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THE REACTION $e^+e^- \to \gamma\pi^0 \to \gamma\nu\bar{\nu}$ AS A PROBE OF NEUTRINO MASS

R.V.Konoplich+*[1] *and R.Mignani**[2]

**Dipartimento di Fisica "E.Amaldi" Università di Roma*
I - 00146 Rome, Italy
and
INFN Sezione di Roma 1 c/o Dipartimento di Fisica Università degli Studi "La Sapienza"
00185 Rome, Italy

+ *Center for Cosmoparticle Physics "Cosmion"*
125047 Moscow, Russia
and
Moscow Engineering Physics Institute
115409 Moscow, Russia

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The reaction $e^+e^- \to \gamma\pi^0 \to \gamma\nu\bar{\nu}$ is considered. It is shown that this reaction possesses a clear signature, producing in the resonance region practically monocromatic photons, which can be easily distinguished from background bremsstrahlung photons. Since the cross section of the reaction is proportional to the square of the neutrino mass, such a reaction can be used as a probe for neutrino mass.

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The question of neutrino mass is one of the most important problems facing both particle physics and cosmology. In the case of particle physics, neutrino mass provides a clue to understanding the origin of the mass of all particles. In the so-called grand unified theories, based on the standard electroweak theory, nonzero neutrino masses are expected on general backgrounds since in these theories strong, electromagnetic and weak interactions are unified at a large energy scale

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[1] e-mail: konoplic@etp.mepi.msk.su

[2] e-mail: mignani@romal.infn.it

and neutrinos acquire masses which are inversely proportional to this scale. There are a lot of intriguing hypotheses on the role of massive neutrinos in cosmology and astrophysics. The big bang theory predicts the existence in the Universe of a relic neutrino background similar to a cosmic microwave background radiation. If neutrinos have masses in the range of several to several dozen electron volts, then they could give a significant contribution to dark matter in the Universe. In the case of much smaller masses, neutrino oscillations could deplete the flux of solar electron neutrinos by converting some of them into other neutrino species, thus permitting to solve the solar neutrino puzzle.

However, until now there is no experimental evidence from direct searches for nonzero neutrino mass. They set only upper limits on respective neutrino masses. The analysis of the endpoint in nuclear β-decay gives the formal upper limit [1]

$$m(\nu_e) < 5.1 \text{ eV}. \tag{1}$$

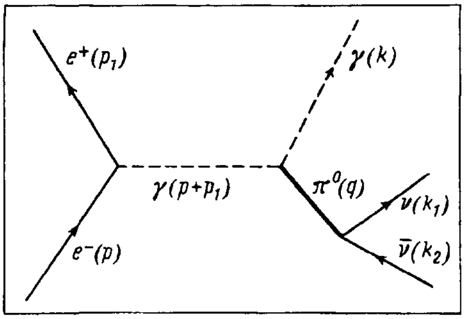
Particle physics limits for the masses of muon neutrino and tau neutrino come respectively from the measurement of the muon momentum in the $\pi \to \mu\nu_\mu$ decay and from the kinematical analysis of tau-lepton decay modes:

$$m(\nu_\mu) < 0.27 \text{ MeV [1]}, \qquad m(\nu_\tau) < 24 \text{ MeV [2]}. \tag{2}$$

In this article we consider the possibility to improve the upper limit on the neutrino mass from an experimental investigation of the process

$$e^+e^- \to \gamma\pi^0 \to \gamma\nu\bar{\nu}. \tag{3}$$

In the π^0 decay into neutrino and antineutrino, momentum and angular-momentum conservations imply that the helicities of both final particles must be the same. Because the probability to change the helicity is proportional to the neutrino mass, the π^0 decay will occur only in the case of massive neutrinos (or/and if lepton number is not conserved) with the amplitude proportional to neutrino mass (see for example [3,4]). In the following, we shall consider the standard electroweak model minimally extended to include a nonzero neutrino mass.



The Feynman diagram for the process (3)

Let us calculate the cross section for the reaction (3) assuming a nonvanishing neutrino mass. The Feynman diagram corresponding to the process (3) is shown in Figure. In this case the amplitude of the process is:

$$M = \bar{\nu}_e \; ie\gamma_\alpha u_e \frac{g^{\alpha\sigma}}{(p+p_1)^2} \frac{ie^2}{4\pi f_\pi} \epsilon_{\gamma\delta\sigma\xi} \epsilon^{*\gamma} (p+p_1)^\xi k^\delta \times$$

$$\times \, D_\pi f_\pi \frac{G}{\sqrt{2}} q_\beta \bar{u}_\nu \gamma^\beta (1+\gamma_5) \nu_\nu \quad , \tag{4}$$

where $\epsilon^{*\gamma}$ is the polarization vector of the outgoing photon, G is the Fermi constant, α is the fine structure constant, f_π is the pion decay constant, D_π is the π-meson propagator. All other notations are shown in Figure. Standard straightforward calculations give us the differential cross section

$$\frac{d\sigma}{d\omega \cdot dz} = \frac{G^2\alpha^3 m^2}{16\pi^2 S} \frac{\omega^3 q^2 \sqrt{1-4m^2/q^2}}{[(q^2-m_\pi^2)^2+\Gamma^2 m_\pi^2]} (1+z^2) \ , \tag{5}$$

where ω is the photon energy, $z = \cos\theta, \theta$ is the angle between the electron momentum and the photon momentum, m and m_π are the neutrino and pion mass respectively, $\sqrt{S}$ *is the total energy in the center of mass of the reaction* (3), Γ is the total pion width, $q^2 = S - 2\sqrt{S}\omega$. As is seen from equation (5), the process (3) exhibits a resonant behavior: the cross section (5) increases significantly in the resonance region at $q^2 \approx m_\pi^2$, leading to a production of practically monochromatic photons with energy

$$\omega_0 = \frac{\sqrt{S}}{2}(1 - m_\pi^2/S) \ , \qquad \Delta\omega \approx \Gamma \approx 7.7eV \ . \tag{6}$$

