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SECOND CLASS CURRENTS IN THE μ^--CAPTURE BY POLARIZED LIGHT NUCLEI

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The problem of second class current (SCC) has a significant value for our understanding of the weak interaction structure. Weinberg [1] classified the weak hadron currents by their transformation properties under the G-parity operation (where $G = C \exp(i\pi T_2)$). The first class currents (FCC) which dominate in the weak interaction and form the basis of the Standard Model, behave under G-parity transformation as

$$G V_\alpha^I G^{-1} = + V_\alpha^I \quad \text{and} \quad G A_\alpha^I G^{-1} = - A_\alpha^I .$$

SCC, which are a serious problem (see, for example, [2,3]) for the renormalized gauge theories of the electroweak interaction, behave oppositly to FCC under the G-parity operation:

$$G V_\alpha^{II} G^{-1} = - V_\alpha^{II} \quad \text{and} \quad G A_\alpha^{II} G^{-1} = + A_\alpha^{II} .$$

Following this classification the Dirac (F_1), Pauli (F_2), axial-vector (F_A) and pseudoscalar (F_P) form factors belong to FCC, and the scalar (F_S) and tensor (F_T) form factors - to SCC.

From the investigation of the mirror asymmetry of β-decay [4] the values of F_T are found to be equal to the form factor F_2 within the experimental accuracy. On the other hand, in a series of papers (see, for example, [5]) from the data on the angular distribution of β-particles with respect to the nuclear spin it is concluded that the G-parity of the weak nuclear current is strongly conserved, i.e.

$F_T = 0$. SCC were also searched for in the iso-elastic scattering of $\nu n \to \mu p$ [6], but they were not observed.

Recently the τ-lepton decay channels taking place due to SCC have been observed at colliding e^-e^+-beam ($\tau \to \omega\pi\nu_\tau$ [7] and $\tau \to \eta\pi\nu_\tau$ [8]). Nevertheless, the subsequent analysis of these data throws doubt upon the conclusions of the SCC existence (see, for example, [9]).

Thus, at present there is a contradictory and uncertain experimental situation concerning the search for SCC. It seems that for the complete solution of the SCC problem it is necessary to search for new effects, induced by SCC, and to carry out a number of independent experiments on measurement of various physical characteristics of electroweak processes.

Since the momentum transferred in the μ^--capture is much higher than in the β-decay, the search for SCC in the μ^--capture is preferable [10, 11], although the pure effects [12 – 14], induced by SCC, may be also observed in nuclear β-decay.

The present work, developing the [10, 14 – 17], is devoted to the study of the polarized muon capture by the polarized light nuclei

$$\mu^- + (A,\ Z) \longrightarrow (A,\ Z-1) + \nu_\mu, \qquad (1)$$

with allowance for the SCC and the muon neutrino mass.

The matrix element of process (1) in the framework of the current-current theory of the weak interaction may be written as

$$\langle f; \vec{p}_\nu, s_\nu |\ \hat{H}_W\ | \vec{p}_\mu, \vec{s}_\mu; i \rangle = -\frac{G_F}{\sqrt{2}}\, l_\alpha\, J_\alpha(\vec{q}), \qquad (2)$$

where $J_\alpha(\vec{q}) = \int d\vec{r}\, e^{-\vec{q}\vec{r}} \langle f | \phi_{1S}(\vec{r})\ \hat{J}_\alpha(\vec{r}) | i \rangle$ is the nuclear weak current; $G_F = 1.023 \times 10^{-5}\ m_p^{-2}$ is the Fermi constant of the weak interaction (m_p is the proton mass); $q_\alpha = (p_\mu - p_\nu)_\alpha = (\vec{q},\ iE_0)$ is the 4-momentum transfer; p_μ^α and p_ν^α are the 4-momenta of the muon and muonic neutrino; $l_\alpha = i\, \bar{u}_{\nu_\mu} \gamma_\alpha (1 + \gamma_5)\, u_\mu$ is the muon current; u_i ($i = \nu_\mu,\ \mu$) are the Dirac spinors.

