NUCLEAR FORCES AND THE THEORY OF THE MESON

Uspekhi Fiz Nauk, No 2, 1947 V. L. Ginzburg

Introduction

The meson theory comprehends all problems concerning, on the one hand, the path of the meson as observed in cosmic rays, and on the other hand, the meson theory of nuclear forces. Both of these divisions of the theory are far from finished and are still being worked out, in spite of great difficulties. It is therefore natural that a final statement cannot be made on this subject; our purpose is merely to elucidate its present state. (This article was written in Sept 1946).

At present the name meson or mesotron is given not only to the very heavy particles observed in cosmic rays, but also to the num~~b~~erous hypothetical particles whose masses lie between the masses of the proton and the electron. We shall use the term "meson" to specify when necessary what sort of particle (hypothetical or observed) is under discussion.

Mesons were discovered in cosmic rays in 1937 /1/; the hard components of cosmic rays at sea level or low altitudes are basically composed of just these particles. Moreover, at sea level the meson hard component amounts to about 70% of all the particles in cosmic radiation. Under laboratory conditions, as far as is known, meso~~tron~~s have not yet been obtained. The study of ~~the~~ properties ~~of~~ meso~~tron~~s in cosmic rays is rendered difficult by many circumstances, the first of which is that any large quantity of soft particles is lacking in them. Consequently, in spite of intensive experimental work, a whole series of basic characteristics has not yet been established for the meso~~tron~~. Moreover, it is even impossible to affirm that only one sort of very heavy particle can be observed in cosmic rays or to say whether there are very heavy particles with a single value of the ~~rest~~ mass. The magnitude ~~size~~ of the charge and, ~~so~~ a fortiori, ~~much the more~~ the value of the spin of the meso~~tron~~ cannot be considered as definitely ~~reliably~~ established by experiment.

Nevertheless, without taking into consideration the reliability of the data on hand, we can make the following assertions ~~statements~~:

1. There are meso~~tron~~s with both positive and negative charges. The value ~~size~~ of the charge, evidently, equals $\pm e$, where e is the charge of the ~~an~~ electron. In any case the charge of the meso~~tron~~ does not equal $\pm 2e$ and so forth; ~~it may be assumed,~~ however, ~~that~~ the charge of the meson ~~mesotron is~~ may be assumed to be close to $\pm e$, but apart from this value, we have no starting point.

2. The mass of the meso~~tron~~ is approximately 200 electron masses; that is, $m = 200\ m_0$, where m_0 is the mass of the electron. The most frequent values of m lie between 150 m_0 and 250 m_0. Hence, in any case the overwhelming number of very heavy particles of cosmic rays at sea level have a mass close to 200 m_0; the hypothesis that the majority of particles have only one value for the mass does not seem contrary to experiment.

3. The meso~~tron~~ decays ~~decomposes~~ spontaneously, and the lifetime ~~span~~ in the system of coordinates associated ~~connected~~ with it equals ~~[illegible]~~

(p. 175)

$\tau_0 \cong 2 \cdot 10^{-6}$ second. An electron (or positron) flies out during meson decay. The neutrino, fastest of all, is the second particle to fly off. But this is not proven and it is impossible altogether to exclude the possibility of the decay of the meson into an electron and photon. If decay proceeds with the escape of an electron and a neutrino, the spin of the meson equals zero or one, since the spins of the electron and neutrino equal one half and a full spin must be conserved during decay. It is more probable that the value of the spin equals zero (See § 1). If the meson decays with the escape of an electron and a photon, the spin of the meson equals one half. (The spin is expressed in $\hbar$ units; i. e., if we say that the spin equals $\frac{1}{2}$ or 1, we mean that it is equal to $\frac{1}{2}\hbar$ or $\hbar$).

Of basic importance in the study of meson properties is the quantitative comparison of experimental data with theoretical results from assumptions as to the properties of the meson. Thus, for example, in order to form an opinion as to the meson spin, the great ionization pulses observed in experiment ~~was~~ were compared with the pulses calculated on the hypothesis that the meson spin equals $\frac{1}{2}$ or 1. /2/

To calculate the various effects dependent on the interaction of mesons with matter, it is necessary to know the original properties of a meson

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(mass, spin), and the nature of its interaction with the electromagnetic field (photons), light weight particles (electrons and neutrinos), and heavy nuclear particles (protons and neutrons). At present no definite assertions can be made on either of these problems of the theory. But if the examination be limited to particles with definite values of spin and rest mass, the number of equations and expressions for the energy of interaction possible from the viewpoint of the requirements of relativistic invariance will prove to be relatively small. (This statement about spin and rest mass means that variants of the theory permitting change in the spin and mass of particles (see [3]) are not examined. The theory of particles with variable properties is relatively complicated and indefinite. Consequently the limitation at the start in all cases is perfectly natural.) Moreover, at least in the beginning, it is natural to limit the examination to particles with a spin not exceeding unity. The reason for this assumption is that the theory of particles with a spin greater than 1 appears to be very complicated and the value of a spin less than or equal to 1 is clearly differentiated not only by its simplicity, but also by certain essential peculiarities [4]. Above, in speaking of the spin of mesons, we took this circumstance into consideration by assuming [redacted] $\frac{1}{2}$ spin for a neutrino and meson spin not greater than unity (if, for instance, the spin of a neutrino equals 3/2, which is possible in principle, the decay of the meson into an electron and neutrino would be compatible with the hypothesis that the spin of a meson equals 2; similarly, the decay

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of a meso~~tron~~ into an electron and photon is compatible with the assumption ~~statment~~ that meson ~~the~~ spin ~~of the mesotron~~ equals 3/2).

On the basis of the above statements, the theory of the meso~~tron~~ and nuclear forces deals almost exclusively with particles of ~~with~~ spins 0, $\frac{1}{2}$ or 1.

The interaction of meso~~trons~~ with the electromagnetic field is the simplest. This interaction is determined in the first place by the presence of an electric charge in the electron. The electromagnetic interaction of ~~the~~ mesons ~~electrons~~, leading to the formation of (delta) -electrons and "retardation" ~~brake~~ radiation, is essential in determining the spin of the mes~~tr~~on and will be discussed in § 1.

The most ~~im~~ complicated and at the same time ~~most~~ important problem is the interaction of meso~~trons~~ with nuclear particles as well as with electrons and neutrinos. ~~The disintegration of the~~ meso~~tron~~ decay (if into electrons and neutrinos) and nuclear disintegration are ~~the~~ processes dependent upon these interactions and essential to cosmic rays. (see [5] for discussion). Furthermore, inasmuch as meso~~trons~~ are unstable, they cannot come from ~~universal~~ outer space but must be generated mainly in the upper layers of the atmosphere; however, the formation of meso~~trons~~ by primary cosmic particles, which are probably always protons, obviously is not of an electromagnetic nature but depends on nuclear interaction.

The importance of the problem of the interaction of ~~meso-trons~~ mesons with nuclear particles, however, is connected not only with cosmic ray processes but also, to a great extent, with the problem of nuclear forces. As we know, in 1934 after the presentation of Fermi's theory of beta-decay ~~disintegration~~ , [redacted] Tamm developed the theory of nuclear forces relating ~~which connected~~ the appearance of these forces with the fact that heavy particles (protons and neutrons) were interchanged with light-weight particles (electrons, positrons and neutrinos). In this exchange the proton, for instance, gives off a positron, with ~~and~~ the neutrino being converted into a neutron; then the neutron, absorbing the light weight particles, turns into a proton and so on. As a result of a similar interchange of charges, the proton and neutron , now at a certain distance apart ~~one from the other~~, experience ~~undergo an interchange of~~ strong interactions ~~in strength~~.

