

# DIRECT SEARCH FOR THE NEUTRINO MASS IN THE BETA-DECAY OF TRITIUM. STATUS OF THE "TROITSK $\nu$ -MASS" EXPERIMENT

© 2000 V. M. Lobashev

*Institute for Nuclear Research of Russian Academy of Sciences, Moscow*

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

## 1. INTRODUCTION

The problem of the neutrino rest mass remains one of the most important in Elementary Particle Physics and Cosmology. The direct or kinematic 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. A maximal sensitivity to the 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 the maximal energy is dominated by the neutrino phase space volume, which is proportional to  $pE$ , where  $p$  is the momentum and  $E$  is the total energy of the neutrino. Deviation of this product from  $p^2$  allows one to deduce the mass of the neutrino. At present the lowest limit for the electron neutrino mass was achieved by the study of the shape of the tritium beta spectrum near its end point. Now the spectrometric facilities in Troitsk (Moscow) [1] and in Mainz [2] allowed details of the beta-spectrum at about 5–15 eV below the end point to be observed. Besides significant reduction of the upper neutrino mass limit, the experiment in Troitsk revealed presence of anomalous structure of bump-like shape (for differential spectrum mode) in the tritium spectrum in the region of 5–15 eV below the end point with integral intensity about  $10^{-10}$  of the 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 absence of understanding of its nature, plays the role of systematics for the search for the neutrino mass, strongly increasing a possible error.

## 2. SEARCH FOR ELECTRON ANTINEUTRINO REST MASS

The shape of the beta-spectrum with nonzero neutrino mass is

$$W(E, Z) = AF(E, Z)Ep \times \sum W_i(E_{0i} - E) \sqrt{(E_{0i} - E)^2 - m_\nu^2 c^4} \quad (1)$$

where  $E$  is the total energy and  $p$  is the momentum of the electron.  $W_i$  is the probability and  $E_{0i}$  is the end-point energy of the partial decay into the  $i$ th final state. The effect of the nonzero neutrino mass emerges as a cutoff of the spectrum at  $E_{0i} - E = m_\nu c^2$  and intensity deficiency smoothly declining to lower energy. The decay of tritium provides a unique opportunity for such experiments due to low end-point energy, high specific

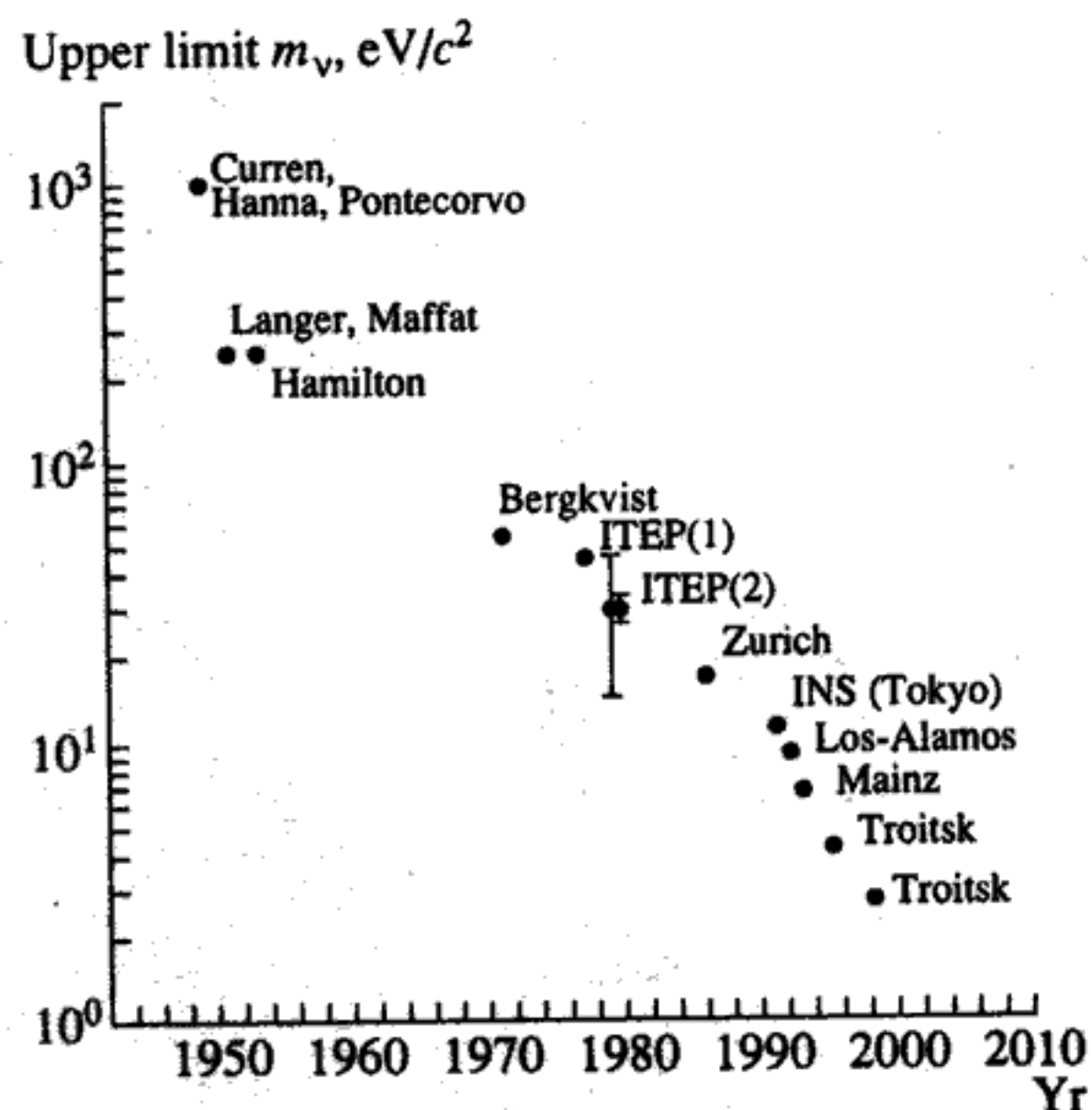


Fig. 1. Progress in upper limit improvement in neutrino mass measurement in tritium beta decay.

