Neutrino scattering on polarized electron target and neutrino magnetic moment

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Abstract

The completed and proposed experiments for the measurement of the neutrino magnetic moment are discussed. To improve the sensitivity of the search for the neutrino magnetic moment we suggest to use a polarized electron target in the processes of neutrino (antineutrino) – electron scattering. It is shown that in this case the weak interaction term in the total crosssection is few times smaller comparing with unpolarized case, but the electromagnetic term does not depend on electron polarization.

The search of new bounds on the neutrino magnetic moment $\mu_\nu$ in laboratory experiments would be very important for checking of new Physics beyond the Standard Model (SM) and for different astrophysical implications. The Resonant Spin-Flavor Precession (RSFP) scenario (Akhmedov, 1988; Lim and Marciano, 1988) in the case of a non-vanishing neutrino magnetic moment $\mu_\nu \neq 0$ is still considered as a possible solution to the Solar Neutrino Problem (SNP) (Berezinsky, 1998). The observations of neutron stars gave an information about the existence of strong magnetic fields (even more than the critical value $B_c = m^2_e/e = 4.41 \cdot 10^{13}$ G) which can interact with neutrino through its magnetic moment. The nature of a neutrino (Dirac or Majorana) determines the properties of neutrino magnetic moments, so a Dirac neutrino can have diagonal and transition (off-diagonal) moments, while Majorana neutrinos can have transition moments only (Schechter and Valle, 1981). All these hints claim direct laboratory measurements of the neutrino magnetic moment.

There is the laboratory bound on the electron neutrino magnetic moment from the experiments with reactor’s neutrino combined by Derbin (1994), $\mu_{\nu_e} < 1.8 \cdot 10^{-10} \mu_B$. There are also different astrophysical constraints that are even more stringent than previous one. For the detailed discussion and references see Raffelt (1996).

To probe neutrino magnetic moment at a more lower level $\mu_{\nu_e} \sim 10^{-11} \mu_B$ some artificial neutrino sources of well-known activity and spectra can be used. There are some experiments planned with different possible artificial sources, e.g. $^{51}$Cr (Ferrari et al., 1996), $^{90}$Sr (Mikaelyan et al., 1998; Ianni and Montanino, 1999), $^{147}$Pm (Kornoukhov, 1997; Barabanov et al., 1997), $^{55}$Fe (Golubchikov et al., 1996). The recently proposed measurement of neutrino magnetic moment at a level better than $10^{-11} \mu_B$ ($\sim 3 \cdot 10^{-12} \mu_B$) with the use of the tritium neutrino emitter (antineutrino source with the energy spectrum endpoint 18.6 keV) and a semiconductor cryodetector is planned to reach extra low threshold about 1.1 eV (Trofimov et al., 1998; Bogdanova, 2000) (see Table 1).
We suggest to use a polarized electron target for more precise measurements of a neutrino magnetic moment in the processes of neutrino (antineutrino) – electron scattering (Rashba and Semikoz, 2000). Kinematics of such scattering for which the recoil electron energy \( E_e = E_\tilde{p}_1 - m_e \) should be measured is shown in Fig.1. We have fixed z0x-plane based on the initial neutrino momentum \( \vec{k}_1 \) directed along z-axis and on the 3-vector part \( \vec{\xi}_e \) of the four-spin \( a_\mu = (0, \vec{\xi}_e) \) at the rest frame of the initial electron (\( \vec{p}_1 = 0 \)) entering the Mishel–Wightman density matrix, \( \rho(p_1) = (\hat{p}_1 + m_e)(1 + \gamma_5 \hat{a}) \).

