APPENDIX

Yukawa's Two Unpublished Articles on the Meson Theory

Editorial Note

Yukawa's papers on the Meson Theory were reprinted in the Progress of Theoretical Physics Supplement No. 1 (1955). All his scientific articles were also reproduced in *"Hideki YUKAWA, Scientific Works"* published by Iwanami Shoten, Publishers (Tokyo, 1979).

There are, however, some unpublished papers which were written in the early days of the Meson Theory but remain unprinted.*) These are in the possession of Yukawa Hall Archival Library (YHAL), Research Institute for Fundamental Physics, Kyoto University. We include two of them in these Proceedings by permission of YHAL for the sake of historical interest.

We would like to thank the co-author of the second article, Professor M. Taketani, for his permission of reproducing the paper here.

Editors

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*) Cf. *"Hideki Yukawa Self-Selected Essays"*, Vol. 5 (Asahi Press, Tokyo, 1971; in Japanese), p. 243 and M. Taketani, "Soryushi-ron Group no Keisei" in *"Shinri no Ba ni tachite"* (with H. Yukawa and S. Sakata, Mainichi Press, Tokyo, 1951; in Japanese), p. 160, which is also found in *"Soryushi no Tankyu"* (Keiso-shobo, Publishers, Tokyo, 1965; in Japanese), p. 135.

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A Consistent Theory of the Nuclear Force and the β-Disintegration

In spite of many attempts to develop the so-called "β-hypothesis of the nuclear force",1) there still remains in the current theory the well known inconsistency between the small probability of the β-decay and the large interaction of the neutron and the proton. Hence, it will not be useless to give on this occasion a brief account of one possible way of solving this difficulty which was proposed by the present writer about two years ago.2)

First, we introduce the field which is responsible for the short range force between the neutron and the proton and assume it to be something different from the so-called "electron-neutrino field" in contradistinction to the current theory. The simplest conceivable one is perhaps such that can be derived from two scalar potentials U and $\tilde{U}$, which are conjugate complex to each other and satisfy, in the presence of a heavy particle, the equations

$$\left\{\varDelta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\lambda^2\right\}U=-4\pi g\tilde{v}u \qquad \text{or} \quad 0 \tag{1}$$

$$\left\{\varDelta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\lambda^2\right\}\tilde{U}=0 \qquad \text{or} \quad \sim 4\pi g\tilde{u}v \tag{2}$$

according as the latter is initially in the neutron state u or in the proton state v, where g is a constant with the same dimension as the electric charge and λ is another with the dimension of reciprocal length. These equations indicate the possibility of the transition of the heavy particle from the neutron to the proton state and vice versa owing to its interaction with the U-field. We can easily deduce from them the exchange force with the potential

$$g^2\frac{e^{-\lambda r}}{r}$$

between the neutron and the proton. This force was found to be of Heisenberg type, but the Majorana force can also be obtained, if we assume additional potentials with the character of the space vector.

Next, we consider that this field interacts, on the other hand, with the light particle and lead the latter from the electron to the neutrino state and vice versa. Thus, we add to the right hand sides of (1) and (2) terms referring to the light particle with another constant g' instead of g, so that we can compute the probability of β-decay as due to the indirect interaction between the light and the heavy particles by means of the U-field. The result becomes essentially the same as that of Fermi, if we put $4\pi gg'/\lambda^2$ equal to his g. Hence, three constants λ, g and g' can be adjusted so as to give correct magnitudes both for mass defects and the probability of β-decay. If we take, for example $\lambda=5\times10^{12}$ cm^{-1}, g should be about 10 times smaller than g, which means that the energy liberated by the transition of a heavy particle from the neutron to the proton state, for instance, is almost always taken up by another heavy particle, which in turn makes the inverse transition, without the aid of the intermediary transition of the light particle, in contrast to the assumption of the current theory. These conclusions are not altered essentially, if we modify the mathematical formulation so as to be in accord with the result of Konopinsky and Uhlenbeck.

