Derivation of the Formula for the Cross Section for Formation of High Energy Neutrons in Deuteron-Nuclei Collisions

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SOMEWHAT prior to the appearance of Serber's article,[1] we suggested that the formation of a narrow beam of neutrons upon interaction of high energy deuterons with matter, was due to the stripping of deuterons colliding with atomic nuclei. We derive here the formula for the effective cross section for the formation of neutrons by the stripping reaction; this was set forth in an unpublished report[2].

The formation of a neutron by stripping will of course take place every time that the proton in the deuteron interacts with the nuclear surface, while the neutron is outside the nuclear force radius. Let R be the nuclear radius, and d be average distance between the neutron and the proton of the deuteron. We shall call r the distance between the neuteron and the point at which the pn (proton-neutron) line intersects the nucleus. Let θ be the angle between the x-axis (the x-axis is drawn from the center of the nucleus through the point where the pn line intersects the nuclear surface) and the pn direction; the cross section for formation of neutrons for given values of θ, r, and $R \gg r$ is then:

$$\sigma_{r\theta} = \pi(\rho^2 - R^2) \approx 2\pi Rr\cos\theta,$$
$$\rho^2 = R^2 + r^2 - 2Rr\cos(\pi - \theta) \approx R^2 + 2Rr\cos\theta.$$

The average cross section for neutron formation for a given r and arbitrary θ is:

$$\sigma_r = \frac{1}{2\pi}\int_0^{\Omega\max} \sigma_{r\theta}d\Omega \approx \frac{1}{2\pi}\int_0^{\pi/2} 2\pi Rr\cos\theta\, 2\pi\sin\theta d\theta = \pi Rr,$$
$$\Omega_{\max} \approx \pi/2 - (d-r)/2\pi R,$$

where $d\Omega = 2\pi\sin\theta d\theta$ is the solid angle formed by a change in the deuteron direction from $\theta + d\theta$. The average cross section for neuteron formation for arbitrary θ and r is found the formula:

$$\sigma = \frac{1}{d}\int_0^d \sigma_r dr = \frac{\pi}{2}Rd;$$

this is the effective cross section which we were seeking.

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[1] R. Serber, Phys. Rev 72, 1008 (1947).
[2] V. S. Anastasevich, Otchet Akad. Nauk SSSR (Nov., 1947).

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Possible Correlations in π-μ-e Decay

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LEE and Yang[1] have recently shown that if parity is violated in π-μ-e decay, there must be correlations between the orientations of the momenta of the μ-mesons and the electrons. We present here the results of computations of such correlations when parity is violated in both the $\pi \to \mu + \nu$ decay and the $\mu \to e + 2\nu$ decay.

The interaction leading to π-meson decay has the form:

$$H_\pi = f\varphi_\pi\overline{\psi}_\nu(1 + \alpha\gamma_5)\psi_\mu. \tag{1}$$

The coefficient a characterizes here the degree of violation of parity conservation. The probability that during the decay of π-meson, a μ-meson will be emitted with momentum **n** and spin **s** is given by

$$\frac{dW_\pi}{d\Omega} = \frac{f^2}{16\pi}\left\{(1 + |\alpha|^2)\left(1 + \frac{m^2 - \mu^2}{m^2 + \mu^2}\right) + (\alpha + \alpha^*)(\mathbf{ns})\right\} \times \frac{(m^2 - \mu^2)^2(m^2 + \mu^2)}{m^5} = u_1 + u_2(\mathbf{ns}), \tag{2}$$

where m is the mass of π-meson and μ the mass of the μ-messon. Expression (2) indicates that the μ-meson is longitudinally polarized. It may be shown that if $a = 1$, the μ-meson is completely polarized in the rest system of the μ-meson.

Let us consider now the decay of a μ-meson at rest. The interaction for this process has the form

$$H_\mu = \sum_1^5 g_i(\overline{\psi}_\mu(1 + \alpha_i\gamma_5)O_i\psi_e)(\psi_\nu O_i\psi_\nu). \tag{3}$$

If the two neutrinos which appear during the decay of the μ-meson are identical, then it is well known that $g_2 = g_3 = 0$. Applying Lenard's method[2], one obtains the following expression for the angular distribution of decay electrons:

$$d^2W_\mu/d\Omega d\varepsilon = (2\pi)^{-4}\varepsilon_m^5\varepsilon^2\{(a_1+a_5)(1-\varepsilon)+{}^8/_3 a_3(3-\varepsilon) + {}^2/_3(a_2+a_4)(3-2\varepsilon)+[(b_1+b_5)(1-\varepsilon) - {}^8/_3 b_3(1+\varepsilon)+{}^2/_3(b_2+b_4)(1-2\varepsilon)](\mathbf{sl})\}, \quad (4)$$

where $\mathbf{l}$ denotes a unit vector in the direction of the momentum of the electron, and

$$a_i = g_i^2(1+|\alpha_i|^2), \quad b_i = g_i^2(\alpha_i+\alpha_i^*).$$

Integrating the probability (4) over the energy of the electron yields

$$\frac{dW_\mu}{d\Omega} = \frac{\varepsilon_m^5}{(2\pi)^4}\left\{\left(\frac{a_1+a_5}{12}+2a_3+\frac{a_4+a_2}{3}\right) + \left(\frac{b_1+b_5}{12}-\frac{14}{9}b_3-\frac{b_2+b_4}{9}\right)(\mathbf{sl})\right\} = v_1+v_2(\mathbf{sl}). \quad (5)$$

