ON THE THEORY OF THE VECTON

I. Yu. KOBZAREV and L. B. OKUN'

Institute for Theoretical and Experimental Physics, Academy of Sciences, U.S.S.R.

Submitted to JETP editor February 28, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 499-506 (1959)

Consequences of the hypothesis that strong interactions arise as a result of the interaction of a neutral vector particle—the vecton—with the baryon current are considered. The problem of the origin in such a model of isotopic invariance, and, in particular, of the appearance of a π-meson triplet is discussed. Experimental possibilities of detecting the vecton are examined in detail.

INTRODUCTION

In this paper we would like to make a number of remarks about a hypothetical neutral vector meson to which we shall from now on refer as the vecton and which we shall denote by ρ^0. The vecton is not a new entity in the physics of elementary particles. The idea that strong interactions, in analogy to electromagnetic interactions, are due to the exchange of neutral vector mesons has been widely discussed already in the 1930's and 1940's (cf. the well-known books of Wentzel[1] and Pauli[2]). However, at that time such a model was rejected because, firstly, charged mesons ($\pi^{\pm}$) were discovered, and secondly, within the framework of perturbation theory the vecton theory of strong interactions contradicted experiment: in particular, it was not possible to obtain the correct sign of the quadrupole moment of the deuteron.[2]

In the late 1950's theoreticians again turned to the vecton for an explanation of the electromagnetic properties of the nucleon (Nambu[3]) and of spin-orbit nuclear forces (Sakurai,[4] Breit[5]). These authors considered the vecton together with other mesons, both actual and hypothetical, basing their work explicitly or implicitly on the idea that all the known mesons and baryons are of an equally elementary nature. In addition to these papers there appeared the paper of Fujii,[6] in which the vecton was treated as the only elementary meson responsible for the interaction between the elementary baryons (proton, neutron and Λ hyperon). He treated the other mesons and baryons as compound particles (the Sakata model[7-9]).*

*The problem of the vecton in connection with the Sakata model was also considered by Feynman[10] and by Gell-Mann.[11]

STRANGENESS AND ISOTOPIC INVARIANCE

In common with Fujii[6] we assume that the Lagrangian for the strong interaction has the form

$$L_s = j_{s\alpha} B_\alpha, \tag{1}$$

where B_α is the vecton field, while the strong interaction current $j_{s\alpha}$ is given by

$$j_{s\alpha} = \sqrt{4\pi}\, g (\bar{\psi}_p \gamma_\alpha \psi_p + \bar{\psi}_n \gamma_\alpha \psi_n + \bar{\psi}_\Lambda \gamma_\alpha \psi_\Lambda). \tag{2}$$

In the approximation in which all the interactions with the exception of the strong interaction are switched off there is degeneracy between the three baryons. The consequences of this degeneracy have been examined in detail by Ohnuki et al.[12] We know from experiment that the strong interactions of the Λ particle are not identical with the strong interactions of the nucleons (the $\Lambda\Lambda\pi$ vertex is absent, the K-meson mass exceeds the π-meson mass by more than a factor of three, etc.). Consequently, there must exist a mechanism responsible for lifting the degeneracy between the Λ particle and the nucleons.

There exist several possible mechanisms for lifting the degeneracy. Some of these amount to the supposition that the Λ particle has some sort of an additional interaction compared to the nucleons; others amount to the supposition that it is the nucleon which has such an additional interaction. For example, Sakurai assumed that nucleons interact with a triplet of hypothetical nuclear mesons.

In our paper[13] we have assumed that there exists a neutral meson which interacts with the Λ hyperon and with the muon. This has enabled us to remove the degeneracy not only between Λ and n, but also between μ and e. Finally, it is possible to assume that the reason for the splitting lies in the bare mass of the Λ hyperon, which