The above theory should be extended further, so that it can include the interaction of the U-

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*) The number of resources in Yukawa Hall Archival Library (YHAL).

field with the electromagnetic field.[3] A noticeable result, which can be predicted without lengthy calculations, is that the above field should be accompanied by quanta obeying Boses statistics with the elementary charge either $+e$ or $-e$ and the proper mass $m_U = \lambda \hbar / c$, which is about 200 times as large as the electronic mass, if we take the above value for λ. Nevertheless, we can hardly expect the creation of such quanta by ordinary nuclear reactions, since at least an energy of the order of 10^8 eV is needed. On the contrary, if they ever exist, their tracks may be found in the cloud chamber photographs of cosmic ray. Now it is not altogether impossible that the anomalous tracks discovered by Anderson and Neddermeyer,[4] which are likely to belong to unknown rays with e/m larger than that of the proton, are really due to such quanta, as the range-curvature relations of these tracks are not in contradiction to this hypothesis. At present, much reserve is, of course, indispensable owing to the scantiness of the experimental information.

Complete account of the theory will be given in the later issue of the Proc. Phys.-Math. Soc. Japan.

Hideki Yukawa

Osaka Imperial University
Osaka, Japan

Jan. 18

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1) See for example, Bethe and Bacher, Rev. Mod. Phys. 8, 82, 1936 and further Weizsacker, Zeits. f. Phys. **102**, 572, 1936; Iwanenko and Sokolow, ibid. **102**, 119, 1936.

2) Proc. Phys.-Math. Soc. Japan **17**, 48, 1935.

3) The mathematical development in this case follows on much the same line with that of Pauli and Weisskopf, Helv. Phys. **7**, 709, 1934.

4) Phys. Rev. **50**, 263, 1936.

YHAL E16 011 U05

On the Theory of the New Particle in Cosmic Ray

As already suggested by several authors,[1] the existence of the new particle in cosmic ray, if confirmed, will be a strong support to the theory which had been proposed by one of the present writers[2] and recently by Stueckelberg. Thus it will not be useless to give here a brief account of further consequences of the theory and their bearings on cosmic ray and nuclear phenomena.

The aim of the theory was to remove the well-known difficulty in the so-called "β-hypothesis of the nuclear force", in a natural way, by introducing a new field, which was responsible for the short range exchange force between the neutron and the proton, as well as for the β-disintegration. We could arrive at consistent results by assuming the interaction of the new field with the heavy particle to be much larger than that with the light particle. As one of the simplest possible forms, the field was considered to be described by two scalar potentials U and $\tilde{U}$ conjugate complex to each other, which satisfy the wave equations

$$\left(\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\varkappa^2\right)U=-4\pi g\tilde{\Psi}Q\Psi\ , \tag{1}$$

$$\left(\Delta-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\varkappa^2\right)\tilde{U}=-4\pi g\tilde{\Psi}Q^*\Psi\ , \tag{2}$$

where Ψ and $\tilde{\Psi}$ are the wave functions for the heavy particle and Q and Q^* are operators which transform the neutron into the proton and vice versa respectively. g and $\varkappa$ are two new constants. The interaction between the neutron and the proton at a distance r due to the intervention of U-field was shown to be an exchange force of Heisenberg type with the potential $4\pi g^2(e^{-\kappa r}/r)$. The force of Majorana type can be derived by assuming, for instance, the potentials to be tensors and the terms in the right hand sides of (1) and (2) to contain the spin of the heavy particle. Further, we can obtain short range force between like particles as higher order term with the attractive potential $-(g^4/\hbar c)(iH_0^{(1)}(2i\varkappa r)/r)$, which is the same order of magnitude as the unlike particle force.[3]

Similarly, in the presence of the light particle, the right hand sides of (1) and (2) should be added by terms corresponding to the transition of it from electron to neutrino state and vice versa respectively. In this case, however, the constant g should be replaced by another constant g' which is much smaller. Thus we obtained a theory of β-disintegration essentially equivalent to that of Fermi. The well-known modification due to Konopinski and Uhlenbeck can also be adopted in this theory, if we assume the source terms to contain derivatives of the wave functions for the light particle.

