A SHORT HISTORY OF THE MESON THEORY FROM 1935 TO 1943

(PART I)

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The present article is an analytical history of the stages of development of the meson theory of nuclear forces since Yukawa's postulation of the meson field up to 1943, when Sakata's two-meson hypothesis was formulated in the face of the prevailing belief in the identity of the Yukawa meson and the cosmic-ray meson. It starts with a brief description of the persistence of the general idea of a possible connexion between nuclear beta-emission and nuclear forces till the abandonment of the attempts to reconcile them. Attempts to postulate a suitable kind of conveyer of nuclear forces culminated in Yukawa's meson hypothesis, although a parallel hypothesis of electron-positron pair field competed with it for some time till experimental confirmations of the existence of a cosmic-ray particle of 'intermediate mass' vindicated the meson concept. The new concept found serious advocates as well as sceptic critics. The theoretical invocation of a neutral meson for explaining the experimentally observed charge-independence of nuclear forces was welcome, but still none of the meson theories involving the neutral meson could comprehensively explain all nuclear phenomena. Also the so-called 'mixed' meson theory, which paved the way for a proper two-meson hypothesis, could not save itself against theoretical objections. Theoretical and experimental results on the lifetime and mass of the nuclear meson and of the cosmic-ray meson created great conceptual problems. At that situation the meson-pair theory was formulated, which ensured the charge-independence of nuclear forces without invoking the 'unobserved' neutral meson. But arguments in favour of the existence of the neutral meson were forthcoming. Although the mixed meson theories foreshadowed a two-meson theory, there was also a parallel trend of reluctance to accept the two-meson picture. Speculations about the strength of the meson-nucleon coupling (weak or strong) could not lead to any definite conclusion till the discovery of the two unlike mesons in 1947. The developments of the period 1943–47 would be discussed in a separate article.

GENERAL INTRODUCTION

The massless quantum of light has been known as the conveyer of electromagnetic interactions. Likewise, nuclear interactions or the forces between neutrons and protons must require some conveyer. When Fermi explained nuclear beta-emission in terms of the pair of conveyers, electron and neutrino, it was natural to suspect a connexion between beta-emission and nuclear forces. But soon it was found that if the electron-neutrino pair is considered to be the conveyer or 'field' of nuclear forces, the calculated force would be very small compared with the empirical value. New attempts were made to invent electron-positron pair field for explaining nuclear forces, but the descriptions were only qualitative. In 1935 Yukawa conceived of a new field particle of mass about 200 times that of the electron which would yield the correct empirical values of the nuclear forces and would also explain beta-decay in terms of its disintegration into an electron and a neutrino. Although subsequently the experimental discovery of some cosmic-ray components of mass approximately equal to that of the postulated field particle (later named 'meson') took place in America, it was the American Physical Society that ignored for some time the new nuclear field theory. But at that very moment a series of articles advocating (and improving upon) the Yukawa theory appeared in the Proceedings of the Royal Society of London. Yukawa had dealt with a spin-0 or spinless meson, but improvements were made by introducing a spin-1 meson. Moreover, a 'neutral' meson was involved in order to satisfactorily explain the experimentally established fact that the same charge-independent force exists between two protons or between two neutrons as that between a proton and a neutron. Thus a 'symmetric meson theory' was set up in which both charged and neutral mesons were needed for describing the nuclear forces. Having watched all these developments Bethe not only drew the attention of the American Physical Society to the ignored theory, but even did away with the charged meson, and chose to describe the nuclear forces exclusively in terms of the unobserved neutral meson ('neutral meson theory'), and actually succeeded in quantitatively explaining the deuteron quadrupole moment in contrast to the failure of the symmetric theory, but could not evidently explain the beta-decay and could not do away with the arbitrary 'cut-off' radius. Møller and Rosenfeld attempted to eliminate the arbitrary 'cut-off' prescription by superposing or 'mixing' two co-operating meson fields represented by spinless and spin-1 mesons. Since already a problem was created by the discrepancy between the observed lifetime of the cosmic-ray meson (*c.* 10^{-6} sec.) and the theoretical lifetime of the Yukawa meson (*c.* 10^{-8} sec.), the Møller-Rosenfeld 'mixture' apparently reconciled this difficulty by assuming that the nuclear field contains *both kinds* of mesons, one having a short life responsible for beta-decay and the other a long life. This theory was an adumbration of the proper theory of two distinct mesons (now known as *pi*- and *mu*-meson), but it failed to realize that the nuclear field is not a 'mixture' of both, but is to be represented uniquely by the short-lived meson, which must differ from the other meson not only in lifetime, but also in mass and in the strength of coupling with the nucleon. Already some nucleon-nucleon scattering experiments had created the suspicion that the nuclear meson is heavier than the cosmic-ray meson. Although the Schwinger 'mixture' attempted to modify the Møller-Rosenfeld theory by considering the spin-1 meson to be more massive than the spinless one, it did not improve matters, and the M.-R. mixture continued to be favoured; thus the question of any mass difference between the two kinds of mesons remained somewhat neglected till the formulation of the two-meson hypotheses by Sakata and by Marshak just before the discovery of *pi*- and *mu*-mesons. It is interesting that just four years before this discovery the 'mixed' meson theory was criticized by Pauli, who expressed his reluctance to accept a new particle by suggesting that the spin-1 meson was an 'excited state' of the spinless meson, and not an independent particle, the introduction of which would be 'admittedly undesirable' (*see* § 20). An important phase in the history of the meson theory is Marshak's formulation of the 'meson-pair theory', which sought to do away with the 'unobserved' neutral meson, and to utilize only the observed cosmic-ray mesons in the description. This was a modified extension of the electron-positron pair field theory that tried to compete with the Yukawa theory. However, in later modifications of the meson-pair theory the neutral meson was also included in the face of the usual criticisms against the neutral particle (*see* Part II). Another significant phase of this history (up to 1943) is that serious attempts were started to investigate whether the meson-nucleon coupling is strong or weak, but no definite conclusion could be arrived at (*see* § 19); it is to be noted that the non-identity of the mass and coupling strength of the two kinds of 'mixture' mesons was yet to be suspected, and correct spin values were yet to be assigned. Although Sakata had proposed the appropriate 'two-meson' hypothesis as early as 1943, war circumstances prevented its publication before 1946.

1. Fermi Field and Nuclear Forces

In a popular article on 'What Holds the Nucleus Together?' Hans A. Bethe remarked: 'We are confronted with a problem which is just the opposite of the one physicists had when they began to study the atom as a whole. They were completely familiar with the forces (electric) at play, but had to discover the laws (quantum mechanics) that governed the operation of these forces. In the case of the nucleus, we are fairly confident about the governing laws (again quantum mechanics), but must discover the force.'

The necessity of introducing specific nuclear forces, which could not be interpreted in terms of electromagnetic interactions between charged particles, was felt just after the discovery of the neutron that must be strongly bound to the nuclear protons and neutrons. Heisenberg's early attempt at explaining the nuclear proton-neutron interaction in terms of an exchange electron was soon followed by Fermi's formulation of the beta-decay theory of 'electron-neutrino field'. It is interesting that Heisenberg, who had initially ignored Pauli's neutrino hypothesis, was the first to suggest (lectures at the Cavendish

Laboratory, Cambridge 1934) a probable connexion between the 'electron-neutrino field' and the proton-neutron forces. A great expectation was created in favour of the possibility of accounting for nuclear forces in terms of the 'Fermi field'. Attempts along this line by scientists like Nordsieck, Tamm and Iwanenko very soon encountered grave difficulties. The problem of the proton-neutron force becoming infinitely divergent for $r = 0$ (r being the separation between the interacting nucleons) was sought to be overcome (accepting Uhlenbeck and Konopinski's modified form of the Fermi field) by the 'cutting-off' procedure at the observed range of nuclear forces (10^{-13} cm), but the calculated force was found to be too small by a factor of 10^{12}. All subsequent attempts to reconcile nuclear forces with the Fermi field turned out to be a battle for a lost cause. Nevertheless the obsession in favour of the Fermi field was not easily dispelled. This is clearly expressed in a comprehensive review article[2] on nuclear physics by Bethe and Bacher (April 1936): 'This highly unsatisfactory result is, of course, due to the extremely small value of the constant g which governs the β-emission. However, the general idea of a connection between β-emission and nuclear forces is so attractive that one would be very *reluctant to give it up*' (Italics mine).

