DIRECT SEARCH FOR NEUTRINO MASS AND ANOMALY IN THE TRITIUM BETA-SPECTRUM

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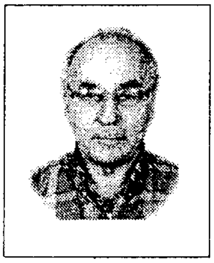

Results of the "Troitsk ν-mass" experiment on search for the neutrino rest mass in the tritium beta-decay are presented. Study of time dependence of anomalous, bump-like structure at the end of the beta spectrum reported earlier gives indication of a periodic shift of the position of the bump with respect to the end-point energy with period of 0.5 year. New upper limit for electron antineutrino rest mass $m_\nu < 2.5 eV/c^2$ is derived after accounting for the bump.

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. The maximal sensitivity to mass effect may be attained when neutrino energy is minimal. Such a situation can usually be obtained in a three-body or multibody decay. The 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. Fast decreasing of spectrum intensity by approaching the end point energy makes the main difficulty of the experiment. At present the lowest limit for electron neutrino mass was achieved by studing of the shape of tritium beta spectrum near its end point. The spectrometric facilities in Troitsk (Moscow) [1] and in Mainz [2] allowed one to observe the details of the beta-spectrum extraordinarily close to the end point producing significant reduction of the neutrino mass upper limit. Beside it, the experiment in Troitsk revealed in the spectrum one existance of a bump-like enhancement (for differential spectrum mode) in the region of $5 - 15\,eV$ below the end point with integral intensity of about 10^{-10} of total decay rate. A very enigmatic feature of this structure turned out to be a periodic shift of its position with time.This structure in the condition of absence of understanding of its nature plays the role of systematics for the search for the neutrino mass, strongly increasing a possible error.

2 The Troitsk ν-mass set-up.

The main parts of this set-up are the integral electrostatic spectrometer with a strong inhomogeneous magnetic field providing adiabatic guiding and collimation of electrons and the gaseous windowless tritium source which also has a strong magnetic field. The strong guiding magnetic field in the spectrometer permitted to couple it in a natural way with a gaseous tritium source. A gaseous tritium source has a number of advantages in comparison with a solid state source. The most essential are: homogeneity over its cross section, practically no correction for backward scattering, weakness of interactions of tritium with other molecules, easy control for admixtures, absence of selfcharging and some other solid state effects. Energy resolution of the spectrometer was set at $3,5 - 4\,eV$ (FW), luminosity amounted to $0,2cm^2$. Details of the set-up design and of the measurement procedure may be found in [1], [4], [5] and [6].

The tritium spectrum was measured by changing the spectrometer high voltage in steps. The direction of high voltage scanning was reversed each cycle ($1-2$ hours). The measurements were made in the range of the spectrometer potential from 18000 to 18770 V. Data aquisition system allowed one to record an amplitude and time of each detector pulse. High voltage stability was checked by independent measurement by 3 attenuators. Altogether, in the period of 1994-1999 the time of measurement amounted to about 250 days.

3 Data analysis.

The data analysis was made by fitting of theoretical spectum with all the correction factors and some variable parameters to the experimental one by means of the minimum χ^2 procedure. The experimental spectrum was corrected to dead time and pile-up, drift of the source intensity, to the cutting out of the part of the detector spectrum, and to events of tritium decay within the spectrometer. The theoretical spectrum was taken in a classical form. It's extension to negative (unphysical) values of m_ν^2 was taken as in [1]. The spectrum was convoluted with integral spectrum of energy losses of the electrons in the source, the final states spectrum and was corrected to trapping effect in the source. The final state spectrum of decay product (FSS) was taken from [7]. The special system with an electron gun and adiabatic magnetic transportation of the monochromatic electrons to the rear end of the source allowed us to measure the integral spectrum of inelastic losses of electrons in tritium as well as the density of the source. The results of the measurement of the total cross section of 18,6 keV electrons with tritium as well as inelastic losses spectrum are published in [10]. As a basic set of variable parameters in χ^2 fit procedure we used 4 parameters : normalization factor, end point energy, background and m_ν^2. The fit was made for the spectrum interval with low energy boundary (E_{low}) from $18000, eV$ to $18530, eV$ and upper boundary $18770, eV$. Variation of E_{low} is very important for recognizing systematical effects.

4 Anomalous structures in the spectrum

The data fit with 4 basic variable parameters after introducing all the corrections resulted in the value of m_ν^2 equal to $-10 - 20, eV^2$ mostly independent of (E_{low}). The negative values for m_ν^2

obviously indicated that there exists 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 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 a variable hight (size) 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. 1).

