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FIRST RESULTS OF TROITSK EXPERIMENT ON SEARCH FOR ELECTRON ANTINEUTRINO REST MASS IN TRITIUM BETA-DECAY

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ПЕРВЫЕ РЕЗУЛЬТАТЫ ТРОИЦКОГО ЭКСПЕРИМЕНТА ПО ПОИСКУ МАССЫ ЭЛЕКТРОННОГО АНТИНЕЙТРИНО В БЕТА-РАСПАДЕ ТРИТИЯ

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АННОТАЦИЯ

Представлены первые результаты исследований бета-спектра трития около конечной точки, полученные в эксперименте ИЯИ РАН - ИЯФ "КИ" /Троицк/. Экспериментальная установка представляет собой интегральный электростатический спектрометр с адиабатической магнитной коллимацией и газовый тритиевый источник электронов. Обработка данных эксперимента дает $m_\nu^2 = -18 \pm 6 eV^2$. Изучение бета-спектра в области на 7÷15 eV ниже конечной точки указывает на возможность того, что эффект отрицательной m_ν^2 может быть объяснен присутствием пика /в дифференциальном спектре/, соответствующего полной вероятности распада около 6×10^{-11}. Мы получаем верхний предел для m_ν равный 4.5eV при 95% уровне достоверности.

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INTRODUCTION

We report in this paper first results of the experiment on search for electron antineutrino rest mass in tritium beta decay. The experiment is being carried out at the Institute for Nuclear Research of Russian Academy of Sciences in the city of Troitsk of the Moscow region. The main features of the experiment are the use of integral electrostatic spectrometer with adiabatic magnetic collimation and gaseous tritium source of electrons. The main ideas of this experiment were first proposed in [1]. Some description of the experimental set-up was given in [2] and will be published in detail elsewhere. Spectrometer device based on similar principles was independently developed in Mainz, the main distinction being the use of frozen tritium source of electrons [3].

The problem of direct measurement of neutrino mass by investigation of the end point of beta-decay spectrum remains actual. Many experimental groups pushed down the upper limit on neutrino mass below $8 \div 10\,eV$ during the last decade, thus refuting the evidence for the nonzero value obtained by the ITEP group in the 80ths, but revealing also many difficulties in measuring and analyzing beta spectra.

In this paper we present the results of measurements which allowed us to achieve statistical accuracy of data a few times better than in the previous experiments and to avoid some systematical uncertainties.

EXPERIMENTAL INSTALLATION

Schematic lay-out of the experimental set-up is given in Fig. 1. The essential part of the spectrometer and the tritium source is a set of superconducting solenoids producing longitudinal continuous magnetic field through the whole set-up. The field varies from $1\,Tl$ to $5\,Tl$ in the source and up to $8\,Tl$ at the entrance of the spectrometer. Then it decreases down to $1\,mTl$ at the medium plane of the spectrometer and finally achieves $2.6\,Tl$ at the detector region.

A cylindrical electrode in the central part of the spectrometer comprises an integral electrostatic analyzer. All the magnetic and electrostatic fields are adjusted to ensure the adiabaticity of electron motion through the source and the spectrometer along the magnetic field lines. Therefore, Li-drifted silicon counter $20\,mm$ in diameter detects only those electrons which were produced on the magnetic field lines crossing the detector surface. This allows us to avoid detection of electrons produced by tritium atoms located on the walls of the spectrometer and the source except the far end of the source volume, which is placed in low magnetic field and low tritium pressure. Back-scattered electrons are strongly suppressed due to small acceptance of the source for electrons entering the strong field.

Tritium gas is injected in the center of $3\,m$-tube inside the solenoids and is being pumped out by mercury diffusion pumps on both ends of it. After some additional compression in the buster mercury pump and after purification in a system of hot getters, tritium returns to the injection point thus providing continuous circulation. The temperature of the tritium tube is maintained at $26 \div 28\,^{o}K$. After a second pumping station the rest of the tritium diffusing to the spectrometer is intercepted by internal surfaces of SC-cryostats, covered by a very thin layer of argon condensed at $4.7\,^{o}K$ and refreshed by continuous sputtering. The circulation of tritium was maintained during two weeks with regular addition of fresh tritium from the storage system.

The spectrometer resolution is determined as

$$\Delta E = E\frac{H_{min}}{H_{max}}, \tag{1}$$

where E is electron energy, H_{max} - the intensity of the magnetic field at the entrance of spectrometer solenoid, and H_{min} - the intensity at the spectrometer medium plane [1]. In our measurements the energy resolution was adjusted to be equal to $3.7\,eV$ (FW) at $18.6\,keV$. The spectrometer luminosity was $0.27cm^2$ and the effective surface density of T2+TH+H2 was maintained at the level of about $1 \div 1.7 \times 10^{17}\,atoms/cm^2$. The efficiency of the detector was 87% in the window $15 \div 19.5\,keV$ with the resolution $1.3\,keV$ (FWHM).

The background of the detector was $5 \div 7\,mHz$ in the window $15 \div 19.5\,keV$ with the spectrometer high voltage equal to $18.7\,keV$ and nominal magnetic fields . With the full intensity of tritium source the intensity dependent background was about $15\,mHz$. The spectrometer vacuum was maintained at about $10^{-9}Torr$. The main pumping was provided by the cold surfaces of cryostats.

