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ABSORPTION OF POLARIZED NEGATIVE MUONS BY NUCLEI AND NEUTRON POLARIZATION

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Formulae are obtained for the polarization of neutrons emitted in the absorption of polarized μ^- mesons by nuclei. Estimates are given for O^{16} and Ca^{40}.

In references 1 and 2, the angular distribution of neutrons produced in the capture of polarized μ^- mesons by nuclei through the reaction

$$\mu^- + P \rightarrow N + \nu \qquad (1)$$

was calculated. From measurement of the coefficient of anisotropy, it would be possible to obtain definite information about the type of interaction between μ mesons and nucleons. Measurement of the polarization of the emitted neutrons provides another means of establishing the type of interaction. In this article, the polarization of neutrons produced through reaction (1) in the absorption of polarized μ^- mesons in complex nuclei is calculated. Formulae for the polarization of neutrons produced in the capture of μ^- mesons by free protons are also presented.

1. NEUTRON POLARIZATION

The neutron polarization vector $\mathbf{P}_N$ is defined as the mean value of the neutron spin operator σ:

$$\mathbf{P}_N = \mathrm{Sp}\,(\rho\sigma)\,/\,\mathrm{Sp}\,\rho, \qquad (2)$$

where ρ is the density matrix, the diagonal elements of which determine the probability of neutron emission.

From general considerations, $\mathbf{P}_N$ can be represented as

$$\mathbf{P}_N = a\mathbf{P}_\mu + b\mathbf{k}_N + c\,\mathbf{k}_N \times \mathbf{P}_\mu, \qquad (3)$$

where $\mathbf{P}_\mu$ is the polarization vector of the μ^- meson and $\mathbf{k}_N$ is the neutron momentum. It is clear that the coefficients b and c are different from zero only if spatial parity is not conserved in the process (1). For unpolarized μ^- mesons ($P_\mu = |\mathbf{P}_\mu| = 0$), the neutron polarization is directed along its momentum.

It should be noted that at low energies (~ 1 Mev) it is experimentally difficult to separate neutrons emitted in the direct process from those arising in the decay of the compound nucleus. Therefore, the conclusion reached in reference 1 about the necessity of selecting in the measurements neutrons of energy $E_N \gtrsim 3$ Mev applies here.

The Hamiltonian for the interaction of μ mesons with nucleons, taking into account nonconservation of parity, was taken as

$$H = \sum_k (\overline{\Psi}_N O_k \Psi_P)(\overline{\Psi}_\nu [g_k - g_k' \gamma_5] O_k \Psi_\mu) + \text{Herm. conj.} \qquad (4)$$

in the calculations, where k = s, v, p, t, a denotes the scalar, vector, pseudoscalar, tensor and pseudovector variants of the interaction, respectively. The explicit forms of the operators O_k are given in reference 1.

Calculation of the neutron polarization was carried out under the same assumptions as the calculation of the angular distribution in reference 1. The final formulae are, strictly speaking, only applicable to nuclei having completely filled proton subshells. Two cases were considered. In the first case, the spin-orbit interaction of the neutrons with the nucleus was neglected; in the second case, this interaction was taken into account. The wave functions for the proton in the nucleus Ψ_P, neutron Ψ_N μ^- meson Ψ_μ and neutrino Ψ_ν were given in references 1 and 2.

We choose the coordinate axes in the following way:

$$\mathbf{n}_x = \frac{[\mathbf{P}_\mu \times \mathbf{k}_N]}{|\mathbf{P}_\mu \times \mathbf{k}_N|}, \quad \mathbf{n}_y = \frac{\mathbf{k}_N \times [\mathbf{P}_\mu \times \mathbf{k}_N]}{|\mathbf{k}_N \times [\mathbf{P}_\mu \times \mathbf{k}_N]|}, \quad \mathbf{n}_z = \frac{\mathbf{k}_N}{|\mathbf{k}_N|}. \qquad (5)$$

Then the polarization of neutrons of energy E_N, emitted at angle θ to the direction of μ^--meson polarization, with neglect of the spin-orbit interaction of the neutron with the nucleus, is given by the following formulae:*

*The notation used in the following formulae is explained in the appendix.

