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Exclusive production of pseudoscalar mesons in neutrino–photon interactions

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ABSTRACT

Exclusive production of the π mesons in neutrino–photon interactions at low momentum transfer is studied within the standard model. The corresponding cross sections are calculated analytically. Potential astrophysical implications and the significance for testing the standard model are discussed. The presented formalism applies to other pseudoscalar mesons as well.

1. Introduction

Neutrino–photon interactions can play an important role in astrophysical and cosmological phenomena such as stellar evolution, production of high energy cosmic rays, detecting the relic neutrino background. In the past few decades this type of interactions has attracted some interest and a definite progress has been reached in this field [1–21].

For example, it has been realized that the inelastic process $\nu\gamma \to \nu\gamma\gamma$ significantly dominates over elastic scattering $\nu\gamma \to \nu\gamma$ [3,8,9,11]. In its turn, when the energy threshold of the electron–positron pair production is crossed, the reaction $\nu\gamma \to \nu e^+e^-$ becomes the dominant one [14].

Neutrino–photon reactions with relatively low energy thresholds as those mentioned above are of special interest for astrophysics. They are crucial for understanding processes of the energy loss by stars [22], especially the collapsing ones, when they may loose a significant part of their masses by the neutrino emission [23].

In the conservative estimation, temperature in the interiors of a supernova ranges from 10 MeV up to 100 MeV and $\nu\gamma$ reactions are therefore able to produce final states with masses as large as the mass of the π meson. Thus, in addition to the traditionally considered energy loss resulting from production of structureless particles in inelastic $\nu\gamma$ scattering [14], pair, photo-, plasma, bremsstrahlung and recombination neutrino processes [22], one should also take into account the possibility of excitation of states like the π mesons by neutrinos propagating through the star.

Due to above reasons the exclusive production of the π mesons in the reactions

$$\nu_e\gamma \to e^-\pi^+, \tag{1}$$

$$\nu_l\gamma \to \nu_l\pi^0 \tag{2}$$

is studied in the present Letter. In (2) l stands for e, μ and τ.

It should be noted that the reactions (1) and (2) have not only astrophysical implications but also provide crucial tests of the standard model. Actually, (1) is the crossed reaction of the radiative pion decay $\pi^+ \to e^+\nu_e\gamma$ ($\pi_{e2\gamma}$). The latter and other light pseudoscalar decays are extensively discussed in the literature as possible tests of the $V-A$ structure of the weak interaction (see, for example, [24] and the references therein). Processes closely related to (2) are also candidate solutions of the problem of the excess of electron-like events observed by the MiniBooNE Collaboration in a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations which arouses a hot discussion today [25,26].

2. Pion production and its crossed reactions

2.1. Exclusive production of a charged pion in $\nu_e\gamma$ interactions

Let us consider the reaction (1) at low momentum transfer satisfying the condition $q^2 \ll M_W^2$ so that one may use the Fermi approximation. The corresponding Feynman diagrams in the leading order are presented in Fig. 1.

One can show that the contributions of the diagrams (a) and (b) are helicity suppressed being proportional to the electron mass

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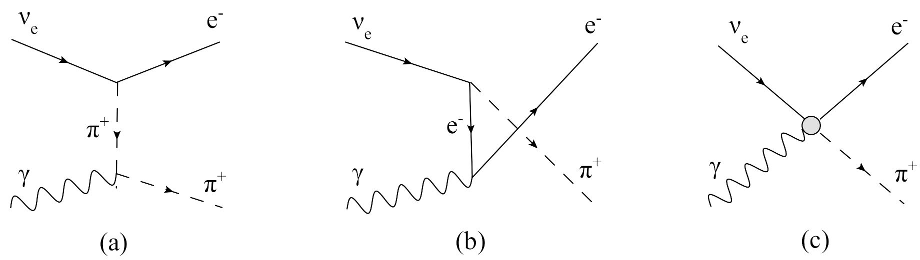

Fig. 1. Feynman diagrams contributing to the reaction $\nu_e\gamma \to e^-\pi^+$. The diagrams (a) and (b) are helicity suppressed, (c) depends on the structure of the π meson.

