the integrals over the rotational states of the molecule and the summation over M_J and M'_J were done in Ref. 2.

Summing the spin matrix elements, we get for the transitions in parahydrogen

$$d\sigma_{00}^{J'0} = 0;\quad d\sigma_{00}^{J'1} = {}^4/_3\, a^2 (\mathfrak{M}/m)^2 (k_{J'0}/k)\, \Sigma(0, J')\, d\Omega$$

and in orthohydrogen

$$d\sigma_{11}^{J'0} = {}^4/_9\, a^2 (\mathfrak{M}/m)^2 (k_{J'1}/k)\, \Sigma(J', 1)\, d\Omega;$$

$$d\sigma_{11}^{J'1} = {}^8/_9\, a^2 (\mathfrak{M}/m)^2 (k_{J'1}/k)\, \Sigma(J', 1)\, d\Omega,$$

where

$$\Sigma(J', J) = (2J'+1) \sum_L (2L+1)\, C_{LJJ'}\, j_L^2 (k_{JJ'} R_0/2),$$

$$L = J + J',\quad J + J' - 2, \ldots, |J - J'|,$$

$$C_{LJJ'} = {}^1/_2 \int_0^\pi P_L(\cos\theta)\, P_J(\cos\theta)\, P_{J'}(\cos\theta) \sin\theta\, d\theta,$$

$$j_L(x) = \left(\frac{\pi}{2x}\right)^{1/2} J_{L+1/2}(x),$$

$R_0 = 1.4\hbar^2/m_e e^2$ is the internuclear separation in the H_2 molecule. Summation over all possible J' gives the total cross section for transition of the μ-mesic atom to the lower hyperfine structure state:

$$d\sigma_{\text{para}} \approx 1.02 a^2 \frac{k_0}{k}\, d\Omega,\quad d\sigma_{\text{ortho}} \approx 0.86 a^2 \frac{k_0}{k}\, d\Omega.$$

We thus confirm the conclusion[1] that there is complete depolarization of μ mesons in hydrogen. This result enables us, in principle, to determine the polarization of the neutrino emitted in the process $\mu^- + p \to n + \nu$, by measuring the polarization of the neutron along its direction of motion, which under these conditions should be complete. At the same time we see that it is not possible to do experiments in hydrogen for studying the $(\mu p n \nu)$ interaction using polarized μ^- mesons.

In conclusion I express my sincere thanks to Ia. B. Zel'dovich and L. D. Landau for valuable comments.

[1] S. S. Gershtein, J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 463 (1958), Soviet Phys. JETP **7**, 318 (1958).

[2] M. Hamermesh and J. Schwinger, Phys. Rev. **69**, 145 (1946).

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NON-CONSERVATION OF PARITY IN PROCESSES OF NEUTRINO CAPTURE BY PROTONS AND DEUTERONS

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EXPERIMENTAL researches have been reported recently on the capture of neutrinos by nuclei (induced β-decay).[1] In this process, parity is not conserved, inasmuch as the reaction is brought about by β-interaction.[2] Formulas are given below for the cross section of the induced β-decay of protons

$$p + \bar{\nu} \to n + e^+ \tag{1}$$

and deuterons

$$d + \bar{\nu} \to 2n + e^+ \tag{2}$$

with account of the polarization of the incident antineutrinos, wherein the target nuclei are also considered to be polarized.

It is easy to show that the density matrix of a polarized beam of particles of spin $\frac{1}{2}$ and mass zero is

$$\rho = {}^1/_2 (1 + i\gamma_5 (\mathbf{Q}\gamma) \mp \lambda\gamma_5) \frac{(-i\hat{q})}{2q} \gamma_4, \tag{3}$$

where $\mathbf{q}$ is the momentum of the particle $\mathbf{Q}$ = a pseudovector perpendicular to $\mathbf{q}$, λ = pseudoscalar, the upper sign referring to particles, the lower sign to antiparticles.

