Mesons and Nuclear Forces

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Nowadays it is well-known that there is an intimate connection ~~by~~ between the stucture of atomic nuclei and the existence of a family of particles known as <u>mesons</u>. Although we do not yet have the final answer to the questions ~~of~~ related to mesons and nuclei, we notice that we came nearer to the goal due to the remarkable progress in nuclear physics since 1932, when the neutron was discovered. Up to that time, physicists had used to suppose that the atomic nucleus consist of protons and ~~ny~~ electrons. However, if we start from such a model and apply quantum mechanics, which proved to be so successful in the entire field of atomic physics, to problems of the nucleus itself, we encounter immediately a number of serious difficulties. For example, we know from~~the~~ the analysis of the molecular spectra that the nitrogen nucleus $_7N^{14}$ has spin 1 in units of   and obeys Bose-Einstein statistics, whereas the above model predicts that it shoud have half integer spin and obey Fermi- Dirac statistics, because it consists of an odd number of particles, i. e. 14 protons and 7 electrons, ~~which~~ each of which has spin 1/2 and obeys Fermi-Dirac statistics. All this and similar difficulyies disappeared at once, when physicists adopted the new hypothesis that atomic nuclei consisted of <u>nucleons</u>, i. e. protons and neutrons, both of which had spin ~~s~~ 1/2 and obeyed Fermi-Dirac statistics. Thus, for instance, $_7N^{14}$ consists of an even number of nucleons, i. e. 7 protons and 7 neutrons.

On the other hand, however, the necessitiy of introductionof specific nuclear forces, which could not be reduced to electromagnetic forces between charged particles, became more obvious. Even in the older model for the nucleus, the electrostatic attraction between electrons and protons turned out to be much too small to account for the enormous binding energy of the nucleus. For example, the binding energy of the alpha- particle ${}_2He^4$, which was supposed to consist of four protons and two electrons, was more than 50 in units of m_ec^2, where m_e is the rest mass of the electron, while the electrostatic energy between a proton and an electron amounted only to m_ec^2 at a distance e^2/m_ec^2 or 2.8 10^{-13}cm. If we adopt the new model, the arguments for the existence of specific nuclear forces of non-electromagnetic origin ~~bt~~ between nucleons become more convincing, because protons must repel each other electrically, while neutrons are electrically neutral. Both the proton and the neutron have magnetic moments, but they are much too small to contribute appreciably to the nuclear binding.

Now it is clear that the specific nuclear forces are to be effective only when two nucleons are at a distance of a few times of 10^{-13}cm or less from each other. As a matter of fact, since 1911, when Rutherford had concluded from the scattering of alpha-particles by atoms the nuclear structure, it has been recognized that the Colomb repulsion was the only predominant force between an alpha-particle and a nucleus, unless they came to each other at a distance of the order of ~~10~~ 10^{-12}cm. If we apply quantum mechanics to the new model for the nucleus, we find that the nuclear forces must have a very short range of the order of 10^{-13}cm, in order to account for the rapid ~~increase~~ increase of the binding energy from 2.2 MeV for the deuteron to 28 MeV for the alpha-particle. On the other hand, the binding ~~energy~~ 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 itself. This indicates that nuclear forces are saturated for some reason. Heisenberg suggested a mechanism analogous to the chemical valence force. Namely, if we assume a force between a proton and a neutron, for instance, due to the exchange of the electric charge, the saturation of such a force can be concluded just as in the case of the chemical bond between a hydrogen atom and a proton due to the exchange of an electron. Soon afterwards, Fermi 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 <u>neutrino</u>, i. e. a hypothetical neutral particle with a very small mass and an enormous penetrating ~~po~~ power. 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 exchange forces thus obtained was much to small, because the beta-decay was a very slow process, whereas the extremely rapid exchange of the electric charge between nucleons was required as the mechanism of nuclear forces.

The idea of themeson field was introduced in 1935 in order to make up for this gap.[1] Original assumptions of the meson theory were as follows:

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

in vacuum, where is a constant with the dimension of reciprocal length. When there is a nucleon, it becomes a point source of the field U of strength g, which is a constant with the same dimension as the electric charge.