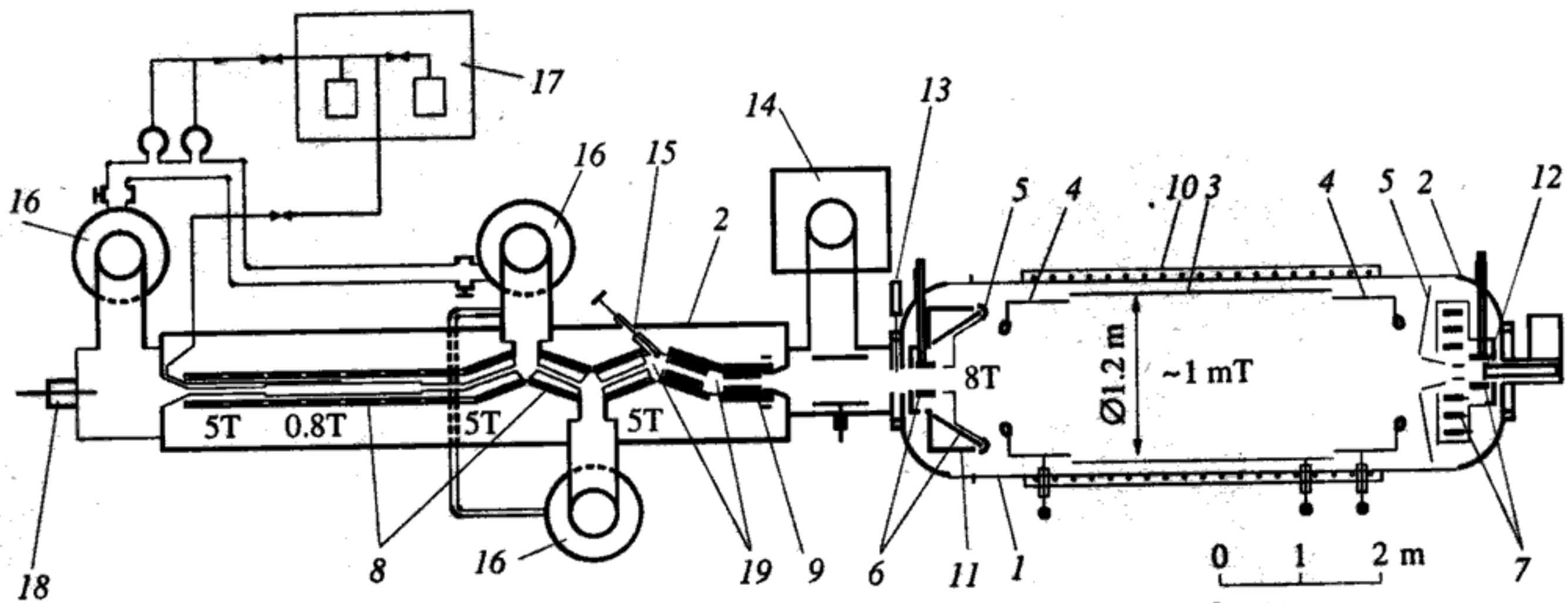


Fig. 2. Experimental set-up. (1, 2) vacuum tanks; (3, 4) electrostatic analyzers; (5) grounded electrode; (6-9) superconducting coils (the-system, 4.7 K); (10) warm coil; (11)  $LN_2$  jacket; (12) Si(Li) detector; (13) fast shutter; (14) Ti pump; (15) cold valve; (16) Hg diffusion pump; (17)  $T_2$  purification system (27 K); (18) electron gun; (19)  $\mu$  argon pump.

activity, the lowest  $Z$ , and a possibility of calculating most of the corrections for its superallowed spectrum.

The history of the search for neutrino mass in the tritium beta decay is almost 50 years long. An illustration of the experimental progress during this time is given in Fig. 1. In 1980 steady improvement of the upper limit for the neutrino mass was suddenly speeded up by the report of the ITEP group from Moscow on the observation of the neutrino mass effect corresponding to the rest mass of about  $30 \text{ eV}/c^2$  [3]. This report stimulated more than 20 experimental proposals with an intention to check this claim. After several years the experimental groups from Zurich [4], Tokyo University [5], Los Alamos [6] produced results which refuted the ITEP group claim, but revealed many difficulties in measuring and analyzing the beta spectra.

Much efforts were made to develop a new tritium source. The most radical step was done by the Los-Alamos group by construction of a windowless gaseous tritium source with a strong solenoidal magnetic field transporting electrons to a spectrometer of the Tretyakov type [7].

### 3. THE TROITSK $\nu$ -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) [8-10]. Similar ideas independently emerged at the Institute for Physics of Mainz University [11]. The main feature of this approach is an integral electrostatic spectrometer with a strong inhomogeneous magnetic field providing guiding and collimation of the electrons. The early variant of such a spectrometer was proposed for spectroscopy of electrons with energy below a hundred eV [12, 13]. Extension of the application area of the spectrometer to a few tens of

keV proved to be possible due to special tailoring of magnetic and electric fields. The Troitsk set-up is shown in Fig. 2. An essential part of it is a chain of superconducting solenoids which produce a continuous longitudinal magnetic field through the entire set-up. The cylindrical electrode in the central part of the spectrometer with a low-intensity magnetic field is an integral electrostatic analyzer. All the magnetic and electrostatic fields are adjusted to ensure adiabaticity of the electron motion through the source and through the spectrometer along the magnetic field lines. The electron detector detects only electrons which have been produced in the magnetic field flux tube crossing the detector surface. The magnetic fields in the spectrometer and in the source are adjusted so that this flux tube does not touch the walls.

The spectrometer resolution is a step function with an almost linear slope from 0 to 1, the total width of the slope is  $\Delta E = E \frac{H_{\min}}{H_{\max}}$ , where  $E$  is the electron energy,

$H_{\max}$  is the intensity of the magnetic field at the entrance of spectrometer solenoid, and  $H_{\min}$  is its intensity at the spectrometer medium plane (Fig. 2). The main advantage of this spectrometer is the energy resolution, amounting to 3.5-4 eV (FW), and luminosity. The strong guiding magnetic field in the spectrometer permitted its natural coupling with the gaseous windowless tritium source, also with a strong magnetic field comprising the second essential part of the Troitsk set-up. The gaseous tritium source has a number of advantages in comparison with the solid-state source. The most essential of them are absence of 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, 14, 15].

