Endpoint Structure in Beta Decay from Coherent Weak-Interaction of the Neutrino

J.I. Collar[a,b,*]
[a] CERN, EP Division, CH-1211 Geneve 23, Switzerland
[b] Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208

Recent tritium beta decay experiments yield unphysical negative best-fit values for the square of the neutrino mass. An unidentified bump-like excess of counts few eV below the endpoint in the electron energy spectrum has been tentatively recognized as the source of this anomaly. It is shown that the repulsive potential acting on the emitted antineutrino and originating in its coherent weak-interaction with the daughter atom may effectively account for this excess.

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* E-mail: Juan.Collar@cern.ch

The evidence for a non-zero electron neutrino mass $m_\nu \sim 30$ eV/c^2, obtained by the ITEP group in the 80's [1] from a measurement of the endpoint region in the $\beta-$decay of tritium, has been amply refuted in later experiments [2–7]. These subsequent attempts have nevertheless consistently produced unphysical $m_\nu^2 < 0$ values, prompting the Particle Data Group to devise a special recipe [8] to translate them into sensible upper limits to the positive value of m_ν^2. Recently, a common origin for this anomaly has been independently suggested by some of these groups [5–7,9]: a broad spike or bump-like excess of counts centred 5 to 30 eV below the endpoint energy E_0 in the electron kinetic energy (E_e) spectrum, is able to explain the effect. Best values for the position, intensity and spectral shape of this bump are somewhat different from one experiment to another. This is expected from the low signal-to-background ratio close to E_0 (the first statistically significant data points are typically found 5 to 20 eV below the endpoint) and the different energy resolutions of the spectrometers (∼5 to 15 eV at best). The origin of this structure is yet unknown and several hypothesis such as residual radioactivity generating a monochromatic electron line [6,7] or an increased shake-off probability [5] have been ruled out. Stephenson [9] has revised the Los Alamos result [3] including the competing process of relic neutrino absorption, which is expected to generate a weak monochromatic electron line at or above E_0 [10]. In his interpretation, the actual contribution from this process would be an essentially constant addition to the region $E_0 - E_F < E_e < E_0$, where $E_F \sim$ few eV is the energy of the relic neutrino Fermi sea. Stephenson nevertheless finds that the required present-epoch relic neutrino density necessary to produce the observed excess is a factor 10^{14} larger than the $\sim 110\ \nu/cm^3$ predicted by standard Big-Bang cosmology.

The possible link between the position and intensity of the bump has not been examined yet. Fig. 1 shows their available best-values and error bars as listed in refs. [6] (Troitsk), [7] (Lawrence Livermore National Laboratory) and [9] (Los Alamos National Laboratory). The position (centroid) is defined by an energy ε below E_0 and the intensity by the fraction of the total $\beta-$decay strength under the bump. The Troitsk group gives a best-value ε =7 eV with no associated error bar, but elsewhere in [6] they define ε ∼7 - 15 eV. As for the LANL result, the shaded region in fig. 1 spans over fits with the proposed relic-absorption spectral shape of [9] that give a goodness-of-fit equivalent to their earlier attempt [3] at fitting a sharp spike at $\varepsilon = 0$ (yielding an intensity $\sim 10^{-9}$ of the total decays). The Mainz group [5] does not offer a best value, but the position and magnitude of the deviation is reported as "remarkably similar" to the LLNL result [7]. The fraction of the decays for which $E_e > E_0 - \varepsilon$, that is, $f(\varepsilon) = \int_{E_0-\varepsilon}^{E_0} P(E_e)dE_e / \int_0^{E_0} P(E_e)dE_e$, where $P(E_e)dE_e$ is the electron differential kinetic energy spectrum, is also depicted in fig. 1. The theoretical $P(E_e)dE_e$ is calculated following Morita [11] and includes the Coulomb-screening correction to the relativistic Fermi function [12,13] and the finite deBroglie wavelength correction. E_0 =18575 eV is adopted ($f(\varepsilon)$ is not very sensitive to a variation of ∼20 eV in this value). The solid line represents the case $m_\nu = 0$ while the dotted line is for $m_\nu = 5$ eV.

The closeness of these experimental best-values and the theoretical curve $f(\varepsilon)$, compatible with a small m_ν, is remarkable; there is no self-evident reason why such a finely-tuned correlation between the position and intensity of the bump should exist. Its presence in all experiments points at a common cause and provides an intuitive hint of its origin: antineutrinos emitted accompanying electrons with $E_0 - \varepsilon < E_e < E_0$ have a small kinetic energy $< \varepsilon$; imposing a requirement that antineutrinos always carry a minimum amount of total energy, $E_\nu > V_c$, where $V_c \sim$ few eV is some repulsive potential acting on them, might in principle effectively translate into "lifting" $P(E_e)dE_e$ around $E_e \sim E_0 - V_c$ by an amount equivalent to $f(V_c)$, i.e., as if electron emission into $E_e > E_0 - V_c$ was energetically forbidden and these electrons piled-up at $E_e = E_0 - V_c$. This description is nevertheless shown below to be formally inaccurate.