It is noteworthy that Yukawa's pioneering paper on meson field was published in 1935 in Japan, but it drew the attention of the western scientific circles as late as mid-1937. This paper was first mentioned in the *Physical Review* (June 1937) by Oppenheimer and Serber[3] in connexion with their comments on the 'nature of cosmic-ray particles'. Already by 1936 evidence was strong against considering the penetrating corpuscular rays of the cosmic radiation as protons and by mid-1937 the results of Anderson and Neddermeyer and those of Street and Stevenson[4] almost convincingly indicated the existence of cosmic-ray particles of mass intermediate between that of the proton and electron. Oppenheimer and Serber, when discussing the nature of the penetrating cosmic-ray particles, mentioned Yukawa's paper in their note because of its suggestion of an exchange particle of intermediate mass; however, they commented on the Yukawa theory in the following terms: '... In trying to account in detail along these lines for the characteristics of nuclear forces, one meets with difficulties hardly less troublesome than in the various forms of electron-neutrino theory which have been proposed. In particular, the reconciliation of the approximate saturation character of nuclear forces with the apparent equality of like and unlike particle forces and with the magnetic moments of neutron and proton could here too be achieved only by an extreme artificiality. These considerations therefore cannot be regarded as the elements of a correct theory, nor serve as any argument whatever for the existence of the particles; their valid content can at most be this: that these particles may be emitted from nuclei when sufficient energy ($> \mu c^2$) is available, and that they will ultimately prove relevant to an understanding of nuclear forces.' When these authors wrote this, the idea of the equality of like-particle (*nn* or *pp*) forces and unlike-particle (*np*) forces was almost accepted subsequent to the convincing proton-proton scattering experiment of Tuve, Hafstad and Heydenburg in 1936.[5] The assumption that the forces between all kinds of nuclear particles are the same had however been put forward by Young[6] as early as 1935, i.e. at a time when Yukawa's theory of nuclear forces excluded the *pp*- and *nn*-interactions, and considered only the *np*-interaction. The critical attitude towards the Yukawa theory, as expressed in the above-quoted passage, is to be judged against such a context of theorizations and experimentation.

Even a few months before this mention of Yukawa's suggestion of a scalar charged meson field, that is, before it came to the notice of the western circle of nuclear physicists, serious attempts[7] were being made to reconcile the beta-decay and the nuclear forces by invoking an artificial function. But such a modification of the Fermi coupling was not satisfactory, as is clear from the following statement of Camp[8] : '. . . A simple form of this function leads to a phenomenological description of beta-decay and proton-neutron interaction. The application of this function to the like-particle interactions, however, gives for them poorly defined ranges and magnitudes which are too small. The discrepancies seem to be intrinsic, so that this attempt to reconcile beta-decay and heavy particle interaction has been abandoned.'

2. Electron-positron Pair Theory of Nuclear Forces

Attempts to explain the nuclear forces took some new directions. Gamow and Teller chose to modify[9] the beta-transformation theory in a convenient way that would explain, they claimed, the nuclear forces between the nucleons and also their magnetic moments. They tried to explain these effects as due to electron-positron pair emission ($n \rightarrow n+e^{+}+e^{-}$, or $p \rightarrow p+e^{+}+e^{-}$) instead of electron-neutrino pair emission of the ordinary beta-decay that renders both the above effects too small by a factor of about 10^{12}. By arbitrarily assuming the probability of electron-positron emission to be 10^{12} times greater than that of the ordinary electron-neutrino emission Gamow and Teller arrived at the result that the nuclear interaction is attractive between any pair of nucleons without any dependence on their charges—a result, which, so to say, was in conformity with the result of the *pp*-scattering experiment of Tuve, Hafstad and Heydenburg performed in 1936. It is interesting that even the prospect of explaining the *charge-independence* of nuclear forces on the basis of the newly suggested electron-positron emission process could not create a *very* enthusiastic universal response to this approach. However, we find some serious discussions of this suggestion in a few subsequent papers on nuclear forces. Kemmer, however, pursued[10] this line of treatment and suggested the so-called charge-independence hypothesis or 'CIH' that stated that the electric charge of the nucleons seems to be irrelevant as far as the specifically nuclear forces are concerned. It is noteworthy that Kemmer himself put forward his CIH the very next year (1938) on the basis of his new assumption of the existence of a *neutral* 'heavy electron' shortly after the Yukawa theory came to his notice. We postpone the discussion of the 'heavy electron' approach. We should mention that simultaneously with Gamow-Teller proposal, Wentzel[10a] also independently put forward the electron *pair* theory.

3. Groping for a New Concept

By mid-1937 the time was already ripe for invoking a radically new concept. The nuclear physicists were groping for it. They were not only uncertain about the nature of the transmitting particles for nuclear interactions, but were also formulating speculative hypotheses on the form of the dependence of the nuclear forces on the separation between the nucleons. This situation was clearly indicated by Bethe and Bacher,[2] who were then (1936) unaware of Yukawa's first paper: 'The determination of analytical *form* of the dependence of the nuclear forces upon the distance between the nuclear particles is at present quite hopeless. Any rapidly decreasing function, whether $e^{-\alpha r^2}$, $e^{-\beta r}$, a rectangular potential hole, or a more complicated function, having the same characteristic behaviour, will fit the experimental data equally well as long as no *very* accurate calculations of the binding energies expected for a given force, are available.'

Before Yukawa's theory came to the limelight Wentzel put forward[11] a theory of nuclear forces and beta-decay in which it was assumed that both the proton and neutron can change into both charged and uncharged spinless unstable particles (obeying Bose-Einstein statistics)—the so-called 'singlet-proton' and 'singlet-neutron' (singlet state indicating spinlessness) having slightly greater mass than that of the proton and neutron. The changes were imagined to take place by the emission or absorption of an electron or a neutrino:

neutrino $\longleftrightarrow$ '*s*-neutron'+neutrino
neutrino $\longleftrightarrow$ '*s*-proton'+electron
proton+electron $\longleftrightarrow$ '*s*-neutron'
proton+neutrino $\longleftrightarrow$ '*s*-proton'.

The nuclear forces and the magnetic moments of the proton and neutron were found to be in qualitative agreement with experimental results. The like-particle interactions were found to be of the same order as that of unlike-particle interactions. Wentzel was bold enough to conceive of unobserved particles for explaining nuclear forces as well as beta-decay by means of a unitary mechanism, but he himself admitted that the interaction calculated by him was valid for scattering processes at high velocities 'but surely not for the neutrons and protons bound in a nucleus'.

4. Yukawa Hypothesis

Before Wentzel's proposal could make any impression, experimental evidence became strong enough in favour of the existence of a heavy component of the cosmic radiation; and at this moment the arrival of Yukawa's imaginative postulation of an unobserved particle of mass *c.* 200m$_e$ (m_e = mass of the electron) as the conveyer of nuclear forces and also as the conveyer of nucleon-lepton interactions put the efforts of the groping minds on the right track.[12] The pioneering role of Yukawa's theory consists, among other things, in its original suggestion of a relationship between the range of the nuclear forces and the mass of the conveyer particle. Yukawa however did not formulate his theory in a relativistically invariant form, and considered only the neutron-proton interaction to the exclusion of the proton-proton and neutron-neutron interactions. He referred to the *pp*-interaction as the 'electrostatic repulsion between the protons'. This was the only conceivable idea about the interaction between protons before the results of the proton-proton scattering experiment (1936) of Tuve *et al.* (*see* ref. 5) were reported, which convincingly indicated that there must be a force between two protons *besides* the Coulomb force, and that the former must be attractive and short-range. The characterization of the *pp*-interaction as merely an 'electrostatic repulsion' seems to suggest that the idea of probable equality of the forces between like and unlike nucleons did not occur to Yukawa. Even with this limitation, Yukawa's non-relativistic theory of a scalar nuclear potential of the form $U \sim \dfrac{e^{-\lambda r}}{r}$ satisfactorily explained the strong interaction between the nucleons and the so-called 'U-particles' or 'Yukawa particles' or 'heavy electrons' which must have integral spin and must obey Bose statistics. Yukawa also sought to explain the weak interaction of beta-decay in terms of the postulated U-particles, which, according to him, decayed into an electron and neutrino.

