Charged current cross section for massive cosmological neutrinos impinging on radioactive nuclei

R. Lazauskas, P. Vogel, C. Volpe

1 Institut de Physique Nucléaire, F-91406 Orsay cedex, France.
2 Kellogg Radiation Laboratory, Caltech, Pasadena, California, 91125, USA.

We discuss the cross section formula both for massless and massive neutrinos on stable and radioactive nuclei. The latter could be of interest for the detection of cosmological neutrinos whose observation is one of the main challenges of modern cosmology. We analyze the signal to background ratio as a function of the ratio $m_{\nu}/\Delta$, i.e. the neutrino mass over the detector resolution and show that an energy resolution $\Delta \lesssim 0.5$ eV would be required for sub-eV neutrino masses, independently of the gravitational neutrino clustering. Finally we mention the non-resonant character of neutrino capture on radioactive nuclei.

PACS numbers: 13.15.+g, 25.30.-c, 95.55.Vj

Keywords:

I. INTRODUCTION

Modern big-bang cosmology firmly predicts the existence of a relic neutrino background, and relates its temperature to the temperature of the background microwave radiation

$$T_{\nu}/T_{\gamma} = (4/11)^{1/3}, \quad (1)$$

see, e.g. the basic texts [1, 2]. Verifying the existence of the relic neutrino sea represents one of the main challenges of modern cosmology.

Clearly, in contrast to the study of the background microwave radiation that has a long history and has reached an unprecendented accuracy (see, e.g. the latest results in [4]), detection of relic neutrinos remains an unfulfilled dream. Various strategies have been proposed so far, based on laboratories searches [5, 6, 7, 8, 9, 10, 11] and astrophysical observations [12, 13, 14, 15, 16], such as absorption dips in the flux of Ultra High Energy neutri-

nus (for a review see e.g. [17]). As far as their detection in laboratory experiments is concerned, one needs to overcome two main obstacles: the low cross section characteristic of weak interactions and the low energy of relic neutrinos. The second obstacle can be overcome if the corresponding detection reactions have vanishing thresholds. Therefore we discuss here the possibility of detecting the relic neutrinos by the charged current reactions using radioactive unstable nuclei as targets.

The paper is organized as follows: In the next section we derive expressions for the charged current neutrino induced reaction cross sections involving nonrelativistic neutrinos. We show that such cross sections, when the corresponding reaction has a vanishing threshold, scale with $c/v_\nu$ so that the number of events converges to a constant for $v_\nu \rightarrow 0$. In the following section we discuss the possibility to use a tritium target to detect the cosmological $\nu_e$. We show that the main challenge is the separation of the produced electrons with energies just above the endpoint of the $\beta$ spectrum from the overwhelming flux of the electrons from the tritium $\beta$ decay that extends just below the 18.6 keV endpoint. We also discuss the possibility of a resonance enhancement of reactions involving cosmological neutrinos. We show that the charged current reactions, included the radiative ones, do not have a resonance character. In the conclusion we summarize our findings and stress the need for an extreme energy resolution if sensitivity to detect sub-eV mass relic neutrinos should be reached.

II. CROSS SECTIONS FOR MASSIVE NEUTRINOS

Let us first recapitulate briefly the cross section for massless neutrinos. We use the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (2)$$

as an example. This can be easily modified for reactions without threshold such as

$$\nu_e + n \rightarrow e^- + p \quad (3)$$

Since we are interested in very low energy neutrinos, we can treat nucleons nonrelativistically, and keep only the lowest order terms in $E_\nu/M$ and $E_e/M$. The standard expression is then (for $h = e = 1$, see e.g. [18])

$$\frac{d\sigma}{dq^2} = \frac{G_F^2 \cos^2 \theta_C}{\pi} \frac{|M|^2}{(s - M_p^2)^2}, \quad (4)$$

where $q^2$ is the momentum transferred squared and $s$ is the square of the center-of-mass (CM) energy.