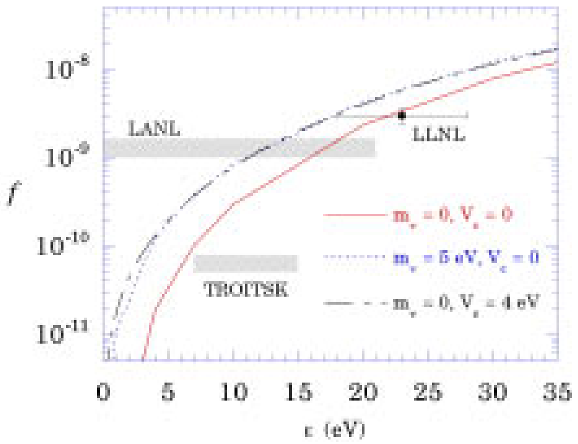

FIG. 1. Fraction of tritium decays, f, with electron kinetic energy $E_0 - \varepsilon < E_e < E_0$, as a function of ε and for different values of the neutrino mass m_ν and coherent weak potential V_c (E_0= 18.575 keV). The line corresponding to $m_\nu = 5$ eV is shifted to the left by 5 eV so that $f(0) = 0$. The boxes and dot (see text) correspond to experimental best-values for the location and intensity of the spectral excess responsible for the unphysical $m_\nu^2 < 0$ values obtained.

Such a potential V_c has been studied for long, albeit in a different context and not yet introduced as a correction to $\beta-$decay. (Anti)neutrinos of long-enough deBroglie wavelength ($\bar{\lambda}_\nu(cm) = 1.97 \cdot 10^{-5}/p_\nu(eV/c)$), when immersed in nuclear matter, cover a macroscopic number of nucleons (or quarks) in $\bar{\lambda}_\nu$; hence, the collective effect of nuclear matter on the neutrino is coherent and averaged over $\bar{\lambda}_\nu$. This is expressed in terms of a weak-interaction potential or alternatively as an index of refraction associated with the neutrino crossing from one material to another. A review of the quantum-mechanical principles leading to coherent neutrino scattering is given in [14]. This mechanism is behind the proposed methods (reviewed in [15]) to detect the relic neutrino background via small forces caused by their reflection and refraction in target materials. More recently, Loeb [16] has employed this potential to show that supernova neutrinos emitted with $E_\nu \lesssim 50$ eV must remain bound to the remnant neutron star. Using his notation, $V_c(eV) \simeq -3.8 \cdot 10^{-14} K \rho_n$, where ρ_n is the density of nuclear matter in g/cm^3, $K = \pm\frac{1}{2}\left(1 + \ell\,\frac{m_\nu}{E}\right)$, and E is the total neutrino energy. The upper sign in K is for neutrinos with helicity, $-\ell$ and the lower sign for antineutrinos with helicity, ℓ ($\ell = \pm 1$). It must be kept in mind that for nonrelativistic Majorana neutrinos, $K \rightarrow 0$, i.e., the presence of the potential can cast light on the nature of the neutrino emitted. Equivalent expressions for V_c can be found in [17]. In $\beta-$decay, the emitted antineutrino should therefore experience *ab initio* a small repulsive V_c arising from the coherent weak-interaction with the daughter atom. This V_c is then the traditional potential associated with the crossing of a low-energy neutral particle of mass m

through the boundary between two different materials (daughter nucleus and vacuum in this case), therefore changing its momentum, $\frac{p_2^2}{p_1^2} = 1 - \frac{2mV_c}{p_1^2}$ [17]. Taking a representative nuclear radius $R \sim 1.2 \cdot 10^{-15} A^{1/3}$ m (A is the daughter's mass number) yields $\rho_n \sim 2.3 \cdot 10^{14}$ g/cm^3 and $V_c \sim 4.4$ eV for tritium if $m_\nu = 0$. Since a small variation in the adopted R changes V_c rapidly, it is sufficient to conclude at this point that $V_c \sim$ O(1) eV.