Since the wave function of the muon $\phi_{1S}(\vec{r})$ in the 1S Bohr orbit of the mesoatom is a slowly varying function within the nuclear volume, it will be a "good" approximation if one extracts it from the inside of the matrix element (2) and use its average value [18]:

$$|\phi_{1S}|^2_{av} = R\,|\phi_{1S}(0)|^2 = (R/\pi)\left[Z\alpha m_\mu M_A/(m_\mu + M_A)\right]^3.$$

Here R is a reduction factor taking into account the finite extent of the nuclear transition density; M_A and Z are the mass and the charge of the nucleus; α is the fine structure constant.

In order to calculate the nuclear matrix elements the multipole expansion method [18] of the nuclear weak current $\hat{J}_\alpha(\vec{q})$, is used.

The coordinate system (see Fig. 1) taking into account the nuclear polarization is defined as follows: $\vec{e}_z = \vec{q}^{\,o} = \vec{q}/q$, the unit vectors $\vec{e}_x$ and $\vec{e}_y$ are parrallel to the vectors $(\vec{p}_\nu \times \vec{s}_\mu) \times \vec{q}$ and $(\vec{p}_\nu \times \vec{s}_\mu)$, respectively. The angles θ^* and φ^* describe the direction of the quantization axis (Z'-axis) with

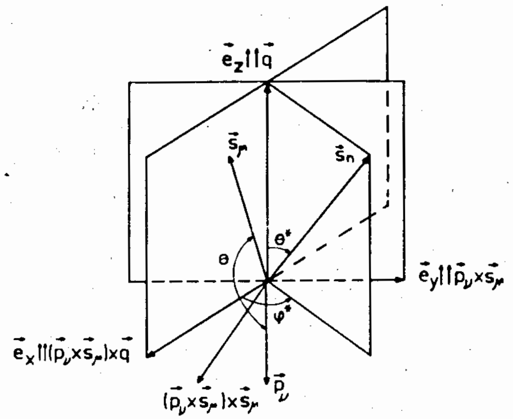

Fig. 1. The coordinate system used in the polarized muon capture by the polarized nuclei.

respect to the fixed Z-axis. Below the method of taking into account the nuclear polarization described in [14, 19, 20] is used. The order of the multipole operators, determining the expression for the differential rate of the transition $(J_i^{\pi_i};\ T_i M_{T_i} \rightarrow J_f^{\pi_f};\ T_f M_{T_f})$, is defined by the selection rule: $|J_i - J_f| \le J \le |J_i - J_f|$. In the case of the pure Gamow-Teller transition ($J = 1$) the differential rate of process (1) with allowance for the muon and nuclear polarization and the longitudinal polarization of the neutrino (the mass of which is supposed to be not zero), calculated using (2) in the lower order of the perturbation theory, is given by

$$dW = \frac{G_F^{\,2}}{(4\pi)^2}\, d\Omega_\nu E_\nu p_\nu |\phi_{1S}|^2_{av} \begin{pmatrix} T_f & 1 & T_i \\ -M_{T_f} & -1 & M_{T_i} \end{pmatrix}^2 F(\theta, \theta^*, \varphi^*). \qquad (3)$$

Here $d\Omega_\nu = \sin(\theta)d\theta d\varphi$ is the solid angle of the neutrino; $p_\nu = (E_\nu^2 - m_\nu^2)^{1/2}$, $E_\nu = E_\mu - \Delta E$ (where $\Delta E = E_f - E_i = E_\mu - E_\nu$ is the energy transfer), m_ν are the momentum, energy and mass of the neutrino; $E_\mu = m_\mu - \varepsilon_B$, m_μ and ε_B are the energy, mass and binding energy (in the 1S Bohr orbit of a mesoatom) of the muon; E_i (E_f) is the energy of the initial (final) nucleus.