By starting from this assumption, we can show that, when there are two nucleons at a distance r, the static interaction between them is given by a potential

$$g^2 \exp(-\ \ r)/r,$$

so that the range of nuclear forces becomes ~~b~~ 1/ . The numerical value of the constant g must be a few times larger than the elementary charge e, in order that the above ~~pt~~ potential is large enough to account for the binding energies of nuclei.

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

and the spin 0, obeying Bose-Einstein statistics. The mass can be inferred from the range of nuclear forces. If we take, for instance, $= 5\ \ 10^{12}\,cm^{-1}$, we obtain

$200\ m_e$.

Now, if we assume that U is ~~are~~ a real function accompanied by neutral particles, i. e. neutral mesons, we obtain ordinary attractive force of short range between two nucleons.

III. In order to obtain an exchange force between a proton and a neutron, we have to assume that U is a complex function accompanied by mesons with 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 state to the proton state. Thus the mechanism of the exchange force between a proton and a neutron is reduced to the exchange of charged mesons just as two charged particles interact electromagnetically by exchanging photons.

In this way, we obtain an exchange force of Heisenberg type with the appropriate range and magnitude. However, the force thus obtained turned out to have the wromg sign in that it ~~was~~ was repulsive for triplet S-state of the deuteron in contradiction to the experiment. Moreover, we could not derive the exchange force of Majorana type, which was necessary in order to account for the saturation of nuclear forces just at the alpha-particle, while the exchange force of Heisenberg type was to be saturated already at the deuteron. In order to remove these defects, more general types of meson fields including vector, pseudoscalar and pseudovector fields in addition to the scalar field were considered by various authors.(2) In particular, the vector field was investigated in detail, mainly 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~~ ground state of the deuteron was to be a mixture of triplet S and triplet D states. This implied, in turn, that the charge~~d~~ distribution in the deuteron was not spherically symmetric, but the density was to be larger in the directions, which was perpendicular to the direction of the resultant spin. In other words, the electric quadrupole moment of the deuteron was to be negative. However, according to the experiment by Rabi and others(3), it was known to be positive. For this reason, the vector theory finally gave place to the pseudoscalar theory, which gave the correct signs both for nuclear forces and the quadripole moment of the deuteron.(4) In any case, it noticeable that the non-central part of the nuclear potential, which is usually called <u>tensor force</u>, is of the same order of magnitude as the central force, whereas, in the case of the ~~l~~ electromagnetic interaction, the central force which was derived from the Coulomb potential was predominant.

There was another feature of nuclear forces, which was to be accounted for in some way or other as the consequence of meson theory. Namely, the results of experiments on the scattering of protons by protons at high energy up to a few MeV indicated that the type and magnitude of forces between two protons were, at least approximately and at least in singlet S-state, the same as those between a proton and a neutron, apart from the Coulomb force in the formar case. 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. The terms proportional to g^4 are, in general, smaller than those proportional to g^2, unless the coupling constant g is unusually large for some particular reason as in the case of pseudoscalar meson field with pseudoscalar coupling. Even in the latter case, the type and range of forces which are proportional to g^4 are different from those of g^2-forces.

IV. Thus it seems to be almost inevitable to assume further that, in addition to the charged mesons, there are the neutral mesons with the mass either exactly or approximately equal to that of the charged mesons. They must also have the integer spin, obey Bose-Einstein statistics and interact with the nucleons about as strongly as the 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 between matter and cosmic ray particles with energies much larger than Mc^2, which was of the order of 100 MeV. In fact, the discovery of charged particles of intermediate mass in cosmic rays in 1937 by Anderson and Neddermeyer(5) 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 forces.[6] Indeed, cosmic ray mesons had the mass around 200 m_e as predicted and moreover, there was the definite evidence for the spontaneous decay of mesons, which was the consequence of the following assumption of the original theory:

V. Charged 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.[7]

According to this assumption, the proper life-time, i. e. the mean life-time at rest, of the charged scalar meson, for instance, is given by

