He_2^+ agrees with Tyndall and Powell's measured value of 21.4 (cm/sec.) per (volt/cm). The mobility of He^+ in He, neglecting charge transfer, may be determined by the extrapolation of the curve given in Fig. 8 (reference 1) as $\mu_+ = 26$ (cm/sec.) per (volt/cm). The mobility of He_2^+ should be $\frac{1}{2}\sqrt{3}$ times this value of 22.5 (cm/sec.) per (volt/cm). The agreement between this predicted value and Tyndall and Powell's measured value suggests that they may have measured the mobility of He_2^+. It appears, in any case, that the measurements made by Tyndall and Powell and in our experiment are for two different ions, but the exact identity of the ions in each experiment is not known. Mass spectrographic analysis of our ions is planned.

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Comment on the Nuclear Capture of Negative Mesons

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June 7, 1949

A NUMBER of different authors have observed that when negative mesons are stopped in an element with high atomic number the negative mesons do not undergo the normal decay process and it was therefore assumed that they are captured by the nuclei. This interpretation, however, encounters some difficulties because it does not explain the failure to detect stars at the end of such meson tracks.[1] I would like to suggest an explanation to account for the fact that no decay electrons were observed if lead was used as stopping material.

If—and this is rather plausible—the negative meson is captured on a K-shell, then almost the double of the K-shell energy of the meson is needed to liberate the decay electron from the atomic binding. Hence, the decay electron of a meson disintegrating in lead will lose 38.6 Mev of its energy merely in order to be able to get out from the atom. This energy loss is rather considerable, since 54 Mev represents the upper limit of the energy of the decay electrons. It seems rather reasonable to assume that no decay will occur whenever the electron does not obtain an energy sufficient for leaving the K-shell and hence these latter cases might bear the aspect of a nuclear capture leading to no stars at the end of the meson track.

For example, in Retallack's[2] experimental arrangement, where lead plates were placed in the cloud chamber, he observed a total of 27 negative meson tracks stopped in lead. Computing with the same 31 percent probability, experimentally found for positive mesons which can get out of the lead plate and produce a track in the cloud chamber, we would have to expect 8 decay electron tracks, whereas only one was observed. If, however, 38.6 Mev are needed in order that a decay electron should be able to leave the lead atom, and, moreover, we assume a continuous spectrum of the decay electrons between 5 Mev and 55 Mev with a most probable electron energy of about 40 Mev, then we immediately see that out of the 27 negative mesons merely 9 electrons could get out of the lead atom. Moreover, these 9 electrons will have energies between 0 and 15 Mev, hence it is most probable that only about one of them can emerge from the lead plate and produce a track in the cloud chamber.

In order to test the validity of the above given interpretation, it would be of interest to perform cloud-chamber measurements by using as stopping material, for instance, barium, in which case the energy loss of the electron within the atom would amount to 18 Mev, hence we would have to expect a shifting in the energy spectrum of the electrons by 18 Mev toward lower energies.

Our interpretation of the failure to detect decay electron tracks from lead does not, however, explain the apparent shortening of the lifetime of negative mesons in lighter materials (NaF; Al: S) because even for iron the decay electron needs only 3.9 Mev to be released from the meson K-shell, hence this energy loss is quite negligible as compared with the average initial energy of the electron. It remains an open question whether we are confronted, in the apparent lifetime shortening of the negative mesons, with a nuclear capture[3] or with a true decrease of the lifetime occurring in the K-shell.[4] Anyhow, the missing decay electron tracks from lead can no longer be considered as a proof in favor of the nuclear capture conception.

The author would like to point out that similar experiments performed with cloud chambers and by using as stopping materials substances with atomic numbers ranging between sulfur and iron will probably decide between the above-mentioned two alternatives. Because in these materials a quite considerable shortening of the lifetime is to be expected, whereas the energy needed for the electron to leave the K-shell of the meson is still quite negligible.

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Spontaneous Decay Rate of Heavy Mesons

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THE assumption of a direct coupling between heavy (π) and light (μ) mesons that leads to the observed rate of $\pi-\mu$-decay, also explains the observed rate of capture of negative μ-mesons by nuclei as a second-order process.[1] Alternatively, it has been proposed[2] that μ-mesons are directly coupled to nucleons. This latter assumption leads to $\pi-\mu$-decay as a second-order process even if no direct $\pi-\mu$-coupling is postulated.[3] If, in addition, a direct coupling between electrons (e) and nucleons is assumed,[2] $\pi-e$ decay also appears as a second-order process. A comparison of the rates of $\pi-\mu$- and $\pi-e$-decay with observation can therefore be expected to throw some light on the validity of the assumption of direct couplings of μ-mesons and electrons with nucleons.