$$P_N^x(E_N, \theta) = P_\mu \{2B_0(E_N)\,\mathrm{Im}\,(h_{st} + h_{sa} + h_{vt} + h_{va}) - 2B_1(E_N)\,\mathrm{Im}\,(h_{pt} + h_{pa}) + G_0(E_N)\,[({}^1/_2)(h_{ss} + 2\mathrm{Re}\,h_{sv} + h_{vv}) - ({}^3/_2)(h_{tt} + 2\mathrm{Re}\,h_{ta} + h_{aa}) + \mathrm{Re}\,(h_{st} + h_{sa} + h_{vt} + h_{va})] + 2G_1(E_N)\,\mathrm{Re}\,(h_{pt} + h_{pa}) - ({}^1/_2)\,G_2(E_N)\,h_{pp}\}\sin\theta / W(E_N, \theta); \quad (6a)$$

$$P_N^y(E_N, \theta) = P_\mu \{2\,[(f_{tt} + 2\mathrm{Re}\,f_{ta} + f_{aa}) + \mathrm{Re}\,(f_{st} + f_{sa} + f_{vt} + f_{va})]\,A_0(E_N) - ({}^2/_3)\,\mathrm{Re}\,(f_{ps} + f_{pv})\,[A_1(E_N) - H(E_N)] - ({}^2/_3)\,\mathrm{Re}\,(f_{pt} + f_{pa})\,[2A_1(E_N) + H(E_N)] + \mathrm{Im}\,(f_{ps} + f_{pv} - f_{pt} - f_{pa})\,I(E_N)\}\sin\theta / W(E_N, \theta); \quad (6b)$$

$$P_N^z(E_N, \theta) = (\{2\,[(h_{tt} + 2\mathrm{Re}\,h_{ta} + h_{aa}) - \mathrm{Re}\,(h_{st} + h_{sa} + h_{vt} + h_{va})]\,B_0(E_N) + 2\mathrm{Re}\,(h_{ps} + h_{pv})\,B_1(E_N) + 2\mathrm{Im}\,(h_{st} + h_{sa} + h_{vt} + h_{va})\,G_0(E_N) + 2\,\mathrm{Im}\,(h_{ps} + h_{pv})\,G_1(E_N)\} + P_\mu \{[(f_{tt} + 2\mathrm{Re}\,f_{ta} + f_{aa}) + \mathrm{Re}\,(f_{st} + f_{sa} + f_{vt} + f_{va})]\,A_0(E_N) - ({}^2/_3)\,\mathrm{Re}\,(f_{ps} + f_{pv}) \times [A_1(E_N) + 2H(E_N)] - ({}^4/_3)\,\mathrm{Re}\,(f_{pt} + f_{pa})\,[A_1(E_N) - H(E_N)] - 2\mathrm{Im}\,(f_{ps} + f_{pv} - f_{pt} - f_{pa})\,I(E_N)\}\cos\theta) / W(E_N, \theta) \quad (6c)$$

$$W(E_N, \theta) = \{[(f_{ss} + 2\mathrm{Re}\,f_{sv} + f_{vv}) + 3\,(f_{tt} + 2\mathrm{Re}\,f_{ta} + f_{aa})]\,A_0(E_N) - 2\mathrm{Re}\,(f_{pt} + f_{pa})\,A_1(E_N) + f_{pp}A_2(E_N)\} + P_\mu \{[-(h_{ss} + 2\mathrm{Re}\,h_{sv} + h_{vv}) + (h_{tt} + 2\mathrm{Re}\,h_{ta} + h_{aa})]\,B_0(E_N) + 2\mathrm{Re}\,(h_{pt} + h_{pa})\,B_1(E_N) - h_{pp}B_2(E_N) + 2\,\mathrm{Im}\,(h_{st} + h_{sa} + h_{vt} + h_{va})\,G_0(E_N) + 2\mathrm{Im}\,(h_{pt} + h_{pa})\,G_1(E_N)\}\cos\theta. \quad (6d)$$

Formulae for the neutron polarization, taking into account the spin-orbit interaction, are much more lengthy and will not be given here.

