We wish to point out in this note certain theoretical implications which the existence of such charge asymmetries would entail.

According to present ideas there are two possibilities. As is pointed out in reference 5, charge asymmetries can arise if the two lifetime components of a single kind of K, $\bar{K}$ complex interfere with each other. Suppose, for example, that charge asymmetries are observed after a time interval following K-meson production which is large compared to 1 5$\times10^{-10}$ sec. Such charge asymmetries could not come about from $\theta_1-\theta_2$ interference. If they are caused by interference effects at all, there must be a second K, $\bar{K}$ complex whose two lifetime components both are comparable to or larger than the experimental time interval, i.e., there must exist a second neutral meson complex, call it τ, $\bar{\tau}$, different from θ, $\bar{\theta}$.

If the weak interactions are not invariant with respect to charge conjugation, there is another possibility. As has been pointed out by Lee, Oehme, and Yang,[6] noninvariance with respect to charge conjugation can lead to charge asymmetries in the long-lived component of a single K, $\bar{K}$ complex. The main point which we wish to make here is that this can occur only if time-reversal invariance is violated together with charge conjugation invariance.[7] This can easily be seen on the basis of the Lüders-Pauli theorem,[8] which states that a system is always invariant with respect to the product of space inversion P, charge conjugation C, and time reversal T. If a system is invariant with respect to T, it must then be invariant with respect to the product CP. In this case the two lifetime components K_1 and K_2 of a K, $\bar{K}$ complex would each be eigenstates of the operator CP. For a system involving only two independent momenta, such as the system (e,π,ν) arising from K-decay, a space inversion asymmetry is undetectable unless the spins of the particles are measured.[9] Thus if time reversal invariance holds, the system will appear to be charge conjugation invariant if spins are not measured. Conversely, detection of charge asymmetries would imply noninvariance with respect to time reversal.[10]

Thus, according to present ideas, if charge asymmetries are discovered in the long-lived component of K-meson decay, it means that either there are two different K-mesons or time-reversal invariance does not hold. It is possible to distinguish between these two possibilities experimentally by studying the time dependence of the asymmetry, i.e. the variation of the asymmetry as the detecting device is moved farther and farther from the K-meson source. The interference effect discussed in reference 5 is strongly dependent on time, so that if the first possibility discussed above holds, there should be time variations in the asymmetry. On the other hand, the charge asymmetries in the decay of a single lifetime component of a single meson are time independent.

[1] Lande, Booth, Impeduglia, Lederman, and Chinowsky, Phys. Rev. **103**, 1901 (1956).

[2] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955).

[3] A. Pais and O. Piccioni, Phys. Rev. **100**, 1487 (1955).

[4] K. M. Case, Phys. Rev. **103**, 1449 (1956).

[5] S. B. Treiman and R. G. Sachs, Phys. Rev. **103**, 1545 (1956).

[6] Lee, Oehme, and Yang, Phys. Rev. **106** (to be published) (1957).

[7] After completion of this letter the authors learned in private communication from C. N. Yang and T. D. Lee that this fact was also known to them.

[8] G. Lüders, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **28**, No. 5 (1954); W. Pauli, *Niels Bohr and the Development of Physics* (Pergamon Press, London, 1955). See also reference 6.

[9] If the K-meson has a nonvanishing spin and if this spin is polarized, there may be differences in the angular distributions of (e^+,π^-,ν) and (e^-,π^+,ν) but the integrated transition rates will be the same.

[10] This can also be proved using the Weisskopf-Wigner method as discussed by Lee, Oehme, and Yang (reference 6). In the notation of their paper, there are no charge asymmetries if $|p|=|q|$ (see appendix of reference 6). Now it is easy to show that if time-reversal invariance holds, products of matrix elements of the form $H_{aj}H_{jb}$ are real. This then implies that Γ_{12} and M_{12} are real and hence that $p^2=q^2$ [see Eq. (30) of reference 6].