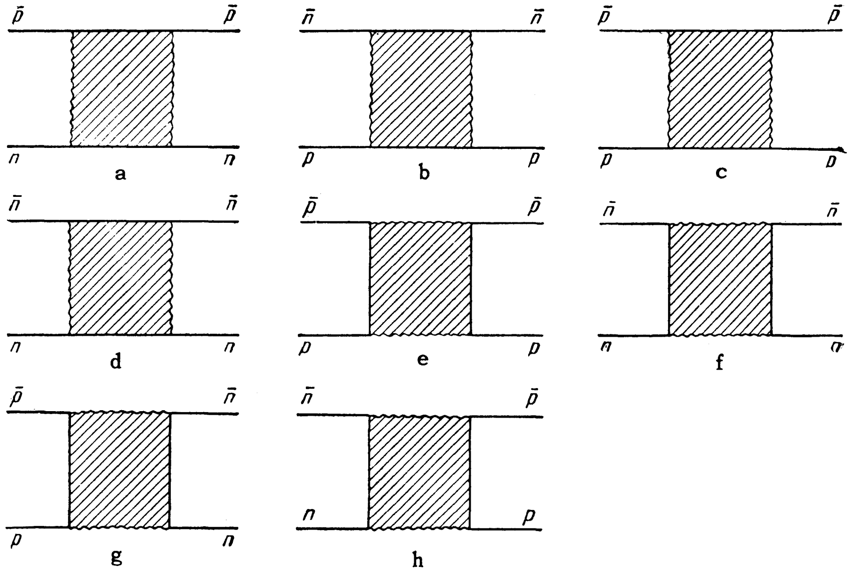


FIG. 1. a – $a(\bar{p}n)^2$, b – $a(\bar{n}p)^2$, c – $a(\bar{p}p)^2$, d – $a(\bar{n}n)^2$, e – $b(\bar{p}p)^2$, f – $b(\bar{n}n)^2$, g – $b(\bar{p}p)(\bar{n}n)$, h – $b(\bar{n}n)(\bar{p}p)$.

may be unequal to the bare masses of the proton and the neutron. The difference between the masses of the Λ hyperon and the nucleon will lead as a result of virtual processes to a difference in the strong interactions of these particles in spite of the fact that the "initial" strong interaction (2) is completely identical in the two cases. Thus, the bare mass of the Λ hyperon can be responsible for strangeness.

In order for strong interactions to be isotopically invariant within the framework of the scheme under consideration it is necessary and sufficient that the bare masses of the proton and the neutron should be equal, since it can be easily seen that the Lagrangian (1) is an isotopic scalar. Thus, the isotopic invariance of strong interactions with all its ramifications (the existence of isotopic multiplets, the relation between the interaction constants of the particles composing a given multiplet, the existence of selection rules with respect to isotopic spin, etc.) is a consequence of the symmetry of the current (2) with respect to the proton and the neutron and of the equality of the bare masses of these particles.

Apprehensions can arise that the Lagrangian (1) is too symmetric (since it contains only the neutral current) so that, for example, it will not yield a splitting between the π^0 meson and the π_0^0 meson (the hypothetical pseudoscalar meson of isotopic spin equal to zero). However, it can be easily seen that these apprehensions are unfounded. In order to do this we consider the diagrams representing the scattering of a nucleon by an antinucleon (Fig. 1) where the shaded regions denote virtual ρ mesons and closed nucleon loops. Since the ρ meson is an isotopic scalar, the contributions of diagrams a, b, c, d (Fig. 1) are all equal; we denote them by a. The contributions of diagrams e, f, g, h are also all equal; we denote them by b. The amplitudes for the different diagrams are shown in the caption for Fig. 1. We see that the $\bar{p}p$ and $\bar{n}n$ states are not diagonal; we introduce their linear combinations

$$\pi^0 = (\bar{p}p - \bar{n}n)/\sqrt{2}, \qquad \pi_0^0 = (\bar{p}p + \bar{n}n)/\sqrt{2}.$$

The sum of the amplitudes c–h can then be written in the form

$$a[(\bar{p}p)^2 + (\bar{n}n)^2] + b\,[\bar{p}p + \bar{n}n]^2 = a\,[\pi^0]^2 + (a + 2b)\,[\pi_0^0]^2.$$

We see that 1) a splitting of the π^0 and π_0^0 states has occurred, 2) the π^0 state has the same amplitude as the $\pi^- = (\bar{p}n)$ and $\pi^+ = (\bar{n}p)$ states described by diagrams a and b. (We note that in the first approximation of perturbation theory $b = 0$ for the pseudoscalar state of the nucleon + antinucleon system.)

The Lagrangian (1) also does not lead to any undesirable isotopic degeneracies in a system of two or several nucleons. This can be easily understood if we note that the isotopic variables in the nucleon system are essentially superfluous: they contain no new information since in virtue of Pauli's principle the isotopic state of a system of nucleons is completely determined by its orbital and spin states. As a result of the above discussion we think that the introduction in addition to the ρ^0 meson of three other vector mesons "corresponding to the existence of the isotopic group" [4] is superfluous.

