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† Heisenberg assumed that between the neutron and the proton the interaction by "Platzwechsel" was most important.(1) †

DATE ~~Nov. 1, 1934~~

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On the Interaction of Elementary Particles. I.

By Hideki Yukawa

(Read Nov. 17, 1934.)

§ 1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction between elementary particles. ~~We are not sure whether is the interaction between neutron and proton an ordinary attraction or a sort of "Platzwechsel" proposed by Heisenberg(1).~~ † Recently Fermi(2) ~~has~~ treated the problem of β-ray disintegration on the hypothesis of "neutrino". According to this theory a neutron and a proton can interact by emitting and absorbing a neutrino and an electron. Unfortunately the energy of interaction calculated on such assumption(3) is much too small to account for the binding energies between neutrons and ~~elec~~ protons forming a nucleus. To remove this defect, it ~~will~~ may ~~not be unnatural to~~ ~~we can~~ modify the theory ~~in~~ of Heisenberg ~~of Pauli~~ or Fermi in the following way.

(1) W. Heisenberg, Zeits. f. Phys. 77, 1 (1932); 78, 156 (1932); 80, 587 (1933). We shall denote them I, II and III.
(2) E. Fermi, Zeits. f. Phys. 88, 161, (1934).
(3) Ig. Tamm, Nature, 133, 981 (1934); D. Iwanenko, ibid., 981 (1934).

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Between elementary particles, forces may act other forces besides the electromagnetic force and the "Platzwechsel" force of above considered, but we neglect them for the moment.

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The transition of a heavy particle from neutron state to proton state is not always accompanyed by the emission of light particles, i.e. a neutrino and an electron, but the energy liberated by the transition is taken up frequently by another heavy particle, which, consequently transfers from proton state into neutron state. If the probability of the latter process is much larger than that of the former, the interaction between a neutron and a proton increases much more than in the case of Fermi.

Now such interaction between the elementary particles can be described by a field of force just as the interaction between charged particles are described by electromagnetic field. In the quantum theory this field will be accompanied by a new sort of quanta, just as electromagnetic field is accompanied by photons.

The above considerations show that the interaction of heavy particles with this field is much larger than that of light particles with the latter.

In this paper the nature of this field and the quanta accompanying it will be discussed briefly

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and also their bearing on the nuclear structure, the β-ray disintegration, the scattering of neutrons and neutrinos by matter ~~and~~ the cosmic ray and will be considered.

Fuller account will be made in the next paper.

§ 2. Field describing the interaction of elementary particles.

In analogy to scalar and vector potentials of the electromagnetic field we introduce a scalar function $U(x, y, z, t)$ and a vector function $B(x, y, z, t)$ describing the field between a neutron and a proton. These function of force will satisfy equations similar to the wave equations for the electromagnetic potentials.

Now the equation

$$\left\{ \Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} \right\} U = 0 \qquad (1)$$

has only static solution with central symmetry

$$\frac{1}{r}$$

except the additive and multiplicative constants. The potential of force between ~~x~~ neutron and ~~x~~ proton,

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$\frac{e^2}{\hbar} = \text{erg.} = m l^3 t^{-2}$
$e \cong m^{\frac{1}{2}} l^{\frac{3}{2}} t^{-1}$
and λ is a constant with dimension cm^{-1}

however, is recognized not to be Coulomb type, but to decrease more rapidly with distance. It can be expressed for example by

$$+ \text{ or } - \quad g^2 \frac{e^{-\lambda r}}{r} \qquad (2)$$

where g is a constant with the same dimension as ~~corresponding~~ to the electric charge ~~in case of electromagnetic interaction~~. Since this function is, as well known, a static solution with central symmetry of the wave equation

$$\left\{ \Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2 \right\} U = 0 \quad , \qquad (3)$$

let us assume (3) to be the correct equation for U in vacuum. ~~where~~ In the presence of the heavy particles the U-field interact with them and causes the transition from neutron state to proton state. ~~so that, if we denote the wave functions of the neutron~~ Now, if we introduce the matrices[4)]

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

and denote the neutron state and the proton state by $\tau_3 = 1$ and $\tau_3 = -1$ respectively,

4) Heisenberg, loc. cit. I.

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the wave equation is given by

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2\right\} U = -4\pi g\, \tilde{\Psi}\, \frac{\tau_1 + i\tau_2}{2}\, \Psi, \quad (4)$$

where Ψ, ~~a function of x, y, z, t and τ_3', which take~~ denotes the wave function of the heavy particle and is a function of x, y, z, t and τ_3', which ~~means~~ takes eigenvalues ± 1 of τ_3.