The next natural step was an attempt at a relativistic formulation of Yukawa's original theory. Yukawa himself (in collaboration with Sakata) took this step.[13] His description of the motion of the U-particle again by means of a scalar potential led to the problem already dealt with by Pauli and Weisskopf in 1934 that had indicated the similarity between the relativistic Schroedinger equation of a Bose particle of *finite mass* (involving a *scalar* function) and the electromagnetic equation involving *massless* photons and a *vector* potential. But the calculated result did not give the correct form of nuclear forces, since it turned out that the ^3S-state of the deuteron is always repulsive and the ^1S-state is always attractive with the same absolute value, which is contrary to observation. The theory of Yukawa and Sakata led to wrong spin-dependence of the nuclear forces.

5. Advocacy of Yukawa Hypothesis

At that appropriate time (1936) Proca indicated that a scalar wave function is not the only possible wave function for Bose particles. He showed that just as photons, which are massless, are described by a vector field, such a *vector* field can also be used to describe Bose particles with a finite rest mass. Proca's theory[14] arrived just before the theory of Yukawa and Sakata failed to account for the magnetic moment of the nucleons and the nuclear forces in terms of the simplest relativistic wave equation for Bose particles, i.e. the Klein-Gordon equation involving a scalar wave function. Proca's theory now offered the next reasonable choice of assuming a vector wave function for the Yukawa particle (satisfying Bose statistics). Fröhlich *et al.*[15] made this assumption, and concluded that only for the vector formalism the sign and spin-dependence of the neutron-proton force is in agreement with empirical evidence.

The *np*-potential turned out to be *attractive* for the ^3S-term as well as ^1S-term. With some satisfaction the above authors commented: 'Although in our theory three constants are available, this success (of explaining the nuclear forces) is by no means trivial. . . Only the vector scheme leads to a qualitative agreement with the experiments.' Here the statement in favour of the vector scheme is very categorical. But about the same time one of the above authors, Kemmer, pointed out[16] that there are four inequivalent but equally simple possibilities—scalar, vector, pseudovector and pseudoscalar—of formulating a field theory of Bose particles, and that the similarity of all the cases studied is so great that it would be unjustified to discriminate in favour of any them *a priori*; however, 'for reasons of economy it is of course to be hoped that a comparison with experience will prove that one of the cases alone is sufficient to give a description of reality'. Comparing the four competing cases with experimental data he justified the preference for the vector formalism.

Here it is relevant to mention that after the appearance of Yukawa's paper Stueckelberg[17] independently suggested the existence of some non-linear tensor field for explaining the nuclear interactions, and described matter by a 16-component spinor, each group of four components referring to the electron, neutrino, proton and neutron states respectively. This implied the existence of some Bose particles of integer spins and mass exceeding $24m_e$ associated with the so-called 'generalized radiation field'. A proton was stated to decompose into a neutron and a newly postulated Bose particle of positive charge, which in turn would decay into a positron and an antineutrino. The reason why the theory of this field with tensorial and spinorial components did not gain much favour is understandable from a remark by Kemmer: 'In each case (of the scalar, vector, pseudoscalar and pseudovector formalisms) the energy density is essentially positive; this is a special characteristic of these simple cases. If we had proceeded from any more complicated examples of Dirac's spinor equations, we would not have obtained this result... It seems certain that any alternative formalism would have to be a great deal more complicated for physically satisfactory results to be expected. A theory for spin values greater than unity therefore immediately leads to serious difficulties.'

6. Invocation of the Neutral Meson

The theory of charged 'heavy electrons' gave a satisfactory account of the neutron-proton interaction. But the explanation of the proton-proton interaction (besides the Coulomb force) in terms of charged heavy electrons called for double transitions (emission of heavy electrons by each of the two protons and their absorption by the other), i.e. second order process or fourth power order process proportional to g^4, whereas the first approximation process of *np*-interaction is proportional to g^2. As already mentioned, the possibility of the sameness of the *pp*-, *nn*- and *np*-interactions had been proposed as early as 1935, and by 1936 experiments on *pp*-scattering had suggested this equality. But Fröhlich, Heitler and Kemmer clearly expressed intheir above discussed paper that they were not ready to accept the equality of the *pp*-force and *np*-force, nor the strongly attractive character of the *pp*-force. Therefore they considered it desirable to work out their theory for the *pp*-interaction as a second order force in terms of charged heavy electrons. This second order force was calculated to be *repulsive*. Although they themselves felt that the *pp*-force would turn out to be a first order attractive force of the same magnitude as of the *np*-force just by invoking a neutral heavy electron or so-called 'neutretto' (as Yukawa *et al.*[18] in fact did), their scepticism about the equality of the *pp*- and *np*-interactions and about the attractive character of the *pp*-force prevented them at that time from taking the bold step of introducing the postulated neutral particle for reformulating the CIH (charge-independence hypothesis) which Kemmer had suggested in 1937 within the framework of a modified Fermi theory. In an almost contemporary paper by Bhabha,[19] where he obtained the desired *np*-interaction by describing the motion of the heavy electrons in terms of four wave functions transforming like a four-vector, he did not consider the existence of a neutral heavy electron as improbable, but considered the invocation of this particle as unnecessary, because he thought that 'the introduction of such particles has nothing to do formally with the theory of U-particles which can be formulated without them and is in addition to it. The theory of neutral Bose particles can be formulated exactly as the theory of U-particles with trivial modifications'.

However, within a few months after these negative attitudes towards the neutral particle were expressed, Kemmer reformulated his CIH by introducing a *neutral* heavy electron on the basis of a newly conceived symmetry between the charged particle and its uncharged counterpart in analogy with the symmetry between the proton and neutron ('and probably between electron and neutrino'—Kemmer). It is evident that in the above-discussed joint paper Kemmer together with Fröhlich and Heitler did not attach any importance to the suggestion of Breit *et al.*[20] who showed that the results of the 1936 experiment of Tuve *et al.* on *pp*-scattering could be theoretically interpreted by assuming a strongly attractive force between protons at close distances of approach. But towards the end of 1937 Tuve *et al.* made another experiment[21] on *pp*-scattering and cogently vindicated the assumption of a strongly attractive short-range force (acting in addition to the repulsive Coulomb force). Kemmer, in his reformulated CIH,[22] considered the 1937 experiment of Tuve *et al.* as a convincing evidence in favour of the assumption of the equality of *np*-, *nn*- and *pp*-interactions and the assumption of the attractive character of *pp*-interaction. Kemmer also showed that the postulated neutral particle does not involve the existence of its corresponding antiparticle (neutral), and that this 'apparent asymmetry' leads to the correct interactions between nucleons. The particle-antiparticle symmetry was eliminated, but both charged and neutral heavy electrons were introduced in terms of another symmetry (later known as symmetrical meson theory).