The situation here is similar to the interaction of two moving electrons, for example, which depends on photon interchange. In the electromagnetic case it is possible to proceed from the idea of waves instead of (from the idea) ~~that~~ of an exchange of photons; from this standpoint each electron creates around itself a field which acts upon another electron. Similar wave concepts are used for nuclear forces. Thus it may be said that a neutron creates around itself an electron- neutrino ~~neutrinic~~ field acting on a proton , etc.

In a quantitative relation the theory of ~~electronic~~ electron-neutrino ~~neutrinic~~ nuclear forces (or so-called beta-forces) seems ~~seemed~~ inadequate since, because of the weakness of beta-interaction, the forces prove less than necessary by ~~for~~ a factor of the order of 10^{10}—10^{12} (see [7]).

To obviate ~~evade~~ the difficulties in the theory of beta-forces, in 1935 Yukawa formed a hypothesis about the existence of a special field of nuclear forces. During ~~In~~ quantization, this field is associated ~~connected~~ with certain particles analogous to protons, which appear when the electromagnetic field in quantized. In the absence of photons the new particles, which we

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shall now call meso~~trons~~ns, may, generally carry a ~~specifically be~~ charged and, in addition, their rest mass will not equal zero. It is easy to show (see § 2) that the mass m of the particles is directly related to ~~connected with~~ the radius r_0 of ~~the~~ action of the forces dependent on the exchange of these particles, as follows:

$$r_0 \approx \frac{1}{k} = \frac{\hbar}{mc}. \qquad (1)$$ [p177]

It is known from experimental data that the radius of action of nuclear forces is of the order $r_0 \approx 2\cdot 10^{-13}$ cm and hence, in accordance with (1), $m \approx 200\ m_0$. The mass of the new particles thus appears to be of exactly the same order as the mass of a cosmic ray meso~~tron~~n. It is therefore understandable that after the discovery of very hard particles in ~~the~~ cosmic rays, the meso~~tron~~n theory received a powerful stimulus towards further development.

According to this theory, these forces depend on the exchange of protons and neutrons with meso~~trons~~ns. Thus ~~Herein~~, if the spin of the meso~~tron~~n ~~is integral and~~ equals 0 or 1, the exchange can be affected ~~carried out~~ by one meso~~tron~~n, since the spin of a proton (neutron) during conversion to a neutron (proton) may change to 0 or 1. (But in the beta-force theory the exchange takes place through two particles, each with a spin ~~force~~ $\frac{1}{2}$.) The assumption that the spin of a meso~~tron~~n is an integer is, therefore, simpler and was accepted by Yukawa. ~~Yukawa.~~ To include in his own theory ~~the~~ beta-decay ~~disintegration~~, Yukawa ~~Yukawa~~ assumed that ~~the~~ meso~~trons~~ns could decay ~~be disintegrated~~ into electrons and neutrinos. Further, inasmuch as there are both ~~electronic~~ beta-negative (electron) and beta-positive (positron)

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disintegrations, mesons are assumed to have charges of both signs. Both these assumptions are in agreement with the properties of mesons as observed in cosmic rays. This fact gives additional corroboration to the whole concept of the connection of nuclear forces with mesons.

However, the effort to construct a quantitative theory which would agree with all of the experimental data has not as yet been successful and has met with serious difficulties. In this connection there is no complete theory of nuclear forces and, properly speaking, a relation between mesons observed in cosmic rays and nuclear forces cannot be considered definitely established. Nevertheless, the combination of qualitative considerations mentioned above and the almost certain presence of the nuclear reaction of mesons in cosmic ray showers afford no serious occasion to doubt the interrelation of the whole group of problems in regard to mesons and nuclear forces.

The meson theory of nuclear forces will be taken up in more detail in § 2.

§ 1. Wave Equations for Mesons.

Interaction with Electromagnetic Fields

The form of equations which must be satisfied by the wave function ψ of a meson is determined by the value to be assumed by the spin of this particle. Therefore, the equations must be relativistic invariants and consequently the wave function becomes a spinor of some rank or other (or in the general case, it becomes a combination of spinors). The number

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of independent components of the wave function ~~psi~~ must obviously be related to the number of possible projections of the spin in any direction--it is this that suggests the idea of describing particles by the aid of multicomponent functions. To a considerable extent what has been said above defines the character of the wave function and the corresponding wave equation.

If the meson spin equals zero, the wave function [redacted] has but one component and is thus either a scalar or a pseudoscalar. This, as we know, is equivalent to a completely antisymmetric tensor of the fourth rank φ_{iklm} with only one independent component, for example, the component φ_{1234}. (A magnitude behaving like a tensor for all transformations of coordinates reduced to rotations is called a pseudotensor. When the sign of any space coordinate changes, the sign of the components of the tensor and the sign of the components of the pseudotensor may undergo different changes. For example, a pseudotensor of zero rank, (that is, a pseudoscalar) has only one component, the sign of which differs in the right and left systems of coordinates. A completely antisymmetrical tensor of the fourth rank φ_{iklm} with only one independent component $\varphi_{1234} = \varphi_{2314} = -\varphi_{2341} = -\varphi_{2134}$ ... has the same properties.)

(p 178, bottom)

(footnote p178 →)

The wave equation for a particle of zero spin is:

(2)

[p. 179] (top)

If the wave function is pseudoscalar, it is necessary to substitute φ_{iklm} for φ in equation (2).

Equation (2) like other wave equations discussed below is the equation of some field--in the present case, the field of the scalar φ. The relation between the classic field and the combination of particles corresponding to it is established by quantizing this field; in quantizing, the field Ψ (in case (2) the field of the scalar φ) is considered an operator. We shall not linger here on the quantum theory of wave fields (see [9] and [10]) but limit ourselves to the simplest method, mentioned above, of relating the mass of the particles with the magnitude [redacted] κ appearing in equation (2).

A horizontal wave, the solution of equation (2), takes the form:

[p. 179] (3)

Moreover, in accordance with the basic assumption of quantum mechanics, namely, de Broglie's relation between the momentum of a particle $p = \hbar k$ and the square of the energy, we have:

p 179 → $$E^2 = m^2c^4 + p^2 = (\quad)^2.$$

From this and from (3) it follows that equation (2) describes particles with a rest mass m determined by the equation

[p. 179] (4)

One of the important results of the quantum theory of the field is the deduction that particles of integral spin described by ordinary tensors must conform to Bose-Einstein statistics; particles of half spin, described by spinors of odd rank, must satisfy Fermi-Dirac's statistics [11, 9].

The well-known difference between the cases where the wave function ψ is a scalar and a pseudoscalar appears if equation (2) be replaced by a system of equations of the first order. For a scalar we shall have:

/p. 179/ (5)

where, hereafter, $i = 1,2,3,4$; summation takes place, according to the usual rules of tensor analysis, when indices are the same.

In the pseudoscalar case

/p. 180/ (top) (6)

Systems (5) and (6) are equivalent to equation (2) for φ or φ_{iklm}, as may readily be shown by eliminating from (5) or (6) the corresponding χ_i or χ_{klm}. The difference between scalar and pseudoscalar mesons with the same spin, equaling zero, and the same mass (if the constants η in (5) and (6) are equal, appears only on examining their interaction with particles of half spin (see § 2). With respect to interaction with the electromagnetic field, both systems (scalar and pseudoscalar) are absolutely equivalent. Hence, in this paragraph we shall simply speak about the meson (particle) of zero spin.

