HIDEKI YUKAWA

Meson theory in its developments

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The meson theory started from the extension of the concept of the field of force so as to include the nuclear forces in addition to the gravitational and electromagnetic forces. The necessity of introduction of specific nuclear forces, which could not be reduced to electromagnetic interactions between charged particles, was realized soon after the discovery of the neutron, which was to be bound strongly to the protons and other neutrons in the atomic nucleus. As pointed out by Wigner[1], specific nuclear forces between two nucleons, each of which can be either in the neutron state or the proton state, must have a very short range of the order of 10^{-13} cm, in order to account for the rapid increase of the binding energy from the deuteron to the alpha-particle. The binding energies of nuclei heavier than the alpha-particle do not increase as rapidly as if they were proportional to the square of the mass number A, i.e. the number of nucleons in each nucleus, but they are in fact approximately proportional to A. This indicates that nuclear forces are saturated for some reason. Heisenberg[2] suggested that this could be accounted for, if we assumed a force between a neutron and a proton, for instance, due to the exchange of the electron or, more generally, due to the exchange of the electric charge, as in the case of the chemical bond between a hydrogen atom and a proton. Soon afterwards, Fermi[3] developed a theory of beta-decay based on the hypothesis by Pauli, according to which a neutron, for instance, could decay into a proton, an electron, and a neutrino, which was supposed to be a very penetrating neutral particle with a very small mass.

This gave rise, in turn, to the expectation that nuclear forces could be reduced to the exchange of a pair of an electron and a neutrino between two nucleons, just as electromagnetic forces were regarded as due to the exchange of photons between charged particles. It turned out, however, that the nuclear forces thus obtained was much too small[4], because the beta-decay was a very slow process compared with the supposed rapid exchange of the electric charge responsible for the actual nuclear forces. The idea of the meson field was introduced in 1935 in order to make up this gaps. Original assumptions of the meson theory were as follows:

I. The nuclear forces are described by a scalar field U, which satisfies the wave equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\varkappa^2\right)U=0 \tag{1}$$

in vacuum, where x is a constant with the dimension of reciprocal length. Thus, the static potential between two nucleons at a distance r is proportional to $\exp(-xr)/r$, the range of forces being given by $1/x$.

II. According to the general principle of quantum theory, the field U is inevitably accompanied by new particles or quanta, which have the mass

$$\mu=\frac{\varkappa\hbar}{c} \tag{2}$$

and the spin 0, obeying Bose-Einstein statistics. The mass of these particles can be inferred from the range of nuclear forces. If we assume, for instance, $x = 5 \times 10^{12}$ cm^{-1}, we obtain $\mu \cong 200\ m_e$, where m_e is the mass of the electron.

III. In order to obtain exchange forces, we must assume that these mesons have the electric charge $+e$ or $-e$, and that a positive (negative) meson is emitted (absorbed) when the nucleon jumps from the proton state to the neutron state, whereas a negative (positive) meson is emitted (absorbed) when the nucleon jumps from the neutron to the proton. Thus a neutron and a proton can interact with each other by exchanging mesons just as two charged particles interact by exchanging photons. In fact, we obtain an exchange force of Heisenberg type between the neutron and the proton of the correct magnitude, if we assume that the coupling constant g between the nucleon and the meson field, which has the same dimension as the elementary charge e, is a few times larger than e.

However, the above simple theory was incomplete in various respects. For one thing, the exchange force thus obtained was repulsive for triplet S-state of the deuteron in contradiction to the experiment, and moreover we could not deduce the exchange force of Majorana type, which was necessary in order to account for the saturation of nuclear forces just at the alpha-particle. In order to remove these defects, more general types of meson fields including vector, pseudoscalar and pseudovector fields in addition to the scalar fields, were considered by various authors[6]. In particular, the vector field was investigated in detail, because it could give a combination of exchange forces of Heisenberg and Majorana types with correct signs and could further account for the anomalous magnetic moments of the neutron and the proton qualitatively. Furthermore, the vector theory predicted the existence of non-central forces between a neutron and a proton, so that the deuteron might have the electric quadripole moment. However, the actual electric quadripole moment turned out to be positive in sign, whereas the vector theory anticipated the sign to be negative. The only meson field, which gives the correct signs both for nuclear forces and for the electric quadripole moment of the deuteron, was the pseudoscalar field[7]. There was, however, another feature of nuclear forces, which was to be accounted for as a consequence of the meson theory. Namely, the results of experiments on the scattering of protons by protons indicated that the type and magnitude of interaction between two protons were, at least approximately, the same as those between a neutron and a proton, apart from the Coulomb force. Now the interaction between two protons or two neutrons was obtained only if we took into account the terms proportional to g^4, whereas that between a neutron and a proton was proportional to g^2, as long as we were considering charged mesons alone. Thus it seemed necessary to assume further:

IV. In addition to charged mesons, there are neutral mesons with the mass either exactly or approximately equal to that of charged mesons. They must also have the integer spin, obey Bose-Einstein statistics and interact with nucleons as strongly as charged mesons.

