ELSEVIER

5 August 1999

Physics Letters B 460 (1999) 227–235

PHYSICS LETTERS B

Direct search for mass of neutrino and anomaly in the tritium beta-spectrum

V.M. Lobashev, V.N. Aseev, A.I. Belesev, A.I. Berlev, E.V. Geraskin, A.A. Golubev, O.V. Kazachenko, Yu.E. Kuznetsov, R.P. Ostroumov, L.A. Rivkis, B.E. Stern, N.A. Titov, S.V. Zadorozhny, Yu.I. Zakharov

Institute for Nuclear Research, Academy of Sciences of Russia, 60-th October Anniversary Prospect 7a, 117312 Moscow, Russia

Received 23 April 1999
Editor: K. Winter

Abstract

Results of the ''Troitsk ν-mass'' experiment on the search for the neutrino rest mass in the tritium beta-decay are presented. Study of time dependence of anomalous, bump-like structure at the end of beta spectrum reported earlier gives indication of periodic shift of the position of the bump with respect to the end-point energy with a period of 0.5 year. A new upper limit for electron antineutrino rest mass $m_\nu < 2.5$ eV/c^2 95% C.L. is derived after accounting for the bump. © 1999 Published by Elsevier Science B.V. All rights reserved.

Keywords: Tritium; Spectrum; Neutrino mass; Anomaly

1. Introduction

The direct or kinematical approach to the search for the neutrino rest mass is based on the study of neutrino momentum-energy balance in weak semileptonic decays. In this case any dependence on the leptonic or flavor quantum numbers is excluded. Maximal sensitivity to mass effect may be attained when neutrino energy is minimal. A such situation usually can be obtained in three-body or multibody decay. Total energy spectrum of visible particles in the vicinity of maximal energy is dominated by the neutrino phase space volume which is proportional to pE where p is momentum and E total energy of the neutrino. Deviation of this product from p^2 allows one to deduce the mass of neutrino. Smallness of this product defines fast decreasing of the measured spectrum intensity by approaching the end point energy and makes the main difficulty of the experiment. At present the lowest limit for electron neutrino mass was achieved by studying the shape of tritium beta spectrum near its end point. The new spectrometric facilities in Troitsk (Moscow) [1] and in Mainz [2] allowed one to observe details of beta-spectrum at about 5–15 eV below the end point. Besides significant reduction of the neutrino mass upper limit the experiment in Troitsk revealed the presence of a bump-like anomalous structure (for differential spectrum mode) in the spectrum in the region of 5–15 eV below end point with integral intensity of about 10^{-10} of total decay rate. A very enigmatic feature of this structure turned out to be

PII: S0370-2693(99)00781-9

periodic shift of its position with time. This structure in the condition of absence of understanding of its nature plays a role of systematics for the search for the neutrino mass, strongly increasing possible error.

2. The Troitsk ν-mass set-up

The development of a new approach to spectroscopy of tritium started at the end of 1982 at the Institute for Nuclear Research of the Russian Academy of Sciences (Troitsk) [3]. Independently similar ideas emerged at the Institute for Physics of Mainz University [4]. The main feature of this approach is an integral electrostatic spectrometer with strong inhomogeneous magnetic field providing guiding and collimation of the electrons. The spectrometer represents a magnetic bottle with a large ratio of field intensity in the bottleneck and in the center. Cylinder electrode in the center of bottle acts as an integral electrostatic analyzer. The earlier variant of such type spectrometer was proposed for spectroscopy of electrons with energy below hundred eV [5]. Extension of application area of the spectrometer toward a few tenth keV proved to be possible due to special tailoring of magnetic and electric fields. The main advantage of such a spectrometer is large improvement in energy resolution, amounting to 3.5–4 eV (FW), and luminosity.