The cross section of the electron neutrino (antineutrino) scattering off electrons consists of two terms: weak and electromagnetic ones without interference term that can be neglected in the massless limit \( m_e \to 0 \),

\[
\left( \frac{d\sigma}{dT_e d\phi} \right) = \left( \frac{d\sigma}{dT_e d\phi} \right)^\text{weak} + \left( \frac{d\sigma}{dT_e d\phi} \right)^\text{em}.
\]

(1)

After integration over the azimuthal angle \( \phi \) (see Fig.1) the weak cross sections have the following forms:

\[
\left( \frac{d\sigma}{dT_e} \right)^\text{weak} = \frac{2G_F^2 m_e}{\pi} \left[ g_{eL}^2 \left( 1 + |\vec{\xi}_e| \cos \theta_\xi \right) + g_R^2 \left( 1 - \frac{T_e}{\omega_1} \right)^2 \times \right.
\]

\[
\left. \left( 1 - |\vec{\xi}_e| \cos \theta_\xi \left( 1 - \frac{m_e T_e}{\omega_1 (\omega_1 - T_e)} \right) \right) - g_{eL} g_R \frac{m_e T_e}{\omega_1^2} \left( 1 + |\vec{\xi}_e| \cos \theta_\xi \right) \right]
\]

(2)

for left-handed neutrino and

\[
\left( \frac{d\sigma}{dT_e} \right)^\text{weak} = \frac{2G_F^2 m_e}{\pi} \left[ g_R^2 \left( 1 - |\vec{\xi}_e| \cos \theta_\xi \right) + g_{eL}^2 \left( 1 - \frac{T_e}{\omega_1} \right)^2 \times \right.
\]

\[
\left. \left( 1 + |\vec{\xi}_e| \cos \theta_\xi \left( 1 - \frac{m_e T_e}{\omega_1 (\omega_1 - T_e)} \right) \right) - g_{eL} g_R \frac{m_e T_e}{\omega_1^2} \left( 1 - |\vec{\xi}_e| \cos \theta_\xi \right) \right]
\]

(3)

for right-handed antineutrino, where \( |\vec{\xi}_e| \) is the value of the initial electron polarization. Here \( G_F \) is the Fermi constant; \( g_{eL} = \sin^2 \theta_W + 0.5 \), \( g_R = \sin^2 \theta_W \) (\( \sin^2 \theta_W \approx 0.23 \)) are the couplings in the SM; \( \omega_1 = k_1 \) is the initial neutrino energy; \( \theta_\xi \) is the angle between the neutrino momentum \( k_1 \) and the electron polarization vector \( \vec{\xi}_e \). If the new (experimental) parameter \( |\vec{\xi}_e| \cos \theta_\xi \) vanishes, \( |\vec{\xi}_e| \cos \theta_\xi \to 0 \), our results convert to the standard ones (Okun’, 1990).

Electromagnetic terms of the neutrino (antineutrino) scattering cross section do not depend on the electron polarization \( \vec{\xi}_e \) and have the same form for neutrinos and antineutrinos. If CP holds\textsuperscript{1} the electromagnetic

\[\text{Table 1. Proposed and planning experiments and neutrino magnetic moments which can be measured.}\]

\begin{tabular}{|c|c|c|c|}
\hline
Reference & \( \nu(\bar{\nu}) \) source & Detector & \( \mu_\nu / \mu_B > \) \\
\hline
Ferrari et al., 1996 & \( ^{55}\text{Fe} \) & BOREXINO & \( 5 \cdot 10^{-11} \) \\
Ianni et al., 1999 & \( ^{53}\text{Cr}, ^{89}\text{Sr} \) & BOREXINO & \( 6 \cdot 10^{-11} \) \\
Miranda et al., 1999 & \( ^{53}\text{Cr}, ^{89}\text{Sr} \) & HELLAZ & \( 6 \cdot 10^{-11} \) \\
Beda et al., 1998 & Reactor & Ge-Nal & \( 3 \cdot 10^{-11} \) \\
TEXONO, Wong, 1999 & Reactor, Taiwan & CsI & \( 3 \cdot 10^{-11} \) \\
Kurchatov-PNPI, Kozlov, 1999 & Krasnoyarsk reactor & Si & \( 2 \cdot 10^{-11} \) \\
MUNU, Brogmini, 1999 & Bugey reactor & CF\(_4\) & \( 2 \cdot 10^{-11} \) \\
Mikaelyan et al., 1998 & \( ^{89}\text{Sr} \) & BOREXINO & \( 1.5 \cdot 10^{-11} \) \\
Golubchikov et al., 1996 & \( ^{57}\text{Fe} \) & Si & \( 5 \cdot 10^{-12} \) \\
Kornoukhov, 1997 & \( ^{149}\text{Pm} \) & Ge, Si or NaI & \( 5 \cdot 10^{-12} \) \\
Barabanov et al., 1997 & \( ^{147}\text{Pm} \) & NaI & \( 3 \cdot 10^{-12} \) \\
Trofimov et al., 1998 & Ti\(_2\) & Si & \( 3 \cdot 10^{-12} \) \\
\hline
\end{tabular}