This assumption obviously increased the number of arbitrary constants in meson theory, which could be so adjusted as to agree with a variety of experimental facts. These experimental facts could-not be restricted to those of nuclear physics in the narrow sense, but was to include those related to cosmic rays, because we expected that mesons could be created and annihilated due to the interaction of cosmic ray particles with energies much larger than μc^2 with matter. In fact, the discovery of particles of intermediate mass in cosmic rays in 1937[8] was a great encouragement to further developments of meson theory. At that time, we came naturally to the conclusion that the mesons which constituted the main part of the hard component of cosmic rays at sea level was to be identified with the mesons which were responsible for nuclear force[9]. Indeed, cosmic ray mesons had the mass around 200 m_e as predicted and moreover, there was the definite evidence for the spontaneous decay, which was the consequence of the following assumption of the original meson theory :

V. Mesons interact also with light particles, i.e. electrons and neutrinos, just as they interact with nucleons, the only difference being the smallness of the coupling constant g’ in this case compared with g. Thus a positive (negative) meson can change spontaneously into a positive (negative) electron and a neutrino, as pointed out first by Bhabha[10]. The proper lifetime, i.e. the mean lifetime at rest, of the charged scalar meson, for example, is given by

$$\tau_0 = 2\left(\frac{\hbar c}{(g')^2}\right)\left(\frac{\hbar}{\mu c^2}\right) \tag{3}$$

For the meson moving with velocity v, the lifetime increases by a factor $1/\sqrt{1-(v/c)^2}$ due to the well-known relativistic delay of the moving clock. Although the spontaneous decay and the velocity dependence of the lifetime of cosmic ray mesons were remarkably confirmed by various experiments[11], there was an undeniable discrepancy between theoretical and experimental values for the lifetime. The original intention of meson theory was to account for the beta-decay by combining the assumptions III and V together. However, the coupling constant *g*’, which was so adjusted as to give the correct result for the beta-decay, turned out to be too large in that it gave the lifetime τ_0 of mesons of the order of 10^{-8} sec, which was much smaller than the observed lifetime 2 x 10^{-6} sec. Moreover, there were indications, which were by no means in favour of the expectation that cosmic-ray mesons interacted strongly with nucleons. For example, the observed cross-section of scattering of cosmic-ray mesons by nuclei was much smaller than that obtained theoretically. Thus, already in 1941, the identification of the cosmic-ray meson with the meson, which was supposed to be responsible for nuclear forces, became doubtful. In fact, Tanikawa and Sakata[12] proposed in 1942 a new hypothesis as follows: The mesons which constitute the hard component of cosmic rays at sea level are not directly connected with nuclear forces, but are produced by the decay of heavier mesons which interacted strongly with nucleons.

However, we had to wait for a few years before this two-meson hypothesis was confirmed, until 1947, when two very important facts were discovered. First, it was discovered by Italian physicists’s that the negative mesons in cosmic rays, which were captured by lighter atoms, did not disappear instantly, but very often decayed into electrons in a mean time interval of the order of 10^{-6} sec. This could be understood only if we supposed that ordinary mesons in cosmic rays interacted very weakly with nucleons. Soon afterwards, Powell and others[14] discovered two types of mesons in cosmic rays, the heavier mesons decaying in a very short time into lighter mesons. Just before the latter discovery, the two-meson hypothesis was proposed by Marshak and Bethe[15] independent of the Japanese physicists above mentioned. In 1948 , mesons were created artificially in Berkeley[16] and subsequent experiments confirmed the general picture of two-meson theory. The fundamental assumptions are now[17]

(i) The heavier mesons, i.e. n-mesons with the mass m_π about 280 m_e interact strongly with nucleons and can decay into lighter mesons, i.e. π-mesons and neutrinos with a lifetime of the order of 10^{-8} sec; π-mesons have integer spin (very probably spin o) and obey Bose-Einstein statistics. They are responsible for, at least, a part ofnuclear forces. In fact, the shape ofnuclear potential at a distance of the order of $\hbar/m_\pi c$ or larger could be accounted for as due to the exchange of π-mesons between nucleons.

(ii) The lighter mesons, i.e. μ -mesons with the mass about 210 m_e are the main constituent of the hard component of cosmic rays at sea level and can decay into electrons and neutrinos with the lifetime 2×10^{-6} sec . They have very probably spin ½ and obey Fermi-Dirac statistics. As they interact only weakly with nucleons, they have nothing to do with nuclear forces.

