The neutrino mass determination from the β spectrum of tritium in valine (ITEP-84)

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

(Submitted 23 May 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **42**, No. 3, 107–111 (10 August 1985)

The spectrum of the β decay of tritium in a valine molecule is studied with use of an upgraded ITEP spectrometer. Considerable attention is given to the analysis of the instrumental functions. The neutrino mass and the end-point energy are estimated: the neutrino mass is > 20 eV, the mass difference between ^3H and ^3He, which can be found from the end-point energy of the spectrum, is in good agreement with the highly accurate data on mass-spectroscopy based on ion-cyclotron resonance.

In this letter we report the results of measurements of the β spectrum of tritium in a valine molecule carried out with use of an upgraded ITEP magneto-electrostatic spectrometer. The spectrum was scanned by changing the accelerating electrostatic field while holding the focusing field constant. We have gained the following important advantages by modifying the spectrometer: 1) The energy efficiency of the detector has no effect on the measured shape of the β spectrum; 2) the main component of the background produced by tritium contamination of the spectrometer can be strongly suppressed by setting the energy of the focused electrons at 22 keV during electrostatic acceleration; 3) the optical resolution can be maximized relative to a background of ≈ 25 eV by introducing a "pointlike" source on a weakly conducting substrate and by reducing the size of the detector's gaps.

The spectrometer was calibrated by means of 29 conversion lines of ^{169}Yb and by using the known γ-ray transition energies. We have estimated the calibration accuracy to be 5 eV.

The preliminary results of the analysis of this series of measurements ($\approx 1/3$ statistical base, a single source) were reported at the Brighton Conference.[1] The results of this study (which were reported at the Leipzig Conference[2]) were based on a com-

TABLE I.

Source	$B1$	$B2$	$B3$	Expectation values
ω	0,333	0.395	0.415	
	$\Delta E = 1680$ eV			
M_ν^2, eV^2	1364 ± 63 [260]	1174,0 ± 81 [180]	1146,0 ± 140 [200]	1215 ± 130
E_0, eV	18585,2 ± 0,3 [3]	18584,1 ± 0,3 [2,5]	18583,5 ± 0,5 [2,7]	18584,2 ± 1,6
χ^2/N	317/303	523/509	471/508	
	$\Delta E = 330$ eV			
M_ν^2, eV^2	1384,0 ± 175 [170]	1416,0 ± 156 [120]	1261,0 ± 283 [130]	1375 ±140
E_0, eV	18585,2 ± 1,2 [2,4]	18585,5 ± 0,9 [2,0]	18584,4 ± 1,5 [2,2]	18585,1 ± 1,4
χ^2/N	184/165	266/318	294/316	

plete statistical base obtained with use of three sources of different thicknesses. The relative thicknesses of the sources, which are characterized by the probability that an electron does not interact with the material of the source (see ω in Table I), were measured experimentally.

The complete resolution function is the sum of the spectrogram of the noninteracted electrons, i.e., of the optical resolution function, and of the secondary spectrogram of the electrons whose energy changes as a result of interaction in the source. We represent the secondary spectrum as a convolution of the ionization-loss spectrum and the backscattering spectrum with the optical resolution function. These components of the complete resolution function were analyzed in the energy range 10–60 keV by using the L_1 and M_1 conversion lines. The contribution of the natural width to the lineshape was eliminated by solving the inverse problem for the convolution equation with $\Gamma(L_1) = 5.2$ eV and $\Gamma(M_1) = 14.7$ eV.

The main difference between our analysis and that of Boris *et al.*[1] is that they used a symmetric optical resolution function. Symmetrization was achieved by inverting the high-energy slope of the conversion line. Symmetrization of the optical resolution function evidently reduces the dispersion of the complete resolution function and hence lowers the estimate of M_ν. The value of χ^2 was found to be large. We have carefully analyzed the shape of the optical resolution function and determined the contribution of the shake-off effect to the conversion line shape. The shake-off spectrum was found from the L_1 and M_1 lines which were measured in various γ-ray transitions in the energy range 10–60 keV. The analysis was based on the assumption that each measured line can be represented as a sum of two components: 1) a monoen-