CONSERVATION OF CURRENT

It can be easily seen that the current $j_{s\alpha}$ is a conserved quantity. This leads to a number of consequences. Firstly, the interaction (1) is renormalizable (cf., for example, [6]) in spite of the vector nature of the ρ^0 meson. Secondly, the $\Lambda\Lambda\rho$, $nn\rho$ and $pp\rho$ vertex parts renormalized taking virtual strong interactions into account are all equal to one another for $q^2 = 0$ where q is the vecton momentum. We shall from now on give the name vecton charges to such vertices for $q^2 = 0$.

This conclusion is completely obvious if we take into account the analogy between the vector current $j_{s\alpha}$ and the electromagnetic current.* The same analogy also enables us to conclude that the vecton charges of the compound baryons (Σ and Ξ) are also equal to the vecton charge of the nucleon and the Λ hyperon:

$$g_\Lambda = g_N = g_\Sigma = g_\Xi = g.$$

The vecton charges of all the antibaryons are equal to $-g$. The vecton charges of the K and π mesons must be equal to zero. The vecton charge of the nucleus must be equal to gA, where A is the number of nucleons in the nucleus.

POLE DIAGRAMS

Unfortunately, a rigorous physical interpretation can be given only to the vecton charge defined at the point $q^2 = \mu^2$ where μ is the vecton mass, and not at the point $q^2 = 0$ as has been done above. The magnitude of $g(q^2 = 0)$ could be obtained from experiment only provided the contribution of the pole diagram of the type of Fig. 2 would not be compensated by contributions of other diagrams. Strictly

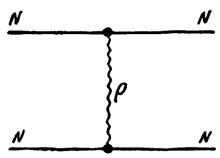


FIG. 2

speaking there are no reasons for the nonexistence of such compensation. On the other hand, we cannot prove that it must necessarily occur. Therefore, we shall draw attention to some properties of the pole diagram. It would be useful to determine whether these properties manifest themselves experimentally.

1) The cross section determined by the diagram of Fig. 2 does not decrease as the energy of the colliding nucleons increases (as was the case for the π-meson pole diagram), but tends to the constant limit

$$\sigma = 4\pi g^2/\mu^2.$$

2) The angular distribution of the nucleons has a maximum at 0°, with $d\sigma(0)\, d\Omega = 4g^2E^2/\mu^4$, where E is the energy of the nucleons in the center of mass system.

3) The scattering amplitude corresponding to the 0° angle determined by the diagram of Fig. 2 is purely real and increases linearly with E.

4) The diagram of Fig. 2 taken together with other diagrams (giving contributions to the imaginary part of the amplitude) leads to the existence of strong polarization in the scattering of high energy nucleons. Sakurai [4] has pointed out the possible role of this diagram in the explanation of the spin-orbit interaction.

We note that if the contribution of diagram 2 is not compensated then in the forward scattering of baryons the real part of the amplitude must be different from zero ($\mathrm{Re}\, f(0) \neq 0$), while there is no basis for this in the case of π and K mesons (their vecton charges are equal to zero). Moreover, in the case of baryons the real part must be negative: in the case of pp-scattering there must exist constructive interference with the Coulomb scattering. (At low energies, when the exchange of π mesons predominates, $\mathrm{Re}\, f > 0$, and the fact of the existence of nuclei is associated with this.) In the case of nuclei $\mathrm{Re}\, f(0°)$ must be proportional to A (in analogy to the fact that the amplitude of Coulomb scattering is proportional to Z). In order to observe this kind of coherent scattering of nucleons by nuclei we should separate out the small scattering angles when the momentum transferred to the nucleus is small compared to $m_\pi/A^{1/3}$ —the reciprocal nuclear dimensions. In the case of scattering by nuclei the possibility of compensation of the single meson diagram (Fig. 2) by other diagrams appears to be very probable due to the heavy absorption of the nucleon wave in the nucleus.*

We note that also in the case of scattering by a nucleon we can hope that there is no compensation only for low values of the transferred momentum. It is obvious that for large values of the transferred momentum the diagrams involving several virtual mesons will be significant. The experimentally observed angular distribution [15] falls off with angle much more rapidly than would follow from a single meson diagram.

*The problem of gauge invariance of the theory of heavy vector mesons interacting with a conserved current has been considered recently by V. Ogievetskii and I. Polubarinov (private communication).

*This remark is due to I. Ya. Pomeranchuk.

