Letters to the Editor

DEPOLARIZATION OF MU MESONS IN HYDROGEN

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WE have shown[1] that, in the collision of a μ-mesic hydrogen atom with a free proton, the cross section for transition of the μ-mesic atom from its upper hyperfine structure state (with angular momentum $F = 1$) to the lower ($F = 0$) state is sufficiently large to result in complete depolarization of mesons in hydrogen. We should note that actually in hydrogen this process is determined not by the collision of the mesic atom with a free proton, but rather by collision with an H_2 molecule, since the energy transferred to the proton is considerably less than its binding energy in the molecule.

The collision of a μ-mesic atom with an H_2 molecule can be treated by a method analogous to that proposed by Fermi for calculating the scattering of slow neutrons by molecules. To do this we note that the cross section which was calculated[1] for transition of the μ-mesic atom from the upper to the lower hyperfine structure state:

$$d\sigma = \frac{1}{3} a^2 \frac{k_0}{k} d\Omega; \quad a^2 = \frac{150}{4}\left(\frac{\hbar^2}{m_\mu e^2}\right)^2; \quad k_0 = \sqrt{2m\Delta\varepsilon}/\hbar \gg k$$

($\Delta\epsilon$ is the hyperfine structure splitting in the μ-mesic atom), can be gotten formally from the Born approximation, if the interaction of the μ-mesic atom with a proton is described by the pseudopotential

$$\hat{U} = (2\pi\hbar^2/m)\, a\delta(\mathbf{r} - \mathbf{r}_p)\hat{R},$$

where $\mathbf{r}_p$, $\mathbf{r}$ are the coordinates of the proton and the mesic atom (taken as a point particle); $1/m = 1/M_p + 1/(M_p + m_\mu)$; $\hat{R}$ is an operator which takes the μ-mesic atom from the state with angular momentum 1 to the state with angular momentum 0 (as a result of interaction with the spin of a free proton). It is easy to verify that the operator $\hat{R} = 2(\mathbf{s} - \mathbf{j})\mathbf{i}/\sqrt{3}$ has this property; $\mathbf{s}$, $\mathbf{j}$, $\mathbf{i}$ are spin operators of the μ meson, the proton in the mesic atom, and the free proton, respectively.

The interaction potential of the μ-mesic atom with an H_2 molecule is given by:

$$\hat{V} = \frac{2\pi\hbar^2}{m} a \frac{(\mathbf{s}-\mathbf{j})}{\sqrt{3}} \{(\mathbf{i}_1 + \mathbf{i}_2)[\delta(\mathbf{r} - \mathbf{r}_1) + \delta(\mathbf{r} - \mathbf{r}_2)] + (\mathbf{i}_1 - \mathbf{i}_2)[\delta(\mathbf{r} - \mathbf{r}_1) - \delta(\mathbf{r} - \mathbf{r}_2)]\},$$

where $\mathbf{i}_1$, $\mathbf{i}_2$ are the spin operators of the protons in the H_2 molecule.

The hyperfine structure energy of the μ-mesic atom (0.183 ev) is not enough to excite vibrational levels of H_2, but can give excitation of the first four rotational levels. The initial and final states of the system have the form

$$\Psi^{(i)}_{J, M_J, I, M_I, 1, M_F} = e^{i\mathbf{kr}} \chi_{1, M_F}(s, j) \times \exp\left\{-i\mathbf{k}\frac{(\mathbf{r}_1 + \mathbf{r}_2)}{2}\right\} \Phi_{J, M}(\mathbf{r}_1 - \mathbf{r}_2)\, \varphi_{I, M_I}(i_1, i_2),$$

$$\Psi^{(f)}_{J', M'_J, I', M'_I, 0, 0} = e^{i\mathbf{k}'\mathbf{r}} \chi_{0,0}(s, j) \times \exp\left\{-i\mathbf{k}'\frac{(\mathbf{r}_1 + \mathbf{r}_2)}{2}\right\} \Phi_{J', M'_J}(\mathbf{r}_1 - \mathbf{r}_2)\, \varphi_{I', M'_I}(i_1, i_2),$$

where χ_{1,M_F} and $\chi_{0,0}$ are the spin functions of the mesic atom in states with $F = 1$ and $F = 0$; Φ_{J,M_J} is the wave function of H_2 in the J-th rotational level; φ_{I,M_I} are the spin functions of the H_2 molecule ($I = 1$ for ortho, and $I = 0$ for parahydrogen).

The term in the potential $\hat{V}$ which is symmetric in the proton spins gives rise to transitions between states of the same I, while the antisymmetric term causes transitions between states of different I. The cross section for scattering of the μ-mesic atom (accompanied by a transition $F = 1 \rightarrow F = 0$) is:

$$d\sigma^{J', I}_{J, I} = \frac{4a^2}{9(2I+1)(2J+1)}\left(\frac{\mathfrak{M}}{m}\right)^2 \frac{k_{JJ'}}{k} \sum_{M_J, M'_J, M_I, M'_I, M_F} \left| \int \cos\frac{(\mathbf{k}_{JJ'} - \mathbf{k})\mathbf{r}}{2} \times \Phi^*_{J', M'_J}(\mathbf{r})\, \Phi_{J, M_J}(\mathbf{r})\, (d\mathbf{r}) \right|^2 \left| \langle 0, I, M'_I | (\mathbf{s} - \mathbf{j})(\mathbf{i}_1 + \mathbf{i}_2) \times | M_F, I, M_I \rangle \right|^2 d\Omega,$$

$$d\sigma^{J', I'}_{J, I} = \frac{4a^2}{9(2I+1)(2J+1)}\left(\frac{\mathfrak{M}}{m}\right)^2 \frac{k_{JJ'}}{k} \sum_{M_J, M'_J, M_I, M'_I, M_F} \left| \int \sin\frac{(\mathbf{k}_{J'J} - \mathbf{k})\mathbf{r}}{2} \times \Phi^*_{J', M'_J}(\mathbf{r})\, \Phi_{J, M_J}(\mathbf{r})\, (d\mathbf{r}) \right|^2 \left| \langle 0, I', M'_I | (\mathbf{s} - \mathbf{j})(\mathbf{i}_1 - \mathbf{i}_2) \times | M_F, I, M_I \rangle \right|^2 d\Omega,$$

where $1/\mathfrak{M} = 1/(M_p + m_\mu) + 1/2M_p$; $\hbar k_{JJ'} = \{2\mathfrak{M}(\Delta\epsilon + \epsilon_J - \epsilon_{J'})\}^{1/2} \gg \hbar k$. The calculation of 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 $\mu^- + p \rightarrow n + \nu$, 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

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

and deuterons

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

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 ½ 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:

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

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

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

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