A particle of spin 1 must be described by a wave function with three independent components, as the projection of the spin in this case must take the values 0 and $\pm$ 1. Next to the scalar, the simplest tensor wave function--a four-dimensional vector--has four components. Nevertheless, a particle of spin 1 is described by the vector wave function φ_i which satisfies the equation:

/p. 180/ (7)

This equation has four solutions, not three, one of which deals with a particle ~~with a~~ of spin ~~of~~ zero. To ~~shut out~~ eliminate this superfluous solution it is necessary also to ~~apply to~~ assume the following equation :

(180)

$$\frac{\partial \phi_i}{\partial x_i} = 0 \tag{8}$$

The system of equations (7) and (8) describes a particle ~~with~~ of spin 1 and a mass determined ~~in accordance with~~ by (4).

In many cases, instead of equations (7) and (8) it is convenient to use ~~the~~ an equivalent system of the first order:

(180)

$$\frac{\partial \phi_k}{\partial x_i} - \frac{\partial \phi_i}{\partial x_k} = g_{ik} \qquad \frac{\partial g_{ik}}{\partial x_k} = -\kappa^2 \phi_i \tag{9}$$

A particle ~~with a~~ of spin 1 may also be described by a pseudovector, not a vector, wave function or, ~~which~~ what is equivalent, by the wave function φ_{ikl}, where $\varphi_{ikl} = -\varphi_{kil} = -\varphi_{ilk}$. In this case, instead of (9), we shall have:

(180 bottom)

$$\frac{\partial \phi_{ikl}}{\partial x_l} = g_{ik} \qquad \frac{\partial g_{kl}}{\partial x_i} + \frac{\partial g}{\partial x} + \frac{\partial g}{\partial x} = \kappa^2 \phi_{ikl} \tag{10}$$

The difference between the vector and pseudovector variants of the theory is essential only in examining the interaction ~~with~~ between particles ~~with a~~ of half spin (protons, neutrons, electrons and neutrinos). Hence in this section, unless otherwise specified, the wave function of a particle ~~with a~~ of spin 1 is considered a vector wave function.

Particles ~~with a~~ of spin $\frac{1}{2}$ ~~conform to~~ satisfy the well-known equation of Dirac:

(181)

$$\gamma_k \frac{\partial \psi}{\partial x_k} + \kappa \psi = 0 \tag{11}$$

where γ_k ~~denotes tetraserial~~ are 4th order matrices, Ψ is a ~~bispinor~~ (bispinor) of ~~with~~ four components and where, as before, the ~~relation~~ ratio $\kappa = \frac{mc}{\hbar}$ holds ~~good~~ true (for details see, for instance, [12]).

NOTE $\hbar$

The equation for ~~spin~~ particles ~~with a~~ of spin greater than unity [4] and ~~with a~~ of variable spin [3] can also be written. But ~~theory~~ observation of the ~~ir~~ interaction of these particles with the ~~outer~~ external field or other particles appears to be frought with the well-known difficulties [4, 13] and little studied. Hence we shall not concern ourselves with this question here.

The interaction of particles ~~with~~ of spins of 0, $\frac{1}{2}$ and 1 with an electromagnetic field described by the vector potential A_k is introduced by ~~substituting~~ replacing in equations (2), (5), (6), (9), (10) and (11) [18]

$$\frac{\partial}{\partial x_k} \text{ by } \Pi_k = \frac{\partial}{\partial x_k} - \frac{ie}{\hbar c} A_k \qquad (12)$$

where e is the charge ~~attributed~~ assigned to the particle.

It is clearly possible to substitute (12), especially because the variance of $\frac{\partial}{\partial x_k}$ and A_k is identical; hence, after such a substitution the equations remain relativistically invariant. It should be noted that in its application to the system of equations, the substitution of (12) must be carried out with precaution so that the system may not become contradictory. This might happen, for instance, if (12) were substituted in the system of equations (7) – (8) but not in (9).

Interaction with the electromagnetic field by substituting (12) and also interaction with other fields (particles) are automatically introduced in employing the the variation principle, on which we shall not linger (see, for example, [9, 10])

the Transition to a ~~the~~ non-relativistic approximation or to an equation of the second order shows that particles of ~~with of~~ spins ~~of~~ $\frac{1}{2}$ and 1, whose ~~the~~ interaction ~~of which~~ with the field is determined only by the charge (substitution of (12)), behave as if they ~~/~~ also have ~~had~~ a magnetic moment equal to Bohr's integral magneton [10, 1?]

(p. 181 bottom)

$$\mu_0 = \frac{e\hbar}{2mc} \qquad (13)$$

Thus, under the above conditions the ratio ~~relation~~ of the magnetic moment to the ~~spin moment of an amount of movement~~ angular-momentum spin equals $\frac{e}{mc}$ for particles of ~~with a~~ spin ~~of~~ $\frac{1}{2}$ and equals $\frac{e}{2mc}$ for particles of ~~with a~~ spin ~~of~~ 1.

But apart from "interaction with a charge" in the case of spins ~~of~~ $\frac{1}{2}$ and 1, it is also possible to introduce interaction with a "true" magnetic moment μ_1. For example, in the case of Dirac's equation in the presence of such a moment and also of a charge e ~~also~~, the equation of motion assumes ~~acquires~~ the form: [18]

$$\left(\gamma_k \frac{\partial}{\partial x_k} - \frac{ie}{\hbar c}\gamma A + \frac{\mu_1}{\hbar c}\frac{\gamma_i \gamma_l}{2} F_{il} + \kappa\right)\psi = 0 \qquad (14)$$

where $F_{kl} = \frac{dA_l}{dx_k} - \frac{dA_k}{dx_l}$ is the tensor of ~~the intensity of the~~ electromagnetic field strength.

In a non-relativistic approximation the magnetic moment of a particle described by equation (14) equals (see 16):

[182]
$$\left.\begin{aligned}\mu_0 + \mu_1 &= \gamma\mu_0 \\ \gamma &= \left(1+\frac{\mu_1}{\mu_0}\right)\end{aligned}\right\} \qquad (15)$$

The introduction of an ~~the~~ analogous term in equation (14) containing F_{kl} is possible also in the case of equation (9) for a spin of 1; the total ~~whole~~ moment in this case can also be put in the form of (15).

Finally, in both (14) and (15) it is possible to introduce a term containing F_{kl} and derivatives of ~~the~~ the wave functions. Here, however, the well-known complications arise.

In a non-relativistic approximation all the above equations are converted into an equation of the Pauli type:

[182]
$$i\hbar\frac{\partial\psi}{\partial t} = \left\{\frac{1}{2m}\left[-i\hbar\nabla - \frac{e}{c}A\right]^2 + e\phi - \gamma\mu_0(sH)\right\}\psi \qquad (16)$$

where A and ϕ are three-dimensional vector and scalar potentials; H is the ~~intensity of the~~ magnetic field strength and s is the spin operator. For particles of ~~with a~~ zero spin $\gamma = 0$. For an electron, when the constant μ_1 in (14) equals zero, the spin term takes the well-known form $\mu_0(\sigma H)$, where σ denotes ~~the~~ Pauli's two-row ~~serial~~ matrices and ψ is a function of ~~with~~ two components (Pauli's equation for a particle of ~~with a~~ spin ~~of~~ 1; see, for instance, [14]). The difference between particles of ~~with~~ spins ~~of~~ 0, ½ and 1 appears only in the form of the last term of (16); disregarding this term, we obviously obtain the Schrödinger ~~or~~ ordinary equation.