CONTRIBUTION TO THE ELECTROMAGNETIC FORM FACTOR OF THE NUCLEON

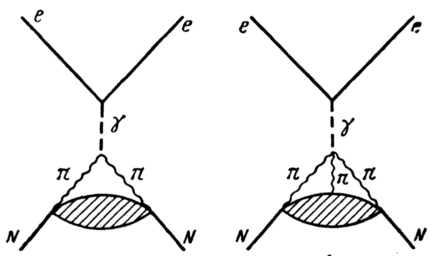
The vecton can make an essential contribution to the electromagnetic form factor of nucleons. The fact that the electric radius of the proton is $\sim \frac{1}{2}m_\pi$, while the electric radius of the neutron is nearly zero shows that the isovector and the isoscalar form factors of the nucleons are approximately equal (and compensate each other in the case of the neutron). This compensation seems strange since the isovector form factor might be expected to have a larger radius than the isoscalar form factor (the latter "begins" with three π mesons, while the former "begins" with two, cf. Fig. 3). Nambu[3] noted that the ρ meson, if it exists, should increase the radius of the isoscalar form factor and should make the compensation noted above more natural.

The contribution of the ρ meson to the electromagnetic form factor is described by a pole diagram (Fig. 4). This diagram corresponds to the amplitude

$$\alpha\,(q^2)\,\frac{q^2}{q^2-\mu^2},$$

where α is an unknown function of q^2; $\alpha(0) \neq 0$. (The factor q^2 in the numerator is determined by gauge invariance; for further details cf. [14].) Here, as before, we assume that the instability of the vecton does not appreciably affect the contribution of the pole diagram. If we assume that $\alpha(q^2)$ does not vary rapidly with increasing q^2, then for $q^2 \gg \mu^2$ the amplitude under consideration gives a contribution to the electric form factor of the nucleon which does not fall off with increasing q^2. Possibly this explains to some degree the appearance in the range $q \approx 0.7 - 0.9$ Bev of a plateau in the electric form factor of the proton recently discovered by Hofstadter's group.[16]

We note that from the fact that the isoscalar part of the anomalous magnetic moment of the nucleon is small it follows that the vecton pole diagram makes a small contribution to the anomalous magnetic moment of nucleons. Therefore,



a b

FIG. 3. a – isovector vertex, b – isoscalar vertex.

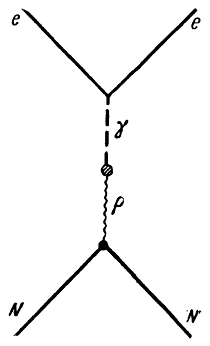


FIG. 4

generally speaking, the magnetic form factor should not have a plateau analogous to the electric form factor.

POSSIBILITIES OF EXPERIMENTAL DETECTION OF THE VECTON

The properties of the vecton should be significantly different, depending on whether its mass μ is greater than or less than $3m_\pi$. In the case when $\mu < 3m_\pi$ since the decay $\rho \rightarrow 2\pi$ is forbidden the ρ meson can decay only as a result of electromagnetic interactions with a lifetime of the order of

$$\sim 1/m_\pi e^2 \sim 10^{-20} - 10^{-21} \text{ sec.}$$

The principal decay is given by

$$\rho^0 \rightarrow \pi^0 + \gamma.$$

In this case the ρ^0 meson could be treated in the theory of strong interactions as an ordinary stable particle. But from the point of view of an experimenter, the ρ^0 meson would be as "good" a particle as the Σ^0 hyperon.

Unfortunately, this possibility is apparently contradicted by the presently available experimental data.

1. In the case when $\mu < m_K - m_\pi = 350$ Mev the decay

$$\begin{array}{l} K^+ \rightarrow \rho^0 + \pi^+ \\ \qquad\ \downarrow \\ \qquad\ \pi^0 + \gamma \end{array}$$

would be possible. The estimate made by Gomez et al[17] shows that data on the spectrum of the τ' decay exclude the possibility of the existence of the ρ^0 meson for $\mu < 320$ Mev.

2. The group at the California Institute of Technology[17] searched for the reaction

$$\gamma + p \rightarrow p + \rho^0.$$

The results of this experiment apparently exclude the possibility of the existence of a ρ^0 meson with a mass in the range $300 - 430$ Mev. Somewhat earlier a less accurate search for the same photoproduction reaction $\gamma + p \rightarrow p + \rho^0$ carried out with the accelerator at Frascatti[18] led to the conclusion that the cross section for this reaction is $\sigma < 6 \times 10^{-31}$ cm^2 for a meson of mass $\mu \lesssim 500$ Mev. A search for singularities in the scattering of π^- mesons by protons on the threshold of production of a ρ^0 meson led to a negative result in the mass range $\mu \lesssim 370$ Mev (Pontecorvo, private communication).

