SOME REMARKS ON A COMPOUND MODEL OF ELEMENTARY PARTICLES

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An examination is made of some properties of a compound model of elementary particles, in which Λ particles and nucleons are assumed as the primary particles.

1. INTRODUCTION

THE number of strongly interacting elementary particles is very large: already known at the present time are seven kinds of mesons, eight kinds of baryons (including Ξ^0), and eight kinds of antibaryons; two of these last ($\bar{p}$ and $\bar{n}$) have already been found, and scarcely anyone doubts that the others will be found in the very near future. This very abundance of strongly interacting particles makes one doubt their elementary nature. It is therefore quite natural that many papers have recently appeared in which attempts are made to reduce somehow the number of "elementary" particles by regarding them as compound systems constructed from a small number of "truly elementary" particles. The first step in this direction was made by Fermi and Yang,[1] who suggested that the π meson may be a bound state of a nucleon and an antinucleon. The compound models of the elementary particles that are being discussed at the present time can be divided into two groups.

The first group incldues schemes in which the basic particles are taken to be K mesons and nucleons (KN scheme), K mesons and Ξ hyperons ($K\Xi$ scheme), or K mesons and Λ hyperons ($K\Lambda$ scheme). The KN scheme has been considered by Goldhaber,[2] Gyorgyi (D'erdi),[3] and Zel'dovich,[4] and the $K\Xi$ scheme has been discussed by Neganov.[5]

In our opinion these schemes have a number of shortcomings. In the first place, the construction of compound baryons and π mesons (if the latter are not also assumed to be elementary particles) requires two different types of forces: baryon-boson forces are used for the construction of the compound baryons, and baryon-antibaryon forces for the construction of π mesons. Secondly, the KN, $K\Lambda$, and $K\Xi$ schemes postulate the existence of two types of weak interactions: lepton-fermion, of type $(np)(e\nu)$, and letpon-boson, of type $K(\mu\nu)$, since other wise one cannot explain all the various letpon decays of mesons and baryons. Thirdly, to explain the existence of the decays $K_{\mu 3}$ and K_{e3} in these schemes one must either introduce one more additional weak interaction with the leptons, or else introduce a strong interaction $gKK\pi$, which is possible only if there is a parity doublet of K mesons (in this connection see Ref. 6). All this to a considerable extent deprives the KN, $K\Xi$, and $K\Lambda$ schemes of the economy which is the main motive for their construction.

The other group of schemes is essentially a generalization of the Fermi-Yang model. In Markov's model[7] all the hyperons were included along with nucleons as primary particles (NY scheme). In Sakata's model,[8] considered subsequently by King and Peaslee,[9] nucleons and Λ particles are taken as the elementary particles ($N\Lambda$ scheme).

In this paper we make a number of remarks about the $N\Lambda$ scheme, which obviously makes it possible to describe in a unified way both the structure and also the interactions of the various particles. Following Sakata we shall assume three particles to be the primary ones: the Λ hyperon, the proton, and the neutron. These primary particles have the same parity, spin, charge, and strangeness as the actual physical Λ, p, and n, but, generally speaking, the masses of the physical and primary particles can be different. In particular, we can assume that for the primary particles $m_\Lambda = m_N$. The values of the charge Q, the strangeness S, the isotopic spin T, the isotopic spin component T_3, the spin I, the parity P,* and the baryon number $\mathfrak{N}$ for the primary particles and antiparticles are shown below (a

*Since the weak interactions do not conserve parity and strong interactions conserve strangeness, the parity of the Λ particle, and also of other particles with $S = \pm 1$, is not a physically observable quantity. Therefore the choice of the parity of the Λ particle which we have made is purely conventional. As a physically observable quantity one has, for example, the product of the parities of Λ particle, K meson, and nucleon, $P_\Lambda P_K P_N$ (see below).

bar over a letter denotes the antiparticle).