The simplest problem in which interaction is taken into account is the motion ~~movement~~ of a particle in a given field; the Coulomb field $\left(e\phi = -\frac{e^2Z}{r}\right)$ is the most interesting. The solution of this type of problem, based on the use of (16) forms the basic content of non-relativistic, quantum mechanics.

The relativistic theory of the hydrogen atom is based on solving ~~the solution of~~ the problem of ~~the movement of an~~ electron motion, which satisfies ~~conforming to~~ (equation) (14): $\mu_1 = 0$, ~~and~~ $A = 0$ and $e\varphi = -iA_4 = \frac{e^2 Z}{r}$ (p. 183, top) (see [12]). The agreement of ~~the~~ theory with experiment which occurs in this case is the ~~a~~ basic argument for the application of Dirac's equation, with $\mu_1 = 0$, to the electron. The problem of the motion ~~movement~~ of a particle of ~~with a~~ zero spin in a Coulomb field [12] is likewise solved. In both these cases the proper functions (eigenfunctions) of the problem form a complete orthogonal system and satisfy the obvious general requirements (they provide for the obvious finiteness of energy, etc). In the case of particles of ~~with a~~ spin 1 with $\gamma = 1$ and $\gamma \neq 1$ and also particles of ~~with a~~ spin $\frac{1}{2}$ with $\gamma \neq 1$ (that is, with $\mu_1 \neq 0$), on the contrary, the problem of motion ~~the movement~~ in a Coulomb field has no solution [15, 16], in the sense that the admissible solutions do not form a complete system of functions, but ~~They do, however,~~ yield ~~provide~~ solutions corresponding to the fall of a particle upon a central ~~on a~~ force of attraction ~~center~~. The cause ~~principle~~ of the fall is that for a spin $\frac{1}{2}$ when $\gamma \neq 1$ and for ~~in~~ the case of spin 1 when $\gamma = 1$ ~~also~~, the particle has a magnetic moment even in a relativistic approximation*.

*) Dirac's electron, for which μ_1 in (14) equals zero, in a non-relativistic approximation has a magnetic moment $\frac{e\hbar}{2mc}$; but in a highly relativistic approximation the electron behaves like a particle without a magnetic moment [13, 14, 15, 73].

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The energy of interaction of this moment with a field possessing a central Coulomb force takes the form:

(p. 183)

(17)

In a field of the type, (17), both in the classic and the quantum theory, the motion is limited; that is, the fall of the particle takes place towards the center (for more detail see § 2). The presence of a moment in a particle leads to difficulties also in studying various radiational processes (light scattering, "retardation", radiation, etc.). The problem of the difficulties met in the theory will be discussed in more detail in § 3.

Let us now spend a few moments on the results of calculating the effective cross sections for various electromagnetic processes, carried out for particles of various spins and values of γ (summary of the results borrowed chiefly from Pauli's outline [10]. (Some cross sections are compared also in the article by Rossi and Greisen.)

All cross sections are calculated in the first non-vanishing approximation according to the theory of perturbations.

Table 1 gives the effective cross sections for the scattering of mesons by a fixed Coulomb force center; Table 2, for the scattering by an electron (δ -formation).

The spin is expressed throughout in units of $\hbar$, and the magnetic moment in units of $\mu_0 = \frac{e\hbar}{2mc}$.

Table 1

~~Diffusion~~ Scattering of Meso~~tron~~ns by a Coulomb force Center ← (Title)

E and m are the initial energy and mass of the meso~~tron~~n; θ is the angle of ~~diffusion~~ scattering; $\eta = \frac{E}{mc^2}$ (the energy E includes the potential energy); $d\Omega$ is a solid angle; $r_0 = \frac{e^2}{mc^2}$.

	Spin	Magnetic Moment (Value of γ)	Cross Section for ~~Diffusion~~ Scattering	Reference to Bibliography
I				
II				
III				
IV				
V				

[see p 184]

In both tables the cross sections for ~~cases~~ III and IV are of a higher order relative to the value $\eta = \frac{E}{mc^2}$ than for ~~cases~~ I and II. For ~~case~~ V the cross section is of an even higher ~~in~~ order. Here we notice the previously ~~noted~~ mentioned role of the magnetic moment, actively affecting the dependence of ~~the~~ cross-section ~~on the~~ upon energy. ~~makes its appearance.~~ The ~~cases~~ sections cited for ~~cases~~ III, IV and V ~~at~~ for high energies are shown to be wrong [22, 23]. This is already manifest from Table 1 because the problem of the ~~movement~~ motion of a meso[redacted]n in a Coulomb field (for cases III, IV and V), strictly speaking, has no solution and, therefore, the results obtained by the method of ~~the theory of disturbance~~ perturbations ~~are lacking~~ are in need of ~~of~~ special research ~~for a complete clarification of~~ to clarify completely their [redacted] areas of application. Cross sections for ~~cases~~ I and II are entirely possible in every case and there is no good reason to doubt their ~~justice~~ correctness.

Table 2

Elastic ~~Diffusion~~ Scattering of Meso[redacted]ns ~~in~~ by an Electron (Title)

εE ~~denotes~~ is the energy given off by an electron. Terms of the order of $\frac{m}{m_0}\frac{mc^2}{\varepsilon E}$ and less are discarded (m_0 is the mass of an electron). $E \geqslant mc^2$. For other notations see Table 1. ~~Table 1~~

[185]

	Spin	Magnetic Moment (Value of γ)	Cross Section ~~at~~ for one ~~"boundaryless"~~ collision (in a system of coordinates where the electron is at rest at the ~~beginning~~ origin)	Reference to Bibliography
I				
II				
III				
IV			[p 185]	
V				

Table 3 gives the differential and ~~full~~ complete cross sections for the scattering of light by a meson. The values appearing in the table for the initial and final energies of a photon are related to the well-known expression

(page 185)

$$k = k_0 \frac{1}{1 + \frac{k_0}{mc^2}(1 - \cos\theta)}$$

The effective cross sections for "retardation" radiation and the production of meson pairs from photons are given in Tables 4 and 5. In it the nucleus is considered finite and of radius

(p-185)

$$R = \frac{5}{6} Z^{1/3} \frac{\hbar}{mc} .$$

The formulae in [29] for case II are shown with the change corresponding to this hypothesis.

The cross sections shown in Tables 3, 4, and 5 for cases I and II occasion no doubts as to the energies being as high as desired. On the contrary, for cases III and IV (Case V was not studied) cross sections were obtained with an inadmissible increase in energies. They were therefore correct only for energies not too high (see [21, 22, 23, 33] and § 3). For instance, in the case of light scattering (Compton effect) cross-sections III and IV of Table 3 held good only if

[p. 186]

or

(18)

We cite the corresponding cross-sections mainly to serve as a guide and to illustrate at a glance the effect of spin and magnetic moment on various processes.

Table 3

[p. 187] Scattering of Light by Mesons

It is assumed that the scattering meson is at first at rest. k_o and k are the initial and final energies of a photon. For other notations see Table 1.