It is assumed in this note that π-mesons are scalar particles μ-mesons, electrons, neutrinos (ν), neutrons (N), and protons (P) are all Dirac particles, and that all couplings are of the scalar type that involve the Dirac β-operator. The interaction term in the Hamiltonian then has the form

$$H' = G\int \psi_\pi(\psi_P{}^*\beta\psi_N)d\tau + g_\mu\int(\psi_\nu{}^*\beta\psi_\mu)(\psi_P{}^*\beta\psi_N)d\tau + g_e\int(\psi_\nu{}^*\beta\psi_e)(\psi_P{}^*\beta\psi_N)d\tau + \text{c.c.} \quad (1)$$

The strength of nuclear forces gives G the approximate value $(4\pi\hbar c^3/3)^{\frac{1}{2}}$. The interaction (1) leads to a reciprocal mean life for decay of a π-meson at rest

$$\frac{1}{\tau_\pi} = \frac{G^2 g^2 p^2}{2\pi^5 m\hbar^8 c^5}\left|\int_0^\infty \frac{P^4 dP}{(P^2+M^2c^2)^{\frac{3}{2}}}\right|^2. \quad (2)$$

In (2), m is the mass of the π-meson, p is the momentum of the emitted neutrino, M is the mass of the nucleon, and the integration is carried over all intermediate nucleon momenta P. The formula gives $1/\tau_{\pi\mu}$ or $1/\tau_{\pi e}$ according as g is given the value g_μ or g_e. A term $\pm mc$ has been neglected in the energy denominator in comparison with $(P^2+M^2c^2)^{\frac{1}{2}}$.

The divergence of the integral in (2) places any quantitative conclusions drawn from this formula on doubtful ground. Since, however, this integral is the same for the rates of both $\pi-\mu$- and $\pi-e$-decay, it cancels out of their ratio, to give

$$\tau_{\pi\mu}/\tau_{\pi e} = (g_e{}^2 p_e{}^2/g_\mu{}^2 p_\mu{}^2); \quad (3)$$

p_μ and p_e are the momenta of the neutrinos emitted in the two modes of decay. If we assume, as suggested by Tiomno and

Wheeler,[2] that g_μ and g_e are likely to be equal, the ratio (3) is approximately equal to 4. If, on the other hand, we adopt their best observational values $g_\mu \cong 10^{-49}$ erg-cm^3 and $g_e \cong 2.2\times 10^{-49}$ erg-cm^3, the ratio is approximately equal to 20. In both cases, there is clear disagreement with recent results at Berkeley,[4] which indicate that the ratio (3) is substantially less than unity.

An estimate for the magnitude of the integral in (2) can be obtained by taking its upper limit to be roughly equal to Mc; this is equivalent to assuming that nucleon theory is valid in the non-relativistic domain, and that relativistic intermediate states can be ignored. Alternatively, the self-energy of a π-meson at rest due to intermediate nucleons can be calculated, and set equal to mc^2. The same integral appears (again with neglect of a factor $-mc$ in the energy denominator), and the values obtained for it in the two ways are approximately the same. When the latter evaluation of the integral is used, and g_μ is taken equal to 10^{-49} erg-cm^3 in order to obtain agreement with the rate of nuclear capture of negative μ-mesons, we obtain $\tau_{\pi\mu} \cong 2.3\times 10^{-9}$ sec., which is in fair qualitative agreement with the observed value.[5] This makes the computed mean life for $\pi - e$ decay much too small to agree with experiment; while the discrepancy could be removed by the assumption of a direct $\pi - e$ coupling that largely cancels the second-order contribution, this is a rather unlikely possibility. Thus, it would seem that the rate of nuclear beta-decay is too large to be consistent with the small rate of $\pi - e$ decay, if either $\pi - e$ coupling[1] or nucleon-electron coupling is assumed by itself.

The interaction (1) also leads to $\mu - e$ decay as a second-order process, but the rate computed in this way is far too small to agree with experiment.

