MESONS AND NUCLEONS

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I SHOULD like to direct attention to an approach to the problem of the relation between mesons and nucleons, which, although speculative, seems to give a reasonable account of the main features of our present knowledge, including the fundamental work recently carried out at Bristol. The main assumptions, some of which have already been discussed by other physicists, are given below. We use the nomenclature employed by the Bristol observers for the different categories of mesons observed in photographic plates.

(1) The ordinary cosmic-ray meson (μ-meson), and its neutral counterpart, are particles of spin $\hbar/2$ with Fermi statistics. The decay of a charged meson is a true β-process, giving rise to a neutral meson, an electron and a neutrino.

(2) These particles interact by means of a Yukawa field corresponding to positively and negatively charged particles of integral spin, Bose statistics, and masses of mesonic order of magnitude. There being only charged particles of this kind, interactions of pair type will be essential. The role of these particles, and their properties, being similar to those of the photons, we may perhaps call them 'electro-photons', reserving the name meson for the particles mentioned in (1). Some σ-mesons may be of this kind, and they may be expected to occur in penetrating showers.

(3) π-Mesons, and possibly other mesonic particles of still higher mass[1], are supposed to be metastable compound systems of mesons, held together by means of the interaction mentioned above. Moreover, as a working hypothesis, we shall assume the nucleons themselves to be stable compound systems of mesons.

Having stated them, we shall now attempt a brief discussion of the arguments in favour of these assumptions, and the difficulties which they raise. Thus, in the first place, we encounter a well-known feature of any relativistic theory: the difficulty of forming a compound system with dimensions smaller than the Compton wave-length of the constituent particles. In the present instance, this length is of the same order of magnitude as the range of the forces. Dr. N. Hu has kindly pointed out to me that this difficulty is much more pronounced in an s-state than in one where the particle has an angular momentum. This may mean that a stable compound system contains only one particle in an s-state—two such particles involving a great increase in the strength of the field in which each of them moves—and, in addition, as many particles in states with an angular momentum, as is required to make the binding energy per particle as high as possible. Without a more developed theory of the interaction, it is, of course, difficult to predict how large the number of particles will be, but making use of the actual mass values of the particles in question, we may, hypothetically, regard a neutron as being built up of seventeen neutral mesons. We may assume that these particles form complete p-groups (six particles), d-groups (ten particles), and a single particle in an s-state. Of course, this classification of the separate particles according to their angular momentum is only valid in the Hartree approximation; nevertheless, it would seem to be a sufficient approximation in the present case. In order to balance the very high kinetic energy of these particles, contained in a volume of the order of magnitude $(\hbar/\mu c)^3$, where μ is a mass of mesonic order of magnitude, the forces must, of course, be much stronger than those occurring between the nucleons in the atomic nuclei. Since, however, in most nuclear force theories, a 'cut-off' procedure is applied at a distance comparable with the range of the forces, this may not require any particularly high value of the interaction constant g, but only a less violent 'cut-off'.

Suppose now that the rest mass, m_ν, of the neutral meson is $120\, m_e$, m_e being the electron rest-mass, a value which seems to be consistent with the conclusions of the Bristol workers. In fact, the values $m_\nu = 120\, m_e$, m_μ (mass of ordinary charged meson) $= 220\, m_e$, and m_π (mass of π-meson) $= 365\, m_e$, would correspond to a kinetic energy of the decay meson in the Bristol experiments of 4·4 MeV., and a ratio $m_\pi/m_\mu = 1 \cdot 66$. Comparing the value $17 \times 120\, m_e$ with the mass of the neutron, $1839\, m_e$, we obtain a binding of 100 MeV. for the neutron, a value which seems not unreasonable in view of the recent Berkeley experiments, which may perhaps be taken as an indication that nucleons can be broken up in collisions at an energy of some hundred MeV.

