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Tritium decay and the hypothesis of tachyonic neutrinos

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Abstract. Numerous recent measurements indicate an excess of counts near the endpoint of the electron energy spectrum in tritium decay. We show that this effect is expected if the neutrino is a tachyon. Results of calculations, based on a unitary (causal) theory of tachyons, are presented. The hypothesis of tachyonic neutrinos also offers a natural explanation of the vector-axial (V-A) structure of the weak leptonic current in neutrino interactions.

1 Introduction

For several years numerous experiments have been performed with the aim of measuring the electron antineutrino mass in tritium decay, ${}^3\mathrm{H} \to {}^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ [1–4]. This quantity squared, $\xi = m^2_{\bar{\nu}_\mathrm{e}}$, may be determined by fitting the electron energy spectrum near the endpoint with the formula given below in a simplified form:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \sim p(E_{\max} - E)\sqrt{(E_{\max} - E)^2 - \xi}, \qquad (1)$$

where E ($E_{\max}$) denote (maximal) energy of the electron in this decay and p its momentum. Surprisingly, all recent experiments yielded negative values of the parameter ξ. Owing to the increasing resolution of modern spectrometers, the reason for such results has been attributed to a peculiar unexpected shape of the spectrum in the vicinity of the endpoint. In qualitative terms this phenomenon, hereafter referred to as the *endpoint effect*, can be viewed as an excess of counts in that region. This is contrary to common expectations since if the neutrino were massive ($\xi > 0$) a depletion of counts towards the endpoint would be expected as compared to the massless neutrino case. The enhancement under consideration has been found in the spectra collected at Mainz [1], Troitsk [2] and earlier at LLNL [3]. In particular, numerous measurements performed by the two former groups deliver firm evidence in favour of the effect which may be considered as well established experimentally. Attempts to determine the electron neutrino mass using formula (1), without additional assumptions concerning the origin of the enhancement, lead to doubtful results in these circumstances.

The *endpoint effect* has not been convincingly explained on conventional grounds. The Mainz and Troitsk groups both made significant efforts towards understanding their apparatus, data evaluation methods and considered a wide class of related physical phenomena. Moreover, dedicated studies have demonstrated that the *endpoint effect* could not originate from mistreatment of molecular effects [5]. A possibility that it might be related to methods of evaluating the data near the end of the physical region has also been considered [6]. Lack of a credible explanation of the effect made room for unconventional hypotheses [7].

In this paper we present calculations of the electron energy spectrum in tritium decay assuming that the neutrino is a tachyon. It must be stressed that changing the sign in front of the parameter ξ in (1) in no way converts it to the correct formula describing a beta decay spectrum with a tachyonic neutrino.

A tachyon is a particle which moves with velocities always greater than c, relative to any reference frame. The energy–momentum relation reads: $E^2 - \mathbf{p}^2 = -\kappa^2$, where κ will be called the *tachyonic mass*. Tachyons cannot be described within the framework of the Einstein–Poincaré (EP) relativity because of causality violation (this has been a repeated argument to reject them as possibly existing particles). It also proved impossible to construct a unitary field theory of tachyons on these grounds. The unitary (causal) theory of tachyons proposed recently [8], free of these difficulties, is the basis for calculations presented in this paper. This theory does not invalidate nor modify the EP theory of relativity for massive and light-like particles. In what follows the term 'neutrino' stands for 'electron neutrino' or 'electron antineutrino'. We use the following symbols: total particle energy (momentum), $E(p)$; kinetic energy, T; endpoint energy, $E_{\max}$, $T_{\max}$, respectively.