The strong guiding magnetic field in the spectrometer bottleneck permitted to couple it in a natural way with the gaseous windowless tritium source, also with strong magnetic field, comprising the second essential part of the Troitsk set-up. Strict conservation of adiabaticity of electron movement over all the length of the spectrometer and the source makes possible to control both transmission function and luminosity. Apparatus energy resolution function has a very simple shape. For monochromatic electrons it represents a step with practically linear slope. Width of the slope is $\Delta E = E_0 \cdot H_m / H_0$. where E_0 – kinetic energy of electron, H_0 – magnetic field in the input bottleneck and H_m – field in the center of the bottle. The shape of the step was checked by means of electron gun. Accuracy of this check was limited only by monochromaticity of the gun (~ 0.5 eV). Gaseous tritium source has a number of advantages in comparison with solid state source. The most essential ones are: homogeneity, no correction for backward scattering, weakness of interactions of tritium with other molecules, easy control for admixture, absence of charging effects. Details of the set-up design and of the measurement procedure may be found in [1,6,7].

The tritium spectrum was measured by changing the spectrometer stopping potential in steps. Direction of high voltage scanning was reversed each cycle (1–2 h). The measurements were made in the range of the spectrometer potential from 18000 to 18770 V. Data acquisition system allowed one to record amplitude and time of each detector pulse. The detector is a small $Si(Li)$ drifted semiconductor counter with a thin window. The spectrometer stopping potential stability was checked by independent measurement by 3 attenuators. Altogether, in the period of 1994–1998 the time of measurement amounted to about 200 days. Analysis of data was done by fit of theoretical spectrum with variable parameters and all the correction factors to experimental spectrum by means of the minimum χ^2 procedure.

Experimental spectrum was corrected for dead time, pile-up of the detector pulses, drift of the source intensity, for cutting out of the part of the detector spectrum, and for events of tritium decay within the spectrometer. The latter display themselves as bunches of pulses 10–20 s long with instant counting rate corresponding to probability less than 10^{-4}–10^{-5} in comparison with regular rate. They are produced by trapping of the decay electrons in the magnetic field of spectrometer, which represents a magnetic bottle. Trapped electrons in the vacuum 10^{-9} torr gradually loose energy by ionization and ionization electrons are accelerated by electric field to the detector. The search for such events was possible in the area of low counting rate from 18530 to 18770 eV. Below 18530 the average of bunch counts for corresponding time was subtracted from counts of each point. The statistical error for these points were increased taking into account dispersion of bunch counts.

Theoretical spectrum was taken in classical form. Its extension to negative (unphysical) values of m_ν^2 was taken as in [1]. The spectrum was convoluted with integral energy losses spectrum of the electrons in the source, summed over the final states spectrum and corrected for trapping effect in the source. The latter was the reason for an intensity rise of the spectrum toward low energy reported in [1]. The final state spectrum of decay product (FSS) was taken from the most recent theoretical calculations [9]. Corrections for inelastic interactions of electrons in tritium gas as well as the FSS spectrum corrections strongly correlate with mass of neutrino and some other parameters of the spectrum. A special system with electron gun and adiabatic magnetic transportation of the electrons to the rear part of the source was constructed in order to measure integral spectrum of inelastic losses of electrons in tritium as well as density of the source. These measurements gave total inelastic interaction cross-section of electron with molecules of tritium in good accordance with theoretical value $3.45 \cdot 10^{-18}$ cm^2 at electron energy 18.6 keV. Spectrum of inelastic losses was found to be somewhat different from usually accepted one. In particular, ratio of excitation to its ionization parts proved to be equal to 0.51/0.49, in disagreement with usually quoted 0.4/0.6.

Four parameters were used as a basic set of variable parameters in χ^2 fit procedure: normalization factor, end point energy, background and m_ν^2. The end-point energy includes excitation energy of the lowest levels of the decay product ($\sim$ 1.6 eV). The fit was made using spectrum interval with a low energy boundary (E_{low}) from 18000 eV to 18530 eV, and an upper boundary 18770 eV. Variation of E_{low} is very important for recognizing systematical effects.

3. Anomalous structures in the spectrum

An example of the experimental spectrum near the end-point is given in Fig. 1. Fitting of the data