Cooling down the superconducting system was carried out by helium refrigerator of about $60\,W$ cooling power (at $4.6\,^{\circ}K$) working on-line in two-phase circulation regime.

MEASUREMENTS

The investigation of the tritium spectrum was performed by scanning the spectrometer high voltage. The relative stability of the HV potential was maintained at the level of about $\pm 0.16\,V$. which was continuously controlled by comparison of HV data from three different attenuators.

Despite of good interception of tritium from the source on its way to the spectrometer, about one tritium atom decay per hour was observed in the spectrometer volume, producing bunch-type background. This tritium came mainly from the volume between the spectrometer and the source, which was previously contaminated due to improper operation during warming up of all the system between the runs. The events of tritium decay in the spectrometer were clearly distinguished from regular counts at low counting rates as bunches of pulses with the energy corresponding to the spectrometer potential. They were produced by decay electrons being trapped by the magnetic field and gradually loosing their energy due to ionization of residual gas. The ionization electrons are accelerated and moving to the detector along the magnetic field lines. Typical rate of the events in the bunches was $10 \div 30$ pulses for $10 \div 20$ seconds. They were eliminated by arrival-time amplitude analysis. The correction for too small bunches to detect and the correction at high counting rates was introduced on the basis of bunch statistics and taking into account an additional spread produced by them which was included in final errors of each point of the spectrum.

Measurements of spectra were carried out by changing the spectrometer potential in steps. A typical time of measurement for one point was $100\,sec$ decreasing down to $50\,sec$ and then $20\,sec$ at high counting rate points. The maximum counting rate was $1000\,counts/sec$ at $18175\,V$. This point was also referred to as a monitoring point. After each 5 point measurements the potential was returned to the monitoring point for $20\,sec$ calibration. This allowed us to perform correction for slow variations of the source intensity. Amplitudes and the arrival times of all the pulses over some threshold were recorded for further analysis.

In total the experimental data included 317 series. Each series consisted of 37 measurement points in the first run and 51 points in the second one. The dead time was measured by counting the pulses from pulse generator. The dead time corrections were about 2.5% for maximal rate of $1000\,counts/sec$.

The measurements were made in the range of spectrometer potential from $18175\,V$ to $18770\,V$. The lower energy part of the spectrum was measured with reduced source intensity down to $16\,kV$-point. These measurements were carried out in order to check dependence of the detector efficiency upon the energy. The analysis of spectra obtained showed that the detector efficiency is constant within the accuracy of 1.5% over $3\,keV$ interval.

The measurement of the spectrometer resolution function was made using an electron gun with photoemission induced by ultraviolet lamp. It was shown that the monochromaticity of the source of such type is better than $0.5\,eV$. The measurements showed good correspondence to the calculated function shape. This gun was also used for the measurement of energy losses in tritium and hydrogen. In this case electrons from the gun were injected at the tritium source far end and traversed the whole length of it. This allowed us to calibrate both the transmission factor and the spectrum of energy losses with respect to the pressure in tritium circulation loop and counting rate at the monitoring point. The accuracy of the transmission factor measurement was estimated as 5%.

The measurement of isotope ratio in tritium system was regularly performed by mass-spectrometer and these data allowed us to check the tritium density in the source taking into account the counting rate and luminosity of the spectrometer, geometrical dimensions and the magnetic field intensity.

DATA ANALYSIS

The procedure of data analysis included a search for tritium decay events and correction for missed bunches, a correction for the source intensity drift, and dead time corrections.

The dependence of the background on the spectrometer potential was measured up to $19700\,V$. No dependence was found within the accuracy of 10%. This allows us to content ourselves with a constant background approximation in further analysis of the data.

Two runs of measurements with about 10 days of data acquisition each were carried out. The data of both runs are consistent within statistical errors.

In Fig. 2 there is presented a part of the measured spectra near the end-point energy. The data of the both runs were summed up taking into account the statistical weight of each point after subtraction of the background, calculated by averaging the points near and beyond the end point. It should be noticed that statistically significant deviation of spectrum points from the background level starts about $7\,eV$ below the effective end point ($18570.5\,eV$). The theoretical spectrum was calculated similar to [3] with the distinction of using the spectrum for free tritium molecule final states according to [5]. The energy loss function was calculated using the transmission factor from the experiment and the spectrum of losses approximated as well as in [4]. Earlier it was shown that this approximation gives reasonable agreement with measured energy loss spectrum.

The fitting procedure at first step included 4 free parameters: normalization factor, the background, the end-point energy, and m_ν^2. The lower limit of the fit interval of the spectrum (E_{low}) was changed from $18175\,eV$ to $18520\,eV$ that is from about $400\,eV$ to

Table 1:

$E_{low}\,(eV)$	18175	18300	18350	18400	18450	18500	18520
$m_\nu^2\,(eV^2)$	-37.5 ± 4.3	-19.3 ± 4.8	-20.2 ± 5.3	-18.6 ± 6.1	-25.5 ± 7.3	-35.7 ± 10.2	-30.0 ± 14.0
E_0 $(E - 18000\,eV)$	573.15 ± 0.08	573.60 ± 0.10	573.55 ± 0.11	573.60 ± 0.12	573.35 ± 0.18	572.95 ± 0.38	573.25 ± 0.57
χ^2	83.0	39.70	39.30	37.40	33.50	30.00	29.54
degrees of freedom	42	39	37	35	33	31	27

$50\,eV$ below the end point. The upper limit of the fit interval was $18770\,eV$. Backward scattering and detection efficiency energy dependence were not included into the analysis because it was shown that their influence on the result of fit is insignificant.