Theory of μ-Meson Decay with the Hypothesis of Nonconservation of Parity

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LEE and Yang[1] have proposed experiments for testing the nonconservation of parity in weak-coupling processes: the β decay of oriented Co^{60} nuclei and μ-meson decay. Those experiments have been completed[2] and they confirm the Lee and Yang hypothesis. In their paper,[1] these authors computed the decay rate for the β-decay experiment, but not for the μ-meson decay. We present here the result of theoretical computation for the latter phenomenon. If parity is not conserved in $\pi-\mu$ decay, the μ meson is then polarized.[1] This polarization is longitudinal in the π-meson restframe. Let **s** be a pseudovector in the direction of the μ-meson momentum, such that in the μ-meson rest frame $\mathbf{s}^2=1$. The μ-meson polarization is along $\pm\mathbf{s}$ with the degree of polarization $|\zeta|$ (where $-1\leq\zeta\leq1$). We shall choose the sign of ζ such that the μ-meson polarization is along $\zeta\mathbf{s}$ in its restframe. We use the usual β-decay Hamiltonian (with ordinary neutrino theory) for even and odd couplings with g_i and g_i' for their complex coupling constants ($i=1$ to 5; reality of the g_i and g_i' corresponds to invariance under time reversal). It is well known that a change in the order of the four fields in the interaction Hamiltonian preserving parity is equivalent to a relabeling of coupling constants (the new ones are linear combinations of the old ones). This property can be extended to the type of Hamiltonian we have to consider.[3] Moreover, it is easily found that the study of the electron momentum in the μ decay at rest[4] measures only four real parameters, functions of the coupling constants. We use $\hbar=c=1$. Let E, $\mathbf{p}$, and ϵ be the electron total energy, momentum, and mass, μ the meson mass, and $W=(\mu^2+\epsilon^2)/2\mu$ the maximum energy of the electron. We write $\mathbf{p}\cdot\mathbf{s}=p\cos\theta$. The electron spectrum for the μ^+-meson decay at rest[5] is

$$P(E)\sin\theta\,d\theta\,dE$$
$$=\frac{\sin\theta\,d\theta\,dE}{48\pi^3}Q\mu pE\left\{3(W-E)+\tfrac{2}{3}\rho\left(4E-3W-\frac{\epsilon^2}{E}\right)\right.$$
$$+3\eta\frac{\epsilon}{E}(W-E)+\frac{p}{E}\left[-3\alpha(W-E)\right.$$
$$\left.\left.+2\beta\left(W-2\,E+\frac{\epsilon^2}{E}\right)\right]\zeta\cos\theta\right\}. \quad (1)$$

When one neglects ϵ/E, formula (1) can be simplified to

$$P(E)=\frac{Q\mu E^2}{48\pi^3}[3(W-E)+\tfrac{2}{3}\rho(4E-3W)]\times(1-S\zeta\cos\theta), \quad (2)$$

where

$$S=3\left(\frac{2\beta+(3\alpha-4\beta)y}{2\rho+(9-8\rho)y}\right),$$

with

$$y=\frac{W-E}{W}. \quad (2')$$

Two cases must be distinguished: (i) The μ meson decays with emission of one neutrino and one antineutrino; then

$$0\leq\rho\leq1,\quad -(1-\tfrac{2}{3}\rho)\leq\alpha\leq1-\tfrac{2}{3}\rho,\quad -\tfrac{1}{3}\rho\leq\beta\leq\tfrac{1}{3}\rho. \quad (3)$$

(ii) The two emitted neutrinos are identical; then

$$0\leq\rho\leq\tfrac{3}{4},\quad -(1-\tfrac{4}{3}\rho)\leq\alpha\leq1-\tfrac{4}{3}\rho,\quad -\tfrac{1}{3}\rho\leq\beta\leq\tfrac{1}{3}\rho. \quad (3')$$

The measure of the asymmetry ζS as a function of y gives $\zeta\alpha$ and $\zeta\beta$. The magnitude of the parameter ζ, which is the degree of polarization of the μ meson, depends on the characteristics of the $\pi-\mu$ decay. The theory is ruled out if S does not have an energy dependence of the form (2′). (See, however, reference 6.)

It seems premature to discuss the consequences of the nonconservation of parity for the hypothesis of a universal Fermi interaction[3,6]; we have now the choice among ten complex coupling constants (as compared to five real g_i formerly), and new experimental data are still scarce. However, one can introduce nonconservation of parity by using one new constant only. We write $g_i'=\xi g_i$. If ξ is real we can require $-1\leq\zeta\leq1$. (If $|g_i'/g_i|>1$, then we define $\xi=g_i/g_i'$; indeed, couplings and pseudocouplings play a completely symmetrical role.) Then this quantity ξ has a simple physical interpretation. Indeed, to pass from the ordinary interaction Hamiltonian in β radioactivity to the new Hamiltonian, one has just to replace ψ_ν by $(1+\xi\gamma_5)$ [where $(\gamma_5)^2=1$]. On the other hand, if the neutrino mass is zero, $(1\pm\gamma_5)/2$ are the projectors which project ψ_ν onto states of pure circular polarization.[7] Then ξ can be interpreted[8] as a degree of circular polarization. In a theory preserving parity ξ is a pseudoscalar quantity and it is changed into $-\xi$ by particle-antiparticle conjugation Thus the introduction of ξ can lead us to the following neutrino theory: all neutrinos in nature are circularly polarized; the degree of circular polarization is $|\xi|$. Neutrinos are right- (or left-) circularly polarized; antineutrinos are left- (or right-) circularly polarized. In the limiting case $|\xi|=1$ such a theory has been introduced by Salam,[9] and as we just learned, by Lee and Yang.[9] Since two neutrinos are emitted in μ-meson decay, this theory is not exactly equivalent to that which gives (1) and (2). Furthermore, $\zeta=\pm\xi$ (when the μ meson is not depolarized during its life). The sign depends on whether a neutrino or an antineutrino is emitted in the $\pi-\mu$ decay. The value of ξ could be in principle directly measured.[4]