In experiments on induced β-decay, neutrinos emerging from a reactor were employed. Under these conditions, it is clearly difficult for the polarization of the neutrino to be other than longitudinal. We therefore assume in what follows that $\mathbf{Q} = 0$.* The usual calculations then lead to the following expression for the capture cross section of an antineutrino by protons:

$$d\sigma/d\Omega = Mp\varepsilon/8\pi^2,$$

$$M = \alpha_1 + \alpha_2 m/\varepsilon + \alpha_3 \mathbf{qp}/q\varepsilon + \alpha_4 \mathbf{q}\boldsymbol{\zeta}/q + \alpha_5 (m/\varepsilon)\, \mathbf{q}\boldsymbol{\zeta}/q + \alpha_6 \mathbf{p}\boldsymbol{\zeta}/\varepsilon + \alpha_7 \boldsymbol{\zeta}\, [\mathbf{q}\times\mathbf{p}]/q\varepsilon.$$

$$\alpha_1 = |C_S|^2 + |C'_S|^2 + |C_V|^2 + |C'_V|^2 + 3(|C_T|^2 + |C'_T|^2 + |C_A|^2 + |C'_A|^2) + 2\lambda \operatorname{Re}(C_S C'^*_S + C_V C'^*_V + 3C_T C'^*_T + 3C_A C'^*_A),$$

$$\alpha_2 = -2 \operatorname{Re}(C_S C^*_V + C'_S C'^*_V + 3C_T C^*_A + 3C'_T C'^*_A)$$

$$- 2\lambda \operatorname{Re}(C_S C_V'^* + C_V C_S'^* + 3C_T C_A'^* + 3C_A C_T'^*),$$

$$\alpha_3 = -|C_S|^2 - |C_S'|^2 + |C_V|^2 + |C_V'|^2 + |C_T|^2 + |C_T'|^2 - |C_A|^2 - |C_A'|^2 + 2\lambda \operatorname{Re}(- C_S C_S'^* + C_V C_V'^* + C_T C_T'^* - C_A C_A'^*),$$

$$\alpha_4 = - 2 \operatorname{Re}(2C_T C_T'^* + 2C_A C_A'^* + C_T C_S'^* + C_S C_T'^* + C_A C_V'^* + C_V C_A'^*) - 2\lambda (\operatorname{Re}(C_T C_S^* + C_T' C_S'^* + C_A C_V^* + C_A' C_V'^*) + |C_T|^2 + |C_T'|^2 + |C_A|^2 + |C_A'|^2),$$

$$\alpha_5 = 2 \operatorname{Re}(2C_A C_T'^* + 2C_T C_A'^* + C_T C_V'^* + C_V C_T'^* + C_A C_S'^* + C_S C_A'^*) + 2\lambda \operatorname{Re}(2C_A C_T^* + 2C_A' C_T'^* + C_T C_V^* + C_T' C_V'^* + C_A C_S^* + C_A' C_S'^*),$$

$$\alpha_6 = 2 \operatorname{Re}(2C_A C_A'^* - 2C_T C_T'^* + C_T C_S'^* + C_S C_T'^* - C_A C_V'^* - C_V C_A'^*) + 2\lambda (|C_A|^2 + |C_A'|^2 - |C_T|^2 - |C_T'|^2 + \operatorname{Re}(C_T C_S^* + C_T' C_S'^* - C_A C_V^* - C_A' C_V'^*),$$

$$\alpha_7 = 2 \operatorname{Im}(C_T C_S^* + C_T' C_S'^* + C_V C_A^* + C_V' C_A'^*) + 2\lambda \operatorname{Im}(C_T C_S'^* - C_S C_T'^* + C_V C_A'^* - C_A C_V'^*). \qquad (4)$$

Here $\mathbf{q}$ and $\mathbf{p}$ are momenta of the incident antineutrino and emitted positron, ϵ = energy of the positron, m = its mass, $\boldsymbol{\zeta}$ = polarization vector of the protons. The cross section is referred to an element of solid angle of the momentum of the positron. The energy of the positron is fixed in (4) by the law of conservation of energy $\epsilon = q - \Delta$, Δ = difference in the masses of the neutron and proton. In this case it is assumed that the Hamiltonian of the interaction has the same form as that of Lee and Yang.[2]

It is easy to see that we can establish whether or not time parity is conserved in the capture of the neutrino by polarized protons. Measuring the total number of electrons emitted to the left and right from the plane $\mathbf{q}$, $\boldsymbol{\zeta}$, we get for the difference in cross section:

$$\sigma_+ - \sigma_- = (\alpha_7 / 4\pi)\, p^2 \zeta \sin\theta,$$

where θ = angle between $\mathbf{q}$ and $\boldsymbol{\zeta}$. If temporal parity (time reversal) is conserved, then $\alpha_7 = 0$, $\sigma_+ = \sigma_-$.

