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PROSPECTS OF MEASUREMENT OF TRITIUM β-DECAY ENDPOINT ENERGY BY X-RAY SPECTROSCOPY

(Presented by E. Lippmaa)

The possibilities of the endpoint energy of the tritium β-spectrum measured by determining the endpoint energy of the X-ray bremsstrahlung spectrum generated by β-decay of tritium dissolved in palladium are considered. One can attain the precision 150 eV by using an X-ray spectrometer with a crystal grid and a detector of the size of 1 dm^2 mounted some kilometers underground.

1. Introduction

So far the measurement of the endpoint regions of non-energetic β-decay spectra such as ^3H and ^{35}S has been the most reliable method for determining the rest mass of the electron antineutrino. The value of $m_{\tilde{\nu}}$ is obtained by the subtraction of two experimental figures encoded in the endpoint region of the β-decay spectrum:

$$m_{\tilde{\nu}}c^2 = E_m - E_0, \tag{1}$$

where E_m is the actual value of the endpoint energy, and E_0 is the total energy released at the reaction. The latter is a constant consisting of all kinetic energies and the rest energy of the antineutrino, and it is revealed by the shape of the spectral curve near the endpoint.

Thus, using the same spectrum for the determination of both E_m and E_0, several groups have investigated β-decay of tritium [1–8], and so far the precision of the measurements has reached 8 eV that results in the antineutrino mass $m_{\tilde{\nu}}=0$ with the upper limit as high as 16 eV.

As a matter of fact, by using an ICR spectrometer, E_0 has been measured by Lippmaa et al. [9] by measuring the difference of the ion masses of tritium and its decay product ^3He. They obtained

$$\Delta M_{T-He} = 18599 \pm 2 \text{ eV}. \tag{2}$$

The precision exceeds that of β-spectrometry achieved so far and for that reason only one figure, E_m, has to be determined from the β-decay spectrum. This leads us to the conclusion that besides universal spectrometers specific ones can be designed for the determination of the endpoint of the spectrum, which, however, may be inappropriate for measuring other parts of the spectrum.

2. Characteristics of the spectrometer

We propose the following idea for a spectrometer of limited application. Tritium is dissolved in palladium. The energetic β-decay electrons hit the Pd atoms and so create X-ray bremsstrahlung. At that each value

of the electron energy E_e generates a certain spectrum of the energy of the X-quanta, the peak energy of which equals E_e. The whole spectrum depends on a number of circumstances, but the peaks of the energies of the electrons and X-rays coincide.

Why choose palladium? There are three reasons for that: *

1. The cross-section of the creation of X-rays is greater for atoms with a greater Z.

2. The K-level of Pd (24.349 keV) is a bit higher than the endpoint to be determined. This results in lesser absorption of the X-quanta of peak energies, while unnecessary noise-creating parts of the spectrum are intensely absorbed.

3. Pd can be charged with large amounts of hydrogen.

Compared to electron spectrometers known so far, the method proposed has some advantages of principle, notably:

1. Contrary to electrons, X-quanta, when passing through matter are either absorbed completely or not at all, but they do not lose energy gradually. The radiation that comes from the interior of the sample can be used. The source is spatial and need not be placed in vacuum.

2. There is no need for shielding against electric and magnetic fields.

3. The expenses depend linearly on the dimensions of the source.

The disadvantages are the following:

1. Each energy value of the electrons is distributed over a wide spectrum of X-rays. This results in intensity losses.

2. In spite of the first advantage, losses due to the absorption in Pd cause the Pd source to be quite a thin sheet with a large surface.

3. A large X-spectrometer is sensitive to background radiation.

3. Absorption of X-rays

The endpoint of the tritium β-decay spectrum 18.6 keV corresponds to the wave length of 0.667 Å. The loss due to the absorption in air is $\sim 0.1\ \mathrm{m}^{-1}$, that means 10% per meter [10].

For the absorption in metals one has to find the depth of penetration of the X-rays with $\lambda = 0.7$ Å. The intensity reduces twice at distances:

$$\begin{aligned} &\text{for} \quad \mathrm{Al} \quad d = 0.5 \text{ mm}, \\ &\qquad\ \ \mathrm{Pd} \quad d = 0.026 \text{ mm}. \end{aligned} \tag{3}$$

This confines the thickness of the source to 0.05 mm and the effective thickness can be taken as $d = 0.03$ mm.

4. β-activity

Let us have a 1 dm^2 sheet of palladium, 0.03 mm thick, loaded with ^{3}H in a 500 times greater volume. The amount of ^{3}H is $1.5 \cdot 10^{-2}\ \mathrm{m}^3$ of gas at normal pressure, or

$$N = 4 \cdot 10^{21} \text{ molecules}. \tag{4}$$

The half-life $T_{1/2}$ of tritium is 12.6 $y = 4 \cdot 10^8$ s, and the β-activity of the total amount of ^{3}H is

$$\frac{\mathrm{d}N}{\mathrm{d}t} = N \frac{\ln 2}{T_{1/2}} = 1.4 \cdot 10^{13} \frac{1}{\mathrm{s}}. \tag{5}$$

* Other candidates for the metal could be Nb or Mo for their good location of the K-level, or Al for its 20 times better transparency to X-rays than that of Pd.

The β-decay spectrum in the case of $m_{\tilde{\nu}}=0$ is

$$\frac{dN(E)}{dt} \sim \sqrt{E^2 - m_e^2 c^4}\, E (E_0 - E)^2, \quad m_e \leqslant E \leqslant E_0, \tag{6}$$

where E is the electron's total energy and m_e is its rest mass. Near the endpoint $E \approx E_0$ the activity for the interval of energies

$$E_0 - \Delta E < E < E_0 \tag{7}$$

is

$$\frac{\Delta N}{N_d} = \left(3.5 \cdot 10^{-13} \frac{1}{(\mathrm{eV})^3}\right) \Delta E^3, \tag{8}$$

where N_d is the total amount of atoms decayed.

