysts is, however, real if it is not more possible for them to spend time at the big labs. The argument from undergraduate education seems week; a laboratory does not have to have a semiprofessional group running an accelerator to get the desired teaching atmosphere - a technically oriented instrumentation programme would have a similar effect.

6. Par.14. The word "satellites" is unclear. Does it mean "geographically close" or "dependent" in some pejorative sense? The problem of presence at the large lab is, however, clearly real and the present level of help to outside groups perhaps insufficient (both from the large labs and from the outside universities themselves, administratively).

7. Summary: It is surely an easier administrative solution to cut everybody equally, not to be selective. The PPA/CEA decisions are just the "rough decisions" mentioned in Par.8, and they have been taken by a Committee.

Some of these comments are, perhaps, more debating points than substantive, but Strauch's memo is polemical anyway. He asks for a sofar missing objective study and then tries to give only the arguments on one side.

B. Factors to be taken into account in considering accelerator closures.

There will be a series of arguments against centralization based on administrative difficulties for the University staff and students, domestic problems for people, and on the value for overall scientific efficiency of having the machine on the campus. I will not try to evaluate these arguments, which may be very specific to the U.S. situation.

The financial pros and cons are more easy to list and to discuss.

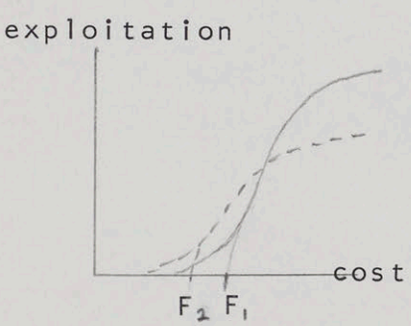
8. The zero approximation.

a) Accelerators (and other big facilities like bubble chambers, site plant) have a large element of fixed cost, perhaps 75% or more, if they are run as a professional service.

b) This fixed cost would be available for spending mainly on more and better physics operations at other accelerators if the local machine were closed down completely in a period of long term budget stringency.

c) Another way of presenting it is to say that all the accelerator operating staff/salaries, plus their overhead payments, plus the money they normally spend could be added to the staff and money for mounting and running experiments elsewhere. This might, roughly, double present levels of total user expenditure.

9. Corrections to the simple picture.



a) The fixed cost (F_1) may not be completely fixed: closing down one experimental area and associated services may permit a reduction in fixed cost (to F_2) without closing the accelerator. Similarly, running only at weekdays etc., or even replacing operators by graduate students. The total effect of such measures may be a smaller saving and larger reduction in usefulness and efficiency of the machine to all users than hoped for: heating, patrolling, safety etc. must probably still be kept up and not reduced proportionately, and operational reliability may fall off alarmingly.

b) Even with complete closure, some fixed costs may remain (e.g. patrolling, building maintenance) although they might be transferred out of the AEC high energy budget.

c) The "unit costs" of doing physics largely away from home may rise
- travel and subsistence will certainly increase
- equipment transport costs
- equipment will probably have to be better designed and built, though this might even make a saving in the long run by avoiding lash-up equipment
- services available "for nothing" at home may have to be paid for at the central laboratories
- the transfer from a (small) local to a large central machine may change the aims of the experiments (to higher energy, intensity, completeness, accuracy) which will lead to higher costs, though, hopefully, to better physics!

d) Capital costs.

- If the closure of the local machine is <u>not</u> accompanied by a reduction in the physics effort, but merely a transfer of operations to the central laboratory, then the central lab will need some once-for-all capital expenditure to provide more floor space, beam and power equipment, lab space etc. for the additional visitors. Some of the beam equipment etc.could be transferred from the closed down machine, but there will be costs of transport, modifications, power and cooling plant in the central lab.
- The total HEP budget planning might be such that, as well as closure, a reduction in total number of users will be needed even after using the saving in fixed costs to support operations. Then extra capital expenditure at the central lab may be partially at least avoided.

e) Numbers. The zero approximation would suggest that more than 50% of the total cost of a medium-size laboratory (perhaps even 60-65%) is "fixed", and would become available for extra physics, or for making up support to existing physics to a better level. Good estimates for the "corrections" in this par.9 will need the study asked for by Strauch, at least in a few typical cases. However, the European experience (via ECFA) suggests that there is still a considerable reduction in total cost per physicist

by centralization on the side of CERN compared with the NIMROD, DESY, Saturne style of operation.

The cost of extra beams etc. at the central laboratory will be a non negligible amount, in the rough order of 1 M$ per fully occupied place on the floor which could support new two groups.

10. a) Implications for the central laboratories.

- The closure of one of the smaller machines is decided in the interest of the whole HEP community, not to penalize one group. The resulting pains and benefits must be shared equitably to all concerned.

- In particular, the physics groups at the closed laboratory will need an increase in money to cover their extra operating and equipment costs (par.8c above).

- In addition the central laboratory must take steps to see that increases in its budget do go to provide more beams, lab space, technical help etc. for the new visitors, and not to insulate the in-house groups from any general reduction of resources to the user community.

- Policies of central laboratories on
  i) mixed groups and the support they can provide to weak visitors;
  ii) general technical assistance, including computing, for visitors and groups;
  iii) standardization of equipment;
  should be reviewed. On iii), there has been, and still is, in USA and Europe, a considerable degree of expensive duplication of equipment design and building (film analysis, electronics, beam equipment) which may no longer be the optimum compromise between economy and freedom and flexibility (if it ever were).

b) Implications for the university laboratories.