Gaseous tritium is injected in the center of a 3 m long tube inside the solenoids and is being pumped out by mercury diffusion pumps installed at both ends of the tube. After additional compression in the buster mercury pump and after purification tritium returns to the injection point, thus providing continuous circulation. The tritium spectrum was measured by changing the high voltage of the spectrometer in steps. Direction of the high voltage scanning was reversed at each cycle (1–2 h). The measurements were made in the range of the spectrometer potential from 18000 to 18770 V. The data acquisition system allowed one to record the amplitude and the time of each detector pulse. High voltage stability was checked by independent measurement by 3 attenuators. Altogether, in the period 1994–1998 the time of measurement amounted to about 200 d. Analysis of data was done by fit of the theoretical spectrum with all the correction factors and some variable parameters to the experimental spectrum by means of the minimum  $\chi^2$  procedure. The experimental spectrum was corrected for dead time and pile-up, drift of the source intensity, for the cutting-out of the part of the detector spectrum, and for events of tritium decay into the spectrometer. The latter manifest themselves as bunches of pulses with an instant counting rate corresponding to the probability less than  $10^{-4}$ – $10^{-5}$  in comparison with the regular rate. The search for such events was possible in the area of the low counting rate from 18530 to 18770 eV. Below 18530 the average of bunch counts was subtracted which corresponding increase of the statistic error due to larger scattering of bunched counts.

The theoretical spectrum was taken in accordance with (1). Its extension to negative (unphysical) values of  $m_\nu^2$  was taken as in [1]. The spectrum was convoluted with the integral spectrum of energy losses of the electrons in the source, the final states spectrum and corrected for the trapping effect in the source. The latter caused the intensity rise of the spectrum toward low energy reported in [1]. The final state spectrum of the decay product (FSS) was taken from the most recent theoretical calculations [16]. Corrections for inelastic interactions of electrons in tritium gas as well as the FSS strongly correlate with the neutrino mass and some other parameters of the spectrum. A special system with an electron gun and adiabatic magnetic transportation of electrons to the rear part of the source allowed one to measure the integral spectrum of inelastic losses of electrons in tritium as well as the density of the source. These measurements gave the total inelastic interaction cross-section of electrons with molecules of tritium in good accordance with the theoretical value  $3.45 \times 10^{-18} \text{ cm}^2$  at the electron energy 18.6 keV. The spectrum of inelastic losses was found to be different from the usually accepted one. In particular, the ratio of excitation to ionization parts of it proved to be equal to 0.51/0.49, in disagreement with the usually quoted value 0.4/0.6. As a basic set of variable parameters in the  $\chi^2$  fit procedure, we used 4 parameters: normalization factor, end point

energy background and  $m_\nu^2$ . The fit was made for the spectrum interval with the low-energy boundary ( $E_{\text{low}}$ ) from 18000 eV to 18530 eV and the upper boundary 18770 eV. Variation of  $E_{\text{low}}$  is very important for recognizing systematic effects.

#### 4. ANOMALOUS STRUCTURE IN THE SPECTRUM

Fitting of the data with four basic variable parameters with all the above-mentioned corrections resulted in the value  $m_\nu^2 = -10$ – $20 \text{ eV}^2$  mostly independent of ( $E_{\text{low}}$ ). The negative values for  $m_\nu^2$  obviously indicated existence of some systematic effect not taken into account [1]. Inspection of the spectra showed that there is small enhancement near the end point which resembles a small step superimposed on the regular spectrum. In the differential mode such an addendum would be seen as a bump-like structure with small width (about the resolution of the spectrometer). Addition of a step-like function with variable height (size) and position ( $E_{\text{step}}$ ) to the theoretical spectrum made the theoretical and experimental spectra consistent over all the measured part of it and brought the value of  $m_\nu^2$  to about zero thus eliminating the negative value problem (Figs. 3, 4).

Parameters of the step function turn out to vary from run to run. The average variation of  $\Delta N_{\text{step}}$  is about  $6 \times 10^{-11}$  of the total decay intensity (except the last run) and  $E_0 - E_{\text{step}}$  varies within 5–15 eV. In the majority of the runs, where the fit program was able to give meaningful values for the six-parameter fit with the step function, the value of  $m_\nu^2$  turned out to be about zero within fit errors. An impossibility of obtaining definite minima of  $\chi^2$  in the six-parameter fit for some run was connected with strong correlation of  $\Delta N_{\text{step}}$  and  $m_\nu^2$  when the step position is too close to the end point. For such a run the step parameters were obtained by putting  $m_\nu^2 = 0$ . Changeable positions of the step with respect to the end-point energy from run to run seemed to be evidence for some systematics. The situation became more enigmatic when the values of  $E_0 - E_{\text{step}}$  were plotted versus calendar time of the corresponding run. The plot is given in Fig. 5. Its very surprising feature turned out to be the possibility to describe the time dependence of the step position by a sinusoid.

The period of the fitted sinusoid proved to be equal to  $0.499 \pm 0.003 \text{ yr}$ , the mean value of the position was 10.4 eV and the amplitude was 4.35 eV. Dependence of  $\chi^2$  on the value of the period obtained in the fit with a variable mean value, amplitude and phase of the sinusoid is given in Fig. 6. It is seen that a half-year period is the most probable one.