Next, corresponding to the inverse transition from ~~a~~ proton state to ~~a~~ neutron state, the complex conjugate potential $\tilde{U}(x\,y\,z\,t)$, ~~is introduced~~ satisfying the equation

$$\left\{\Delta - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \lambda^2\right\} \tilde{U} = -4\pi g\, \tilde{\Psi}\, \frac{\tau_1 - i\tau_2}{2}\, \Psi, \quad (5)$$

is introduced.

Similar equations will hold for the vector potentials, but we disregard it for the moment, since there's no correct relativistic theory for the heavy particle. ~~Therefore~~ Henceforth, simple non-relativistic Schrödinger equations will be used for the heavy particle, which ~~are~~ is

$$\left\{\frac{\hbar^2}{4}\left(\frac{1+\tau_3}{M_N} + \frac{1-\tau_3}{M_P}\right)\Delta + i\hbar\frac{\partial}{\partial t} - \frac{1+\tau_3}{2}M_N c^2 - \frac{1-\tau_3}{2}M_P c^2 - g\left[U\,\frac{(\tau_1 - i\tau_2)}{2} + \tilde{U}\,\frac{(\tau_1 + i\tau_2)}{2}\right]\right\}\Psi = 0, \quad (6)$$

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† their relatively velocity being small.

~~and~~ $D = M$

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where $\hbar$ is the Planck's constant~~s~~ divided by 2π, ~~and~~ M_N, M_P are the masses of neutron and proton respectively. The reason for taking − sign before g will be mentioned later.

The equation (6) can be derived from a Hamiltonian ~~of~~

$$H = \left(\frac{1+\tau_3}{4M_N} + \frac{1-\tau_3}{4M_P}\right)p^2 + \frac{1+\tau_3}{2}M_Nc^2 + \frac{1-\tau_3}{2}M_Pc^2 + \frac{g}{2}\left\{U(\tau_1 - i\tau_2) + \tilde{U}(\tau_1 + i\tau_2)\right\} \quad (7)$$

{where p is the ~~operator $-i\hbar$ grad~~ momentum operator,}

operating on Ψ. If we ~~neglect the mass difference~~ put $M_N - M_P = D$ and ~~put~~ $M_N + M_P = 2M$, (7) becomes approximately

$$H = \frac{p^2}{2M} + \frac{g}{2}\left\{U(\tau_1 - i\tau_2) + \tilde{U}(\tau_1 + i\tau_2)\right\} + \tau_3 D, \quad (8)$$

where ~~dropping~~ the term $2Mc^2$ is omitted.

Now, consider two heavy particles at points (x_1, y_1, z_1) and $(x_2\, y_2\, z_2)$ respectively†. The fields at (x_1, y_1, z_1) due to the particle at $(x_2\, y_2\, z_2)$ ~~is~~ are, from (4) and (5),

$$U(x_1, y_1, z_1) = g\frac{e^{-\lambda r_{12}}}{r_{12}}\,\frac{(\tau_1^{(2)} + i\tau_2^{(2)})}{2}$$

and

$$\tilde{U}(x_1 y_1 z_1) = g\frac{e^{-\lambda r_{12}}}{r_{12}}\,\frac{(\tau_1^{(2)} - i\tau_2^{(2)})}{2}, \quad (9)$$

~~where~~ so that the Hamiltonian for the system is given, ~~by~~ in the absence of the external fields, by

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$$H = \frac{p_1^2}{2M} + \frac{p_2^2}{2M} + \frac{g^2}{4}\left\{(\tau_1^{(1)} - i\tau_2^{(1)})(\tau_1^{(2)} + i\tau_2^{(2)}) + (\tau_1^{(1)} + i\tau_2^{(1)})(\tau_1^{(2)} - i\tau_2^{(2)}) + (\tau_3^{(1)} + \tau_3^{(2)})D\right\}\frac{e^{-\lambda r_{12}}}{r_{12}}$$

or

$$= \frac{p_1^2}{2M} + \frac{p_2^2}{2M} + \frac{g^2}{2}\left(\tau_1^{(1)}\tau_1^{(2)} + \tau_2^{(1)}\tau_2^{(2)} + (\tau_3^{(1)} + \tau_3^{(2)})D\right)\frac{e^{-\lambda r_{12}}}{r_{12}}, \qquad (10)$$

where p_1, p_2 are the momentum operators for the particles and $\tau_1^{(1)}, \tau_2^{(1)}$ and $\tau_1^{(2)}, \tau_2^{(2)}$ are the matrices relating to the first and the second particles respectively. This Hamiltonian is equivalent to Heisenberg's Hamiltonian (1)[5], if we take for "Platzwechselintegral"

$$J(r) = -g^2\frac{e^{-\lambda r}}{r}, \qquad (11)$$

except the interaction between neutrons and the electrostatic repulsion between protons are not considered in our case.