7. American Physical Society and Yukawa Hypothesis

We may note that the papers of Fröhlich, Kemmer and Heitler and of Bhabha, where the 'heavy electron' theory of nuclear forces was seriously developed, reached the editorial office by February 1938, but that the American Physical Society ignored Yukawa's theory even up to that time is evident from the fact that none of the papers presented at the 219th meeting[23] of the Society on 25–26 February 1938 made any mention of that theory. Marshak and Bethe, in their paper, chose to conceive of the nuclear interaction in terms of the electron-positron field suggested already by Gamow and Teller (*see* ref. 9). Critchfield and Teller, in their paper,[24] also stated that a nucleon 'can emit an electron-positron pair into one definite (or a few definite) quantum state of finite extension L (this assumption violates relativity but secures convergence)'. Thus the Yukawa theory remained undiscussed at this meeting after an unfavourable criticism of the so-called 'dynaton' theory (meson theory) by Serber at the 217th meeting[25] of the Society of 17–18 December 1937. Yukawa's failure to account for (on the scalar relativistic theory) the known stability of the triplet state of the deuteron and the strongly believed equality of the like- and unlike-particle forces was stated by Serber to be an intrinsic weakness of the dynaton hypothesis. Yukawa's theory was discussed by Lamb and Schiff in a 'Physical Review' article[26] at a time when the American Physical Society did not receive the new theory favourably. In this article they did not take the electron-positron pair theory of nuclear forces (after a prepublication perusal of the paper of Teller and Critchfield) seriously. But they compared the relative advantages of the electron-neutrino field and the dynaton field in affording a description not only of the nuclear forces, but also of the magnetic properties of the single nucleons. They found the dynaton field theory to be more convergent than the electron-neutrino field theory, but stated (following Serber) that since the scalar dynaton has no spin and hence no magnetic moment, there would not be any resultant magnetic moment of the proton or neutron; they chose to introduce, in addition to the scalar dynaton, another kind of dynaton having unit spin and described by a six-vector wave function; on this theory, the neutron is found to have the same magnetic moment (same sign) as the proton in contradiction with experimental evidence. They therefore stated: 'On the electron-neutrino theory, any magnetic moment that might appear would come from the relativistic electron current, and thus the introduction of a new kind of particle is unnecessary.'

It is interesting that at the very time when it was thus considered unnecessary to introduce a new kind of particle, Fröhlich, Heitler and Kemmer in their above-discussed joint paper made the postulated Yukawa particle responsible for the magnetic moments of the neutron and proton. The magnetic moment of the nucleon was found to be due to the emission and reabsorption of the transverse waves associated with the 'heavy electron' or 'dynaton'. In the charged meson theory: physical proton = bare neutron + positive meson cloud, physical neutron = bare proton + negative meson cloud. According to Fröhlich *et al.* the contribution to the magnetic moment of the bare nucleon amounts to nearly one nuclear magneton in the physical proton state, and is practically zero in the physical neutron state: $\mu_p \cong 1+\mu_m$, $\mu_n \cong -\mu_m$. Here μ_p, μ_n, μ_m mean the magnetic moments of the proton, neutron and meson respectively. μ_p and μ_n were calculated to have the right sign. Using the then determined value of $\mu_p = 2{\cdot}46$ n.m., they found $\mu_n = -1{\cdot}80$ n.m. With these values the mass of the heavy electron was found to be $180m_e$, which was in good agreement with the value suggested by Yukawa.

In the 220th meeting (20–28 April 1938) of the American Physical Society, Bethe took the lead in seriously reviewing the so-called 'barytron' (meson) theory proposed and advocated by Yukawa, Bhabha and Kemmer. Thus he appears to have broken the sceptical silence over the Yukawa theory that the American Physical Society had maintained since Serber's unfavourable criticism of the same in the 217th meeting.

8. Eddington's 'Fundamental Equation' and Yukawa Hypothesis

The heavy electron hypothesis was favourably received from another viewpoint. Eddington, in his consistent effort at linking the universe to the atom, set up the so-called 'fundamental equation': $10\,m^2 - 136\,m.m' + m'^2 = 0$ (*see* Eddington's 'Relativity Theory of Protons and Electrons', 1936), where m' is the mass of a 'scalar particle', i.e. a particle, the expectation value of the spin and charge of which are zero, m denotes the mass of a charged particle with spin $\frac{1}{2}$. The two values of m are shown to be associated respectively with the two signs of the charge and writing them as m_{proton} and m_{electron} we have

$$m_p : m' : m_e :: 1847{\cdot}6 : 135{\cdot}9 : 1.$$

Eddington wrote that the scalar particle is 'a mathematical fiction, having no counterpart in experimental physics'. But after the discovery of the cosmic-ray particle of intermediate mass, attempts were made to reinterpret the neutral scalar particles, which, according to Eddington, do not exist. For example Corben[27] accepted (1938) Eddington's fundamental equation, but treated the scalar particle 'with as much independent existence as is usually ascribed to the neutrino'. According to him, this neutral particle of mass $m' = 135{\cdot}9m_e$ combines with an electron or positron with the emission of a massless neutrino and yields a 'heavy electron'—negative or positive—obeying Bose statistics and having a mass between 136 and $137m_e$. This result, according to him, was in 'close agreement' with the Yukawa theory 'supported by facts so far as present experimental accuracy goes'. Thus once the initial scepticism about the Yukawa theory was dispelled, such an opinion in favour of the existence of Eddington's neutral scalar particle was put forward not only for supporting the Yukawa theory, but also the controversial 'fundamental equation'. About the same time Arnot[28] for example, attempted to give a new interpretation of the 'heavy electron' as the combination of an electron and a 'heavy neutrino' of mass 136 spin $\frac{1}{2}$ (the heavy electron mass being considered $137m_e$) because he wanted 'to do away entirely with the conception of the massless neutrino'. It is interesting that one scientist with his enthusiasm for supporting Eddington's fundamental equation and another scientist with his enthusiasm for rejecting the hypothesis of massless neutrino attached a uniqueness of mass to the heavy electron ($137m_e$), which was never ascertained when (1938) they put forward their respective viewpoints. Rather (excepting the first measurement by Street and Stevenson (*see* ref. 4) in 1937: $\approx 130m_e$) the average mass lay in the neighbourhood of $200m_e$ in 1938. The question of uniqueness of mass however remained uncertain even after the end of the Second World War.

9. Problem of Meson Mass

We have already said that the 'barytron' (meson) theory was gaining favour among the circle of the American nuclear physicists after Bethe's review of the theory at the Washington meeting of the American Physical Society in April 1938. The proton-proton scattering experiments, performed already by Tuve, Heydenburg and Hafstad (THH) in the energy region between 200 kev and 900 kev (1936, 1937), were extended to the high energy region 900 kev–2400 kev by Herb, Kerst, Parkinson and Plain (HKPP) in 1939[29] on the advice of Breit, who, together with Present and Condon, had theoretically interpreted the experimental results of THH in terms of an assumed strong and short-range attractive interaction. The results of HKPP were now analysed by Breit *et al.*[30] at the end of 1938. After attempting to interpret the data in terms of a 'Gaussian' potential $Ae^{-\alpha r^2}$ and an exponential potential $Be^{-2r/b}$ they expressed their scepticism about the validity of these assumed forms of interaction potentials; and at the same time they stated: 'It may be that a solution of the problem (*pp*-scattering) will be given by a development of the mesotron theories of nuclear interactions.' (The name 'mesotron' for the so-called heavy electron was universally accepted tentatively by the nuclear physicists after Millikan[31] had placed before Bohr, towards the end of 1938, this suggestion of Anderson and Neddermeyer. However, the name 'mesotron' was soon—1939—modified to 'meson' after Bhabha argued in favour of the latter[32].) Subsequently, Breit *et al.*[33] spoke more emphatically in favour of the validity of the 'meson potential' in preference to the square well and the Gauss potential. It should be mentioned here that the *pp*-scattering data suggested a neutral meson mass *c.* $330m_e$, which is much larger than the mass of the charged cosmic-ray mesons *c.* 180–$240m_e$. Referring to this aspect the above authors later[34] remarked: 'The partial success of the meson potential . . . to fit experiment is far from being a definite encouragement for the meson theory of nuclear forces . . . The discouraging feature is the very poor agreement of the mass of the meson as obtained from proton-proton scattering area and from cosmic-ray evidence . . . Quantitative applications of the meson theory to problems of nuclear structure are still very questionable.' We should note that this statement was made in 1939, and that the *pi*-meson (mass *c.* $300m_e$) and *mu*-meson (mass *c.* $200m_e$) were discovered in 1947. The neutral *pi*-meson was discovered still later. Therefore, the unhappiness about the inequality of the masses of the 'neutral meson' and 'cosmic-ray meson' (as they were understood till 1947) may be appreciated against the historical context.