Starting with the usual current $\times$ current weak interaction

$$[\bar{u}_n (\gamma_\mu f - \gamma_\mu \gamma_5 g) u_p] [\bar{e}_\nu \gamma^\mu (1 - \gamma_5) \nu_e] \quad (5)$$


where \(f, g\) are the vector and axial-vector form factors respectively, we arrive at the squared matrix element (see, e.g. [19])
\[
|M|^2 = (f + g)^2(p_p \cdot p_e)(p_n \cdot p_\nu) + (f - g)^2(p_n \cdot p_\nu) (p_p \cdot p_e) + (g^2 - f^2)M_nM_p(p_p \cdot p_e). 
\]
(Eq. 6)
Evaluating it in the laboratory frame where the proton is at rest, and keeping only the leading terms one gets
\[
|M|^2 = M_nM_pE_\nu E_e[(f^2 + 3g^2) + (f^2 - g^2)v_\nu v_\nu \cos \theta]. 
\]
(Eq. 7)
with \(M_n, M_p\) the neutron and proton masses. Furthermore, using \(s = (p_\nu + p_p)^2 = M_n^2 + 2M_pE_\nu\) in the laboratory frame, and using the Jacobian
\[
\frac{d\sigma}{d\cos \theta} = 2E_\nu p_e, 
\]
we obtain the usual lowest order expression [18]
\[
\left.\frac{d\sigma}{d\cos \theta}\right|_0 = G^2E_\nu p_e[(f^2 + 3g^2) + (f^2 - g^2)v_\nu v_\nu \cos \theta]. 
\]
(Eq. 9)
with \(G = G_F \cos \theta_C/\sqrt{2}\).

Let us now consider the case of massive neutrinos. In Eq. (1) one should then substitute [20]
\[
(s - M_p^2)^2 \rightarrow [s - (M_p + m_\nu)^2][s - (M_p - m_\nu)^2] = 4M_p^2m_\nu^2, 
\]
where the last expression is again in the laboratory frame. The Jacobian in Eq. (8) becomes instead
\[
\frac{d\sigma}{d\cos \theta} = \frac{2}{v_\nu}p_e. 
\]
(Eq. 11)
The cross section is then given by (using \(M_n \sim M_p\) as in the Eq. (5))
\[
\frac{d\sigma}{d\cos \theta} = \frac{G^2}{v_\nu}E_\nu p_e[(f^2 + 3g^2) + (f^2 - g^2)v_\nu v_\nu \cos \theta]. 
\]
(Eq. 12)

Presenting a \(1/v_\nu\) dependence\(^2\). Such a behaviour is in agreement with the general form for the cross section associated to exothermic reactions of nonrelativistic particles [22]. We see that this form is a “natural one” that in most cases of practical importance, when \(v_\nu \rightarrow c\), acquires the standard form Eq. (7).

The interaction cross section of very low energy neutrinos, Eq. (12) was implicitly used long time ago by Weinberg [23]. Very recently this process has attracted particular interest thanks to the work by Cocco et al. [24] where the authors have considered the possibility of detecting cosmological neutrinos through their capture on radioactive beta decaying (and hence with no threshold) nuclei.

In the case of nuclear (stable or unstable) targets, i.e. reactions
\[
\nu_e + A_Z \rightarrow e^- + A^*_Z+1 \quad \text{or} \quad \bar{\nu}_e + A_Z \rightarrow e^+ + A^*_Z-1 
\]
when possible, one would use the usually known \(ft\) value of the inverse radioactive decay to eliminate the fundamental constants and the nuclear matrix element (see e.g. [25])
\[
\sigma = \sigma_0 \times \left(\frac{E_\nu p_e F(Z, E_e)}{2I + 1}\right) \frac{2I' + 1}{2I + 1} 
\]
(Eq. 14)
with
\[
\sigma_0 = \frac{G_F^2 \cos^2 \theta_C m_\nu^2 |M_{\text{nucl}}|^2}{\pi} \frac{2.64 \times 10^{-41}}{ft_{1/2}}. 
\]
(Eq. 15)
in units of \(\text{cm}^2\). Here the averaging is done over the incoming flux, \(t_{1/2}\) is in seconds, the statistical function \(f\) and the electron energy \(E_e\) and momentum \(p_e\) are evaluated with \(m_e\) as a unit of energy, and the nuclear matrix element is excluded using the relation \(|M_{\text{nucl}}|^2 \approx 6300/ft_{1/2}\). For the neutrino capture on stable targets (i.e. with a threshold) the electron energy is simply (neglecting recoil) \(E_e = E_\nu - E_{\text{thress}} + m_e\). So, for the \(\bar{\nu}_e\) induced reactions \(E_{\bar{\nu}e} = E_\nu - Q_\beta - m_e\) and for the \(\nu_e\) induced reactions \(E_{\nu e} = E_\nu + Q_{EC} + m_e\). For the capture on a radioactive target \(E_{\nu e} = E_\nu + Q_{EC} + m_e\) and \(E_{\bar{\nu}e} = E_\nu + Q_{EC} + m_e\).