In the case of capture of a μ^- meson by a free proton, without taking account of the hyperfine structure of the μ-mesic hydrogen,* calculation with relativistic wave functions leads to the following result†

$$P_N^{\mathrm{hf}} = \frac{P_\mu (c_{\mathrm{hf}} n_x + d_{\mathrm{hf}} n_y)\sin\theta + (k_{\mathrm{hf}} + P_\mu l_{\mathrm{hf}}\cos\theta)\,n_z}{a_{\mathrm{hf}} + P_\mu b_{\mathrm{hf}}\cos\theta} \quad (7)$$

It should be noted that the influence of the spin-orbit coupling on the polarization of the emitted particle is, in our case, apparently not as important as in scattering. The spin-orbit interaction here does not produce the polarization, although it can change it. Estimates carried out for several special cases show that taking into account the spin-orbit coupling changes the results obtained from Eqs. (6) only little (~10 to 15%). Although this result cannot be considered conclusive for the general case, none the less, in view of the complexity of the formulae which take into account the spin-orbit coupling for the neutron, the following considerations and numerical calculations will be based on Eqs. (6), i.e., with neglect of the spin-orbit interaction between neutron and nucleus. Here it might be expected that the spin-orbit coupling would affect the transverse components of polarization P_N^x and P_N^y more strongly than the longitudinal component P_N^z.

Equations (6) make it possible to draw the following conclusions:

(1) As can be seen from Eq. (7), in the case of μ^- capture in mesic hydrogen, P_N^x is not zero only when the Hamiltonian (4) is not invariant not only with respect to reflection of the spatial axes, but also with respect to time reflection. In the case of μ^- capture in nuclei, the interaction of the neutron with the nucleus leads to additional terms in the expression for P_N^x, which do not go to zero even in the case in which temporal parity is conserved.

(2) The presence of a second transverse component P_N^y of polarization is not connected with the degree of nonconservation of spatial parity in the Hamiltonian (4).

(3) In contradistinction to P_N^x and P_N^y, which are proportional to the degree of the μ^--meson polarization P_μ, the longitudinal polarization of the neutron P_N^z does not go to zero for unpolarized μ^- mesons. This fact is valuable, in that — as demonstrated by experiments[5] — the longitudinally-polarized μ^- mesons produced in the decay of π^- mesons are strongly depolarized in slowing down in matter and with formation of mesic atoms; the degree of their polarization in the K orbit is of order[5] ~0.15 to 0.20. Therefore, P_N^z can attain larger values than P_N^x and P_N^y.

We consider several simplifications which can be made in Eqs. (6). Firstly, one can neglect the pseudoscalar interaction, if the pseudoscalar coupling constant g_p is not too large in comparison with other constants. Further, it should be noted

*Gershteĭn has shown[3] that the hyperfine structure and the effect of the μ^- meson jumping from one hydrogen atom to another lead, under the assumption of a longitudinal neutrino, to neutrons, emitted in the decay of μ-mesic hydrogen, which are completely polarized longitudinally.

†This formula was given for the special case of a longitudinal neutrino by Wolfenstein.[4]

that, as estimates show, $G_0(E_N)$ is much smaller than $A_0(E_N)$. and $B_0(E_N)$. For nuclei with filled proton shells $G_k(E_N) \equiv 0$, if the dependence of the binding energy of the proton in the nucleus on the total angular momentum j is neglected. Finally, it is interesting to look at the special case, important in practice, of a longitudinal neutrino,[6] which corresponds to $g_k = -g'_k$ in Eq. (4).

In the first approximation, leaving out the pseudoscalar interaction and neglecting terms proportional to $G_0(E_N)$, we obtain for the longitudinal neutrino:*

$$P_N^x(E_N, \theta) = \frac{P_\mu 2\,\mathrm{Im}(g_1^* g_2)\,\beta_0(E_N)\sin\theta}{(|g_1|^2 + 3|g_2|^2) - P_\mu(|g_1|^2 - |g_2|^2)\,\beta_0(E_N)\cos\theta}; \tag{8a}$$

$$P_N^y(E_N, \theta) = \frac{P_\mu 2\,[|g_2|^2 + \mathrm{Re}(g_1^* g_2)]\sin\theta}{(|g_1|^2 + 3|g_2|^2) - P_\mu(|g_1|^2 - |g_2|^2)\,\beta_0(E_N)\cos\theta}; \tag{8b}$$

$$P_N^z(E_N, \theta)$$
$$= \frac{2\{[|g_2|^2 - \mathrm{Re}(g_1^* g_2)]\,\beta_0(E_N) + P_\mu[|g_2|^2 + \mathrm{Re}(g_1^* g_2)]\cos\theta}{(|g_1|^2 + 3|g_2|^2) - P_\mu(|g_1|^2 - |g_2|^2)\,\beta_0(E_N)\cos\theta}. \tag{8c}$$

