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Electromagnetic Effects in Deep Inelastic Neutrino-Proton Scattering

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1 Introduction

Deep inelastic scattering on nucleons is the main process of interaction of high-energy neutrinos with matter. The corresponding cross sections are measured, for example, in the IceCube experiment on the basis of the dependence of the neutrino flux registered in the range 60 TeV - 10 PeV on the direction of its arrival in the detector [1]. This provides a unique opportunity to study the effects of physics beyond the Standard Model at high and ultrahigh neutrino energies. In particular, the search for the electromagnetic properties of neutrinos is of interest [2]. We have taken into account the contribution of neutrino charge and magnetic form factors in the theoretical formalism of the process of deep inelastic neutrino scattering on the proton. We obtained expressions for the differential and total cross sections, which can be used to analyze and interpret the experimental data on deep inelastic neutrino scattering on nucleons in order to find the electromagnetic properties of neutrinos.

2 Neutrino electromagnetic properties

The electromagnetic interactions of neutrinos are one of the unsolved fundamental problems in neutrino physics. They are actively studied theoretically and searched in various experiments. The neutrino electromagnetic properties are directly related to the basics of elementary particle physics. For example, they can be used to distinguish between Dirac and Majorana neutrinos. Since the neutrino electromagnetic properties are absent in the Standard Model with massless neutrinos, their discovery will open a window to new physics [2].

2.1 Neutrino electromagnetic form factors

The electromagnetic properties of neutrinos are contained in the vertex function (see fig. 1), which is a matrix in spinor space. It can be decomposed in terms of linearly independent products of Dirac matrices and 4-vectors l and l'.

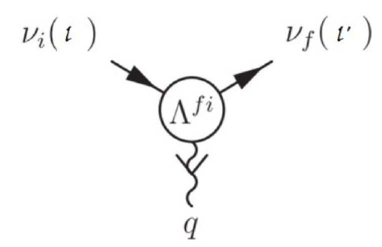

Figure 1: The effective vertex of the neutrino electromagnetic interaction

The electromagnetic vertex can be written as follows:

$$\Lambda_\mu(q) = \mathrm{f}_Q\left(q^2\right)\gamma_\mu - \mathrm{f}_M\left(q^2\right) i\sigma_{\mu\nu}q^\nu + \mathrm{f}_E\left(q^2\right)\sigma_{\mu\nu}q^\nu\gamma_5 + +\mathrm{f}_A\left(q^2\right)\left(q^2\gamma_\mu - q_\mu \not{q}\right)\gamma_5. \tag{1}$$

For brevity, we refer to the combination

$$\mathrm{f}_Q - q^2\mathrm{f}_A$$

as the *charge form factor*, desnoting it by f_Q, and to the combination

$$\mathrm{f}_M - i\mathrm{f}_E$$

as the *magnetic form factor*, denoting it by f_M.

2.2 Experimental constraints

The research into the influence of electromagnetic fields on neutrinos and their electromagnetic properties has been conducted since the early 1960s. Since then, many dedicated experimental and theoretical studies have been carried out. Below we briefly outline the strongest constraints on the neutrino electromagnetic properties obtained in those studies.

2.2.1 Neutrino millicharge

The strongest limit on the neutrino electric charge (millicharge) obtained in experiments on neutrino scattering on a target is [3]

$$e_\nu \leq 1.5 \cdot 10^{-12} e_0.$$

It follows from the analysis of the data of the GEMMA experiment [4] on the scattering of reactor neutrinos on electrons.

The strongest limit on the neutrino millicharge obtained from astrophysical data is

$$e_\nu \leq 1.3 \cdot 10^{-19} e_0.$$

It is based on the study of the motion of neutrinos having a nonzero electric charge in magnetized neutron stars [5].

2.2.2 Neutrino magnetic moment

One of the strongest of the available laboratory limits on the neutrino magnetic moment was also obtained in the GEMMA experiment [4]:

$$\mu_\nu \leq 2.9 \cdot 10^{-11} \mu_B,$$

where μ_B is the Bohr magneton.