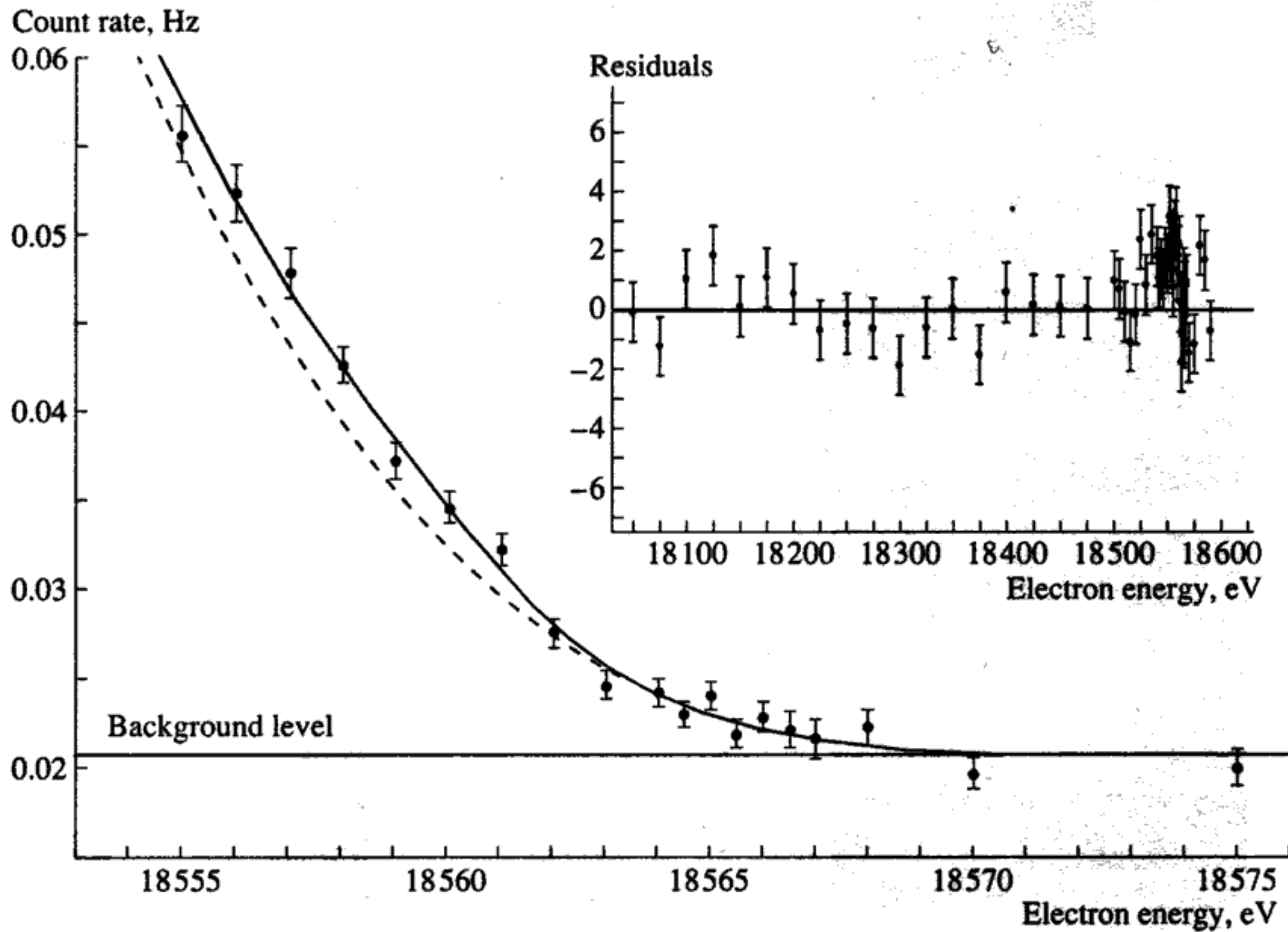


Fig. 3. Part of the experimental spectrum near the end-point. The solid line is the fitted theoretical spectrum with a step function. The dotted line is the theoretical spectrum with a subtracted step function. Upper right corner: the spectrum of residuals for entire measured part of the spectrum. Residuals are  $(N_{\text{exp}} - N_{\text{theor}})/\sigma$ , where  $N_{\text{exp}}$  is the same as the dotted line in the previous plot,  $\sigma$  is the standard deviation at each point.

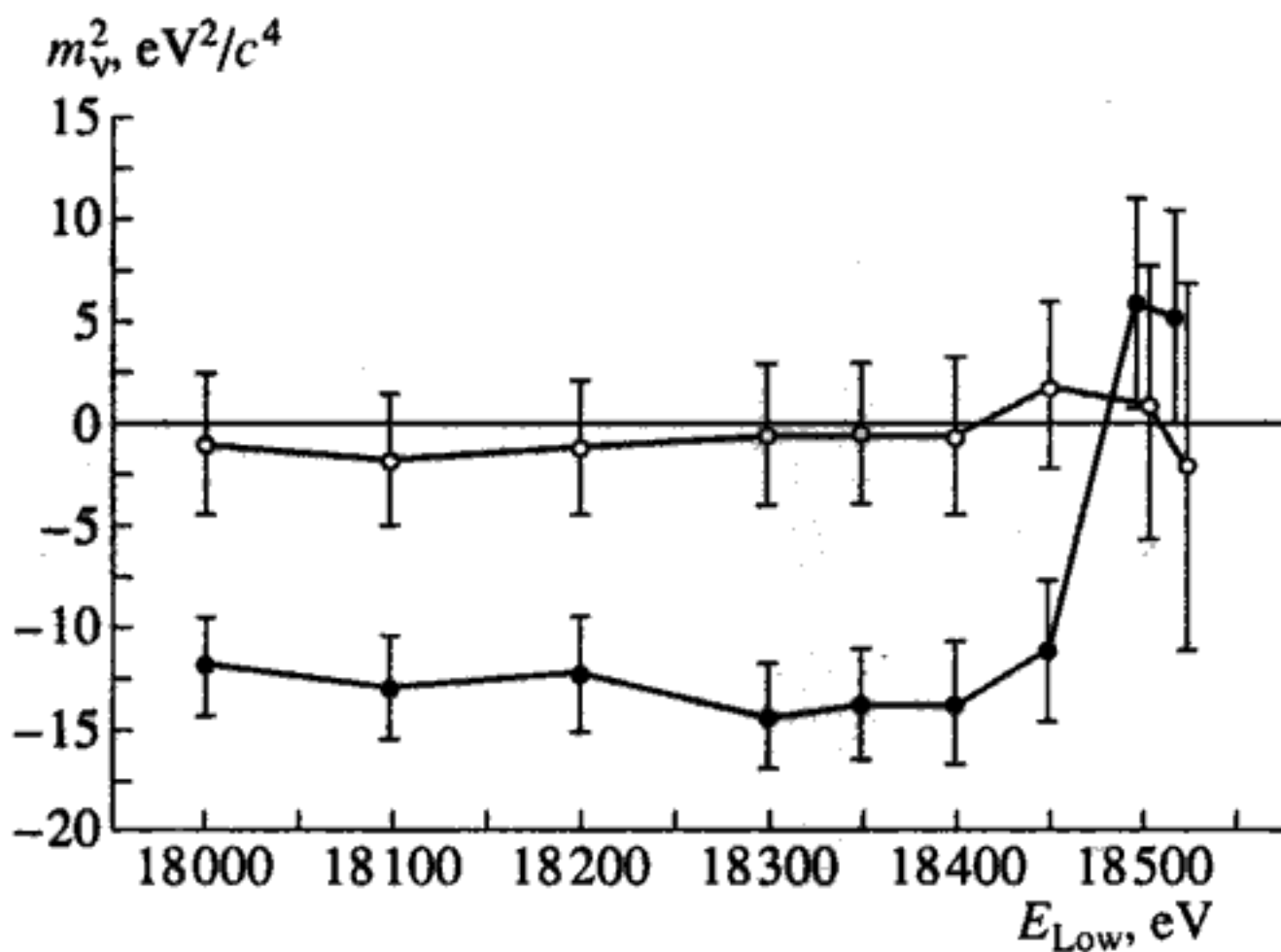


Fig. 4. Dependence of  $m_\nu^2$  on  $E_{\text{low}}$  for the sum of the Runs 94, 96, 97.2, 98 data. Closed circles are the fit without the step function (4-parameter fit). Open circles are the fit with the step function (6-parameter fit).

