Neutrino mass determined from the β spectrum (ITEP-86)

S. D. Boris, A. I. Golutvin, L. P. Laptin, V. A. Lyubimov, N. F. Myasoedov,[1)]
V. V. Nagovitsyn, V. Z. Nozik, E. G. Novikov, V. A. Soloshchenko,
I. N. Tikhomirov, and E. F. Tret'yakov
Institute of Theoretical and Experimental Physics

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Recent results of experimental measurements of the neutrino mass are reported. This new series of measurements was carried out with the ITEP spectrometer during 1985–1986. The results of these measurements are analyzed jointly with the data obtained in the preceding series of measurements.

The ITEP-86 study is a continuation of a cycle of experimental studies.[1–3] The aim of this study was to thoroughly analyze the total resolution function (TRF), including the optical component of this function (ORF) and the component which is determined by the ionization loss spectrum (ILS) of the source material. All these functions were determined experimentally, and the method used to determine them is described in Ref. 4. The suitability of TRF for experimental data was tested by analyzing the β spectra of the experimental material. The β spectra were studied over a broad energy range and the fitting was done over energy intervals of various widths. The shorter the energy interval of the fitted data, the smaller is the effect of TRF on the parameters (including the physically important parameters) of the model which are obtained: M_ν and E_0. Conversely, the broader the interval, the stronger is the dependence of the parameters on the shape of the TRF. The parameters which are found are independent of the width of the energy interval only when the TRF is totally compatible with the actual conditions. Choosing the narrowest (allowed statistically) energy interval, we find the physical parameters M_ν and E_0 with the lowest systematic errors due to the indeterminacy of the TRF. At the same time, a broad energy interval is used to test the suitability of TRF. The fact that the parameters obtained by fitting

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in the energy intervals of various widths could be compared proved to be a very sensitive tool in choosing the correct shape of TRF.

In the last series of measurements (ITEP-86), the interval over which the β spectrum was measured was extended to 5.5 keV. Furthermore, the statistical base was increased tenfold in the principal fitting energy interval (1.7 keV) All these factors have made it possible to appreciably reduce (by a factor of 1.5) the systematic errors due to the uncertain shape of the TRF (ionization losses, backscattering, ORF tails).

The neutrino mass and the end-point energy were estimated by fitting the experimental data to the model-based spectrum (see the equations in Ref. 4). The results of the fitting in the various energy intervals for all the series of measurements between 1983 and 1986 are summarized in Table I. These results correspond to the theoretical spectrum of the final states of a valine molecule (valine is the working material of the source) in the decay of tritium.[5] The probability for the transition to the ground state, $W_0 = 0.612$, and the integrated characteristics of the final-state spectrum, $\Delta\overline{E}^* = \bar{\epsilon} = 18.8$ eV and $\sigma_T^2 = \bar{\epsilon}^2 - \epsilon^2 = 1281.6\ \text{eV}^2$, were calculated very accurately in Ref. 5. The last values include all possible discrete states and the continuum. The discrete values ϵ_k and their probabilities W_k were calculated with allowance for the electron correlations. The probability for the transition to all calculated states is $\Sigma W_k = 0.893$. The residual part of the spectrum, which was not calculated by the authors, includes the discrete levels, which were omitted because of the disregard for some of the electronic configurations, and the continuum, which cannot be calculated. The values $M_\nu = 29 \pm 3$ eV and $E_0 = 18580.9 \pm 4$ eV, which are averaged over the data of Table I, and the values obtained in Ref. 4, which are approximately equal to them (the values of Ref. 4 do not include the experimental data obtained in 1986), were obtained under the assumption that the residual part of the spectrum can be represented by a single level with $W_r = 0.10 \pm 0.02$ and $\epsilon_r = (\Delta\overline{E}^* - \bar{\epsilon}_k)/W_r = 61.6$ eV. The errors in the values of M_ν and E_0 were obtained as the sum of the statistical error at the 95% confidence level and of the systematic error. The systematic error includes all variations of the TRF components and of the calibration within the error limits of their experimental determination, except for the variations of the theoretical final-state spectrum. We will examine here such variations and their effect on the physical parameters.