Since, according to the above assumptions, the decay of the ordinary meson is, so to speak, the prototype of all β-processes, it is important that the value of the life-time, $\tau = 2 \times 10^{-6}$ sec., and the energy available in the process $\sim 100\, m_e c^2$, fit in very well with the value to be expected from our knowledge of the β-decay. Let ε be the energy available divided by $m_e c^2$, and $F\ (\varepsilon)$ the well-known Fermi function, which for large ε-values may be taken as $\varepsilon^5/50$. We then obtain for the product $\tau . F\ (\varepsilon)$—putting $\tau = 2 \times 10^{-6}$ sec. and $\varepsilon = 100$—the value 667, which is of about the expected magnitude. The value $\varepsilon = 100$ would also seem to be consistent with the energy values indicated by the small number of cloud-chamber pictures of decaying mesons. (The above considerations were essentially stimulated by a communication kindly made to me by Prof. J. Blaton in connexion with an interesting attempt to regard the π-meson as a compound system of a neutral and a charged meson. In this approach, the component particles were supposed to be of integral spin, and kept together by forces of the original Fermi type, corresponding to an interaction by means of electron-neutrino pairs. It was then found that the interaction constant corresponding to the meson life-time is of the same order of magnitude as that to be expected from Fermi's original theory of β-disintegration, a result which is, of course, identical with that of the above calculation; see also Konopinski[4].)

Proceeding now to the proton, we shall again assume a system of seventeen particles, but with a unit charge. Owing to the strong interaction with the Yukawa field, this charge would probably belong to the whole system rather than to any individual meson. Keeping in mind that the charged meson is about $100\, m_e$ heavier than the neutral meson, the question arises how this difference can be more than compensated in the compound system, so as to give the observed difference in mass of the proton and the neutron. A possible explanation may be that the interaction corresponding to an exchange of a single electrophoton, in the interaction between unlike particles, has to be added to the pair interaction in the case of like particles. An estimate of the constant g of this interaction, required to compensate the mass difference in question, is seen to give a very reasonable value of the order of magnitude of the electronic charge. In fact, since the size of a nucleon is probably of the order of magnitude of, or even smaller than, the range of the forces in question, we may estimate this effect by considering the decrease of potential energy of a sphere of N particles each of electric charge g, to which a particle of charge $-g$ is added. This, now, will be equal to $\frac{3}{5} \cdot \frac{(2N+1)}{a} g^2$, if a is the radius of the sphere. With $N = 16$, we obtain thus the following approximate relation

$$\frac{3}{5} \cdot \frac{33g^2}{a} \simeq 100\, m_e c^2 = 100\, \frac{e^2}{a_0},$$

where a_0 is the radius to the electron; or, $g^2 \simeq 5\, \frac{a}{a_0}\, e^2$. From the well-known sizes of atomic nuclei, we get, as an upper limit to the value, $1{\cdot}2 \times 10^{-13}$ cm.; while $a_0 = 2{\cdot}8 \times 10^{-13}$ cm.; and thus $g^2 \lesssim 2e^2$.

The problem of the capture by nuclei would, of course, be a rather different one for the mesons and for the electrophotons. The latter particles would probably behave in accordance with the theories developed along the lines of Yukawa's original ideas, mesons taking now the role of nucleons. On the other hand, the former particles may either be captured in a way somewhat analogous to the K-capture (similar to suggestions put forward by Pontecorvo and Weisskopf[2]), with the emission of a neutral meson and a neutrino pair; or in an annihilation process of the Dirac type. As Dr. B. Bruno has kindly pointed out to me, this latter process will have a considerable probability, a point to which he hopes to return in connexion with a study of the problem of meson capture.

As to the Yukawa particles or electrophotons, their relation with the meson being similar to that of mesons and nucleons in the current meson theories, we should expect to observe their creation by *Bremsstrahlung*—in processes, for example, such as the impact between fast nucleons or mesons. Moreover, we should expect that mesons could be created in pairs by electrophotons as well as by photons of high energy, a phenomenon which may, perhaps, play a part in the penetrating showers. On the other hand, collisions between fast particles and nuclei may lead to the break-up of nucleons, whereby metastable compound systems like the π-meson may be formed. In such processes we should expect an excess of positive particles, although negative particles of this kind are perhaps not excluded, owing to the strong interaction of the mesons with the electrophotons. Nevertheless, we should expect the positive and negative mesons, like positrons and electrons, to be separated by an energy gap equal to twice the rest-mass energy. Just as the ordinary neutron is closely connected with the positive proton only, we should expect that there would be two kinds of neutral mesons, connected with the positive and the negative mesons respectively, which would probably have magnetic moments of opposite sense relative to the spin.