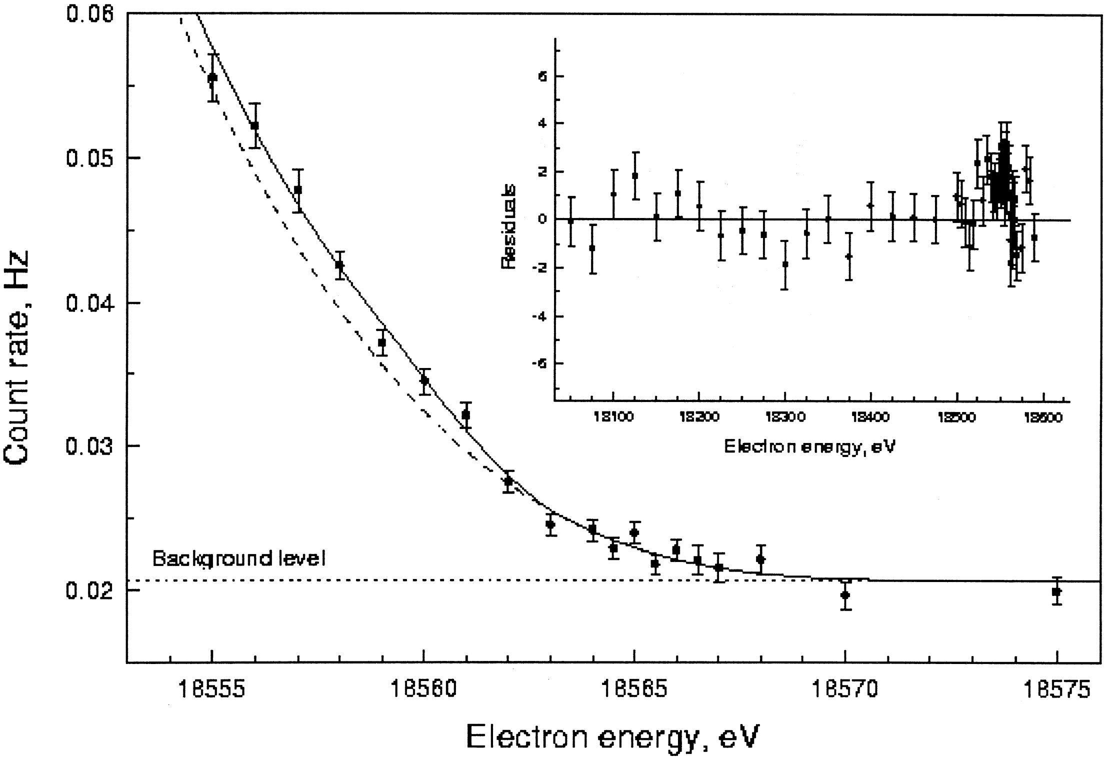

Fig. 1. Part of experimental spectrum near the end-point. Solid line is the fitted theoretical spectrum with step function. Dotted line is theoretical spectrum with subtracted step function. Upper right corner: spectrum of residuals for all measured part of spectrum. Residuals are $(N_{\mathrm{exp}} - N_{\mathrm{theor}})/\sigma$, where N_{exp} is the same as dotted line in previous plot, σ is standard deviation in each point.

with 4 basic variable parameters resulted in the value of m_ν^2 equal to -10–$20\,\mathrm{eV}^2$ mostly independent of (E_{low}). The negative values for m_ν^2 obviously indicated that there exist some systematic effect, not taken into account [1]. Inspection of the spectra showed that there is a small enhancement near the end point which resembles a small step superimposed on the regular spectrum. In differential mode such addendum would be seen as a bump-like structure with a small width (about resolution of the spectrometer). Addition to the theoretical spectrum of a step-like function with variable step size (ΔN_{step}) and position (E_{step}) made the theoretical and the experimental spectra consistent over all the measured part of it and brought the value of m_ν^2 to about zero thus eliminating the negative value problem (see Fig. 2).

Parameters of the step function turned out to vary from run to run but resulted in average ΔN_{step} about $6 \cdot 10^{-11}$ of total decay intensity (besides the last run) and E_0–E_{step} varying within 5–15 eV. In majority of the runs, where fit program was able to give meaningful values for 6 parameter fit with step function, the value of m_ν^2 turned out to be about zero within fit errors. An impossibility to obtain definite minimum of χ^2 in the 6-parameter fit for some run was connected with a strong correlation of ΔN_{step} and m_ν^2 when step position is too close to endpoint. For such run the step parameters were obtained putting $m_\nu^2 = 0$. Changeable positions of the step with respect to end point energy from run to run for the first look was evidence for some systematics. The situation became more enigmatic when the values of E_0–E_{step} were plotted versus calendar time of the corresponding run. The plot is given in Fig. 3. It's very surprising feature turned out to be a possibility to describe the time dependence of the step position by a sinusoidal curve.