- The need for adequate travel budgets, flexibility in teaching schedules etc. have already been mentioned.

- Even so, there will be some extra emphasis on the planning and analysis ends of the experimental process, and the local computing facilities and their relation

to those in the central laboratory will be important problems. Remote input/output connections to a large central machine are now quite feasible, and more emphasis will be needed on collaborative writing of efficient programs (which will be good educational material).

c) Both for the central lab and for the universities, policy and machinery for scheduling experiments will become even more important. Local machines in the past have made it possible to run risky experiments, and experiments either to provide theses or to keep professors busy, as well as to run first rate proposals. How much of this should be transferred to the central labs, and how it should be organized has been discussed in Europe by ECFA with no overt policy emerging.

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29.3.70

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(N. Hynes)

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The argument from undergraduate education seems weak; a laboratory does not have to have a semi-professional group running an accelerator to get the desired teaching atmosphere, & a technically oriented instrumentation programme would have a similar effect.

6. §14. The word "satellites" is unclear. Does it mean "geographically close" or "dependent" in some pejorative sense? The problem of presence at the large lab is, however, clearly real & the present level of help to outside groups perhaps insufficient (both from the large labs & from the outside universities themselves, administratively).

The example of CERN seems to suggest that one can have a strong interaction between universities & the central lab. under in a much more 'centralized' situation than in the USA.

7. Summary. It is surely an easier ~~decision~~ administrative solution to cut everybody equally, not to be selective. The PPA/CEA decisions are just the "rough decisions" mentioned in §8, & they have been taken by a committee.

Some of these comments are, perhaps, more debating points than substantive, but Strauch's memo is polemical anyway. He asks for a so far missing objective study & then tries to give only the arguments on one side.

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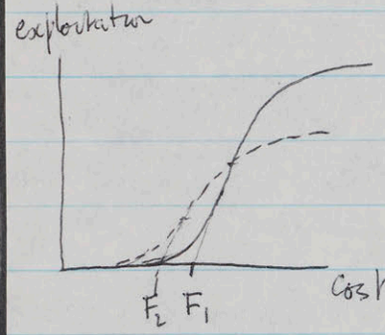
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OVER →

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-

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→ OVER

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29.3.70

the closed laboratory will need an increase in money to cover their extra operating & equipment costs (§ 8 c above)

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- Even so, there will be some extra

29.3.80

emphasis on the planning & analysis ends of the experimental process, & ~~consequently~~ the local computing facilities & their relation to those in the central laboratory will be important problems. Remote in put/output connection to a large central machine are now quite feasible, & more emphasis will be needed on collaborative writing of efficient programmes (which will be good educational material).

c) Both for the central lab & for the universities, policy & machinery for scheduling experiments will become even more important. Local machines in the past have made it possible to ~~do~~ run risky experiments, & experiments either to provide theses or to keep professors busy, as well & as to run first rate proposals. How much of this should be transferred to the central labs, & how it should be ~~its~~ organized has been discussed in Europe by ECFA with no overt policy emerging.

Matt.

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON 20545

March 25, 1970

TO: HIGH ENERGY PHYSICS ADVISORY PANEL MEMBERS

The attached information regarding personnel losses in high energy physics was prepared for the Joint Committee. I thought it would be of interest to you, and a copy is enclosed for your information.

William A. Wallenmeyer
Assistant Director for High
Energy Physics Program
Division of Research

Enclosure:
As stated

Q. How many people will be lost to the high energy physics program as a result of funding cutbacks?

A. The table below indicates anticipated high energy physics personnel reductions during FY 1970 and FY 1971 of about 1,120 from the ongoing, research-oriented, program. This loss is partially offset by an anticipated increase of about 390 people in the construction-oriented program at NAL, leaving an overall program loss of about 730 people - a ten percent reduction in two years. Many of the personnel reductions being levied during FY 1970 are in recognition of the limitations of the FY 1971 funding represented in the President's Budget Request.

The reductions are particularly discouraging with respect to the participation of young scientists in this field. Though about 300 Ph.D.'s per year are currently being granted in the field of high energy physics in the U. S., there will be fewer Ph.D.'s in total able to practice research in this field at the end of FY 1971 than in FY 1969 because of funding limitations. Further discouragement is reflected in the larger-than-proportionate (about twelve percent in two years) decrease of graduate students supported in the program.

Substantial additional losses prior to FY 1970 for individual laboratories and the university program are also indicated in the table which follows.