\textsuperscript{1}In the Dirac neutrino case when CP conserves the diagonal electric dipole moment is absent, \( d_\nu = 0 \). For Majorana neutrino this form is valid if CP parities of initial and final neutrino states are opposite hence the electric dipole moment does not contribute, \( d_\nu = 0 \) (Schechter and Valle, 1981). For the Dirac neutrino transition moment we should substitute \( |\mu_\nu|^2 \to |\mu_{ij} - id_{ij}|^2 \) where \( \mu \) and \( d \) are not separated and obey the equality \( \text{Re} \mu \text{Re} d + \text{Im} \mu \text{Im} d = 0 \) (Raffelt, 1996).
term in Eq. (1) can be written as
\[
\left( \frac{d\sigma}{dT_e} \right)^{em} = \frac{\pi \alpha^2}{m_e^2} \left( \frac{1}{T_e} - \frac{1}{\omega_1} \right) \frac{|\mu_\nu|^2}{\mu_B^2},
\]
here \( \mu_B \) is the Bohr magneton.

As well as for the case of an unpolarized target \( (\xi_e = 0) \) the electromagnetic interaction via a large magnetic moment increases very significantly in the region of small energy transfer \( T_e = \omega_1 - \omega_2 \ll m_e, \omega_1 \) and can be comparable or greater than the weak interaction. This gives a possibility to determine an upper limit on the neutrino magnetic moment or to measure it.

Weak interaction cross sections (Eqs. (2) and (3)) occur very sensitive both to the polarization of electron target \( |\xi_e| \) and to the angle \( \theta_\xi \) between the neutrino momentum and the initial electron polarization. For the known values of the SM parameters \( (g_{eL}^2 = 0.533, g_L^2 \approx 0.053 \text{ and } g_{eL} g_R \approx 0.168) \) one can observe from Eqs. (2) and (3) a new possibility for decreasing of the main weak term \( (\sim g_{eL}^2) \) in the cross section Eq. (1) choosing large polarization values \( (|\xi_e| \rightarrow 1) \) and with a choice of the specific geometry \( (\theta_\xi = \pi) \). The weak cross sections for \(^{51}\text{Cr} \) neutrino source and different values of the initial electron polarization are shown in Fig. 3.

In the case discussed above \( (|\xi_e| \cos \theta_\xi = -1) \) the weak interaction cross sections are proportional to \( g_{eL}^2 \). It means that target electrons (in laboratory system) that are fully polarized in the opposite direction to the neutrino momentum will interact with a neutrino as right chiral particles. This can be explained by the following way. Let’s make the Lorentz boost from the laboratory system to the ultrarelativistic one which moves along neutrino momentum with \( V \sim c = 1 \). In this system initial electron is an ultrarelativistic particle and it can be considered as a massless one. Since the modulo of electron polarization is Lorentz-invariant, \( |\xi_e| = \sqrt{-\epsilon_{\mu} \epsilon^\mu}, \) and the electron momentum direction appeared in chosen system is parallel to its polarization vector such electron is the right-handed particle (right-helicity = +1) having same chirality (+1) in massless limit.