The period of the fitted sinusoid proved to be equal to 0,496 ± 0,003 years, mean value of the position 10,4 eV and sinusoid amplitude 4,35 eV. In Fig. 4 dependence of χ^2 on the value of the period is given. In this plot the period was changed point by point and three other parameters of sinusoid were fitted. It is seen that half a year period is the most probable one. The nearest minimum at the period of 0,238 year is narrow and has to be unstable by small variation of parameters.

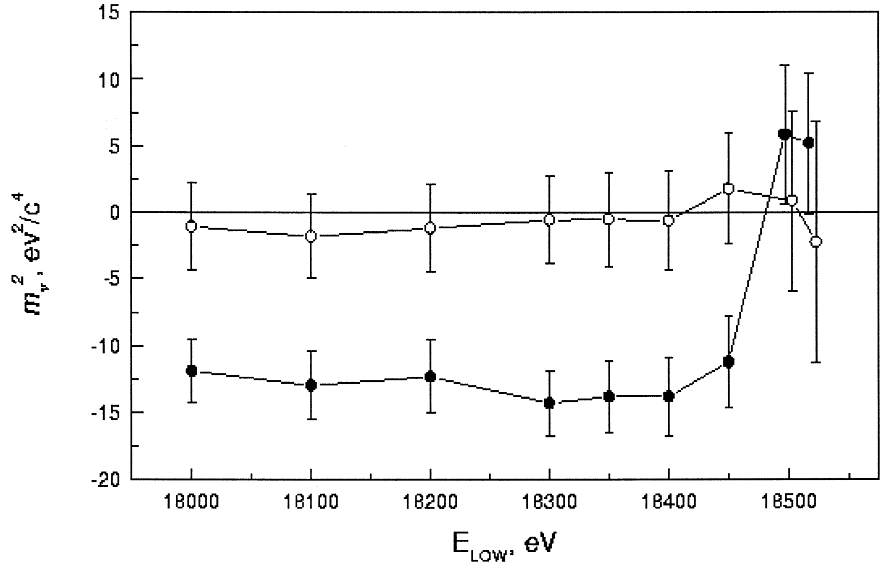

Fig. 2. Dependence of m_ν^2 on E_{low} for sum of data Run94, 96, 97(2), 98. Closed circles – fit without step function (4 parameter fit) Open circles – fit with step function (6 parameter fit).

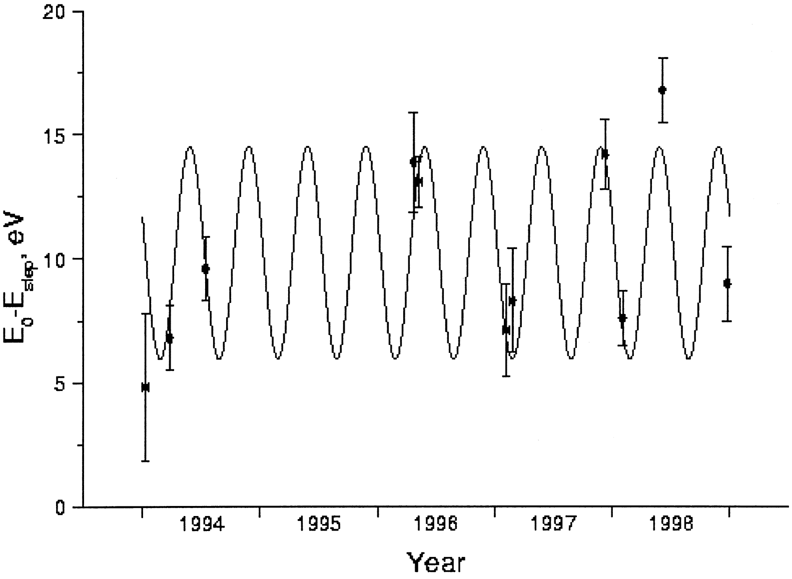

Fig. 3. The step position dependence on the calendar time of measurements. Parameters of the fitted sinusoid are: Period 0,496 ± 0,003 year, mean value 10,4 ± 0,4 eV, amplitude 4,3 ± 0,55 eV, phase 2,6 ± 0,23 rad.