AEC HIGH ENERGY PHYSICS PROGRAM MANPOWER

		Manpower At Peak and Year		Manpower 6/30/69	Change During FY 70	Change[1] During FY 71	Manpower[1] 6/30/71	Change From[1] Peak to 6/30/71	% Change[1] From Peak
PPA	TOTAL	336	FY 67	295	-207	- 88	0	-336	-100%
	Physicists	7		7	- 3	- 4	0	- 7	-100%
	Other Professional	52		50	- 29	- 21	0	- 52	-100%
CEA	TOTAL	208	FY 66	190	- 62	- 13	115	- 93	- 44%
	Physicists	15		18	+ 1	- 9	10	- 5	- 33%
	Other Professional	44		41	- 14	- 1	26	- 18	- 41%
BNL	TOTAL	1355	FY 69	1334	- 8	-118	1208	-147	- 11%
	Physicists	117		110	+ 4	- 15	99	- 18	- 17%
	Other Professional	191		187	+ 3	- 18	172	- 19	- 10%
ANL	TOTAL [2]	755	FY 68	699	- 60	- 37	602	-153	- 20%
	Physicists	62		64	0	0	64	+ 2	+ 3%
	Other Professional	173		156	- 21	- 13	122	- 51	- 29%
LRL	TOTAL	1441	FY 67	1261	-107	-120	1034	-407	- 28%
	Physicists	108		103	- 1	- 2	100	- 8	- 7%
	Other Professional	204		184	- 11	- 13	160	- 44	- 22%
	Graduate Students	111		104	- 12	- 7	85	- 26	- 23%
SLAC	TOTAL	1236	FY 70	1230	- 62 [4]	- 9	1165	- 71	- 6%
	Physicists	101	(10/69)	100	- 11	- 1	89	- 12	- 12%
	Other Professional	189		190	- 6	- 1	182	- 7	- 4%
UNIVERSITIES	TOTAL [3]	2330	FY 68	2235	-125	-105	2005	-325	- 14%
	Physicists	610		605	- 15	- 10	580	- 30	- 5%
	Other Professional	250		235	- 20	- 20	195	- 55	- 22%
	Graduate Students	570		545	- 35	- 25	480	- 90	- 16%
SUBTOTAL (Excluding NAL)	TOTAL			7244	-631	-490	6129		
	Physicists			1007	- 25	- 41	942		
	Other Professional			1043	- 98	- 87	857		
	Graduate Students			649	- 47	- 32	565		
NAL	TOTAL			410	+260	+130	800		
	Physicists			47	+ 28	+ 25	100		
	Other Professional			70	+ 75	+ 15	160		
TOTAL PROGRAM	TOTAL			7654	-371	-360	6929		
	Physicists			1054	+ 3	- 16	1042		
	Other Professional			1113	- 23	- 72	1017		
	Graduate Students			649	- 47	- 32	565		

1/ FY 71 manpower projections based on President's Budget.

2/ ANL indirect manpower estimated using indirect costs.

3/ About 40% of university program surveyed. Totals given are based on extrapolation from this survey and results of 1968 manpower survey.

4/ SLAC FY 70 changes are from the peak in 10/69 rather than from the 6/30/69 manpower levels.

A copy for your info as per our conversation

MAW 3/24/70

→ Peg Weisenberg

AEC HIGH ENERGY PHYSICS PROGRAM MANPOWER

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY · HARVARD UNIVERSITY

CAMBRIDGE ELECTRON ACCELERATOR

HARVARD UNIVERSITY
42 OXFORD STREET
CAMBRIDGE, MASS. 02138

March 19, 1970

The enclosed remarks are being sent to members of HEPAP, to Paul McDaniel and his staff, and to colleagues and friends who might be interested. I raise these points because I feel that they need discussing.

Sincerely,

Karl Strauch

Karl Strauch
Director

KS/bm

HARVARD UNIVERSITY

Some Personal Thoughts on the Present Trend in the AEC High Energy Program

Karl Strauch

March 19, 1970

1. Unless the present trend is reversed, only NAL, SLAC and BNL will have running accelerators in a very few years. PPA, CEA, LRL, ZGS accelerators will have been mothballed.

2. The above trend is by no means the inevitable result of present boundary conditions in government support. These I take in this discussion to be a constant budget for high energy physics.

3. What is inevitable under present boundary conditions is that all of the remaining accelerator laboratories together must reduce their budget very significantly in order to permit effective use of NAL.

4. I am unaware of any careful study by the physics community or other of the various alternatives by which the overall reduction can be carried out in such a way as to minimize the harmful effect on the High Energy Program. Many possibilities exist between the extremes of reducing all budgets uniformly and the closing of all but two of the existing accelerators. It is unfortunate that the 1969 report of the Weisskopf committee is already out of date since it was based on an expanding budget.

5. In the absence of a comprehensive study, administrative decisions affecting major research programs and the professional work and future of large groups of people are by necessity made on an ad hoc basis which has resulted in the trend stated in 1.

6. It is my own guess that a realistic study will indicate that the best overall course would consist in keeping running several of the threatened accelerators, but at a budgetary level severely reduced from their present level. I emphasize that this is only a guess - this question simply has not been explored sufficiently to make more than a guess! And this is unfortunate.

7. Why does no comprehensive study exist on how High Energy Physics will best survive under present financial boundary conditions? Clearly, the main reason is that nobody wants to accept these boundary conditions and is loath to even give the appearance of acceptance by making such a study. I submit that this attitude, understandable as it is, effective as it has been, is no longer valid at this time. Asking a laboratory for a realistic minimum cost of remaining a viable institution might well open a bag of worms. Not asking the question is likely to open a casket!

8. Another reason is that no committee likes to make tough decisions. But somebody has to, and is making them, and the physics community at least should provide them with well-studied advice.

9. What are the main arguments for the closing of an accelerator besides the obvious (and non-negligible) one of administrative ease? The main point seems to me as follows: a laboratory that receives only a fraction of the support of another similar laboratory, simply cannot remain competitive. This is a strong but uncompelling reason. The effective budget of DESY has been at least twice as large as that of CEA. DESY has done more experiments and several in a more definitive fashion. But in terms of firsts in ideas and measurements both in physics and technology, CEA has more than held its ground. This is because besides money people also count in the work of a laboratory.