	Q	S	T	T_3	I	P	$\mathfrak{N}$
p	+1	0	1/2	+1/2	1/2	+1	+1
$\bar{p}$	−1	0	1/2	−1/2	1/2	−1	−1
n	0	0	1/2	−1/2	1/2	+1	+1
$\bar{n}$	0	0	1/2	+1/2	1/2	−1	−1
Λ	0	−1	0	0	1/2	+1*	+1
$\bar{\Lambda}$	0	+1	0	0	1/2	−1*	−1

2. THE ISOTOPIC SCHEME

The isotopic scheme set forth in this section essentially repeats the contents of the paper of Sakata.[8]

The Mesons. The mesons are bound states of the primary particles and antiparticles with $\mathfrak{N} = 0$. Thus the π meson, having $T = 1$, is a bound state of a nucleon and an antinucleon:

$$T_3 = +1,\ \pi^+ = \bar{p}n; \quad T_3 = -1,$$
$$\pi^- = p\bar{n};\ T_3 = 0,\ \pi^0 = (p\bar{p} + n\bar{n})/\sqrt{2},$$

The K and $\bar{K}$ mesons, having $T = \frac{1}{2}$, are the bound states $N + \bar{\Lambda}$ and $\bar{N} + \Lambda$, respectively:

$$K^+ = p\bar{\Lambda},\quad T_3 = {}^1\!/_2;\quad K^0 = n\bar{\Lambda},\quad T_3 = -{}^1\!/_2;$$
$$K^- = \bar{p}\Lambda,\quad T_3 = -{}^1\!/_2;\quad \bar{K}^0 = \bar{n}\Lambda,\quad T_3 = {}^1\!/_2.$$

Thus the strangeness of the K meson is $S = +1$, and for the $\bar{K}$ meson $S = -1$.

In the framework of this scheme there is the possibility of two additional neutral mesons, which have not so far been observed:

$$\rho_1^0 = \Lambda\bar{\Lambda},\quad \rho_2^0 = (p\bar{p} - n\bar{n})/\sqrt{2}.$$

The isotopic spin of the ρ mesons is zero. Their other properties are considered briefly in Sec. 3.

The Hyperons. In the present scheme the hyperons are bound states of two particles and one antiparticle with $\mathfrak{N} = 1$.

Thus the Σ particle with $T = 1$ can be represented in the form

$$\Sigma^+ = \bar{p}n\Lambda,\quad T_3 = +1;\quad \Sigma^- = \bar{p}n\Lambda,\quad T_3 = -1;$$
$$\Sigma^0 = (p\bar{p}\Lambda + n\bar{n}\Lambda)/\sqrt{2},\quad T_3 = 0.$$

In an equally natural way one gets the isotopic doublet of the cascade particle:

$$\Xi^- = \Lambda\Lambda\bar{p},\ T_3 = -{}^1\!/_2;\quad \Xi^0 = \Lambda\Lambda\bar{n},\quad T_3 = +{}^1\!/_2.$$

The isotopic multiplets of the antihyperons are obtained from the hyperon multiplets by the interchange $\Lambda \longleftrightarrow \bar{\Lambda}$, $n \longleftrightarrow \bar{n}$, $p \longleftrightarrow \bar{p}$.

3. SPIN AND PARITY

The data on the spins and parities of the Λ particle, the proton, and the neutron are shown in the table.

It is well known that the π meson has spin $I = 0$ and parity $P = -1$. This means that the primary nucleon and antinucleon forming the π meson are in a $^1S_0$ state. It is natural to assume that the particles forming the K meson are also in a $^1S_0$ state. Then we find that, like the π meson, the K meson has $I = 0$ and $P = -1$. The entire body of experimental data relating to the weak interactions of K mesons (decays), and also to the strong interactions, indicates that the spin of the K meson is zero. As regards the parity of the K meson, it is as yet unknown. In our present model $P_K P_N P_\Lambda = -1$. In the KN scheme, in the form considered by Zel'dovich,[4] for example, $P_K P_N P_\Lambda = +1$. In this connection the measurement of the quantity $P_K P_N P_\Lambda$ is of great importance as a test of the correctness of our present scheme.

Assuming that the particles forming the ρ^0 meson are also in a $^1S_0$ state, we find that in this case $I = 0$, $P = -1$. The masses of ρ^0 mesons must obviously be considerably larger than those of π mesons, since otherwise a number of effects would occur which could not have remained unobserved. In particular, the existence of ρ^0 mesons would manifest itself in the phase-shift analysis of the scattering of π mesons by nucleons, since in addition to the process $\pi^- + p \to \pi^0 + n$ the process $\pi^- + p \to \rho^0 + n$ would also occur. Another example of a possible manifestation of the ρ^0 meson is the decay of the K meson. For example, besides the decay $K^+ \to \pi^+ + \pi^0$ there would have to occur the decay $K^+ \to \pi^+ + \rho^0$. We note that for this decay one does not have the forbidden character arising from the selection rule $\Delta T = \frac{1}{2}$, which decreases the probability of the decay $K^+ \to \pi^+ + \pi^0$ by a factor of several hundred. This is readily understood if we note that for the system $\pi^+ + \pi^0$ with $I = 0$ the state with $T = 1$ is forbidden, while for the system $\pi^+ + \rho^0$ it is allowed.