At fixed values of W_0 and $\Delta\overline{E}^*$ the variation of W_r between 0.05 and 0.15 (which is 2.5 times higher than the error in Ref. 5), with a proportional variation of $W_{k\neq 0}$ and an unambiguous determination of ϵ_r, does not change the physical parameters appreciably. We call attention, however, to the dipersion of such a final-state spectrum. In a single-level representation of the residual part of the spectrum, the dispersion is considerably *smaller* ($\sigma_1^2 = 696.7\ \text{eV}^2$) than σ_T^2. By using the information contained in σ_T^2 and fixing the dispersion of the final-state spectrum at this level allows us to represent the residual part of the spectrum by using two levels, ϵ_{r1} and ϵ_{r2}, or a continuous power function with a single variable parameter (ϵ_{r1}, for example). At first glance, the use of the final-state spectrum with a *larger* dispersion would seem only to increase the value[6] of M_ν. Upon fixing the values of W_0, $\Delta\overline{E}^*$, and σ_T^2, however, the presence of the adjusting parameters, α_L and α_S (see Ref. 4), in the β-spectrum model accounts for such ranges of variation for which the mass parameter

TABLE I.

Width of the energy interval ΔE (keV)			3.4			1.7			0.3		
Exposition		T/T_0	M_ν^2	$E_0 - 18500$	χ^2	M_ν^2	$E_0 - 18500$	χ^2	M_ν^2	$E_0 - 18500$	χ^2
–	1	2, 82	–	–	–	809 ± 58	80, 3 ± 0, 3	$\frac{316}{299}$	893 ± 133	80, 8 ± 0, 9	$\frac{188}{165}$
83	2	2, 27	–	–	– –	805 ± 61	80, 1 ± 0, 3	$\frac{484}{505}$	954 ± 109	81, 1 ± 0, 7	$\frac{264}{318}$
–	3	2, 10	–.	–	–	810 ± 120	80, 8 ± 0, 5	$\frac{463}{504}$	990 ± 198	82, 1 ± 1, 2	$\frac{301}{316}$
85		1, 98	942 ± 371	80, 2 ± 0, 8	$\frac{444}{366}$	887 ± 88	82, 4 ± 0,3	$\frac{337}{302}$	682 ± 148	81, 2 ± 0, 9	$\frac{185}{193}$
86		2, 57	837 ± 99	80, 1 ± 0, 3	$\frac{831}{683}$	794 ± 106	79, 9 ± 0, 3	$\frac{469}{410}$	709 ± 244	79, 4 ± 1, 2	$\frac{72}{67}$
–		–	844 ± 96	80, 1 ± 0, 3	–	818 ± 34	80, 7 ± 0, 16	–	860 ± 66	81, 0 ± 0, 4	–
–		–	846 ± 35 (138)	81, 0 ± 0, 16 (1, 5)	$\frac{633}{601}$	855 ± 33 (103)	81, 0 ± 0, 15 (1, 4)	$\frac{580, 7}{541}$	822 ± 75 (126)	80, 9 ± 0, 4 (1, 4)	$\frac{289}{272}$

T-Thickness of the source

T_0-Mean free path of electrons.

TABLE II.

	Model for the residual part of the final-state spectrum							
	One level		Two levels				E^{-2}	$E^{-3,3}$
E_{r_1}/E_{r_2}, эВ	61.6/–	79.0/–	51.6/585	41.6/242	31.6/195	21.6/121	17/540	35/∞
W_{r_1}/W_{r_2}, %	10.0/0.0	5.0/0,0	9.8/0,2	9.3/0,7	8.6/1,4	7.8/2,2	10.0	10.0
M_ν^2	855 ± 33	868 ± 35	733 ± 38	646 ± 39	641 ± 38	675 ± 36	662 ± 38	756 ± 36
$E_0 - 18500$	81.0 ± 0.2	80,9 ± 0,2	80,1 ± 0,2	79,2 ± 0,2	78,7 ± 0,2	78,4 ± 0,2	78,7 ± 0,2	80,0 ± 0,2
χ^2	581/541	583/541	572/541	575/541	596/541	624/541	586/541	579/541

$\Delta E = 1,7$ keV

Parameters of the two-level residual part of the spectrum:

$$W_{r_1} = \frac{W_r \Delta\sigma^2}{\Delta\sigma^2 + W_r(\epsilon_r - E_{r_1})^2},\ W_{r_2} = W_r - W_{r_1};\ E_{r_2} = \epsilon_r + \frac{\Delta\sigma^2}{W_r(\epsilon_r - E_{r_1})}\ \Delta\sigma^2 = \sigma_T^2 - \sigma_1^2.$$