10. There are of course differences in the minimum support required to keep various accelerators viable machines in viable laboratories. At least for some of the accelerators endangered by the present trend the minimal cost is small compared to budgets of the large accelerators. The damage caused by the present uncertainties could be worse than a carefully planned reduction in support to a minimum level.

11. What are the arguments for keeping some accelerators working, even at minimum levels of support? I believe there are strong arguments on both physics, technical and educational grounds. Large centers are more likely to do the careful, definitive measurements that are so important. But new ideas and techniques, both in physics and technology, depend on the existence of a few imaginative people and many of these are also found around the smaller accelerators. There is nothing like the problems of an active laboratory to kindle the imagination! The amount of data is perhaps proportional to the budget of a laboratory, but the number of really new ideas and developments

has not been, at least for some cases with which I am familiar. Thus low-budget accelerator laboratories can still make significant contributions to physics, and very competitively with similar amounts of money spent at a large accelerator.

12. Besides its exciting nature, high energy physics has an important role in attracting good young people into physics. It is probably true that the growth in the number of academic and academically oriented positions has just about stopped for a while. However, I cannot believe that the country will not need a continuing supply of good people trained in the most basic of sciences, physics. Many of these will work on applied or technological problems. Thus I agree that we will need fewer narrow particle theorists or model-oriented data analysts. What will be needed are young people who have a broader training and interest. I submit that concentration of running accelerators will not only cause a probable reduction in the number of students engaged in high energy physics, but more seriously, greatly reduce the number of those that plan and work directly with equipment and not just with photographs and tape. The smaller laboratories have had and are having a disproportionately larger share in training of young physicists, particularly of those with a broad training.

These remarks do not just apply to graduate education; undergraduate physics education benefits in many schools located in the vicinity of accelerator laboratories.

13. It appears fashionable to joke that High Energy Physics is losing importance because it has not had a great discovery in the last six years! I am old enough to have heard this before! High Energy Physics is just as much at the frontier of fundamental knowledge as it ever was, and just as exciting as it ever was! And thus it is just as important as before to bring this excitement to the young people the best of whom will do the next generation of experiments. As much as possible, the direct involvement of the universities in High Energy Physics should be kept up!

14. One of the primary reasons for the strength of the U.S. high energy research program has been the tremendous interaction between university groups and accelerator laboratories. Both have benefited immensely. As the laboratories grow larger, this interaction is decreasing. Take away the Bubble Chamber pictures, SLAC has few outside users who are not satellites. There is nothing sinister about this, it simply is a reflection of the fact that it is not easy to be in two places at the same time, either for the student or the professor, and that

complex equipment requires continuous efforts over several years. In my view, the concentration on three running accelerators will inevitably reduce the interaction between universities and accelerator laboratories. This will be very bad for both, and thus for High Energy Physics.

Summary

The remarks made in the preceding lines are neither original, profound nor complete. They are undoubtedly colored by my position as a director of one of the threatened laboratories (CEA). But I wish to emphasize that the present trend of concentrating all running accelerators into 3 laboratories is not a necessary consequence of the fiscal plateau, and that in my opinion it is a mistake. However, this being administratively the easiest solution, it is likely to happen unless there is strong contrary pressure and guidance from the physics community.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY · HARVARD UNIVERSITY

CAMBRIDGE ELECTRON ACCELERATOR

HARVARD UNIVERSITY
42 OXFORD STREET
CAMBRIDGE, MASS. 02138

March 11, 1970

Professor Victor F. Weisskopf
Room 6-303
M.I.T.
Cambridge, Mass. 02139

Dear Vicki:

As you know the reduction in the programmed FY 71 operation budget for CEA has led to a complete reassessment of the role and the program of our laboratory. The main conclusions are summarized in my letter to Paul McDaniel of February 11, 1970, of which I enclose a copy. I believe that this matter is of great interest to HEPAP and I would very much appreciate the opportunity to discuss our situation with your group at your next meeting at Stanford in April.

Some present trends in the U.S. High Energy Physics Program are open to serious question. These trends, it seems to me, have not been studied and discussed sufficiently. I am preparing a note on some personal thoughts on this matter which I intend to send to members of HEPAP and other interested members of our community.

With warm personal regards,

Karl

Karl Strauch
Director

KS/mr

Enc.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY · HARVARD UNIVERSITY

CAMBRIDGE ELECTRON ACCELERATOR

HARVARD UNIVERSITY
42 OXFORD STREET
CAMBRIDGE, MASS. 02138

February 11, 1970

Dr. Paul W. McDaniel, Director
Division of Research
U.S. Atomic Energy Commission
Washington, D. C. 20545

Dear Dr. McDaniel:

This letter is to give you a first reaction on the impact on our laboratory of the reduction in programmed funds for FY 71 compared to those available for FY 70. The size (more than 30%, from $3.475 M to $2.40 M) and suddenness (we had no indication of such a cut) of this reduction have created such a host of problems that only today, more than one week after your phone call telling me the news, do I feel able to provide you with an overall picture.

I appreciated your thoughtfulness in personally informing me of the reduction. We all know the difficult boundary conditions under which you and your staff are operating. I also know that you want me to most frankly tell you the effects of the programmed reduction on our laboratory and its program. These effects are of the utmost seriousness.