The results of fitting for combined spectrum from the both runs are presented in Table 1. The residuals from one of the fits are given in Fig. 3. The residual for each point is the difference between the measured value and the calculated one, divided by the experimental error in the point.

It is seen from the table the value of m_ν^2 is definitely negative for all E_{low} and there is a rise of negative value both at the lowest and highest E_{low}. Moreover the fit for the lowest E_{low} has bad χ^2, meaning that the set of parameters is not sufficient to describe the experimental spectrum. More definitely it could be seen in Fig. 3 when spectrum calculated with $E_{low} = 18400\,eV$ is extrapolated down to $18175\,eV$, that there is a rise of intensity of about 1% at $18175\,eV$ starting below $18350 \div 18300\,eV$. In these runs the rise occurs only for last three points and is somewhat dependent on fitting interval used for extrapolation. Nevertheless, it seems that this effect is similar to the phenomenon observed in Mainz experiment [3]. Based on the assumption that this rise is due to some missed final-state component of beta-decay one can estimate its exitation energy between $100 \div 150\,eV$ and probability of a few percent.

The known calculations of the final state spectrum do not agree with the existence of such a component [5]. From the other side it could be shown numerically that fitting the spectrum with this shifted component, not taken into account in the final-state spectrum, produces negative m_ν^2 effect and it is quite likely that in experiments with a large interval of fitting [4] the negative m_ν^2 effect could arise in this way. For this reason we restrict the interval of fitting by $E_{low} = 18350\,eV$.

Definitely negative value for m_ν^2 and rise of it with increasing E_{low} also need explanation

Table 2:

Range of averaging (V - 18kV)	$563 \div 560$	$559 \div 552$	$550 \div 535$	$530 \div 475$	$563 \div 475$
ΔN weighted average (mHz)	2.91 ± 0.68	2.24 ± 0.65	2.46 ± 0.82	1.70 ± 2.26	2.51 ± 0.40

because to explain this effect as a statistical fluctuation looks hardly probable.

Examination of the spectra presented in Fig. 2 draws our attention to the group of points below $18564\,eV$, that is about $7\,eV$ below the end point. These several points seem to form some step starting from about $18563\,eV$ and extending to lower energy. It is worth mentioning that for integral spectra any local excess of counting rate will form a step-like structure extending from some point down to the very beginning of the spectrum. Taking into account this observation, we made an attempt to check possible connection between this step-like structure and the effect of negative m_ν^2.

Some results of fitting are given in Fig. 4 for different E_{low} for the spectrum with subtracted step-like functions starting at $18563\,eV$ with different magnitudes corresponding to counting rates from 0 to $7\,mHz$. For each magnitude of the steps a value of minimal χ^2 and corresponding m_ν^2 are given in the figure. The curves of dependence of χ^2 on the magnitude of the step clearly exhibit a parabolic shape with the minimum at about $2.5 \div 3\,mHz$. The m_ν^2-dependence on the magnitude of the step forms more or less linear function with all the graphs crossing the axis corresponding to $m_\nu^2 = 0$ around the point $2.5\,mHz$.

The existence of the minimum of χ^2 just around $m_\nu^2 \approx 0$ appears to be an important indication of connection of this step-like structure in original spectrum with the phenomenon of negative m_ν^2 for the fitting interval with $E_{low} > 18350\,eV$.

Somewhat more definitely this step can be seen in Fig. 5 where the difference is presented between the experimental spectrum and the calculated one at the minimum of χ^2-parabola corresponding to $m_\nu^2 = +2\,eV^2$. Table 2 presents weighted average of this difference for several intervals of the spectrum. It is seen that within the errors these values do not depend upon averaging intervals, thus demonstrating a small width of the spike in differential spectrum.

If we postulate $m_\nu^2 = 0$, leaving the other parameters (including ΔN) free, we obtain $\Delta N = 2.61 \pm 0.63\,mHz$ corresponding to B.R.=$(6.3 \pm 1.5) \times 10^{-11}$ of the total decay rate.

With m_ν^2 taken again as a free parameter, it is necessary to form χ^2-distribution on a two-dimensional plot with the axis being the step magnitude and m_ν^2. This plot with two-standard-deviation contours is given in Fig. 6. It could be seen that the magnitude of the step and m_ν^2 are strongly correlated and this leads to a significant increase of upper limit for m_ν^2 which has to be deduced from the projection of the 2-sigma contour on the axis of m_ν^2.

Accepting the positive part of the projection for most restrictive case (E_{low} equals $18350\,eV$) one can deduce the upper limit

$$m_\nu^2 < 20\,eV^2, \tag{2}$$

thus implying

$$m_\nu < 4.5\,eV \text{ at } 95\% \text{ C.L.} \tag{3}$$

This limit is essentially lower than those published up to now and involves a new kind of systematics which was not seen previously.

