Beta decay in external field and neutrino mass

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Abstract

The results of the investigation of electromagnetic field effects on the process of beta decay are used for analyzing experimental data on direct neutrino mass search.

The investigation of the effect of electromagnetic fields on the process of beta decay was started long ago. In particular, the effect of plane-wave fields on this process was discussed in [1, 2, 3]. The obtained results indicate that beta spectrum is strongly affected by electromagnetic radiation. On the other hand spectral distribution of β-electrons is most sensitive to neutrino mass \( m_\nu \). In papers [1, 2, 3] the emphasis was made on very strong fields. In our work we consider very weak fields and their effect on beta spectrum.

Let us choose the monochromatic circularly polarized plane wave with frequency \( \omega \) and intensity \( E \) as the model of external field and suppose that \( \omega \ll m_\nu \). Then the total probability of the allowed β-decay for the model with massive Dirac neutrino is:

\[
\frac{W}{W_0} = \frac{\xi^2}{4} \left\{ \int_{t_1}^{t_2} dt \int_{y_1}^{y_2} dy \Phi(t, y) + \Theta(\xi_0 - \xi) \int_{t_0}^{t_1} dt \int_{y_1}^{y_2} dy \Phi(t, y) \right\},
\]

(1)

Here

\[
\Phi(t, y) = (t + y)(\varepsilon_0 - y) \left[ (\varepsilon_0 - y)^2 - \mu^2 \right]^{1/2} \left[ \xi^2 + (y - t)^2 \right]^{-3/2},
\]

(2)

\[
t_0 = 1, \quad \xi_0 = \left[ 2(\varepsilon_0 - \mu - 1) \right]^{1/2}, \quad \beta = (1 - 1/t^2)^{1/2},
\]

where

\[
\xi = eE/m\omega, \quad \mu = m_\nu/m, \quad t = p^0/m, \quad \varepsilon_0 = (M_i - M_f)/m,
\]

(3)

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and $e, m, p^0$ are the charge, mass and total energy of $\beta$-electron. The lower and upper limits of the integral (1) are given by

$$t_{1,2} = (\varepsilon_0 - \mu)(1 + \xi^2/2) \mp \xi(1 + \xi^2/4)^{1/2} [(\varepsilon_0 - \mu)^2 - 1]^{1/2},$$

$$y_{1,2} = t[1 + \xi^2/2 \mp \xi(1 + \xi^2/4)^{1/2}\beta].$$

(4)

For the neutron and approximately for tritium we have $\tilde{W} = G_F^2 m^5 (1 + 3\alpha_0^2) / 2\pi^2$, where $\alpha_0$ is the ratio of the axial and vector constants of weak interaction, and $G_F$ is the Fermi constant.

The behavior of the spectrum is illustrated by plots in Fig. 1 - 5 where $W_0$ is the total probability of beta decay without external field.

When $\xi \ll 1$,

$$t_{\text{max}} \approx \varepsilon_0 - \mu + \xi(\varepsilon_0^2 - 1)^{1/2}.$$  

(5)

Eq. (5) allows us to evaluate the field strength, which is required to observe the effect. If the shift of the spectrum end point induced by neutrino mass is equal to the shift induced by external field, one has

$$E\lambda = \frac{2\pi}{\sqrt{\varepsilon_0^2 - 1}} m_\nu.$$  

(6)

Here $E$ is the radiation field strength (V/m), $\lambda$ is the wavelength of radiation (m), and $m_\nu$ is the neutrino mass (eV).

Figure 1: Tritium beta spectrum.
Figure 2: Tritium beta spectrum: $m_\nu = 0$; $W$ corresponds to $\xi = 0$, $W_1$ corresponds to $\xi = 0.00005$.

Figure 3: Tritium beta spectrum near its end point: dashed line corresponds to $m_\nu = 0$, $\xi = 0$; dotted line corresponds to $m_\nu = 6.8 \text{ eV}$, $\xi = 0$; solid line corresponds to $m_\nu = 0$, $\xi = 0.00005$. 
Figure 4: Tritium beta spectrum near its end point: circles correspond to $\xi = 0$, $m_\nu = 0$; solid lines correspond to $m_\nu = 0$, $\xi = 0.00005$; 0.000034; 0.000017.