It is possible that the presence of a maximum at $E = 900$ Mev in the scattering of π^- mesons is due to the ρ^0 meson. In this case the mass of the ρ^0 meson must be of the order of the nucleonic mass. Such a ρ^0 meson should decay into three π mesons (the decay into two π mesons is forbidden by parity) in a time of the order of 10^{-23} sec.

If we make no additional assumptions, nothing can be said about the spins and parities of the Σ and Ξ particles within the framework of our present model.

4. THE STRONG INTERACTIONS

The interactions leading to the formation of bound baryon-antibaryon systems must be stronger than ordinary nuclear forces by several orders of magnitude. It is known that the depth of the potential well in nuclei is on the order of 30 Mev. The estimate made by Fermi and Yang[1] of the depth of the "well" containing the nucleon and antinucleon forming a π meson gave a value on the order of 30 Bev (on the assumption that the radius of the well is $r \sim \hbar/M_N c$). The presence of such a strong interaction between nucleons and antinucleons is confirmed by the measurements recently made of the interaction cross-sections between antinucleons and nucleons. Fermi and Yang assumed further that also between two nucleons, in addition to the usual interaction, there is a strong interaction comparable in magnitude and range with that between nucleon and antinucleon, but that this nucleon-nucleon interaction is a repulsive one.

As a generalization of the idea of Fermi and Yang it is natural to postulate that there is a strong interaction between any two baryons, attractive in the case of particle interacting with antiparticle, and repulsive in the case of two particles or two antiparticles. In our present model there are three types of vertex parts, corresponding to:

(a) the interaction of nucleon with nucleon (interaction constant g_1);

(b) the interaction of a nucleon with a Λ particle (constant g_2);

(c) the interaction of two Λ particles (constant g_3) (see Fig. 1).

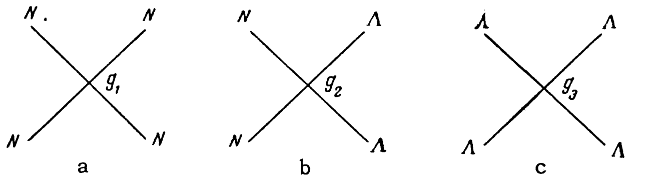

FIG. 1

The interaction characterized by the constant g_1 is responsible for the formation of a bound state of a nucleon and an antinucleon — the π meson. This same interaction is responsible for the production of nucleon-antinucleon pairs, the production of π mesons, and so on. The processes caused by the interaction g_1 are well described by a statistical theory.

The interaction characterized by the constant g_2 is responsible for the formation of a bound state of a nucleon and an antihyperon — the K meson. This same interaction is responsible for the production of hyperon-antihyperon pairs, the production of K mesons, and so on. Indeed, any process in which strange particles appear from collisions of ordinary particles must include at least one vertex of the type g_2, corresponding to the production of a pair $\Lambda + \bar{\Lambda}$. The fact that the mass of the K meson is considerably larger than π meson masses suggests that the interaction g_2 is weaker than the interaction g_1. The same thing is indicated by numerous experiments such as those reported at the 1957 Rochester conference, according to which the cross-sections for the production of K mesons by the action of γ rays, π mesons, and nucleons are about an order of magnitude smaller than the corresponding π-meson cross-sections and the cross-sections obtained on the basis of statistical calculations.

If we proceed on the assumption that $g_2 < g_1$, it must be expected that the cross-section for the production of a real hyperon-antihyperon pair in a beam of π mesons or nucleons must be smaller by about an order of magnitude than the cross-section for the production of a nucleon-antinucleon pair, if we consider both processes sufficiently far from their thresholds. On the other hand, the cross-section for the production of an antihyperon-nucleon pair in collisions of K^+ mesons with nucleons may not turn out to be small, since in this case there will occur a reaction analogous to the disintegration of the deuteron and not involving the relatively weak interaction g_2:

$$K^+ + p = (\bar{\Lambda} + p) + p \xrightarrow{g_1} \bar{\Lambda} + p + p.$$

The same also applies to the cross-section for scattering of $K^\pm$ mesons, which, as is well known, is not small. This process can go through the vertex g_1 alone. Another cross-section which turns out not to be small is that for absorption of K^- mesons (reactions of the type $K^- + p \rightarrow \Sigma^- + \pi^+$), which can also go through the strong interaction g_1 alone.

