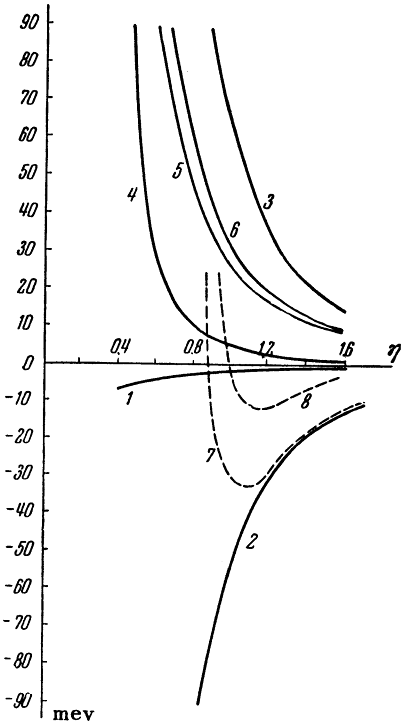
a function of the parameters η, μ, λ.



1– $\langle V_2\rangle/A$; 2– $\langle V_4^{(a)}\rangle/A$; 3– $\langle V_4^{(b)}\rangle/A$; 4 – $\langle V_{12}\rangle/A$; 5 – T/A; 6 – E/A; 7 – $\langle V\rangle/A = (\langle V_2\rangle + \langle V_4^{(a)}\rangle + \langle V_{123}\rangle)/A$; 8 – $E/A = (\langle V\rangle + T)/A$. Curves 1–6 were computed by us, curves 7–8 taken from Ref. 3. All refer to $G^2/4\pi = 10$, $r_c = 0.38\ \hbar/\mu c$.

In the figure we show the potential, kinetic and total energy per nucleon as a function of η, assuming $G^2/4\pi = 10$, $r_c = 0.38\ (\hbar/\mu c)$. The curves show that the energies ($\langle V_{12}\rangle/A$) and (E/A) are positive in the range $0.3 \leq \eta \leq 1.6$. The energy $\langle V_4^{(b)}\rangle$ due to two–particle repulsions completely cancels the attractive energy $\langle V_2\rangle + \langle V_4^{(a)}\rangle$, and so the binding energy does not saturate at normal nuclear density ($\eta \sim 1$). The same behavior of (E/A) occurs also for $(G^2/4\pi) = 7.5, 5.2, 1$ and $r_c = 0.38\ (\hbar/\mu c)$. Thus it is not necessary, in considering the nuclear saturation problem with the potential (5) derived from pseudoscalar meson theory, to introduce the three–particle repulsion which adds a positive term $\langle V_{123}\rangle$ to the nuclear energy. This result contradicts our earlier statement[3] that the Lévy potential (without the $V_4^{(b)}$ term)

$$V_{12} = \begin{cases} V_2 + V_4^{(a)}, & r > r_c, \\ \infty & r < r_c, \end{cases}$$

supplemented by the three–particle repulsion, will produce saturation in heavy nuclei. Actually, the term ($\langle V_{123}\rangle/A$) due to three–particle repulsions, in the absence of the $V_4^{(b)}$ term, just sufficiently weakens the strong attraction ($\langle V_{12}\rangle/A$) so that the total energy per nucleon (E/A) has a minimum of –12 mev at normal nuclear density (η = 1–1.5). Our calculation shows that the Lévy–Klein potential defined by Eq. (5) gives no nuclear saturation, either with or without the addition of a three–particle repulsion.

In conclusion I thank Professor A. A. Sokolov for criticism and valuable comments.

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The Problem of Parity Non-conservation in Weak Interactions

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ONE of the possible theoretical explanations of the paradox of the θ and τ–decay of K-mesons[1] is the hypothesis of parity non-conservation in weak interactions. Lee and Yang[2] showed that parity non-conservation in weak interactions could not have been detected by any experiments which have yet been performed (except, of course, the *K*-meson decay experiments), and they proposed several experiments by which the conservation of parity could be tested. However, Yang and Lee did not require that the weak interactions be invariant under time-reversal or charge-conjugation.* If one assumes that space-parity is not conserved, and that the θ and τ particles are identical, then the existence of a long-lived K°-particle [4] can be explained by supposing either that charge-parity or time-parity is conserved. The analysis of correlation experiments by Lee and Yang assumes that time-parity is conserved and charge-parity is not conserved.

