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Effects of the mass and magnetic moment of the neutrinos in $\nu e \rightarrow \nu e \gamma$[⋆]

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ABSTRACT

We study the inelastic νe scattering and consider possible deviations from the Standard Model. We perform a numerical analysis of the cross section as a function of the angle and energy of the bremsstrahlung photon and show that the degree of circular polarization of the photon can be used to obtain new limits on the masses and/or magnetic moments of the neutrinos.

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About 60 years after the Pauli hypotesis, the neutrino remains a mysterious particle. Moreover the search for the neutrino mass and magnetic moment is of great significance for the choice of the gauge theory of particle interactions and to understand phenomena like stellar evolution, supernovae explosions and the solar neutrino problem. The importance of the reaction $\nu e \rightarrow \nu e\gamma$ for the study of neutrino properties such as mass and electromagnetic interactions was pointed out several years ago [1-6]. In [1] the cross section of that reaction was calculated including electromagnetic form-factors of the neutrino. However, it is very difficult to detect deviations when the cross section is itself very small.

It has been shown [2-6] that the study of polarization effects could provide new restrictions on the parameters of the theoretical models describing neutrino-electron interactions. In [6] it was suggested that the degree of circular polarization of the photon in the radiative νe scattering should depend on the contribution to this process coming from the direct interaction of the neutrino with the electromagnetic field. Our aim is to find what deviations from the Glashow-Weinberg-Salam model (GWS) in the cross section for radiative νe scattering would arise from non-standard mass and magnetic moment of the neutrino.

The limits on the electron-neutrino mass from different experiments are

$$\begin{array}{rlrl} 17 < & \mathrm{m}_{\nu_e} < 40eV\,, & \mathrm{m}_{\nu_e} \simeq 30eV\ [7]\,, \\ & \mathrm{m}_{\nu_e} < 27eV\ [8]\,, & \mathrm{m}_{\nu_e} < 18eV\ [9]\,. \end{array}$$

For the muon- and tau-neutrinos,

$$\mathrm{m}_{\nu_\mu} < 0.25MeV\ [10]\,,\ \ \mathrm{m}_{\nu_\tau} < 35MeV\ [11]\,.$$

The limits obtained from laboratory experiments on the magnetic moments of ν_e and ν_μ are

$$\mu_{\nu_e} < 1.4 \,\mathrm{x}\, 10^{-9}\mu_{\mathrm{B}}\ [12]\,,\ \ \mu_{\nu_\mu} < 0.95 \,\mathrm{x}\, 10^{-9}\mu_{\mathrm{B}}\ [13]\,,$$

where $\mu_{\rm B} = e/2m_e$ is the Bohr magneton. From cosmological considerations, the upper bound, $\mu_\nu < (1\text{-}2) \times 10^{-11} \mu_{\rm B}$, was derived [14] for the magnetic moment of the three neutrino species.

Let us consider the inelastic neutrino-electron scattering

$$\nu_l e \xrightarrow{Z,\gamma} \nu_l e \gamma \tag{1}$$

where $l = e, \mu, \tau, \ldots$ The Feynman diagrams of the t channels are shown in fig. 1. The first two diagrams, 1.a-b), correspond to the neutral weak interaction through the Z-boson exchange and the diagrams 1.c-d) to the exchange of a virtual photon coupling to a neutrino with non-zero magnetic moment.