When the mesons are moving with the velocity v, their mean life-time increases by a factor due to the well-known relativistic delay of the moving clock. Although the spontaneous decay and the velocity dependence of the life-time of cosmic ray mesons seemed to confirm the above assumption, there was an undeniable discrepancy between theoretical and experimental values for the proper life-time. 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 life-time of the order of 10^{-8} sec., which was much smaller than the observed value 2 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 cosmic ray mesons with the mesons, which were supposed to be resposible for nuclear forces, became doubtful. Tanikawa and Sakata[8] proposed in 1942 the following modification of meson theory: The mesons which constitute the hard component of cosmic rays at sea level are not directly connected with nuclear forces, but are produced in the upper atmosphere by the decay of heavier mesons which interact strongly with nucleons. However, we had to wait for a few years until 1947, when two very important facts were discovered and seemed to cofirm the above <u>two--meson hypothesis</u>. Firstly, it was discovered by Italian physicists[9] that the negative mesons in cosmic rays, which had been captured by light atoms, did not disappear instantly on account of the interaction with nuclei, 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 accepted the assumption that ordinary mesons in cosmic rays interacted very weakly with nucleons. Soon afterwards, Powell and others[10] discovered two types of mesons in cosmic rays at the high altitude, 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[11] independent of the Japanese physicists above mentioned. In 1948, mesons were created artificially for the first time in Berkeley[12] and subsequent experiments on artificial mesons further confirmed the general picture of two-meson ~~hypothesis~~ theory.[13]

Now the fundamental assumptions which are substitued for the original assumption V are as follows:

(i) The heavier mesons, i. e.   -mesons with the mass m   around 276 m_e, interact strongly with nucleons and can decay into lighter mesons, i. e.   -mesons, and neutrinos with a life-time of the order of 2 10^{-8} sec.   -mesons have integer spin (very probably spin 0) and obey Bose-Einstein statistics. They are responsible for, at least, a part of nuclear forces. This is because the shape of nuclear potential at a distance of the order of /m c = 1.4 10^{-13}cm or larger must be inseparably connected with the strong interaction of mesons with nucleons.

(ii) The lighter mesons, i. e. -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 life-time 2 10^{-6}sec. They have very probably spin 1/2 and obey Fermi-Dirac statistics. As they interact only very weakly with nucleons, they have nothing to do with nuclear forces.

Now, if we accept these assumptions together with the assumption IV, the existence of the neutral -meson inaddition to the charged -meson is naturally expected. However, 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 in a very short time.(14) In particular, a neutral meson with spin 0 can decay into two photons and the life-time is likely to be of the order of 10^{-14}sec. or may be even less than that. Recently, it became clear that some of the experimental results obtained in Berkeley(15) could be accounted for consistently by assuming that, in addition to charged -mesons, neutral -mesons with the mass approximately equal to that of charged -mesons were created by high energy nuclear collisions and that these neutral mesons decayed into two photons with the life-time of the order of 10^{-13}sec. or less. Thus, the spin of neutral mesons must be 0. Other experiments in Berkeley are also not only consistent with this assumption, but indicate further that both charged and neutral mesons are pseudoscalar, although the mass of the neutral -meson turns out to be around 265 m_e, which is a little less than that of the charged -meson.(16) Generally speaking, this is what we have expected theoretically, because the pseudoscalar meson theory was known to be the only one which could reproduce qualitatively all the required properties of nuclear forces.

However, if we go into details, ~~th~~ we find that the situation is still very unsatisfactory. We could not yet arrive at the quantative agreement between theory and experiment. Moreover, there are a number of important problems, which must be intimately connected with the problems of -mesons and nuclear forces, but are not yet fully investigated. Among other things, we don't know much about the mesons heavier than -mesons, although recent experiments show beyond doubt the existence in cosmic rays of very unstable mesons, which are much heavier than -mesons. We don't know yet whether some of the heavier mesons contribute to nuclear forces at very short distances appreciably. Furthermore, the present form of field theory including meson theory as a particular case is not free from the divergence difficulties. Meson theory has changed a great deal during these sixteen years. Nevertheless, we shall probably have to go through another revision, before we shall finally arrive at the complete understanding of the nuclear structure and of a great variety of phenomena occurring in high energy region.

References

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