10. Bhabha's Neutral Meson Theory

It is interesting that once the postulation of the neutral meson became acceptable, after Kemmer's formulation of the symmetrical meson theory (*see* ref. 22), a new theoretical reasoning developed which considered the neutral meson as the sole conveyer of the nuclear forces (to the *exclusion* of the charged mesons).

Bhabha, who had earlier (*see* ref. 19) considered the invocation of the neutral meson as theoretically redundant, now built up[34a] a 'classical' theory of mesons, in which the supposed similarity of the meson field equations to Maxwell's equations necessitated a preferential acceptance of only the neutral meson. This theory dealt with a fundamental constant $\chi = \mu/\hbar$(μ being the rest mass of meson) with no explicit appearance of μ or $\hbar$, where the limit $\mu = 0$ (i.e. $\chi = 0$) would lead to the Maxwell equations. And this classical theory *did* conveniently put $\chi = 0$ (i.e. the mass of the individual mesons was *neglected* compared with the rest mass of nucleons) in calculations only on the basis of the assumption that the mesons are *neutral*. On the other hand, the theory shows that for a charged meson field one could not put $\mu = 0$ at any stage, because such a field cannot exist without having a mass μ or fundamental length χ associated with it. Bhabha justified the classical treatment with neutral mesons: 'The treatment of a field classically instead of quantum-mechanically is equivalent to a neglect of the momentum properties of the individual light quanta. We may therefore expect the classical theory to give correct results for all processes where the momenta of individual mesons is small compared with the rest mass of neutrons (or protons).' Kemmer reviewed this peculiar situation[34b] that demanded a matrix treatment of the meson theory in view of the very evident appearance of mesons as *particles* to the experimental worker but at the same time required the formulation of the meson-nucleon interaction in terms of its similarity to Maxwell's field equations: 'There can hardly be any doubt that it (matrix treatment of meson theory) may serve to simplify practical calculations in cases where the meson appears primarily as a *particle*. It has not been here attempted to include the interaction of the meson with protons and neutrons, and it can be readily seen that in the scheme here used this would not be simple. It is, however, clear that in that interaction the meson enters primarily as a *field* (although a non-classical charged one), and it is then only natural to *retain the old formulation*.' (Last italics mine.) This was the theoretical context against which we are to view Bhabha's consistent subsequent attempts to improved 'classicals' meson theories, where neutral mesons would play the field-conveyer role, or the postulation of the proton 'isobars' would (*see* § 16) put the charged meson theory on the same footing as the neutral theory.

11. Bethe's Neutral Meson Theory

As already mentioned, Bethe broke the temporary silence of the American Physical Society over the meson theory. He went a step further. Bethe assumed that nucleons interact only with neutral mesons.[35] He took the mass to be *c.* $177m_e$, and considered it to have spin 1 and to obey Bose statistics. And it was on the basis of this neutral theory that Bethe predicted the correct sign and value (*c.* $2{\cdot}7 \times 10^{-27}$ cm^2) of the deuteron quadrupole moment in close agreement with those obtained from the experiments of Kellog, Rabi, Ramsey and Zacharias reported a few months earlier. In contrast to this, the symmetry theory gave 'improbably high values for the quadrupole moment (in addition to the wrong sign . . .)'. However, Bethe admitted that according to his neutral theory 'it is of course difficult to explain the beta-decay and the magnetic moments of proton and neutron'. This theory could not be taken very seriously. For the purpose of testing its validity, Breit and Kittel[36] utilized it in their attempt to estimate the p-wave effects of neutron scattering by protons. The problem of the meson mass (180 or $300m_e$) however continued to remain, among other unsatisfactory features, in the computation of the total scattering. Subsequently Breit *et al.*[37] considered the p-wave effects for proton-proton scattering on the basis of Bethe's neutral theory. Here again the problem of the meson mass (*c.* 180 or *c.* $300m_e$) presented itself. The possibility of the existence of a heavier meson of mass *c.* $300m_e$ was not seriously considered by the nuclear physicists at that time.

Bethe pursued his investigation of the nuclear forces in terms of his neutral meson theory.[38] The neutral theory suggested complete equivalence and indistinguishability of neutron and proton as far as the associated meson fields are concerned. It was then indicated that the part of the force independent of the nucleon spin (total interaction = spin-independent part U or $g^2e^{-kr}/r+$ spin-dependent part V involving f^2) does not serve any useful purpose in the theory since this part is repulsive in the neutral theory as well as in the symmetrical theory for the ^1S-state, whereas experimentally there is an attractive potential in ^1S-state. Bethe hypothesized that the spin-dependent interaction is the sole nuclear force ('single force hypothesis' or SFH), and claimed that this force can explain all the empirical facts about two-body systems. The spin-dependent interaction V consists of two parts V_1 and V_2, the latter part being a 'tensor interaction' that causes the ground state of the deuteron to have a quadrupole moment. However, V_2 diverges as $1/r^3$; therefore it was found necessary to cut off the potential at small distances and replace it by a more slowly diverging (less than $1/r^2$) or non-divergent one. 'The exact value r_0 (cut-off distance), and the way in which the interaction must be cut off cannot at the moment be deduced from first principles but can only be obtained from a quantitative treatment of the two-body problem in conjunction with empirical data on binding energies, scattering, etc.' Arbitrariness of the process is evident. Bethe's theory had to deal with two unknowns, f, the strength of the interaction, and r_0, the cut-off distance. He carried out calculations with two alternative ways ('zero cut-off' assuming the potential inside r_0 to be zero, or 'straight cut-off' retaining the value it had at r_0) of cutting off, and arrived at $2{\cdot}70\times10^{-27}$ and $2{\cdot}61\times10^{-27}$ cm^2 for the value of the deuteron quadrupole moment (for the two methods of cutting off) in agreement with the experimental value, whereas, as already mentioned, the symmetrical theory gave the value 10 times too large and of the wrong sign. Moreover, the neutral theory gave a reasonable 'cut-off' distance of about one-third the range of the nuclear forces, in contrast to an unacceptably large cut-off distance computed by the symmetrical theory. But Bethe referred to the results to be 'regrettable, since only the symmetrical theory gives a natural explanation of the beta-decay and of the extra magnetic moments of neutron and proton'. He admitted that the neutral theory has to fall back on the electron-neutrino field of the Fermi theory, whereas the symmetrical theory explains the beta-decay by assuming that mesons are an intermediate stage in beta-emission which, according to him, 'provides a much more unified picture of nuclear phenomena'. Moreover, he felt that 'it seems rather unlikely that the charged meson which, after all, is known to exist should play no role at all in nuclear phenomena'. Bethe however referred to a 'serious argument against the symmetrical theory'[39] because of its computation of the half-life of the meson as *c.* 10^{-8} second in contradiction to the cosmic-ray meson life *c.* 10^{-6} second—a discrepancy of the order of 100 which according to him cannot be removed by any 'reasonable change of the meson mass' (*see* ref. 38). Moreover, this theory gives an impossible range of the nuclear forces (*c.* 10^{-12} cm). Here we again remark that this difficulty was essentially due to the fact that the distinction between the Yukawa meson or *pi*-meson (lifetime *c.* 10^{-8} sec.) and the cosmic-ray meson or *mu*-meson (lifetime *c.* 10^{-6} sec.) was yet to be suspected.