We have found that, in the absence of conservation of space-parity, there exists an experimental test to decide whether charge-parity or time-parity is conserved in weak interactions. Namely, if time-parity is conserved, the long-lived (odd with respect to time-reversal) K°-particle can decay into 3 pions or into 3 π°-mesons forming an *S*-state, while this process is forbidden if charge-parity is conserved. We shall show that if one assumes conservation of charge-parity one is led to results quite different from those of Lee and Yang.

The invariance of the Hamiltonian under charge conjugation implies certain well-known phase-relations[3,5] between the coefficients multiplying the various interactions. Consider first of all the decay $\Lambda^\circ \to p + \pi$. If parity-conservation is dropped, the interaction Hamiltonian for this process must have the form

$$H = g(\overline{\psi}_p \psi_\Lambda)\varphi_\pi + iG(\overline{\psi}_p \gamma_5 \psi_\Lambda)\varphi_\pi + g^*(\overline{\psi}_\Lambda \psi_p)\varphi_\pi^+ + iG^*(\overline{\psi}_\Lambda \gamma_5 \psi_p)\varphi_\pi^+ . \quad (1)$$

assuming that interactions containing derivatives are excluded. The operation of charge-conjugation is as usual described by

$$\varphi'(x) = \varphi^+(x);$$

$$\psi'(x) = -\overline{\psi}(x)C^{-1}; \quad \overline{\psi}'(x) = C\psi(x),$$

where the matrix C satisifies the conditions

$$C^T = -C; \quad CC^+ = 1; \quad \gamma_\mu^T = -C\gamma_\mu C^{-1}.$$

We use the Feynman notations

$$\gamma_\mu = \{\beta\alpha,\ \beta\}; \quad \gamma_5 = -i\gamma_1\gamma_2\gamma_3\gamma_4,$$

$$\hat{a} = \gamma_\mu a_\mu = -\beta\alpha\mathbf{a} + \beta a_4.$$

We apply the operation of charge-conjugation to Eq. (1), remembering that $\gamma_5^T = C\gamma_5 C^{-1}$, and conclude that for invariance it is necessary that g and G be real*.

When parity is not conserved, the square of a transition matrix element may contain pseudoscalar as well as scalar terms. To determine whether pseudoscalar terms appear in the Λ°-decay, we consider the decay of a polarized Λ° at rest. Assuming the Hamiltonian (1), the square of the matrix element, summed over the proton spin and with neglect of the proton-meson interaction, becomes

$$\sum |M|^2 = \{g^2 \overline{u}_\Lambda (\hat{p} + m) u_\Lambda - G^2 \overline{u}_\Lambda \gamma_5 (\hat{p} + m)\gamma_5 u_\Lambda + igG\overline{u}_\Lambda [\gamma_5(\hat{p} + m) + (\hat{p} + m)\gamma_5] u_\Lambda\} / 2E_p, \quad (2)$$

Here $\hat{p}$ is the proton momentum and m its mass. A pseudoscalar term (proportional to σp, where σ is the spin of the Λ°) can only appear in the interference term, but it anyway vanishes since

$$\overline{u}_\Lambda \gamma_5 u_\Lambda = 0.$$

In a similar way, it is easy to show that pseudoscalar terms proportional to pσ must vanish even when both scalar and vector interactions are present. It follows that in the two-step process, $\pi^- + p \to \Lambda^\circ + K^\circ$, $\Lambda^\circ \to p + \pi^-$, considered by Lee and Yang, the differential probability will not contain any pseudoscalar term proportional to $(\mathrm{p}_\pi \mathrm{p}_\Lambda \mathrm{p}_p)$; in this case the only effect of the first strong interaction is to produce polarized Λ°-particles. Hence it is impossible to detect any non-conservation of parity by observing the angular distribution of protons in Λ°-decay. A test of parity conservation is possible only by observing radiative Λ°-decay. In the radiative decay the pseduoscalar interference terms again vanish, but the photon spectrum will be different according as parity is or is not conserved. Only if parity is not conserved can terms proportional to g^2 and to G^2 exist together in the expression for the spectrum*. All these remarks apply equally to the decay of $\Sigma^\pm$-particles.

