



ELSEVIER

5 August 1999

PHYSICS LETTERS B

Physics Letters B 460 (1999) 219–226

# High precision measurement of the tritium $\beta$ spectrum near its endpoint and upper limit on the neutrino mass

Ch. Weinheimer <sup>1</sup>, B. Degenddag <sup>2</sup>, A. Bleile, J. Bonn, L. Bornschein,  
O. Kazachenko <sup>3</sup>, A. Kovalik <sup>4</sup>, E.W. Otten

*Institute of Physics, Joh. Gutenberg University, 55099 Mainz, Germany*

Received 22 April 1999

Editor: K. Winter

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## Abstract

The Mainz neutrino mass experiment investigates the endpoint region of the tritium  $\beta$  decay spectrum to determine the mass of the electron antineutrino. By the recent upgrade the former problem of dewetting  $T_2$  films has been solved and the signal-to-background-ratio was improved by a factor of 10. The latest measurement leads to  $m_\nu^2 = -3.7 \pm 5.3_{\text{stat}} \pm 2.1_{\text{sys}} \text{ eV}^2/c^4$ , from which an upper limit of  $m_\nu < 2.8 \text{ eV}/c^2$  (95% C.L.) is derived. Some indication for the anomaly, reported by the Troitsk group, was found, but its postulated half year period is contradicted by our data. © 1999 Published by Elsevier Science B.V. All rights reserved.

PACS: 14.60.Pq; 23.40.-s

Keywords: Neutrino mass; Tritium  $\beta$  spectrum

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## 1. Introduction

The results from the atmospheric and solar neutrino experiments [1,2] seem to require non-zero neutrino masses, which have strong consequences for particle physics as well as for astrophysics and cosmology. These neutrino oscillation experiments de-

termine differences of neutrino mass squares not absolute mass values. The latter are accessible via the kinematics of weak decays. The investigation of the tritium  $\beta$  spectrum near its endpoint is the most sensitive of these so-called direct methods <sup>5</sup>. If the differences between the different neutrino mass eigenvalues are as small as indicated by the solar and atmospheric neutrino experiments, not only hierarchical neutrino mass scales but also degenerate masses in the  $\text{eV}/c^2$  range become interesting be-

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<sup>1</sup> Corresponding author. Address: see above; E-mail: christian.weinheimer@uni-mainz.de; Tel.: +49 6131 395955; Fax: +49 6131 393428.

<sup>2</sup> This work includes parts of the doctoral thesis of B. Degen.

<sup>3</sup> On leave from INR, Troitsk/Russia.

<sup>4</sup> On leave from JINR, Dubna/Russia.

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<sup>5</sup> The search for neutrinoless double  $\beta$  decay is not fully direct, since it is only sensitive to Majorana-type neutrinos and it depends on the neutrino mixing matrix.

cause of their contribution to the missing dark matter in the universe [3].

Tritium  $\beta$  decay experiments are currently running at Mainz and Troitsk [4,5]. In this paper we report on the upgrade of the Mainz experiment which aimed not only at improving the sensitivity to  $m_\nu$ , down to an ultimate limit of 2 eV/c<sup>2</sup> but also at checking the anomalous excess in the spectrum close to the endpoint which was communicated by the Troitsk group [6]. We present further the results of the first 4 runs with the upgraded setup in 1997 and 1998, which covered a total of 4 months of data taking.

## 2. Problem of $m_\nu^2 < 0$

The analysis of our previous data, taken in 1991 [7] and 1994 [8], had been hampered by a residual unexplained excess of energy loss of  $\beta$  particles, which had shifted a few percent of spectral strength towards an effective endpoint some 70 to 100 eV below the one of the dominant (54%) elastic component at  $E_0 = 18.574$  keV. This spectral deterioration drove the fit of  $m_\nu^2$  towards unphysical negative values the more, the further the interval of data included in the fit was extended towards lower energies. These complications had forced us to limit the interval from which  $m_\nu^2$  was extracted to the last 140 eV of the spectrum yielding upper limits for  $m_\nu$  of 7.2 eV/c<sup>2</sup> [7] and 5.6 eV/c<sup>2</sup> [8].

