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Direct Search for Neutrino Mass and Anomaly in the Tritium Beta-Spectrum: Status of "Troitsk Neutrino Mass" Experiment

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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. New data on the time dependence of the anomalous, bump-like structure at the end of the beta spectrum reported earlier are discussed. Possible systematics is considered in view of contradiction of "Troitsk nu-mass" observation with those of "Mainz neutrino" set-up. An upper limit for electron antineutrino rest mass remains at $m_\nu < 2.5 eV/c^2$ at 95% C.L.

1. Introduction.

The direct 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 maximum sensitivity to mass effect may be attained when neutrino energy is minimum. Such situation can usually be obtained in a three-body or multibody decay. The total energy spectrum of visible particles in the vicinity of maximum 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. At present the lowest limit for electron antineutrino mass was achieved by studying 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. It produced significant reduction of the neutrino mass upper limit. However the experiment in Troitsk revealed existence in the spectrum 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 reasonable understanding of its nature plays the role of systematics for the search for the neutrino mass, strongly increasing 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 also with strong magnetic field. It permits to couple both of them in a natural way. Gaseous tritium source has a number of advantages in comparison with frozen tritium source. The most essential are:

Homogeneity over any cross section.

Practically no correction for backward scattering.

Weakness of interactions between tritium molecules making possible to use assumption of isolated molecule in calculation of final state spectrum and inelastic energy losses.

Easy control for admixtures.

Absence of self charging of the source.

Absence of solid state effects in the source.

Energy resolution of the spectrometer was set

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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 acquisition system allowed one to record an amplitude and time of each detector pulse. High voltage stability was checked by comparison of independent measurement by 3 attenuators with accuracy ±0,1 V . Altogether, in the period of 1994-1999 the time of measurement amounted to about 250 days.The length of continuous run varied from two weeks up to one and a half month. Frequency of runs was dictated mostly by financial and personal problems.

3. Data analysis.

The data analysis was made by fitting of theoretical spectrum 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 for trapping effect in the source. The latter arises due to bottle-like configuration of magnetic field in the source. Decay electrons with momenta corresponding to trapping in the bottle gradually brake but some part of them may escape trapping zone by relatively large angle scattering. Such electrons due to long traveling in the source before scattering lose some energy and getting to spectrometer enrich low energy part of the spectrum . Calculation of this effect is carried out in adiabatic approximation and involves as a main parameter the ratio of large angle to stopping cross sections. The first is mostly a usual quasielastic electron-electron scattering and the second is now known from [8] with accuracy of about 3%. The contribution of this process is sufficient only below 18300 eV.

The final state spectrum of decay product (FSS) is only correction factor which cannot be verified experimentally. Here it was taken from [7] where the calculations were done in sudden approximation for free molecules. This approach is considered as most reliable including all second order corrections.

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 directly the integral spectrum of inelastic losses of electron energy 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 energy losses spectrum are published in [8]. 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 $18770\,eV$. Study of the dependence of the fit results on E_{low} is very important for recognizing systematic 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 $-10 - 20\,eV^2$. The negative values for m_ν^2 obviously indicated that there exists some effect not taken into account [1]. Inspection of the spectra showed that most probably this effect appeared to be due to small enhancement near the end point of the spectrum which resembles small step superimposed on the regular spectrum.

In differential mode such an enhancement would be seen as a bump-like structure with a small width (about resolution of the spectrometer). Addition to the theoretical spectrum of