If $|\xi|<1$, the parameter ρ has its full range (3) and (3′) of possible values. For μ-meson decay, although the sign of the asymmetry $\Sigma=\zeta S$ is arbitrary in that theory, it is the *same* for μ^+ and μ^- decay.

When the two emitted neutrinos are identical, the asymmetry is

$$\Sigma=\pm\left(\frac{2\xi^2}{1+\xi^2}\right)\left(\frac{3(3-4\rho)y}{2\rho+(9-8\rho)y}\right) \quad (4)$$

[i.e., $\zeta=\xi$, $\beta=0$, and $\alpha=2\xi/(1+\xi^2)$ in (2′)].

When one neutrino and one antineutrino are emitted in μ-meson decay,

$$\Sigma=\left(\frac{2\xi^2}{1+\xi^2}\right)\left(\frac{6\delta(1-2y)}{2\rho+(9-8\rho)y}\right), \quad (4')$$

where $-\frac{1}{3}\rho\leq\delta\leq\frac{1}{3}\rho$ when $0\leq\rho\leq\frac{3}{4}$ and $\rho-1\leq\delta\leq1-\rho$ when $\frac{3}{4}\leq\rho\leq1$ [i.e., $\zeta=\xi$, $\alpha=0$, and $\beta=2\delta\xi/(1+\xi^2)$ in (2′)].

When $|\xi|=1$, the parameter ρ has a fixed value: $\rho=0$ for (4) and $\rho=\frac{3}{4}$ for (4′) in agreement with reference 10 (then $|\delta|=\frac{1}{4}$).

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[2] The experiment on Co[60] has been done by Wu, Ambler, Hudson, Hoppes, and Hayward, Phys. Rev. **105**, 1413 (1957). The experiment on μ-meson decay has been done by Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957), and by J. L. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).

[3] For details, and earlier references, see for instance L. Michel, thesis, Memorial des Poudres, **35**, annexe p. 77 (1953).

[4] Calculations related to possible observation of the polarization of the electron in μ-meson decay and nuclear β radioactivity, and the direct measurement of the polarization of the μ meson are in progress.

[5] Electromagnetic radiative corrections to this decay are not very small. In a recent paper on this subject, Behrends, Finkelstein, and Sirlin [Phys. Rev. **101**, 866 (1956)] have shown that Eq. (1) is still valid but that the parameters are slowly varying functions of the energy.

[6] For the sake of completeness we give here the explicit dependence of the parameters on the g_i and g_i'. For ease of calculation, we have taken the order $\epsilon\mu\nu\nu$ in the interaction Hamiltonian. When the two emitted neutrinos are distinguishable, we define $a_i^2=g_i\bar{g}_i+g_i'\bar{g}_i'$, $a_{ij}=g_i\bar{g}_j'+g_i'\bar{g}_j$, $c_1^2=a_1^2+a_5^2$, $c_2^2=a_2^2+a_4^2$, $c_3^2=a_3^2$, $b_1c_1^2=a_{15}+a_{51}$, $b_2c_2^2=a_{24}+a_{42}$, and $b_3c_3^2=a_{33}$; we see that, for $k=1$, 2, and 3, $c_k^2\geqslant 0$, $-1\leqslant b_k\leqslant 1$. Then $Q=c_1^2+4c_2^2+6c_3^2$, $\rho Q=3(c_2^2+2c_3^2)$, $\eta Q=a_1^2-2a_2^2+2a_4^2-a_5^2$, $\alpha Q=b_1c_1^2-2b_3c_3^2$, and $\beta Q=b_2c_2^2-2b_3c_3^2$. When the two emitted neutrinos are identical, one has moreover $g_2=g_3=g_3'=g_4'=0$; it follows that $c_3^2=b_3=0$.

[7] See for instance V. Bargmann and E. P. Wigner, Proc. Nat. Acad. Sci. U. S. **34**, 211 (1948).

[8] L. Michel and A. S. Wightman, Phys. Rev. **98**, 1190 (1955).