The tragedy of this sudden reduction in funds is that it comes at a time when

1) the colliding beam program has reached the exciting stage where all parts of the system are brought together as a whole,

2) the conventional physics program has just been built up to a new peak of results both in electroproduction and in photoproduction experiments with new facilities unique to CEA such as our high resolution two-arm spectrometer in beam 7.

Our Visiting Board has testified to the good condition of our laboratory and the quality of its work at its most recent meeting in December 1969. The members of the Visiting Board are: Prof. J. W. Cronin (Princeton); Dr. M. Goldhaber (Brookhaven); Prof. J. D. Jackson (Berkeley); Prof. B. D. McDaniel (Cornell); Prof. W. K. H. Panofsky (Stanford); and Dr. J. B. Fisk (Bell Laboratories), Chairman.

The substance of your letter left us no alternative but from now on to plan our activities for the reduced FY 71 level of support. On Tuesday, February 3, 1970, I made a statement to the entire laboratory announcing the new level of support and that it undoubtedly required a sizable reduction in personnel from our FY 70 level of 185 employees. On Thursday, February 12, 1970, we are giving termination notices effective June 30, 1970, to 58 employees. On the same day announcement of the abolishment of 3 administrative and technical positions will be made. 6 scientific staff positions must be eliminated as soon as our commitments are fulfilled.

The new level of support required a complete re-examination of our laboratory program for FY 71 and extraordinary decisions on how to make the transition to our new rate of activity. The Scientific Subcommittee, the CEA staff, CEA users and wise friends from our universities, all have been involved in nearly continous discussion during this last week. We have reached the following conclusions:

1) It is clear that we can no longer pursue in parallel two big programs such as our colliding beam development and the electro and photoproduction experiments. This is a tragedy in terms of loss in physics for we have done both successfully and effectively so far.

2) Even at the reduced rate of funding, CEA is a great scientific asset to our local community and the U.S. We must make every effort to keep it going during these lean times with the expectation that future successes will help restore more reasonable levels of support.

3) With this in mind and the belief that the most exciting physics accessible to our laboratory is likely to result from the colliding beam experiment, we have decided for the present to phase out all conventional physics before June 1, 1970, and to concentrate for a while all laboratory efforts on the colliding beam effort.

4) Although we will now carry out this decision with all the vigor that we can command, we have reached it with great reluctance. We continue to believe that under normal circumstances a balanced program will result in better physics and a better laboratory. The reduced level of activity essentially has forced us away from a long range point of view.

5) The unexpected suddenness with which we are being forced to make our transition to the new level of activity has created a set of most difficult problems. The number of "approved" experimental shifts is considerably larger than the number we can now provide before June 1, 1970. The number of shifts on the expectation of which the equipment has been assembled is very much larger. The Executive Committee on February 9, 1970, has empowered a group composed of Prof. F. Low (M.I.T.), Prof. Curry Street (Harvard), Prof. Don Yennie (Cornell) [Prof. Albert Silverman (Cornell) has since been added], to establish priorities among the already approved experiments on the basis of quality of physics. This will be a difficult and heartbreaking task.

It is not necessary to explain in detail at this time what difficulties this sudden and unexpected shift in our program is causing to students, research workers and professors. Much excellent physics is being postponed at best - much for many years to come. We are taking this difficult course in the belief that it is the one course which by speeding up the exciting colliding beam development (although at the loss of very much conventional physics) is most likely to insure continuation of our laboratory into hopefully better times with resumption of a more balanced program.

I can think of no better proof of the continued support of CEA by the local physics community than the unanimity with which the above course of action has been approved by all members concerned, particularly by those whose research, co-workers and students are most directly and disastrously affected by the sudden transition.

After we have had time to make further analysis, I will submit to you a more detailed plan on how to minimize the difficulties of our transition period and permit a more flexible program.

Let me now comment on some general problems which are being brought into a sharp focus by sudden changes in support of carefully built up institutions such as CEA. One of the greatest contributions of the United States to the advancement of science and one of the main reasons for our present eminence in this area has been the successful development of the team effort in the creative pursuit of fundamental knowledge. One of the primary

causes of this successful development has been the steady and enlightened support by the government based on long range plans for the benefit of the country. Creative ideas and discoveries cannot, like the development of a consumer product, be turned on or off on short notice. It takes years to build up productive groups of intellectual eminence. They can be destroyed on short notice. Few actions are more likely to have disastrous effects than sudden scientifically unjustified shifts in support and abandonment of the long range point of view of what is best for science.

Besides the importance of increasing our store of basic knowledge of nature, a most important mission is to develop the new generation of scientists on which the future of our country and the world will depend. Experience has shown that there is no better way to interest the best brains available than to engage them directly and as early as possible in the most exciting fields of endeavor. Again, only an enlightened long range point of view can produce the conditions necessary for attracting and keeping the best young people in science. During last spring's student unrest at Harvard, I was able to very effectively use CEA as a shining example of the enlightened attitude of our government toward the pursuit of fundamental knowledge. I enclose a copy of a letter of mine published in the May 13 issue of the Harvard Crimson as an illustration. Most unfortunately, some of my strongest arguments valid then are now no longer correct! What will the young people so seriously affected by these sudden decisions which we are forced to make think of the wisdom of putting their life's effort into science? What will their brothers and friends think?

