# Outline of the Meson Theory

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§1. It is needless to say that the central problem of physics today is to investigate the nature of ultimate constituents of matter and the interaction between any two of them thoroughly. It may, indeed, be a problem which can never be solved completely, but it seems that we are drawing nearer to the goal through recent progress of nuclear physics, culminating in the discovery of the mesotron or meson in the cosmic ray.

Nowadays it is no doubt that the mesons as the main constituent of the hard component of the cosmic ray have the mass or masses about two hundred times as large as that of the electron and the elementary charge either positive or negative. Other properties, however, cannot easily be determined by experiment alone and depend more or less on theoretical assumptions, so that we have to compare the results, which follow from each of various possible assumptions, with the experiment in detail, before we arrive at the final decision. Although this tedious task does not yet end, most important cases has already been investigated fully by many authors.

§2. In the earliest stage of the meson theory, which was first introduced in order to obviate the wellknown breakdown of the β-decay idea of ascribing the origin of nuclear forces to the β-decay directly, the following fundamental assumptions were made:[1]

i) The meson satisfies the scalar relativistic wave equations of second order

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

in vacuum, where $\psi$ is a scalar function of $x, y, z$ and $t$ and $\kappa = \frac{\mu c}{\hbar}$, $\mu$ being the rest mass of the meson.

1) Yukawa, Proc. Phys.-Math. Soc. Japan 47(1935), 48; Yukawa and Sakata, ibid. 19(1937) 1084.

(i) is equivalent to assign 0 spin to the meson.
~~This corresponds to the fact th~~
corresponding to the fact that

ii) It obeys the Bose-Einstein statistics in conformity with the general rule that the elementary particle with the integer spin obeys the B. E. statistics, whereas that with the half integer spin the Fermi-Dirac statistics. An elegant proof of this rule was given by Fierz[1] recently starting from the wave equations of Dirac for the particle with arbitrary spin.[2]

iii) The meson has the charge +e or -e. A positive meson is emitted absorbed when the nuclear particle changes from the neutron state to the proton state, while a negative meson is emitted absorbed when the nuclear particle changes from the proton to the neutron state. The simplest interaction of this type is given by

where denote the wave functions for the neutron and the proton and g is a constant with the dimension of the electric charge and characterising the magnitude of interaction between the nuclear particle and the meson.

From these assumptions, it follows that

a) the nuclear particles interact with each other by exchanging the mesons just as the charged. Thus ~~is of~~ an exchange force of Heisenberg type is obtained ~~Therefore thus obtained/has~~ with the potential depending ~~on the mutual dis-~~ between tance r as we obtain

so that the effective range of the force is given by

which takes a value 2 $10^{-13}$ cm for = 200m.

1) Fierz,

2) Dirac

We assume further that

iv) there is the interaction between the meson and the light particle, which has a form similar to that between the meson and the nuclear particle. Namely, a positive meson can change spontaneously into a positive (negative) electron and a neutrino, so that the meson has a finite life time as firtst pointed out by Bhabha[1]. If we denote by g' the constant characterising the magnitude of the interaction, the proper life time, i.e. the mean life time at rest, of the meson becomes

When the meson is moving with the velocity v, the life-time increases by the relativistic factor $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$, due to well known delay of the moving clock.

By combining iii) and iv) together, we can interpret the $\beta$-decay as follows.

b) A neutron, for instance, in the nucleus changes according to iii) with the simultaneous emission of a negative meson, which in turn disintgrates into an electron and a neutrino according to iv). The meson appears, of course, only in the intermediate state, since the available energy is in general smaller than the proper energy $\mu c^2$ of the meson, which is necessarry for creaing it and has a value $10^8$eV for $\mu$=200 m. Thus we arrive at the results, which are essentially the same as those of Fermi's original theory of $\beta$-decay, so far as the light particles are emitted with energies small compared with $Mc^2$. We find thereby that the constant g' should be far smaller than g, in order to account for the small probability of $\beta$-decay in contrast to the large interaction between the nuclear particles.