3. In the annihilation of antiprotons $\bar{p} + p$ in addition to other strongly interacting particles ρ mesons should be emitted decaying into $\pi^0 + \gamma$:

$$\rho \rightarrow \pi^0 + \gamma$$

in the case when $\mu < 3m_\pi$. Annihilation with the participation of a ρ meson should be favored by the fact that the corresponding statistical weight contains the factor $2I + 1 = 3$. In such a case the fraction of the annihilation energy available to the charged particles should turn out to be[19] less than $2/3$, while experimentally[20] in the annihilation of $\bar{p}$ in a hydrogen bubble chamber the energy of the charged $\pi^\pm$ mesons amounts to $(64 + 4)$ % of the total energy.

4. A direct search for the ρ meson of $\mu < 3m_\pi$ in the annihilation $\bar{p}+p$ has apparently yielded a negative result.[21]

In view of the interest in this problem it appears desirable that these results be checked further. In this connection it is of interest to measure directly the number and the spectrum of the hard protons arising in the annihilation of antinucleons. In the case $m_K - m_\pi < \mu < 3m_\pi$ (350 Mev $\lesssim \mu \lesssim$ 420 Mev) the decay $K^+ \rightarrow \rho^0 + \pi^+$ is not possible. However, in this case the following decay can occur

$$\begin{array}{l} K^+ \rightarrow \rho^0 + e^+ + \nu \\ \qquad\quad \downarrow \\ \qquad\quad \pi^0 + \gamma, \end{array}$$

and this would lead to an apparent softening of the spectrum of the K_{e3} decay. Therefore, a measurement of the spectrum of the K_{e3} decay can give an answer to the problem of the existence of the ρ^0 meson in this mass range.

In the case when the mass of the ρ meson is greater than $3m_\pi$ the ρ meson will decay into three π mesons with a nuclear lifetime:

$$\rho \rightarrow \pi^+ + \pi^- + \pi^0, \quad \tau_{\rho^0} \sim 10^{-23} \text{ sec.}$$

For low values of $Q = \mu - 3m_\pi$ the probability of the $\rho \rightarrow 3\pi$ decay falls off as Q^4. In this case the instability of the ρ meson should be taken into account in an essential manner in constructing a theory of strong interactions in accordance with the proposed scheme. Experimentally a ρ meson with such a lifetime should appear as a 3π resonance.

It can be easily seen that in this case μ cannot be significantly smaller than m_K for otherwise the following decay would occur

$$\begin{array}{l} K^+ \rightarrow \rho^0 + e^+ + \nu \\ \qquad\quad \downarrow \\ \qquad\quad \pi^+ + \pi^- + \pi^0. \end{array}$$

The probability of the decay $K^+ \rightarrow e^+ + \nu + \rho$ is equal to

$$w = (G^2\beta^2/40\pi^3M^4)\,Q^5, \tag{3}$$

where M is the nucleon mass, G is the coupling constant for the weak interaction, $Q = m_K - \mu$ and β is an unknown numerical coefficient. Since decay of strange particles is usually suppressed, it is sensible to take $\beta^2 \approx 0.1 - 0.01$.

The decay $K^+ \rightarrow \rho^0 + e^+ + \nu$, $\rho^0 \rightarrow \pi^+ + \pi^- + \pi^0$ would have the appearance of an anomalous τ decay. On taking into account the fact that among 2000 observed τ decays such decays were not observed we obtain for w the upper limit $w < 2.5 \times 10^3$ sec^{-1}. Comparing with (3) we obtain for $\beta^2 = 0.1$ the value $Q \leq 40$ Mev or $\mu \gtrsim 450$ Mev.

At the present time no experimental data are known which would contradict the possibility of the existence of a ρ meson with $\mu \gtrsim m_K$ with the fundamental decay

$$\rho \rightarrow 3\pi.$$

Such a meson should appear in the reactions of annihilation and of multiple production. The most direct answer to the problem of the existence of such a ρ meson would be given by a measurement of the recoil spectrum in the reactions*

$$p + d \rightarrow He^3 + \rho^0 \quad (a), \qquad d + d \rightarrow He^4 + \rho^0 \quad (b),$$

$$\pi^+ + d \rightarrow p + p + \rho^0 \quad (c), \qquad K^- + p \rightarrow \Lambda^0 + \rho^0 \quad (d).$$

