the resonances of reference 1 were reduced by 10%. Since the absolute cross sections of reference 1 are known to only about ±15% and since there are possible systematic errors (as large as ±7%) in the absolute magnitude of the scattering cross section, this adjustment is well within the errors in the absolute sizes of the two cross sections being compared. The difference between the experimental points and the smooth curve at the higher energies is probably significant. It represents more absorption than is given by the two Lorentz lines used to predict the scattering cross section. The neutron yield cross section of reference 1 is also higher than the Lorentz lines in this energy region.

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DOUBLING OF FERMIONS?

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The recent discovery that the long sought π-e mode of decay does indeed exist,[1,2] and that its intensity[3] relative to the π-μ mode is compatible with the assumption of equal interactions for electrons and μ mesons,[4,5] removes a stumbling block to further thinking about the remarkable similarity between these two particles. Except for their mass difference, the electron and μ meson of a given electric charge behave, as far as their known interactions are concerned–i.e., electromagnetic, as well as weak interactions–like two states of one particle. Tentatively we shall assume that they differ by a hitherto unknown internal parameter. This parameter is presumably connected with their mass difference, but does not affect their known interactions which may be held to be invariant with respect to the internal parameter. Many examples of invariance of interactions with respect to an internal parameter are well established, e.g., the charge independence of nucleon interactions. On this view, one might refer to the μ meson as a "heavy electron"–a name by which it was once known–and use the symbols e_1 and e_2 for e and μ, respectively.

One might go further and ask, again assuming the view outlined to be correct, whether the heavier fermions, the baryons, might not also appear as doublets of which only the lighter members have so far been observed. Although the baryons possess strong interactions, in addition to the electromagnetic and weak ones, it is conceivable that whatever the cause of the doubling of electrons into light and heavy ones might be, it might also be responsible for a doubling of baryons. In the absence of definite knowledge on this point, it would seem worthwhile to start out by inquiring why the "heavy baryons," if they actually do exist, might have so far escaped detection.

Take the case of the proton, where besides the ordinary proton p_1, a "heavy proton," p_2, might exist. Simple considerations show that it would have been difficult to recognize such a particle without a deliberate search. What would be some possible modes of production of p_2? For guidance, let us remind ourselves of the processes which give rise to μ mesons. Two essentially different processes are known: μ mesons may appear as decay products of π or K mesons, or they may be produced by photons in pairs: $\mu^+ + \mu^-$. The pair production is difficult to observe, and it was only discovered as a result of a deliberate and careful search.[6] In analogy with these phenomena, we might look for heavy nucleons both in decay processes and in pair production. Depending on the mass of the heavy nucleons, it might or might not be energetically possible for a heavy nucleon to appear as a decay product of one of the known hyperons. However, a process of this type would only have been found with a reasonable probability if the mass difference $\Delta = m(p_2) - m(p_1)$ were considerably smaller than the Q value of hyperons. There remains, as a more systematic approach, the deliberate search for the pair-production process $p_2 + \bar{p}_2$. Here we have the advantage, compared with the case of μ-pair production, that we can make use of the strong interactions, besides the electromagnetic ones.

What would be the characteristics of a p_2, or its antiparticle $\bar{p}_2$ (apart from their mass), by which they might be distinguished from the known particles? Since the mass difference Δ cannot be estimated at present, we can only speculate about possible decay modes of p_2. It might, e.g., decay by a β interaction: $p_2 \to n_1 + e_{1,2}^{+} + \nu$. Other weak decay modes might exist; in particular, one or more π mesons or K mesons might be emitted if Δ were sufficiently high. Since p_2 must be assumed to have also strong interactions, though not in decay, it may occur bound to other, ordinary, nucleons, and its decay in such a state may resemble a hyperfragment disintegration.[7] The same holds for $\bar{p}_2$, which could either annihilate "slowly" inside a nucleus through its weak interaction, e.g., $\bar{p}_2 + n_1 \to e_{1,2}^{-} + \bar{\nu}$, or first decay into $\bar{p}_1$ or $\bar{n}_1$ with consequent rapid annihilation.

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RADIATIVE CORRECTIONS TO PION BETA DECAY*

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Recent experiments[1] have shown that the ratio R_0 of the rates Γ_e, Γ_μ for $\pi \to e + \nu$ and $\pi \to \mu + \nu$ modes of decay is in the neighborhood of the value predicted by the universal beta-decay theory,[2,3] i.e., $R_0 = (12.78 \times 10^{-5})$. However, to compare the results of a precise experiment with the predicted number the radiative corrections should be included in the theoretical estimate of the ratio. The corrections do not cancel in the ratio since they depend on the electron and muon masses and, furthermore, produce a surprisingly large correction to the ratio.

Using the universal (V, A) theory[3] we express the general matrix element for the process $\pi \to (e \text{ or } \mu) + \nu + \gamma$ to order e as

$$M_\nu = [f_1 \delta_{\mu\nu} + f_2 k\mu\, p_\nu + f_3 p_\mu p_\nu]$$

$$\times \bar{\Psi}_{l_2} \gamma_\mu (1 + i\gamma_5) \Psi_{l_1} \cdots \quad , \qquad (1)$$

where p and k are the momentum of the pion and photon, respectively, and where each of the covariants f_1, f_2, f_3 depend on the scalars m_π^2, $p \cdot k$, k^2. In addition to M_ν we also consider the matrix elements which arise from bremsstrahlung photons. In writing Eq. (1) we have used the Lorentz condition to eliminate terms such as $k_\nu p_\mu$, $k_\nu k_\mu$. We note that gauge invariance implies that f_1 at $k=0$ is determined by the amplitude for $\pi \to (e \text{ or } \mu) + \nu$.

In the phenomenological theory with direct π-(e or μ) coupling only f_1 would be present in Eq. (1). In a realistic theory involving virtual nucleon loops, the other covariants f_2, f_3 would be expected to enter. If we consider the decay of the pion to occur through one virtual nucleon pair then we find that $f_{2,3} \sim (1/M^2) f_1$ where M is the nucleon mass and that in the limit of very large nucleon mass f_1 does not depend on $p \cdot k$ and k^2. If we consider $(k^2/M^2) \ll 1$ then application of the Ward identity leads to the same conclusions to all orders in the pion-nucleon coupling. We therefore have neglected $f_{2,3}$ in the calculation of the radiative corrections, and have assumed f_1 is independent of k. In this case f_1 will cancel out in the ratio of the rates.

Using the first term of Eq. (1) we have calculated the radiative corrections, in the usual manner, by including all possible real and virtual electromagnetic processes to order e^2. Since the inclusion of the inner bremsstrahlung changes the number of particles in the final states from two to three there is now a spectrum of energies available to the electron or muon. If we ask how the ratio of rates is affected for electrons or muons having an energy near the maximum energy and suffering an energy loss less than