Heisenberg took the sign of $J(r)$ positive, so that the spin of the lowest energy state of H^2 was zero, whereas in our case, owing to the negative sign before g^2, the lowest energy state has the spin 1, which agrees with the experiment.

5) Heisenberg, loc. cit. I.

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Two constants g, λ appearing in the above equations should be determined by comparing with experiments. For example, using the Hamiltonian (10) for two heavy particles, we can calculate the mass defect of H^2 and the probability of scattering of a neutron by a proton, provided that the velocity is small compared with the light relative velocity.[6)] Rough estimation shows that the calculated values agree with the experimental results if we take λ between 10^{12} cm^{-1} and 10^{13} cm^{-1} and g a few multiple of the elementary charge e. In the above considerations, no direct relations between g and e were suggested, although their numerical values were found to be of the same order.

§ 3. Nature of the quanta accompanying the U-field.

In the quantum theory the U-field should be quantized according to the general principle. Since the neutron and the proton both obey Fermi's statistics, the quanta accompanying the U-field should obey Bose's statistics, so that the quantization can be carried on the similar line with that of the electromagnetic

6) Mr. Tomonaga has previously made these calculations according to the theory of Heisenberg. A little modification is necessary in our case. Detailed accounts will be made in the next paper.

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field. ~~According to the ex From~~ the The law of conservation of the electric charge demands that the quantum should have ~~+ or − e~~ the charge $+e$ or $-e$. The ~~quantized~~ field quantity U corresponds to the operator which increases the number of the negatively charged quanta by one and decreases the number of the positively charged quanta by one. ~~The field $\tilde{U}$~~, The complex conjugate of U, which does not commute with U, corresponds to the inverse operator.

Next, denoting

$$p_x = -i\hbar\frac{\partial}{\partial x}, \text{ etc} \qquad W = i\hbar\frac{\partial}{\partial t},$$

$$m_U c = \lambda\hbar,$$

the wave equation for U in free space can be written in the form

$$\left\{p_x^2 + p_y^2 + p_z^2 - \frac{W^2}{c^2} + m_U^2 c^2\right\} U = 0, \qquad (12)$$

so that the quantum accompanying the field has the proper mass $m_U = \frac{\lambda\hbar}{c}$. Assuming, for example, $\lambda = 5 \times 10^{12}\,\mathrm{cm}^{-1}$ we obtain for m_U a value 2×10^2 times as large as electron mass. Thus the result is rather surprising and ~~the existence of~~ such a quantum with large mass and positive or negative charge ~~is was~~ has never

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~~not yet confirmed~~ been found by the experiment, ~~We can show~~ so that the above theory seems to be on a wrong line. We can show, however, that in the ordinary ~~case~~ nuclear transformation such a quantum can not be emitted in the outer space.

Let us consider ~~the transition~~, for example, the transition from a neutron state ~~[illegible]~~ of energy W_N to a proton state of energy W_P, both including the proper energies. ~~We denote~~ We can denote ~~The wave functions of these states by~~ These states can be expressed by the wave functions

$$\left.\begin{aligned}\Psi_N(xyzt, +1) &= u(xyz)\, e^{-iW_Nt/\hbar}\\ \Psi_N(xyzt, -1) &= 0\end{aligned}\right\}$$

and

$$\Psi_P(xyzt, +1) = 0$$

$$\Psi_P(xyzt, -1) = v(xyz)\, e^{-iW_Pt/\hbar},$$

so that in the right hand side of the equation (4) for U the term

$$-4\pi g\, \tilde{v} u\, e^{-\frac{it}{\hbar}(W_N - W_P)}$$

appears.