A first hint towards an explanation of the enhanced energy loss came from the observation [9] that frozen films of H<sub>2</sub> and D<sub>2</sub> are dewetting from the substrate at temperatures around 4 K forming individual crystals. This effect has been confirmed meanwhile for our T<sub>2</sub> films [10,11] and an enhancement of multiple inelastic scattering events in such dewetted films has been observed in our spectrometer for the case of 17.8 keV K-32 conversion electrons from <sup>83m</sup>Kr [12]. At temperatures below 2 K, however, which are reached in our improved setup this effect is effectively suppressed by a time constant of tens of years [10].

The Troitsk group has described its anomaly as a sharp step of the count rate at a few eV below  $E_0$  [6]. Since their spectrometer is also integrating like ours, this step corresponds to a line in the primary spec-

trum with a relative intensity of about 10<sup>-10</sup> of the total decay rate. In 1998 the Troitsk group reported that the position of this line oscillates with a frequency of 0.5 years between 5 eV and 15 eV below  $E_0$  [13]. If not considered in their analysis, the fits give significantly negative values for  $m_\nu^2$  in the range of -10 to -20 eV<sup>2</sup>/c<sup>4</sup>. The origin of such a monoenergetic line is not clear within standard physics. An independent experimental check is mandatory.

## 3. The improved Mainz setup

The principle of the Mainz spectrometer, Magnetic Adiabatic Collimation followed by a retarding Electrostatic Filter (MAC-E-Filter, also called Solenoid Retarding Spectrometer), combines both a very high energy resolution <sup>6</sup> ( $\Delta E = 2-6$  eV at 20 keV) and a large acceptance ( $\Delta\Omega/2\pi = 0.2-0.8$ ) [4,14]. The main limitations of the 1991 and 1994 measurements came from the T<sub>2</sub> source. The source cryostat did not allow temperatures low enough to avoid safely the dewetting of the T<sub>2</sub> film. Moreover, the signal-to-background-ratio was limited by T<sub>2</sub> gas evaporating from the source into the spectrometer causing background there. These and other shortcomings were overcome by the following measures (compare Refs. [11,14]):

- A new source cryostat, running stable at  $1.86 \pm 0.03$  K, suppresses effectively the dewetting of the T<sub>2</sub> film.
- A pair of superconducting solenoids, tilted by 20° to each other, was installed between source and spectrometer. Consequently  $\beta$  particles from the source are still guided magnetically around the corner into the spectrometer without losses, whereas tritium molecules evaporating from the source are trapped on the bend of the LHe cold tube covered with graphite.

<sup>6</sup>  $\Delta E$  gives the full rise of the transmission function  $f_{\text{trans}}$  from 0% to 100%. It is defined [4] for a given energy  $E$  only by the ratio of the minimum magnetic field in the analysing plane  $B_{\text{min}}$  and the maximum magnetic field between source and analysing plane of the spectrometer  $B_{\text{max}}$  through  $\Delta E = EB_{\text{min}}/B_{\text{max}}$  by which it can be adjusted.

- The electrode system was slightly modified to lower the background contribution from the spectrometer itself. Due to a better alignment of the whole system the spectrometer can operate now at a higher energy resolution of 4.4 eV compared to 6.3 eV in 1994 at same count rate.
- An experiment control system combined with an alert system based on cellular phones was installed in order to run the experiment automatically. Human intervention is needed only for filling of LHe and LN<sub>2</sub>.

#### 4. The 4 runs of 1997 and 1998

With the improved setup 4 runs (labelled Q2–Q5) have been taken in 1997 and 1998 of 4 month measurement time in total. To increase the signal rate we used much thicker T<sub>2</sub> films of 973 Å (Q2) and 490 Å (Q3–Q5), respectively, compared to 126 Å in 1994. The increase of electron scattering within the T<sub>2</sub> film was partly compensated by reducing the maximum path length within the film by decreasing the emission cone of accepted β particles from 78.5° (1994) to 45°. The film thickness was measured by laser ellipsometry and found to remain constant over each run. With a residual gas analyser we checked that the hydrogen contamination of our T<sub>2</sub> films caused by exchange processes on the walls during film preparation varies between 5% and 20% for the different runs.