Data of all the years including points of the Mainz group reported in this conference are combined in one year plot (Fig. 7). It confirms that the variation of the step position has biseasonal character.

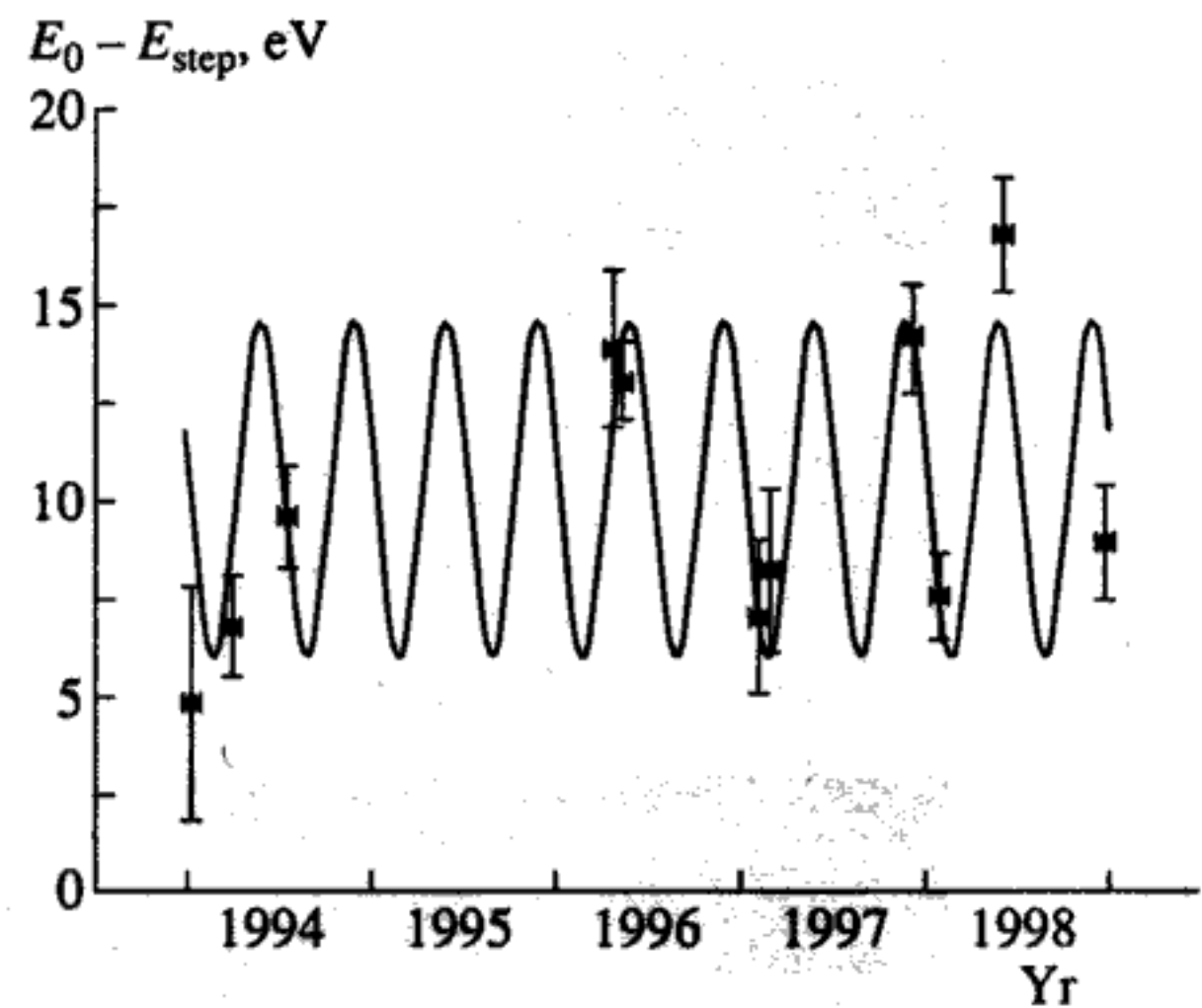


Fig. 5. Dependence of the step position on the calendar time of measurements. Parameters of the fitted sinusoid: Period  $0,499 \pm 0.003$  yr, mean value  $10.4 \pm 0.4$  eV, amplitude  $4.3 \pm 0.55$  eV, phase  $2.6 \pm 0.23$  rad.

The plot of step size values given in Fig. 8 proved to be more peculiar. The data obtained before 98.3 roughly agreed, at least for the first maximum, with the half-year period so that a larger step size corresponds to a