An important and inevitable consequence of the above theory was that the new field should be accompanied by quanta satisfying Bose statistics with the elementary charge either $+e$ or $-e$ and the mass m_U about 200 times as large as that of the electron, if we take the range of the nuclear force $1/\varkappa$ to be 2×10^{-13} cm, for instance.[4] It is possible, further, to decompose the quadratic equations of the type (1) or (2) into linear equations, which can be considered as a generalization of Maxwell's equations.

If we take the electromagnetic field into account, the equations are altered in the usual manner and it follows that the quanta have spin 1, so that the anomalous magnetic moment of the heavy particle can be interpreted in the following way. Namely, if we assume the self energy of the heavy particle due to the U-field to be responsible for the whole mass M of the heavy particle, its "radius" becomes about g^2/Mc^2 and the additional magnetic moment comes out to be about

$$- \text{ or } + \sqrt{\frac{2g^2}{\pi\hbar c}\frac{e\hbar}{2m_U c}} \cong - \text{ or } + \ 2.5\times\frac{e\hbar}{2Mc}.$$

for the neutron or the proton, which is in good agreement with the observed value $\mp 2(e\hbar/2Mc)$.

Next, we want to refer briefly to the problem of the passage of high energy heavy quanta through matter. In addition to the energy loss due to the ionization, the heavy quanta can be captured by the nuclei with subsequent emission of heavy particles, heavy quanta or γ-rays. The process, in which a heavy quantum of kinetic energy E is captured and a heavy particle is emitted, was dealed with in a manner analogous to the ordinary photoelectric effect. We find that the absorption coefficient in lead due to this process alone is about 0.02 cm^{-1} for E of the order of 10^8 eV and 4 cm^{-1} for E about 10^7 eV. It increases rapidly as E decreases, so that the heavy quanta slowed down by ionization will soon be absorbed into matter. These results are, at least, not in contradiction with known properties of hard component of the cosmic ray.

In this way, the above theory seems to be very promising for consistent interpretation of the nuclear phenomena as well as of the cosmic ray, although it cannot be avoided for the time being that the mathematical scheme becomes more and more complicated, as we want to fit the theory better to the experiment. Detailed account of the whole subject will be given in later issues of the Proc. Phys.-Math. Soc. Japan.

In conclusion, the authors wish to express their cordial thanks to Dr. Y. Nishina for valuable discussions.

Hideki Yukawa
Shoichi Sakata
Mitsuo Taketani

Physics Department
Osaka Imperial University
Osaka, Japan
Oct. 4, 1937

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1) Oppenheimer and Serber, Phys. Rev. **51**, 1113, 1937; Yukawa, Proc. Phys.-Math. Soc. Japan **19**, 712, 1937; Stueckelberg, Phys. Rev. **52**, 41, 1937. It should be noticed that the criticism of Oppenheimer and Serber is not well founded, since many of the difficulties in the current theory do not appear in our theory, as will be shown in the following paragraphs.

2) Yukawa, Proc. Phys.-Math. Soc. Japan **17**, 48, 1935.

3) $H_0^{(1)}$ denotes Hankel function and the potential decreases as $e^{-2\kappa r}/r^{3/2}$ for large r. It should be noticed, however, that the like particle force becomes only about 1/10 of the unlike particle force, if we take $\kappa=5\times10^{12}$ cm^{-1} and $g^2/\hbar c=1/10$. Thus, it may happen to be necessary to consider neutral heavy quanta, if we accept the current assumption of approximate equality of two forces.

4) According to the preliminary result of the experiment of Nishina, Takeuchi and Ichimiya, the mass of the new particle in the cosmic ray is the order of 1/10 of the protonic mass in fair accord with the theory.