A combination of (5) and (8) yields

$$\Delta N = \left(4.9 \frac{1}{\mathrm{s\ (eV)}^3}\right) \cdot \Delta E^3. \tag{9}$$

5. Intensity of X-rays

The intensity of the continuous X-ray spectrum created by monochromatic electrons is given by [11]

$$I_\nu = cZ(\nu_0 - \nu), \tag{10}$$

where I_ν is the energy of X-rays in the unit interval of frequencies ν corresponding to a single electron,

$$c = 5.0 \cdot 10^{-57}\ \mathrm{Js}^2, \tag{11}$$

Z is the atomic number of the metal, ν_0 is the frequency corresponding to the short-wave boundary of the X-rays. Equation (10) can be given in the form

$$\frac{dn_1}{dE} = \frac{cZ}{h^2 E_0} \Delta E e, \tag{12}$$

where n_1 is the number of X-ray quanta and the energies are given in eV-s.

For palladium ($Z=46$) and $E=18600$ eV,

$$\frac{dn_1}{dE} = (4.5 \cdot 10^{-12}\ (\mathrm{eV})^{-2}) \Delta E. \tag{13}$$

For the detection of the endpoint energy the distance ΔE from the endpoint may be taken as equal to the precision of the measurement dE. The integration will add the factor 1/2.

$$\Delta n_1 = (2.3 \cdot 10^{-12}\ (\mathrm{eV})^{-2}) \Delta E^2, \tag{14}$$

which means the number of quanta in the interval ΔE created by one electron.

The total number of X-ray quanta for our 1 dm² source equals the product of (9) and (14):

$$n = (1.1 \cdot 10^{-11}\ \mathrm{s}^{-1}\ (\mathrm{eV})^{-5}) \Delta E^5, \tag{15}$$

i. e. for $\Delta E = 300$ eV $\quad n = 27\ \mathrm{s}^{-1}$

100 eV $\quad 0.1\ \mathrm{s}^{-1}$ (16)

30 eV $\quad 2.7 \cdot 10^{-4}\ \mathrm{s}^{-1} = 1\ \mathrm{h}^{-1}$.

6. Prospects of X-ray spectroscopy

The problem is again reduced to the determination of the endpoint of the bremsstrahlung spectrum at $\lambda = 0.667$ Å. For a crystal grid spectrometer the beam scattering is limited by the dimensions of the spectrometer in one (call it vertical) direction and by the relative precision needed in the other (horizontal) direction. Let us take the vertical scattering 0.1 radians and the horisontal one

$$\Delta E/(20 \text{ keV}) \text{ radians.} \tag{17}$$

Thus, the detectable part of the quanta is

$$\frac{0.1 \cdot \Delta E}{4\pi \cdot 20 \text{ keV}} = \left(4 \cdot 10^{-7} \frac{1}{\text{eV}}\right) \Delta E \tag{18}$$

that gives the number of quanta to be registered as

$$n_r = (4.4 \cdot 10^{-18} \text{ s}^{-1} (\text{eV})^{-6}) \Delta E^6, \tag{19}$$

or,

for $\Delta E = 1000$ eV	$n_r = 4.4$	s^{-1}
300 eV	11	h^{-1}
150 eV	4.3	d^{-1}
100 eV	0.4	d^{-1}
50 eV	0.2	month^{-1}.

(20)

At low counting rates the main obstacle is the radiation background; especially the presence of tritium can make the elimination of radioactive contamination difficult. To suppress the background of cosmic origin the device must be mounted deep underground. At the depths of 5 km of water equivalent the cosmic muon background is 1 muon per day to square meter [12]. At depths twice bigger (or smaller), the muon radiation changes by two orders of magnitude. That would limit the precision of our measurements to 50 eV.

Still, the decisive limiting factor would be the natural γ-ray background. Following [13], one can estimate the counting rate for a 1 dm×1 dm×1 mm Ge(Li) detector as 4 $(\text{keV} \cdot \text{d})^{-1}$. The detector resolution of 0.3 keV would give the background γ-ray counting rate as 1.3 d^{-1}.

Thus, the conclusion can be drawn that the method described enables to achieve a precision as high as 150 eV. Further increase in the precision is possible by improving the energy resolution of the detector and by using an underground site with smaller natural radioactivity.

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TRIITIUMI β-LAGUNEMISE TIPPENERGIA MÕÕTMISE PERSPEKTIIVID RÖNTGENSPEKTROSKOOPIA ABIL

On uuritud võimalust mõõta triitiumi β-lagunemise spektri tippenergiat, määrates röntgen-pärsskiirguse spektri tippenergia, mis tekib pallaadiumis lahustatud triitiumi β-lagunemisel. Rakendades röntgenspektromeetrit, mille kristallvõre ja detektor on 1 dm^2 suurusjärgus ja mis on paigutatud mitme kilomeetri sügavusele maa alla, võib saavutada täpsuse 150 eV.

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ПЕРСПЕКТИВЫ ИЗМЕРЕНИЯ ЭНЕРГИИ КОНЦА СПЕКТРА β-РАСПАДА ТРИТИЯ С ПОМОЩЬЮ РЕНТГЕНОВСКОЙ СПЕКТРОСКОПИИ

Обсуждаются перспективы измерения энергии конца спектра β-распада трития путем измерения рентгеновского спектра, который появляется при β-распаде трития, растворенного в палладии. Используя расположенный в нескольких километрах под землей рентгеновский спектрометр с кристаллической решеткой и детектором размерами в один квадратный дециметр, можно достичь точности до 150 эв.