Combining data of all the years in one year plot confirms that the variation of the step position have biseasonal character (see Fig. 5). It is worth while to mention that the set of data given in Fig. 3 is

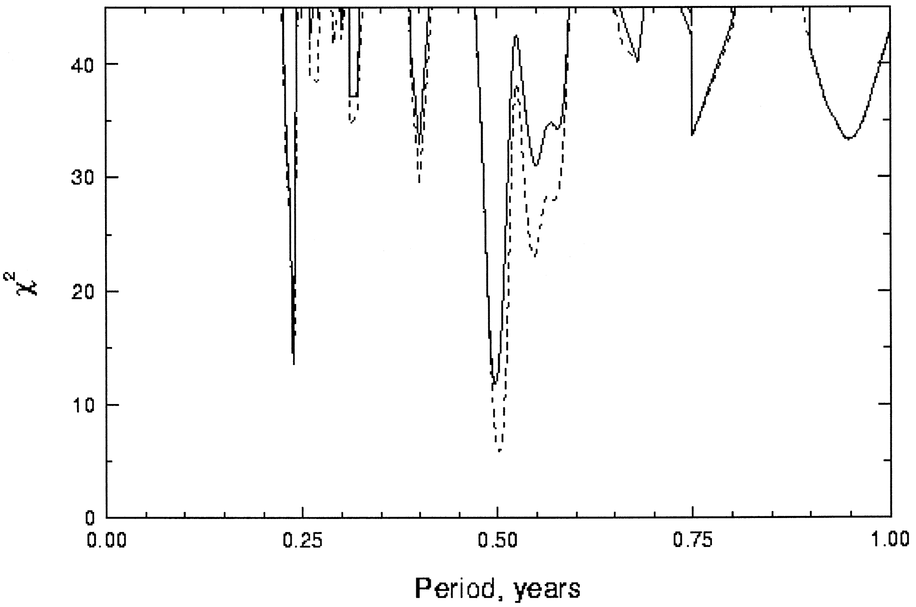

Fig. 4. The χ^2 dependence on the period of sinusoid fitted to step position plot versus calendar time of measurement. Period value was scanned and 3 other parameters were left variable. Solid line corresponds to all the run fit and dotted line to that with the last run (December 1998) being omitted.

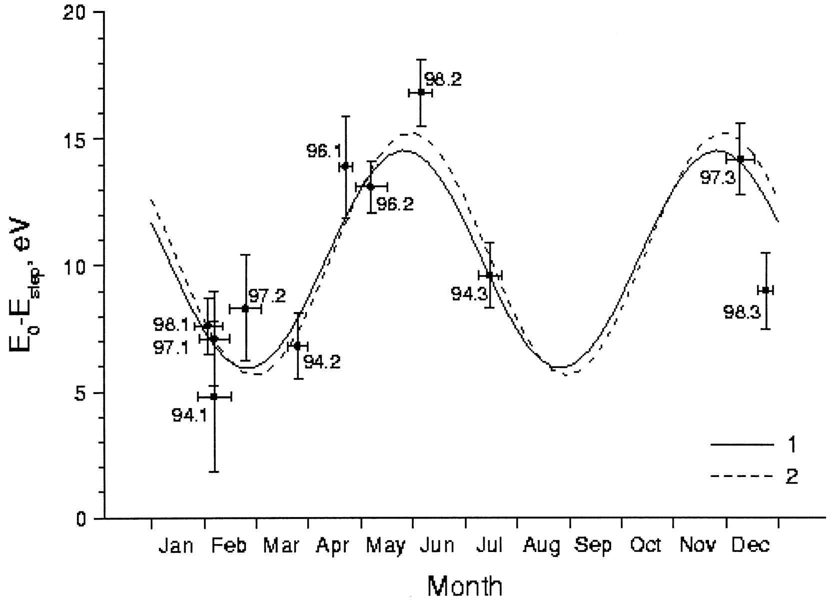

Fig. 5. The plot of step positions versus time of the year. Fitted sinusoid is the same as in Fig. 3, but with the period being 0.500 year. Horizontal bars are length of the run. Indexes of points are: year and number of the run.