### III. Applications

Let us now consider the possibility to use the neutrino capture by radioactive beta-decaying nuclei to detect cosmological neutrinos. For this aim the relevant quantity is the number of events, i.e. the cross section times the flux. For the latter, the dependence on \(v_\nu\) in Eqs. (12) (14) is canceled out and one obtains the number of events that converges to a constant when \(v_\nu \rightarrow 0\), in agreement with [23] [24]. As an example of the possible application of the above finding let us consider the \(\nu_e\) capture on tritium, as done in [24]. While our conclusions are qualitatively similar to the conclusions reached by Cocco et al. [24], they differ in several significant details.

Tritium decays into \(^3\)He with the half-life of 12.3 years. The decay \(Q_\beta\) value is 18.6 keV, and \(ft_{1/2} = 1143\). From Eq. (14) (15) we deduce the cross section for \(T = 1.9\) K nonrelativistic neutrinos
\[
\sigma = 1.5 \times 10^{-41} \left(\frac{m_\nu}{eV}\right)^2 \text{ cm}^2, \quad \text{or} \quad \frac{\sigma}{\nu_\nu} \approx 7.6 \times 10^{-45} \text{ cm}^2. 
\]
(Eq. 16)

Here, in the first equation we used that \(v_\nu/c \sim 3T/m_\nu\). In making that estimate we neglected the \(v_\nu \sim 10^{-3}c\) virial motion of massive neutrinos in the galactic halo, and the motion of Earth and Solar System with respect to the random motion of the neutrinos.

\(^2\) Note that in Ref. [21], where the cross section for charged current neutrino capture on a free neutron, Eq. (3), was evaluated, these modifications were not made and are not reflected in Fig. 1 of that paper.
In order to evaluate possible count rate, we have to know the number density of the background \( \nu_e \) sea. Its average value, for neutrinos evenly distributed throughout the whole Universe, corresponds to \( T_\nu \sim 1.9 \) K. For neutrinos (or antineutrinos) of one flavor only \( \langle n_\nu \rangle \) is \( \sim 55 \) cm\(^{-3}\). Massive neutrinos will be gravitationally clustered on the scale of \( \sim \) Mpc for neutrinos with \( m_\nu \sim 1 \) eV, that is on the scale of galaxy clusters (probably the clustering scale is even larger). Assuming that in that case the ratio of the dimensionless neutrino and baryon clustering scales \( \Omega_\nu/\Omega_b \sim 0.5 \) remains the same as in the Universe as a whole, we obtain

\[
\frac{n_\nu}{\langle n_\nu \rangle} \sim 9 \times 10^6 n_b \left( \frac{m_\nu}{\text{eV}} \right) \sim 10^{-3} - 10^{-4}. \tag{17}
\]

for \( m_\nu = 1 \) eV and \( n_b = (10^{-3} - 10^{-4}) \) cm\(^{-3}\) for a cluster of galaxies. In the following we do not use the last estimate and treat this ratio as an unknown \( m_\nu \) dependent parameter. A more elaborated study of neutrino clustering is made for example in [26], giving smaller but nonnegligible clustering for \( m_\nu = 1 \) eV.

Note, however, that much larger neutrino clustering was considered in Refs. [27, 28]. The authors of these papers speculate that features in the cosmic-ray spectra, in particular the ‘knee’ at \( \sim 3 \) PeV, are associated with the threshold of the \( p + \nu_e \rightarrow n + e^+ \) reaction on \( \sim 0.5 \) eV mass neutrinos. The physics basis for the required clustering of \( \frac{n_\nu}{\langle n_\nu \rangle} \sim 10^{13} \) is not provided in those papers.

The capture rate per tritium atom is

\[
R = \sigma \times v_\nu \times n_\nu \sim 10^{-32} \times \frac{n_\nu}{\langle n_\nu \rangle} \text{ s}^{-1}. \tag{18}
\]

Let us assume, probably much too optimistically, that one can use a Megacurie source of tritium (1 Mcu = \( 3.7 \times 10^{16} \) decays/s, i.e. \( 2.1 \times 10^{25} \) tritium atoms \( \sim 100 \) g of tritium). The number of events is then

\[
N_{\nu \text{ capt}} \sim 6.5 \times \frac{n_\nu}{\langle n_\nu \rangle} \text{ year}^{-1} \text{Mcu}^{-1}. \tag{19}
\]

Thus, if our assumption about the gravitational clustering is at least nearly correct, the capture rate would be reasonably large. However, the main issue would be whether the primordial background neutrino capture signal would be detectable given the overwhelming rate of the radioactive decay.