In the reactions (a), (b), (c) the recoil momentum of He^3, He^4, p+p can be measured directly. In the reaction (d) the momentum of the Λ particle is equal to the total momentum of the decay products. If the ρ^0 meson exists, then in the recoil spectrum a peak should be observed corresponding to the production of the ρ^0 meson against the background of the spectrum of the various possible many-particle reactions. The cross section for the production of the ρ^0 meson in (a), (b), (c), (d) must be of nuclear order of magnitude. We note that the reaction (a) gives such a maximum corresponding to $\mu = 310 \pm 10$ Mev (experiments of the Berkeley group[22]). However, such a mass apparently contradicts the nonexistence of the de-

*The reaction (c) was proposed by N. G. Birger.

cay $K^+ \to \rho^0 + \pi^+$ (cf. above). A further investigation of the reaction (a) is necessary and, in particular, a check of whether an analogous maximum exists in the reaction

$$p + d \to H^3 + \rho^+.$$

If such a maximum exists, then the corresponding meson has an isotopic spin equal to unity, and has no relation whatsoever to the isosinglet particle considered by us. V. Baĭer (private communication) has drawn our attention to the fact that the existence of a ρ^0 meson would lead to a resonance in the scattering of electrons by positrons in the process $e^+ + e^- \to \mu^+ + \mu^-$ at an energy of $e^+ + e^-$ in their center-of-mass system equal to the mass of the ρ^0 meson. This resonance is determined by the diagram shown in Fig. 5.

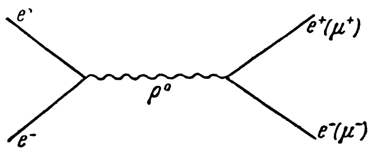


FIG. 5

The authors are grateful to V. Baĭer, N. G. Birger, V. I. Gol'danskii, Ya. B. Zel'dovich, V. Kolkunov, I. Ya. Pomeranchuk, B. M. Pontecorvo, and K. A. Ter-Martirosyan for a number of valuable comments.

[1] G. Wentzel, Einführung in die Quantentheorie der Wellenfelder, Edwards Bros., 1946.

[2] W. Pauli, Meson Theory of Nuclear Forces, Interscience, N.Y., 1946.

[3] Y. Nambu, Phys. Rev. **106**, 1366 (1957).

[4] J. J. Sakurai, Ann. Phys. **11**, 1 (1960); Phys. Rev. **119**, 1789 (1960); Nuovo cimento **16**, 388 (1960).

[5] G. Breit, Phys. Rev. **120**, 287 (1960).

[6] Y. Fujii, Progr. Theoret. Phys. (Kyoto) **21**, 232 (1959).

[7] S. Sakata, Progr. Theoret. Phys. (Kyoto) **16**, 686 (1956).

[8] L. B. Okun', JETP **34**, 469 (1958), Soviet Phys. JETP **7**, 322 (1958); Report at the Venice-Padua Conference, 1957.

[9] L. B. Okun', Proc. VIII Geneva Conv., 1958, p. 223.

[10] M. Gell-Mann, Proc. X Rochester Conf. 1960, p. 508.

[11] R. F. Feynman, Proc. X Rochester Conf. 1960, p. 501.

[12] Y. Ohnuki, Proc. X Rochester Conf. 1960, p. 843.

[13] I. Ya. Kobzarev and L. B. Okun', JETP (in press).

[14] Kobzarev, Okun', and Pomeranchuk, JETP **41**, 495 (1961), this issue p. 355.

[15] Cork, Wenzel, and Causey, Phys. Rev. **107**, 859 (1957).

[16] Bumiller, Croissiaux, and Hofstadter, Phys. Rev. Letters **5**, 263 (1960).

[17] Gomez, Burkhard, Daybell, Ruderman, Sands, and Talman, Phys. Rev. Letters **5**, 170 (1960).

[18] Bernardini, Querozoli, Salvini, Silverman, and Stoppini, Nuovo cimento **14**, 268 (1959).

[19] V. I. Gol'danskii and V. M. Maksimenko, JETP **39**, 841 (1960), Soviet Phys. JETP **12**, 584 (1961).

[20] Horwitz, Muller, Murray, and Tripp, Phys. Rev. **115**, 472 (1959).

[21] F. Solmitz, Proc. X Rochester Conf. 1960, p. 164.

[22] Abashian, Booth, and Crow, Phys. Rev. Letters **5**, 258 (1960).

Translated by G. Volkoff
92