The function $F(\theta, \theta^*, \varphi^*)$ has the form

$$F(\theta, \theta^*, \varphi^*) = f_1\phi_1 + 2f_2\phi_2 + f_3\phi_3 + f_4\phi_4 + f_5\phi_5 +$$
$$+ \frac{A}{2} P_2(\cos\theta^*)[f_1\phi_1 + 2(f_2\phi_2 - f_3\phi_3 - f_4\phi_4 - f_5\phi_5)] +$$
$$+ AP_2^1(\cos\theta^*)\cos\varphi^* \,(f_6F^5_{L1}F^5_{E1} + f_7F^5_{L1}F_{M1} + f_8F^5_{C1}F^5_{E1} +$$
$$f_9F^5_{C1}F_{M1}) - \frac{A}{4} P_2^2(\cos\theta^*)\cos 2\varphi^* f_{10}[(F^5_{M1})^2 - (F^5_{E1})^2] -$$
$$- 3PP_1^1(\cos\theta^*)\cos\varphi^* \,(f_6F^5_{L1}F_{M1} + f_7F^5_{L1}F^5_{E1} + f_8F^5_{C1}F_{M1} +$$
$$f_9F^5_{C1}F^5_{E1}) - \frac{3}{2} PP_1(\cos\theta^*)(2f_1\phi_2 + f_2\phi_1). \qquad (4)$$

Here A and P are the alignment and the polarization of the nuclei; $P_L^M(\cos\theta^*)$ are the associated Legendre polynomials;

$$\phi_1 = ((F_{M1})^2 + (F^5_{E1})^2), \qquad \phi_2 = F_{M1}F^5_{E1},$$

$$\phi_3 = (F^5_{L1})^2, \qquad \phi_4 = F^5_{L1}F^5_{C1}, \qquad \phi_5 = (F^5_{C1})^2, \qquad (5)$$

where F_{M1}, F^5_{C1}, F^5_{L1} and F^5_{E1} are the matrix elements of the vector magnetic, axial-vector electric, Coulomb and longitudinal multipole operators.

The arbitrary polarization of muons and the longitudinal polarization of the muonic neutrino taken into account the leptonic functions f_i (i = 1, 2, ..., 10), entering into the differential rate (3), have the form:

$$f_1 = 2\delta(1 - s_\nu\cos\theta), \qquad f_2 = -2\delta(s_\nu - \cos\theta),$$
$$f_3 = 2\delta(1 + s_\nu\cos\theta), \qquad f_4 = 4\delta(s_\nu + \cos\theta),$$
$$f_5 = 2\delta(1 + s_\nu\cos\theta), \qquad f_6 = \sqrt{2}s_\nu\delta\sin\theta,$$
$$f_7 = -\sqrt{2}\delta\sin\theta, \qquad f_8 = \sqrt{2}\delta\sin\theta,$$
$$f_9 = \sqrt{2}s_\nu\delta\sin\theta, \qquad f_{10} = 0. \qquad (6)$$

Here $\cos\theta = (\vec{\xi}_\mu\vec{p}^{\,0}_\nu) = -(\vec{\xi}_\mu\vec{q}^{\,0})$, where $\vec{\xi}_\mu$ is the unit vector of the muon polarization and $\vec{p}^{\,0}_\nu = \vec{p}_\nu\ /p_\nu$ is the unit vector in the direction of the neutrino momentum; $\delta = 1 - s_\nu\beta_\nu$, where $s_\nu = \pm 1$ and $\beta_\nu = |\vec{\beta}_\nu| = p_\nu/E_\nu$ are the helicity and the velocity of the muonic neutrino.

After summing eq. (3) over neutrino spin states, we obtain the following expressions for the functions f_i (i = 1, 2, ..., 10):

$$f_1 = 4(1 + \beta_\nu\cos\theta), \qquad f_2 = 4(\beta_\nu + \cos\theta),$$

$$f_3 = 4(1 - \beta_\nu\cos\theta), \qquad f_4 = -8(\beta_\nu - \cos\theta),$$
$$f_5 = 4(1 - \beta_\nu\cos\theta), \qquad f_6 = -2\sqrt{2}\beta_\nu\sin\theta,$$
$$f_7 = -2\sqrt{2}\sin\theta, \qquad f_8 = 2\sqrt{2}\sin\theta,$$
$$f_9 = -2\sqrt{2}\beta_\nu\sin\theta, \qquad f_{10} = 0. \qquad (7)$$