2 Theory of spin-$\frac{1}{2}$ tachyons

The time synchronization scheme is a convention in special relativity, therefore there is a freedom in the definition of the coordinate time. The standard choice is the

Einstein–Poincaré synchronization with the one-way velocity of light isotropic and constant. This choice leads to the well known form of the Lorentz group transformations but the EP coordinate time implies covariant causality for time-like and light-like trajectories only. In order to describe tachyons, a different synchronization scheme must be chosen, namely that of Chang–Tangherlini (CT), preserving invariance of the notion of the instant-time hyperplane [8,9]. In this synchronization scheme the notion of causality is universal, i.e. space-like trajectories (tachyons) are physically admissible too, the only inconvenience being that the Lorentz group transformations, which incorporate transformation rules for the velocity of a distinguished (preferred) reference frame, have a more complicated form. *The EP and CT descriptions are equivalent for the time-like and light-like trajectories; however a consistent (causal) description of tachyons is possible only in the CT scheme.* A very important consequence is that if tachyons exist then the relativity principle is broken, i.e. there exists a preferred frame of reference; however, the Lorentz symmetry is preserved. The interrelation between EP (x_{EP}) and CT (x) coordinates reads:

$$x^0_{\mathrm{EP}} = x^0 + u^0\mathbf{ux}, \quad \mathbf{x}_{\mathrm{EP}} = \mathbf{x}, \tag{2}$$

where u^μ is the four-velocity of the privileged frame as seen from the frame (x^μ). On the basis of these considerations, a fully consistent, Poincaré covariant quantum field theory of tachyons has also been proposed [8]. In the case of the fermionic tachyon with helicity $\frac{1}{2}$ the corresponding free field equation reads:

$$\left(\gamma^5\left(\mathrm{i}\gamma\partial\right) - \kappa\right)\psi = 0, \tag{3}$$

where the bispinor field ψ is simultaneously an eigenvector of the helicity operator with the eigenvalue $\frac{1}{2}$. The elementary tachyonic states are thus labelled by helicity. The γ-matrices are expressed by the standard ones in analogy to the relations (2). The solution of the equation (3) is given by:

$$\psi(x,u) = \frac{1}{(2\pi)^{\frac{3}{2}}}\int \mathrm{d}^4k\,\delta(k^2+\kappa^2)\theta(k^0)\left[w(k,u)\mathrm{e}^{\mathrm{i}kx}b^\dagger(k) + v(k,u)\mathrm{e}^{-\mathrm{i}kx}a(k)\right], \tag{4}$$

where the operators a and b correspond to neutrinos and antineutrinos respectively. The amplitudes v and w satisfy the following conditions:

$$w(k,u)\bar{w}(k,u) = (\kappa - \gamma^5 k\gamma)\frac{1}{2}\left(1 - \frac{\gamma^5[k\gamma, u\gamma]}{2\sqrt{q^2+\kappa^2}}\right) \tag{5}$$

$$v(k,u)\bar{v}(k,u) = -(\kappa + \gamma^5 k\gamma)\frac{1}{2}\left(1 - \frac{\gamma^5[k\gamma, u\gamma]}{2\sqrt{q^2+\kappa^2}}\right) \tag{6}$$

$$\bar{w}(k,u)\gamma^5 u\gamma w(k,u) = \bar{v}(k,u)\gamma^5 u\gamma v(k,u) = 2q \tag{7}$$

$$\bar{w}(k^{\Pi},u)\gamma^5 u\gamma v(k,u) = 0. \tag{8}$$

Here $q = u_\mu k^\mu$ is equal to the energy of the tachyon in the preferred frame and Π denotes the space inversion operation. In the massless limit, $\kappa \to 0$, the above relations are identical with those obtained in Weyl's theory. An equation similar in its form to (3) has already been proposed in the EP synchronization [10], however, the theory based on the latter is not unitary.

3 Beta decay with a tachyonic electron neutrino

3.1 Amplitude

On the grounds of the formalism presented in Sect. 2 we calculate the amplitude for a β decay, $\mathrm{n} \to \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu}_{\mathrm{e}}$, with a tachyonic electron antineutrino, using an effective four-fermion interaction. In the rest frame of the decaying particle the decay rate for this process reads:

$$\mathrm{d}\Gamma = \frac{1}{4m_{\mathrm{n}}(2\pi)^5}\,\mathrm{d}\Phi_3\,|M|^2\,, \tag{9}$$

where $\mathrm{d}\Phi_3$ is the phase-space volume element:

$$\mathrm{d}\Phi_3 = \theta(k^0)\,\theta(l^0)\,\theta(r^0)\delta(k^2-m_{\mathrm{p}}^2)\,\delta(l^2-m_{\mathrm{e}}^2) \times\delta(r^2+\kappa^2)\,\delta^4(p-k-l-r)\,\mathrm{d}^4k\,\mathrm{d}^4l\,\mathrm{d}^4r. \tag{10}$$

