Neutrino Mass from the Beta Spectrum in the Decay of Tritium

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(Received 12 November 1986)

The data from the spectrum measurement of the tritium decay in a valine molecule carried out in a wide energy range (3.4 keV) with the Institute of Theoretical and Experimental Physics spectrometer are analyzed. The combined analysis of both these data and the data of the previous cycle gives the neutrino mass 30.3^{+2}_{-8} eV. The model-independent mass interval $17 < M_\nu < 40$ eV is derived from the mass difference of the doublet ^{3}H-^{3}He.

PACS numbers: 23.40.Bw, 14.60.Gh

This paper is the further development of the known investigation on the neutrino mass in beta decay.[1-3] The results of a new series of measurements and the analysis of the beta spectrum of tritium in a valine molecule are presented. The magneto-electrostatic spectrometer is described in Ref. 2. We note that the beta spectrum is scanned by electrostatic-field variation while the focusing magnetic field was kept constant, i.e., the value of electron energy registered by the detector was fixed. In the given set of measurements the electrons at the energy 21.2 keV were focused by the magnetic system, which exceeds the electron-energy limit of the tritium spectrum.

A proportional chamber with six channels is used as a detector. The measurements are taken with a nonequipotential source, yielding a continuous focusing potential secured by the backing made of weakly conducting glass. In this way we reached the 20-eV resolution by narrowing the detector slits and regained intensity by increasing the number of channels. With the improved resolution we can explore the "mass-sensitive" 25-eV end portion of the spectrum where the effect and background contributions are nearly equal. The spectrometer calibration was carried out with more than twenty conversion lines of different gamma transitions of ^{169}Tm. The calibration coefficients are determined from the energy balance for a conversion electron, the transition energies being known with high precision (not employing the data on electron-shell binding energy for ^{169}Tm). From this equation we extracted the differences of binding energies for different shells, and they are in good agreement with Sevier,[4] except for those involving the shell M_3. We estimate the accuracy of the calibration measurements as 3 eV. As before, for the evaluation of the neutrino mass and the end-point energy we used the data-fitting procedure employing the model spectrum,

$$N^{\text{th}}(E) = AS(E), \quad S(E) = \int dE' R(E,E')[1+\alpha_L(E'-E_0)][1+\alpha_S(E'-E_0)^2]\sum_k W_k f_k(E',M_\nu,E_0),$$

$$f_k(E',M_\nu,E_0) = PE_t F(E')(E_0-\epsilon_k-E')[(E_0-\epsilon_k-E')^2-M_\nu^2]^{1/2}.$$

This investigation was aimed at thorough experimental analysis of the resolution function, involving its optical component and the component determined by the ionization losses in the source. The beta-spectrum measurements performed in a widened energy range are sensitive to the long tails of the function R, as well as to the possible heavy-neutrino admixture in the mass below 3 keV.

The total response function of the spectrometer (TRF) is the convolution of the optical resolution function (F_{OR}) with the ionization-loss spectrum (S_{IL}) of monoenergetic electrons interacting with the source material (including the spectrum of backward scattering from the backing).

The F_{OR} measurement was carried out in a direct experiment free from any assumptions about the test-line shape. The conversion of the L_1 line of ^{169}Tm ($E_c = 10.6$ keV) was thoroughly measured in the accelerating field with the focusing energy $E = 21.2$ keV corresponding to the working cycle of measurements. The line obtained under these conditions is the convolution of the sought optical line which corresponds to the working conditions, $F_{\text{OR}}(21.2)$, with S_{IL} in Yb, with the shake-off spectrum (S_{SO}), and with a Lorentzian with $\Gamma = 5.2$ eV:

$$L_1(21.2) = F_{\text{OR}}(21.2) * S_{\text{IL}} * S_{\text{SO}} * \Gamma.$$

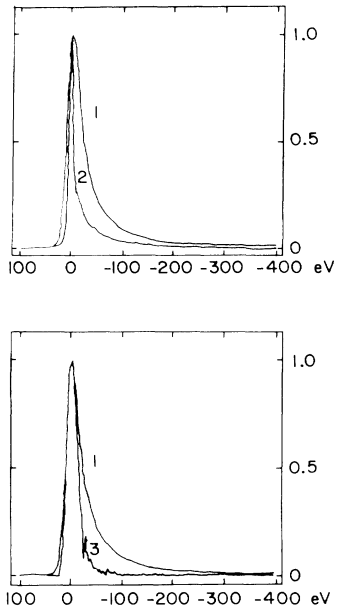

FIG. 1. The F_{OR} determination in the direct experiment. Curve 1, $-L_1(21.2)$; curve 2, $-L_1(2)$; curve 3, $-F_{OR}$.

Then the same line was measured with "deceleration" at $E=2$ keV:

$$L_1(2)=F_{OR}(2)*S_{IL}*S_{SO}*\Gamma.$$

When one passes from "acceleration" to deceleration S_{IL}, S_{SO}, and Γ remain unchanged while F_{OR} gets narrower by an order of magnitude turning into the δ function.