Capture of the antineutrino by unpolarized deuterons was considered by Weneser[4] without account of A and V variants, while the nonconservation of parity was not considered. Taking it into consideration that the neutrons in reaction (2) are in the main formed in the S state, and that $(\mathbf{p}-\mathbf{q})^2/4M\epsilon_0 \ll 1$ ($\mathbf{p}-\mathbf{q}$ is the total momentum transferred by the neutrons, and ϵ_0 is the binding energy of the deuteron), we obtain as a result of the calculations:

$$d\sigma = (|R_f|^2/64\pi^5)\, N p \varepsilon\, d\varepsilon\, d\Omega M f\, d\Omega_f,$$

$$N = \beta_1 + \beta_2 \frac{m}{\varepsilon} + \beta_3 \frac{\mathbf{pq}}{q\varepsilon} + 9\beta_3 (\langle I_z^2 \rangle - {}^2/_3) \left(\frac{(\mathbf{pj})(\mathbf{qj})}{q\varepsilon} - \frac{1}{3} \frac{\mathbf{pq}}{q\varepsilon} \right) + \langle I_z \rangle \left(\beta_4 \frac{\mathbf{qj}}{q} + \beta_5 \frac{m}{\varepsilon} \frac{\mathbf{qj}}{q} + \beta_6 \frac{\mathbf{pj}}{\varepsilon} \right), \qquad (5)$$

$$R_f = \int \psi_f^*(\mathbf{r})\, \psi_d(\mathbf{r})\, d^3 r,$$

$$\beta_1 = |C_T|^2 + |C_T'|^2 + |C_A|^2 + |C_A'|^2 + 2\lambda \operatorname{Re}(C_T C_T'^* + C_A C_A'^*),$$

$$\beta_2 = - 2 \operatorname{Re}(C_T C_A^* + C_T' C_A'^*) - 2\lambda \operatorname{Re}(C_T C_A'^* + C_A C_T'^*),$$

$$\beta_3 = \frac{1}{3} (|C_T|^2 + |C_T'|^2 - |C_A|^2 - |C_A'|^2 + 2\lambda \operatorname{Re}(C_T C_T'^* - C_A C_A'^*)),$$

$$\beta_4 = - 2 \operatorname{Re}(C_T C_T'^* + C_A C_A'^*) - \lambda (|C_T|^2 + |C_T'|^2 + |C_A|^2 + |C_A'|^2),$$

$$\beta_5 = 2 \operatorname{Re}(C_A C_T'^* + C_T C_A'^*) + 2\lambda \operatorname{Re}(C_A C_T^* + C_T' C_A'^*),$$

$$\beta_6 = - 2 \operatorname{Re}(C_T C_T'^* - C_A C_A'^*) - \lambda (|C_T|^2 + |C_T'|^2 - |C_A|^2 - |C_A'|^2).$$

Here $\langle I_Z \rangle$ and $\langle I_Z^2 \rangle$ are the average values of the projection of the moment of the deuteron on the Z axis and its square, $\mathbf{j}$ = unit vector in the direction of the Z axis, M = mass of the nucleon, f = momentum of the relative motion of the neutrons in the final state, ψ_d = wave function of the deuteron, and ψ_f = wave function of the relative motion of the generated neutrons. The rest of the notation is the same as in (4). The quantity f is determined by the law of conservation of energy $q = (f^2/M) + \epsilon + \Delta$. We note that $(\langle I_Z^2 \rangle - {}^2/_3)$ vanishes for unpolarized deuterons.

Since R_f is essentially different from zero for $f \lesssim \alpha$, then for $q \gg \alpha^2/M$ in (5) we can carry out the summation over f approximately, making use of the completeness of the functions ψ_f. Then we get

$$d\sigma = (4\pi^2)^{-1} N p \varepsilon\, d\varepsilon\, d\Omega. \qquad (6)$$

In conclusion, we express our deep thanks to I. M. Shmushkevich and V. N. Gribov for useful advice in discussions.

*If we keep terms in (3) proportional to Q, then there arise components in the expression for the cross section of the process under consideration which change sign upon substitution of the primed constant for the unprimed. This apparent contradiction with the work of Pauli[3] is explained by the fact that Q is not a directly observable quantity and, as can be shown, itself changes sign upon substitution of the primed constant for the unprimed in an interaction which corresponds to the creation of a neutrino.

[1] Cowan, Reines, Harrison, Kruse and McGuire, Science **124**, 103 (1956).

[2] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
[3] W. Pauli, Nuovo cimento **6**, 204 (1957).
[4] J. Weneser, Phys. Rev. **105**, 1335 (1957).