The amplitude squared, $|M|^2$, can be derived (on the tree level) directly from the lepton–hadron part of the effective Fermi weak-interaction Lagrangian:

$$\mathcal{L}_I = -G_{\mathrm{F}} j_\mu J^\mu, \tag{11}$$

where j_μ and J^μ denote leptonic and hadronic currents respectively. However, under the condition that in the limit of the zero neutrino mass the leptonic current takes the standard V–A form, we have two natural choices, which we denote *helicity* and *chirality* coupling. Namely, we can choose the corresponding part of the leptonic current in the form:

$$\bar{u}_{\mathrm{e}}\gamma^\mu w \qquad \text{(helicity coupling)} \tag{12}$$

or

$$\bar{u}_{\mathrm{e}}\gamma^\mu \tfrac{1}{2}(1-\gamma^5)w \qquad \text{(chirality coupling)}, \tag{13}$$

respectively. In the former case the square of the amplitude ($M \equiv M_{\mathrm{h}}$) reads:

$$|M_{\mathrm{h}}|^2 = 2\,G_{\mathrm{F}}^2\,\mathrm{Tr}\left[u_{\mathrm{e}}\bar{u}_{\mathrm{e}}\gamma^\mu w\bar{w}\gamma^\nu\right] \times\mathrm{Tr}\left[u_{\mathrm{p}}\bar{u}_{\mathrm{p}}\gamma_\mu\left(1-g_{\mathrm{A}}\gamma^5\right)u_{\mathrm{n}}\bar{u}_{\mathrm{n}}\gamma_\nu\left(1-g_{\mathrm{A}}\gamma^5\right)\right], \tag{14}$$

while in the latter case (chirality coupling: $M \equiv M_{\mathrm{ch}}$):

$$|M_{\mathrm{ch}}|^2 = 2\,G_{\mathrm{F}}^2\,\mathrm{Tr}\left[u_{\mathrm{e}}\bar{u}_{\mathrm{e}}\gamma^\mu \tfrac{1}{2}(1-\gamma^5)w\bar{w}\gamma^\nu \tfrac{1}{2}(1-\gamma^5)\right] \times\mathrm{Tr}\left[u_{\mathrm{p}}\bar{u}_{\mathrm{p}}\gamma_\mu\left(1-g_{\mathrm{A}}\gamma^5\right)u_{\mathrm{n}}\bar{u}_{\mathrm{n}}\gamma_\nu\left(1-g_{\mathrm{A}}\gamma^5\right)\right]. \tag{15}$$

Here p, k, l, r are the four-momenta of n, p^+, e^- and $\bar{\nu}$ respectively; the corresponding masses are denoted by m_{n},

$m_{\rm p}$, $m_{\rm e}$ and κ. $G_{\rm F}$ and $g_{\rm A}$ are the Fermi constant and the axial coupling constant. The amplitudes $u_{\rm n}$, $\bar{u}_{\rm n}$, $u_{\rm p}$, $\bar{u}_{\rm p}$, $u_{\rm e}$, $\bar{u}_{\rm e}$ satisfy usual[1] polarization relations: $u_{\rm n}\bar{u}_{\rm n} = p\gamma + m_{\rm n}$, $u_{\rm p}\bar{u}_{\rm p} = k\gamma + m_{\rm p}$, $u_{\rm e}\bar{u}_{\rm e} = l\gamma + m_{\rm e}$, whereas $w\bar{w}$ is given by (5). After elementary calculations (14) and (15) read:

$$
\begin{aligned}
|M_{\rm h}|^2 &= 16G_{\rm F}^2 \\
&\times \Bigg\{ \left[m_{\rm n}m_{\rm p}(1-g_{\rm A}^2) - kp(1+g_{\rm A}^2)\right] \Big(4m_{\rm e}\kappa \\
&\quad - \frac{1}{\sqrt{(ur)^2+\kappa^2}} \left[4(\kappa^2 lu + lr\cdot ur) \right.\\
&\quad \left. -2\kappa^2 lu - 2ur\cdot lr\right]\Big) \\
&\quad + (1+g_{\rm A}^2)\Big(2m_{\rm e}\kappa(pk) \\
&\quad - \frac{1}{\sqrt{(ur)^2+\kappa^2}} \left[2pk(k^2 lu + lr\cdot ur) \right.\\
&\quad \left. -2\kappa^2(pl\cdot uk + kl\cdot up) - 2ur(pl\cdot kr + kl\cdot pr)\right]\Big) \\
&\quad + 4g_{\rm A}\Big(pr\cdot kl - pl\cdot kr \\
&\quad + \frac{m_{\rm e}\kappa}{\sqrt{(ur)^2+\kappa^2}}(kr\cdot up - pr\cdot uk)\Big)\Bigg\} \qquad (16)
\end{aligned}
$$

and

$$
\begin{aligned}
|M_{\rm ch}|^2 &= 16G_{\rm F}^2 \\
&\times \Bigg\{ \left(1 + \frac{ur}{\sqrt{(ur)^2+\kappa^2}}\right) \Big[(g_{\rm A}^2-1)m_{\rm n}m_{\rm p} lr \\
&\quad +(g_{\rm A}^2+1)(lp\cdot kr + pr\cdot kl) \\
&\quad +2g_{\rm A}(kl\cdot pr - lp\cdot kr)\Big] \\
&\quad + \frac{\kappa^2}{\sqrt{(ur)^2+\kappa^2}} \Big[(g_{\rm A}^2-1)m_{\rm n}m_{\rm p} ul \\
&\quad +(g_{\rm A}^2+1)(lp\cdot uk + up\cdot kl) \\
&\quad +2g_{\rm A}(kl\cdot up - lp\cdot uk)\Big]\Bigg\} \qquad (17)
\end{aligned}
$$

In order to calculate the differential energy spectrum of electrons in the β decay with a tachyonic electron neutrino, $\mathrm{d}\Gamma/\mathrm{d}l^0$, it is necessary to account for the velocity of the preferred frame, u. We take $u_\mu = (1,0,0,0)$ for simplicity, i.e. we derive the result in a reference frame which is at rest with respect to the preferred frame (consequences of a non-negligible velocity of the preferred frame are discussed in Sect. 4). The spectrum $\mathrm{d}\Gamma/\mathrm{d}l^0$ may be obtained for both considered cases (helicity and chirality coupling) by means of formulae (9), (10), (16) and (17), after elementary integration with respect to $\mathrm{d}^4k\,\mathrm{d}^3\mathbf{l}\,\mathrm{d}^3\mathbf{r}$, from the following formula (which gives identical results in the limit $\kappa^2 \to 0$ as that for the massless neutrino):

$$
\frac{\mathrm{d}\Gamma}{\mathrm{d}l^0} = \frac{1}{128\pi^3 m_{\rm n}} \int_{\max(r_-,0)}^{r_+} \mathrm{d}r^0 \, \left|M(l^0,r^0)\right|^2 \qquad (18)
$$

with

$$
\begin{aligned}
r_\pm &= \Big\{ -\Delta m^2 l^0 + \Delta m^2 m_{\rm n} + 2(l^0)^2 m_{\rm n} - 2l^0 m_{\rm n}^2 \\
&\pm \sqrt{(l^0)^2 - m_{\rm e}^2}\,\left[(\Delta m^2)^2 + 4\kappa^2 m_{\rm e}^2 - 4\Delta m^2 l^0 m_{\rm n} \right.\\
&\left. -8\kappa^2 l^0 m_{\rm n} + 4\kappa^2 m_{\rm n}^2 + 4(l^0)^2 m_{\rm n}^2\right]^{\frac{1}{2}} \Big\} \\
&\times \left[2(m_{\rm e}^2 - 2l^0 m_{\rm n} + m_{\rm n}^2)\right]^{-1}. \qquad (19)
\end{aligned}
$$