Note that the coefficient α which characterizes the degree of parity violation may be either real (for invariance under time reversal) or purely imaginary (for invariance under charge conjugation). In the latter case, the coefficients u_2 and v_2 are easily seen to be identically equal to zero, and there is no correlation. If α is real, then the correlation between the direction of the momentum of the μ-meson and that of the electron is given by

$$W(\mathbf{l},\mathbf{n}) = \sum_{s_1 s_2} W_\pi(\mathbf{ns}_1)\, W_d(\mathbf{s}_1,\mathbf{s}_2)\, W_\mu(\mathbf{s}_2\mathbf{l}). \quad (6)$$

W_π and W_μ are obtained from Eqs. (2) and (5), and $W_d(\mathbf{s}_1, \mathbf{s}_2)$ is the probability for depolarization of the μ-meson as it is slowed down. If the depolarization is small, *i.e.*, if $W_d \sim \delta(\mathbf{s}_1-\mathbf{s}_2)$, Eq. (6) is easily solved:

$$W(\mathbf{ln}) = u_1v_1+u_2v_2(\mathbf{ln}). \quad (7)$$

Note that the effect of parity violation shows up in (7) through the appearance of a scalar quantity (**ln**), and not a pseudoscalar as is usually the case. This is linked to the fact that parity is violated twice in the process under consideration, during the decay of the π-meson, and during that of the μ-meson.

In conclusion, we remark that experimental observation of this correlation is very difficult due to the fact that strong depolarization takes place during the lifetime of the μ-meson ($\sim 10^{-6}$ sec).

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[1] T. D. Lee and C. N. Yang, Phys. Rev 104, 254 (1956).

[2] A. Lenard, Phys. Rev. 90, 968 (1953).

[3] Ioffe, Okun', and Rudik, J. Exptl. Theoret. Phys. U.S.S.R. 32, 396 (1957).

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Polarization in Reverse Reactions

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IN this note, we shall demonstrate a relation which holds between the polarization of final particles in forward and reverse reactions. Consider an arbitrary reaction of the form $a + X \to b + Y$, where a, b, X, Y are arbitrary particles of spin ½; we shall assume that the product of the intrinsic parities of the particles before the reaction is the same as the product of the intrinsic parities of the particles formed after the reaction. We shall denote the spin states of the initial and final systems by the components ζ_{sm} of a column vector, where s is the total spin and m its z-component. It may be shown that the amplitude of the final particles has the form

$$\frac{e^{ik_1r}}{r}\frac{\sqrt{\pi}}{ikk_1}\cdot\begin{vmatrix} a-f & c-d_2 \\ b & g-b & 0 \\ c & f & a-d_2 \\ d_1 & 0 & d_1 & e\end{vmatrix}\cdot\begin{vmatrix}\zeta_{11}\\ \zeta_{10}\\ \zeta_{1-1}\\ \zeta_{00}\end{vmatrix} = \frac{e^{ik_1r}}{r}M\cdot\begin{vmatrix}\zeta_{11}\\ \zeta_{10}\\ \zeta_{1-1}\\ \zeta_{00}\end{vmatrix}, \quad (1)$$

where k and k_1 are the wave vectors before and after the reaction, ζ_{sm} is the spin function for the initial state (particles a and X), and the coefficients a, b, c, ... are expressed by means of the elements of the reaction matrix $M_{ls,\,l's'}$ and the scattering angle θ. If we know the operator M, we can solve for the average values of the spin operators of particles b and Y and the reaction cross section $d\sigma$ $d\sigma/do$.

$$\overline{\sigma_i^{(b)}} = \langle\sigma_i^{(b)}\rangle/(d\sigma/(do); \ \overline{\sigma_i^{(Y)}} = \langle\sigma_i^{(Y)}\rangle/d\sigma/do$$
$$\langle\sigma_i^{(b,\,Y)}\rangle = (k_1/k)\ \mathrm{Sp}\,(M\rho M^+\sigma_i^{(b,\,Y)});$$
$$d\sigma/do = (k_1/k)\,\mathrm{Sp}\,(M\rho M^+). \quad (2)$$

ρ is here the spin density matrix for the initial state, and $i = x, y, z$.