In the local approximation, $-(q-q')^2 \ll M_{\rm Z}^2$, the matrix element of the Z channel is

$$M_{\rm Z} = M_{\rm Z}^a + M_{\rm Z}^b\,, \tag{2}$$

where

$$M_{\rm Z}^a = -C_{\rm Z}\, \overline{u'_\nu} \gamma^\alpha (1-\gamma_5)\, u_\nu\, \overline{u'_e} \gamma_\alpha (g_{\rm V} - g_{\rm A}\gamma_5)\, \frac{2\varepsilon^* \cdot p - \not{k}\not{\varepsilon}^*}{2p\cdot k} u_e\,, \tag{3}$$

$$M_{\rm Z}^b = C_{\rm Z}\, \overline{u'_\nu} \gamma^\alpha (1-\gamma_5)\, u_\nu\, \overline{u'_e}\, \frac{2\varepsilon^* \cdot p' - \not{k}\not{\varepsilon}^*}{2p'\cdot k} \gamma_\alpha (g_{\rm V} - g_{\rm A}\gamma_5)\, u_e\,, \tag{4}$$

correspond to the diagrams 1.a) and 1.b) respectively. For the scattering via virtual photon exchange the matrix element is given by

$$M_\gamma = M_\gamma^c + M_\gamma^d\,, \tag{5}$$

$$M_\gamma^c = C_\gamma\, \overline{u'_\nu}\, \frac{\sigma^{\alpha\beta}(q-q')_\beta}{(q-q')^2} u_\nu\, \overline{u'_e} \gamma_\alpha \frac{2\varepsilon^* \cdot p - \not{k}\not{\varepsilon}^*}{2p\cdot k} u_e\,, \tag{6}$$

$$M_\gamma^d = -C_\gamma\, \overline{u'_\nu}\, \frac{\sigma^{\alpha\beta}(q-q')_\beta}{(q-q')^2} u_\nu\, \overline{u'_e}\, \frac{2\varepsilon^* \cdot p' - \not{k}\not{\varepsilon}^*}{2p'\cdot k} \gamma_\alpha u_e\,. \tag{7}$$

Here $C_{\rm Z} = G_F e/\sqrt{2}$, $C_\gamma = 4\pi\alpha\mu_\nu$, G_F is the Fermi coupling constant, μ_ν is the neutrino magnetic moment, $g_{\rm V} = -1/2 + 2\sin^2\theta_W$ and $g_{\rm A} = -1/2$

as in the GWS model; u_e and u_ν (u'_e and u'_ν) are the Dirac spinors of the incoming (outgoing) electron and neutrino with 4-momenta p and q (p' and q') respectively; k and ε are the 4-momentum and polarization vectors of the bremsstrahlung photon. We follow the metric convention and notations of Bjorken and Drell [15]. In the case of $\nu_e e$ scattering we should also consider the charged weak current. However, by applying Fierz transformations to the matrix element one obtains that the contribution from the W exchange is equivalent to a change in the above coupling constants $g_{\rm V}$ and $g_{\rm A}$. From the eqs. (6-7) we see that the contribution of the magnetic moment interaction becomes more important at low neutrino energies. This point is also discussed in the refs. [5], [16], [17].

In our calculations we neglect the contribution to the differential cross section from $|M_\gamma|^2$ which is proportional to μ_ν^2. The evaluation of $|M|^2$ averaged over initial and summed over final electron and neutrino polarizations, and the exact analytic integration of the cross section over the neutrino and electron phase space were carried out with finite electron and neutrino masses. Using a Reduce program we obtained the differential cross section as a linear combination of the integrals

$$I(n,m) = \int \frac{d\vec{p'}}{E_{p'}}\frac{d\vec{q'}}{E_{q'}}\delta(p'+q'-\Delta)B^{-n}L^{-m}\,,$$

$$I(n,m,X_1,\cdots,X_j) = \int \frac{d\vec{p'}}{E_{p'}}\frac{d\vec{q'}}{E_{q'}}\delta(p'+q'-\Delta)\frac{p'{\cdot}X_1\cdots p'{\cdot}X_j}{B^n L^m}\,,$$

where: $B = -(q-q')^2$, $L = 2p'{\cdot}k$ and $n,m = 0,1,2$; $\Delta = p+q-k$; $E_{p'}$ ($E_{q'}$) is the energy of the outgoing electron (neutrino) and $X_1,\cdots,X_j$ are any of the particle 4-momenta. We did the analytic calculation using the method of covariant integration [18] and the results presented in refs. [19] for the integration over the phase space of two identical final particles - more details on our calculations are in ref. [20]. The differential cross section of the reaction (1) in the rest frame of the electron, summed over the photon helicity, can be written as