	Spin	Magnetic Moment (Value of γ)	Cross Section of scattering for angle θ. Holds good for all energies(except case III)	Complete cross section of scattering provided that $k_o \gg mc^2$	Reference to Bibliography
I					
II					
III			[p. 186]		
IV					

Experimental research on the processes carried out by a cosmic ray meson may make it possible, in principle, to determine its spin. Up to the present the only effect which has been successfully used for this purpose is the formation of great ionization pulses under considerable thicknesses of lead and iron. If the ionization effect is assumed to be

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determined by the electromagnetic "retardation" radiation of mesons (the formation of -electrons seems unimportant), corresponding calculations can be made and compared with experiments [2, 34]. Moreover, calculations are found in agreement with experiments if the spin of the meson is assumed to equal 0 or $\frac{1}{2}$ ($\gamma = 1$). It is as yet impossible to distinguish between 0 and $\frac{1}{2}$ spins since the accuracy of the experiments and the theoretical computations ~~are~~ is insufficient and does not exceed 100%. It is also impossible completely to exclude the possibility that the spin of a meson equals 1 (or $\frac{1}{2}$ with $\gamma \neq 1$). The fact is that in calculations it is necessary to make use of effective cross sections for "retardation" radiation in the high energy field, where it is not strictly applicable; furthermore, at a certain energy it is actually necessary to reduce this cross section. Under such conditions, the exclusion of spin value 1 may be conclusive only if the effective cross section employed is the smallest possible for this spin and also if excluding spin 1 leads to the formation of a considerably larger number of pulses than experimentally observed. According to many authors [2, 33], this is just what has taken place. But in my opinion [35], the cross section used [2, 33] is not the minimum one, since it is based on the use of the formula for a Compton effect up to an energy of $\hbar\gamma \approx \frac{mc^2}{\alpha}$, which is contrary to condition (18). Hence, the above-mentioned comparison of theory with experiment, properly indicates only that there is no particular basis for the hypothesis of unity meson spin from the viewpoint of experiments in cosmic ray studies.

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Furthermore, if the spin of a meson is equal after all to unity, then the calculations based on the perturbation theory are inapplicable in the case of energies less than those generally assumed [2, 34]. Finally, it is possible to reach the conclusion that "retardation" radiation and other processes dependent on nuclear, not electromagnetic, forces do not have a great part to play, since already the minimum possible electromagnetic "retardation" radiation of a particle of zero spin permits an explanation of the observed ionization effects.

Table 4

"Retardation" Radiation of Mesons

Initial energy of a meson $E \gg mc^2$; εE is the energy of an emitted photon; Z is the atomic number of the substance; $A = \frac{12(1-\varepsilon)}{5mc^2\varepsilon Z^{1/3}}$, $\alpha = \frac{e^2}{\hbar c}$,

[p. 187]

	Spin	Magnetic Moment (Value of g)	Cross Section (in the system of coordinated where the nucleus is at rest)	Reference to Bibliography
I				
II				
III				
IV				

Table 5

[188] Production ~~Origin~~ of Mesotron Pairs From Photons

E is the energy of a photon ($E \gg mc^2$); εE is the energy of a positive mesotron; Z is the atomic number of the substance; $B = \frac{12\varepsilon(1-\varepsilon)}{5mc^2 Z^{1/3}} E$.

	Spin	Magnetic Moment (Value of γ)	Cross Section (in ~~the~~ a system of coordinates where the nucleus is at rest)	Reference to Bibliography
I				
II				
III				
IV				

§ 2. Nuclear Forces

Special nuclear forces act between the nuclear particles (protons and neutrons); in the nucleus these forces not only compensate for the electrostatic repulsion between protons but also serve to stabilize the nucleus. The scattering ~~diffusion~~ of neutrons by ~~on~~ protons and the difference in the observable scattering ~~diffusion~~ of protons by protons from the scattering ~~that~~ to be expected in the presence of only ~~one~~ Coulomb interaction are explained by the action of nuclear forces. These forces have a very short range ~~period~~ of action, ~~during which~~ their radius of action ~~is~~ being of the order of $r_0 \approx 10^{-13}$ cm. At short distances (order of r_0) the energy of interaction, corresponding to the nuclear forces is very great and amounts to ~~reaches~~ MeV. Furthermore, nuclear forces depend on the reciprocal orientation of the spin of nuclear particles and have the property of saturation. This means that the energy connected with a large number A of nuclear particles increases in proportion to A, not to A^2 as happens, for instance, in the case of Coulomb interaction in a system of charges. For this reason, the volume of the nucleus is approximately proportional to A, in contrast to the atom, whose dimensions are but slightly dependent upon Z.

The problem of the theory of nuclear forces obviously amounts to explaining the above-mentioned qualitative properties of these forces and to establishing the relation between the various nuclear dimensions measured experimentally. For quantitative proof of the theory, data may be used which refer to protons, neutrons, and deuterons (calculation of the heavier nuclei, because of its extreme complexity, is not interesting from this standpoint). The following points are known by experiment: the energy associated with a deuteron equals 2.18 meV [36]; the quadripole moment of the deuteron $Q = +2.7 \cdot 10^{-27}$ cm^2 (see, for example [37]); the constants characterising proton-neutron and proton-proton scatterings (see [38, 39]). Taken in a broader sense, the theory of nuclear forces also includes problems referring to separate protons and neutrons and their interaction with other particles. In this experimental field, values are known for the magnetic moment of a proton [40] and a neutron [41], respectively equaling $\mu_p = 2.789\mu_o$ and $\mu_N = -1.93\mu_o$, where $\mu_o = \frac{e\hbar}{2Mc}$ is the nuclear magneton and M is the mass of a proton. (The negative sign of a magnetic moment signifies that this moment is in a direction contrary to that of the spin; that is, to proper mechanical moment of the neutron.) In addition, we know the

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constants of beta-decay in various nuclei, which permit one on the basis of certain hypotheses (see, for example, [7]) approximately to ascertain the lifetime of a free neutron, which must finally be converted into a proton plus an electron plus a neutrino. To this set of problems must be referred the interaction of nuclear particles with mesons (scattering, pair-production) and of mesons with light particles (decay of mesons).

Inasmuch as nuclear forces also act between uncharged neutrons, it is generally considered obvious that these forces are absolutely separate from electromagnetic forces. Such a viewpoint is not necessarily true, since it is conceivable that nuclear forces are explained by the specific properties of the motion of particles of spin 1 in an electric field [42]. However, the existence of non-electromagnetic reactions, evidenced by the very fact of beta-decay and many other considerations, forces us to think that nuclear forces cannot be reduced to electromagnetic forces and that they are explained by the meson theory, as indicated in the introduction.

The classic form of the meson theory is especially simple and graphic. It utilizes the concept of a non-quantized meson field. Moreover, the detailed classic scheme has not only an illustrative, but a completely real importance, since in a static approximation, where the state of nuclear particles is assumed to be unchanged, the results of the classic and the quantum theories coincide [37, 43]. The situation here is the same as in electrodynamics where the Coulomb interaction - $\frac{e^2 Z}{r}$ (upper case Z)

(pick up next page)

can (either) be taken ~~either~~ from the classic theory, as is usually done, or (can be) obtained as a result of examining (photon) exchanges ~~by photons~~. [44]. The use of ~~a~~ static interaction is justified when non-static reaction is disregarded. ~~in that case, generally speaking,~~ This is generally admissible ~~on~~ in the deuteron theory (inasmuch as the velocities of the proton and the neutron in the the deuteron are small ~~as~~ in comparison ~~compared~~ with the velocity of light). Of course, for a more complete and exact study of the problem of nuclear forces, it is necessary to utilize the theory of a quantized meson field; but this refers to ~~the~~ calculations of meson ~~diffusion~~ scattering by ~~in~~ nuclear particles, etc.

Our intention in what follows is merely to explain ~~the~~ special moments of the theory and to discuss ~~its~~ results. So we shall only go into detail on the classical theory mentioned (quantizing the meson field ~~as~~ applied to the theory of nuclear forces, see [9, 45, 46]).