The best case of the antiparallel neutrino (antineutrino) beam \( \cos \theta_\xi = -1 \) can be generalized for a more realistic case with an integration over \( \theta_\xi \) accounting for a concrete geometry of the artificial (isotope) neutrino source placed outside of the detector with known sizes.

Note that the polarization contribution to the \( \bar{\nu}e \)-scattering vanishes at the two points:
\[
T_{e1} = \frac{\omega_1^2}{m_e + \omega_1}\left(1 + \frac{g_R}{g_{eL}}\right), \quad T_{e2} = \omega_1\left(1 - \frac{g_R}{g_L}\right).
\]

For the tritium antineutrino source the polarization reduces (enhances) the unpolarized part of the SM weak cross section below (above) \( T_{e1} \). For the same source the second root \( T_{e2} \) occurs out of the kinematic allowed region, \( T_{e2} > T_{max} = 2\omega_1^2/(m_e + 2\omega_1) \). Hence in the case of the \( \bar{\nu}e \)-scattering the low energy region \( T_e < T_{e1} \) is preferable to look for an electromagnetic effect from the sum Eq. (1).

One can easily check that in the case of the \( \bar{\nu}e \)-scattering \( (g_{eL} \leftrightarrow g_R) \) both roots Eq. (3) are out of the kinematic allowed region and the polarization term reduces the SM weak cross-section for any energy \( T_e \).

Let us consider the spectra of recoil electrons from an antineutrino (neutrino) source calculated via the averaging of the differential cross-sections over the antineutrino (neutrino) spectrum \( \rho(\omega_1) \),
\[
S_{free}(T_e) = \int_{\omega_{1min}} d\omega_1 \frac{d\sigma_{weak}(T_e, \omega_1)}{dT_e} \rho(\omega_1),
\]
\[
S_{free}(T_e) = \int_{\omega_{1min}} d\omega_1 \frac{d\sigma_{em}(T_e, \omega_1)}{dT_e} \rho(\omega_1),
\]
where weak and electromagnetic cross-sections are given by Eqs. (2), (3) and Eq. (4) correspondingly and \( \omega_{1min} = (T_e/2)[1 + \sqrt{1 + 2m_e/T_e}] \) is the minimal neutrino energy given by the kinematic limit \( T_e \leq T_{max} \). The ratio of total recoil electron spectra to weak one for different values of initial electron polarization and neutrino magnetic moment for the tritium antineutrino source is shown in Figures 2, 6 and 7. The same plots for the \(^{51}\text{Cr} \) neutrino source are shown in Figures 4 and 5.
It was found by Kopeikin et al. (1997), that inelastic spectra \( S_{in}(q) \) which depend on the energy transfer \( q = \varepsilon_i + T_e \) for a bound initial electron knocked out from the \( i \)-shell coincide with the spectra Eq. \( \text{(5)} \), \( S_{in}(q) = S_{\text{free}}(q) \theta(q - \varepsilon_i) \), when the value \( q \) is larger than the binding energy \( \varepsilon_i \), \( q > \varepsilon_i \). Really, \( q \) is exactly the event energy measured in the experiment since soft X-quanta and mainly Auger electrons emitted by an atom from which a recoil electron was knocked out are automatically absorbed in the detector fiducial volume or their total energy \( \varepsilon_i \) adds to the kinetic energy \( T_e \) (Kopeikin et al., 1997).