We will in our new mode of operation do everything we know how to justify your goal "to continue to seek means of providing for the operation of this important facility at a more productive and desirable level". We are optimistic of success within reasonable schedules and financial conditions. Your support, and that of your staff, can and will be, I am sure, of great help in restoring the present low state of morale of all the workers of CEA upon whose dedication our future rests.

Sincerely yours,

Karl Strauch

Karl Strauch
Director, Cambridge Electron Accelerator
Professor of Physics
Harvard University

KS/mr

Enclosure

sept meetings

MASSACHUSETTS INSTITUTE OF TECHNOLOGY · HARVARD UNIVERSITY

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CAMBRIDGE, MASS. 02138

◆

March 11, 1970

Professor Victor F. Weisskopf
Room 6-303
M.I.T.
Cambridge, Mass. 02139

Dear Vicki:

Just a short addition to the formal letter concerning next HEPAP meeting.

Looking over the list of members of the Committee, I cannot help but be struck by how "large laboratory" oriented and "establishment" oriented the membership of active people really is. With the possible exception of Bill Willis whom I do not know very well, there is nobody like Mel Schwartz, Val Telegdi, Jim Cronin - active physicists both of great distinction and independence. Again, possibly excepting Aihud Pevsner, not one member of the Committee has worked at or with the two smaller accelerators (PPA or CEA) or is likely to be familiar with them. But two members are very familiar with L.R.L.!

I wish to emphasize very strongly that I am not implying any favoritism or stacking of the deck. My concern in this matter comes entirely from wishing to have as wise and broadly experienced a group as possible tackle the difficult problems of our field.

Best regards,

Karl

Karl Strauch
Director

KS/mr

(Corr - P

3.3.70

Substance of Telex to Panofsky

1. Total Expenditure on HEP in W. Europe

	1966	1968	1970 (Calendar Year)
CERN	172	284	325
National	391	515	600 (approx)
Total	563	799	925 (app)

Cost in M Swiss Francs at ~~past~~ actual prices ~~of the~~

CERN costs in 1966, 1968 each include 4 MFr preparations for 300 GeV machine. Cost in 1970 will be about 15 MFr in addition if project approved.

Cost ~~Price~~ changes ~~Effects of increases due to~~ due to inflation ~~so far~~ about ~~?~~ ~~7%~~ ≈ 3.5% or more per annum for 1966 - 1968 and 4.5% for 1968 - 1970 are contained in above figures.

[See next page for continuation]

2. Numbers of HE physicists

	1966	1968
Experimenters	1436	1799
Theorists	827	970

Physicists are, in US terms, graduate students and above, working mainly ~~the~~ on particle physics aspects of experiments & theory. ~~Full~~ ~~Time~~ Bubble chamber, electronics, data processing etc specialists are excluded.

Prof)

3.3.70

1. Cont. Costs include ~~most of medium energy physics (US definition)~~ i.e. nuclear structure work done on accelerators able to produce pions and corresponding capital for ~~Villigen SC and CER~~ machines, e.g. Villigen and CERN SC., ~~that is~~ This corresponds to ~~cost~~ most of US Intermediate energy physics.

4 Costs include all salaries of physicists, supporting technicians ~~+ large laboratory staff~~, and ~~some~~ most University overheads. Large laboratory budgets are complete.

5 Costs include operating ~~costs~~ and annual expenditures on equipment + construction, not ~~annual appropriations~~ obligations.

~~Costs for Sol~~

Salaries in Europe are lower than in US Materials costs equal or higher at 4.3 Fr = 1 $.

TD

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3. Comparison of CERN and BNL in FY1969.

CERN data here is for US FY 1969, omitting ISR, SC, serpukhov beam equipment and corresponding services, but includes French-German shares in two large bubble chamber construction projects.

BNL data is for US FY 1969 including an estimated 15 M$ ~~from obligations for~~ expenditures on AGS conversion and other equipment and buildings associated with HEP.

CERN cost 210 M Fr including 60 MFr for large ~~projects~~ construction projects and buildings and ~~MF~~ 40 MFr for equipment + development

BNL cost about 35 M$ including about 15 M$ for construction and equipment expenditures.

CERN programme involve about 5.5 M bubble chamber picture per year plus 14-15 electronic experiment~~s~~ set ups at PS + Serpukhov

BNL programm involves about 3.5 M pix plus 7-8 set ups at AGS

Pief

(4)

3.3.70

4. National guide line for future total expenditure on HEP are around 3-5% per annum in ~~real terms~~ constant dollars for France + ~~Ger~~ Britain, ~~somewhat~~ at least more for Germany. These must (in long run ~~include~~ 300 GeV costs ↑ CERN Meyrin ↑ total expenditure will be constant ~~in constant dollars~~ from 1970 onwards at ~~340~~ 350 MFr (~~1969~~ 1970 prices ~~Francs~~) = for 4-5 years 300 GeV machine ~~cost~~ expenditures should rise to ↑ about 250 MFr ↑ plateau ~~level~~ by 1973 if project is approved soon.