It is worth mentioning that separation of m_ν^2 from the step-size effect proved to be possible only due to high statistics and low background achieved in this experiment.

We do not include other uncertainty factors like transmission and energy loss inaccuracy because their influence on m_ν^2 limit is relatively small.

The spike-like structure in tritium beta spectrum of B.R. $\sim 10^{-10}$ could not be seen in the previous experiments [3, 4] due to insufficient statistical accuracy. At present it cannot be reasonably understood on the basis of usual beta-decay processes. In order to check a trivial way of generation of a monochromatic electronic line with the energy occasionally very close to the end point of the tritium spectrum (such as presence of an unidentified radioactivity in the source walls or circulation gas) we carried out a measurement with tritium absorbed in the getter trap. Due to low temperature of the tritium tube ($27\,^\circ K$) only gasses like neon could remain in gaseous state and not be absorbed by the getter. This measurement showed that the step magnitude is less than $0.7\,mHz$ at 95% C.L.

Generation of the step-like rise of background seems to be very improbable for too small width of the step and independence of the step position on spectrometer magnetic fields, which were slightly changed several times during the data acquisition period. thus not permitting one to propose a realistic mechanism of the process.

At the moment it seems to be early to discuss some exotic explanations of spike-like effects in tritium decay until this phenomenon is studied more carefully. It is possible in near future to improve both statistical and systematical accuracy of this experiment at least by a few times thus making the situation clearer.

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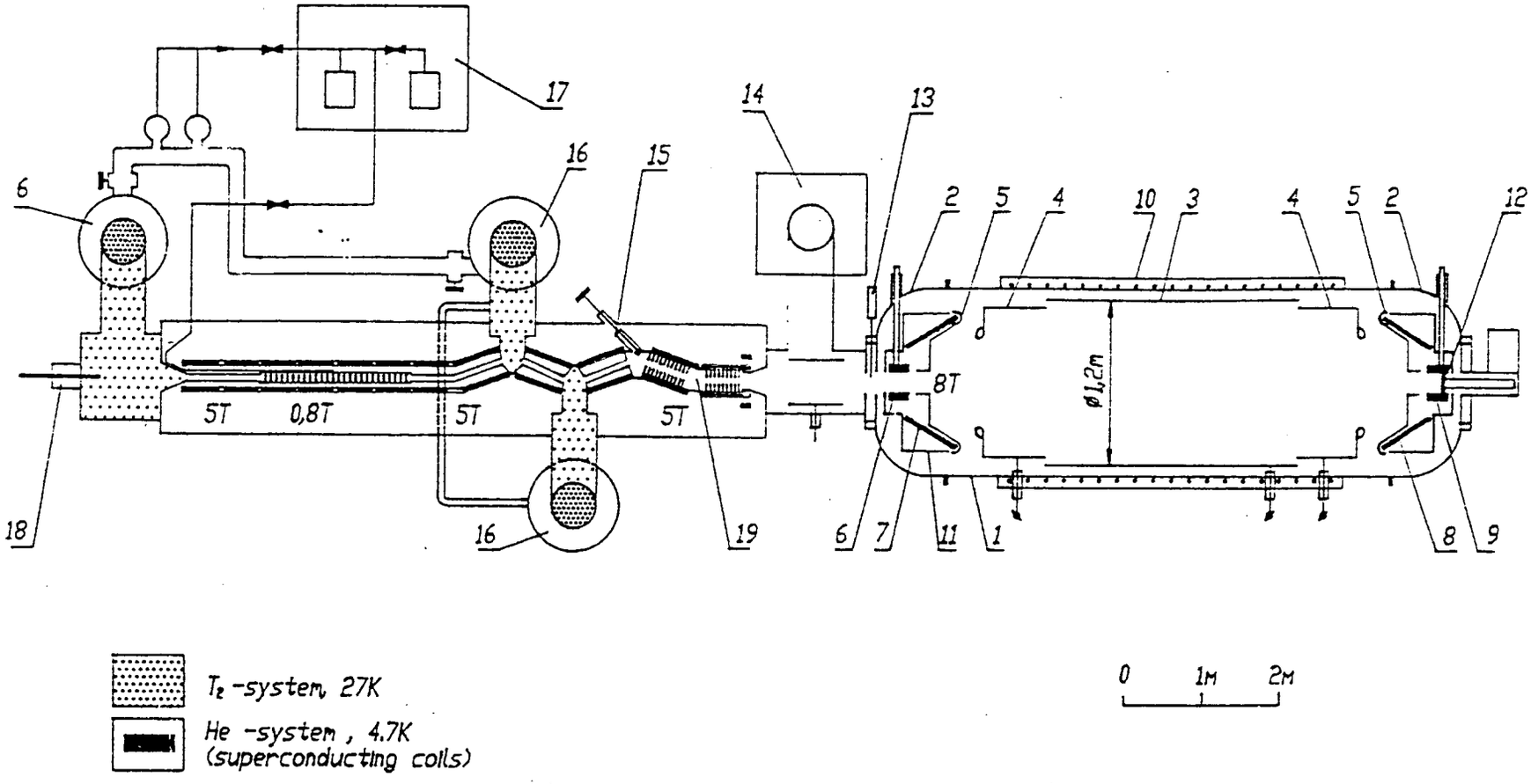

Fig. 1. Experimental set-up. 1,2 - vacuum tank; 3,4 - electrostatic analyzer; 5 - grounded electrode; 6,7,8,9 - superconducting solenoids; 10 - warm coil; 11 - liquid-N_2 jacket; 12 - detector; 13 - fast shutter; 14 - Ti-pump; 15 - cold valve; 16 - Hg diffusion pump; 17 - T_2 purification system; 18 - electron gun; 19 - argon pump.