Here the quantities $g_1 \equiv g_s + g_v$ and $g_2 \equiv g_t + g_a$, corresponding to the constants of Fermi and Gamow-Teller couplings, have been introduced.

From Eq. (8) it can be seen that measurement of only the longitudinal component P_N^z of polarization makes it possible to determine the ratios of the moduli of the Fermi and Gamow-Teller constants and their relative phase (to within a sign). Analogous information can be obtained from measurement of P_N^y. The sign of the phase can be determined from P_N^x. If the interaction of μ mesons with nucleons is described by the theory of Gell-Mann and Feynman[7] ($g_V = \pm g_a$, $g_S = g_P = g_t = 0$) then, as noted in reference 1, the asymmetry in the angular distribution of the neutrons vanishes. As to the neutron polarization, it follows from Eq. (8) that at least its longitudinal component is not zero.

Equations (6) and (8) relate to a neutron with a definite energy E_N. If integration over the neutron energy E_N is carried out, then we obtain formulae which differ from Eqs. (6) and (8) only in that functions of the energy $A_k(E_N)$, $B_k(E_N), \ldots, Z(E_N)$, $\beta_0(E_N)$ are replaced by constants $\tilde{A}_k$, $\tilde{B}_k, \ldots$, $\tilde{Z}$, $\tilde{\beta}_0$.

2. NUMERICAL EVALUATION FOR $_8O^{16}$ AND $_{20}Ca^{40}$

Since, with neglect of the pseudoscalar interaction, the same coefficients A_0, B_0 and G_0 enter into the expressions for the polarization of the neutron as for the angular distribution, we can use the quantities in reference 1, obtained in the calculation of the angular distribution of neutrons from $_8O^{16}$ and $_{20}Ca^{40}$ nuclei. The assumptions under which the calculation was carried out are described in detail in reference 1.

The neutron polarization, averaged over the spectrum, under the assumption of a longitudinal neutrino, is determined by Eqs. (8) with $\tilde{\beta}_0$ in place of $\beta_0(E_N)$. For $_8O^{16}$ and $_{20}Ca^{40}$ and two different values of the imaginary part of the potential, describing the interaction of the neutron with the potential, $\tilde{\beta}_0$ takes on the following values

$$_8O^{16}: \tilde{\beta}_0 = 0.034 \text{ for } \zeta = 0; \qquad \tilde{\beta}_0 = 0.476 \text{ for } \zeta = -0.15;$$
$$_{20}C^{40}: \tilde{\beta}_0 = 0.145 \text{ for } \zeta = 0; \qquad \tilde{\beta}_0 = 0.528 \text{ for } \zeta = -0.15.$$

It is easy to show that $|P_N^x(\theta)|$ and $|P_N^y(\theta)|$ are maximal for values of near to $\pm\pi/2$. Then

$$P_N^y\left(\pm\frac{\pi}{2}\right) = \pm P_\mu \frac{2\,[|g_2|^2 + \mathrm{Re}(g_1^* g_2)]}{|g_1|^2 + 3|g_2|^2}.$$

Thus, the dependence P $(\pm\pi/2)$ on the ratio of Fermi and Gamow-Teller coupling constants turns out to be the same for all nuclei. $P_N^y(\pm\pi/2)$ varies from zero for $g_1 = -g_2$ to P_μ for $g_1 = g_2$. For pure Gamow-Teller coupling $P_N^y(\pm\pi/2) = \pm 2/3\, P_\mu \approx \pm 0.12$. The longitudinal component $|P_N^z(\theta)|$ attains a maximum for $\theta = 0$, if $|g_2|^2 > \mathrm{Re}(g_1^* g_2)$ and for $\theta = \pi$ if $|g_2|^2 < \mathrm{Re}(g_1^* g_2)$. For pure Gamow-Teller coupling and $P_\mu \sim 0.20$ and $\zeta = -0.15$, for $_8O^{16}$ and $_{20}Ca^{40}$ nuclei, $P_N^z(0) = 0.45$ and $P_N^z(\pm\pi/2)$ $2/3\,\beta_0 \approx 0.33$ (for a free proton, without account of hyperfine structure, $P_N^3(\pm\pi/2) \approx 2/3$).