Electrons from the ordinary \( \beta \) decay are distributed over the kinetic energy interval \( (0 - (Q_\beta - m_\nu)) \), smeared by the resolution of the detection apparatus. On the other hand, electrons from the background neutrino captures are monoenergetic with the kinetic energy \( Q_\beta + m_\nu \) again smeared by resolution. Thus, the signal to noise ratio will critically depend on the neutrino mass \( m_\nu \) and on the energy resolution \( \Delta \). Note that the fraction of electrons in an energy interval of width \( \Delta \) just below the endpoint is \( \sim \left( \frac{\Delta}{Q_\beta} \right)^3 \).

To appreciate the problem we show in Fig. 1 the tail of the spectrum of tritium \( \beta \) decay folded with a Gaussian resolution function and the signal of the cosmological \( \nu_e \) capture electrons evaluated for \( \frac{n_\nu}{\langle n_\nu \rangle} = 50 \) and clearly separated in this idealized situation from the background.

Remarkably, the ratio of the background neutrino capture rate and the competing \( \beta \) decay with final electron within the resolution interval \( \Delta \) just below the endpoint, does not depend on the corresponding \( Q_\beta \) value (see [24], their Eq.(23)) and, naturally, on the nuclear matrix element. For \( m_\nu < \Delta \) the corresponding ratio is

\[
\frac{\lambda_\nu}{\lambda_\beta} \sim 6\pi^2 \frac{n_\nu}{\Delta^3} \sim 2.5 \times 10^{-11} \times \frac{n_\nu}{\langle n_\nu \rangle} \frac{1}{(\Delta(\text{eV}))^3}. \tag{20}
\]

This appears to be a hopelessly small number.

Before discussing the issues further, let us point out that other sources of background, for example the capture of solar \( pp \) neutrinos, are not dangerous. The total solar \( pp \) neutrino flux is \( \sim 6 \times 10^{10} \nu_e \) cm\(^{-2}\) s\(^{-1}\) distributed over 420 keV [25]. Thus, the flux in the lowest 10 eV is only about \( 10^9 \nu_e \) cm\(^{-2}\) s\(^{-1}\), which is less than 1% of the effective flux of the primordial \( \nu_e \), even for \( m_\nu \geq 1 \) eV.

One should note that the discussed method is interesting only as long as neutrinos are non-relativistic with \( v < c \). For higher energy neutrinos (like thermal solar neutrinos that have an estimated flux of \( 10^8 - 10^9 \text{cm}^{-2}/\text{sec}/\text{MeV} \) and energies \( \sim 1 \) keV [26]) the signal becomes well separated from radioactive ion decay background, however the number of expected events will be very small, since one is obliged to work with very
small amount of active material. The ~keV mass sterile neutrinos, considered in the literature (see, e.g. [30]) are unobservable due to their extremely small mixing with the active neutrinos.

If one could achieve a resolution \( \Delta \) that is less than the neutrino mass \( m_\nu \), the signal to background ratio would increase since the \( \beta \) spectrum ends at \( Q - m_\nu \) while the electrons from neutrino capture have energy \( Q + m_\nu \). The corresponding gain, i.e. the suppression of the tail of the \( \beta \) decay spectrum, is estimated in [24]. For \( m_\nu \geq \Delta \) it is

\[
\rho \simeq \frac{1}{\sqrt{2\pi}} e^{-2(m_\nu/\Delta)^2} \quad (21)
\]

i.e., it is an extremely steep function of \( m_\nu/\Delta \). According to such a signal a ratio of order of unity could be reached if the ratio \( m_\nu/\Delta \sim 3 \). Since \( m_\nu \) remains unknown, an experiment with a fixed resolution \( \Delta \) would be able to observe the background neutrino sea only if \( m_\nu \) is large enough.