The beta-decay is another weak process in which effects of non-conservation of parity might be observed. If parity is not conserved, the interaction

Hamiltonian becomes

$$H = (\overline{\psi}_p \psi_n)\,(c_S \overline{\psi}_e \psi_\nu + i c'_S \overline{\psi}_e \gamma_5 \psi_\nu) \qquad (3)$$

$$+ (\overline{\psi}_p [\gamma_\mu, \gamma_\nu]\, \psi_n)\, \{c_T\, (\overline{\psi}_e\, [\gamma_\mu, \gamma_\nu]\, \psi_\nu)$$

$$+ i c'_T\, (\overline{\psi}_e \gamma_5\, [\gamma_\mu, \gamma_\nu]\, \psi_\nu)\} + \text{Herm. conj.}$$

$$[\gamma_\mu, \gamma_\nu] = {}^1/_2\, (\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu),$$

We confine the discussion to the scalar and tensor interactions which have been experimentally observed. Invariance under charge conjugation implies that C_S, C_S', C_T, C_T' be real.

We consider the β-decay of a polarized nucleus. We calculate from Eq. (3) the square of the transition matrix element and sum over the neutrino spin. The only surviving pseudoscalar terms are those arising from interference of the scalar and tensor interactions, since the terms proportional to C_S, C_S' and to $C_T\, C_T'$ vanish identically. After summing over the electron spin, we find

$$(4 / E_\nu E_e)\,(c'_S\, c_T - c_S\, c'_T) \qquad (4)$$

$$\times \Big\{ \mathrm{Im} \Big(\int \overline{\psi}_p \psi_n \exp\,[-i\,(\mathbf{p}_e - \mathbf{q})\,\mathbf{r}]\; d\mathbf{r}$$

$$\times \int \overline{\psi}_n \sigma \psi_p \exp\,[i\,(\mathbf{p}_e - \mathbf{q})\,\mathbf{r}]\, d\mathbf{r} \Big) \Big(\mathbf{q} E_e - \mathbf{p} E_\nu \Big)$$

$$+ \mathrm{Re} \Big(\int \overline{\psi}_p \psi_n\, \exp\,[-i\,(\mathbf{p}_e - \mathbf{q})\,\mathbf{r}]\, d\mathbf{r}$$

$$\times \int \overline{\psi}_n \alpha \psi_p \exp\,[i\,(\mathbf{p}_e - \mathbf{q})\,\mathbf{r}]\, d\mathbf{r} \Big)\, [\mathbf{pq}] \Big\}$$

where $\mathbf{q}$ is the neutrino momentum. Equation (4) is easy to evaluate in the case of the beta–decay of a polarized free neutron. If we suppose that the polarization of the proton is not observed and sum over the proton spin, the result is again zero.

In the case of any allowed transition, Eq. (4) still vanishes. For an allowed transition we may keep only the first term in the curly bracket and replace the exponential $\exp\,[i\,(\mathbf{p}_e - \mathbf{q})\,\mathbf{r}]$ by unity. Then the presence of the scalar interaction requires that initial and final state have the same values of total angular momentum and of z–component of angular momentum. But the diagonal elements of the Hermitian matrices σ are real, so that Eq. (4) is zero. For allowed transitions, Eq. (4) still vanishes, at least to order $(Ze/\hbar v)$, when the Coulomb interaction is taken into account.

Thus we have shown that for the simplest beta-decay processes, if charge-conjugation invariance holds, there is no difference between the consequences of conservation and non-conservation of space-parity.

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*Pauli[3] has discussed these problems in a general way. It is important to observe that, when parity is not conserved, charge conjugation ceases to be equivalent to time reversal. Pauli proved that, assuming the ordinary relation between spin and statistics, the Lagrangian must be invariant under the combined operation of charge-conjugation and inversion of all four coordinates.

*We assume that spinors belonging to different fields anticommute. If we assumed that they commute, we should obtain only a common unobservable phase-factor.

*This situation could however be simulated if there exist two Λ^0-particles with opposite parity and almost equal lifetime.

Note added in proof. (February 14, 1957)
We recently heard of the results of the experiments of Professor Wu on the β-decay of oriented cobalt nuclei. In these experiments a correlation was found between the nuclear spin and the direction of the electron momentum (a term $\sigma\mathbf{p}$). The arguments given above show that this implies a non-conservation in beta-decay of both space-parity and charge-parity.

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Diffractive Production of Proton-Antiproton Pairs by High Energy Photons

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THE production of a proton-antiproton pair by a photon may be considered as a first-order