[9] A. Salam, Nuovo cimento **5**, 299 (1957); T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957); L. D. Landau, Nuclear Phys. (to be published). We thank the authors for preprints of their work.

Proton Polarization in (d,p) Reactions

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The proton polarization in (d,p) reactions was calculated by Cheston[1] under the assumption that the final-state proton scatters in a spin-orbit potential. The transition operator T for the (d,p) reaction was taken to be the neutron-proton central interaction potential $V_{np}(|\mathbf{r}_n-\mathbf{r}_p|)$ in the zero-range approximation.

Recently Hillman[2] compared his data for the $C^{12}(d,p)C^{13}$ reaction with Cheston's numerical results for that reaction. However, it appears that Cheston's paper is in error.

Cheston neglects the proton spin-flip terms. To establish his Eq. (5) he says that with the quantization axis chosen along the vector $\mathbf{K}\times\mathbf{k}$ a proton "produced in a definite state of spin orientation (μ_p) in the original stripping act will maintain this orientation after scattering in the spin-orbit potential." However, if initially the deuteron spin projection $\mu_d=0$, there is no definite orientation of the proton spin along the axis of quantization.

First, his Eq. (5) should read

$$\begin{aligned}&\langle\psi(J,L,M_J)\psi(l,m)\mathrm{X}(\tfrac{1}{2},\mu_n)|T|\phi(L_d,M_d)\\&\quad\times\mathrm{X}(\tfrac{1}{2},\mu_n')\mathrm{X}(\tfrac{1}{2},\mu_p')\rangle\\&=\sum_{\mu_p''}C_{L,\frac{1}{2}}(J,M_J;M_J-\mu_p'',\mu_p'')\\&\qquad\times\langle\psi(J,L,M_J-\mu_p'')\chi(\tfrac{1}{2},\mu_p'')\psi(l,m)\\&\qquad\quad\times|T|\phi(L_d,M_d)\chi(\tfrac{1}{2},\mu_p')\rangle\times\delta(\mu_n,\mu_n').\end{aligned}\tag{1}$$

Consequently, Cheston's Eq. (6) should read

$$\begin{aligned}&\mathfrak{M}(\mu_d\rightarrow\mu_f,\mu_p)\\&=\sum_{L_d,L,J,M_d,M_L}\sum_{\mu_p''}a(L,M_L)b^*(L_d,M_d)\\&\quad\times C_{L,\frac{1}{2}}(J,M_L+\mu_p;M_L,\mu_p)\\&\quad\times C_{L,\frac{1}{2}}(J,M_L+\mu_p;M_L+\mu_p-\mu_p'',\mu_p'')\\&\quad\times C_{l,\frac{1}{2}}(j_f,\mu_f;\mu_f-\mu_d+\mu_p'',\mu_d-\mu_p'')\\&\quad\times C_{\frac{1}{2},\frac{1}{2}}(1,\mu_d;\mu_d-\mu_p'',\mu_p'')\langle\psi(J,L,M_L+\mu_p-\mu_p'')\\&\qquad\times\psi(l,\mu_f-\mu_d+\mu_p'')|T|\phi(L_d,M_d)\rangle.\end{aligned}\tag{2}$$

With Cheston's transition operator T, the selection rule $M_d=M_L+\mu_p+\mu_f-\mu_d$, being independent of μ_p'', cannot reduce the sum over μ_p'' to only the term $\mu_p''=\mu_p$ provided $\mu_d=0$. Thus whatever the a's and b's, i.e., independently of the system of reference, both μ_p'' contribute provided $l>0$. The only cases in which only $\mu_p''=\mu_p$ contributes are (1) no spin-orbit coupling in the final-state proton potential, and (2) $l=0$. Unfortunately, Cheston's numerical example involves $l=1$.[3]

Further, Cheston writes for the distortion parameters $\beta(L,J)=\frac{1}{2}\eta(L,J)$. If, however, $\eta(L,J)$ are the usual average reflection coefficients, it should read $\beta(L,J)=\frac{1}{2}[1-\eta(L,J)]$.

Finally, it should be noted, in connection with Cheston's paper, that in the first Letter by the author on the (n,p) polarization problem,[4] Eqs. (4) and (6) held only for $l_f=0$.

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[2] P. Hillman, Phys. Rev. **104**, 176 (1956).
[3] Nevertheless it is probable that the spin-flip contribution is rather small.
[4] J. Sawicki, Nuovo cimento **2**, 1322 (1955).

Singular State in Relativistic Cosmology

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As is well known, the isotropic cosmological solutions of general relativity start from a singular state in the finite past. In a recent paper Komar[1] has investigated the question as to whether this singularity persists under more general circumstances and has found that such a singularity does occur unless one