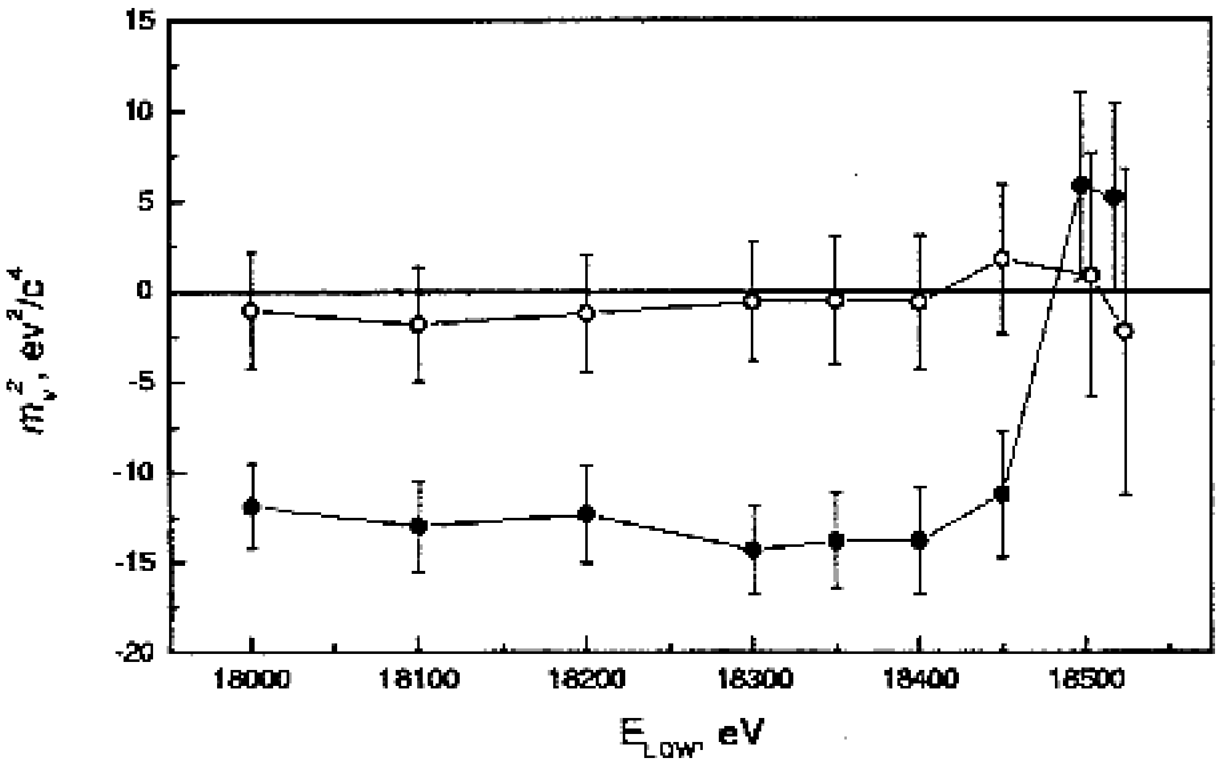

Figure 1. Dependence of m_ν^2 on E_{low} for sum of data Run 1-4, 7, 9, 12. Closed circles - fit without step function (4 parameter fit) Open circles - fit with step function (6 parameter fit).