As regards the problem of the interaction of nucleons, the above considerations would imply some modifications of the theory by the introduction of a natural radius of a nucleon; that is, a strong repulsion when the distance between the nucleons gets below a certain value, $\simeq 10^{-13}$ cm. This may have some consequence for the scattering problem, as well as for the problem of the saturation of nuclear forces. Further, if a nucleon is a compound system of some seventeen particles, the value of the interaction constant for the force between two nucleons will have a less fundamental significance than in the ordinary meson field theory. Since the Yukawa theory of β-radioactivity would have to be applied to the mesons interacting with electrophotons, we shall expect the life-time of the latter particles to be considerably shorter than that of the mesons, which may account for the lack of evidence for the existence of these particles. It would perhaps be worth while, however, to consider the possibility that the large spread of the mass values obtained for the cosmic ray mesons may be partly due to some of the measured particles being electrophotons. In an attempt to regard the nuclear field force theory as a generalization of the relativistic field theory of electromagnetism and gravitation, I obtained the following expression for the rest mass μ_e of a charged Dirac particle, as compared with the rest mass of the corresponding neutral particle μ_n:

$$\mu_e = \sqrt{\mu_n^2 + \mu^2},$$

where μ is the mass of the electrophoton[3]. Apart from the ambiguity still present in the basic assumptions, this formula neglects possible self-energy effects on the masses of the particles. Still, it is interesting that, with the above values for μ_e and μ_n, it gives a reasonable value for μ, namely, 185 m_e.

According to the view developed here, the building up, as well as the destruction in any appreciable amount, of nucleons would require conditions differing even more from those prevailing in the known parts of the universe than those necessary for the building up and destruction of nuclei. Thus an equilibrium in which there is a considerable dissociation of nucleons into mesons would seem to require a temperature corresponding, at least, to $kT \simeq 100$ MeV. At this temperature, the mass density of meson pairs, as calculated from the ordinary Fermi distribution formula, would approach that in the interior of an atomic nucleus.

In concluding these remarks, it may be stressed that owing to the strong assumed interaction between mesons and electrophotons, and the size of the Compton wave-length as compared with the range of the forces, we are at the extreme limit of the region where it is permissible to speak about systems built up of individual particles. Although this would suggest that great caution should be observed in the handling of the problem, it would not seem, *a priori*, to make fruitless an attempt such as that under consideration.

Note added to proof. Since the above was written, definite evidence has appeared in favour of a mass value $\sim 300\, m_e$ for the σ-mesons; their production in the Berkeley experiments and their star-producing capacity making it, moreover, very probable that they are the true Yukawa particles or electrophotons. Their assumed identity with the π-mesons, which, if correct, would necessitate important alterations of the hypothetical postulates put forward in the above note, seems to me less evident, however; and it is perhaps not out of place to discuss the consequences of the opposite assumption in the light of the new results.

Thus it would seem natural to assume the mass m_σ of the σ-meson to be smaller than $m_\nu + m_\mu$, the sum of the masses of the two μ-mesons, charged and neutral; while m_π, the mass of the π-meson, would have to be greater than $m_\nu + m_\mu$. Using the values of the above example, we should have $m_\pi > 340\ m_e > m_\mu$, an inequality which does not seem contradictory to present experience. While on this assumption the σ-meson could not spontaneously give rise to a pair of μ-mesons (charged and neutral), such a process would be possible in the field of a nucleus, if the energy is sufficient—as it might easily be under the Berkeley conditions. It is suggested that this may be the explanation of the comparatively large number of μ-mesons observed in the Berkeley plates. While the most probable process under those conditions seems to be the formation of σ-mesons by *Bremsstrahlung*, the observed cases of π-decay might on the above view be due to a break-up of nucleons, a process which would be expected to occur with measurable probability, the energy quantum (frequency multiplied by Planck's constant), corresponding to the collision time, being of the same order of magnitude as the assumed binding energy of the nucleon.