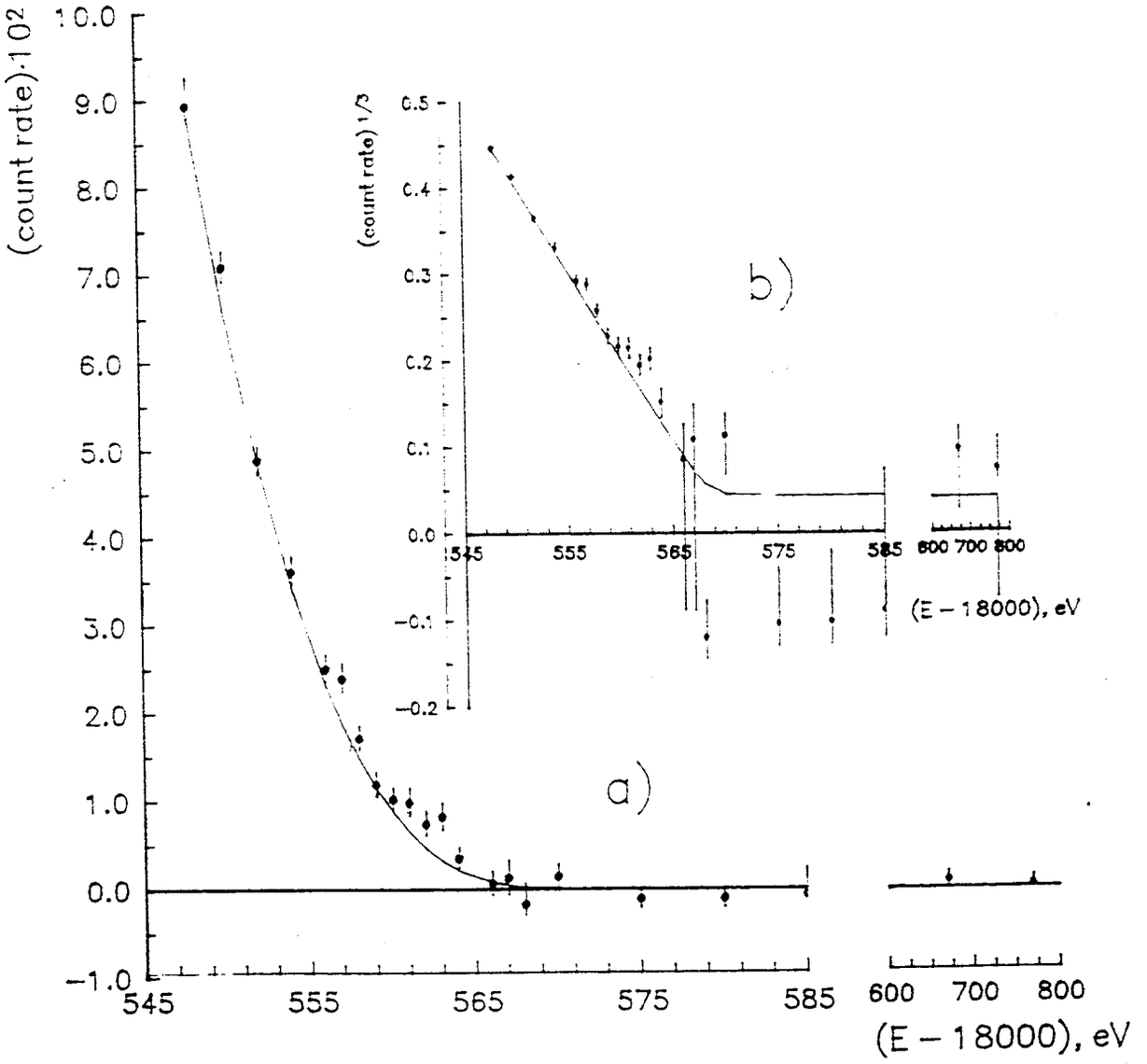

Fig. 2. Part of the tritium spectrum (a) and Curie-plot (b) near the end point.