Putting $U = U'(xyz)\, e^{-i\omega t}$,

we have from (4)

$$\left\{\Delta - \left(\lambda^2 - \frac{\omega^2}{c^2}\right)\right\} U' = -4\pi g\, \tilde{v} u, \qquad (13)$$

where $\omega = \dfrac{W_N - W_P}{\hbar}$. Integrating this equation we obtain a solution

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Now the elastic or inelastic scattering of a neutron by a nucleus can be considered as the result of the double process: the neutron falls into a proton level in the nucleus and a proton in the nucleus jumps to a neutron state of positive kinetic energy, the total energy being conserved throughout the process. Hence the probability of scattering of a neutron by the nucleus may increase in some case with the velocity of the neutron.

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$$U'(\mathbf{x}) = g \iiint \frac{e^{-\mu|\mathbf{x}-\mathbf{x}'|}}{|\mathbf{x}-\mathbf{x}'|} \tilde{v}(\mathbf{x}')u(\mathbf{x}')dv' \quad (14)$$

where $\mu = \sqrt{\lambda^2 - \frac{\omega^2}{c^2}}$.

~~In the case~~ If $\lambda > \frac{\omega}{c}$ or $m_0 c^2 > W_N - W_P$, μ is real and the function $J(r)$ of Heisenberg has the form $-g^2 e^{-\mu r}/r$, in which μ, however, depends on $W_N - W_P$ and becomes smaller and smaller as the latter becomes nearer and nearer to $m_U c^2$. This means that the range of interaction between a neutron and a proton increases when $W_N - W_P$ increases.

According to the experiment of Bonner (7), the collision cross section of the neutron and the nucleus increases with the velocity of the neutron in case of lead, whereas it decreases in e case of carbon and hydrogen. The rate of decrease is slower in case of carbon than hydrogen. ~~This of~~ The origin of this effect is not clear, ~~and may be due~~ but ~~the~~ above considerations do not, at least, contradict with it. For, ~~example~~ if the binding energy of the proton to the nucleus becomes comparable to $m_U c^2$, the interaction of the neutron and the proton will increase considerably with the velocity of the neutron, so that the cross section

(7) T. W. Bonner, Phys. Rev. **45**, 606 (1934).

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will decrease slower in such case than in case of hydrogen, i.e. free proton. Now the binding energy of the ~~outer~~ proton of C^{12} is estimated from the difference of masses of C^{12} and B^{11}, which is

$$12.0036 - 11.0110 = 0.9926$$

This corresponds to a binding energy

$$0.0152$$

in mass unit and about thirty times of the electron mass, so that in case of carbon we can expect the effect observed by Bonner. The above argument, of course, is by no means conclusive and other explanations are not excluded.

Next if $\lambda < \frac{\omega}{c}$ or $m_U c^2 < W_N - W_P$, μ becomes pure imaginary and U expresses a spherical undamped wave, which means that a quantum with energy greater than $m_U c^2$ is emitted in outer space by the transition of the heavy particle from neutron state to proton state, provided $W_N - W_P > m_U c^2$. The phase velocity of U-wave is greater than the light velocity c, but the group velocity is smaller than c, as in the case of the electron wave.

~~Now the mass m_U is hundred times as great as the electron mass, so that~~ and the condition $W_N - W_P > m_U c^2$

~~The reason~~

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It may be

~~is not satisfied in~~ ordinary nuclear ~~transformations~~, ~~so that which me~~ is the reason why ~~such more~~ massive quanta are not yet discovered, ~~is~~ that the mass m_U is large and the condition $W_N - W_P > m_U c^2$ is not ~~so large that~~ satisfied in ordinary nuclear transformation.

§4. Theory of β-Disintegration

Hitherto we have considered only the interaction of U-quanta with heavy particles. Now, according to our theory, the quantum emitted when a heavy particle jumps from a neutron state to a proton state can be absorbed by a light particle which jumps consequently from a neutrino state of negative energy to an electron state of positive energy. Thus an anti-neutrino and an electron are emitted from the nucleus. Such intervention of a massive quantum does not alter essentially the probability of β-disintegration, which has been calculated on the hypothesis of direct coupling of a heavy particle and a light particle, just as in the theory of internal conversion the intervention of the photon does not affect the coefficient of internal

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conversion[8]) Our theory, therefore, does not differ essentially from Fermi's theory.

Fermi ~~has assumed~~ considered that an electron and a neutrino are emitted simultaneously from the radioactive nucleus, but this assumption is formally equivalent to assume that a light particle jumps from a neutrino state of negative energy to an electron state of positive energy.