The further averaging of expression (3) over the muon spin states gives a simple form of the functions f_i:

$$f_1 = 4, \quad f_2 = 4\beta_\nu, \quad f_3 = 4, \quad f_4 = -8\beta_\nu,$$
$$f_5 = 4, \quad f_6 = -2\sqrt{2}\beta_\nu, \quad f_7 = -2\sqrt{2}, \quad f_8 = 2\sqrt{2},$$
$$f_9 = -2\sqrt{2}\beta_\nu, \quad f_{10} = 0. \qquad (8)$$

In the case of unpolarized muons and for production of the longitudinally polarized neutrino the functins f_i are given by

$$f_1 = 2\delta, \quad f_2 = -2s_\nu\delta, \quad f_3 = 2\delta, \quad f_4 = 4s_\nu\delta,$$
$$f_5 = 2\delta, \quad f_6 = \sqrt{2}s_\nu\delta, \quad f_7 = -\sqrt{2}\delta, \quad f_8 = \sqrt{2}\delta,$$
$$f_9 = \sqrt{2}s_\nu\delta, \quad f_{10} = 0. \qquad (9)$$

For the polarized muon capture by the polarized ^{6}Li nuclei in the framework of the shell model with the harmonic oscillator potential the matrix elements F_{M1}, F^5_{C1}, F^5_{L1} and F^5_{E1} have the form

$$F_{M1} = \frac{1}{\sqrt{\pi}}\frac{q}{M_n}e^{-y}[k_1F_1 + \mu(k_2 + k_3y)],$$

$$F^5_{E1} = \frac{2}{\sqrt{\pi}} e^{-y} (k_2 + k_3 y) F_A,$$

$$F^5_{C1} = \frac{1}{\sqrt{\pi}} \frac{q}{M_n} e^{-y} [k_4 F_A + (k_5 + k_6 y)(q_o F_P + 2M_n F_T)],$$

$$F^5_{L1} = - \frac{2}{\sqrt{\pi}} e^{-y} (k_5 + k_6 y)(F_A - \frac{q^2}{2M_n} F_P). \qquad (10)$$

Here $k_1 = 0.178$; $k_2 = 0.561$; $k_3 = -0.354$; $k_4 = 8.6 \cdot 10^{-3}$; $k_5 = -0.397$; $k_6 = 0.293$; $y = (bq/2)^2$, where b (= 2.03 fm [18]) is the oscillator parameter.

In the long wave lenth limit ($q/M_n \approx 0$, $y \approx 0$) the function determining the differential rate of the μ^--capture by the polarized nuclei, is given by

$$F(\theta, \theta^*, \varphi^*) = F_A(2f_1 + f_3) + 4qf_2F_2 - qf_4F_T +$$
$$+ AP_2(\cos\theta^*) [F_A(f_1 - f_3) + 2qf_2F_2 + qf_4F_T] +$$
$$+ AP^1_2(\cos\theta^*)\cos\varphi^* \sqrt{2}(f_6F_A + qf_7F_2 - qf_8F_T) +$$
$$+ \frac{A}{2} P^2_2(\cos\theta^*)\cos 2\varphi^* f_{10} F_A + 3 P P_1(\cos\theta^*) (f_2F_A +$$
$$+ 2qf_1F_2) + 3\sqrt{2} P P^1_1(\cos\theta^*)\cos\varphi^* (f_7F_A + qf_6F_2 -$$
$$- qf_9F_T). \qquad (11)$$

The angular distribution of the neutrino with respect to the muon spin orientation is described by the asymmetry coefficient, defined by

$$\alpha_{\mu\nu} = \frac{dW(\vec{s}_\mu \uparrow\uparrow \vec{p}^o_\nu) - dW(\vec{s}_\mu \uparrow\downarrow \vec{p}^o_\nu)}{dW(\vec{s}_\mu \uparrow\uparrow \vec{p}^o_\nu) + dW(\vec{s}_\mu \uparrow\downarrow \vec{p}^o_\nu)}. \qquad (12)$$

By neglecting the terms proportional to q_0/M_N and q^2/M^2_N in the case of unpolarized nuclei and neutrino, we obtain a simple expression for the coefficient $\alpha_{\mu\nu}$ with allowance for the form factor F_T:

$$\alpha_{\mu\nu} = \frac{1}{3} \beta_\nu \left\{1 - \frac{8}{3} E_\nu \frac{F_T}{F_A}\right\}. \qquad (13)$$