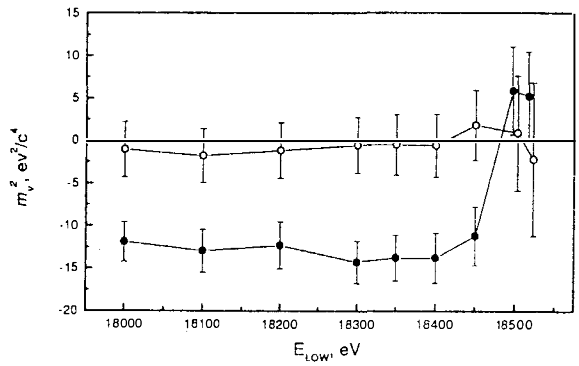

Figure 1: Dependence of m_ν^2 on E_{low} for sum of data Run 1-4, 7, 9, 12. Closed circles - fit without step function (4 parameter fit) Open circles - fit with step function (6 parameter fit).

The parameters of the step function turned out to vary from run to run but resulted in average for ΔN_{step} about $6 \cdot 10^{-11}$ of total decay intensity (besides the runs 10 and 14) and $E_0 - E_{step}$ changing within $5-15\,eV$. Changeable positions of the step with respect to the end point energy from run to run were very strange and became more enigmatic when the values of $E_0 - E_{step}$ were plotted versus calendar time of the corresponding runs. The plot is given in Fig. 2. The most surprising turned out to be the possibility to describe the time dependence of the step position by a sinusoidal curve with a period equal to $0,499 \pm 0,003$ years. The measurements up to run 13 allowed us to describe the step position versus time by a single sinusoid. Now, after run 13 (October 99) more adequate it seems to describe the time dependence by superposition of two sinusoids with periods 0,5 year (70%) and 1,0 year (30%). The $\chi^2 = 12,3$ at 9 d.o.f. The combined data of all the years in one year plot confirm that the variation of the step position has a biseasonal character (see Fig. 3). More peculiar proved to be the plot of step size values given in Fig. 4 The data obtained before run (10) roughly agreed, at least for the first maximum, with a half year period with a larger step size corresponding to a larger distance from the end-point. The measurement of run (10)(the second half of December, 98) resulted in almost 3 times larger step size with respect to the average value and the same happened in run 14 where the step size also rised about 3 times but $E_0 - E_{step}$ jumped up to 22 eV. Most surprizing is that both outbursts were observed in the same time interval between 15-22 December. All these observations may signify that the step phenomenon can variate in size and position with characteristic time less than a month, while keeping the main period of variation 0,5 years. The present set of data needs of course to be sufficiently extended. In particular the absence of measurement within the period July-October and continuous measurement during all the year

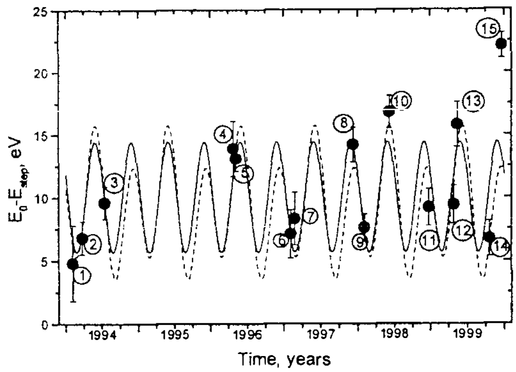

Figure 2: The step position dependence on the calendar time of measurements. Parameters of the fitted sinusoid are: solid line: runs 1 - 11, period $0.500 \pm 0,003$ y, $\chi^2 = 17.2$; 7 d. o. f.; dotted line: runs 1 - 14, I period $0.503 \pm 0,0025$ y (70%), II period 1.0 y (30%),$\chi^2 = 12.6$; 9 d. o. f.

makes it possible to fit a more complicated periodic curve but with a half year component as dominant one.

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 a half period of Earth circulation around the Sun and other features of it allows one to remind speculation about an effect produced by capture of the cosmological degenerated neutrino by tritium atoms with emission of almost monochromatic electrons [8]. In order to produce the bump intensity, corresponding to 10^{-10} of total decay rate it is necessary to suppose existence of neutrino cloud with density as high as $0,5 \cdot 10^{15} \nu/cm^3$, that is 10^{13} times more than generally accepted average density of relic massless neutrino.

Observation of bump below end point of beta spectrum corresponds to capture of neutrino with negative energy, and to 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 accordingly position of the step. The size of neutrino cloud in this case must be comparable with the Earth orbit and it does not contradict to average density of relic neutrino in the Universe. Observation of relatively short outbursts of step size needs further investigation. 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 is more complicated than a one-bump structure. Nevertheless it appears to be established that the centrum of gravity of a 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.