~~National~~

5. European ~~&~~ data ↑ at ~~are~~ confidential until 1st April 1970 at least ~~=>~~ ~~&~~ are not in final form.

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

FEB 2 1970

Professor Karl Strauch
Cambridge Electron Accelerator
Harvard University
Cambridge, Massachusetts 02138

Dear Professor Strauch:

The high energy physics program is faced with a serious fiscal crisis in FY 1971. After careful study, including extensive discussions with the High Energy Physics Advisory Panel, we have reluctantly decided to institute a reduced mode of operation at the Cambridge Electron Accelerator (CEA). In the President's Budget for FY 1971 $2.4 million of operating funds are programmed for the CEA. It is anticipated that this level of funding will permit the colliding beam program to be maintained but will probably force cessation of conventional electromagnetic experiments at CEA.

During the past year we have given careful study to the problem of how best to respond to the ever increasing budget restrictions being imposed on the high energy physics program. It is clear that the cumulative effect of several years of restrictive budgets has caused a situation in which high energy physics contractors are all having serious difficulties and there is no encouragement that relief from budgetary pressures may be expected during the next few years. In order to somewhat ease the impact of these restrictive budgets on the highest priority research facilities and their associated research programs, we have concluded that selectively greater reductions at certain other facilities are necessary. The decision to apply such a reduction to the CEA has been most difficult. We recognize that the CEA is performing important experiments and can be expected to continue as a major element in the nation's high energy physics effort. We anticipate that the indicated new level of funding will permit continuance of the top priority colliding beam research program. We will continue to seek means of providing for the operation of this important facility at a more productive and desirable level.

We are available to provide whatever assistance we can to help you carry out the difficult actions required by this funding reduction.

Sincerely,

Paul W. McDaniel, Director
Division of Research

cc: New York Operations Office

FEB 2 1970

Professor Milton G. White
Director
Princeton-Pennsylvania Accelerator
Princeton University
Princeton, New Jersey 08540

Dear Professor White:

On November 10, 1969 you were advised of the AEC decision to reduce the annual level of funding for the Princeton-Pennsylvania Accelerator to about $3.5 million. This action, which contemplated continued accelerator operation in a reduced mode, resulted from reductions imposed on the FY 1970 high energy physics budget and anticipated stringencies for FY 1971.

The process of formulating the President's Budget for FY 1971 is now complete and allowances approved for the High Energy Physics Program are significantly less than earlier anticipated. Due to the severely restrictive fiscal situation a complete reassessment of plans for FY 1971 was required. After detailed consideration by AEC staff and consultation with the High Energy Physics Advisory Panel, the Commission has determined that the operation of the Princeton-Pennsylvania Accelerator must be terminated in FY 1971. Accordingly, we plan to program about $2.0 million in FY 1971 operating costs to provide for an orderly phase out of operations.

The decision to terminate operation of PPA results from an assessment of priorities within the High Energy Physics Program. It is recognized that the PPA and its associated university groups have made and are making meaningful contributions to the nation's high energy physics research effort. The potential for future contributions to research as well as the possibilities for incorporation of new capabilities are also recognized. However, the severe funding limitations facing the program and urgent needs of the highest priority parts of the program appear to leave no reasonable alternative to termination of the PPA operation.

We recognize the difficulties that this letter will give you and your colleagues. Please let us know how we can help you accomplish this most difficult and unpleasant task.

Sincerely,

Original Signed by
Paul W. McDaniel

Paul W. McDaniel, Director
Division of Research

UNITED STATES
ATOMIC ENERGY COMMISSION
WASHINGTON, D.C. 20545

FEB 2 1970

Dr. Edwin M. McMillan
Director
Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

Dear Dr. McMillan:

You are well aware of the budgetary strictures that our physical research programs have been operating under for the last several years. In the High Energy Physics Program, in particular, bringing major new facilities such as SLAC, the AGS Conversion, and the 200 BeV Accelerator into operation over this same lean period has hastened our arrival at the crucial juncture where difficult choices must be made in the interest of maintaining a viable research capability in the U. S. In order to meet these urgent needs within a reduced overall funding level for FY 1971, we have found it necessary to make the unpleasant decision to shut down one of our accelerator laboratories and to drastically reduce the level of operation of others.

The Division of Research has given careful consideration to the problem of how best to allocate the reductions. As a result of this analysis, which included extensive consideration by the High Energy Physics Advisory Panel, we have decided to assign a substantial reduction to LRL. In the President's Budget for FY 1971 $16.8 million of High Energy Physics operating funds are programmed for LRL. We are painfully aware that this budget, which represents a decrease of $940,000 from LRL's already austere FY 1970 budget, will cause extreme difficulties within the Laboratory.

Following your analysis of the detailed implications of this level of funding, we would like to understand your anticipated means of accommodating the operation of the Laboratory to this budget.

If there is anything we can do to help, please do not hesitate to call on us.

Sincerely,

Paul W. McDaniel

Paul W. McDaniel, Director
Division of Research

2cc: E. C. Shute, SAN

January 14, 1970

Professor Robert Marshak
Dept. of Physics
University of Rochester
Rochester, New York 14627

Dear Bob:

Thanks for sending me your correspondence with Bob Sachs in regard to the Division of Particles and Fields and the meeting they plan at the Washington APS meeting. I think it is a good idea to have a panel discussion on the status of the field and the financial plight of the situation. I also think that the discussion that Bob Sachs has in mind and the one that I have in mind are very similar and should be united.

Let me make sure that my suggestion was not necessarily a discussion of the HEPAP report, which was issued several months ago. My idea was to acquaint the high energy physicists with the activities, problems, and difficulties which HEPAP has. In this respect, the two topics are not so different. One could formulate the situation in the following way--HEPAP is more concerned with the fate of the field in the near future, whereas NAS worries about the fate of the field in the long run.