somewhat different from that reported in [7]. Difference concerns mainly fit of the data of Runs 97.1 and 97.2. It was found that minimum of χ^2 dependence on the position of the step is somewhat asymmetric. This leads to shift of minimum found by the MINUIT program from center of parabolic curve fitted to this minimum. Taking parameters of the parabola for evaluation of minimum point increases the error, but produces more reliable result. Such an asymmetric structure of the χ^2 multidimensional surface is the consequence of discontinuity of derivative in the point $(E_0-E)^2 = m_\nu^2$ of the theoretical spectrum. Approximation of the spectrum around this point by bidimensional splines allows one to avoid large errors but nevertheless may produce false minimum and requires careful check of the minimum given by MINUIT.

The plot of step size values given in Fig. 6 proved to be more peculiar. The data obtained before the last run (R98,3) roughly correlated with the first wiggle of sinusoid given in Fig. 3. The larger step size corresponded to the larger distance from the endpoint. The last measurement (98,3) however, being relatively short, resulted in factor of 3 larger step size and E_0-E_{step} somewhat below the sinusoid fitted to previous data. This rise may signify that step phenomenon, if not to consider it like some apparatus effect, may fluctuate in size with characteristic time less than a month, at the same time the position being close to sinusoid. This may be confronted with the measurement of the Mainz group, where they did not find the step effect a few weeks earlier [11]. Unfortunately the Troitsk set-up did not run at that time.

Of course the present set of data needs to be sufficiently extended. In particular the absence of measurement within the period July-December and absence of continuous measurement during all the year make possible to fit more complicated periodic curve but with a half year component as a dominant one. The latest revision of data revealed for a few runs some asymmetry of spectra with respect to direction of high voltage scanning. This asymmetry is compensated by regular change of the direction, but its origin is not yet spotted with a good confidence. Continuous control for stopping potential stability excludes explanation of this effect as a voltage dependence on the direction of scanning. Control measurement with an electron gun does not give indication of this effect either. It is worth mentioning

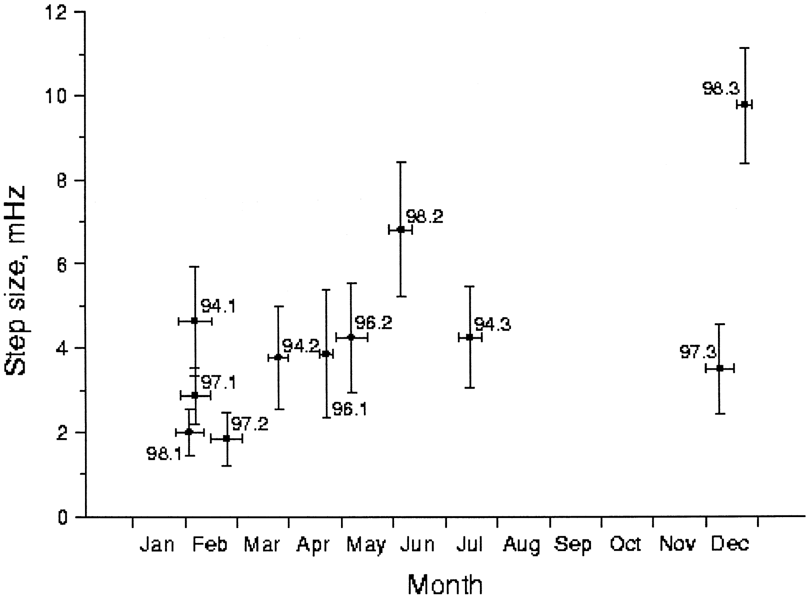

Fig. 6. Plot of step size versus time of the year. All the size values are reduced to the same intensity of source.

that some possible plasma-like effects in the spectrometer are not studied yet with a good thoroughness, though their role seems to be valid only for background origin. Another possible apparatus effects as a reason for step appearance was considered earlier in [1].

At the moment it seems to be impossible to propose any ''customary'' explanation of this phenomenon. The proximity of the oscillation period of the step (bump) to half period of Earth circulation around the Sun and other features of the phenomenon allows one to remind an old speculation about an effect produced by capture of the cosmological degenerated neutrino by tritium atoms with emission of almost monochromatic electrons [10]. In order to produce the bump intensity, corresponding to 10^{-10} of total decay rate a neutrino cloud should be supposed to exist with a density as high as $0{,}5 \cdot 10^{15} \nu/\mathrm{cm}^3$, that is 10^{13} times more than generally accepted average density of relic massless neutrino.