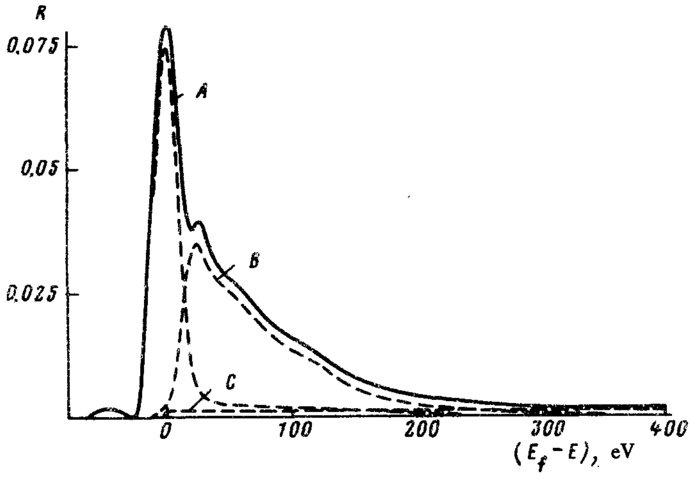

FIG. 1. Total resolution function. V2 source. Detector channel No. 2. Dashed curve—Contribution from (*A*) optical resolution function, (*B*) ionization-loss spectrum convoluted with the optical resolution function, and (*C*) backscattering spectrum.

ergetic line, i.e., the optical resolution function which for a magnetic spectrometer has a constant shape on the relative-momentum scale ($\Delta P/P = \text{const}$) and 2) an accompnaying spectrum which is constant along the absolute energy scale and which can be interpreted as the shake-off effect.

Analysis of four lines showed that the shake-off spectrum comprises $\approx 30\%$ of the total intensity of the conversion line and has features at 15 and 50 eV. The final shape of the complete resolution function for the primary energy of the 18.4-keV electrons and for a focusing energy $E_f = 22$ keV is shown in Fig. 1. Fitting of the experimental data was essentially the same as that in Ref. 1. The total fit contains three parameters: M_ν^2, E_0, and α coefficient of the correction $\alpha \cdot (E_0 - E)^2$ to the β-spectrum shape. The spectrum of the final states of the valine molecule measured during the β decay was taken from Ref. 3, where the authors used the electron correlations in developing the method for calculating the excitations. The experimental data on the atomic spectrum of the final states and on the single-level model of the source (the "nucleus") were also analyzed.

Figure 2 is a Fermi plot of the experimental data on three sources in the region near E_0. Also shown here are the results of the total fit and the theoretical spectrum for $M_\nu = 0$, although E_0 and α are taken from the total fit. Figure 3 shows the data and the curve for the total fit over the entire range analyzed. In this representation, the theoretical spectrum with $M_\nu = 0(E_0$ and α are taken from the total fit) is on the abscissa.

Table I gives the fitted parameters for the spectrum of the final states of valine.[3] It also gives the χ^2 values and the degrees of freedom. Note that χ^2 are much smaller than those in Ref. 1 because of the use of the optical resolution function with a residual asymmetry (Fig. 1). To test the neutrino-zero-mass hypothesis, we have fitted the data with $M_\nu = 0$ and the free parameters E_0 and α. We have obtained the values 680/304,

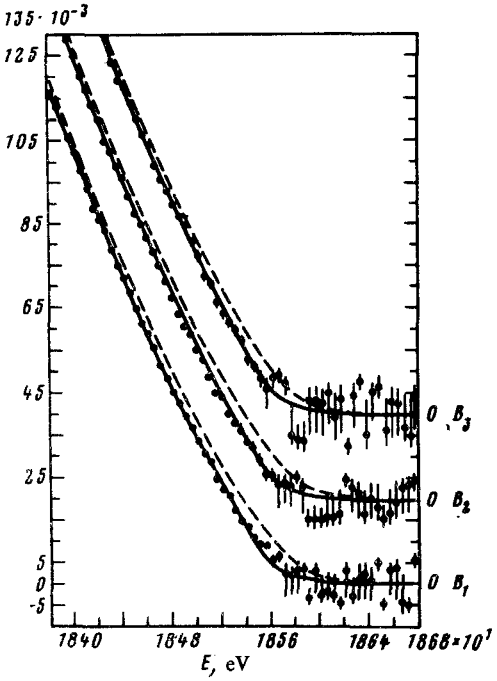

FIG. 2. Fermi plot for the experimental data, for the total fit (the solid curve), and for the theoretical curve (see the text proper).

751/510, and 550/509, respectively, for the three sources. The parameter errors, enclosed in square brackets, include the parameter fluctuations due to the variation (within tolerable limits) of all functions in the β-spectrum model: the complete resolution function, α-term variation, etc. The total errors are given for the expectation values.