Parameters of the power-law model are determined from the following equations:

$$\int_{E_{r_1}}^{E_{r_2}} NE^{-\alpha}\,dE = W_r;\ \int_{E_{r_1}}^{E_{r_2}} NE^{-\alpha+1}\,dE = \epsilon_r;\ \int_{E_{r_1}}^{E_{r_2}} NE^{-\alpha+2}\,dE = \epsilon_r^{\,2} + \frac{\Delta\sigma^2}{W_r}.$$

decreases appreciably. The data on the variation of the residual part of the spectrum are given in Table II. The result of these variations, with averaging over the various hypotheses of the residual part of the spectrum, can be represented as $M_\nu = 29 \pm^{3}_{8}$ eV, where the magnified statistical error corresponds to the limiting possibility of the final-state spectrum, which reduces the mass, or it can be represented as $M_\nu = 26 \pm^{6}_{5}$ eV and $E_0 = 18\ 579.4 \pm 4$ eV, which is more realistic and which corresponds to the most probable (in χ^2) representation of the residual part of the spectrum. The last result thus corresponds to the final-state spectrum of valine, with a reasonably complete allowance for the uncertainty of its calculation.

The difference in the masses of neutral tritium and helium atoms can be calculated from the value of E_0 and electron-shell energies.[5] The value $\Delta M_{\text{T-He}} = 18\ 598.9 \pm 4$ eV obtained in this manner is in excellent agreement with the measurement of the difference in masses of the doublet T–He carried out by Lipmaa *et al.*[7] with the ICR spectrometer: $\Delta M_{\text{T-He}} = 18\ 599 \pm 2$ eV. It is also in excellent agreement with the average value obtained in Ref. 8. These data make it possible to determine the mass interval, regardless of the particular shape of the final-state spectrum and the total resolution function. There is a strong correlation between the parameters M_ν^2 and E_0 for any variation of these functions (E_0 decreases with decreasing mass and vice versa). This correlation is nearly universal in nature. It is clear, moreover, that the data on $\Delta M_{\text{T-He}}$ impose a constraint on the possible values of E_0. The use of the model for the final-state spectrum with a single level (a "nucleus"), instead of the final-state spectrum for valine, for example, decreases E_0 by 18 eV, inconsistent with the data of Ref. 7.

Having a correlation-dependence trajectory on the M_ν^2 and E_0 plane and knowing E_0 from the mass difference,[7] we found the interval $17 < M_\nu < 40$ eV, which is least sensitive to the models.

This result was reported at the Moriond conference.[4] It has, of course, not changed, since in this method the variations of both the final-state spectrum and the total-resolution function have no effect on the result. Only the absolute calibration of the apparatus is important in this case.

The results of similar experiments carried out by three groups were also reported at this conference. They obtained the upper limits on the neutrino mass $M_\nu < 36$ eV (Ref. 9), $M_\nu < 31$ eV (Ref. 10), and $M_\nu < 18$ eV (Ref. 11), which are formally consistent with our values. The experiment of the Swiss group,[11] who imposed the most severe constraints, is not free of criticism for two reasons.

1. The reported precision in determining the mass seems to be overestimated. The results of four series of measurements were reported (see Table I; Ref. 11). The confidence mass interval is based on the statistical error sum of the joint fit (at the 95% confidence level) and the systematic error (Table II; Ref. 11). At the same time, the authors do not give an adequate explanation for the ≈7-eV scatter of the parameter E_0 for a statistical accuracy of 0.2 eV. Since there is a correlation between the parameters ($\Delta M_\nu^2/\Delta E_0 = 80\text{–}100\ \text{eV}^2/\text{eV}$), the scatter of M_ν^2 should be expected to be several times greater than the statistical error of M_ν^2 (63 eV^2) reported by the authors. The confidence interval is underestimated by 300-400 eV^2 in this case.

2. The spectrum for the loss of energy in the source was obtained from model-based calculations from the experimental data of Ref. 12. The authors in this case have disregarded (in obvious contradiction of the experimental data) the tail with losses > 180 eV, which inevitably leads to a systematic under-estimation of M_ν. The disregard of the absorption of the material at the surface of the source, whose presence can hardly be dismissed, accounts for an effect of this type.

[1)] Institute of Molecular Genetics, Academy of Sciences of the USSR.

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