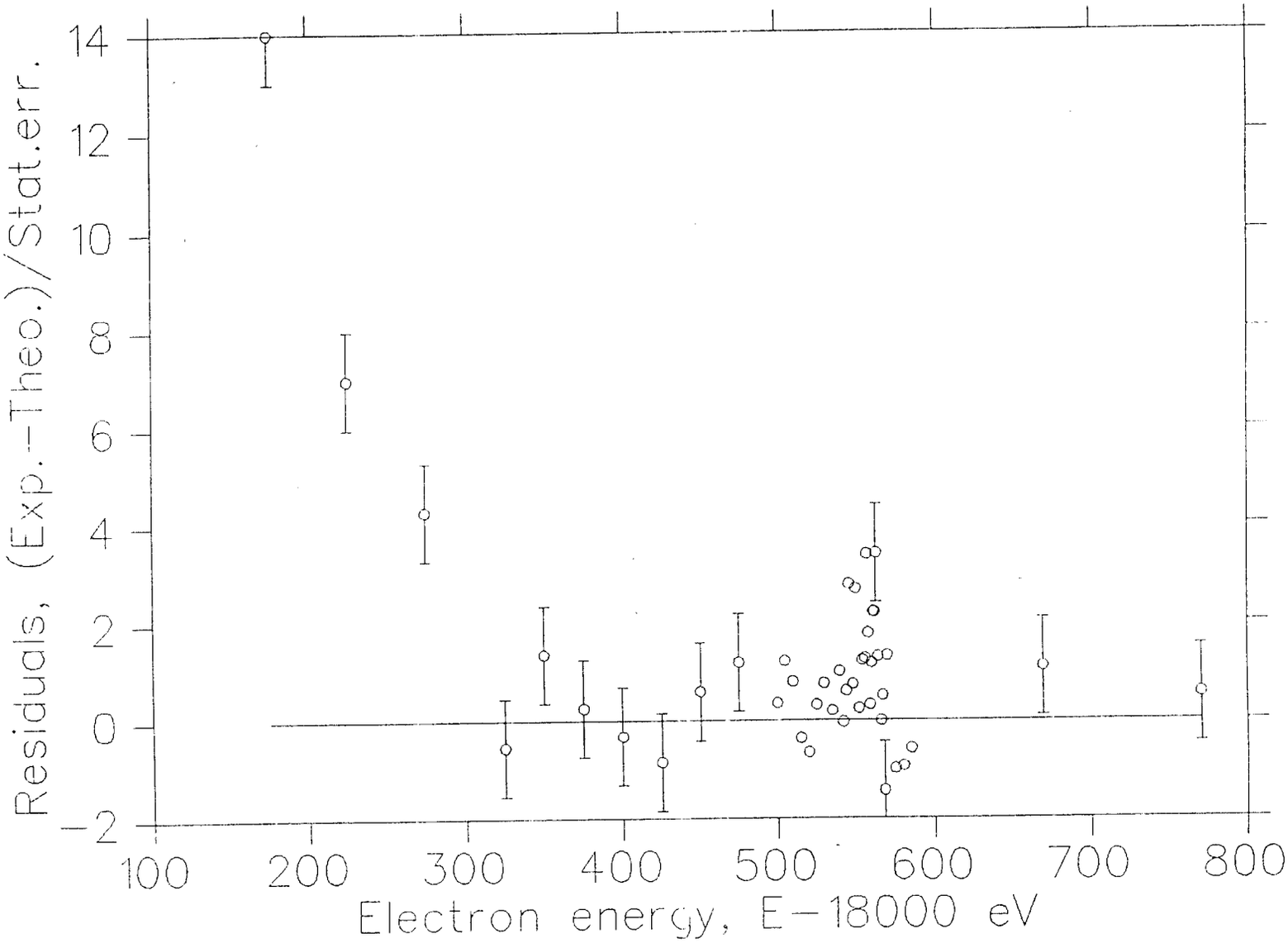

Fig. 3. Residuals from the fit of the tritium spectrum. The residual for each point is the difference between the measured value and the calculated one, divided by the point's error. The calculated spectrum was obtained for $m_\nu^2 = 0$, $E_{low} = 18350\,eV$ and step magnitude $2.5\,mIIz$.