In this case the resonance region gives a dominant contribution to the total cross section. Carrying out the integration over this region and a trivial integration over z ($|z| \le z_0$, where z_0 is the experimental cutoff), we obtain

$$\sigma \approx 2.4 \cdot 10^{-46} z_0 (1 + \frac{z_0^2}{3})(\frac{m}{m_e})^2 (1 - \frac{m_\pi^2}{S})^3 \quad \mathrm{cm}^2 \ , \tag{7}$$

where m_e is the electron mass. We note that in deriving eq.(7) it was assumed that $S > m_\pi^2$ in order to be in the resonance region. Therefore, in the special but reasonable case $\theta_0 = 30^\circ$ and $S = 10 m_\pi^2$, we find the following value of the cross section:

$$\sigma \approx 2 \cdot 10^{-46} (m/m_e)^2 \ \mathrm{cm}^2 \ . \tag{8}$$

Of course for ν_e the cross section (8) is completely negligible, but this is not the case for ν_μ and especially for ν_τ. In the nearest years at accelerators a luminosity of about 10^{34} cm^{-2}·sec^{-1} will be reached. There are also discussions about the construction of accelerators with the luminosity 10^{36} cm^{-2}·sec^{-1}. For such accelerators we could expect about 15 events in a year due to the reaction (3) in the case of the existence of tau neutrino with mass near the present experimental limit [2]. Moreover, although the cross section (7) is very small, the signature of the process (3) is very clear. Photons are produced in reaction (3) practically at the fixed energy (6), and can be therefore easily distinguished from the $1/\omega$ behavior of the background bremsstrahlung spectrum. Let us compare the result (7) with the prediction for the neutrino counting experiment with a bremsstrahlung photon in the final state

$$e^+e^- \to \gamma Z \to \gamma\nu\bar{\nu} \ . \tag{9}$$

The cross section for this process, far from the Z-pole, is given by [5,6]

$$\frac{d\sigma}{d\omega \cdot dz} = \frac{\alpha}{3\pi^2}\frac{[(x^2z^2/4)+(1-x/2)^2]}{x(1-z^2)})(1-x)G^2\sqrt{S}[N(g_V^2+g_A^2)+2(g_V+g_A)+2], \tag{10}$$

where $x = 2\omega/\sqrt{S}$, $g_V = 2\sin^2\theta_W - 1/2$, $g_A = -1/2$, $N = 3$ is the number of light neutrino species. Carrying out the integration in eq.(10) over $|z| < \sqrt{3}/2$ and $\omega_0 - \Gamma < \omega < \omega_0 + \Gamma$, we find that the reaction (3) can be seen over the background reaction (9) in the case of a neutrino mass $m > 10$ KeV. Even if we choose the wide region of photon energies $\Delta\omega/\omega \leq 0.01$, the process (3) dominates over the process (9) for $m > 15$ MeV. Let us note that it follows from eqs.(7), (10) that the cross section (7) of the reaction (3) depends weakly on the total energy, while the cross section (10) grows like $\sqrt{S}$ and therefore the ratio signal/background decreases with increasing total energy. So the investigation of the process (3) could be carried out at accelerators at small energies $\sqrt{S} < 1$ GeV, where the background conditions are more favorable and where also the number of secondary particles in the final state is small.

The background processes like $e^+e^- \to \gamma\gamma$, $\gamma\gamma\gamma$ and $e^+e^- \to \pi^0 \to \gamma\gamma$, in spite of their large cross sections, are not very dangerous because they produce photons with a completely different signature and in some of them there are additional photons which can be detected. The resonance process $e^+e^- \to \pi^0 \to \gamma\nu\bar{\nu}$ produces photons with completely different kinematical characteristics. The resonance process $e^+e^- \to \gamma\pi^0 \to \gamma\gamma\gamma$ seems more important, but in this case we have three detectable photons with fixed energies.

In conclusion, in this article we considered the application of the resonance reaction (3) to the determination of the neutrino mass. This process possesses three important features: 1) the cross section is proportional to the square of the neutrino mass; 2) the cross section has a resonant behavior; 3) the photons in reaction (3) are produced practically monochromatically. Of course there are problems with the luminosity (due to the small value of the cross section) and with the need to have highly monochromatic electron and positron beams, but these are technical problems which possibly could be solved in the future.

We should also note that even the search for the neutrino mass in the region 1 – 50 MeV is useful, first, because it can give an independent confirmation of the upper limit on the neutrino mass (there are indeed some problems with upper bounds from kinematical methods; see e.g. [1]). Second, even setting the upper bound on neutrino mass at 1 MeV is important, because it allows to rule out or confirm some popular models (for example, an unstable tau neutrino with life time 0.1-100 sec and mass in the range 1-10 MeV can play a basic role within the cold dark matter scenario, in order to get agreement between the spectrum of density perturbations and the observed one).

In the past, the search for the decays $\pi^0 \to \nu\bar{\nu}$ [8,9], $\pi^0 \to \gamma\nu\bar{\nu}$ [10] were proposed to probe the neutrino properties. However, the process (3), in comparison with these decays, offers a clear signature and could be experimentally easier to study in spite of its small cross section.

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