A numerical calculation suggests that in fact \( m_\nu/\Delta \sim 2 \) is enough to achieve a signal to background ratio of order of unity. This is illustrated in Fig. 2 where \( \Delta \) is the full width at half maximum of the assumed Gaussian resolution function and the signal as well as the background are centered at \( Q + m_\nu \) and integrated over an interval of width \( \Delta \). The figure also shows that this ratio is such a steep function of \( m_\nu/\Delta \) that it is essentially independent of the enhancement of \( \lambda_\nu \) due to the gravitational clustering. (Note, however, that the signal itself, i.e. the number of events, is proportional to the clustering ratio \( n_\nu/(n_\nu) \).) Figure 2 shows that in order to achieve sensitivity to sub-eV neutrino masses a resolution width below \( \sim 0.5 \text{ eV} \) would be necessary. Obviously, that is a very challenging requirement.

We wish now to discuss the possible resonance character of the neutrino capture on nuclei at threshold. The interest in the possible resonance effects was whetted by the attempts of Raghavan [31], that even so they are unsuccessful so far, stimulated lively discussion. For the primordial background neutrinos the de Broglie wavelength is extremely large,

\[
\lambda_\nu = \frac{\hbar}{p_\nu} \sim 0.04 \text{ cm} \quad (22)
\]

for \( T_\nu = 1.9 \text{ K} \). That estimate is no longer valid for the gravitationally clustered massive neutrinos, that acquire the corresponding virial velocity. Nevertheless, their de Broglie wavelength remains macroscopically large.

If a resonance reaction could occur, and if it can be somehow described by a Breit-Wigner type formula where the integrated reaction cross section is

\[
\int \sigma_{\text{reaction}} dE = 2\pi^2 \lambda^2 \frac{\Gamma e}{\Gamma} , \quad (23)
\]

a very large cross section could be obtained. Here \( \Gamma e \) is the partial width for the elastic scattering, \( \Gamma \) for the capture, and \( \Gamma \) is the total width. In the case of neutrino induced reactions, obviously, there is only one channel, and all \( \Gamma \) values should be identical.

Mikaleyan et al. [32] considered a resonance scenario for the endothermic reaction (not observed as yet)

\[
\bar{\nu}_e + e^- + A_Z \rightarrow A_{Z-1} \quad (24)
\]

where \( A_z \) is stable, \( A_{Z-1} \) is radioactive with an endpoint \( E_0 \), and the captured electron is an orbital one in \( A_z \). The reaction occurs when \( E_\nu = E_0 + E_b \), where \( E_b \) is the binding energy of the captured electron, so its threshold is \( \sim 2m_e c^2 \) below the threshold for the inverse \( \beta \) decay. It is shown in Ref. [32] that for the process (22) the factor \( \lambda_\nu^2 \) in the cross section formula Eq. (23) is compensated by the \( E_b^2 \) dependence of the total width \( \Gamma (\Gamma_r = \Gamma_e = \Gamma \text{ in this case}) \). Moreover, the resonance electron capture cannot occur for a radioactive (hence exothermic) target \( A_{Z-1} \).

While the reaction (24) is indeed of resonance character and occurs only when the incoming \( \bar{\nu}_e \) has a fixed energy, the zero threshold reactions (with radioactive \( A_{Z-1} \))

\[
\bar{\nu}_e + e^- + A_Z \rightarrow A_{Z-1} + \gamma \text{ or } \bar{\nu}_e + A_Z \rightarrow A_{Z-1} + e^+ \quad (25)
\]

are not of resonance character. They can proceed for any energy of the incoming \( \bar{\nu}_e \), including nonrelativistic energies, but they cannot be described by the resonance formula and the cross section is never close to the value of \( 2\pi^2 \lambda^2 \) as in Eq. (23).
IV. CONCLUSIONS

We have shown that the charged current cross section of nonrelativistic neutrinos scales like $1/v_\nu$ in agreement with the generic behavior of the cross sections for slow particles. That means, in particular, that the charged current reactions with vanishing threshold of nonrelativistic neutrinos have a rate that converges to a finite value as $v_\nu \to 0$. With that in mind we evaluate the cross section and reaction rate of the relic $\bar{\nu}_e$ on tritium nuclei. If a modest gravitational clustering enhancement of the relic neutrino number density is present, the number of events is large enough that it might be potentially observable. The more important issue is the elimination of the overwhelming background of the electrons from tritium $\beta$ decay. We show that signal/background ratio of the order of unity can be achieved only if the neutrino mass $m_\nu$ exceeds the characteristic experimental resolution width $\Delta$ by a factor of two or more. Thus an energy resolution $\Delta \leq 0.5$ eV would be required in order to be possible, even in an ideal experiment, to detect relic neutrinos with sub-eV neutrino masses, independently of the gravitational neutrino clustering.