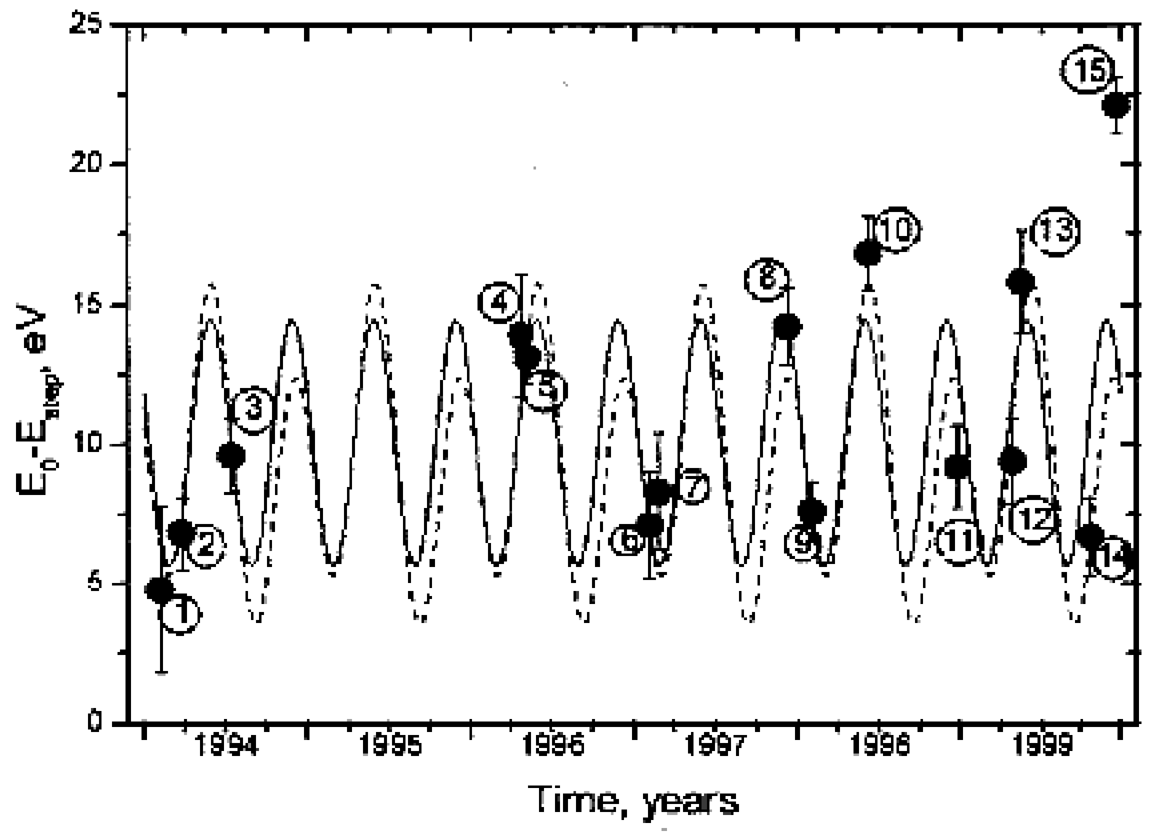

Figure 2. The step position dependence on the calendar time of measurements. Parameters of the fitted sinusoid are: solid line: runs 1 - 11, period 0.500 ± 0.003 y, χ^2 = 17.2; 7 d. o. f.; dotted line: runs 1 - 14, I period 0.503 ± 0.0025 y (70%), II period 1.0 y (30%), χ^2 = 12.6; 9 d. o. f.

a step-like function with a variable height (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 m_ν^2 problem. (see Fig. 1).

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 14 (October 99) it seems more adequate 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 also demonstrate that the variation of the step position has a bi-seasonal character (see Fig. 3).

More peculiar proved to be the plot of step size values given in Fig. 4. The data obtained before run (11) 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 (11) (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 15 where the step size also rises by about 3 times but $E_0 - E_{step}$ jumped up to 22 eV. Surprising is that both outbursts were observed at about the same time between 15-22 December of 1998 and 1999. All these observations may signify that parameters of the step, that is its size and position can vary 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