$$\frac{d\sigma^0}{dE_\gamma\, d\cos\theta_\gamma} = \frac{d\sigma^0_{\rm Z}}{dE_\gamma\, d\cos\theta_\gamma}(1 + R_{\gamma {\rm Z}})\,, \tag{8}$$

where $d\sigma^0_{\rm Z}$ is the non-polarized weak contribution, E_γ is the photon energy, $\cos\theta_\gamma = \vec{k}\cdot\vec{q}/|\vec{k}||\vec{q}|$ and $R_{\gamma {\rm z}}$ denotes the relative contribution of the interference between the diagrams 1.a-b) and 1.c-d).

Since $R_{\gamma {\rm Z}}$ is proportional to the neutrino mass and neutrino magnetic moment we define R as

$$R_{\gamma {\rm Z}} = \frac{m_\nu}{1MeV}\,\frac{\mu_\nu}{\mu_{\rm B}}\,R\,. \tag{9}$$

The numerical analysis shows that for $E_\nu \geq 10MeV$, $|R| \sim 10^9$. Hence, in the case of the electron-neutrino the present experimental limits exclude a non-negligible contribution of the interference term, so we will specialize our numerical results for ν_μ and ν_τ. In view of the small cross sections it is likeky that it will be very difficult to get new results from unpolarized scattering. However, theoretical models which give similar results for observable quantities, when averaged over the particle spins, can give different results for polarization effects because they involve interaction terms independent of each other with different spin structures. As mentioned above, the dependence of the degree of circular polarization on the coupling constants for various theoretical models was discussed in refs. [2-6]. We want to see whether the circular polarization of the photon can also be used to obtain new limits on the masses and/or magnetic moments of the neutrinos. Let us define

$$P_\gamma(E_\gamma, \cos\theta_\gamma) = \frac{d\sigma(s_\gamma = -1) - d\sigma(s_\gamma = +1)}{d\sigma(s_\gamma = -1) + d\sigma(s_\gamma = +1)}\,, \tag{10}$$

where s_γ is the photon helicity ($s_\gamma = -1$ for left-handed and $s_\gamma = +1$ for right-handed photons).

In fig. 2 we plot P_γ for $E_\nu = 50MeV$, $E_\gamma = 0.1MeV$ and various values of m_ν and μ_ν . In fig. 3 we do the same for $E_\gamma = 0.5MeV$ and $E_\gamma = 2MeV$

with $E_\nu = 50 MeV$. It is possible to compare the behaviour of P_γ in the case of the GWS model and for non-standard m_ν and μ_ν. The differential cross section for $m_\nu = 0$ and $\mu_\nu = 0$ is plotted in the fig. 4 as a function of $\cos\theta_\gamma$ for the above values of the neutrino and photon energies. Clearly, the contribution to the photon polarization due to the neutrino mass and magnetic moment is more significant for small photon energies (compared to the energy of the incident neutrino) and large angles of the photon. As far as the cross section is concerned, the fig. 4 shows that it is larger for small energies and angles of the photon.

We conclude that the study of the photon polarization in the process $\nu e \rightarrow \nu e \gamma$ can be used to obtain new limits on the masses and magnetic moments of the muon- and tau-neutrinos. The development of detection methods offers hope of being able to perform experiments in the near future to study the radiative scattering of neutrinos by electrons. In particular, at LAMPF it will be possible to study the $\nu_\mu e$ scattering with neutrino-beam energies bellow $50 MeV$ [21]. As mentioned before, the non-standard effects are enhanced for low neutrino energies - at $E_\nu \leq 10 MeV$ the contribution of the magnetic moment coupling to the cross section might be of the order or larger than the standard model one. It is worth to recall that for these energies the background of the νe radiative scattering is comparatively smaller than for the elastic scattering [5].

