Hamiltonian becomes

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

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

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

$$[\gamma_\mu, \gamma_\nu] = \tfrac{1}{2}(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu),$$

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

$$(4 / E_\nu E_e)(c'_S c_T - c_S c'_T) \tag{4}$$

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

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

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

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

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 σp). 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 process for which the matrix element is given by

$$S_{i\to f} = -\frac{e}{\sqrt{2\omega}} \int \bar{\psi}_p^{(-)} (\gamma e)\, e^{ikx}\, \psi_{-\tilde{p}}^{(+)}\, d^4x; \qquad (1)$$

Here $\psi_p^{(-)}$ is the wave function of a proton in the field of the nucleus, behaving asymptotically like a plane wave of momentum p together with an ingoing spherical wave. $\psi_{-\tilde{p}}^{(+)}$ is the wave-function of a proton with negative energy $-\tilde{E}$, behaving asymptotically like a plane wave of momentum $-\tilde{p}$ with an outgoing spherical wave. e is the polarization vector of the photon. The proton-antiproton interaction is neglected; this is allowable when the photon energy ω is not too close to the threshold. The wave-functions $\psi_p^{(-)}$ and $\psi_{-\tilde{p}}^{(+)}$ are constructed by means of the optical model, in which the interactions of the proton and antiproton with the nucleus are described phenomenologically.

The problem becomes very simple in the limit $\omega \gg 2M$, when the important part of the matrix element comes from a region far from the nucleus, where the wave functions behave like a superposition of a plane wave and a wave diffracted by the nucleus. Akhiezer[1] has worked out the theory of diffraction for spinor waves, and he finds for the wave function of a spin $-1/2$ particle scattered by a completely black absorbing nucleus of radius R

$$\psi_{-\tilde{p}}^{(+)} = -\frac{1}{4\pi} \int \left(\gamma \frac{\partial}{\partial \mathbf{x}} + \gamma_4 \tilde{E} - M\right) \qquad (2)$$

$$\times \frac{e^{i\tilde{p}\,|\mathbf{x}-\rho|}}{|\mathbf{x}-\rho|} (\gamma\tilde{n})\, v_{-\tilde{p}}\, d\rho \cdot e^{i\tilde{E}t},$$

$$(\rho \geqslant R,\ \rho \perp \mathbf{n}).$$

Here the integration extends over a plane through the center of the nucleus and perpendicular to the unit vector $\tilde{n} = (\tilde{p}/|\tilde{p}|)$. $v_{-\tilde{p}}$ is the spinor amplitude of the plane wave with momentum $-\tilde{p}$ and negative energy $-\tilde{E}$. Similarly,

$$\bar{\psi}_p^{(-)} = \frac{1}{4\pi} \qquad (3)$$

$$\times \int \bar{u}_p (\gamma n) \left(\gamma \frac{\partial}{\partial \mathbf{x}} + \gamma_4 E + M\right) \frac{e^{ip\,|\mathbf{x}-\rho|}}{|\mathbf{x}-\rho|}\, d\rho \cdot e^{iEt},$$

$$(\rho \geqslant R,\ \rho \perp n),$$

with $n = (p/|p|)$. The Coulomb interaction between the nucleons and the nucleus is neglected.

The idea of diffractive scattering only makes sense at small angles. Supposing the angles between the pair momenta p, $\tilde{p}$ and the phonon momentum k to be small, and the energies E, $\tilde{E}$ large compared with M, the cross-section for proton-antiproton pair production by a black uncharged nucleus becomes

$$d\sigma = \frac{e^2}{32\pi^3} \frac{E\tilde{E}}{\omega^3} \qquad (4)$$

$$\times \frac{R^2 J_1^2 (MR\,|\xi+\eta|)}{|\xi+\eta|^2} \left[\frac{2(\xi+\eta)^2}{(1+\xi^2)(1+\eta^2)} \right.$$

$$+ \frac{\omega^2}{E\tilde{E}} \left(\frac{\xi}{1+\xi^2} - \frac{\eta}{1+\eta^2}\right)^2$$

$$\left. + \left(2 + \frac{\omega^2}{E\tilde{E}}\right) \left(\frac{1}{1+\xi^2} + \frac{1}{1+\eta^2}\right)^2 \right] d\tilde{E}\, d\xi\, d\eta;$$

with the vectors ξ and η defined by

$$\mathbf{p} = (\mathbf{p}\varkappa)\,\varkappa + M\xi, \quad \tilde{\mathbf{p}} = (\tilde{\mathbf{p}}\varkappa)\,\varkappa + M\eta. \qquad (5)$$
$$\varkappa = \mathbf{k}/\omega, \quad \xi\varkappa = \eta\varkappa = 0;$$
$$d\xi = (E/M)^2\, d\Omega, \quad d\eta = (\tilde{E}/M)^2\, d\tilde{\Omega}.$$

Unlike the Born approximation formulas, the expression (4) cannot be obtained from the corresponding expression[1] for the bremsstrahlung of a proton diffractively scattered by a black uncharged nucleus by substituting $-\tilde{p}$, p, $-k$ for p, p', k. The reason is that in the extreme relativistic limit the diffracted waves hardly overlap at all in bremsstrahlung but overlap strongly in pair-production.

If we assume a finite size for the nucleon,[2] a form-factor will appear in Eq.(4). We have not included any effect of the anomalous magnetic moment of the nucleon.

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Internal Compton Effect in Pair Conversion

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IF the energy difference between excited and ground state is greater than $2\,mc^2$ (m is the