The β spectrum was scanned from 18.370 keV to 18.660 keV by changing the electric potential at the source in time intervals of 10 to 20 s per point and with reduced step size of 1 eV around the endpoint. For each event pulse height and time were digitised and recorded. The data were filtered for obvious hardware failures or large sparks in the high voltage system, no other filtering was applied to the data.

Fig. 1 shows the event rate, averaged over the runs Q3, Q4 and Q5, which were performed under very similar conditions, as function of the retarding energy  $-eU$ . One recognises a gain in signal-to-background-ratio by a factor of 10 and much better statistics with respect to the 1994 data.

The data were fitted by a function derived from the standard formula for an allowed β spectrum, which is summed up for all electronic final states of

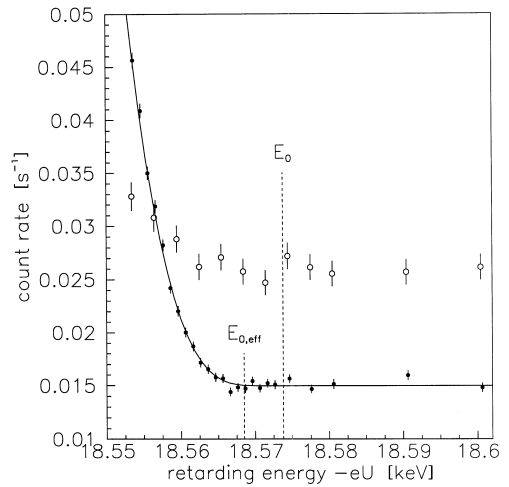


Fig. 1. Averaged count rate of runs Q3, Q4 and Q5 of 1998 (filled circles) compared with the 1994 data (open circles) near the endpoint  $E_0$ , and effective endpoint  $E_{0,\text{eff}}$ , which considers the convolution with the functions  $f_{\text{trans}}$  and  $f_{\text{charge}}$  and the mean rotation-vibration excitation energy of the electronic ground state of the  ${}^3\text{HeT}^+$  daughter molecule. Since the signal is an integral over the β spectrum for  $E > -eU$  it may be roughly approximated in the neighbourhood of  $E_{0,\text{eff}}$  by  $\dot{N}(-eU) = a(E_{0,\text{eff}} + eU)^3$ . From the plot one reads a rate constant of about  $10^{-5}/(\text{s eV}^3)$ . The line shows a fit to the data for  $m_\nu^2 = 0$  over the interval shown.

the daughter molecule of amplitude  $W_i$  and excitation energy  $V_i$  [15,16] and then convoluted with the potential distribution within the tritium film  $f_{\text{charge}}$ , the functions describing the backscattering from the substrate  $f_{\text{bsc}}$ , the inelastic processes within the T<sub>2</sub> film  $f_{\text{loss}}$ , the spectrometer transmission  $f_{\text{trans}}$ , and the energy dependence of the detection efficiency  $f_{\text{det}}$ :

$$\begin{aligned} \dot{N}(-eU) &= \left( AFp(E + m_e c^2) \sum_i W_i (E_0 - V_i - E) \right. \\ &\quad \times \sqrt{(E_0 - V_i - E)^2 - m_\nu^2 c^4} \\ &\quad \left. \otimes f_{\text{charge}} \otimes f_{\text{bsc}} \otimes f_{\text{loss}} \otimes f_{\text{trans}} \otimes f_{\text{det}} \right) + B \quad (1) \end{aligned}$$

$\dot{N}$  is the count rate,  $A$  is a free amplitude,  $F$  is the Fermi function,  $p$  and  $E$  are the electron momentum and kinetic energy, and  $B$  describes a constant background. Fit parameters are  $A$ ,  $E_0$ ,  $m_\nu^2$ , and  $B$ . The

response function  $f_{\text{res}} = (f_{\text{charge}} \otimes f_{\text{bsc}} \otimes f_{\text{eloss}} \otimes f_{\text{trans}} \otimes f_{\text{det}})$  is illustrated in Fig. 2. It is worth to mention, that the response function has no high energy tail at all. Consequently, a count rate significantly above background at a retarding energy of  $E_0 - \Delta E_x$  means, that the neutrino mass has to be smaller than  $\Delta E_x$ .