Consequently, the degree of polarization of the neutron, especially the longitudinal component, can become quite large.

In conclusion, I would like to sincerely thank I. S. Shapiro for his interest in the work and discussion of the results.

APPENDIX

Here we explain the notation employed in the article:

$$f_{ik} = g_i^* g_k + g_i'^* g_k', \quad h_{ik} = g_i^* g_k' + g_i'^* g_k; \tag{A.1}$$

$$H(E_N) = C \sum_{njl} \frac{1}{2} \frac{2j+1}{2l+1} (-1)^l (E_\nu^{njl}/2Mc^2)$$
$$\times \sum_{L\Lambda L'\Lambda'} i^{L+\Lambda-L'-\Lambda'} (2L+1)(2L'+1)(2\Lambda+1)(2\Lambda'+1)$$
$$\times C_{L0L'0}^{20} C_{\Lambda 0\Lambda' 0}^{20} C_{L0\Lambda 0}^{l0} C_{L'0\Lambda' 0}^{l0} W(LL'\Lambda\Lambda';\, 2l)$$
$$\times \mathrm{Re}\,(b_{L\Lambda njl}^*(E_N)\, b_{L'\Lambda' njl}(E_N))\, \rho_{njl}(E_N); \tag{A.2}$$

*For $g_k = -g'_k$ we obtain from Eq. (4) that the neutrino is polarized along its direction of motion. If the neutrino produced in μ^- capture is polarized antiparallel to its direction of motion, one should change in Eq. (8) the sign in front of terms containing $\beta_0(E_N)$.

$$I(E_N) = C \sum_{njl} (2/\sqrt{5})(2j+1)$$
$$\times (-1)^l W(lj1{}^1\!/_2;\ {}^1\!/_2 l)(E_\nu^{njl}/2Mc^2)$$
$$\times \sum_{L\Lambda L'\Lambda'} i^{L+\Lambda-L'-\Lambda'}(2L+1)(2L'+1)$$
$$\times (2\Lambda+1)(2\Lambda'+1) C^{20}_{L0L'0} C^{20}_{\Lambda 0\Lambda' 0} C^{l0}_{L0\Lambda 0} C^{l0}_{L'0\Lambda' 0}$$
$$\times X(\Lambda 2\Lambda';\ L2L';\ l1l)\,\mathrm{Im}\,(b^*_{L\Lambda njl}(E_N)\, b_{L'\Lambda' njl}(E_N))\,\rho_{njl}(E_N); \tag{A.3}$$

$$a_{hf} = (E_N^{hf}+M) f_{ss} + (E_N^{hf}-M) f_{pp}$$
$$+ 2(2E_N^{hf} - M - E_\nu^{hf}) f_{vv} + 2(2E_N^{hf} + M + E_\nu^{hf}) f_{aa}$$
$$+ 2(3E_N^{hf} + 2E_\nu^{hf}) f_{tt} + 2(E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, f_{sv}$$
$$- 2E_\nu^{hf}\,\mathrm{Re}\, f_{st} - 2(E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, f_{ap}$$
$$- 2E_\nu^{hf}\,\mathrm{Re}\, f_{tp} - 4E_\nu^{hf}\,\mathrm{Re}\, f_{ta}$$
$$- 6(E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, f_{vt} + 6(E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, f_{at}; \tag{A.4}$$

$$b_{hf} = (E_N^{hf}+M) h_{ss} + (E_N^{hf}-M) h_{pp} + 2(M + E_\nu^{hf}) h_{vv}$$
$$- 2(M - E_\nu^{hf}) h_{aa} - 2(E_N^{hf} + 2E_\nu^{hf}) h_{tt}$$
$$+ 2(E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, h_{sv}$$
$$- 2E_\nu^{hf}\,\mathrm{Re}\, h_{st} - 2(E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, h_{ap} - 2E_\nu^{hf}\,\mathrm{Re}\, h_{tp}$$
$$+ 4E_\nu^{hf}\,\mathrm{Re}\, h_{va} + 2(E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, h_{vt}$$
$$- 2(E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, h_{at}; \tag{A.5}$$