Best regards,

Victor F. Weisskopf

cc: Robert G. Sachs

THE UNIVERSITY OF CHICAGO
THE ENRICO FERMI INSTITUTE
5630 ELLIS AVENUE
CHICAGO • ILLINOIS 60637
AREA CODE 312-667-4700

December 30, 1969

Prof. Robert Marshak
Dept. of Physics
University of Rochester
Rochester, N.Y. 14627

Dear Bob:

As you probably have heard, the NAS has set up a repeat performance of the Pake Committee in the form of Physics Survey Committee chaired by Allen Bromley. This Committee has organized panels, one of them being an Elementary Particle Physics Panel of which I am chairman. Our job is to look over the entire field of elementary particle physics and to discuss its needs and prospects for the future in the context of our times. We want to have a maximum input from the people most concerned, namely the Particle Physicists, both experimental and theoretical.

Our Panel has had one meeting at which we discussed methods to obtain this information. It was agreed that the Division of Particles and Fields offers us the best means. Therefore we want to request that the Program Committee of The Division plan a Town Hall meeting of some kind at the Washington APS meeting. Members of the Panel will make themselves available to perform in whatever way you suggest. Maybe we should have the entire Panel on the stage to receive and answer questions.

We shall have had a good chance to form our ideas by the time of the meeting and we shall be almost ready to write a preliminary version of our report. Therefore we should be able to lead a discussion.

This matter is of the utmost importance for the future of physics. Therefore I hope that the Executive Committee will be able to discuss it at the Chicago meeting and make a definite commitment at that time.

Sincerely,

Bob

Robert G. Sachs
Director

RGS/pas

CC: A. Rosenfeld
Prof. C.N. Yang
C. Reed
W.W. Havens, Jr.

THE UNIVERSITY OF ROCHESTER
RIVER CAMPUS STATION
ROCHESTER, NEW YORK 14627

DEPARTMENT OF PHYSICS
AND ASTRONOMY

January 8, 1969

Professor R. G. Sachs, Director
The Enrico Fermi Institute
The University of Chicago
5630 Ellis Avenue
Chicago, Illinois 60637

Dear Bob:

Thank you for your letter of December 30, 1969 requesting that the Division of Particles and Fields should organize a meeting at the time of the Washington APS Meeting in order to receive a preliminary report from the Elementary Particle Physics Panel and stimulate discussion of its contents. I have also received a suggestion from Weisskopf that an opportunity be provided at the Washington APS Meeting for a discussion of the HEPAP report of several months ago. Perhaps we can use a single meeting to achieve both purposes. In any case, we should definitely discuss your request (as well as Weisskopf's) at the Executive Committee Meeting in Chicago.

I am taking the liberty of sending a copy of your letter and my reply to Weisskopf so that he might also think about the suggested "double-header" program. You and he might even wish to contact each other before the Executive Committee Meeting and come up with a joint proposal for an interesting special evening meeting of Divisions of Particles and Fields in Washington.

Sincerely yours,

R. E. Marshak

REM:cb
cc: A. Rosenfeld
Prof. C. N. Yang
~~C. Reed~~
W. W. Havens, Jr.
V. F. Weisskopf

January 7, 1970

Professor Robert G. Sachs
Director
The Enrico Fermi Institute
University of Chicago
5630 Ellis Avenue
Chicago, Illinois 60637

Dear Bob:

I am very glad that you have agreed to join Bromley's Committee which, I think, may be of great importance for the future of basic physics.

Bromley has talked me into staying on the Committee but playing a more passive role as a kind of observer. This may perhaps also help you a little in the work that may result for you.

There is no question thatyou could and should have access to the HEPAP report on computer usage. So far, that report does not yet exist, but I will ask Horace Taft to send you an advance draft, after I obtain formal permission from the AEC office. I have no doubt that it will be given.

With very best wishes for the New Year, I remain,

Sincerely yours,

Victor F. Weisskopf

VFW:p

THE UNIVERSITY OF CHICAGO
CHICAGO • ILLINOIS 60637
THE ENRICO FERMI INSTITUTE
5630 ELLIS AVENUE
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Office of the Director

December 31, 1969

Professor V. F. Weisskopf
Department of Physics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Viki:

I heard from Bromley that you have succeeded in persuading him to relieve you of membership on his committee and he has asked me to serve instead. I did agree to take the added responsibility, with the understanding that he would not expect any more paperwork from me than that which is clearly required by the work of the panel I am chairing.

My reason for writing you now has to do with the work of the Panel on Elementary Particle Physics. One question we are expected to speak on concerns the impact of computer techniques on the field. Since Taft's subpanel of HEPAP has recently made its report on computer usage in high energy physics we are reluctant to duplicate the work, assuming that we are capable of it. Therefore, I should like to request HEPAP's permission for our panel to receive and make use of the Taft subpanel report.

As you know, all documents of the Survey Committee are treated as privileged material so I do not believe that there would be any problem about confidentiality.

Would you be kind enough to take whatever steps are necessary to make this document available to us?

Although we are all a little gloomy these days, I still want to wish you a happy New Year.

Regards,

Bob

Robert G. Sachs

RGS/bls
cc: C. Reed
W. Wallenmeyer