Systematic uncertainties were taken into account as follows (the percentages in brackets illustrate their contribution to the total systematic uncertainty on  $m_\nu^2$  for fitting the last 70 eV of the spectrum of data set Q5):

*Inelastic scattering within the tritium film (49%):* In a recent investigation [17] we have measured the energy loss function  $f_{\text{eloss}}$  of 17.8 keV K-32 conversion electrons of  $^{83\text{m}}\text{Kr}$  in  $\text{D}_2$  films. The mean free path was found to be  $\lambda_{\text{free}} = 1204 \pm 63 \text{ \AA}$ , rescaled for an energy of 18.5 keV. This value is about 26% larger than calculated from the total inelastic cross section in gaseous hydrogen for the density of a closely packed crystal. Also the peak position of the excitation spectrum is shifted from 12.6 eV to 14.3 eV. Both effects are expected to occur as result of Pauli blocking of the excited electrons. However, an increase of 17% of  $\lambda_{\text{free}}$  is due to pores within the tritium film, determined by the ellipsometry measurement of its index of refraction giving  $n = 1.14$ ,

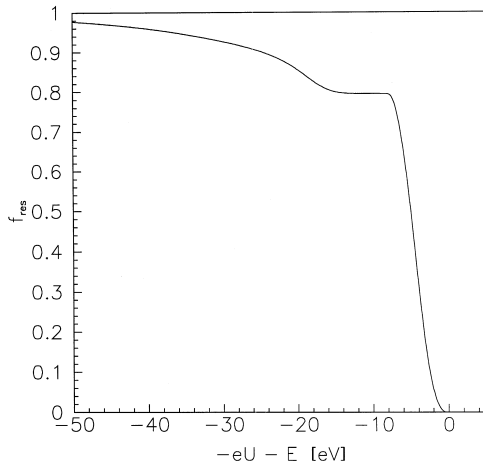


Fig. 2. Normalised response function of the spectrometer  $f_{\text{res}}$  for a monoenergetic electron source of energy  $E$  in dependence on the retarding energy  $-eU$ . The energy loss  $f_{\text{eloss}}$  and the charging effect  $f_{\text{charge}}$  are calculated for a source thickness of 490 Å as used for measurements Q3–Q5.

which is about the same as for our  $\text{D}_2$  films. For the systematics the uncertainties of  $\lambda_{\text{free}}$  and of the film thickness measurement, which varies between 1% and 7%, depending on the substrate quality, were considered.

*Neighbour excitation (26%):* We have considered the observed peak position shift also in the energy loss caused by the sudden excitation of neighbours of the  $\beta$  decaying molecule. The probability of such an event has been calculated to be 5.9% [16]. The observed increase of  $\lambda_{\text{free}}$  leads to an estimated reduction<sup>7</sup> down to 4.6%. The two corrections were added with full amount to the systematic uncertainty for safety.

*Final states (11%):* Pauli blocking effects are also expected for the excited levels of the  $\text{THE}^+$  daughter molecule, but here the effects should be small due to the higher nuclear charge  $Z$  of the He nucleus. A rough calculation results in level shifts of the order of 1 eV for the second and higher excited levels [18]. For safety these shifts are fully taken into account as systematic uncertainty.

*Charging up of the  $\text{T}_2$  film (14%):* For the thick  $\text{T}_2$  films used in 1997 and 1998 a charging up of the films by several volts due to the  $\beta$  emission was observed. By measuring the energy shift of the K-32 conversion line of  $^{83\text{m}}\text{Kr}$  positioned in different depths of the  $\text{T}_2$  film we proved, that the potential within the film increases linearly with the distance to the substrate at a slope of 6 mV/Å [11]. The charging effect leads to a slight decrease of the effective energy resolution. For safety 40% of the total effect is taken into account as systematic uncertainty.

*Other contributions (< 1%):* We also considered uncertainties of the transmission, backscattering, and detector efficiency functions, their influence on Eq. (1) and hence on  $m_\nu^2$  is small compared to the other effects.

Fig. 3 shows the fit results on  $m_\nu^2$  with statistical and total uncertainties (statistical and systematic un-

<sup>7</sup> The 9% increase of  $\lambda_{\text{free}}$  due to Pauli blocking has to be fully taken into account for the decrease of the neighbour molecule excitation, but the application of the 17% increase of  $\lambda_{\text{free}}$  due to the pores depends on the pore size. Considering different scenarios we use a value of 13% as average reduction of the neighbour molecule excitation by the pores.