Thus (see Fig. 1) we get the sought optical resolution function involving the deconvolution procedure,

$$L_1(21.2):L_1(2)=F_{OR}(21.2):F_{OR}(2)=F_{OR}(21.2).$$

(In reality this problem was solved without the above mentioned approximations, made for simplicity.) There were also other experimental ways of the F_{OR} determination.[5] In the subsequent analysis the spread resulting from different ways of the F_{OR} determination was taken into account in terms of systematic errors. Other contributions of the TRF, specifically S_{IL} and the backscatter spectrum, have been studied experimentally.[5] Moreover the wide-range fit interval 3.4 keV has been treated as a sensitive test for the TRF shape adequacy. The total resolution function is shown in Fig. 2.

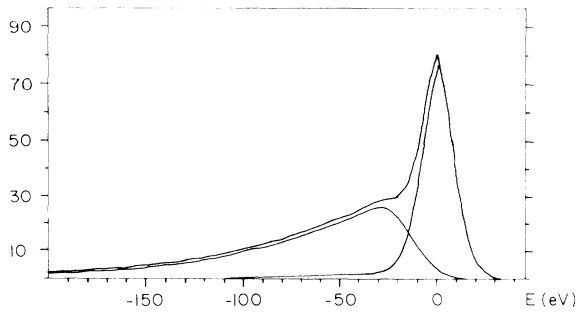

FIG. 2. The total resolution function for the working source. The contributions of F_{OR} and S_{IL} are shown.

The scan of the experimental beta spectrum was made in two runs. The first one was "standard": 41 points in 50-eV steps (A) and 61 points in 5-eV steps (B), exposition time being 100 and 300 sec at each point, correspondingly. On the whole the first run contained 34 series of double (A-B) measurements and covered the interval 1.7 keV of the beta spectrum. The second run, 75 points, 50-eV steps, and 200 sec, contained 14 series and covered the interval 3.4 keV. The total statistics is $55\times10^3/(100\text{ eV})$ at the end-point region.

The shorter the fitting interval is from the end of the beta spectrum, the more insignificant is the influence of the total resolution shape on the value of the obtained parameters including those of physical significance such as M_ν and E_0. Really, the parameter values do not depend at all on the TRF shape beyond the limits of the fitting interval. On the contrary, the wider the fitting interval is, the stronger the dependence of the parameters on the TRF form. Only when the TRF is completely adequate are the fitted parameters independent of the

TABLE I. Experimental spectrum of this work and recalculated spectrum of previous runs (Ref. 3): standard F_{OR} and S_{IL}; valine. The systematic errors are shown in brackets. The total statistic: $130\times10^3/(100\text{ eV})$.

	ΔE (eV)	1680		330	
	T	M_ν^2 (eV^2)	$E_0-18500$ (eV)	M_ν^2	$E_0-18500$ (eV)
This work	1.98	$875\pm109(210)$	$80.9\pm0.6(2)$	$673\pm122(180)$	$79.3\pm0.8(2.5)$
Ref. 3	2.10	$990\pm193(180)$	$81.5\pm1.1(2)$	$965\pm260(130)$	$81.4\pm1.4(2.5)$
	2.27	$1088\pm106(180)$	$81.8\pm0.6(2)$	$1094\pm152(150)$	$81.8\pm0.6(2.5)$
	2.82	$989\pm100(210)$	$80.9\pm0.6(2)$	$773\pm90(180)$	$79.1\pm0.8(2.5)$
Average		$970\pm50(160)$	$81.2\pm0.3(1.7)$	$870\pm70(140)$	$80.3\pm0.4(2.3)$
		$M_\nu=30.3\pm2$	$E_0=18580.8\pm(4)$[a]		

[a]The absolute calibration error included.

TABLE II. Result of joint fit to data of this work and Ref. 3.

ΔE	M_ν^2	E_0	α_L (10^{-5} eV^{-1})	α_S (10^{-8} eV^{-1})	A	χ^2
			M_ν^2 fitted			
3400	984 ± 50	81.0 ± 0.2	-1.65 ± 0.12	0.13 ± 0.02	0.9896 ± 0.0016	510/472
1680	966 ± 50	80.8 ± 0.2	-1.60 ± 0.12	0.13 (fixed)	0.9907 ± 0.0016	429/407
330	852 ± 66	80.0 ± 0.4	-1.60 (fixed)	0.13 (fixed)	0.9991 ± 0.0039	265/247
			M_ν fixed at 0			
3400	0	76.4 ± 0.1	-0.06 ± 0.10	0.35 ± 0.02	1.0139 ± 0.0012	1165/473
1680	0	76.3 ± 0.1	-0.00 ± 0.08	0.35 (fixed)	1.0144 ± 0.0012	1032/408
330	0	74.0 ± 0.2	0.00 (fixed)	0.35 (fixed)	1.0529 ± 0.0024	475/248

width of the fitting interval. The broadening of the beta-spectrum range of measurements, up to 3.4 keV, made in the present work appeared to be an extremely sensitive mode for choosing the right shape of the TRF. Thus, choosing the shortest fitting interval (so far as statistics make it possible) we get the physical parameters (M_ν and E_0) with the smallest systematic errors resulting from uncertainty in the TRF form. At the same time the widest fitting interval serves to test the adequacy of the TRF.