Acknowledgments

R. Lazauskas and C. Volpe acknowledge support from the project ANR-05-JCJC-0023 "Non standard neutrino properties and their impact in astrophysics and cosmology" (NeuPAC). P. Vogel appreciates the hospitality of the Institut de Physique Nucléaire, Orsay and of the Aspen Center for Physics.

[1] P. J. E. Peebles, *Physical Cosmology*, Princeton Univ. Press, Princeton, 1971.
[2] S. Weinberg, *Gravitation and Cosmology*, John Wiley, New York, 1972.
[3] G. Mangano, G. Miele, S. Pastor and M. Peloso, Phys. Lett. B 34, 8 (2002).
[4] D. N. Spergel et al. [WMAP Collaboration], Astrophys. J. Suppl. 170 (2007) 377 [arXiv:astro-ph/0603449].
[5] R. Orpher, Astron. Astrophys. 37, 135 (1974).
[6] R. R. Lewis, Phys. Rev. D 21, 663 (1980).
[7] N. Cabibbo and L. Maiani, Phys. Lett. B 114, 115 (1982).
[8] P. Langacker, J. P. Leveille and J. Sheiman, Phys. Rev. D 27, 1228 (1983).
[9] L. Stodolsky, Phys. Rev. Lett. 34, 110 (1975) [Erratum-ibid. 34, 506 (1975)].
[10] C. Hagmann, [arXiv:astro-ph/9902102].
[11] P. F. Smith and J. D. Lewin, Acta Phys. Polon. B 15 (1984) 1201; P. F. Smith, Prepared for 4th International Workshop on the Identification of Dark Matter (IDM 2002), York, England, 2-6 Sep 2002.
[12] T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982).
[13] T. J. Weiler, Astrophys. J. 285, 405 (1984).
[14] B. Eberle, A. Ringwald, L. Song and T. J. Weiler, Phys. Rev. D 70, 023007 (2004) [arXiv:hep-ph/0401203].
[15] T. J. Weiler, Astropart. Phys. 11, 303 (1999) [arXiv:hep-ph/9710431].
[16] D. Fargion, B. Mele and A. Salis, Astrophys. J. 517, 725 (1999).
[17] G. B. Gelmini, Phys. Scripta T121, 131 (2005) [arXiv:hep-ph/0412305], and references therein.
[18] P. Vogel and J. F. Beacom, Phys. Rev. D 60, 053003 (1999) [arXiv:hep-ph/9905554].
[19] Yu. I. Azimov and V. M. Shchekhter, Soviet Phys. JETP, 14, 424 (1962).
[20] V. B. Beresteckii, E. M. Lifshitz and L. P. Pitaevskii, *Relativistic Quantum Theory, Part 1* Pergamon Press., Oxford, 1971, (see Eq. (65.15a)).
[21] A. Strumia and F. Vissani, Phys. Lett. B 564, 42 (2003) [arXiv:astro-ph/0302055].
[22] L. D. Landau, E. M. Lifshitz, *Quantum Mechanics: Non-Relativistic Theory*, 3rd ed., Pergamon Press, Oxford, 1977.
[23] S. Weinberg, Phys. Rev. 128, 1457 (1962).
[24] A. G. Cocco, G. Mangano and M. Messina, JCAP 0706, 015 (2007) [arXiv:hep-ph/0703078].
[25] J. N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press, Cambridge, 1989.
[26] A. Ringwald and Y. Y. Y. Wong, JCAP 0412, 005 (2004) [arXiv:hep-ph/0408241], and references therein.
[27] R. Wigmans, Astropart. Phys. 19, 379 (2003).
[28] W.-Y. P. Hwang and Bo-Qiang Ma, New J. Phys. 7, 41 (2005).
[29] W. C. Haxton and Wei Lin, Phys. Lett. B 486, 263 (2000).
[30] A. Kusenko, hep-ph/0609158 and references therein.
[31] R. S. Raghavan, hep-ph/0703028 (withdrawn) and private communication.
[32] L. A. Mikaleyian, B. G. Tsinoev and A. A. Borovoi, Sov. J. Nucl. Phys. 6, 254 (1968).