Observation of bump below the end point of beta spectrum corresponds to capture of neutrino with a negative energy, that means assumption of binding of neutrino in the cloud. In the case of binding energy changing over the cloud, the Earth in its movement produces the periodical modulation of binding energy and correspondingly position of the step. It is interesting to point out that this hypothetical binding energy assumed as $V = E_0 - E_{\mathrm{step}} + E_{\mathrm{Fermi}}$ where E_{Fermi} is calculated from the step size, being plotted versus calender time provides somewhat better fit for sinusoid. It gives $\chi^2 = 5{,}3$ for 7 *dof* in comparison with minimum equal to 11,7 for the previous fit.

The size of a neutrino cloud in this case must be comparable with the Earth orbit and it eliminates contradiction with average density of relic neutrino in the Universe [8]. Of course this explanation of step phenomenon is extremely speculative and may be considered only for stimulation of further experiments.

Experimental data up to now do not exclude, that the shape of the end-point region of the tritium spectrum is more complicated than one-bump structure. Nevertheless it appears to be shown that the center of gravity of the step-like enhancement (bump) is below the end-point of the tritium beta-spectrum, and it undergoes periodical shift with respect to the end-point.

4. Neutrino mass upper limit

Deduction of the neutrino mass from the data in presence of unexplained anomaly requires a special approach. As it was mentioned earlier the procedure adopted for this purpose consisted in addition to theoretical spectrum of the step function with two variable parameters supposing that such addition may describe in the first approximation local enhancement in the beta-spectrum near to the end-point. Distortion of beta-spectrum imitating the m_ν^2 effect should also be visible only near end point, otherwise the effect relatively rapidly sinks in growing statistical errors at increasing $E_0 - E$, but unlike the local enhancement it appears as an addition to (for negative m_ν^2) or deficiency (positive m_ν^2) of the spectrum intensity that is linearly increasing with $E_0 - E$. This difference allows one to separate both effects in fit procedure. Of course the size and position of the step being introduced as a free parameter, correlates with m_ν^2 and it increases the final error of neutrino mass thus acting as a kind of systematic error. This increase compensates main part of the uncertainty of substitution of a priory unknown anomaly shape by the step-like function. A possibility to distinguish neutrino mass effect from step strongly decreases with proximity of step position to end-point due to correlation of their parameters. Such correlation made impossible to use the data of Run97(1) and 98(1) for analysis on the neutrino mass in spite of their good statistics.

Systematic errors, besides uncertainty caused by step function, come mostly from the uncertainties of parameters of the correction factors which are introduced in the spectrum before the fit. These factors are: trapping effect, source density, uncertainty of excitation and ionization parts of the inelastic cross section, dead time, and influence of high exited FSS part. Possible uncertainly of the energy resolution function brings only negligible effect to m_ν^2 at present accuracy level. Corresponding error may be estimated as $< 0.3\,\mathrm{eV}^2$. A remarkable property of the total systematic error from these factors is its reduction when E_{low} comes nearer to the end-point. Opposite to it, the systematics connected with a priory unknown step function increases when E_{low} comes closer to the end-point. Taking into account that fit error of m_ν^2 increases with increasing of E_{low} one may select the optimal E_{low}, when the total error, including both the fit and systematic error taken in quadrature, is minimal. For the data given below such E_{low} was found to be equal 18300–18400 eV. The corresponding results for m_ν^2 are:

$$1994\ m_\nu^2 = -2{,}7 \pm 10{,}1_{\mathrm{fit}} \pm 4{,}9_{\mathrm{syst}}\,\mathrm{eV}^2/c^4 \qquad (1)$$

$$1996\ m_\nu^2 = +0{,}5 \pm 7{,}1_{\mathrm{fit}} \pm 2{,}5_{\mathrm{syst}}\,\mathrm{eV}^2/c^4 \qquad (2)$$

$$1997(2)\ m_\nu^2 = -3{,}2 \pm 4{,}8_{\mathrm{fit}} \pm 1{,}5_{\mathrm{syst}}\,\mathrm{eV}^2/c^4 \qquad (3)$$

$$1998\ m_\nu^2 = -0{,}6 \pm 8{,}1_{\mathrm{fit}} \pm 2.0_{\mathrm{syst}}\,\mathrm{eV}^2/c^4 \qquad (4)$$