Thus in our present scheme the smallness of the cross-section for production of strange particles does not necessarily bring with it smallness of the cross-sections for their scattering and their conversion into other strange particles, since basically different interactions are responsible for these processes. This conclusion is in qualitative agreement with a large body of experimental data, according to which strange particles have small cross-sections for production, but large cross-sections for absorption and scattering.

We note that this peculiarity of strange particles does not find its reflection in the model recently proposed by Gell-Mann.[10] According to this model all interactions of baryons with π mesons are equally strong, and the interaction of baryons with K mesons is relatively weak. The conclusions obtained from this are directly contradictory to those at which we arrived above. In particular, according to Gell-Mann's model the cross-sections for scattering of $K^{\pm}$ mesons and that for absorption of K^- mesons must be small. The cross-section for production of a hyperon-antihyperon pair in a beam of π mesons or nucleons must be larger than the cross-section for production of a nucleon-antihyperon pair in a beam of K mesons.

At the present time one cannot draw any conclusions about the strength of the interaction of two Λ particles at small distances (about the quantity g_3). If $g_3 \sim g_1$, then the ratio of the probability of production of four strange particles to that for production of two strange particles must be determined by just the statistical weights. If $g_3 \sim g_2$, it must be an order of magnitude smaller than this. These considerations are also entirely applicable to the production of a cascade particle: if $g_3 \sim g_1$, the production of a Ξ particle in collisions of nucleons must have a probability comparable with that for the production of the other hyperons (Λ and Σ). If, on the other hand, $g_3 \sim g_2$, the probability for Ξ production must be smaller than that for production of Λ or Σ by about an order of magnitude.

5. THE WEAK INTERACTIONS

Two types of decays of baryons and mesons are known: lepton decays and non-lepton decays, the latter being characteristic of strange particles only. A feature that these two types of decay have in common is that the interactions causing them have coupling constants of the same order of magnitude ($F^2 \sim f^2 \sim 10^{-13}$ in units $\hbar = c = \mu_\pi = 1$) and do not conserve spatial and charge-conservation parity. We shall consider first the non-lepton decays, assuming the simplest type of weak interaction between the "primary" particles.

Non-lepton Decays. Examples of these are such as $K \rightarrow 2\pi$, $K \rightarrow 3\pi$, $\Lambda \rightarrow N + \pi$, $\Sigma \rightarrow N + \pi$, $\Xi \rightarrow \Lambda + \pi$, the decays of hyperfragments, and so on. Any one of the non-lepton decays known at present can be described as a process in which one of the links in the slow transition $\Lambda \longleftrightarrow N$ and all of the other links are fast transitions that conserve strangeness. The simplest assumption would seem to be that the $\Lambda \longleftrightarrow N$ transition is a single-particle process, i.e., can be described by the diagram of Fig. 2. But, as can easily be seen, such

FIG. 2

an interaction would lead* to the strict (apart from electromagnetic corrections) selection rule $\Delta T = \frac{1}{2}$ for all non-lepton decays of strange particles (and hyperfragments). Since cases occur in which the rule $\Delta T = \frac{1}{2}$ is known to be violated, we are forced to resort to a more complicated class of slow interactions — two-particle interactions described by the diagrams of Fig. 3.†