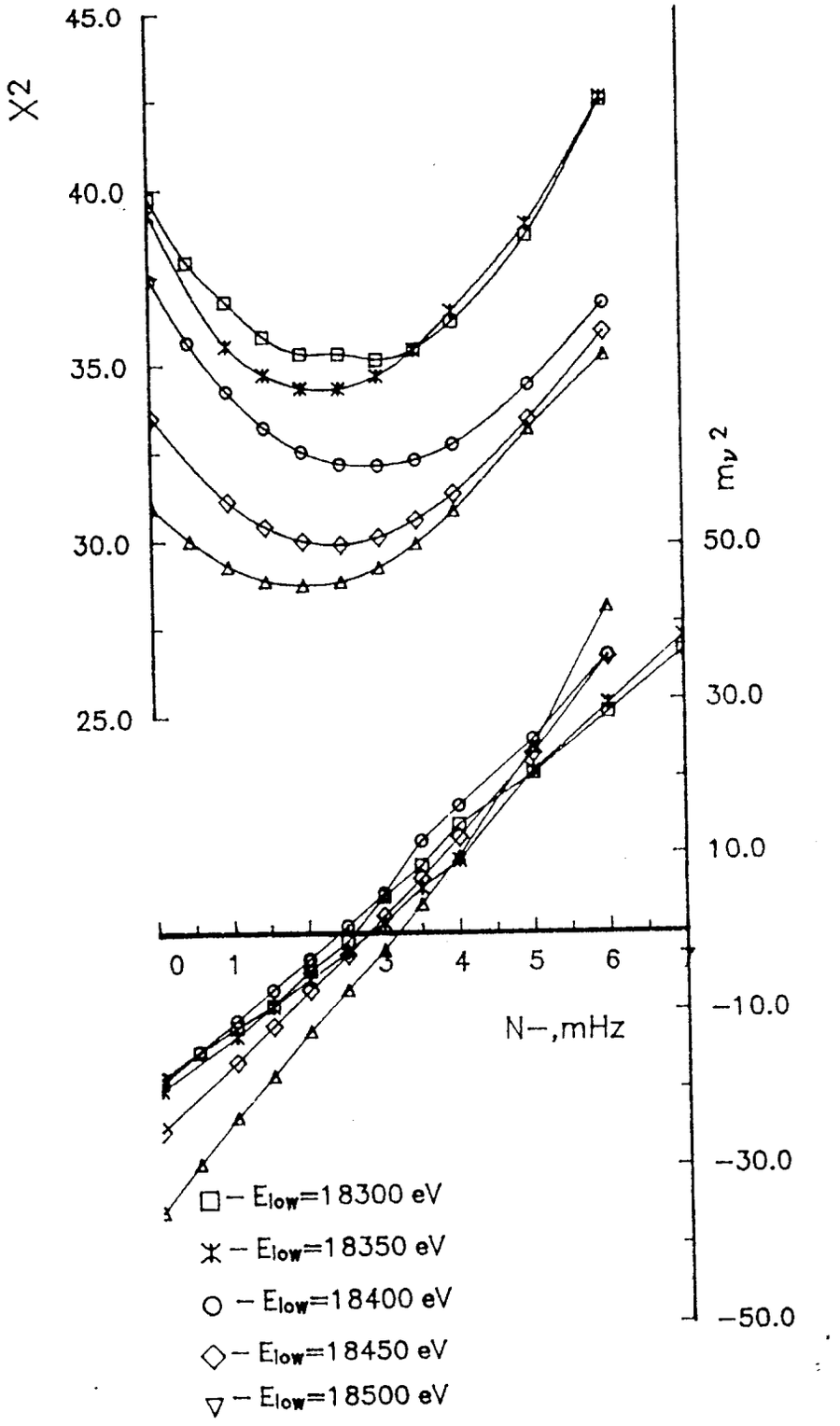

Fig. 4. m_ν^2 and χ^2 versus the step magnitude.