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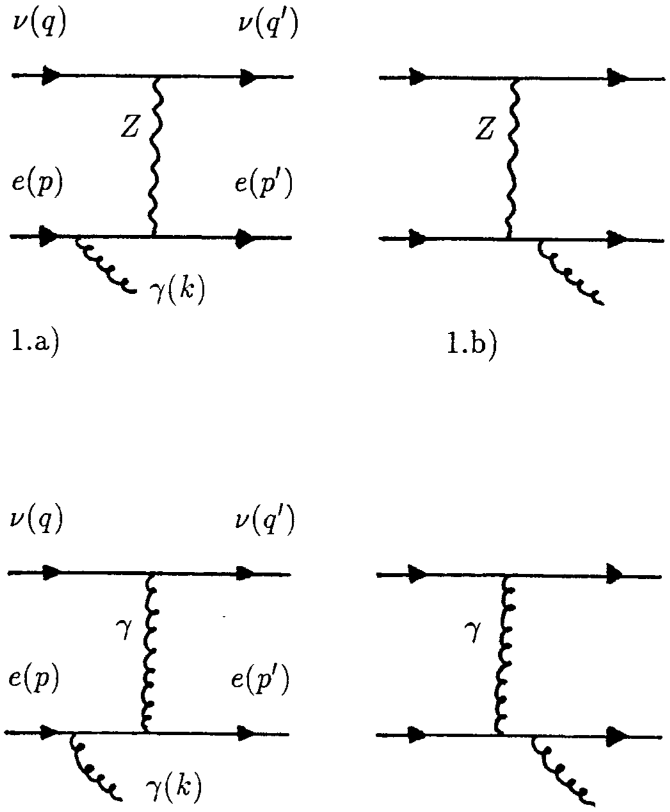
FIGURE CAPTIONS

Fig. 1: Feynman diagrams for the radiative νe scattering.

Fig. 2: P_γ as a function of $cos\theta_\gamma$ in the case of $E_\nu = 50MeV$, $E_\gamma = 0.1MeV$ for: $m_\nu = 0$ and $\mu_\nu = 0$ (dotted curve), $m_\nu = 10MeV$ and $\mu_\nu = 0$ (dashed curve), $m_\nu = 0.25MeV$ and $\mu_\nu = 2\text{x}10^{-11}\mu_B$ (solid curve), $m_\nu = 0.25MeV$ and $\mu_\nu = 10^{-10}\mu_B$ (dash-dotted curve).

Fig. 3: P_γ as a function of $cos\theta_\gamma$ in the case of $E_\nu = 50MeV$, $E_\gamma = 0.5MeV$ and $E_\gamma = 2MeV$. The solid curves correspond to $m_\nu = 0.25MeV$, $\mu_\nu = 2\text{x}10^{-11}\mu_B$, and the dash-dotted curves to $m_\nu = 0$, $\mu_\nu = 0$.