The neutrino total energy and momentum appear explicitly in the expression for $P(E_e)dE_e$. The coherent correction is formally introduced by making the substitution $E_\nu \rightarrow E_\nu + V_c$ in both. In this regard, V_c is inserted in the same fashion as the Coulomb-screening correction [11,13]: E_e is shifted by $V_0(eV) \simeq \pm 30.8\ Z^{4/3}$ (positive sign for positron emission, Z being the daughter's atomic number) wherever it appears in $P(E_e)dE_e$ to account for this screening of the Coulomb field of the nucleus by the atomic electrons. The classical quote by Rose [18] "the electron distribution is always such as though the nucleus were not conscious of the screening and as though it emitted electrons into its immediate vicinity always in the same way; the only effect of the screening is then to accelerate the electrons..." should apply here with "V_c" in place of "the screening" and "antineutrino" as the last word. Fig. 2 displays the *qualitative* spectral change due to V_c when introduced in this fashion, which is precisely an enhancement of the expected count rate in the region immediately below E_0. This excess is enticingly similar in magnitude and shape to the anomaly in refs. [6,7]. It is also possible to rapidly estimate that a coherent potential $V_c \sim$ O(1) eV is indeed able to produce a *quantitative* effect on the electron spectrum equivalent to that coming from the experimentally-evaluated negative m_ν^2: as mentioned, $P(E_e)dE_e$ is proportional to $E_\nu p_\nu = (E_\nu + V_c)\sqrt{(E_\nu + V_c)^2 - m_\nu^2}$; a numerical value $V_c \sim (3/4)^{1/4}\sqrt{|m_\nu^2|}$ is then seen to drive the magnitude of $P(E_e)dE_e$ similarly in the limits

i) $V_c \rightarrow 0$, neutrino kinetic energy $\simeq m_\nu$
and
ii) $m_\nu \rightarrow 0$, neutrino kinetic energy $\simeq V_c$,

i.e., close to the endpoint in both scenarios. Using the weighted average result of all tritium experiments $m_\nu^2 = -27 \pm 20\ eV^2$ [19] in the obtained relation between V_c and m_ν^2 yields $V_c = 4.8$ eV, in good agreement with the expectation for tritium described above; V_c as computed should be able to provide a good fit to the experimental data at hand. Separately and last, it must be mentioned that the fraction $f(\varepsilon)$ is not largely changed by the introduction of V_c (dash-dot line in fig. 1).

The inclusion of this correction in the analysis of present tritium experiments may hopefully recover positive values for m_ν^2 and improve existent limits; a possible common agreement on a $m_\nu^2 > 0$ best-value opens up as an exciting possibility. The fact that most of these experiments seem to be already sensitive to an effect of O(1) eV is encouraging.

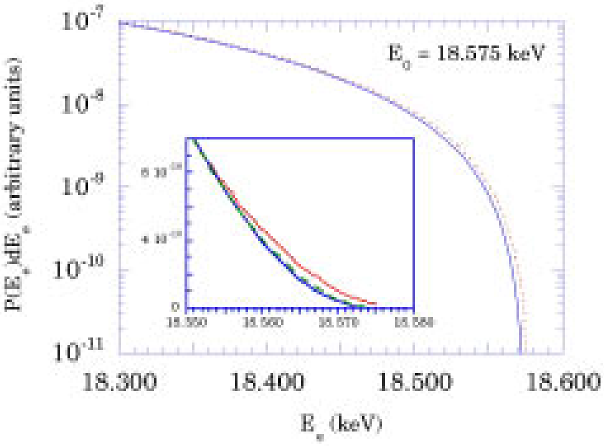

FIG. 2. Tritium theoretical $\beta-$spectrum for $m_\nu = 0$ and a coherent weak potential $V_c = 0$ (solid lines), $V_c = 1\ eV$ (dashed) and $V_c = 4\ eV$ (dotted). The $V_c = 0$ and $V_c = 1\ eV$ lines cannot be differentiated in the log plot. The insert is a linear blow-up of the endpoint region, with all lines normalized to the same value at $E_e = 18.550$ keV. The effect of including the coherent potential correction is similar in shape and magnitude to the endpoint anomaly observed in refs. [5-7,9].

Note added July '99: Some time after the first posting of this preprint, H. Terazawa kindly called my attention to his early work on the neutral current effect in $\beta-$decay [20]. Recently he has revisited this topic [21], arriving at a value $V_c = 4.71\ eV$ for tritium and conclusions similar to those expressed here. After many instrumental improvements, the anomalous $m_\nu^2 < 0$ remains present in the latest data from the Mainz and Troitsk spectrometers [22]. To the knowledge of this author, these groups have not yet attempted to interpret their results in the framework of the present discussion, favoring instead more contrived explanations [22].

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