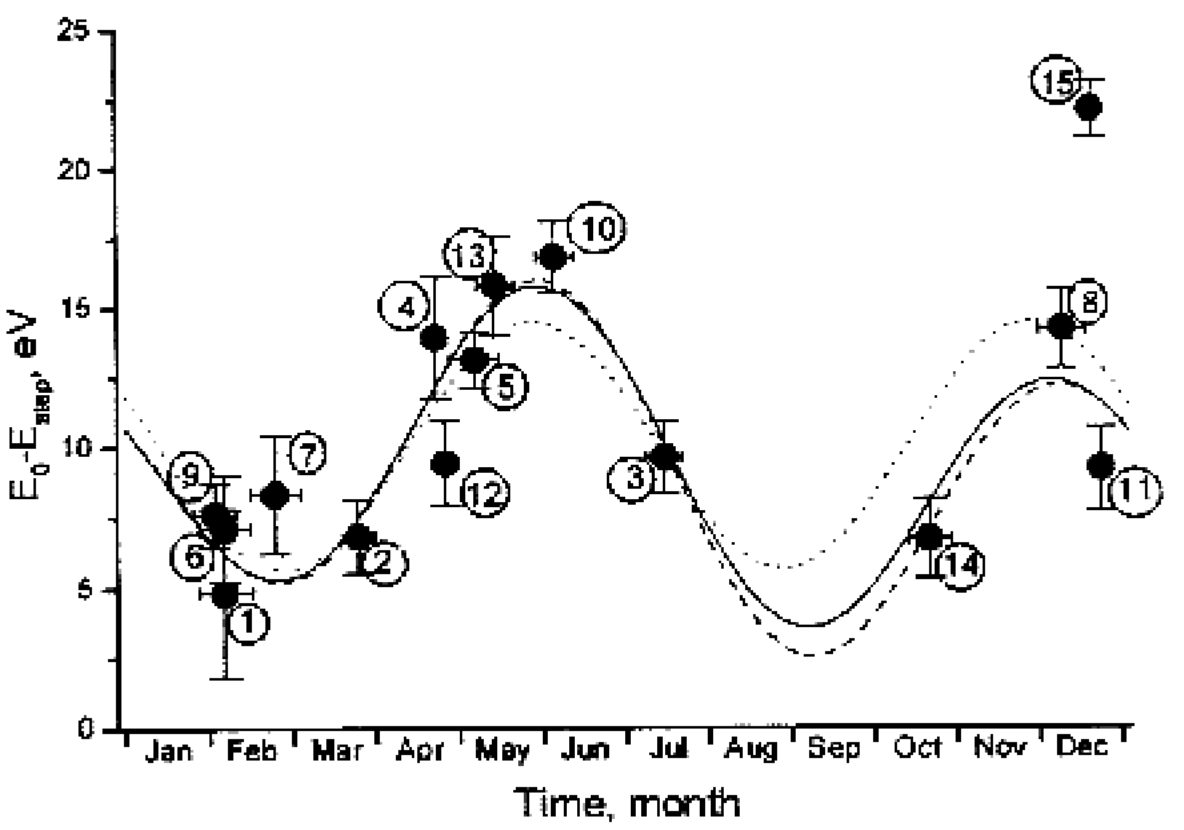

Figure 3. The plot of step positions versus time of the year. Fitted sinusoid is the same as in Fig. 2, but with the period being 0.500 year. Horizontal bars are length of the runs. Indexes of points are: numbers of the run.

sufficiently extended. In particular, absence of measurement within the period July-October as well as absence of continuous measurement during all the year makes it possible to fit a more complicated periodic curve but with a half year component as dominant one. In addition it is not excluded that the shape of spectrum near the end point is more complicated than is supposed by one bump addition.

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. 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. It is naturally that before to consider such exotic hypothesis it would be necessary to obtain at least an independent verification of the effect.

5. Comparison with "Mainz neutrino" results.

One of the most important tests for the conclusion whether the bump is some sophisticated apparatus effect or physical phenomenon is its synchronous observation on two independent set-ups. Last two years "Mainz neutrino" group collected significant set of data with statistic errors near the data of Troitsk group. Unfortunately most of the measurements were made not synchronously due to various technical and personal reasons. Results of the search for step effect reported by Mainz group now proved to be at variance with Troitsk data.One may consider only 3 runs as supporting or not contradicting to time-of-year dependence of Troitsk observation. At least two runs give step size about zero. Besides, the value m_ν^2 obtained in 4 parameter fit is about zero in a few runs and is independent of E_{low} within interval 18370-18530 eV. In this situation it is worth while to analyse more carefully any possible errors which can imitate or produce step effect. Especially important is to reconsider differences in both set-ups and spectrum corrections involved in analysis of the data.