The combined value in quadrature:

$$m_\nu^2 = -1{,}9 \pm 3{,}4_{\mathrm{fit}} \pm 2{,}2_{\mathrm{syst}}\,\mathrm{eV}^2/c^4 \qquad (5)$$

Combined systematic error is obtained by averaging with weights of fit errors. From here one may obtain the standard upper limit for m_ν [12]:

$$m_\nu < 2{,}5\,\mathrm{eV}/\mathrm{c}^2;(95\%\,\mathrm{C.L.}) \qquad (6)$$

5. Conclusion

Reduction of upper limit for electron antineutrino rest mass up to $2{,}5\,\mathrm{eV}/\mathrm{c}^2$ (95% C.L.) on the ''Troitsk ν-mass'' set-up using only part of the accumulated statistics allows one to hope for further progress next years. This limit however was obtained by accounting for the step-like (in integral spectrum) anomaly structure in the vicinity of the end-point energy of tritium β-spectrum, first reported in [1]. Measurements carried out up to now revealed periodical change of step position within 5–15 eV below end-point with most probable period 0.5 year. At the same time size of the step has more complicated variations, amounting from $0.3 \cdot 10^{-10}$ to $1.4 \cdot 10^{-10}$ of total decay probability. It correlates roughly with the first period of position sinusoid (as in Fig. 4), but exhibits a sudden rise of step magnitude with characteristic time less than a month in the last run. New measurements of the tritium spectrum carried out last year on the Mainz University neutrino set-up provided the data with a precision comparable with the Troitsk set-up [11]. The Mainz group observed at least in one run, step-like structure with position in agreement with periodicity found in Troitsk. In two other cases they didn‘t found any step-effect, thus confirming its variability.

One of the most important tasks for next year will be synchronous measurements in Mainz and Troitsk. Such measurements may essentially clarify the origin of the step phenomenon and will permit to improve precision of the neutrino mass measurement to about one eV scale, that is extremely important in present state of neutrino physics. Of course more radical step would be construction of a new facility with an order of magnitude improvement of luminosity and energy resolution. An example of such a facility was discussed in [7].

Acknowledgements

This work was partially supported by the Russian Foundation for Basic Research (grants 3903 and 18633a), by Program for Fundamental Nuclear Physics and INTAS-RFBR grant 95-819. One of the authors (V.M.L.) is very thankful to Alexander-von-Humboldt Foundation for a grant for Scientific Research. All the authors are very thankful to members of the Mainz University neutrino mass group for friendly collaboration. We are very thankful also to M. Pendlebury for coordination of the INTAS project and G.K. Matushko for the help in preparation of this article.

References

[1] A.I. Belesev, et al., Phys. Lett. B 350 (1995) 263.
[2] Ch. Weinheimer, et al., Phys. Lett. B 300 (1993) 210.
[3] V.M. Lobashev, P.E. Spivak, Nucl. Instr. Methods A 240 (1985) 305.
[4] A. Picard, Nucl. Instr. Meth. B63 (1992) 345.
[5] G. Beamson, H.G. Porter, D.N. Turner, J. Phys. E Sci. Instrum. 13 (1980) 64.
[6] V.M. Lobashev, et al., Proceedings of the International Conference NEUTRINO-96, Helsinki, Finland; June 13–19, 1996, World Scientific p. 264–277.
[7] V.M. Lobashev, Progress in Particle and Nuclear Physics 40 (1998) 337.
[8] V.M. Lobashev, Proceedings of the XYIII International Conference on Physics in Collision, Frascati, June 1998, p. 179–194.
[9] S. Jonsell, H. Monkhorst, Phys. Rev. Lett. 76 (1996) 4476.
[10] G.J. Stephenson Jr., T. Goldman, B.H.J. McKellar, Int. Jour. Mod. Phys. A 13 (1998) 2765.
[11] J. Bonn, Report on WIN-99, Cape Town, January, 1999.
[12] G.J. Feldman, R.D. Cousins, Phys. Rev. D 57 (1998) 3873.