For shells ordered, \( i = K, L, M, N, O, . . . \), let us consider low energy transfer, \( \varepsilon_{i-1} > q \geq \varepsilon_i \), when antineutrinos (neutrinos) knock out outer (let us say \( i = O \), main Bohr number \( n = 5 \)) electrons only not touching all inner ones. Moreover, since inner electrons from filled shells with \( J = L = S = 0 \) \( (i - 1 = K, L, . . .) \) do not contribute to the electron polarization one has a sense to consider only the \( \nu e \)-scattering off outer \( i \)-electrons for which the Zeeman splitting energy is given by

\[
E_{J,MJ} = g_J \mu_B MJ H \, ,
\]

where \( g_J \) is the Lande factor and \( M_J = -J, . . . , J - 1, J \) is the projection of the total spin \( \vec{J} \) on the magnetic field direction.

In order to obey such conditions we propose to use a tritium antineutrino source \( (T_{\text{max}} \approx 1.26 \text{ keV}) \) and a cryogenic detector with the lowest threshold \( (\sim \text{eV-region}) \) for which some lower energy bins \( T_{th} \leq T_{th} + \Delta T_e \leq T_{th} + 2\Delta T_e, . . . \) within the interval

\[
T_{th} < q = T_e + \varepsilon_i < \varepsilon_{i-1} \, ,
\]

can be separated. For instance, such low thresholds are considered by Trofimov et al. (1998) for the Si-semiconductor detector without magnetic fields. Hence the recoil electron energy \( T_e \) should be lower than the difference between the binding energy of the last filled shell \( \varepsilon_{i-1} \) and outer (valence) electron energy \( \varepsilon_i \), \( T_e < \varepsilon_{i-1} - \varepsilon_i \). In such case only polarized (outer) electrons contribute to the event spectrum to be measured.

One assumes that a low bin width \( \Delta T_e \sim T_{th} \sim \text{a few eV} \) would be enough to measure the spectrum \( S_{in}(q) = S_{\text{free}}(q) \).

Note that we have discussed above the spectrum \( S_{in}(q) \) for the ionization process \( \nu + e(i) \rightarrow \nu + e \) for an individual electron on the \( i \)-subshell with a free final electron. Accounting for all polarized electrons on that outer \( i \)-subshell of an atom \( Z \) (ion in the detector molecule) we find that the total sum over subshells (Kopeikin, 1997) reduces within the low-energy interval Eq. \( \text{(6)} \) to the fraction of polarized electrons:

\[
\frac{S_{in}(q)}{S_{\text{free}}(q)} = \frac{1}{Z} \sum_{i=K,L_1-L_0,...} n_i \theta(q - \varepsilon_i) \rightarrow \frac{n_O}{Z} \, ,
\]

where \( n_i \) is the number of electrons on the \( i \)-subshell, \( n_O \) is the number of polarized (valence) electrons on the last unfilled, let us say, \( i = O \)-shell.

The equal reduction of weak and electromagnetic inelastic contributions \( S_{in}(q) \) comparing with the hard energy case \( q \gg \varepsilon_i \) (for which \( S_{in} \approx S_{\text{free}} \)) leads to a calculable event statistics decrease. Nevertheless, for low energies Eq. \( \text{(6)} \) near \( T_{th} \) the conserving ratio

\[
\frac{S_{\text{em}}(q) + S_{\text{weak}}(q)}{S_{\text{weak}}(q)} = \frac{S_{\text{em}}(q) + S_{\text{weak}}(q)}{S_{\text{free}}(q)} \, ,
\]

given by Eq. \( \text{(9)} \) is still more sensitive to the neutrino magnetic moment in the case of polarized outer electrons than for unpolarized targets discussed in (Trofimov et al., 1998) (compare in Fig. 2).

The valence electrons can be fully polarized. Really, applying realistic magnetic fields \( H \gtrsim 10^4 \text{ G} \) to a cryodetector one can easily reach the ratio \( \mu_B H/T > 1 \) at low temperatures \( T \lesssim 0.5 \text{ K} \). Known experimental methods (Groot et al., 1965) allow to reach high electron polarization at temperatures less than the Curie point \( T_C \) when the parameter \( \mu_B H/T \) is quite large.