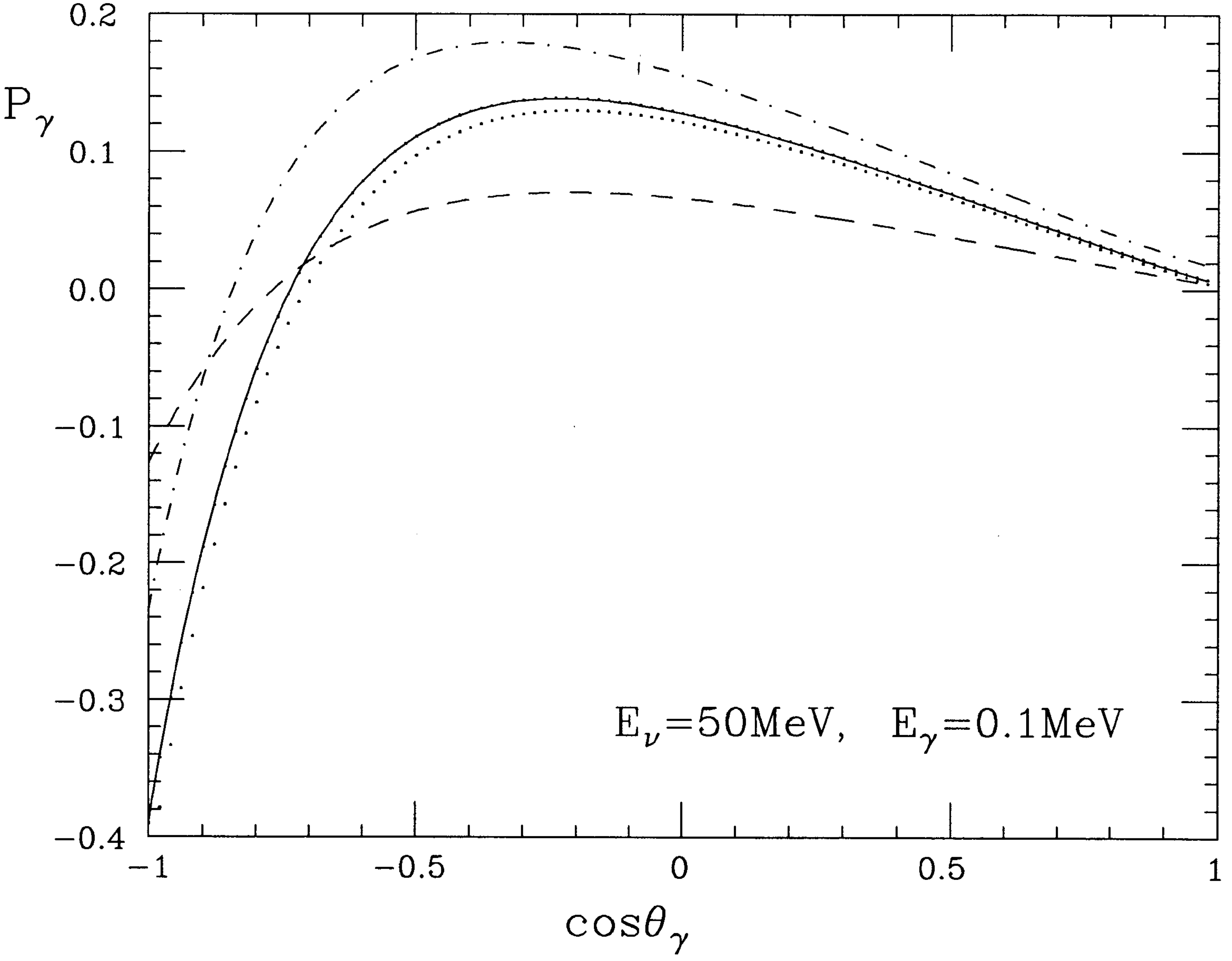
Fig. 4: Differential cross section as a function of $cos\theta_\gamma$ for $E_\gamma = 0.1MeV$ (solid curve), $E_\gamma = 0.5MeV$ (dash-dotted curve) and $E_\gamma = 2MeV$ (dashed curve).



1.a) 1.b)

1.c) 1.d)

Fig. 1



P_γ
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−1
−0.5
0
0.5
1
$\cos\theta_\gamma$
E_ν=50MeV, E_γ=0.1MeV