In this formula the dependence on m_ν is quadratic through the neutrino velocity $\beta_\nu = \{1-[m_\nu/(E_\mu - \Delta E)]^2\}^{1/2}$. Eq. (13) may be used to estimate the neutrino mass m_ν and the form factor F_T. At $F_T = 1.4 \cdot 10^{-3}$ MeV^{-1} the relative contribution from SCC to the coefficient $\alpha_{\mu\nu}$ is $\approx$ 40%. For unpolarized nuclei a detailed analysis of the contribution from SCC to the coefficient $\alpha_{\mu\nu}$ has been done in [10, 17].

One of the interesting characteristics of process (1) is the coefficient of the asymmetry between the polarization directions of the muon ($\vec{s}_\mu$) and the nucleus ($\vec{s}_n$), defined by

$$A_{\mu n} = \frac{dW(\vec{s}_\mu \uparrow\uparrow \vec{s}_n) - dW(\vec{s}_\mu \uparrow\downarrow \vec{s}_n)}{dW(\vec{s}_\mu \uparrow\uparrow \vec{s}_n) + dW(\vec{s}_\mu \uparrow\downarrow \vec{s}_n)}, \qquad (14)$$

where $\vec{s}_n$ is a unit vector in the nuclear polarization direction.

The coefficient $a_{\mu n}$ for the $(1^+ \to 0^+)$-transition has the form

$$A_{\mu n} = \frac{PH_3}{H_1 + AH_2}, \qquad (15)$$

where the functions H_i (i = 1, 2, 3) are given by the expressions

$$H_1 = 3+\beta_\nu\cos\theta + 2E_\nu\tilde{F}_T(\beta_\nu-\cos\theta) + 4E_\nu\tilde{F}_2(\beta_\nu+\cos\theta);$$

$$H_2 = 2\beta_\nu\cos\theta + E_\nu\beta_\nu(3\cos^2\theta-1)(\tilde{F}_2-\tilde{F}_T)+2E_\nu\cos\theta(\tilde{F}_2+\tilde{F}_T);$$

$$H_3 =-3[1+\beta_\nu\cos\theta-E_\nu\beta_\nu\tilde{F}_T\sin^2\theta+E_\nu\tilde{F}_2(\beta_\nu\cos^2\theta+2\cos\theta+\beta_\nu)]. \qquad (16)$$

Here and below $\tilde{F}_X = F_X/F_A$ (where X = 2, T). Note that H_1 give the differential rate averaged over the parent nucleus spin states.

If $\theta = \pi/2$ and the neutrino mass is neglected, the coefficient $A_{\mu n}$ is expressed as:

$$A_{\mu n} = - P\{1 - (1/3)\beta_\nu E_\nu[\tilde{F}_2(1-A)+\tilde{F}_T(5+A)]\}. \qquad (17)$$

At the alignment equal to one (A = 1) we obtain

$$A_{\mu n} = - P(1 - 2\beta_\nu E_\nu\tilde{F}_T). \qquad (18)$$

In this case the relative contribution from SCC to the coefficient $A_{\mu n}$ at F_T = 1,4 10^{-3} MeV^{-1} is ≈ 40%. Note that the information on the value and sign (relative to the form factor F_2) of the form factor F_T may be obtained by using expression (18).

At $\theta = 0^o$ and $A \neq 1$ the coefficient $A_{\mu n}$ will differ from zero only if the non-zero neutrino mass exists, and in this case $A_{\mu n}$ is equal to

$$A_{\mu n} = - (3/4)(m_\nu^2/E_\nu^2)P[1-2E_\nu(\tilde{F}_2+\tilde{F}_T)]/(1-\beta_\nu A). \qquad (19)$$

The latter equation may be used to determine the muon neutrino mass.

For the coefficient $A_{\mu n}$ after integrating the differential capture rate, we obtain the expression

$$A_{\mu n} = P\{1 + (2/3)E_\nu(1-A)(\tilde{F}_2 + \tilde{F}_T)\}. \qquad (20)$$

It follows from here that the contributions from SCC and weak magnetism to the coefficient $A_{\mu n}$ in this case are correlated and it will be difficult to differentiate between them.