Here $|M|^2 = |M_{\rm h}|^2$ or $|M_{\rm ch}|^2$, respectively, and $ul = l^0$, $ur = r^0$, $up = m_{\rm n}$, $uk = m_{\rm n} - l^0 - r^0$, $kp = m_{\rm n}(m_{\rm n} - l^0 - r^0)$, $kl = -m_{\rm n}r^0 - m_{\rm e}^2 + \frac{1}{2}\Delta m^2$, $kr = -m_{\rm n}l^0 + \kappa^2 + \frac{1}{2}\Delta m^2$, $pr = m_{\rm n}r^0$, $lp = m_{\rm n}l^0$, $lr = m_{\rm n}(l^0 + r^0) - \frac{1}{2}\Delta m^2$ and $\Delta m^2 = m_{\rm n}^2 - m_{\rm p}^2 + m_{\rm e}^2 - \kappa^2$.

3.2 Electron energy spectrum

We have calculated differential electron energy spectra, $\mathrm{d}\Gamma/\mathrm{d}l^0$, in tritium decay using the following values for the masses of ^{3}H and ^{3}He: $m_{\rm n} = 2809.94\,\mathrm{MeV}$ and $m_{\rm p} = 2809.41\,\mathrm{MeV}$ respectively (hereafter we use $l^0 \equiv E$). The corresponding value for the electron endpoint kinetic energy in the preferred frame is $T_{\max} = 18\,587.56\,\mathrm{eV}$. Differential electron energy spectra, $\mathrm{d}\Gamma/\mathrm{d}E$, corresponding to decays with a massive, massless and tachyonic neutrino, in the vicinity of the endpoint, are shown in Fig. 1a. The tachyonic spectra for both couplings near the endpoint rise above that for the massless neutrino. Moreover, they terminate at $T = T_{\max}$ with a quasi-step: the function $\mathrm{d}\Gamma/\mathrm{d}E$ decreases linearly to zero over the energy interval of $2\kappa p_{\max}/m_{\rm n}$ (where $p_{\max}$ denotes the maximal electron momentum) which in the tritium decay amounts to $\approx 10^{-3}\,\mathrm{eV}$ for $\kappa = 8\,\mathrm{eV}$. The magnitude (height) of the step depends on the choice of coupling as well as on the value of κ, as can be seen in Fig. 1a,b.

Thus if the neutrino were a tachyon, one would expect an excess of the counting rate near the endpoint, i.e. an effect qualitatively similar to the one actually observed. Since the detectors used in Mainz and Troitsk are integrating spectrometers, we integrated the electron energy spectrum given by (18) and included a simplified experimental resolution function used in these experiments [11], with energy resolution $\Delta E = 4\,\mathrm{eV}$ (not accounting for the final-state energy spectrum). The resulting linearized (cube root) electron energy spectrum near the endpoint is shown in Fig. 2. There is a striking similarity between the predicted shape and that observed in the Troitsk data [2] (last reference) (which is the only published linearized spectrum). We also verified that the *endpoint effect* of the observed magnitude could have hardly been discovered in earlier measurements which had much poorer energy resolution.

For practical purposes the rigorous but complicated expressions for the electron energy spectra (18) may be approximated in order to write them in terms of the variable $(E_{\max} - E)$ and the electron momentum p. The simplified form, valid under the condition $E \le E_{\max}$, for the

[1] But with γ in the CT synchronization [8].