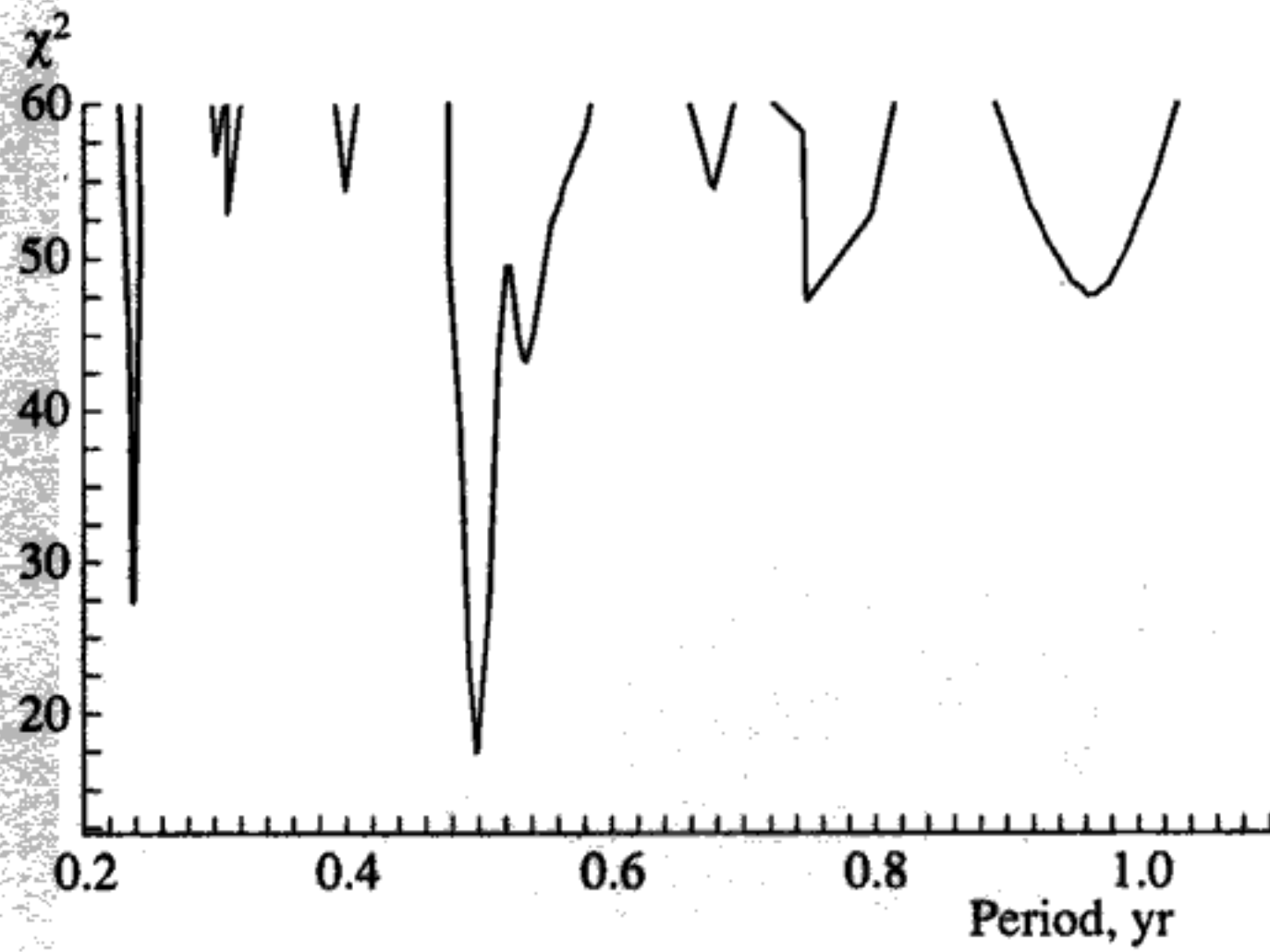


Fig. 6. The  $\chi^2$  dependence on the period of the sinusoid fitted to the step position. Period value was scanned and 3 other parameters were left variable.

larger distance from the end point. The measurement of being relatively short, resulted in an almost 3 times larger step size and  $E_0 - E_{\text{step}}$  somewhat below the sinusoid fitted to the previous data. This outburst may signify that the step phenomenon, if it is not considered as some apparatus effect, may fluctuate in size with characteristic time less than a month. the position being close to a sinusoid. This may be confronted with the latest measurement of the Mainz group where they did not find the step effect a few weeks earlier [17]. Unfortunately, the Troitsk set-up did not run this time.

Of course, the present set of data needs to be sufficiently extended. In particular, absence of measurement within the period July–December and absence of continuous measurement during all the year make it possible to fit a more complicated periodic curve but with the half-year component as a dominant one.

At the moment it seems impossible to propose any "customary" explanation of this phenomenon. The proximity of the oscillation period of the step (bump) to the half-period of Earth's circulation around the Sun and its other features remind us of an old speculation about an effect produced by capture of the cosmological degenerated neutrino by tritium atoms with emission of almost monochromatic electrons [18]. In order to produce the bump intensity corresponding to  $10^{-10}$  of the total decay rate, it is necessary to suppose existence of a neutrino cloud with density as high as  $0.5 \times 10^{15}$   $\nu/\text{cm}^3$ , that is  $10^{13}$  times higher than the generally accepted average density of the relic massless neutrino.

Observation of the bump below the end point of the beta spectrum corresponds to capture of the neutrino with negative energy, and to assumption of binding of neutrinos in the cloud. If the binding energy changes over the cloud, the Earth in its movement produces pe-