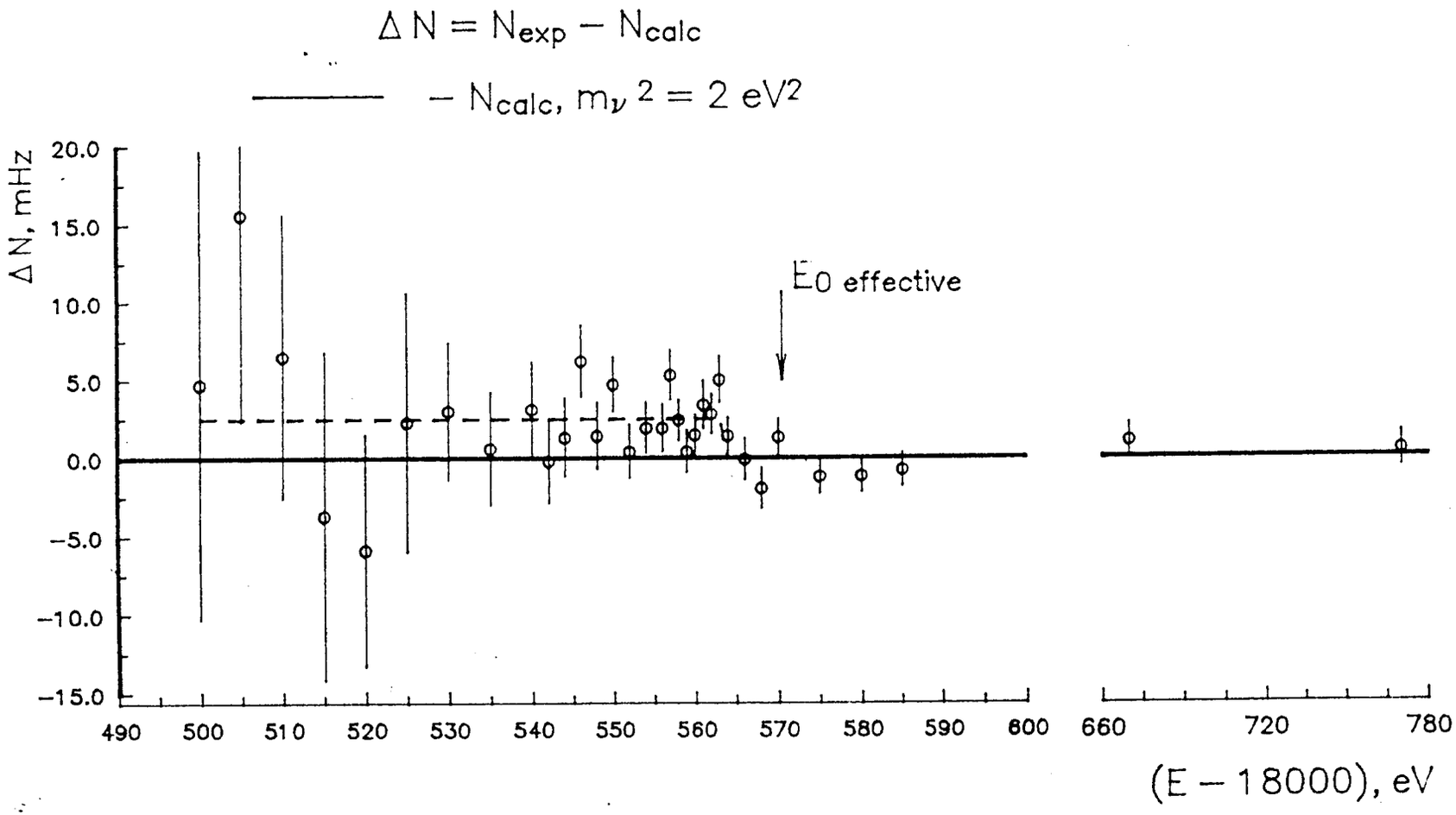

Fig. 5. Difference between the experimental spectrum and the calculated one at the minimum of χ^2 corresponding to $m_\nu^2 = +2\,eV^2$.

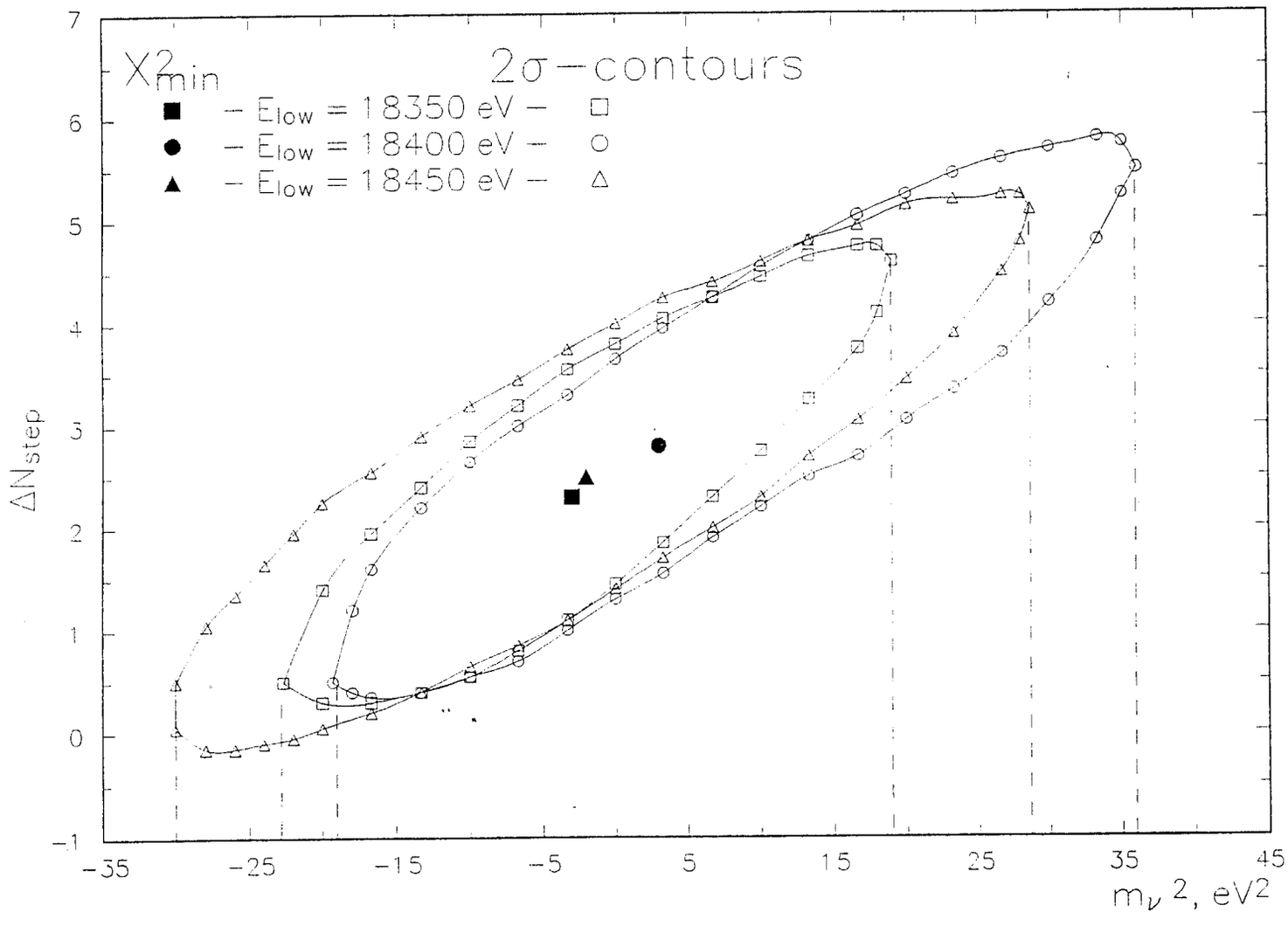

Fig. 6. 2-sigma contours of χ^2 two-dimensional plot.