Now, if we accept the view that π-mesons are the mesons that have been anticipated from the beginning, then we may expect the existence of neutral π-mesons in addition to charged π-mesons. Such neutral mesons, which have integer spin and interact as strongly as charged mesons with nucleons, must be very unstable, because each of them can decay into two or three photons[18]. In particular, a neutral meson with spin o can decay into two photons and the lifetime is of the order of 10^{-14} sec or even less than that. Very recently, it became clear that some of the experimental results obtained in Berkeley could be accounted for consistently by considering that, in addition to charged n-mesons, neutral n-mesons with the mass approximately equal to that of charged π-mesons were created by collisions of high-energy protons with atomic nuclei and that each of these neutral mesons decayed into two mesons with the lifetime of the order of 10^{-13} sec or less[19]. Thus, the neutral mesons must have spin o.

In this way, meson theory has changed a great deal during these fifteen years. Nevertheless, there remain still many questions unanswered. Among other things, we know very little about mesons heavier than π-mesons. We do not know yet whether some of the heavier mesons are responsible for nuclear forces at very short distances. The present form of meson theory is not free from the divergence difficulties, although recent development of relativistic field theory has succeeded in removing some of them. We do not yet know whether the remaining divergence difficulties are due to our ignorance of the structure of elementary particles themselves[20].We shall probably have to go through another change of the theory, before we shall be able to arrive at the complete understanding of the nuclear structure and of various phenomena, which will occur in high energy regions.

1. E. Wigner, *Phys. Rev., 43* (1933) 252.
2. W. Heisenberg, Z. *Physik, 77* (1932) 1; 78 (1932) 156; 80 (1933) 587
3. E. Fermi, *Z. Physik,* 88 (1934) 161.
4. I. Tamm, Nature, 133 *(1934)* 981; D. Ivanenko, *Nature,* 133 (1934) 981.
5. H. Yukawa, *Proc. Phys.-Math. Soc.Japan,* 17 (1935) 48 ; H. Yukawa and S. Sakata, *ibid.,* 19 (1937) 1084.
6. N. Kemmer, *Proc. Roy.* Soc. *London,* A 166 (1938) 127; H. Fröhlich, W. Heitler, and N. Kemmer, *ibid.,* 166 (1938) 154; H. J.. Bhabha, *ibid.,* 166 (1938) 501; E. C. G. Stueckelberg, *Helv.Phys. Acta,* 11 (1938) 299; H. Yukawa, S. Sakata, and M. Taketani, *Proc. Phys.-Math.* Soc. *Japan,* 20 (1938) 319; H. Yukawa, S. Sakata, M. Kobayasi, and M. Taketani, *ibid.,* 20 (1938) 720.
7. W. Rarita and J. Schwinger, *Phys. Rev., 59* (1941) *436, 556.*
8. C. D. Anderson and S. H. Neddermeyer, *Phys. Rev.,* 51 (1937) 884; J. C. Street andE.C. Stevenson, *ibid.,* 51(1937) 1005; Y. Nishina, M.Takeuchi, and T. Ichimiya, ibid., 52 (1937) 1193.
9. H. Yukawa, *Proc. Phys.-Math. Soc. Japan,* 19 (1937) 712; J. R. Oppenheimer and R. Serber, *Phys. Rev.,* 51 (1937) 1113; E. C. G. Stueckelberg, *ibid., 53* (1937) 41.
10. H. J. Bhabha, *Nature,141* (1938) 117.
11. H. Euler and W. Heisenberg, *Ergeb. Exakt. Naturw.,* 1: (1938) 1; P. M. S. Blackett, *Nature,* 142 (1938) 992; B. Rossi, *Nature,* 142 (1938) 993; P. Ehrenfest, Jr. and A. Freon, *Coopt. Rend., 207* (1938) 853 ; E. J. Williams and G. E. Roberts, *Nature,* 145 (1940) 102.
12. Y. Tanikawa, *Progr. Theoret. Phys. Kyoto,* 2 (1947) 220; S. Sakata and K. Inouye, *ibid.,* 1 (1946) 143.
13. M. Conversi, E. Pancini, and O. Piccioni, *Phys. Rev.,* 71 (1947) 209.
14.. C. M. G. Lattes, H. Muirhead, G. P. S. Occhialini, and C. F. Powell, *Nature,* 159 *(1947) 694;* C. M. G. Lattes, G. P. S. Occhialini, and C. F. Powell, *Nature,* 160 (1947) 453,486.
15, R. E. Marshak and H. A. Bethe, *Phys. Rev.,* 72 (1947) 506.
16. E. Gardner and C. M. G. Lattes, *Science,* 107 (1948) 270; W. H. Barkas, E. Gardner, and C. M. G. Lattes, *Phys. Rev., 74* (1948) 1558.
17. As for furtherdetails, see H. Yukawa, *Rev. Mod. Phys.,* 21 *(1949) 474.*

18. S. Sakata and Y. Tanikawa, Phys. *Rev., 57* (1940) 548; R. J. Finkelstein, *ibid., 72 (1947) 415.*
19. H. F. York, B. J. Moyer, and R. Bjorklund, *Phys. Rev., 76 (1949)* 187.
20. H. Yukawa, *Phys. Rev., 77 (1950) 219.*