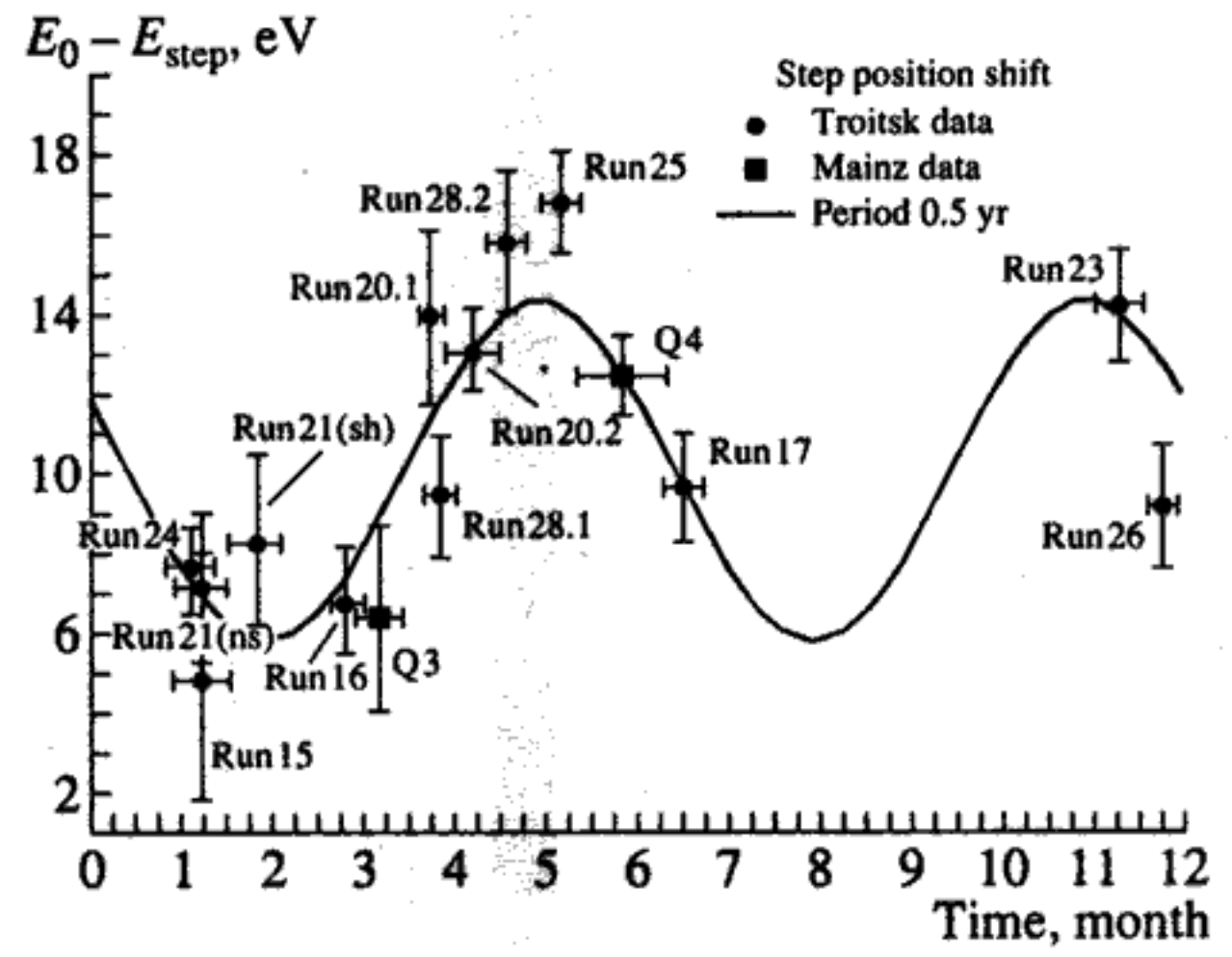


Fig. 7. Step position versus time of the year. The fitted sinusoid is the same as in Fig. 5 but with the period 0.5 yr. Horizontal bars are the duration of the run. Indices of the points indicate the number of the run. Run21(Sh) carried out with potential bias (15V) applied to the tritium source. Run 21(ns) carried out without this bias.

riodical modulation of the binding energy and correspondingly position of the step. It is interesting to point out that this hypothetical binding energy assumed as  $V = E_0 - E_{\text{step}} + E_{\text{Fermi}}$ , where  $E_{\text{Fermi}}$  is calculated from the step size, being plotted as in Fig. 5, provides somewhat better fit for the sinusoid in comparison with the previous fit. In order to explain the half-year modulation period one may suppose that the neutrino cloud has the shape of a flattered disc with the axis of symmetry inclined with respect to the normal direction to the Ecliptic plane.

The size of the neutrino cloud in this case must be comparable with the Earth's orbit and it rejects contradiction with the average density of the relic neutrinos in

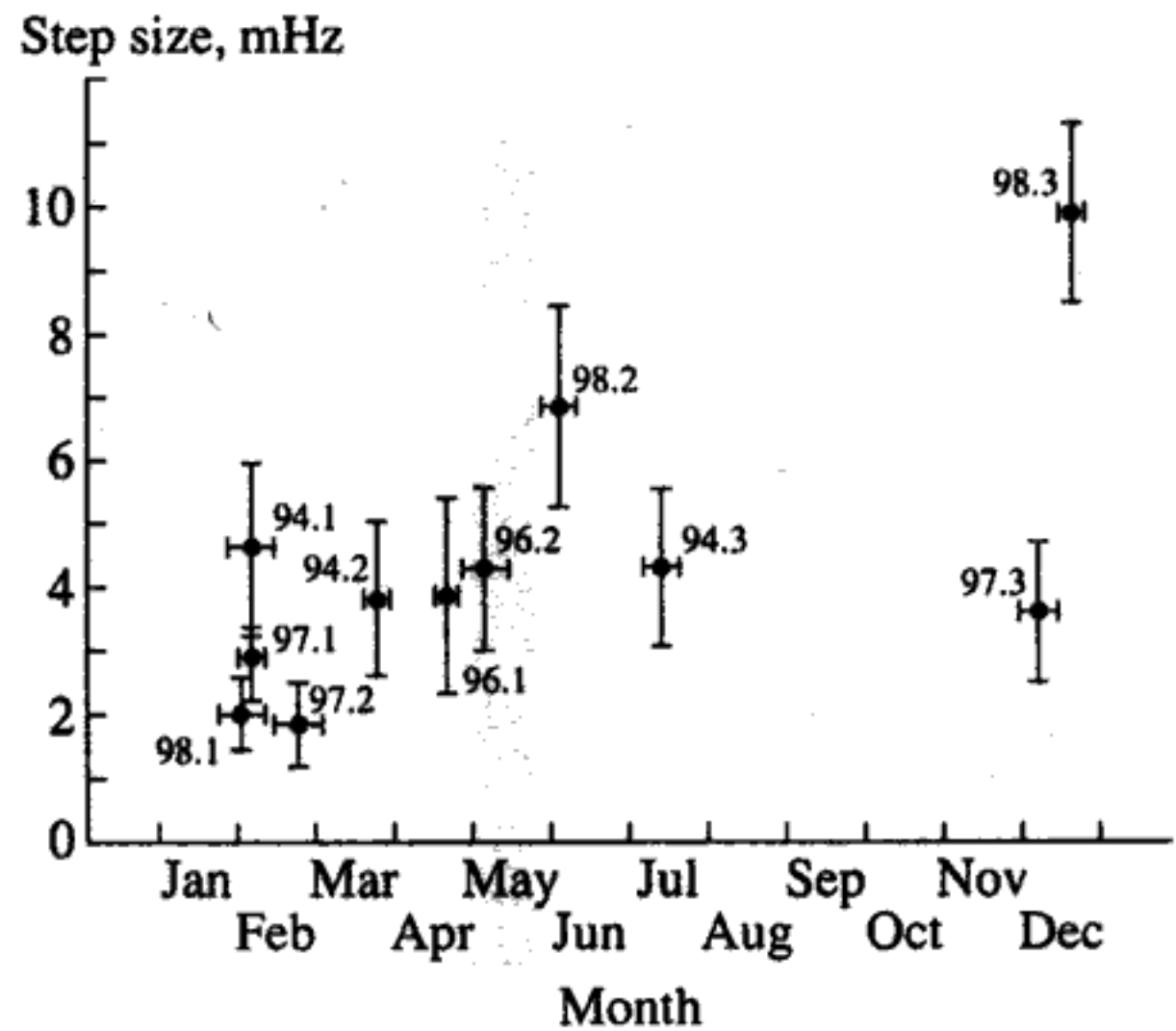


Fig. 8. Step size versus time of the year. All the size values are reduced to the same intensity of the source.

the Universe. Of course, this explanation of the step phenomenon is extremely speculative and may be considered only for stimulation of further experiments.