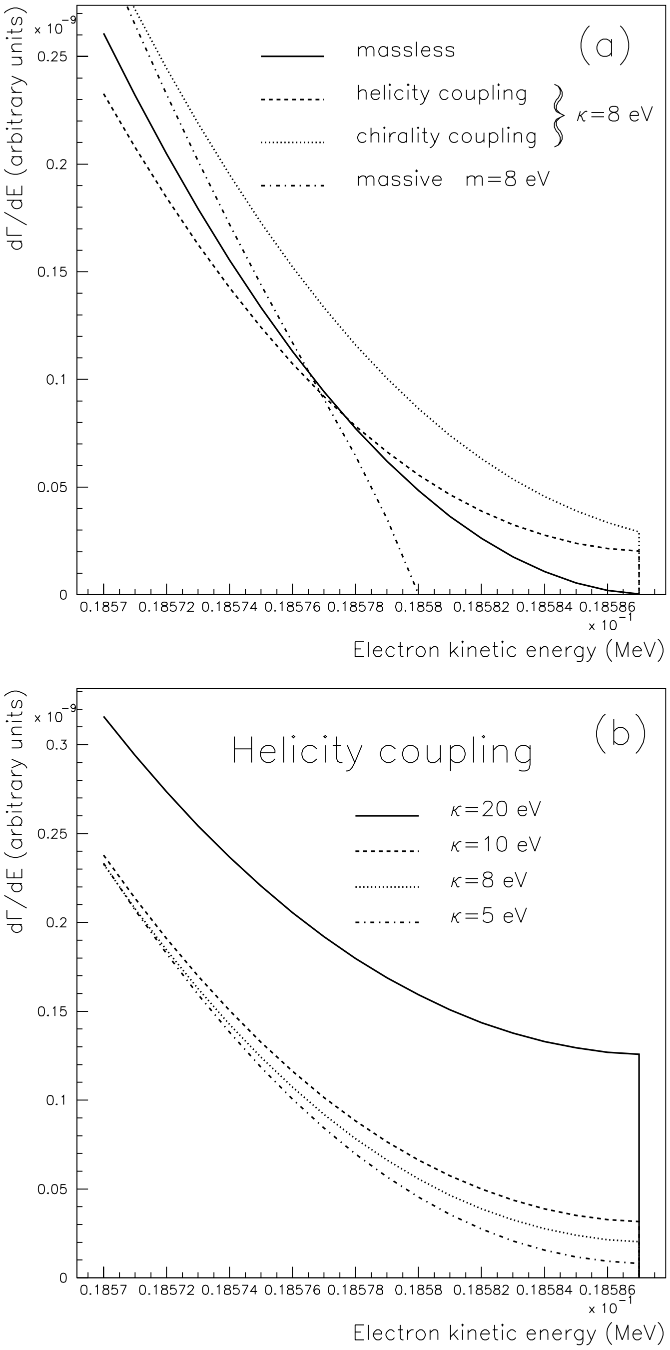

Fig. 1. a Differential electron energy spectra in the vicinity of the endpoint for tritium decay with: a tachyonic antineutrino of mass $\kappa = 8\,\mathrm{eV}$, massless neutrino and massive neutrino of mass $m = 8\,\mathrm{eV}$; **b** as above for a tachyonic electron antineutrino with helicity coupling for a range of tachyonic masses, κ

helicity coupling reads:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \frac{G_{\mathrm{F}}}{2\pi^3}\Big[\kappa m_{\mathrm{e}}(1-3g_{\mathrm{A}}^2) +(1+3g_{\mathrm{A}}^2)E\sqrt{(E_{\max}-E)^2+\kappa^2}\Big] \times p\sqrt{(E_{\max}-E)^2+\kappa^2} \qquad (20)$$