At the moment we cannot point out any correction to results of the fit in Troitsk measurement.Most of the corrections factors introduced in the spectrum were verified experimentally.Direct measurements of the source column density definitely excludes possibility to make an error which is capable to mock up step effect. Other correction plays lesser role. For example, in order to imitate (with larger χ^2) step size about $3mHz$ it is necessary to underestimate column density by about 30%. It is worth while to mention that overestimation of source density may cancel step (if it exists) and correspondingly it may move negative m_ν^2 to zero or to positive value. Of course both groups developed reliable methods of measuring column density and spectrum of inelastic energy losses. It brings uncertainty of this correction to about 3%. Another situation exists with the spectrum of final states (FSS) which appears as even more significant correction than column density at present level of precision. FSS is only one factor which cannot be proved experimentally ,whereas result of the fit very strongly depends on its accuracy. Accuracy by itself is based on the reliability of sudden approximation calculation for molecular hydrogen isotopes. These calculations were verified for free molecule which is the case of gaseous source of Troitsk set-up. Calculation for frozen source as at Mainz set-up has to involve solid state effects which may modify FSS by increasing excitation levels population or suppressing it. In report of Mainz group these correction were made on the base of [9] ascribing 20% systematic uncertainty to additional excitation of environment molecules of tritium which was considered in above paper as only solid state effect. It is interesting to point out that fit of Mainz data (Q4 and Q5 kindly presented to us by Mainz group) neglecting environment excitation shows shift of m_ν^2 to negative value by $6 - 11 eV^2$ (depending on E_{low}) or corresponding increase of step size making it statistically significant. Of course this is not a proof of existence of such modification of FSS in frozen tritium but only indication that it must be carefully reconsidered theoretically using modern apparatus of solid state physics.