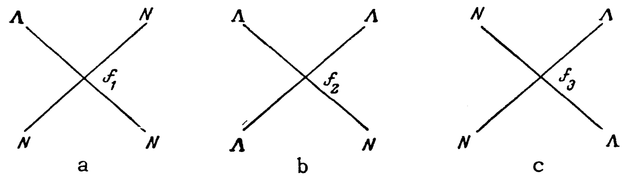

FIG. 3

The interactions described by the constant f_3 (transition of two nucleons into two Λ particles) has not been observed so far. If f_3 were to turn out to be comparable with f_1 and f_2, processes with $\Delta S = \pm 2$ would have probabilities comparable with those of processes with $\Delta S = \pm 1$, to which the first two diagrams of Fig. 3 correspond. In particular, the decay $\Xi^- \rightarrow n + \pi^-$ would have to occur, and the mass difference of the K_1^0 and K_2^0 mesons would be of the order $\Delta m \sim f_3 \mu_\pi \sim 10 - 100$ ev, where f_3 is the dimensionless constant of the weak interaction ($f_3 \sim 10^{-6} - 10^{-7}$) and μ_π is the mass of the π meson. (If $f_3 = 0$ the mass difference of K_1^0 and K_2^0 is $\Delta m \sim f_1^2 \times \mu_\pi \sim f_2^2 \mu_\pi \sim 10^{-5}$ ev). We shall not go further into the discussion of this question, since it has been dealt with in detail in a paper by Pontecorvo and the writer.[11] As for the vertices f_1 and f_2, it is easy to see that for them $\Delta S = \pm 1$; for f_1, $\Delta T = 1/2, 3/2$, and for f_2, $\Delta T = 1/2$. If the rule $\Delta T = 1/2$ holds approximately, this means that $f_1 \ll f_2$. None of the vertices of Fig. 3 gives transitions with $\Delta T = 5/2$, so that such transitions are forbidden. Recently Gell-Mann[12] called attention to the fact that the experimental ratio of the probabilities for the decays $K^0 \rightarrow 2\pi^0$ and $K^0 \rightarrow \pi^+ + \pi^-$ indicates that transitions with $\Delta T = 5/2$ occur. If the experimental data in question are correct, this means that in the framework of our present scheme

*An essential assumption in this proof is that all strong interactions are isotopically invariant.

†We do not distinguish in the diagrams between particles and antiparticles. The vertex f_3 (Fig. 3) differs from the vertex g_2 (Fig. 1) by the fact that for the former $\Delta S = 2$, while for the latter $\Delta S = 0$.

it becomes necessary to introduce three-particle weak interactions of the type shown in Fig. 4, since they alone can give $\Delta T = 5/2$. It seems undesirable to resort to such three-particle weak interactions, and therefore if the presence in the weak interactions of an amplitude with $\Delta T = 5/2$ were proved this would, in our opinion, be a strong argument against the scheme discussed here.

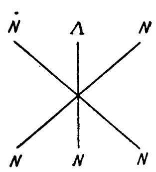

FIG. 4

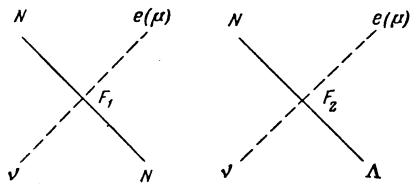

FIG. 5

Lepton Decays. Examples of lepton decays of ordinary particles are the decays $\pi \to \mu + \nu$ and $n \to p + e + \nu$; examples of lepton decays of strange particles are the decays $K \to \mu + \nu$, $K \to \mu + \nu + \pi$, and $K \to e + \nu + \pi$. Lepton decays of hyperons have so far not been observed. In the $N\Lambda$ scheme two types of interactions of the primary baryons with leptons are possible (see Fig. 5). The interaction F_1 causes lepton processes in which π mesons and nucleons are involved. The interaction F_2 causes lepton processes involving K mesons and hyperons. Moreover, it is easy to see that decays

$$\Lambda \to p + e^- (\mu^-) + \bar{\nu},$$

should occur, which have not been observed so far, and that decays of Λ to $e^+ (\mu^+)$ are forbidden, since there is no negative primary baryon. Similarly there should be decays

$$\bar{\Lambda} \to \bar{p} + e^+ (\mu^+) + \nu$$

and decays of $\bar{\Lambda}$ to $e^- (\mu^-)$ are forbidden. Since in our present scheme all lepton decays in which the strangeness of strongly interacting particles changes have to go by way of the lepton decay F_2 of the Λ ($\bar{\Lambda}$) particle, it follows that in decays with $\Delta S = -1$ and $e^+ (\mu^+)$ must appear.