Without entering more closely on the consequences of the opposite assumptions—the identity of σ- and π-mesons—for the above considerations, I should like to state that in my view the interpretation of the μ-meson as an $\hbar/2$-particle with an ordinary β-decay, which is, of course, independent of the hypothesis concerning nucleons and π-mesons, has not only a better foundation than the other assumptions of the above note, but also the more important bearing on the problem of the incorporation of meson theory in the general relativistic field theory. In this connexion it should perhaps be mentioned that the argument given in the note concerning the mass value of the electrophoton can only be expected to give the order of magnitude.

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[3] Klein, O., *Ark. and Mat. Astr. O. Fys.*, **34** A, No. 1 (1946).

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EXCITATION CURVES FOR THE γ-RADIATION FROM LIGHT ELEMENTS BOMBARDED WITH α-PARTICLES FROM POLONIUM

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A LARGE number of investigations have been carried out on the disintegration of light nuclei bombarded with α-particles. In several cases excitation curves have been obtained for the γ-radiation as a function of the energy of the α-particles. (A review of earlier polonium α-particle bombardments of light elements, particularly those which may be of interest for a possible γ-radiation, has been published by the present writer in *Arkiv. Mat., Ast. Fysik*, **35** A, No. **31**; **1948**). The results of different authors, however, are often inconsistent. For that reason I made use of an available polonium sample of about 40 mC. for observing the excitation functions of the γ-radiation from light elements bombarded with α-particles. The energy of the α-particles was varied by means of carbon dioxide.

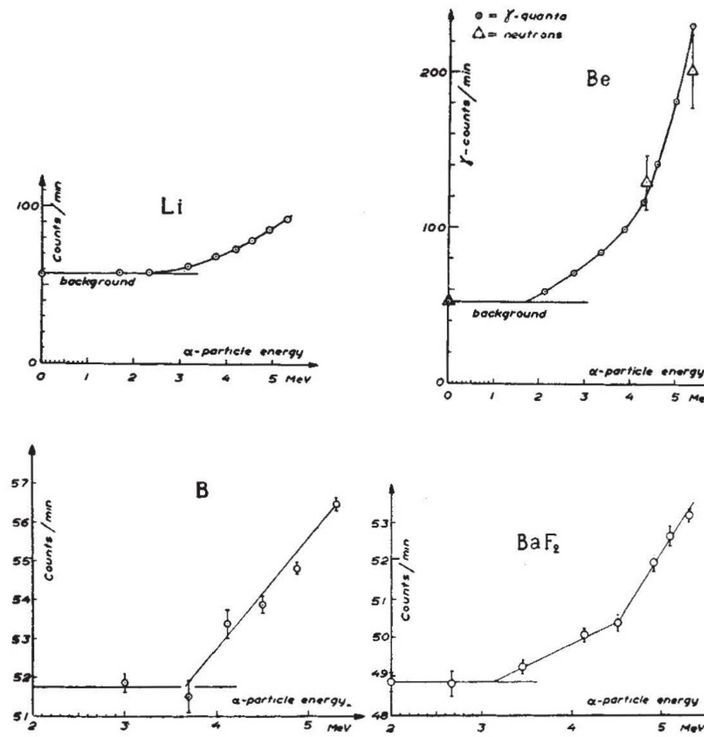

Fig. 1. Emission of γ-quanta (○) from lithium, beryllium, boron, fluorine, and neutrons (△) from beryllium as a function of the energy of the bombarding α-particles

Lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, sodium, magnesium, aluminium, silicon, phosphorus, sulphur, chlorine, potassium, calcium and lead were investigated. γ-Emission was observed from lithium, beryllium, boron, nitrogen, fluorine, sodium, magnesium and aluminium. The intensity of the γ-radiation was measured as a function of the energy of the α-particles for all these except nitrogen (Figs. 1–2). The α-particle threshold values for γ-emission and the relative intensities (as percentage of the measured polonium γ-radiation background) of the γ-quanta are given in the accompanying table.

Element	γ-Emission starts at the α-energy	Intensity of the γ-radiation for 5·3 MeV. α-particles
	MeV.	
Li	2·3	61
Be	1·7	340
B	3·7	9·0
N	—	2·7
F	3·1 (and 4·5)	9·0
Na	4·6	9·5
Mg	3·6	3·7
Al	4·1	7·9

The statistical errors are represented in all the diagrams except the γ-emission curves for lithium and beryllium, where the errors were too small to be