Fig. 2

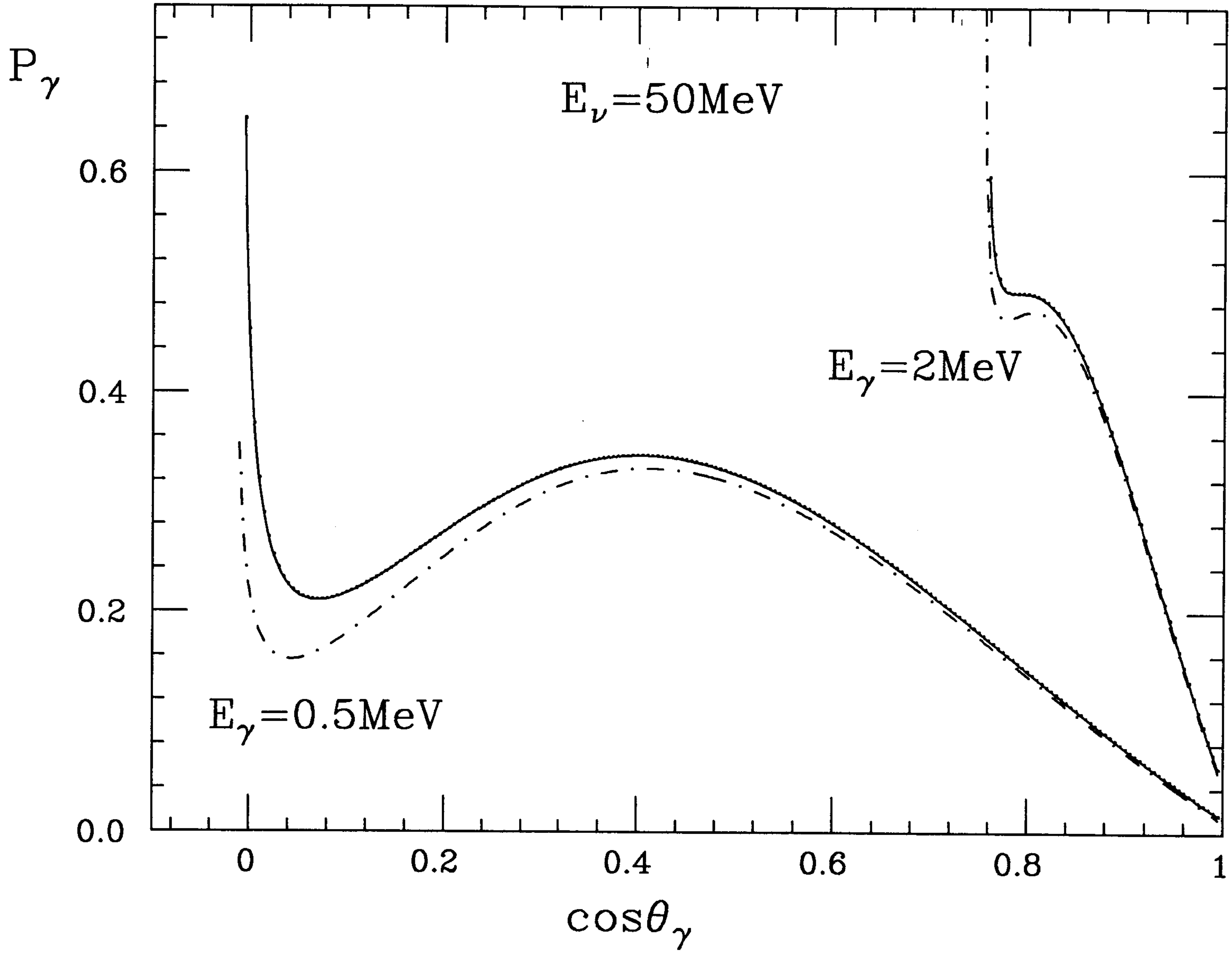

P_γ
E_ν=50MeV
E_γ=2MeV
E_γ=0.5MeV
0.0
0.2
0.4
0.6
0
0.2
0.4
0.6
0.8
1
$\cos\theta_\gamma$