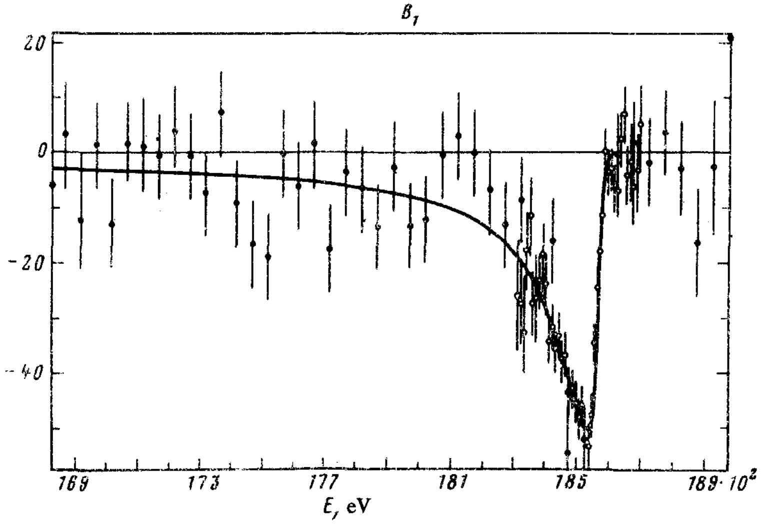

FIG. 3. The difference between the experimental data or the total fit (the solid curve) and the theoretical curve ($M_\nu = 0$). V1 source.

TABLE II.

Final-state spectrum	Valine[3]	Atom	"Nucleus"
M_{ν}^2, eV^2	1215.0 ± 130	954.0 ± 95	190.0 ± 80
M_{ν}, eV	34.8 ± 1.9	$30.9^{+1.5}_{-1.6}$	$13.8^{+2.5}_{-3.5}$
E_0, eV	18584.2 ± 1.6	18580 ± 1.3	18567.4 ± 1.0
$\Delta M(^3H - {}^3He)$	18603.6 ± 6.0	18608.1 ± 6.0	18586.8 ± 6.0

From the parameters of the independent fits for the two energy intervals given in Table I, we see that there is no systematic parameter drift. We wish to emphasize this important point, since the effect of the α term is small in the short interval, and since, correspondingly, the uncertainty in the long tails of the complete resolution function diminishes, which strongly affects its dispersion.

Table II gives the results for various final-state spectra, averaged over the entire statistical base. The mass difference of the neutral ^3H and ^3He atoms was calculated from E_0 and from the energy parameters of the electron shells.[3] The values of $\Delta M(^3H - {}^3He)$ obtained by us differs markedly from the value, 18 573 ± 7 eV, obtained by Smith *et al.*[4] from an analysis of the mass-spectroscopic data. Lipmaa *et al.*[5] have recently carried out precision measurements of the mass difference of the given doublet on a spectrometer which makes use of the ion-cyclotron resonance and which has a resolution 150 times better than that of the spectrometer used in Ref. 4. The result of Ref. 5, $\Delta M = 18\,599 \pm 2$ eV, is in excellent agreement with our value.

The neutrino mass can be conservatively estimated for the "nuclear" model, $M_{\nu} > 9$ eV (90% confidence level). Physically, however, we do not consider this model satisfactory. A realistic estimate of the neutrino mass, based on our analysis, is

$$20 < M_{\nu} < 45 \text{ eV}.$$

We wish to thank M. B. Voloshin for useful discussions of the shake-off effect.

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

[1] S. Boris *et al.*, Proceedings of the Int. Conf. on HEP, Brighton, 1983, p. 386.
[2] S. Boris *et al.*, Proceedings of the Int. Conf. on HEP, Leipzig, Vol. 1, 1984, p.259.
[3] I. Kaplan *et al.*, Dokl. Akad. Nauk SSSR **279**, 1110 (1984) [Sov. Phys. Doklady **29**, 477 (1984)].
[4] L. G. Smith *et al.*, Phys. Lett. **102B**, 114 (1981).
[5] É. T. Lipmaa, R. Ĭ. Pikver, E. R. Suurmaa, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 529 (1984) [JETP Lett. **39**, 646 (1984)]; E. T. Lipmaa *et al.*, Phys. Rev. Lett. **54**, 285 (1985).

Translated by S. J. Amoretty