Having at our disposal the checked form of F_{OR} and S_{IL} we recalculated the experimental spectra of the previous runs.[3] The results are given in Table I.

The results of the earlier investigation[3] are in reasonable agreement with those given in the present work. The results of the joint data fit are given in Table II. The fit of data with the neutrino mass set equal to zero is also presented in the table. The shape of the curve at $M=0$ does not describe the experimental spectrum in any of the fit intervals, which can be seen from the table. Shown in Fig. 3 are the end-point regions of the experimental and fitted spectra.

All results above were obtained with the theoretical spectrum of final states (SFS).[6] Kaplan *et al.* calculated the essential part of the SFS corresponding to the states in the discrete spectrum.

The uncertain residual part (RP) with weight $W_\Gamma = 10\%$ includes discrete levels that have not been calculated because of the limited number of configurations and the whole continuum. At the same time the following properties of the SFS are calculated with high accuracy: the transition probability W_0 to the ground state, the average energy of the SFS, $\Delta\bar{E}^* = 18.8$ eV, and the SFS variance $\sigma_T^2 = 1281.6$ eV^2. The method itself implies that these values comprise the total SFS (although it was not calculated in Ref. 6), and thus provide information about the RP.

The data given in the tables correspond to the single-level representation of the RP with $\epsilon_\Gamma = 61.6$ eV directly determined by W_Γ and $\Delta\bar{E}^*$. The systematic error does not cover the RP uncertainty. At the same time the variance of the SFS with a single level turns out to be substantially smaller (≈ 600 eV^2) than σ_T^2.

The requirement that the variance should be correct makes it possible to represent the RP by two levels with one free parameter. At first glance it seems that the SFS with larger variance will only lead to an increase in M_ν. But the fit shows that there are some regions in the variation of the two-level RP where the decrease of M_ν^2 is distinct.

This fact being taken into consideration, the result can be represented as $M_\nu = 30.3^{+2}_{-8}$ eV where the increase of the systematic error corresponds to the RP with decreased M_ν^2.

The mass difference of the neutral atoms of tritium and helium can be calculated from the fitted value of the parameter E_0, employing the data of Ref. 6. The value $\Delta M_{T\text{-}He} = 18600.3 \pm 4$ eV obtained from E_0 is in excellent agreement with the mass measurements of the doublet T-He carried out by Lipmaa *et al.*[7] with the ion-cyclotron-resonance spectrometer, $\Delta M_{T\text{-}He} = 18599 \pm 2$ eV.

The usual practice of determining both a systematic error and a confidence level is not readily applied in this case because it is difficult to predict the range of unconsidered variations of the SFS and the TRF and even more difficult to estimate the likelihood of their oc-

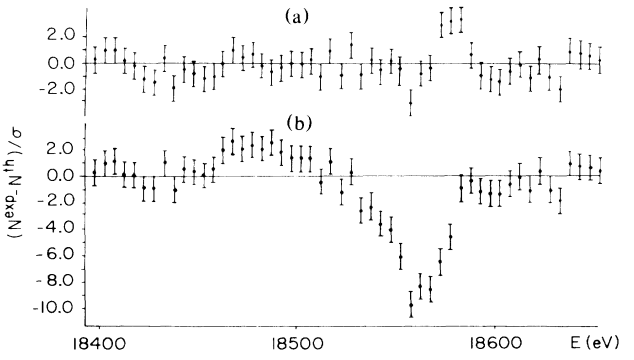

FIG. 3. The end-point region of the experimental and fitted (in the range 1.7 keV) spectra. The fitted curves are taken for the zero lines. The values normalized to standard statistical errors are plotted along the ordinate axis. (a) $M_\nu^2 = 966$, $E_0 = 18580.8$; (b) $M_\nu^2 = 0$, $E_0 = 18576.3$.

currence.

However, there is a possibility of our estimating the mass interval without employment of model allowances, as fit parameters M_ν^2 and E_0 reveal strong correlations with any variation of functions entering in Eq. (1): Decreased E_0 leads to a lower value of M_ν^2 and vice versa. At the same time it is clear that data on $\Delta M_{\text{T-He}}$ limit the possible values of E_0. For example, the employment of the SFS model with one level (nucleus) instead of the SFS for valine decreases E_0 by 18 eV, which is incompatible with the data of Ref. 7.

Thus, having traced out a correlation trajectory on the M_ν^2 and E_0 plane,[8] with E_0 values being restricted to the level ± 6 eV, we obtain the least model-sensitive interval of acceptable mass $17 < M_\nu < 40$ eV.

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[7]E. Lipmaa *et al.*, Phys. Rev. Lett. **54**, 285 (1985).

[8]This dependence is revealed by variation of the SFS and the TRF in the fitting of the experimental data as well as a Monte Carlo procedure.