Fig. 3

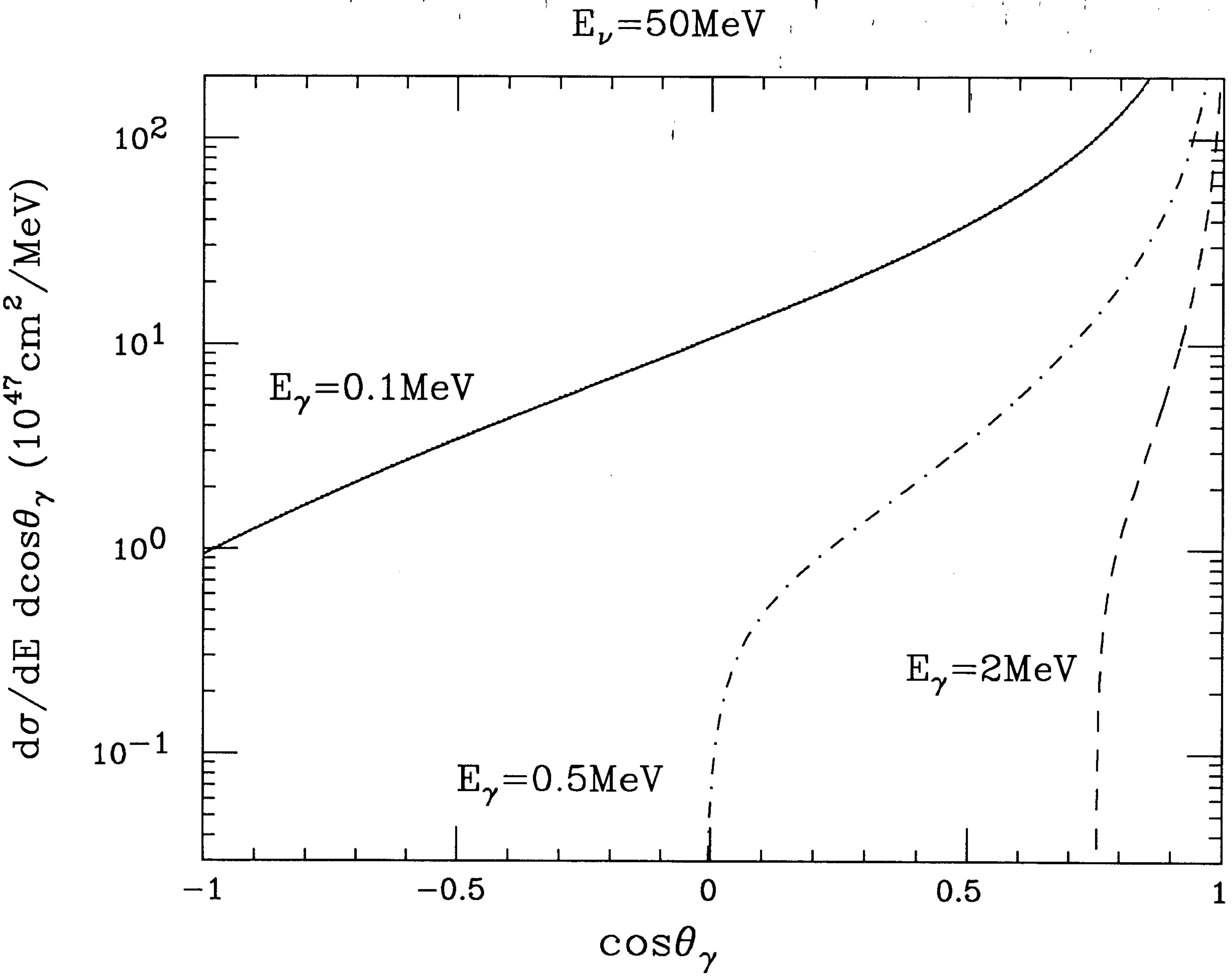

E_ν=50MeV
$d\sigma/dE\ d\cos\theta_\gamma$ (10^{47}cm^2/MeV)
10^2
10^1
10^0
10^{-1}
E_γ=0.1MeV
E_γ=0.5MeV
E_γ=2MeV
−1
−0.5
0
0.5
1
$\cos\theta_\gamma$

Fig. 4