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journal or publication title	CYRIC annual report
volume	1986
page range	4-9
year	1986
URL	http://hdl.handle.net/10097/49318

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The mass of the electron antineutrino has been studied for a long time using the tritium β-ray spectrum, while the mass of the electron neutrino (m_{ν_e}) has been recently investigated using electron capturing isotopes including ^{163}Ho, ^{193}Pt and so on.[1-3] In the latter there are two ways to measure m_{ν_e}; one proposed by De Rújula[4] which is essentially based on three-body phase space in radiative electron capture process, and another which utilizes the m_{ν_e}-dependence of the electron capture rate as discussed by Bennett et al.[5] In both cases, electron capturing nuclei having a low Q value seem to be favorable. A nucleus that decays by electron capture with the lowest Q value of any known β-decay process is holmium-163, which was discovered by the Princeton group in 1968.

Considerations of the intensity of internal bremsstrahlung spectra at electron capture in ^{163}Ho seem to indicate that the first approach is rather difficult for measuring m_{ν_e}. The present report describes our recent measurement of the mass of the electron neutrino using electron capture in ^{163}Ho, which falls under the second category.

If $S_p^{^{163}Ho}$ stands for an M X-ray spectrum from ^{163}Ho, where the number of photons per atom per second is plotted as a function of the energy of the photons, we then have

$$S_p(x)^{^{163}Ho} = (1/N) \times [(dN_{M_1}/dt)S_{M_1}(x)+(dN_{M_2}/dt)S_{M_2}(x)]$$
$$= \lambda_{M_1}S_{M_1}(x)+\lambda_{M_2}S_{M_2}(x) , \qquad (1)$$

where $S_{M_i}(x)$ (i=1,2) is the M X-ray spectrum when there is one vacancy in the M_i subshell only; x is the channel number; dN_{M_i}/dt (i=1,2) is the number of vacancies produced per second in the M_i subshell in the decay $^{163}\mathrm{Ho} \xrightarrow{EC} {}^{163}\mathrm{Dy}$;

N is the total number of ^{163}Ho atoms in a ^{163}Ho source; λ_{Mi} (i=1,2) is the partial M_i-capture decay constant.

Eq. (1) tells us that when we reconstruct $S_p^{^{163}Ho}$ using the S_{M_1} and S_{M_2} spectra, the coefficients of S_{M_1} and S_{M_2} used in the reconstruction correspond to λ_{M_1} and λ_{M_2} , respectively.

The photon spectrum from the ^{163}Ho source was measured in vacuum with a Si(Li) detector (ORTEC) having a Be window 0.3 mm thick (nominal). The production of ^{163}Ho using the ^{164}Dy(p,2n) reaction and the preparation of the ^{163}Ho source are described in our previous paper.$^{2)}$ The whole apparatus was shielded with lead 100 mm thick. The counting time was 28.89 d. The geometry of the Si(Li) detector, including the effective area of a silicon crystal and the solid angle, was carefully measured using several radioactive sources. The thickness of the Be window of the Si(Li) detector was also checked by comparing a photon spectrum measured using this detector with that measured using a windowless Si(Li) detector (HORIBA, Japan).$^{6)}$

The total number of ^{163}Ho atoms in the ^{163}Ho source, N, was measured with isotope-dilution mass spectrometry to be $N = (6.481 \pm 0.012) \times 10^{15}$ atoms, which is in good agreement with the previous value determined by the PIXE method$^{5)}$ within experimental uncertainties.

The number of photons included in the S_{M_1} and S_{M_2} are represented by

$$\begin{aligned} S_{M_1}: \ & \omega_1+f_{12}\omega_2+(f_{13}+f_{12}f_{23})\omega_3 \\ & +(f_{14}+f_{12}f_{24}+f_{13}f_{34}+f_{12}f_{23}f_{34})\omega_4 \\ & +(f_{15}+f_{12}f_{25}+f_{13}f_{35}+f_{14}f_{45}+f_{12}f_{23}f_{35} \\ & +f_{12}f_{24}f_{45}+f_{13}f_{34}f_{45}+f_{12}f_{23}f_{34}f_{45})\omega_5, \end{aligned} \tag{2}$$