For if the eigenfunctions of the electron and the neutrino be ψ_k, φ_k respectively, where $k=1,2,3,4$, in the right hand side of the equation for U a term of the form

$$-4\pi g' \sum_{k=1}^{4} \tilde{\psi}_k \varphi_k \qquad (15)$$

will be added, where g' is a constant with same dimension as g. Now the eigenfunctions of the neutrino state with energy and momentum just opposite to that of the state φ_k is given by

$$\varphi'_k = -\delta_{kl}\tilde{\varphi}_l, \qquad \delta_{jk}\varphi'_k = +\varphi_j^{*}$$

where and conversely $\varphi_k = \delta_{kl}\tilde{\varphi}'_l$,

8) Taylor and Mott, Proc. Roy. Soc. A, 138, 665 (1932).

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$-i\sigma_y\rho_3$

$$\delta = \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix},$$

so that (15) becomes

$$-4\pi g' \sum_{k=1,l}^{4} \tilde{\psi}_k \delta_{kl} \tilde{\varphi}_{l} \qquad (16)$$

Now from the equation (13) and (15), we obtain for the matrix element of the interaction energy of the heavy particle and the light particle

$$gg' \iint \tilde{v}(r_1) u(r_1) \sum_k \tilde{\psi}_k(r_2) \varphi_k(r_2)$$
$$\times \frac{e^{-\lambda r_{12}}}{r_{12}} dv_1 dv_2 , \qquad (17)$$

since ~~provided that~~ $W_N - W_P$, which is nearly equal to the upper limit of the energy of β-ray added by mc^2, is always small compared with $m_u c^2$.

Now λ is much larger than the wave numbers of the electron and the neutrino, so that, for the integrations with respect to $x_2 y_2 z_2$, the function

$$\frac{e^{-\lambda r_{12}}}{r_{12}}$$

can be regarded, approximately as a δ-function multiplied

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by a factor $\frac{4\pi}{\lambda^2}$, for

$$\iiint \frac{e^{-\lambda r_{12}}}{r_{12}} dv_2 = \frac{4\pi}{\lambda^2}.$$

~~Hence~~ Thus (17) becomes

$$\frac{4\pi g g'}{\lambda^2} \iiint \tilde{v}(x) u(x) \sum_k \tilde{\psi}_k(x) \varphi_k(x) \cdot dv, \quad (18)$$

or by (16)

$$\frac{4\pi g g'}{\lambda^2} \iiint \tilde{v}(x) u(x) \sum_{k,l} \tilde{\psi}_k(x) \delta_{kl} \tilde{\varphi}_l(x)\, dv, \quad (18)'$$

which is the same as the equation (21) of Fermi, if we substitute for Fermi's g the factor

$$\frac{4\pi g g'}{\lambda^2}.$$

Thus our theory does not differ essentially from Fermi's theory. Comparing with experimental data, Fermi has taken for his g a value

$$4 . 10^{-50} \; cm^3 \cdot erg,$$

from which we can determine g'. If we take for λ a value 5×10^{12} and for g 3×10^{-9},

$$g' = \frac{\lambda^2}{4\pi g} \cdot 4 \cdot 10^{-50} \cong 3 \times 10^{-17}$$

which is about 10^8 times smaller than g. This

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means that the interaction between a neutrino and an electron is much smaller than between a neutron and a proton, so that the neutrino will be far more penetrating than the neutron and consequently more difficult to observe. The difference of g and g' may be due to the difference of masses of heavy and light particles.

§5. Summary

The interaction of elementary particles are described by considering the quantum with elementary charge and proper mass far larger than that of the electron, satisfying the Bose's statistics. The interaction of such a quantum with the heavy particles should be far greater than with the light particle to account for the large interaction of the neutron and the proton and the small probability of β- disintegration.

Such quanta, if they exist and come ~~near~~ close to the matter, will ~~give~~ their charge and energy to it. sometimes be absorbed, giving Now if the quanta with negative charge come in excess, the matter will be charged up to negative potential. ~~and vice versa.~~

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These arguments, of course, of merely speculative character, agree with the view that the high speed positive particles in ~~the~~ cosmic ray are generated by the electrostatic field of the earth, which are charged to a negative potential.

The massive quanta may also have some relation with the shower produced by cosmic ray.[9)]

In conclusion the writer wishes to express his cordial thanks to Dr. ~~Nisti~~ ~~Nisina~~ and Prof. ~~Kikuti~~ Kikuchi for ~~their~~ the Nishina ~~co~~ encouragement throughout the course of the work.

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9) L. G. H. ~~Hardy~~ Huxley, Nature, **134**, 418, 571 (1934);
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