5 Neutrino mass upper limit

As it was explained earlier the procedure of extraction of the neutrino mass consisted in addition to theoretical spectrum of the step function with two variable parameters supposing that such addition may describe in the first approximation the local enhancement in the beta-spectrum near the end-point. Even if the real origin of the step remains unknown, we may consider it's

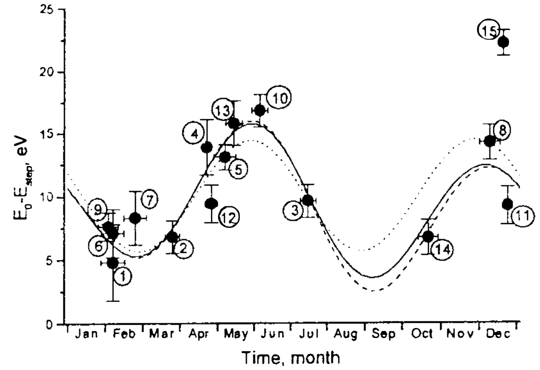

Figure 3: The plot of step positions versus time of the year. Fitted sinusoid is the same as in Fig. 2, but with the period being 0.500 year. Horizontal bars are length of the run. Indexes of points are: numbers of the run.

important features established. In particular observation of periodical shift of step reported here makes it possible to take for neutrino mass measurement the periods when the step is maximally shifted from end point. In this case the most sensitive to neutrino mass effect part of the spectrum appears almost free of step-like distortion. Otherwise speaking in this case the step and neutrino mass effect creates minimum correlation in the fit procedure. Accordingly the runs with maximal proximity of the step to the end point are not useful for fit with neutrino mass, and one should be very careful to use data of such runs even if their fitting seems to provide reasonable results. Of course correlation of the step parameters with m_ν^2 increases the final error of neutrino mass thus acting as a kind of systematic error. This increase sufficiently compensates the uncertainty of substitution of priorily unknown anomaly shape by step-like function. The possibility to distinguish a neutrino mass effect from a step strongly decreases with proximity of step position to end-point due to correlation of their parameters. Such correlation made impossible to use data of Runs 5, 6 and 8 for analysis for the neutrino mass in spite of its good statistics. Run 14 was too short in time and was analysed only for the parameters of the step.

Systematical errors besides the uncertainty caused by the 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 highly excited FSS part. A remarkable property of the total systematic error from these factors is its reduction when E_{low} comes nearer to the end-point E_{low}, opposite to it, the systematics connected with a priori unknown function uncertainty increases when E_{low} comes closer to the end-point, that is automatically taken into account in the fit procedure. Taking into consideration 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 the systematic error taken in quadrature, is minimal. The results for m_ν^2 for all the runs are given below:

$$\text{Run 1, 2, 3} \quad m_\nu^2 = -2,7 \pm 10,1_{fit} \pm 4,9_{syst}\, eV^2/c^4 \tag{1}$$

$$\text{Run 4} \quad m_\nu^2 = +0,5 \pm 7,1_{fit} \pm 2,5_{syst}\, eV^2/c^4 \tag{2}$$

$$\text{Run 7} \quad m_\nu^2 = -3,2 \pm 4,8_{fit} \pm 1,5_{syst}\, eV^2/c^4 \tag{3}$$

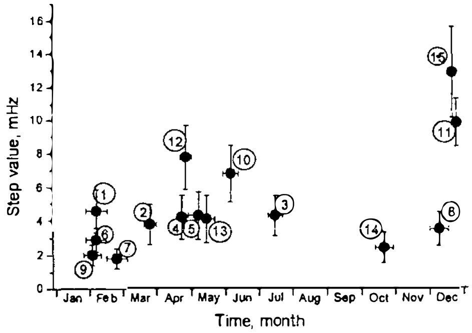

Figure 4: Plot of step size versus time of the year. All the size values are reduced to the same intensity of source.

$$\text{Run 9} \;\; m_\nu^2 = -0,6 \pm 8,1_{fit} \pm 2.0_{syst}\, eV^2/c^4 \tag{4}$$

$$\text{Run 12} \;\; m_\nu^2 = +1,6 \pm 5,6_{fit} \pm 2,0_{syst}\, eV^2/c^4 \tag{5}$$

The combined value in quadrature is:

$$m_\nu^2 = -1,0 \pm 3,0_{fit} \pm 2,1_{syst}\, eV^2/c^4 \tag{6}$$

The combined systematics error is obtained by averaging with weights of fit errors. From here one may obtain 95% C.L. universal upper limit for m_ν:

$$m_\nu < 2,5\, eV/c^2; \tag{7}$$

6 Acknowledgements

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