$$c_{hf} = 2\{E_\nu^{hf}\,\mathrm{Im}\, h_{sv} - (E_N^{hf} + M)\,\mathrm{Im}\, h_{sa}$$
$$- (E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Im}\, h_{st}$$
$$- (E_N^{hf} - M)\,\mathrm{Im}\, h_{pv} + E_\nu^{hf}\,\mathrm{Im}\, h_{pa} + (E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Im}\, h_{pt}$$
$$- 2(E_N^{hf} + E_\nu^{hf})\,\mathrm{Im}\, h_{va} - (E_N^{hf} + M + 3E_\nu^{hf})\,\mathrm{Im}\, h_{vt}$$
$$- (E_N^{ht} - M + 3E_\nu^{hf})\,\mathrm{Im}\, h_{at}\}; \tag{A.6}$$

$$d_{hf} = 2\{-(E_N^{hf} - M + E_\nu^{hf}) f_{vv} + (E_N^{hf} + M + E_\nu^{hf}) f_{aa}$$
$$+ 2M f_{tt} - E_\nu^{hf}\,\mathrm{Re}\, f_{sv} + (E_N^{hf} + M)\,\mathrm{Re}\, f_{sa}$$
$$+ (E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, f_{st} + (E_N^{hf} - M)\,\mathrm{Re}\, f_{pv} - E_\nu^{hf}\,\mathrm{Re}\, f_{pa}$$
$$- (E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, f_{pt} + 2M\,\mathrm{Re}\, f_{va}$$
$$+ (3E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, f_{vt}$$
$$+ (3E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, f_{at}\}; \tag{A.7}$$

$$k_{hf} = 2\{-(E_N^{hf} - M) h_{vv} - (E_N^{hf} + M) h_{aa}$$
$$- (2E_N^{hf} + 3E_\nu^{hf}) h_{tt} - E_\nu^{hf}\,\mathrm{Re}\, h_{sp} + (E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, h_{sa}$$
$$+ (E_N^{hf} + M)\,\mathrm{Re}\, h_{st} - (E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, h_{pv}$$
$$+ (E_N^{hf} - M)\,\mathrm{Re}\, h_{pt} + 2(E_N^{hf} + 2E_\nu^{hf})\,\mathrm{Re}\, h_{va}$$
$$+ (3E_N^{hf} - M + 3E_\nu^{hf})\,\mathrm{Re}\, h_{vt}$$
$$- (3E_N^{hf} + M + 3E_\nu^{hf})\,\mathrm{Re}\, h_{at}\}; \tag{A.8}$$

$$l_{hf} = 2\{(E_N^{hf} - M) f_{vv} + (E_N^{hf} + M) f_{aa}$$
$$+ (2E_N^{hf} + E_\nu^{hf}) f_{tt} - E_\nu^{hf}\,\mathrm{Re}\, f_{sp} + (E_N^{hf} + M + E_\nu^{hf})\,\mathrm{Re}\, f_{sa}$$
$$+ (E_N^{hf} + M)\,\mathrm{Re}\, f_{st} - (E_N^{hf} - M + E_\nu^{hf})\,\mathrm{Re}\, f_{pv}$$
$$+ (E_N^{hf} - M)\,\mathrm{Re}\, f_{pt} + 2E_N^{hf}\,\mathrm{Re}\, f_{va} - (E_N^{hf} - 3M + E_\nu^{hf})\,\mathrm{Re}\, f_{vt}$$
$$+ (E_N^{hf} + 3M + E_\nu^{hf})\,\mathrm{Re}\, f_{at}\}. \tag{A.9}$$

$E_N^f = 4.47$ Mev and $E_\nu^f = 99.1$ Mev, are the energies of the neutron and neutrino, respectively, produced in the decay of μ-mesic hydrogen. The remaining notation encountered in the text of the article and in the appendix is given in references 1 and 2.

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