Figure 5: Tritium beta spectrum near its end point: circles correspond to $\xi = 0$, $m_\nu = 0$; solid lines correspond to $\xi = 0.00005$, $m_\nu = 0$; 5.1 eV; 6.8 eV.
For tritium $\varepsilon_0 \approx 1.03634$, and the shift of the spectrum end point induced by neutrino mass $\sim 1\text{ eV}$ is equal to the shift induced by microwave radiation with the strength $\sim 10^{-100}\text{ V/m}$.

For $t < t_1$ and $t > t_1$ analytical expressions for beta spectrum are different. If $\mu = 0$, $\xi \ll 1$, $\varepsilon_0 - t \ll 1$, $t > t_1$ the following approximation exists (Fig. 6):

$$\frac{d(W_{eff}/\tilde{W})}{dt} = t\sqrt{t^2 - 1} \left[ 2(\varepsilon_0 - t)^2 - (\varepsilon_0 - t)\sqrt{(\varepsilon_0 - t)^2 - \mu_{eff}^2} \right],$$

(7)

where

$$\mu_{eff}^2 = 2\xi^2 \left[ \frac{\varepsilon_0}{\sqrt{\varepsilon_0^2 - 1}} \ln \left( \frac{\varepsilon_0 + \sqrt{\varepsilon_0^2 - 1}}{\varepsilon_0} \right) - 1 \right].$$

(8)

This approximation was used for analyzing experimental data [4, 5] (the so called “negative neutrino mass squared”). Thus the electromagnetic radiation could be the reason for experimentally observed anomaly in tritium beta spectrum.

Using the Curi plot

$$C \sim \sqrt{\frac{dW/dt}{t(t^2 - 1)^{1/2}}},$$

(9)

we can make the representation of our results more obvious (Fig. 7).
Figure 7: Curi plot for tritium in arbitrary units: solid line corresponds to $m_\nu = 0$, $\xi = 0.00005$; dashed line corresponds to $m_\nu = 0$, $\xi = 0$. 
The numerical estimations demonstrate that the shift in the tritium beta spectrum, which corresponds to neutrino mass $\sim 1$ eV (the limiting accuracy of experiments [4, 5]), can be compensated by a microwave radiation field with the strength of the order of tens of V/m. In planned experiment KATRIN [6, 7], in which the measurement accuracy is supposed to be of the order of 0.1 eV, this can be produced by fields with the strength of the order of units of V/m, which is comparable with background values.

In the analysis of the experimental data, one should investigate the role of possible external sources of radiation, as well as radiation of beta electrons. In fact, since in chambers of experimental setups there exist constant magnetic fields with the magnitude of the order of units of Tesla, maximum of $\beta$-electron electromagnetic radiation belongs to cm-range.

It should be noted that in a more detailed investigation it is necessary to allow for effects related to the energy loss due to transitions to excited states of molecular tritium (see [8]), but in our opinion this factor cannot change main conclusions of the present work.

References

[1] Ternov I.M., Rodionov V.N., Lobanov A.E., and Dorofeev O.F. Pisma v Zh. Eksp. Teor. Fiz. 37 (1983) 288.

[2] Ternov I.M., Rodionov V.N., Dorofeev O.F., Lobanov A.E., and Pavlova O.S. Yad. Fiz. 39 (1984) 1125.

[3] Ternov I.M., Rodionov V.N., Zhulego V.G., Lobanov A.E., Pavlova O.S., and Dorofeev O.F. J. Phys. G. 12 (1986) 637.

[4] Weinheimer Ch., Degenndag B., Bleile A. et al. Phys. Lett. B. 460 (1999) 219.

[5] Lobashev V. M., Aseev V. N., Belesev A. I. et al. Phys. Lett. B. 460 (1999) 227.

[6] KATRIN Collaboration, Osipowicz A. et al. hep-ex/0109033 (2001).

[7] Weinheimer Ch. hep-ex/0210050 (2002).

[8] Jonsell S. and Monkhorst H. J. Phys. Rev. Lett. 76 (1996) 4476.