12. 'Mixed' Meson Theory and the Idea of Two Mesons

At this time Møller and Rosenfeld[40] proposed a 'mixed' meson field theory that apparently solved the difficulties of the symmetrical meson theory by introducing two entirely separate meson fields—vector and pseudoscalar. According to them, one of the two types of mesons rapidly decays into electron and neutrino (thus accounting for the beta-decay), while the other type (cosmic-ray meson) decays slowly. They showed that if the nuclear interaction is assumed as due to such a mixed field of two types of mesons of the same mass ($M_{ps} = M_v$) and the same coupling constant, then the tensor force, which is associated with a single-meson field and therefore inherently contains inadmissible singularity of the type $1/r^3$ (thus requiring an arbitrary cut-off), disappears in the non-relativistic region. The mixture provides a solution of the wave equation without 'cutting off'. According to this theory, the deuteron quadrupole moment, which indicates the existence of the tensor force in the nuclear interaction, is essentially a relativistic effect owing to the vanishing of the tensor force in the non-relativistic region. Møller and Rosenfeld actually derived an expression (yielding a value *c.* 4×10^{-27} cm^2) for the quadrupole moment with correct sign. Later in 1945, however, Ning Hu[41] showed by a rigorous examination of the relativistic corrections that the quadrupole moment on the Møller-Rosenfeld theory would vanish in the relativistic region; therefore the mixed field theory proved to be basically unable to explain the quadrupole moment. We postpone the discussion of a later modification of the mixed field theory by Schwinger.

Møller and Rosenfeld passed on their MS. to Bethe before publication. Bethe however was not impressed by this mixed meson theory; he explained the reasons (*see* ref. 38). 'While it must be admitted that the Møller-Rosenfeld theory solves the difficulties of symmetrical meson theory, I do not think that a solution should be sought on these lines ... It seems that one type of mesons, either represented by a vector or by a pseudoscalar field, is entirely sufficient to account qualitatively for all properties of nuclei, i.e. the forces between the nuclear particles as well as the beta-transformation, and it seems rather *superfluous to have a second type* ... There has been added to nuclear theory a very complicated field theory, without achieving any greater definiteness in the results.' (Italics mine.) Then commenting on the symmetrical theory Bethe said: 'If the symmetrical theory is fundamentally correct, I believe it is much more likely that its quantitative aspects will be corrected by a better understanding of the cut-off process ... We do not know the correct method yet.' It is interesting that although Møller and Rosenfeld perhaps complicated the description by invoking a mixture of fields, they were bold enough to introduce the very idea of two types of mesons with different lifetimes (but unfortunately imagined to have the same mass and coupling strength); on the other hand, Bethe reasonably challenged the idea of a mixed field, but could not imagine the possibility of the existence of two types of mesons. This was a transitional stage in the development of the meson theory.

13. Problem of Beta-decay and Meson-decay

We may recall that Yukawa in his first paper suggested that there is a connexion between beta-decay and meson-decay, and that the beta-decay should be considered as taking place through meson as intermediary, rather than through the direct disintegration of the nucleon into an electron and neutrino. In 1938 Yukawa *et al.*, Bhabha and Kemmer together with Fröhlich and Heitler came to the conclusion that the sign and spin dependence of nuclear forces can best be understood by assuming that the meson has a spin one, and obeys the Proca equations. But, as Serber pointed out,[42] the beta-decay lifetime on this theory would be connected to the upper limit of the beta-spectrum by a seventh power of the momentum, while experimental evidence demands a fifth power law. 'The only escape', wrote Serber, 'is to deny the mesotron any role in beta-decay, and return to direct emission of the light particles by the heavy ones ... One is thus forced to give up any theoretical connexion between beta-decay and mesotron decay; both can take place, but they must be supposed completely independent processes.' Bethe re-examined the problem of meson decay (*see* ref. 39) on the vectorial meson theory that led to a Fermi beta-decay theory with Gamow-Teller selection rules, as required by experiment. But the theoretical lifetime of the meson was found to be of the order of 10^{-8} second, which showed great discrepancy with the observed cosmic-ray meson lifetime of the order of 10^{-6} second. Commenting on the failure of the 'currently used form' of the Yukawa theory to give a quantitative account of the meson decay Bethe incidentally reiterated his faith in the possible validity of the neutral meson theory: '... In order to obtain a sufficiently rapid nuclear beta-decay, it seems necessary to introduce again a direct interaction between heavy and light particles such as the original Fermi interaction ... If this is done, there is of course not much point in introducing an additional beta-decay through the meson field, and we may just as well use the neutral meson theory which does not yield any beta-decay at all. However, we must, at the present time, leave the question open whether the introduction of a direct interaction between light and heavy particles is really necessary, or whether Yukawa's theory is still in a stage where quantitative predictions cannot be made ...'

14. Adherents of Electron-positron Pair Theory

Before further discussing the progressive stages in the development of the meson theory, we may here incidentally mention that as late as mid-1939, when the meson theory was being seriously considered along varied lines, the Gamow-Teller theory of nuclear forces in terms of an electron-positron field was still being pursued (to the complete exclusion of the meson theory) by Critchfield and Teller (and also Wigner),[43] i.e. the same group of physicists, who had earlier championed this theory, and had completely ignored the meson theory. In discussing a spin-independent interaction between nucleons and electrons, they, of course, admitted that 'many arbitrary features remain' in their theory of nuclear forces. And in discussing the magnetic moments of the nucleons and the quadrupole moment of the deuteron in terms of a spin-dependent interaction, they concluded that 'a satisfactory theory of nuclear forces may be built upon an interaction of neutrons and protons with the electron-positron field', because they claimed that their estimate of the angular dependence (associated with spin dependence) of the neutron-proton forces indicated the existence of the quadrupole moment of the deuteron ('cigar-shaped' deuteron).

15. Meson-pair Theory

After the partial success of Bethe's neutral meson theory in yielding the correct deuteron quadrupole moment and a reasonable 'cut-off' distance, Marshak, who together with Bethe had used the Gamow-Teller electron pair theory in a paper presented at the 219th meeting (February 1938) of the American Physical Society, now put forward a *meson pair* theory[44] using perturbation method to overcome the anomaly of the meson mass. We may recall that Breit *et al.*[45] used Bethe's neutral theory for theoretically interpreting the experimental data on proton-proton and neutron-proton scattering, and pointed to a range of about $\frac{1}{2}\hbar/Mc$ (M = meson mass) that implied a mass of the field particle to be about twice the mass of the cosmic-ray meson. Marshak was reluctant to accept (early 1940) an unobserved particle in explaining nuclear forces: 'Thus far no real evidence exists for neutral mesons of either the same mass as the charged mesons or twice their mass; moreover it would seem desirable to have recourse only as a last resort to a theory which depends on the postulation of unobserved particles.' He therefore postulated that the field consists of positive-negative *meson pairs* (instead of the electron-positron pairs of the Gamow-Teller theory) which interact with the nucleons; the mass of the field particles (Marshak chose to call them 'heavy electrons and positrons') was taken to be $200m_e$ (identifiable with the cosmic-ray mesons or simply 'mesons', as Marshak chose to call them) and these particles were considered to obey Fermi statistics instead of Bose statistics. Like Bethe he also demanded of his theory that 'one type of coupling alone should be capable of explaining all known facts about nuclear forces ("single force hypothesis"; the arguments for this hypothesis are given in Bethe)'. He showed reasons to eliminate the scalar, vector, pseudovector and pseudoscalar interactions, and there remained 'only the tensor interaction as a possible theory fulfilling the conditions of the single force hypothesis'. Thus Marshak adopted the desirable features of Bethe's neutral meson theory (for example, the explanation of the quadrupole moment, and the equality of the *np*-, *pp*- and *nn*-interactions) and explored the possibility of a theory that only uses particles identifiable with the *observed* cosmic-ray mesons. He emphatically stated that '... this paper has established that the existence of unobserved neutral mesons is not indispensable to a theory of nuclear forces', but he admitted that his conclusion about the range of nuclear forces (i.e. $\frac{1}{2}\hbar/Mc \approx 1{\cdot}1\times10^{-13}$ cm in contrast to $\hbar/Mc$ in Bethe's theory) may not be 'borne out by a detailed investigation of the "cut-off" and the strength of the interaction'.