$$\begin{aligned} S_{M_2}: \ & \omega_2+f_{23}\omega_3+(f_{24}+f_{23}f_{34})\omega_4 \\ & +(f_{25}+f_{23}f_{35}+f_{24}f_{45}+f_{23}f_{34}f_{45})\omega_5 , \end{aligned} \tag{3}$$

where ω_i (i=1,...,5) is the M_i subshell fluorescence yield and f_{ij} is the Coster-Kronig coefficient for vacancy transition from the M_i subshell to the M_j subshell. When the total level width of the M_i subshell is Γ_i , the fluorescence yield for this subshell is defined as

$$\omega_i = \sum_j \gamma_{ij}/\Gamma_i ,$$

where γ_{ij} is the partial radiative width corresponding to the electron transition from the X_j subshell to the M_i subshell, and X denotes shells higher than the M shell.

Since no relativistic calculation of nonradiative transition probabilities for dysprosium has been reported so far, we estimated the values of f_{ij} and Γ_i from the nonrelativistic values of McGuire$^{7)}$ and the relativistic values of Chen et al.[8,9] for holmium and ytterbium. The results are shown in Table 1. The partial radiative width γ_{ij} was taken from the relativistic calculations by Mukoyama and Adachi.[10]

The $S_{M_1}(x)$ and $S_{M_2}(x)$ spectra were constructed from various characteristic X-ray lines corresponding to γ_{ij} in Eqs. (2) and (3) using response functions of the Si(Li) detector used in the measurement of the photon spectrum from the ^{163}Ho source. The response functions were measured using monochromatic photons from the undulator beam line of the 2.5 GeV Electron Storage Ring at the Photon Factory in KEK.

When we tried to reconstruct the $S_p^{^{163}Ho}$ spectrum using the theoretical $S_{M_1}(x)$ and $S_{M_2}(x)$ spectra mentioned above, it was found that there were some discrepancies around the 1.3 keV and 2.0 keV peaks. Therefore, the non-linear least-squares method was applied to minimize the χ^2-value for fitting Eq. (1), taking three radiative widths, $\gamma_{M_5N_7}$, $\gamma_{M_4N_6}$ and $\gamma_{M_1O_{2,3}}$, as unkowns in addition to λ_{M_1} and λ_{M_2}, as shown in Fig. 1.

The results are

$$\lambda_{M_1} = (0.9740\pm0.0041)\times10^{-12}s^{-1},$$

$$\lambda_{M_2} = (0.0817\pm0.0035)\times10^{-12}s^{-1},$$

with

$$\gamma_{M_5N_7} = 1.749\times10^{-3}\ \mathrm{eV}\ ,$$

$$\gamma_{M_4N_6} = 1.340\times10^{-3}\ \mathrm{eV}\ ,$$

$$\gamma_{M_1O_{2,3}} = 2.159\times10^{-3}\ \mathrm{eV}\ .$$

It is worth mentioning that the S_{M_1} and S_{M_2} thus obtained, are compatible with those deduced from fluorescence spectrum measurements on dysprosium using monochromatic photon beams at the Photon Factory in KEK.[6]

On the other hand the halflife of the ^{163}Ho nucleus was determined by measuring the production rate of ^{163}Dy due to electron capture in ^{163}Ho with isotope-dilution mass spectrometry[11] as initially done by Baisden et al.[12] Our result was

$$T_{1/2} = 4569\pm27\ \mathrm{yr}\ (68\%\ \mathrm{CL})$$

or

$$\lambda_t = (4.807\pm0.028)\times10^{-12}s^{-1}\ ,$$

which is in excellent agreement with the value of Baisden et al.[12]

Using the experimental values of λ_{M_1}, λ_{M_2} and λ_t thus obtained as three constrains, m_{ν_e}, the Q-value and the nuclear matrix element, $|m_N|^2$, for the decay of ^{163}Ho, were determined from the formula of the electron capture rate as follows:

$$m_{\nu_e} = 205^{+345}_{-205}\ \text{eV}\ , \quad Q = 2.70^{+0.13}_{-0.02}\ \text{keV}\ ,$$

$$|m_N|^2 = 0.0409^{-0.0033}_{+0.0016}$$

or

$$\log ft = 4.98^{+0.04}_{-0.02}\ .$$

A summary of the final results for m_{ν_e} and the Q-value is shown in Fig. 2.