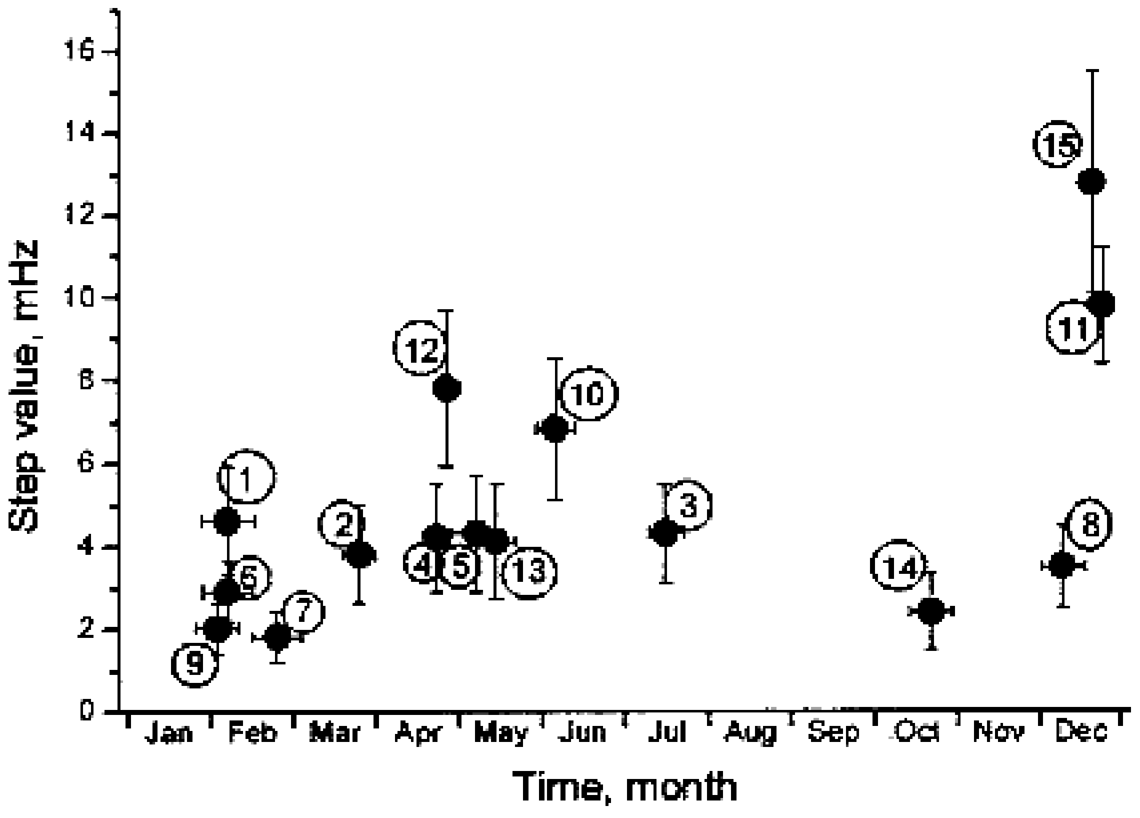

Figure 4. Plot of step size versus time of the year. All the size values are reduced to the same intensity of source.

6. 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 take into account it's important features established during previous years. In particular observation of periodical shift of step reported here makes it possible to define for neutrino mass measurement the periods when the step is maximum 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 maximum proximity of the step to the end point are not useful for fit for neutrino mass, and one should be very cautious in using 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 a priori unknown anomaly shape by step-like function. The possibility to distinguish the neutrino mass effect from the step strongly decreases with proximity of step position to end-point due to correlation of their parameters. For these reasons data of Runs 6, 7 and 9 were excluded from analysis for the neutrino mass in spite of its good statistics. Run 15 was too short in time and was analysed only for the parameters of the step.

Systematical errors, besides the uncertainty caused by the step effect, 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 the inelastic energy loss spectrum, dead time, and FSS. A remarkable property of the total systematic error from these factors is its reduction when E_{low} comes nearer to the end-point E_0. On the contrary, the systematic error connected with the *a priori* unknown step effect increases when E_{low} comes closer to the end-point, which is revealed in the fit with variable step parameters. Neglecting the step in fitting the spectrum will of course decrease the fit error but may meet unrecognized bias of m_ν^2; moreover negative value of it does not always appear as a mark of the step, but may transform into positive m_ν^2 for $E_{low} > 18500\,eV$. Such dependence may be seen in Fig. 1. 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 minimum. The results for m_ν^2 for the runs selected for analysis are given below:

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

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

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

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

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

The combined value in quadrature is:

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

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:

$$m_\nu < 2,5\, eV/c^2. \qquad (7)$$

7. Conclusion.

Study of the tritium spectrum near to end point on the "Troitsk ν-mass" set up reveals very peculiar anomalies (step effect) ,which demonstrate regular variation of their size and positions. In addition to regular periodic shift with period 0,5 year reported earlier two outburst at the same calendar time were observed in December 1998 and 1999. This may signify that step effect (if to consider it as a physical phenomenon) appears as a more variable one then it was reported earlier. Nevertheless selection of measurement periods when the step is maximum shifted from end point allows to obtain reliable upper limit for neutrino mass.

Last two years "Mainz neutrino " group has conducted a number of measurements with good statistical accuracy. Analysis for the step effect reveals that although results of some runs are consistent with Troitsk observations but other run results are in contradiction with them. It calls for further investigation of possible apparatus effects in both set-ups but also for reconsidering of their differences. It must involve new analysis of correction factors introduced in spectrum. Especially sensitive seems to be the final states spectrum corrections. These corrections are based only on theoretical calculation and at the moment cannot be checked experimentally. At the same time accuracy of such calculations for frozen tritium source seems to need new theoretical revision on the basis of modern solid state techniques. Of course it is vitally important also to conduct really synchronous measurements on both set-ups.

It is necessary to stress that all the mentioned uncertainties play role only within m_ν below $2,5\,eV$ given above.

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