While Marshak was reluctant to invoke neutral mesons because they were unobserved, Sakata and Tanikawa had already discussed,[46] a few months earlier (March 1940), the possible reason why neutral mesons could elude detection. They expressed the like-particle interactions as $P \rightleftharpoons P+Y^{\circ}$; $N \rightleftharpoons N+Y^{\circ}$, where Y° represented the postulated neutral meson or the so-called 'neutretto'. They put forward the suggestion that Y° decays spontaneously into photons (photodisintegration), and their rough calculations based on the vector meson theory estimated the lifetime of the neutral meson to be *c.* 10^{-16} second, i.e. about 10^{-10} times as short as that of the charged meson. 'This result', they remarked, 'seems to account for the failure of the experiments to prove the existence of the neutral mesotron in cosmic-rays.'

We may note that the so-called *pair theories* such as the meson-pair theory of Marshak and the electron-positron pair theories of Gamow-Teller-Critchfield as well as of Wentzel,[47] in which the interaction energy of the nucleons is bilinear in the field variables, were developed as competitors to the meson theory, in which the interaction energy with the nucleons is assumed to be linear in the meson field. The meson-pair theory was seriously pursued after Marshak's proposal. Critchfield and Lamb, who had earlier advocated the electron-positron pair theory, now considered the positive and negative mesons as field particles obeying Fermi statistics (spin $\frac{1}{2}$) and having a mass *c.* $180m_e$.[48] However, he introduced a strong meson-nucleon interaction and did not use the perturbation method (which implies weak interaction of nucleons with mesons), whereas Marshak did. The applicability of the perturbation theory in the case of strong interactions began to be seriously doubted.

16. Problem of Meson Scattering by Nucleons

We should here discuss an important stage of the development of the meson theory before we again discuss how the meson-pair theory continued to compete with the single meson theory. This stage is concerned with the problem of the scattering of mesons by nucleons. The importance of scattering experiments for determining the meson spin, for example, was felt as early as 1938. Already Bhabha and Heitler[49] had theoretically calculated (1938) the scattering cross-sections with the wave formulation. Then later (1940) A. H. Wilson, in a paper[50] where he pursued Kemmer's matrix (i.e. particle picture) formulation[51] of the meson field, calculated the scattering cross-section. He found that the limiting cross-section for zero velocity is *c.* 10^{-27} cm^2, while the cross-section is *c.* 10^{-26} cm^2 for meson energy $2mc^2$, i.e. the calculated cross-section increases rapidly as the energy increases. These values are too large to be reconciled with the experimental value of the order of 10^{-28} cm^2 [52]. Attempts were made to eliminate this anomaly. Bhabha suggested[53] that if, in analogy with the radiation damping involved in the scattering of light by electron or meson, the analogue of the radiation damping occurring in the scattering of mesons by nucleons is not neglected in the perturbation calculations of radiation theory, then the scattering cross-sections would be reduced and would not become indefinitely large with increasing energy of the colliding particles. Although this 'classical theory' of radiation damping for mesons was confined to neutral mesons, this approach of Bhabha first introduced the idea that radiation damping may have a decisive effect on the cross-section for the scattering of mesons of large as well as small energies. Bhabha also introduced[54] a new postulate in order to eliminate the discrepancy between the observed and calculated scattering for charged mesons. He postulated that particles of protonic mass and integral charges $2e$, $3e$ ... and $-e$, $-2e$, ... or proton 'isobars' must exist, and that they represent higher excited states of the charge degree of freedom and have higher energies or rest masses than the ordinary nucleon, which represents their lowest state. Charged mesons would then behave like neutral mesons, i.e. this assumption would 'put the theory of charged mesons on the same footing as the quantum theory of neutral mesons'. After this suggestion of Bhabha, Heitler[55] assumed that the spin of the nucleons would also have excited states with spins 3/2, 5/2 ... These inner excited states would cause an increase in the inertia of charge and spin degrees of freedom and hence a reduction in the scattering cross-section. The cross-section calculated on this basis would not increase with the meson energy, and would be of reasonable magnitude compared with observation. Referring to the postulated particles of any integral charge Bhabha however remarked: 'If the theory is correct, these particles are expected to occur in the nuclear explosions produced by cosmic rays, though less frequently than ordinary protons' (*see* ref. 54). Bhabha's suggestion that radiation damping would have a decisive effect on the cross-section of meson scattering was now seriously considered for quantum treatment by Heitler[56] and independently by Wilson.[57] Although the applicability of the perturbation method in the case of *strong* interactions (believed to characterize the meson-nucleon force) was being doubted, and therefore attempts were being made to depart from this method in dealing with the meson theory, Heitler and Wilson found that the perturbation method could be appropriately used if radiation damping was taken into account. The influence of radiation damping on the meson scattering cross-section was calculated. The resulting cross-sections were found to decrease with increasing meson energy; thus the results of the meson theory were rendered much more reasonable. However, referring to the typical divergence difficulty involved in this work, Wilson remarked 'it is necessary to emphasize that, because of the infinite self-energies that have been neglected, the method and results given here can only be considered as probably, and not certainly, correct.'

According to Marshak, who championed the meson-pair theory, the problem of anomalous meson scattering could not be solved with spin-one meson theories of nuclear forces. He and Weisskopf[58] sought to solve it on the basis of the cherished meson-pair theory, in which the mesons possess spin $\frac{1}{2}$ and are described by the Dirac equation that accounts for the two signs of the charge. Their theoretical cross-sections were shown to be in fairly good agreement with the upper limits of the experimental values (*c.* 10^{-28} cm^2). They criticized the concept of new quantum states of postulated nucleons with higher multiples of charge. The theory of radiation damping for reducing the scattering cross-section was yet to be seriously developed by Heitler and Wilson. So Marshak and Weisskopf could not mention it, although Bhabha's suggestion about radiation damping had already appeared along with his proposal on postulated nucleons with higher charge multiples. After arguing in favour of their explanation of the anomalous scattering in terms of spin $\frac{1}{2}$ mesons they however cautiously stated: 'It must be remembered, however, that the above result is derived by using the first approximation only of the perturbation method. Because of the divergences involved in the higher approximations, it is difficult to decide whether the same conclusion would be borne out by a more rigorous treatment.'

Thus, no radical modifications of the meson theory could be convincingly proposed with categorical statements about their validity in explaining all features of nuclear phenomena. The nuclear physicists were fully conscious of the tentativeness and provisionality of their proposals on the forms of interactions.

17. Towards a Two-meson Hypothesis

Because of the inadequacy of the experimental facts known at that time about the meson, no one was able to assign a definite spin and magnetic moment that would exclude all other possibilities. Corben and Schwinger[59] investigated the probability (cross-section) for fractional energy transfer to electrons by energetic mesons with the possible spin values 0, $\frac{1}{2}$ or 1 and magnetic moments of possible values 0, 1 or different-from-unity meson magnetons. They obtained closely similar results for mesons of spin $\frac{1}{2}$, magnetic moment 0 and also of spin 1, magnetic moment 1, as required by experiment. 'On the basis of cosmic-ray evidence therefore one cannot exclude the possibility of a mesotron of spin $\frac{1}{2}$ and magnetic moment different from unity (in particular zero) although such evidence as available from nuclear phenomena indicates that this is not likely.' They excluded the case of zero spin because 'the impossibility of associating an intrinsic magnetic moment with a scalar mesotron implies an energy transfer cross-section varying inversely with the mesotron energy, thus contradicting the experimental evidence'. This remark together with the above remark on the impossibility of spin $\frac{1}{2}$-meson inferred from 'nuclear phenomena' clearly shows that the non-identity of the Yukawa particle and the cosmic-ray meson was yet to be seriously suspected, although the Møller-Rosenfeld mixed meson field theory had already invoked two types of mesons. The Japanese scientists Tomonaga and Araki[60] indicated the possibility of a meson not identical with the ordinary cosmic-ray mesons and having much smaller lifetime ($\ll 10^{-6}$ second), and their compatriot Sakata, who finally in 1943 clearly understood the non-identity of the Yukawa particle and the cosmic-ray meson, also supported in mid-1940[61] the Møller-Rosenfeld hypothesis to remove the discrepancy between the calculated lifetime of the Yukawa particle and the observed lifetime of the cosmic-ray mesons. However, no difference of mass between the two kinds of mesons was suspected; the influence of the Møller-Rosenfeld theory in this respect also persisted. It is interesting that Sakata, in the same note, not only suggested this way of removing the discrepancy, but also suggested an alternative way of removing it by trying to *reconcile the lifetime* 10^{-6} *second with a modified theory,* which hypothesized a reversed connexion between the meson decay and the beta decay. However, we do not have any record of subsequent favourable responses to this attempt of reconciliation.