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Production of π-Mesons by High Energy Nucleons*

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In connection with the programs of accelerators under way in this country, it seemed useful to collect as many data as possible about the production of mesons by high energy particles. When looking through the literature we found that for the case where the bombarding particle is a high energy nucleon, two different results had been obtained. Using straightforward third-order perturbation methods, Urban and Schwarzl[1] obtained for the cross section σ:

$$\sigma = 4(g^2/\hbar c)^3(M/\mu)^2(Mc^2/E_0)^2(\hbar/Mc)^2\log(M/\mu), \qquad (1)$$

where g is the coupling constant, M the mass of a nucleon, μ the mass of the π-meson, and E_0 the energy of the bombarding nucleon. Equation (1) and also the following equations give only the first terms in a series expansion in inverse powers of E_0. This paper was essentially a corrected version of the paper of Nordheim and Nordheim[2] who had arrived at practically the same result, although using an incorrect expression for the perturbation matrix element. As in the following, a charged scalar field was assumed. Independently, the result of Eq. (1) was obtained by us[3] making the same simplifying assumptions.

A different result, however, was obtained by Wang[4] using the Weizsäcker-Williams method. His result was

$$\sigma = K(g^2/\hbar c)^3(M/\mu)(Mc^2/E_0)(\hbar/Mc)^2, \qquad (2)$$

where K is a constant of the order of magnitude unity.

Since it seemed to us that the Weizsäcker-Williams method should give reliable results for high energies, we have performed the third-order perturbation calculations, now retaining all terms. It then turned out that the final result is essentially identical with Wang's formula. Our final result is

$$\sigma = (\pi/8)(g^2/\hbar c)^3(M/\mu)(Mc^2/E_0)(\hbar/Mc)^2. \qquad (3)$$

It is interesting to note that formula (3) does not give an E_0^{-2} dependence as one might expect from dimensional considerations,[5, 6] thus indicating a dependence of the matrix element on energy. The difference between formulas (1) and (3) arises from the fact that in the evaluation of the matrix elements, Urban and Schwarzl,[1] as well as the present authors in their preliminary calculations,[3] neglected terms arising from the momentum of the virtual meson which were taken into consideration in the calculations leading to formula (3). Recoil was also taken into account, but this did not influence the final result.

We should like to express our sincere thanks to Professor H. Wergeland for discussions on the subject of this letter. Detailed calculations will be published in a report of the Purdue Synchrotron Project to the ONR.

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Note on the Resistivity of Gold at Low Temperatures

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As is well known, the wave function of an electron in a perfectly periodic potential field consists of a plane non-attenuated wave, modulated with the period of the potential. In Bloch's model of a solid, the periodicity of this potential is equal to the periodicity of the lattice ions. It follows, therefore, that in such an ideal solid an electron would experience no scattering or in other words the electrical resistivity should be zero.

The above is a fundamental property of an ideal (i.e., rigorously periodic) lattice and is deduced from quantum mechanics without any approximation being involved. If one now inquires as to how closely any real crystal approximates this model, the following modes of departure may be envisaged:

(1) If the situation is such that the states in the lowest Brillouin zone are completely occupied by electrons, and an energy gap between it and the next higher zone exists (no overlap), we should, in the vicinity of absolute zero, have no net current, i.e., the crystal would be an insulator with an infinite resistivity at 0°K.

(2) In the more pertinent case of a monovalent metal such as gold with a half-occupied first zone, departures of the lattice from perfect periodicity can be due to the following: (a) Finite excitation of the Debye waves. This is temperature dependent and will vanish at the absolute zero. (b) Strains and impurities. (c) Crystallite boundaries in polycrystalline material.

These last three will, of course, be temperature independent at low temperatures. Accordingly, as the temperature approaches absolute zero, the resistivity of a conductor should approach zero or at most become temperature independent due to (b) and (c).

In view of all this, the observation made by de Haas, de Boer, and van den Berg[1–3] some years ago that the resistivity of pure gold increased as the temperature was lowered below about 3°K seems exceedingly strange. While all their measurements were made with polycrystalline specimens, even their purest sample (impurity $\sim 10^{-4}$ percent, mainly Cu and Ag) showed a definite minimum in the resistance-temperature curve, although it is true that less pure material gave a more pronounced effect. The