Therefore we conclude

$$m_{\nu_e} < 550\ \text{eV}\quad (68\%\ \text{CL}).$$

In addition it should be noted that our estimation of the log ft value lies in between the value of the CERN-Aarhus group$^{1)}$ and that of the Princeton-Livermore group.$^{12)}$

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Table 1. M-shell Coster-Kronig coefficients f_{ij} and level width Γ_i for dysprosium.

f_{ij}	value	Γ_i	value(eV)
f_{12}	0.307	Γ_1	14.94
f_{13}	0.599	Γ_2	9.04
f_{14}	0.085	Γ_3	9.27
f_{15}	0.116	Γ_4	1.81
		Γ_5	1.24
f_{23}	0.091		
f_{24}	0.665		
f_{25}	0.141		
f_{34}	0.149		
f_{35}	0.747		
f_{45}	0.348		

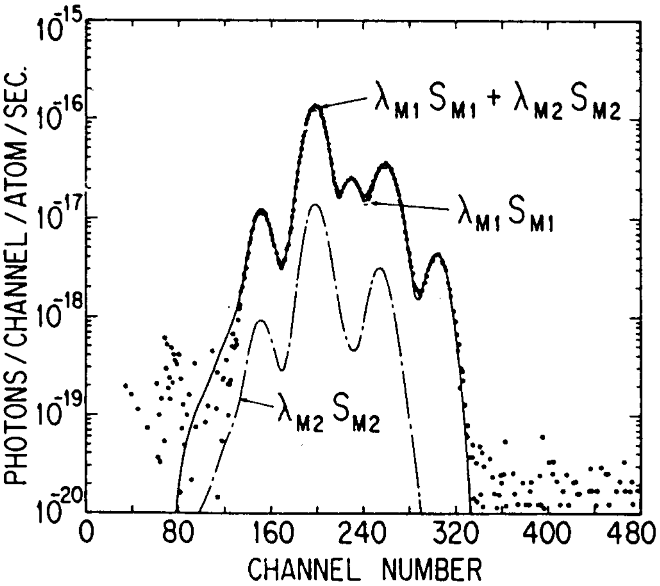

Fig. 1. Reconstruction of the $S_p^{^{163}\mathrm{Ho}}$ spectrum using the S_{M_1} and S_{M_2} spectra. The solid curve, the broken curve and the dot-dashed curve represent $\lambda_{M_1}S_{M_1}+\lambda_{M_2}S_{M_2}$, $\lambda_{M_1}S_{M_1}$ and $\lambda_{M_2}S_{M_2}$, respectively. Closed circles represent experimental data of $S_p^{^{163}\mathrm{Ho}}$.

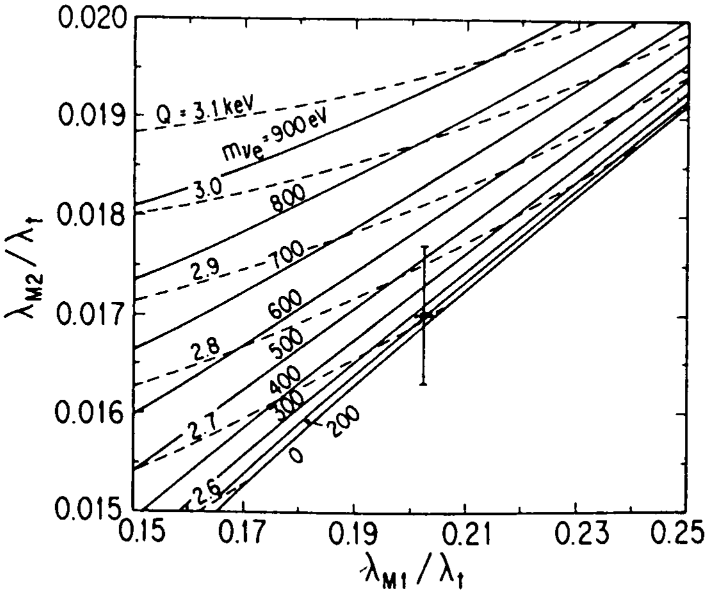

Fig. 2. Summary of the final results for m_{ν_e} and Q-value.