The presumption that the meson has a short lifetime implies that the particles of intermediate mass, constituting the hard component of the cosmic ray should not be of primary origin, but should have been created in the upper atmosphere by some agent, presbably by the soft component, if we want to identify these particles with

1) Bhabha, Nature

the mesons above considered. On this point of view, Euler developed a theory of the cosmic ray and succeeded in obtaining a consistent picture ~~interpreting curious phenomena~~ ~~hitherto left alone.~~ whole phenomena of the of cosmic ray including curious ~~phenomena~~ facts hitherto ~~unexplained.~~ inexplicable.[1] ~~Namely~~ In particular, the fact that the hard component undergoes an excess absorption in air than in the dense medium such as water or lead can be interpreted very naturally by considering the decrease in number of mesons due to the spontaneous decay during their passage through the atmosphere. From this and several other phenomena, which can ~~all~~ be attributed to meson decay, we obtain always a value ~~concluded~~ that for the proper lifetime of the origin of the order of magnitude

$$2 \sim 5 \times 10^{-6}\ \text{sec.}$$

for the proper life-time of the meson. Moreover, two cloud chamber photographs, which can be considered as the direct evidence for the meson decay, were obtained recently by Williams etal[1], so that there remains no ~~there~~ left with little doubt as to the instability of some, at least, of ~~the~~ mesons in the cosmic ray.

§3. In spite of the success of scalar meson theory above mentioned, there remain several points to be improved. The most serious drawback is that only the exchange force of Heisenberg type between the neutron and the proton can be derived from the scalar theory and with the (wrong) opposite sign, so that the force is repulsive in the $^3S$ state of the deuteron. In order to remove this defect, the following modification was made by several authors, almost simultaneously.[2] Instead of ~~the assumption~~ i), we assume that

i)' The meson ~~is~~ satisfies the first order equations of Proca type

in vacuum, where

The wave equations ( ) are equivalent to assign spin 1 to the meson.

1) Euler und Heisenberg, 2) Y. H. K. B. S.

From i)' and ii) and iii), it follows that

a)' The interaction between the neutron and the proton turns out to be includes the exchange forces of both Heisenberg and Majorana types and with the correct sign.

c b) The anomalous magnetic moments of the neutron and the proton can be interpreted qualitatively, at least, as due to the intrinsic magnetic moment of the meson existing virtually in the intermediate state, although
certain
the numerical comparison with the experiment is the diergence of the integral the appearence of a diverging integral in the calculation prevents us from the numerical comparison with the experiment.

These satisfying results are, however, counterbalanced by new dificulties as follows:

neutron-proton
d c) The potential between the neutron involves a term, which increases as $r^{-3}$ with the decreasing distance r, so that the deuteron problem has no cannot be solved have any solution, unless some sort of cut-off is executed for small r.

e d) Alomg with this, the potential depends not only on r, but also on the angle between the vector representing the relative position and the spin vectors of both particles, so that we can speak of a central force. no
no more
Recent discovery of the electric quadripole moment of the deuteron seems by Rabi etal[1] seems to be in favour of this conclusion, but the true
origin of
interpretation for the electric quadripole moment is not clear as yet.

1) Rabi,

8 iv) The cross-sections for various collision processes involving the meson of spin 1 increase very often with the energy so rapidly that we are no more able to consider mesons of this sort as the main constituent of the hard component of the cosmic ray. Especially, the cross-section of scattering of the meson by a nuclear particle[1] turns out to be far larger than the experimental value recently obtained by Wilson[2] even for the moderate energy of the order of $\mu c^2$.

9 v) The proper life-time of the meson due to the spontaneous change into light particles can be calculated by using the experimental data for the nuclear forces and the β-decay and is found to have a value of the order of $10^{8}$ sec, which is far too small compared with the value obtained from the cosmic ray experiment. This discrepancy is also inherent in the scalar theory. An attempt to avoid it was made by Sakata, which could be said to go halfway back to Fermi's theory of the β-decay.

Apart from these perplexing circumstances, meanwhile an important information was obtained from the result of experiment of proton-proton scattering, which seemed to support the view that the type and the magnitude of the interaction between two protons are the same as those between the neutron and the proton. In order to be able to deduce this as a consequence of the meson theory, we have to assume further that

v) The neutral meson exists in addition to the charged one with the same mass, spin and statistics as the latter, contributing to the nuclear forces as well.

This assumption increases the number of constants, which can be controled by experiment, so that the theory is open to modifications of various kinds. A few typical cases among them will be discussed in the following section.