18. Question of Meson Spin

As to the problem of meson spin, Christy and Kusaka[62] proceeded from another direction. They estimated the probability of collisions of high-energy cosmic-ray mesons with atomic electrons (knock-on cross-sections) and with the electric field of heavy nuclei causing gamma-ray emission (bremsstrahlung cross-sections) for postulated meson spin 0, $\frac{1}{2}$, 1 and corresponding magnetic moments 0, 1, 1 (unit magnetic moment $= e\hbar/2mc$). In the case of mesons of spin 0 or $\frac{1}{2}$ and unit moment the agreement with the observed cosmic-ray burst cross-sections was good, whereas the experimental results tended to exclude the possibility of spin 1 and unit moment, because this choice gave much greater calculated burst cross-sections than were observed. In this connexion we may incidentally remark that the mass of the meson was yet to be *uniquely* determined; Lapp[63] pointed out in 1943 that on the assumption that the meson mass is $177m_e$ the agreement between experiment and theory referred to by Christy and Kusaka for spin 0 or $\frac{1}{2}$ was fairly good, though calculations gave slightly greater weight to the spin-0 hypothesis; on taking the meson mass to be 230 electron masses, Lapp showed the theoretical burst cross-section for spin $\frac{1}{2}$ was found to be in closer agreement with the burst data. Thus the spin of the cosmic-ray meson was convincingly determined to be $\frac{1}{2}$. But its non-identity with the spin assignment of the nuclear meson continued to intrigue the meson theorists.

19. Weak *v.* Strong Coupling

At that time it was felt that a decision must be made in favour of either a weak coupling or a strong coupling of the meson field to the nucleon. Empirical evidence proved the existence of a strong interaction between mesons and nucleons, but perturbation-theoretic calculations of meson scattering and nuclear forces were based on the assumption that the coupling is weak—an assumption contradicted by the results of the calculations themselves. Wentzel[64] made a beginning in introducing strong couplings rather than weak ones. In rejecting the perturbation-theoretic formulae, he claimed that more reliable results are expected by employing the method of expansion of the meson-nucleon interaction in decreasing powers ('fallende Potenzen') of the coupling parameter, i.e. in powers of $1/g$, instead of in powers of g. However, this mode of expansion also led to the limiting value of the meson scattering cross-section, $2\pi\ (\hbar/mc)^2$, i.e. the same large value which is still about 100 times greater than the observed value. He himself admitted that the strong approach was not of immediate quantitative usefulness, but pointed out (*Helv. Phys. Acta,* **16**, 1943, p. 551) that 'in any case the different variants of the meson theory must be thoroughly discussed mathematically by assuming a *strong coupling,* before we can subject them to a more quantitative test on the basis of experimental data'.

This strong coupling approach was extended by Oppenheimer and Schwinger,[65] who showed that by assuming a strong coupling between nucleons and mesons of spin zero the small observed meson scattering (*c.* 10^{-28} cm^2) could be explained. This investigation also predicted the excited states or isobars of the nucleon with higher values of charge and spin (hypothesized earlier by Bhabha and Heitler). But the question of nuclear forces was left open by Oppenheimer and Schwinger. At the 246th meeting of the American Physical Society in December 1941 Pauli and Dancoff[66] suggested an extension of the strong coupling approximation to charged pseudoscalar mesons. They treated the nucleons as particles of finite size in order to eliminate the divergence difficulty. They stated that the cut-off procedure 'cannot be consistently formulated in such a way as to satisfy the criterion for weak coupling'. Thus a weak point of the weak coupling hypothesis was indicated. Their theory again resulted in the prediction of charge and spin isobars of the nucleon. They justified the charged meson theory in preference to the symmetrical theory, 'because neutral mesons have never been observed and because in the case of strong coupling the charged theory also leads to forces between two like particles.' In this statement the reluctance to use an *unobserved particle* in developing the theory is somewhat emphatically expressed because of its redundancy in describing the like-particle interactions (for strong coupling), for which the neutral meson had been postulated. The agreement of the calculated meson scattering cross-section with the experimental cross-section was satisfactory in this strong coupling theory. But, contrary to 'the hope that the anomalous moments (of nucleons) would follow in a simple way from the theory' these were predicted to be *equal* and of opposite sign, whereas the contemporary empirical values were $-2{\cdot}79$ nuclear magnetons for proton and $-1{\cdot}9$ n.m. for the neutron. This discrepancy was not admitted by Pauli and Dancoff 'as an unambiguous disproof of the strong coupling hypothesis', because of 'our ignorance of the fundamental properties of the "bare" proton or neutron', whose contribution appears in the expression for the magnetic moment of the physical nucleon (bare nucleon+meson cloud). It may be mentioned here that the term 'nucleon' common to both proton and neutron was used by Pauli and Dancoff. However, in 1939 Belinfante had used the term 'nuclon'.

It is interesting that one of the above advocates of the strong coupling hypothesis, Dancoff, presented (jointly with Serber) at the same meeting (246th) of the American Physical Society another paper on the strong coupling theory of nuclear forces for charged scalar and for neutral pseudoscalar meson fields.[67] They pointed out that for small separations between interacting nucleons, i.e. when the separations are of the order of the range of the forces, the forces (in the strong coupling hypothesis) become ordinary, non-exchange and spin-independent, which are unacceptable because they do not lead to the well-known saturation. Therefore they felt that 'it seems unlikely that any strong coupling theory can lead to suitable forces'.

The strong coupling hypothesis had to compete with the weak coupling hypothesis. In a paper presented by Pauli and Kusaka at a meeting of the American Physical Society towards the end of January 1943 it was emphatically stated in conclusion: 'Thus there is no reason now to consider the strong coupling theory, and we should *go back* to the weak coupling theory.' (Italics mine.) We should discuss the stages leading up to such a conclusion.

20. Two Mesons or One Meson?

At the 246th meeting of the American Physical Society in December 1941, when Pauli and Dancoff discussed their strong coupling hypothesis, Schwinger[68] pointed out that the inadmissible $1/r^3$ and $1/r^2$ singularities, which appear in the tensor nuclear forces predicted by both the weak and strong coupling theories, can be eliminated (leaving only the admissible $1/r$ singularity), if the Møller-Rosenfeld mixed meson theory, in which the vector meson mass equals the pseudoscalar meson mass, can be modified by assuming the vector meson to be of greater mass than the pseudoscalar meson. With this assumption, the correct sign (but not the correct value[69]) of the deuteron quadrupole moment is obtained. This assumption was in agreement with the hypothesis that the vector meson is highly unstable and that it is responsible for the nuclear beta-decay. However, this approach was criticized by Pauli and Kusaka[70]: 'The introduction of a new particle is admittedly undesirable, but we feel that further investigation in this direction is justified for the reason that this may be a first step in the direction of a more far-reaching theory in which the vector meson enters, not as a new independent particle, but as an excited state of the pseudoscalar meson.' They would rather think of the possibility of 'an excited state of the pseudoscalar meson' than that of 'a new independent particle', the introduction of which would be 'admittedly undesirable'. It is interesting that this reluctance to accept a new particle was expressed at a time (early 1943) when evidence was growing in favour of clearly distinguishing between the Yukawa field particle and the cosmic-ray meson; in September 1943 Sakata and Inoue proposed their two-meson theory, whose publication however was delayed till the end of 1946 owing to war circumstances.

In the subsequent period the competition between the strong and weak coupling theories intensified, and evidence accumulated in favour of a two-meson hypothesis, followed by the discovery of the *pi*-meson. Since those developments represent a new phase in the history of the meson theory, we shall discuss it in a separate article.

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