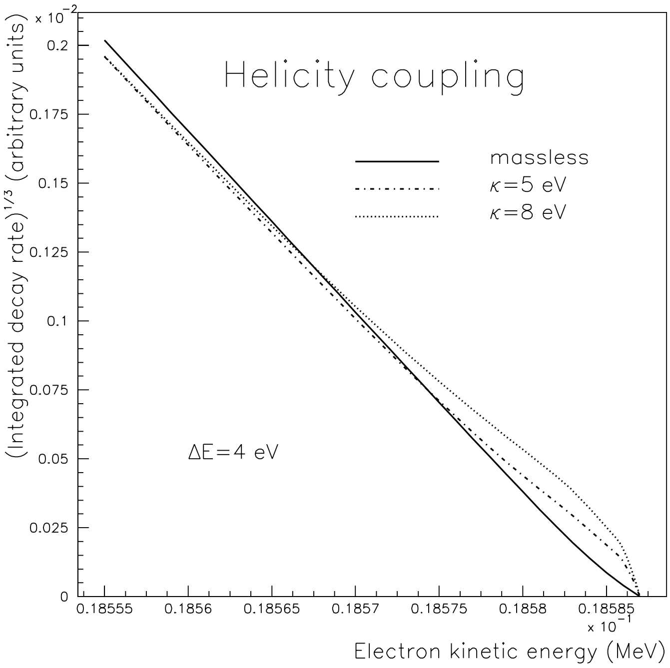

Fig. 2. Linearized (cube root) integral electron energy spectrum with folded experimental resolution function (see text)

and for the chirality coupling:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \frac{G_{\mathrm{F}}}{4\pi^3}(1+3g_{\mathrm{A}}^2)Ep\Big[(E_{\max}-E)^2 +(E_{\max}-E)\sqrt{(E_{\max}-E)^2+\kappa^2}+\kappa^2\Big], \qquad (21)$$

with the additional explicit condition that $\mathrm{d}\Gamma/\mathrm{d}E = 0$ for $E > E_{\max}$ since the approximated spectra do not vanish at $E = E_{\max}$ (step).

4 Preferred frame and time-dependent effects

An interesting property of amplitudes for processes involving tachyonic neutrinos, in particular for the beta decay, is their dependence on the velocity four-vector of the preferred frame, u (16). On the grounds of cosmological considerations one might expect that a frame in which the cosmic microwave background radiation (CMBR) is isotropic is a natural candidate for the preferred frame. In such a case results derived in previous sections are sufficiently precise because the solar system is almost at rest relative to the CMBR[2].

Consider a certain configuration of the momenta of the final-state particles in a beta decay which occurs in a reference frame moving with velocity $\mathbf{u}$ with respect to the preferred frame. The maximal kinetic energy of the electron, $T_{\max}$, depends on $\beta = |\mathbf{u}|/c$ and $\cos\omega$, where

[2] Velocity deduced from the dipole anisotropy in temperature amounts to about 370 km/s [12].

ω is the angle between the neutrino momentum and the vector $\mathbf{u}$:

$$T_{\max}(\beta, \cos\omega) = T_{\max} - \Delta T_{\max}(\beta, \cos\omega) \qquad (22)$$

where

$$\Delta T_{\max}(\beta, \cos\omega) = \frac{\kappa\beta\cos\omega}{\sqrt{1-\beta^2\cos^2\omega}}. \qquad (23)$$

Momenta of the final-state particles in the β decay are aligned at the endpoint and thus the angle ω may be expressed by the angle corresponding to the electron. Assume for simplicity that the electron spectrum is measured in an ideal spectrometer in which electrons are moving along the spectrometer axis. Thus the angle ω between this axis and the vector $\mathbf{u}$ changes with time due to the Earth's rotation, and day–night variations of $T_{\max}$ are expected. If we identify the preferred frame with the CMBR ($\beta \approx 10^{-3}$) we obtain $\Delta T_{\max} < 10^{-2}$ eV for the tachyonic electron neutrino mass of a few eV, i.e. an effect undetectable at present. If, however, the velocity of the preferred frame were large ($\beta > 0.1$), the expected variation of the endpoint energy would be of order eV.

5 Summary and conclusions

We have shown that the electron energy spectrum in a beta decay with a tachyonic neutrino rises above that for the massless neutrino and ends with a quasi-step at $E = E_{\max}$. This feature may explain the excess of counts observed in tritium decay in the vicinity of the endpoint if the neutrino were a tachyon. Our prediction and the measurement of Troitsk show a remarkable similarity when presented on a linearized plot. Since the neutrino field is an eigenvector of the helicity operator with the eigenvalue 1/2, *helicity coupling offers a natural explanation of the V–A structure of the weak leptonic current in neutrino interactions*. Certain preliminary considerations concerning the hypothesis of tachyonic neutrinos may be found elsewhere [13].

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