In classical terminology, the explanation of nuclear forces is connected with the fact that protons and neutrons are the sources of certain fields (meson fields), which, acting on other nuclear particles, and thus provide an interaction of forces. If the field is scalar, then in the absence of sources it conforms ~~is subject~~ to equation (2). The presence of forces means that on the right side of the equation there must be a function which plays the part of the density of a charge or current in electrodynamics. In this latter case, for a point particle the current density equals $e\delta(r - r_0)$, where δ is the delta-function ($\int \delta dr = 1$ and $\delta = 0$ when $r \neq r_0$) and r_0 is the position of the charge.

p 190 (bottom)

In the static case which interests us, equation (2) is converted into $\Delta\varphi - \chi^2\varphi = 0$ and the density of the "meson charge" equals $g\delta(r - r_0)$, where r_0 is the position of the nuclear particle. Hence the equation for the field takes the form:

[p. 191] (19)

Since the position of a nuclear particle is considered fixed, it is clear that it is considered sufficiently heavy and hence capable of classical description. Let us note that in the quantum theory we have for the general case of a non-static scalar field:

[p. 191] (20)

where φ ~~phi~~ must be regarded as an operator and where β ~~beta~~ is a Dirac matrix. The emergence of β ~~beta~~ is connected with the fact that we consider nuclear particles to be in conformity with Dirac's equation. (Let us note that on the right side of equation (20) one more term is omitted which contains derivatives of δ ~~delta~~-functions and is proportional to a constant factor independent of g.)

The solution of equation (19) is as follows:

[p. 191] (21)

Utilizing the expression for the energy of the field, we can demonstrate [9] that two nuclear particles creating a field φ and situated at a distance r, are attracted and that their energy equals (22). (The scalar field φ in a static approximation is similar to Newton's field of gravitation, to which formal transition is made by setting χ equal to zero. Hence it is clear that also in the scalar theory of nuclear forces particles are attracted (see remark below on the assumption that a scalar field is not charged.)) ~~and that their energy equals~~

footnote * p 191

[p. 191] (22)

The radius of the forces, as is clear from (22), is of the order $\frac{1}{\chi}$. Since in the quantum theory $\chi = \frac{mc}{\hbar}$ (see § 1), we thus obtain a relation (1) between the radius of the forces and the mass of the meson. It should be noted that we did not draw any distinctions between protons and neutrons. This can be done only if the field φ is not charged, and, consequently, the particles associated with it are not charged (neutral mesons or neutrettos). This subject will be taken up later.

The interaction of (22) does not depend on the reciprocal orientation of the spins of nuclear particles; this is contrary to the result of experiment. In order to clarify the problem of nuclear forces' dependence upon spin, let us examine the interaction of protons and neutrons with a neutral vector field. Every theory in this instance is very closely allied with conventional electrodynamics and becomes electrodynamic theory if χ is assumed to equal zero. (The close relation mentioned is associated with the fact that electrodynamics is also a theory of a vector field (the potential of the field A_k is a four-dimensional vector)). To put this analogy in a more usual form, let us rewrite the equations for a vector field (9) in another form, introducing the notation:

/p. 192/ (23)

With this notation (23), equation (9) will take the following form:

/p. 192/ (24)

When $\chi = 0$, equations (24) will be transformed into the usual Maxwell's equations for a vacuum. This also holds true for equations (7) and (8), which, in the new notation, become:

/p. 192/ (25)

Let us now assume that nuclear particles create a vector field, having a "meson charge" g and a "meson moment" $\frac{f}{\chi}$. Now, in the general case of the quantum theory, instead of (25), the following equations occur:

mid p 192

[192]

(26)

where β, α and σ are matrices of the Dirac theory and (φ, A) is a quantum field.

In the static case which interests us, φ and A are classical magnitudes. Moreover:

[192]

(27)

In (27) both the fields φ and A and the vector of the spin σ can be treated classically. The solution of system (27) is as follows:

[193]

(28)

In electrodynamics the energy of a particle ~~with a~~ of charge e and a magnetic moment μ, situated in the field (φ, A), equals $e\varphi - (\mu H)$. The form is the same for the interaction energy in the case of a vector meson field; moreover, e corresponds ~~with~~ to g and μ corresponds ~~with~~ to $\frac{f}{\chi}\sigma$. Hence the interaction energy of two identical nuclear particles ~~with~~ of spins σ_1 and σ_2, as follows from ~~elementary expressions~~ simple calculations, proves to be equal [31] to:

[193]

(29)

where r is the radius-vector of one of the particles ~~in relation~~ relative to the other. The interaction ~~with the~~ of the energies in (29) (obviously) reduces to forces dependent on the reciprocal orientation of the spins, and also to (non-central) ~~off center~~ forces dependent on the orientation of the spins ~~in relation~~ relative to r.

The vectors $\frac{f}{\chi}\sigma_1$ and $\frac{f}{\chi}\sigma_2$ are meson "quasi-magnetic" moments of nuclear particles, and in the quantum theory the σ vectors are operators (that is) the well-known Pauli matrices ($\frac{\hbar}{2}\sigma$ is the proper ~~moment of the amount of motion~~ angular momentum of the particle).

Considering the vectors as operators makes no change in the classical solution of (29).

Above we examined the interaction of nuclear particles with scalar and vector fields. Two other cases, when the fields ~~have~~ are of a pseudoscalar and pseudovector type (see §1), can be studied ~~in a~~ similarly ~~manner~~ and can be reduced to the energy of interaction, expressed by a linear combination of the terms U_1, U_2 and U_3 (see (29)). Thus, the general expression of the meson theory for interaction energy will take the form:

p. 193

$$U = C_1U_1 + C_2U_2 + C_3U_3, \tag{30}$$

where C_1, C_2 and C_3 are derivatives.

Until now we have considered the meson field as ~~not~~ non-charged; the difference between such a vector field ~~from~~ and the electromagnetic field only amounts to saying that ~~what~~ the rest mass of "quantum meson ~~mesotronic~~ field"--a meson ~~mesotron~~-- is equal to $m = \frac{\hbar\chi}{c}$, since the rest ~~resting~~ mass of a photon equals zero. We are studying the central field ~~not only~~ because of its greater simplicity and ~~but because of~~ other deeper ~~considerations~~ reasons. If the field is charged (in this case, when it is quantized, there charged mesons ~~mesotrons~~ correspond ~~with~~ to it), an expression of type (30) is obtained also for the forces, but only in case of the interaction of protons and neutrons. But for the case of identical nuclear particles (two protons and two neutrons) the interaction ~~interactive~~ energy is equal to zero in the approximation under consideration. This result is completely understandable from the viewpoint of the quantum scheme operating on the concept of an exchange of mesons ~~mesotrons~~ between nuclear particles, since the proton is ~~only~~ capable of emitting only a positive meson ~~mesotron~~, which can be absorbed by a neutron but cannot be absorbed by other protons, etc. Hence exchange by one charged meson ~~mesotron~~ with ~~between~~ identical nuclear particles cannot occur, but can occur between different nuclear particles. This explains the character of the interaction ~~interactive~~ energy already mentioned. Meanwhile, experimental data furnish evidence that proton-proton and proton-neutron forces are of the same order of magnitude [38]. Within the framework of the scheme developed here, this fact can only be explained by assuming that a neutral meson ~~mesotron~~ (neutretto) exists. It is theoretically possible ~~is possible~~ to avoid the ~~this~~ assumption that a neutretto exists, only by theories ~~which~~ operating ~~operate~~ on the basis of an exchange by pairs of particles or excited charged states (see § 3).