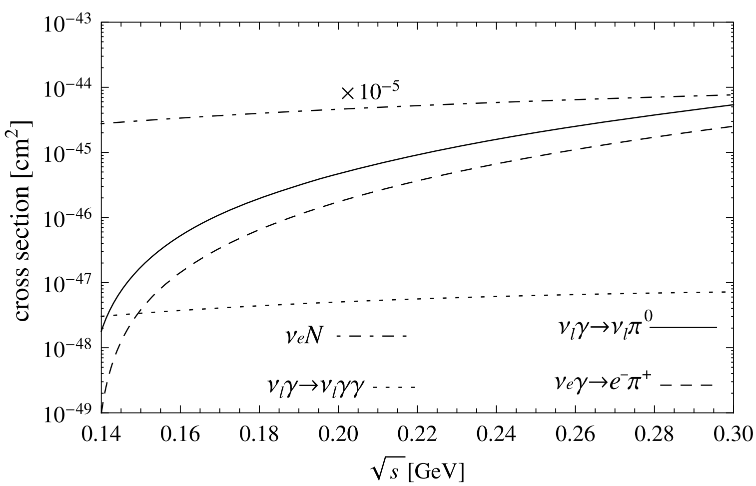

Fig. 2. Dependence of the total cross sections of the reactions $\nu_l\gamma \to \nu_l\pi^0$ and $\nu_e\gamma \to e^-\pi^+$ on the center-of-mass energy $\sqrt{s}$. The cross sections of the reaction $\nu_l\gamma \to \nu_l\gamma\gamma$ [11] and quasielastic neutrino–nucleon scattering ($\nu_e N$) [29] (multiplied by 10^{-5}) are shown for comparison.

m_e exactly as in the case of the π_{e2} decay [24]. For this reason we will neglect them in the subsequent calculations keeping only the diagram (c) which is free of the suppression and depends on the vector and axial-vector weak hadronic currents characterizing the structure of the pion [24,27]. Then, noting that (1) is a crossed reaction of the decay $\pi_{e2\gamma}$ one can find the amplitude just by crossing the corresponding result of [24]:

$$M = -i\frac{G_F}{\sqrt{2}}V_{ud}\varepsilon_\mu \bar{u}(p_e)\gamma_\alpha(1-\gamma_5)u(p_\nu) \times \left[e\frac{F_A}{m_\pi}\left(-g^{\mu\alpha}p_\pi\cdot q + p_\pi^\mu q^\alpha\right) + ie\frac{F_V}{m_\pi}\epsilon^{\mu\alpha\beta\lambda}q_\beta p_{\pi\lambda}\right], \quad (3)$$

where V_{ud} is the Cabibbo–Kobayashi–Maskawa (CKM) matrix element, ε_μ is the photon polarization vector, p_π, p_e, p_ν, and q are the four momenta of π^+, e^-, ν_e and γ, respectively, F_A and F_V are the axial-vector and vector form factors.

Squaring (3), averaging over the two spin states of the initial photon, summing over the final state spins gives

$$|M|^2 = -\frac{e^2G_F^2}{2m_\pi^2}|V_{ud}|^2\, t\left(u^2|F_V+F_A|^2 + s^2|F_V-F_A|^2\right), \quad (4)$$

where the conventional Mandelstam variables are used: $s = (p_\nu+q)^2$, $t = (p_\nu-p_e)^2$, $u = (p_\nu-p_\pi)^2$.

Knowing (4) one obtains the differential cross section

$$\frac{d\sigma}{dt} = -\frac{\alpha G_F^2}{8m_\pi^2}|V_{ud}|^2\, t\left(\frac{u^2}{s^2}|F_V+F_A|^2 + |F_V-F_A|^2\right), \quad (5)$$

where α is the fine structure constant.

Integration of (5) over the physically possible values of t ($m_\pi^2 - s \leqslant t \leqslant 0$) yields the total cross section of the reaction (1):

$$\sigma = \frac{\alpha G_F^2}{96m_\pi^2}|V_{ud}|^2 s^2\left(1-\frac{m_\pi^2}{s}\right)^2 \times \left(\left(1-\frac{m_\pi^2}{s}\right)^2|F_V+F_A|^2 + 6|F_V-F_A|^2\right). \quad (6)$$

Note that though the formfactors depend, in general, on t, in the present analysis they are taken to be constants since we deal with reactions proceeding at conditions comparable to the case of the decay $\pi_{e2\gamma}$ ($t \sim m_\pi^2$) [24]. Thus, throughout this Letter we set $F_V = 0.0272$ and $F_A = 0.0112$ [24].

The dependence of the total cross section on the center-of-mass energy $\sqrt{s}$ is plotted in Fig. 2. One can see that its values are comparable to those of the process $\nu_l\gamma \to \nu_l\gamma\gamma$ [11] at $\sqrt{s} \approx m_\pi$ exceeding the latter by about two orders of magnitude at higher energies.

Conclusions regarding the significance of the reaction (1) for particle physics are the following. Information on the formfactors F_V and F_A is important for testing the standard model, their theoretical values depend on a model and vary in a relatively wide region [24]. The reaction (1) allows to experimentally measure the formfactors in a wider range of the values of t than it is possible in the decay $\pi_{e2\gamma}$. For example, (1) can be studied in scattering of neutrinos from nuclei exploiting the equivalent photon flux of the latter. In this connection another interesting problem concerning the universality of the equivalent photon approximation as a particular case of the parton model arises [20].