For such conditions one can expect 100% polarization of outer (valence) electrons in the sum over \( M_J \) entering the electron polarization \( |\vec{\xi}_e| = P \),

\[
P = \frac{\sum_{|M_J|}[\exp(g_J\mu_B | M_J | H/T) - \exp(-g_J\mu_B | M_J | H/T)]}{\sum_{|M_J|}[\exp(g_J\mu_B | M_J | H/T) + \exp(-g_J\mu_B | M_J | H/T)]} \, .
\]
Here we have used the Boltzman distribution for independent ions (atoms) for which the fraction of the polarized electrons with the total spin projection \( M_f \) is given by the ratio \( N_{M_f} / N_0 = \exp(-|g_f \mu_B M_f H / T) \) where \( N_0 \) is the normalization factor not playing a role in the ratio Eq. (1).

Now let us turn to some experimental prospects. Such weakly interacting Boson gas as atomic hydrogen \( H_2 \) being spin-polarized in high magnetic fields is used for possible Bose-Einstein condensation at low temperatures (Silvera, 1995) and seems could be also used as an ideal polarized (100%) electron target for the \( \nu e\)-scattering. However, we do not know how to register recoil electrons there.

The Neganov-Trofimov-Luke effect of ionization-to-heat conversion (Neganov and Trofimov, 1981; Luke, 1988) that was proposed for the use of cryogenic semiconductor detectors to measure lowest neutrino magnetic moments (Golubchikov et al., 1996; Trofimov et al., 1998) may be modified for such magnetic semiconductors as ferromagnets EuS, EuO where outer \( f \)-electrons are fully polarized along an external magnetic field (Nagaev, 1979).

The method should be similar to Neganov and Trofimov (1981) and Luke (1988) but has some distinctions. At the initial state and low temperatures \( T < T_C \) (\( T_C \sim 14 \text{ K} \) for EuS and \( T_C \sim 69 \text{ K} \) for EuO) there are no electrons (holes) in conductive (valence) zones, \( n_e = n_h = \exp(-E_g / T) \approx 0 \), \( E_g \gg T \). Then a neutrino hits a polarized valence electron which overcomes the semiconductor gap \( E_g \) (\( E_g = 0.9 \text{ eV} \) for EuO or \( E_g = 1.5 \text{ eV} \) for EuS) appearing in the conductive zone where it could be accelerated by an external electric field of the known value applied to the crystal to get a measurable energy \( \Delta E_e \). In the case of a simple semiconductor like Si kept at the thermostat temperature \( T \) the following electron-phonon interaction leads to the heating of such Si-crystal for which a low lattice heat capacity \( c_l \) appearing in the conductive zone where it could be accelerated by an external electric field of the known value applied to the crystal to get a measurable energy \( \Delta E_e \). In the case of a simple semiconductor like Si kept at the thermostat temperature \( T \) the following electron-phonon interaction leads to the heating of such Si-crystal for which a low lattice heat capacity \( c_l \) appearing in the conductive zone where it could be accelerated by an external electric field of the known value applied to the crystal to get a measurable energy \( \Delta E_e \). The accuracy of \( \mu_e \)-calculations depends also on experimental uncertainties including a background, an isotope source activity, a concrete geometry of the experiment, etc. (see e.g. Ianni and Montanino (1999)) that could be done for a future concrete polarized cryodetector with a low threshold and is beyond the scope of the present proposal.

Note that we have omitted radiative corrections (RC) in the main term \( g_{1e}^2 (1 + \alpha f_\pi / \pi)(1 + |\vec{\xi}_e| \cos \theta_\xi) \) (Bahcall et al., 1995) entering Eq. (2) where the RC term \( \alpha f_\pi / \pi \) is expected at the level \( \sim 1 \% \) in the low energy region, or occurs at the negligible level comparing with the strong polarization influence the weak cross-section.

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2Molecular hydrogen \( H_2 \) is diamagnetic.
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Figures

Figure 1. Kinematics of the neutrino scattering off the polarized electron.