Up to now the experimental data do not exclude that the shape of the end-point region is more complicated than the 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.

## 5. UPPER LIMIT FOR NEUTRINO MASS

Deduction of the neutrino mass from the data in the presence of an unexplained anomaly requires a special approach.

As was mentioned earlier, the procedure accepted for this purpose consisted in addition of the step function with two variable parameters to theoretical spectrum supposing that this addition may describe in the first approximation local enhancement in the beta-spectrum near the end-point. Distortion of the beta spectrum imitating the  $m_\nu^2$  effect should also be concentrated near the 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  $m_\nu^2$ ) or deficiency (positive  $m_\nu^2$ ) of the spectrum that linearly increases with  $E_0 - E$ . This difference allows one to separate both effects in the fit procedure. Of course, the size and position of the step, introduced as a free parameter, correlates with  $m_\nu^2$  and increases the final error of the neutrino mass thus acting as a kind of systematic error. This increase sufficiently compensates for the uncertainty of replacement of an a priori unknown anomaly shape by the step-like function. A possibility of distinguishing the neutrino mass effect from the step strongly decreases with proximity of the step position to the end-point due to correlation of their parameters. Such correlation made it impossible to use the data of runs 97.1 and 98.1 for analysis of the neutrino mass in spite of good statistics. Besides the uncertainty caused by the step function, systematic errors come mostly from the uncertainties of the parameters of the correction factors, which are introduced in the spectrum before the fit. These factors are the trapping effect, source density, uncertainty of the excitation and ionization parts of the inelastic cross section, dead time, and influence of the high-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  $E_0$ . To the contrary, the systematics connected with an a priori unknown step function uncertainty increases when  $E_{low}$  comes closer to the end-point, which is automatically taken into account in the fit procedure. Considering that the fit error of  $m_\nu^2$  increases with increasing  $E_{low}$ , one may se-

lect the optimal  $E_{low}$ , when the total error, including both the fit and systematic error, is minimal. The results for  $m_\nu^2$  for all the runs are given below:

$$\begin{aligned} 1994 \quad m_\nu^2 &= -2.7 \pm 10.1_{\text{fit}} \pm 4.9_{\text{syst}} \text{ eV}^2/c^4, \\ 1996 \quad m_\nu^2 &= +0.5 \pm 7.1_{\text{fit}} \pm 2.5_{\text{syst}} \text{ eV}^2/c^4, \\ 1997(2) \quad m_\nu^2 &= -3.2 \pm 4.8_{\text{fit}} \pm 1.5_{\text{syst}} \text{ eV}^2/c^4, \\ 1998 \quad m_\nu^2 &= -0.6 \pm 8.1_{\text{fit}} \pm 2.0_{\text{syst}} \text{ eV}^2/c^4, \\ 1999 \quad m_\nu^2 &= +1.6 \pm 5.6_{\text{fit}} \pm 2.0_{\text{syst}} \text{ eV}^2/c^4. \end{aligned}$$

The combined value is

$$m_\nu^2 = -1.0 \pm 3.0_{\text{fit}} \pm 2.1_{\text{syst}} \text{ eV}^2/c^4. \quad (2)$$

The combined systematic error is obtained by averaging with weights of fit errors. From here one may obtain the 95% C.L. for  $m_\nu$ :

$$m_\nu < 2.5 \text{ eV}/c^2. \quad (3)$$

## 6. FURTHER STUDY OF THE EFFECTS IN THE TRITIUM BETA-SPECTRUM

Further investigation of the bump-like anomaly and the neutrino mass search at the level about  $1 \text{ eV}/c^2$  require major improvement of tritium beta-spectrometry. One of the obvious ways is enlargement of the existing set-up by a few times. Another way could be development of a differential spectrometer with the resolution and luminosity on a par with the integral one. The differential spectrometer allows better study of local anomalies in continuous spectra and will serve both for the search for the kinks from heavy neutrinos and for the above-mentioned tasks. At the moment two approaches to this problem are proposed. One is to use the integral spectrometer with pulsing of the source and the time-of-flight technique for achievement of the differential regime [19]. The loss of luminosity due to pulsing of the source is supposed to be compensated by larger dimensions of the spectrometer. The other approach is considered in [15]. It describes a new type of differential spectrometer designed on the principles of adiabatic motion of electrons in electric and magnetic fields. The apparatus consists of an integral electrostatic spectrometer with adiabatic magnetic collimation and with the central part which is lengthed and bent by 180 or 360 degree. The input part of the spectrometer cuts electrons with the energy below the potential of the central electrode with relative spread less than  $E_0 H_{\text{min}}/H_0$ .

In the central region of the spectrometer the electrons fly in the weak magnetic field with their moments being lined up along the magnetic lines and the energy being  $E_{\text{in}} - eV_0$ , where  $E_{\text{in}}$  is the initial electron energy and  $V_0$  is the potential of the analyzing electrode. The magnetic field in the central part as well as central electrode has a toroid-like shape. Electrons moving adiabatically in-

side the toroidal electrode are in the zero electrostatic field and drift perpendicularly to the toroidal plane owing to the well-known transverse drift. The magnitude of the drift with respect to the magnetic force lines depends on the velocity of the electron and rapidly increases with the electron energy. Although the drift is not large, a multislot collimator with the slots parallel to the toroid plane, mounted inside the toroidal electrode, allows electrons with the drift more than the width of the slot to be cut off.

One can expect some increase in the background due to bombardment of the collimator ends by ions which are accelerated in the detector part of the spectrometer. To avoid this, a slot mask will be mounted on the detector so that the adiabatical images of the end plates of the collimator are projected onto the covered regions of the detector.

Thus only electrons with the energy not more than several eV inside the toroidal electrode can reach the detector. Electrons with higher or very low energy will die on the collimator plates.

Luminosity of such a spectrometer will depend on the cross section of the central electrode and on the dimension of the tubes in the tritium source. The optimal parameters of the spectrometer should be studied in detail but it seems quite possible to construct a device with a resolution about 2 eV and luminosity 1 cm<sup>2</sup>. This could substantially improve all the tritium spectrometry. The competition between two approach would be very desirable in view of complexity of the task.

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