Thus, the present limits on the form factor F_T may be improved by studying the coefficient $A_{\mu n}$ at various values of alignment A.

Let the nucleus be polarized along $\vec{u}_s \uparrow\uparrow (\vec{p}_\nu \times \vec{s}_\mu) \times \vec{s}_\mu$. Then, after summing the differential rate over the neutrno spin states for the asymmetry coefficient defined by

$$A_S = \frac{dW(\vec{s}_n\uparrow\uparrow\vec{u}_s) - dW(\vec{s}_n\uparrow\downarrow\vec{u}_s)}{dW(\vec{s}_n\uparrow\uparrow\vec{u}_s) + dW(\vec{s}_n\uparrow\downarrow\vec{u}_s)}, \qquad (21)$$

we obtain the expression

$$A_S = \frac{PH_3}{H_1 + AH_2}. \qquad (22)$$

The function H_1 is given in (16) and the functions H_2 and H_3 have the form

$$H_2 = -\beta_\nu\cos\theta + E_\nu\beta_\nu(3\sin^2\theta-1)(\tilde{F}_2-\tilde{F}_T)-E_\nu\cos\theta(\tilde{F}_2+\tilde{F}_T);$$

$$H_3 = 3\sin\theta[\beta_\nu + E_\nu\beta_\nu\tilde{F}_T\cos\theta + E_\nu\tilde{F}_2(2-\beta_\nu\cos\theta)]. \qquad (23)$$

In the case of $\theta = \pi/2$ the coefficient A_S has the form

$$A_S = P\,[\beta_\nu + (2/3)E_\nu(\tilde{F}_2 - \tilde{F}_T)(1-A)]. \qquad (24)$$

At $A = 1$ there are no contributions from the form factors F_T and F_2 to the coefficient A_S. At $\theta = 0$ and π the coefficient A_S is equal to zero.

In the case of the polarization of nuclei in the direction that is perpendicular to the reaction plane $(\vec{\xi}_n \uparrow\uparrow \vec{p}_\nu \times \vec{\xi}_\mu)$, the asymmetry coefficient, defined by

$$A_N = \frac{dW(\vec{\xi}_n \uparrow\uparrow \vec{p}_\nu \times \vec{\xi}_\mu) - dW(\text{unpolar.})}{dW(\text{unpolar.})} \qquad (25)$$

is proportional to the alignment A and has the form

$$A_N = -A[F_A\beta_\nu\cos\theta - E_\nu F_T(\beta_\nu - \cos\theta) + E_\nu F_2(\beta_\nu + \cos\theta)]/H_1. \qquad (26)$$

The function H_1 is given in (16).

At $\cos\theta = -1$ for the massless neutrino the coefficient A_N is expressed as

$$A_N = (1/2)A, \qquad (27)$$

and in the case of $\cos\theta = +1$ the coefficient A_N is given by

$$A_N = -(1/4)A. \qquad (28)$$

In these cases the coefficient A_N does not depend on the form factors F_T and F_2.

At $\cos\theta = 0$ the coefficient A_N is equal to

$$A_N = -(1/3)AE_\nu(\tilde{F}_2 - \tilde{F}_T), \qquad (29)$$

which is the same as the expression for the coefficient A_N obtained after the integration of differential rate (3).

Thus, the analysis shows that for getting information on the form factor F_T the angular dependences of various correlation coefficients $(\alpha_{\mu\nu}, A_{\mu n}, A_S$ and $A_N)$ in the μ^--capture by polarized nuclei should be investigated. At $\theta = \pi/2$ and $A = 1$ the coefficient $A_{\mu n}$ depends only on the form factor F_T, and at $\theta = 0^\circ$ and $A \neq 1$ the coefficient $A_{\mu n}$ is not equal to zero only if a non-zero neutrino mass exists. In the case of $\theta = \pi/2$ the coefficient A_S depends on the form factors F_2 and F_T only when $A \neq 1$. At $\theta = 0^\circ$ and π the coefficient A_N does not depend on the form factors F_2 and F_T, and at $\theta = \pi/2$ the quantity A_N is proportional to the difference between F_2 and F_T.

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