Figure 2. The ratio of the total recoil electron spectrum and the weak one (Eq. 10) for different values of the polarization parameter $|\vec{\xi}_e| \cos \theta_{\vec{\xi}} = 0, -1$ and for the fixed neutrino magnetic moment $\mu_\nu = 3 \cdot 10^{-12} \mu_B$ is shown as dashed and solid lines, correspondingly. Tritium antineutrino emitter.

Figure 3. The weak interaction term of the recoil electron spectrum one (Eq. 10) for different values of the polarization parameter $|\vec{\xi}_e| \cos \theta_{\vec{\xi}} = 0, -0.9, -1$ is shown by dash-dotted, dashed and solid lines correspondingly. The dotted line shows the electromagnetic term of the recoil electron spectrum for the neutrino magnetic moment $\mu_\nu = 3 \cdot 10^{-12} \mu_B$. Neutrino source is $^{51}$Cr.

Figure 4. The ratio of the total recoil electron spectrum and the weak one (Eq. 10) for different values of the polarization parameter $|\vec{\xi}_e| \cos \theta_{\vec{\xi}} = 0, -0.9, -1$ and for the fixed neutrino magnetic moment $\mu_\nu = 10^{-12} \mu_B$ is shown by short-dashed, dashed and solid lines, correspondingly. The zero neutrino magnetic moment case is shown by dotted line. Neutrino source is $^{51}$Cr.

Figure 5. The ratio of the total recoil electron spectrum and the weak one (Eq. 10) for fixed maximal value of polarization parameter $|\vec{\xi}_e| \cos \theta_{\vec{\xi}} = -1$ and for different neutrino magnetic moments $\mu_\nu = 0, 3 \cdot 10^{-13} \mu_B, 10^{-12} \mu_B, 2 \cdot 10^{-12} \mu_B$ is shown by dotted, short-dashed, dashed and solid lines, correspondingly. Neutrino source is $^{51}$Cr.

Figure 6. The ratio of the total recoil electron spectrum and the weak one (Eq. 10) for fixed maximal value of polarization parameter $|\vec{\xi}_e| \cos \theta_{\vec{\xi}} = 0, -0.9, -1$ and for the fixed neutrino magnetic moment $\mu_\nu = 3 \cdot 10^{-13} \mu_B$ is shown by short-dashed, dashed and solid lines, correspondingly. The zero neutrino magnetic moment case is shown by dotted line. Tritium antineutrino emitter.

Figure 7. The ratio of the total recoil electron spectrum and the weak one (Eq. 10) for fixed maximal value of polarization parameter $|\vec{\xi}_e| \cos \theta_{\vec{\xi}} = -1$ and for different neutrino magnetic moments $\mu_\nu = 0, 10^{-13} \mu_B, 3 \cdot 10^{-13} \mu_B, 10^{-12} \mu_B$ is shown by dotted, short-dashed, dashed and solid lines, correspondingly. Tritium antineutrino emitter.
Figure 1
Figure 2.

\[ |\xi| \cos \theta_\xi = -1 \]
\[ \mu_\nu = 3 \cdot 10^{-12} \mu_B \]
\[ |\xi| \cos \theta_\xi = 0 \]
\[ \mu_\nu = 0 \]

Figure 3.

\[ \frac{d\sigma}{dT}, 10^{-48} \text{ cm}^2 \text{ keV}^{-1} \]
\[ |\xi| \cos \theta_\xi = -0.9 \]
\[ \text{weak} \]
\[ |\xi| \cos \theta_\xi = -1 \]
\[ \text{weak} \]

\[ \mu_\nu = 3 \cdot 10^{-12} \mu_B \]

Recoil electron kinetic energy T, keV
Figure 4. Recoil electron kinetic energy $T$ (eV)

Figure 5. Recoil electron kinetic energy $T$ (eV)
Figure 6.

Figure 7.