~~In general,~~ It must be admitted that [illegible] of the [illegible] a good deal of weight. But in experiments and, above all, in cosmic rays, no definite indications have as yet been obtained in favor of the ~~presence~~ existence of neutrettos. If there is really a neutretto and if it plays an important part in nuclear forces, its mass must be of the order of the mass of a charged mesotron (this follows from (1)) and its interaction with a nucleus must be relatively strong. Whence it follows that in the earth's atmosphere an appreciable number of neutrettos ~~must~~ should be formed, just as ~~in~~ is the case ~~of~~ with charged mesotrons. The reverse process should also be noted; that is, capture of the neutretto ~~is detained~~ by the nucleus, which leads to nuclear fission. These statements force us to assume that the nuclear fissions ("stars") observed in cosmic rays may to a considerable extent be produced by neutrettos. Present experimental data do not contradict this assumption [48].

Clarification of the problem of the existence of neutrettos is highly essential; the primary interest from this viewpoint obviously lies in the study of the "stars" in cosmic rays [48].

Explaining nuclear forces through exchanges by certain neutral mesotrons ("neutral" theory) is not satisfactory, since in this way the ~~connection~~ relation is lost between nuclear forces and the behavior of charged mesotrons in ~~the~~ cosmic rays, as well as the ~~connection~~ relation with ~~disintegration~~ beta-decay*.

The interaction of nuclear particles and charged mesotrons also makes it possible to show th way to explain the anomalous magnetic moments of a proton and a neutron (as we saw above, these moments are not equal to a nuclear magneton for a proton or to zero for a neutron. This follows from Dirac's theory) [46].

...ENTIAL

Meanwhile, it is just this ~~connection~~ relation which is one of the most attractive features of the ~~mesotronic~~ meson theory of nuclear forces. For this reason several variants of a combination theory are under consideration in which both charged and neutral ~~mesotrons~~ mesons figure. An especially popular type of the combination theory is the so-called "symmetrical" theory [49, 9, 37], in which the proton-proton and proton-neutron nuclear forces are exactly equal (in a state of symmetry with respect ~~in relation~~ to a "charged coordinate" [39]).

In the general theory which takes into account both charged and neutral ~~mesotrons~~ mesons, the static energy of interaction takes the form of (30) and the constants C_1, C_2, C_3 likewise depend on the "charged state" of the proton or the "state" of the neutron.

The "exchange" character of ~~the~~ nuclear forces, ~~which is~~ connected with continuous charge exchange between nuclear particles (from which the term "exchange" force comes), also provides for the saturation of ~~the~~ nuclear forces (see above and, in more detail, in [7]).

~~The solution of~~ To solve problems of nuclear physics in a non-relativistic approximation amounts to integrating Schrödinger's equations for protons and neutrons with potential energy (30). The basic ~~problem~~ factors here, of course, ~~is that~~ are the problem of the deuteron and the examination of ~~the~~ proton-proton and proton-neutron ~~diffusion~~ scattering. But research on these problems meets with ~~an~~ ~~important~~ serious difficulty ~~at~~ in the very first stages. The fact is that nuclear energy takes the form ~~in~~ of (17); it is proportional to $\frac{1}{r^3}$, and in this case Schroedinger's equation has ~~no~~ inadmissible (improper) solutions corresponding to the fall of particles,

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on one another. Or we might put it that, if the potential has a ~~hie~~ ~~higher~~ pole of a higher order than $\frac{1}{r^2}$, then the problem of ~~calculating~~ finding the whole system of stationary states has no solution. To a certain extent this result is classical in type, since in classical mechanics the potentials $-\frac{1}{r^{2+\varepsilon}}$ $(\varepsilon \geqslant 0)$ also ~~conduces~~ reduces to the fall of a particle on the center (see [54]). It is easy to reach this conclusion by quantum mechanics. A particle cannot fall on the center if its average kinetic energy in approaching the center increases more rapidly than the average potential energy diminishes. Moreover, the average kinetic energy of a particle situated in a ~~field~~ region ~~with radius~~ of the order of r from the center equals $T = \frac{p^2}{2m} \approx \frac{\text{const.}}{r^2}$, since, by virtue of ~~the ratio of indeterminateness~~ Heisenberg's indeterminacy relation, $p^2 \geqslant \frac{\hbar^2}{r^2}$. Whence it is clear that, if the average potential energy as r approaches zero ~~when $r \to 0$~~, diminishes more slowly than $-\frac{1}{r^2}$, then the fall is impossible; but if $U \approx -\frac{1}{r^{2+\varepsilon}}$ $(\varepsilon \geqslant 0)$, then a lower level will not exist, since, when the region ~~decreases~~ in which the particle is situated grows smaller, its energy converges toward negative infinity ~~toward −∞~~. Of course, this also ~~holds true for~~ refers to the problem of two bodies, which as we know, with relative coordinates, ~~this latter problem~~ amounts to the ~~the~~ problem of the motion of one particle in a center-force field ~~the field of the center of the forces~~.

Thus, if in (30) $C_3 \neq 0$, the problem of the deuteron has no ~~is~~ solution ~~insoluble~~. It is also impossible to assume that $C_3 = 0$ without more ado, since in all variants of the theory with one type of mesons, ~~mesotrons~~, the constant C_3 is proportional to C_2 [45]. Hence, in assuming that $C_3 = 0$, we leave in (30) only the term C_1U_1, which does not allow spin dependence of the forces, and this is contrary to experiment. To assume that $C_3 = 0$, while simultaneously retaining $C_2 \neq 0$, is possible only on the hypothesis that there are at least two types of mesons ~~mesotrons~~. Such a variant of the theory, in which both vector and pseudoscalar ~~mesotrons~~ mesons are ~~were~~ introduced, achieved a certain amount of circulation [43, 51]. In it the "symmetrical" theory was employed and, ~~as~~ as a result of it all, four types of mesons ~~mesotrons~~ were introduced: neutral (vector and pseudoscalar) and charged (vector and pseudoscalar). The masses of vector and pseudoscalar particles may differ [51]. Aside from the fact that the introduction of various types of mesons ~~mesotrons~~ causes a feeling of dissatisfaction, the theory leads to difficulties which make its success in excluding ~~exclusion of~~ the term with $U \approx -\frac{1}{r^3}$ merely an illusion. First ~~xxxx~~, the $\frac{1}{r^3}$ type of term is eliminated only in a static ~~from a~~ approach but ~~and~~ appears with corresponding complications in nonstatic investigations ~~standpoint~~ [52]. Secondly, the theory leads to a certain result directly contradictory to experiment; namely, it follows from the theory [53, 54] that the scattering ~~diffusion~~ of neutrons on protons must be stronger at a 90° ~~the~~ angle $\pi/2$ than at an angle close to zero (in the coordinate system where the proton is at first at rest). But in experimenting with neutrons with energies higher than 10 MeV, when the effect of asymmetry becomes marked, a reverse dependence is observed [55].

Third and lastly, even if the indicated method of eliminating the term with $1/r^3$ answered the purpose of the theory of nuclear forces, it would not permit one to eliminate ~~eliminating~~ the other, not less important difficulty connected with the first one. The truth is that study of the scattering ~~diffusion~~ of mesons ~~mesotrons~~ by ~~into~~ proton-neutron leads us to the conclusion that, if there is ~~in heavy particles~~

a "quasimagnetic" moment f/χ (see above) in a heavy particle, the effective cross section for scattering would grow with energy without limit /46, 35/, which is inadmissible. (More accurately, unlimited growth of cross section with energy contradicts the general position of the theory only under certain additional conditions /22/, which, however, are satisfied in the cases of interest to us.)