Astrophysical constraints on the neutrino magnetic moment were obtained in [6–8], based on observations of luminosity of globular star clusters:

$$\left(\sum_{i,j} |\mu_{ij}|^2\right)^{1/2} \leq (2.2 - 2.6) \cdot 10^{-12} \mu_B.$$

3 General formalism

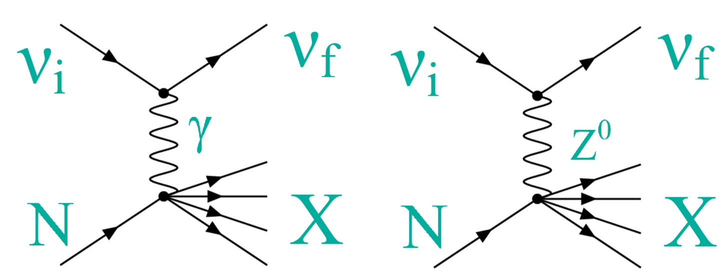

Figure 2: Deep inelastic neutrino scattering on a nucleon

The differential cross section for deep inelastic lepton-nucleon scattering in a laboratory frame is given by (see, for instance, [9])

$$\frac{d^2\sigma^{\ell N}}{dE'd\Omega} = \frac{\alpha^2}{m_N q^4}\frac{E'}{E}\sum_{j=\gamma,\gamma Z,Z} \eta_j L_j^{\mu\nu} W_{\mu\nu}^j, \tag{2}$$

where q is the momentum transfer, E and E' are the initial and final lepton energies, and $L_j^{\nu\mu}$ and $W_{\nu\mu}^j$ are the leptonic and hadronic tensors.

The total cross section derives from the expression

$$\sigma^{\ell N} = \int_{Q_0^2}^{s} dQ^2 \int_{Q^2/s}^{1} dx\, \frac{d^2\sigma^{\ell N}}{dxdQ^2}, \tag{3}$$

with $Q_0 = 1$ GeV [10].

3.1 Notations

$$\eta_\gamma = 1, \qquad \eta_{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2 + M_Z^2}\right), \qquad \eta_Z = \eta_{\gamma Z}^2,$$

$$Q^2 = -q^2 \approx 4EE'\sin^2\frac{\theta}{2}, \qquad s = (\ell + P)^2 \approx m_N^2 + 2m_N E, \qquad x = \frac{Q^2}{2\nu m_N},$$

$$\nu = \frac{(q\cdot P)}{m_N} = E - E', \qquad y = \frac{(q\cdot P)}{(\ell\cdot P)} = \frac{\nu}{E}.$$

4 Cross section

For the differential cross section of the $\nu_i p$-scattering, which accounts for electromagnetic (γ) and weak neutral-current (Z^0) interactions depicted in fig. 2, we get

$$\begin{aligned}\frac{d^2\sigma^{\nu_i p}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\Bigg\{\sum_f \left|\mathrm{f}_Q^{fi}(Q^2)\right|^2 &\left[xy^2F_1^\gamma(x,Q^2) + \left(1 - y - \frac{x^2y^2m_p^2}{Q^2}\right)F_2^\gamma(x,Q^2)\right]\\ -\eta_{\gamma Z}\mathrm{Re}\left\{\mathrm{f}_Q^{ii}(Q^2)\right\}&\left[xy^2F_1^{\gamma Z}(x,Q^2) + \left(1 - y - \frac{x^2y^2m_p^2}{Q^2}\right)F_2^{\gamma Z}(x,Q^2)\right.\\ &\left.\pm\left(y - \frac{y^2}{2}\right)xF_3^{\gamma Z}(x,Q^2)\right]\\ +\eta_Z&\left[xy^2F_1^Z(x,Q^2) + \left(1 - y - \frac{x^2y^2m_p^2}{Q^2}\right)F_2^Z(x,Q^2)\right.\\ &\left.\pm\left(y - \frac{y^2}{2}\right)xF_3^Z(x,Q^2)\right]\\ +\frac{Q^2}{4xm_e^2}\sum_f\left|\mathrm{f}_M^{fi}(Q^2)\right|^2&\left[-xy^2F_1^\gamma(x,Q^2) + \frac{1}{2}(2-y)^2F_2^\gamma(x,Q^2)\right]\Bigg\},\end{aligned} \tag{4}$$

where "+" ("−") refers to neutrinos (antineutrinos). $\mathrm{f}_{Q,M}^{fi}$ are the neutrino charge and magnetic form factors of diagonal ($i = f$) and transition ($i \neq f$) types given in units of elementary charge e_0 and Bohr magneton μ_B, respectively. $F_{1,2,3}^{\gamma,Z,\gamma Z}$ are dimensionless structure functions of the proton. In the quark-parton model, one can use the Callan-Gross relation $F_2 = 2xF_1$. The total cross section is calculated on the basis of Eqs. (3) and (4).

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