The result is that the decays $K^0 \to e^+ (\mu^+) + \nu + \pi^-$ and $\bar{K}^0 \to e^- (\mu^-) + \bar{\nu} + \pi^+$ turn out to be allowed, and the decays $K^0 \to e^- (\mu^-) + \bar{\nu} + \pi^+$ and $\bar{K}^0 \to e^+ (\mu^+) + \nu + \pi^-$ are forbidden. As is shown in Ref. 6, this leads to a quite definite time dependence of the ratio of the numbers of $e^+ (\mu^+)$ and $e^- (\mu^-)$ decays in a beam of neutral K mesons, namely:

$$\frac{n_{e^+}}{n_{e^-}} = \frac{n_{\mu^+}}{n_{\mu^-}} = \frac{e^{-t/\tau_1} + e^{-t/\tau_2} + 2e^{-t/2\tau_1 - t/2\tau_2} \cos(\Delta m t)}{e^{-t/\tau_1} + e^{-t/\tau_2} - 2e^{-t/2\tau_1 - t/2\tau_2} \cos(\Delta m t)}.$$

Here n is the number of the decays in question per unit time and τ_1 and τ_2 are the lifetimes of the K_1^0 and K_2^0 mesons, the former of which has time (combined) parity +1 and the latter, −1. (We assume that the time parity is conserved in the slow decays.) Δm is the difference of the masses of the K_1^0 and K_2^0 mesons.

Another example is that of the decays $\Sigma^+ \to n + e^+ (\mu^+) + \nu$; according to the above statements, these decays are forbidden, while the decays $\Sigma^- \to n + e^- (\mu^-) + \bar{\nu}$ are allowed. Similarly, the decays $\Xi^0 \to \Sigma^- + e^+ (\mu^+) + \nu$ are forbidden, and the decays $\Xi^0 \to \Sigma^+ + e^- (\mu^-) + \bar{\nu}$ are allowed. We note that the decays $\Sigma^+ \to \Lambda + e^+ + \nu$ and $\Sigma^- \to \Lambda + e^- + \bar{\nu}$, which go through the vertex F_1, are allowed in our present scheme.

Since all lepton decays with change of strangeness go by way of the decay of Λ ($\bar{\Lambda}$), it is easy to see that for these decays the rule $\Delta S = \pm 1$ must hold, where S is the strangeness of the strongly interacting particles. From this it follows that the decays

$$\Xi^- \to n + e^- (\mu^-) + \bar{\nu} \text{ and } \Xi^0 \to p + e^- (\mu^-) + \bar{\nu}$$

must be forbidden, while the decays $\Xi^- \to \Lambda + e^- (\mu^-) + \bar{\nu}$ are allowed.

Since in the transition $\Lambda \to p + e^- (\mu^-) + \bar{\nu}$ the isotopic spin of the strongly interacting particles changes by $\Delta T = \frac{1}{2}$, it follows that in all lepton decays of strange particles the isotopic spin of the strongly interacting particles changes by $\Delta T = \frac{1}{2}$.* This makes it possible to obtain a relation between the probabilities of the decays

$$K^+ \to e^+ (\mu^+) + \nu + \pi^0 \text{ and } K^0 \to e^+ (\mu^+) + \nu + \pi^-.$$

Here it turns out that[6]

$$w(K^0) = 2w(K^+).$$

All these conclusions are obtained if we assume that the interactions of strange particles with leptons are represented by the diagram F_2. If we admit the possibility of the existence of more complicated interactions (see, for example, Fig. 6), the rules of forbiddenness and the ratios obtained above disappear. But the consideration of such interactions seems to us extremely artificial.

6. CONCLUSIONS

It can be seen from the above that the $N\Lambda$ scheme makes it possible to give a more or less satisfactory qualitative description of the existing

*In decays of particles with $S = 0$ (π mesons and nucleons), $\Delta T = 0.1$.

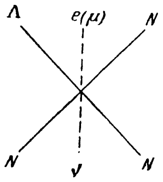

FIG. 6

experimental data and to make a number of predictions which can be tested experimentally. These predictions relate to both the strong and the weak interactions of strange particles. It must be emphasized, however, that many of these conclusions, in particular those relating to the strong interactions, are of an extremely qualitative nature and cannot be considered completely convincing.

As for experimental tests of the NΛ model, it is quite obvious that the experimental confirmation of any particular conclusions among those drawn above cannot by any measure serve as a demonstration of the correctness of the NΛ model, since one could have arrived at these very same conclusions on the basis of an entirely different physical picture (cf. in this connection Ref. 6). A disagreement between the conclusions drawn above and experiment will mean that the assumptions which we have made within the framework of the model, and which appear extremely plausible, are incorrect.

In conclusion we remark that the model that has been considered may take on considerably greater interest if the study of the possibility of constructing a theory of strongly interacting Fermi fields[5] has a successful outcome.

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