This very real difficulty, which we shall consider further under § 3, is not eliminated by introducing two types of mesons, because either type of meson may be scattered independently of the other; and because $f \neq 0$ (though $C_3 = 0$), this scattering will increase without limit with energy. Hence, the "combination" or "symmetrical" theory of Moller-Rosenfeld /47/, Schwinger/51/ and others is unsatisfactory for a number of reasons.

Another group of variants of the theory of nuclear forces was based on "cutting" an inadmissible potential of type $1/r^3$. This means that the expression for the potential $U_3 \backsim -1/r^3$ is considered true only up to some scattering of r_o. When $r < r_o$, this potential is "cut"; that is, it is replaced by some other potential which does not contain an inadmissible feature, for example, by the potential U = a const. (when $r \leqslant r_o$). The "cutting" operation has a formal character; it is non-relativistic and can be justified only because a complete and exact theory leads automatically to some change, or cutting in the potential (or even a deeper change in the entire ordinary system of the introduction of nuclear forces) (see /37/ and § 3). Connected with "cutting" is the introduction

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u.c. l.c.
U(r) ((may be typed in))

of a new constant r_o or, more accurately, a new function U(r) when $r < r_o$. At first glance it might seem that with an arbitrary choice of U(r) any results might be obtained. However, this is not true, since the value of r_o should not exceed the radius of nuclear forces $\frac{\hbar}{mc}$ and the form of the function U(r) on any reasonable hypotheses has no very great effect on the results [37]. After the "cutting" and comparison of the calculations with experimental data, it is possible to exclude certain theoretical possibilities. Thus the "symmetrical" theory with certain vector (charged and neutral) mesons [37] proves unsatisfactory, since to obtain correctly the level of a deuteron and the cross section for neutron-proton scattering it is necessary to assume that $r_o \gtrsim \frac{\hbar}{mc}$ and that the principal sign of the quadripole moment of a deuteron proves incorrect, but its value is approximately 10 times greater than the value observed. (The quadripole moment of a deuteron has a positive sign [40], which corresponds to the elongated cigar-shaped form of the deuteron.) On the contrary, the "neutral" vector theory is in good agreement with data on deuterons [37]. However, as already indicated, utilization of some neutral mesons is unsatisfactory. Besides, it is obviously entirely possible in this scheme to introduce additional and relatively weak proton-neutron interaction with a charged meson. A similar variant of the "unsymmetrical" theory (vector neutrettos plus charged mesons), although known to us, was not verified. A similar, but in some respects simpler and more attractive variant of the "unsymmetrical" theory

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was recently studied by Hulthén [54], though not very thoroughly. In this scheme the neutral meson is scalar and the comparatively weakly interactive, charged meson chosen is pseudoscalar. The type $1/r^3$ term is present for the pseudoscalar ~~mesotron~~, and thus "cutting" is necessary.

~~While~~ In the "symmetrical" theory, neutron-proton and proton-proton forces ~~in~~ the S [1] state are absolutely equal, but in the "unsymmetrical" theory this equality is only approximate in character; this does not run contrary to experiment (see [54, 38, 39]). Besides, in the "summetrical" theory with one type of charged mesons, difficulties arise in comparing the data on beta-decay ~~disintegration~~ in the nucleus and ~~the disintegration of the mesotron~~ meson-decay in cosmic rays [51, 53]. In the "unsymmetrical" theory these difficulties disappear [54].

Furthermore, the above-mentioned conclusion that the scattering ~~diffusion~~ of neutrons by ~~on~~ protons must first be weaker ~~than at a~~ the larger the angle is very general and is obviously inherent in any theory in which the main part of the nuclear forces are of an "exchange" type; that is, dependent on the "exchange" of charged mesons) [53]. The fact is that in an exchange of interaction the proton and neutron are changed in places in the act of scattering ~~diffusion~~. More accurately, because of the exchange in the charge, the particle, formerly a proton, turns into a neutron and vice versa. During (collisions) ~~"soudprenii"~~ a small deflection of the particle is, generally ~~speaking,~~ most probable and so scattering ~~diffusion~~ occurs most frequently at small angles; the disturbing ~~diffusing~~ particle in the case of a quickly falling particle generally flies off at a 90° angle to the latter. But in exchanges the ejected ~~diffused~~ and disturbing ~~diffusing~~ particles in the specified sense are changed here and there. This explains the prevalence of neutron scattering ~~diffusion~~ for 90°.

It is essentially in this case that a proton be ~~is~~ ob-

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served, after first being at rest, transmitting its charge to the falling neutron. This general reasoning as well as calculations [53] show that, if the experiments on ~~diffusion~~ scattering are correct, the basic nuclear interaction is not of an "exchange" type. The simplest theory of nuclear forces without exchanges is based on the introduction of the neutretto which in itself ~~is~~ to some extent an argument in favor of its own introduction and of investigation of the "unsymmetrical" theory. One of the basic problems confronting the "neutral" and also the "unsymmetrical" theories consists in explaining the saturation of nuclear forces. It is very difficult to explain saturation in these cases [37] and in the majority of cases, especially those cited by Hulthén [54], saturation does not take place. ~~However,~~ At present, however, quite independently of the problem of saturation, it is still impossible to tell whether the "unsymmetrical" theory with "cutting" will explain all existing data. As we have seen, in spite of the introduction of "cutting", it is not easy to satisfy all these data. Its very difficulty imparts a certain interest to such efforts.

It is also necessary to bear in mind that ~~in~~ theories which include "cutting" are still faced by the difficulty connected with the unlimited growth of ~~the~~ cross section for ~~the~~ mesotron ~~diffusion~~ scattering, which, apparently, of itself renders these theories unsatisfactory. But here the same argument may be advanced as in the case of "cutting" the $1/r^3$ potential and we may assume that a more complete theory will lead to "cutting" the cross

~~I take this opportunity to thank Professor I.E. Tamm for his~~ valu~~able indications on this subject~~.

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less than [illegible]

r_0 [illegible] /mc; that is, for [illegible]

This does not take place in the "[illegible] metrical" theories and the cross section appears to be larger than that observed when $E \approx mc^2$ [35, 58]. In Hulthen's "~~un~~asymmetrical" theory, in view of the comparative weakness of the interaction with charged particles, the difficulty under consideration obviously disappears ~~drops out~~ [54] (in [54], $f^2/\hbar c \approx 0.01$, but in the "symmetrical" theory, for instance, $f^2/\hbar c \gtrsim 0.1$). In addition, of course, even the reciprocally coordinated cutting of expressions for the potential and scattering ~~the diffusion~~ is a very slight success and for the most part, only shifts the problem's center of gravity to the field of the "cutting" operations. Within the general framework of the theory of nuclear forces, previously discussed, there is another tempting possibility [59], based on the study of non-static forces, the calculation of the relativistic effects. This theory is "~~un~~asymmetrical", and in it as in [53] a neutral meson ~~ton~~ is considered scalar and a charged meson ~~aton~~, pseudoscalar. The essential difference is that the interaction of a pseudoscalar meson with ~~and~~ a proton-neutron is so chosen ~~expressed~~ that it is absent in the non-~~un~~relativistic approximation. (Since C_3 in (30) equals 0, and the "$1/r^3$" difficulty disappears.)

In the relativistic approximation, however, the charged meson conditions an interaction which appears to be very important. In its qualitative aspect Tamm's theory [59] agrees

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