§4,

I) In the symmetrical theory of Kemmer, the mesons with the charge +e, 0, -e contribute equally to the interaction between nuclear particles, so that the neutron-proton, neutron-neutron and proton-proton forces are the same with one another in the $^1S$ state. There is, however, a serious draw-back in this theory as to the sign of the electric quadripole moment of the deuteron. The sign is said to be positive or negative according as the charge dis-tribution in the deuteron is cigar shaped, viz. oblong in the spin direc-tion, or pancake shaped, viz. flat in other directions. The experimental result of Rabi et al. indicates a value

$$q = +2.73 \cdot 10^{-27}\ cm^2$$

for the moment, whilst it takes the negative sign according to the sym-metrical theory. This discrepancy can be removed by increasing the con-tribution of the neutral meson to the nuclear forces and by taking further suitable sign and magnitude for constants charact. the constant between the neutral meson and the nuclear particle. A special and limiting case of this is

II) the neutral theory of Bethe, in which the neutral mesons alone are considered to be responsible for the nuclear forces. In spite of the great advantage of this theory, we have to spare it is to be regretted that the connection of the anomalous magnetic moment of the nuclear particles, the -decay and the cosmic ray phenomena with the nuclear structure.

III) In the mixed field theory of Møller and Rosenfeld, it is assumed that there are mesons which can be described by the scalar, pseudoscalar and pseudovector fields respectivly in addition to the ordinary meson which is described by the vector field. By taking a suitable combination of these fields such as the vectro and the pseudoscalar fields, it is able to remove the difficulties d) and I) and also make the proper life-time of the pseudoscalar meson sufficiently large without giving up its connection with the -decay.[2)]

2) Sakata, Proc. Phys.-Math. Soc. Japan 53 (1941),

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Bhabha — One of the difficulties is that the interaction of the meson with the el. mag. is too large for in the high energy region. The other is that

A very serious difficulty of common to the above three cases are that the cross-section for the scattering of the meson by a nuclear particle is too large by a factor about 10² compared with the cosmic ray data. An attempt to fillup ~~this defect~~ the latter was made recently by Bhabha and Heitler. They assume that the nuclear particle has inner excited states with the charge -e, +2e, etc, and the spin 3/2, 5/2 etc. resctively other than the lowest states, viz. the neutron and the proton states, so that these states interfere with one another in the intermediate state occuring in the scattering process and serve to diminish reduce the cross-section to the value consistent with the experiment, if we take the excitation energy of the lowest excited states to be of the order of 10 2 $10^7$ eV. Other divergence difficulties inherent in the meson theory are also removed or diminished by this assumption. It may ~~not~~ indeed be irrational to ascribe the wide difference in the masses ~~of the the existence~~ of two sorts of particles with the same spin ~~and with widely different masses~~ such as the nuclear particle and the light partcile to the very existence of the excited states in the former. At any rate, whether this hypothesis is appropriate or not will be verified by experiment sooner or later.

In all cases, it is clear that the above asumption of the existence of the meson with the integer spin is ~~most~~ simple and effective in unifying the whole phenomena concerning the nuclear stucture as well as the cosmic ray. ~~Although~~ Another alternative cannot, however, be excluded that Another possibility It cannot, however, be excluded that the spin the meson in the cosmic ray has half integer spin ~~and~~ obeying Fermi statistics. If we assume, for example, that the meson has the spin 1/2 and satisfies Dirac's wave equations, the interaction between nuclear particles can be explained as the virtual emission and absorption of a pair of such heavy electrons as developed recently by Marshak. The nuclear forces, which follow from this meson pair theory, are much the same as those which follow from the neutral theory except that the singularity for zero distance is steeper than in the ordinary theory, and the range of forces reduce to h/2 c instead of h/ c, which seems to make the agreement with the experimental result of the proton-proton scattering better than in the ordinary theory. This theory has a further advantage that the scattering of the meson by the nuclear particle is so small as to be consistent with the experiment. Although this theory has such advantages, it is to be regretted that the problems of the meson decay, the β-decay, anomalous magnetic moment of the nuclear particles, etc. are again separated from one another, unless we make further asumptions we postulate the existence of the neutral meson with the spin 1/2 and further assumptions which are more or less arbitrary.

§5. As discussed in the preceding sections, the meson theory has many defects which can not easily be removed all at a time. Moreover, it is very probable that the difficulties peculiar to the meson theory are intermingled with those concerning the general method of the relativistic quantum mechanics. As suggested by Heisenberg, it is probable that the phenomena involving the creation and annihilation of mesons are entirely outside of the limit of validity of the present method of quantization. The only indubitable fact at present is that there exist in nature particles of intermediate mass, which constitute the main part of the hard component of the cosmic ray and are responsible for the interaction between nuclear particles in a certain manner. Other problems remain to be solved along with the very problem of constructing a method of relativistic quantum mechnics which are free from any divergence difficulty.