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ON THE DETERMINATION OF THE PARITY OF THE K MESON

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THE determination of the parities of K mesons and hyperons has for some time been one of the central problems of the experimental physics of elementary particles. Since the strong interactions conserve strangeness and the weak interactions do not conserve parity, we can speak only of the relative parity of K mesons and hyperons, i.e., of the signs of $P_K P_N P_\Lambda$, $P_K P_N P_\Sigma$, and so on. We discuss below an experiment which provides a possibility of determining the sign of $P_K P_N P_\Lambda$.

Let us consider the capture of a slow K^- meson from an S state by a proton, according to the reactions

$$K^- + p \to \Lambda^0 + \pi^0 + \pi^0, \quad (1)$$

$$K^- + p \to \Lambda^0 + \pi^+ + \pi^-. \quad (2)$$

Since parity is conserved in the strong interactions, the parity of the system $\Lambda + 2\pi$ must be equal to the parity of the system K + p. Let us consider the two possibilities.

1. Suppose $P_K P_N P_\Lambda = +1$. In this case the transition amplitudes for the two reactions have the forms

$$A_1 = -(a + bp^2 + cq^2)/\sqrt{2} + \cdots,$$

$$A_2 = (a + bp^2 + cq^2) + d\mathbf{pq} + \cdots.$$

Here $\mathbf{q}$ is the difference of the momenta of the two π mesons and $\mathbf{p}$ is the sum of their momenta, equal to the momentum of the Λ particle. The energies released in the reactions (1) and (2), if the K meson had zero kinetic energy, are 47 and 38 Mev, respectively, and the maximum momenta p and q are of the order of μ_π (we use units $\hbar = c = 1$). If we assume that the dimensions of the region in which the strong interaction occurs are of the order of $1/m_p < r < 1/\mu_\pi$, then we can suppose that $pr < 1$ and $qr < 1$ and confine ourselves to terms independent of p and q. In this case

$$A_1 = -a/\sqrt{2}, \quad A_2 = a \quad (3)$$

and we find that the angular distributions in the reactions (1) and (2) are spherically symmetric, the Λ particle is not polarized, and consequently the angular distribution of the π mesons coming from its decay is isotropic. If the energies released in the reactions (1) and (2) were the same, then from Eq. (3) we would get for the cross-sections of reactions (1) and (2)

$$\sigma_2/\sigma_1 = 2. \quad (4)$$

Inclusion of the effect of the difference of the masses of $\pi^\pm$ and π^0 in changing the volume in phase space gives instead the ratio

$$\sigma_2/\sigma_1 = 1{,}34. \quad (5)$$

2. Suppose $P_K P_N P_\Lambda = -1$. In this case the transition amplitudes must have the forms

$$A_1 = -a\sigma\mathbf{p}/\sqrt{2}, \quad A_2 = a\sigma\mathbf{p} + b\sigma\mathbf{q}, \quad (6)$$

where $\boldsymbol{\sigma}$ is the vector of the Pauli matrices. Again we have retained the lowest powers of p and q in the expressions for A. Calculating the angular distribution, including effects of the possible polarization of the Λ particle, we get

$$d\sigma_1(p, q, \zeta) = {}^1\!/_4 |a|^2 p^2 d\rho_f, \quad (7)$$

$$d\sigma_2(p, q, \zeta) = {}^1\!/_2 \{p^2 |a|^2 + q^2 |b|^2 + 2\mathrm{Re}(a^* b)\,\mathbf{pq} + 2\,\mathrm{Im}(a^* b)\zeta\,[\mathbf{p} \times \mathbf{q}]\}\, d\rho_f, \quad (8)$$

where $\boldsymbol{\zeta}$ is a unit vector in the direction of polarization of the Λ particle, and $d\rho_f$ is the density of states.

We see from Eq. (7) that as before the cross-section of reaction (1) is isotropic and does not depend on the polarization of the Λ particle, but unlike the case $P_K P_N P_\Lambda = +1$ the matrix element is now proportional to p and the probability for emission of low-energy Λ particles is sharply reduced. The cross-section for reaction (2) is in this case anisotropic and depends on the polarization of the Λ particle. Generally speaking, the Λ particle will be polarized in the direction normal to the plane in which the products of the reaction are emitted. In virtue of the nonconservation of parity in the decay, this has as a result that the numbers of π mesons produced in the decay of the Λ par-