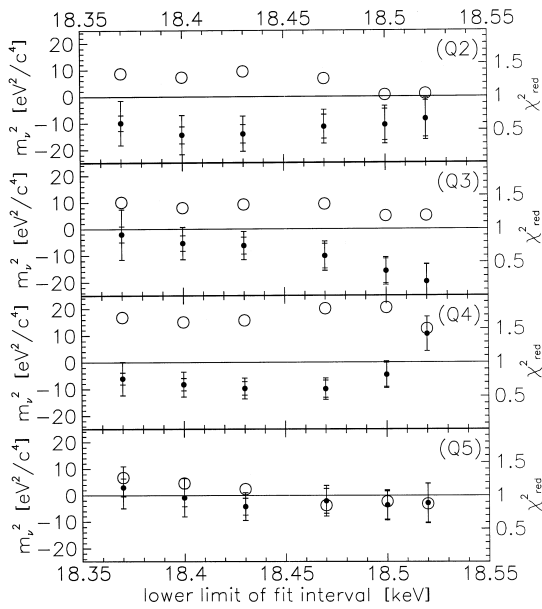


Fig. 3. Fit results on  $m_\nu^2$  (left scale, filled circles) for the 4 different runs with statistical uncertainties (inner bars) and total uncertainties (outer bar) in dependence on the lower limit of the fit interval. The upper limit of the fits is always 18.66 keV, well above the endpoint  $E_0$ . The corresponding values of  $\chi^2_{\text{red}} = \chi^2/\text{d.o.f.}$  of the fits (open circles) can be read from the right scale.

certainties added in quadrature) for the 4 different runs Q2 to Q5 as function of the lower energy limit of the data interval used for the analysis. The following comments apply:

- Systematic uncertainties shrink to a negligible level for small fit intervals, since so close to the endpoint, say above 18.500 keV, only about 15% of events are subjected to any of the electronic excitation processes and their residual uncertainties.
- The monotonous trend towards negative values of  $m_\nu^2$  for larger fit intervals as it was observed for the Mainz 1991 and 1994 data has vanished. This shows that the dewetting of the  $T_2$  film from the graphite substrate indeed was the reason for this behaviour. Now this effect is safely suppressed at the much lower temperature of the  $T_2$  film.
- There is no indication for a non-zero neutrino mass, but, except Q5, the values of  $m_\nu^2$  are still significantly negative and the  $\chi^2$  values are partly too large for reasonable fits. The data suffer from a small spectral anomaly which cannot be at-

tributed anymore to a mistaken energy loss correction, as before, since such effects matter only further from the endpoint.

## 5. Spectral fluctuations and “Troitsk” anomaly

Fig. 3 already indicates some disagreement between the different data sets. Since the runs in 1998 Q3, Q4 and Q5 were performed under almost identical conditions<sup>8</sup> we may search locally for any temporal fluctuation of the data sets by comparing them directly. In order to allow for small differences in amplitude  $A$ , background  $B$  and Endpoint  $E_0$  (due to voltage drift) we compare two data sets  $i$  and  $j$  by fitting rescaling parameters  $r_{ij} = A_i/A_j$ ,  $\Delta B$  and  $\Delta E_0$ , which minimise the following sum of residues squares  $R^2(-eU)$ :

$$\begin{aligned} \chi^2 &= \sum_{\alpha=1}^{64} R^2(-eU_\alpha) \\ &= \sum_{\alpha=1}^{64} \frac{(\dot{N}_i(-eU_\alpha) - \dot{N}_j(-eU_\alpha)r_{ij} + \Delta E_0 d\dot{N}(-eU_\alpha)/dE_0 + \Delta B)^2}{\sigma_i^2(-eU_\alpha) + \sigma_j^2(-eU_\alpha)r_{ij}^2} \end{aligned} \quad (2)$$

This method is almost free of assumptions about the spectral shape<sup>9</sup>. Fig. 4 shows the residues of this comparison for all data sets of 1998. The data set Q4 does not match well the other ones. Especially the curve of smoothed residues shows a difference up to 1.5 (whose probability to appear in such a comparison with this particular smoothing is about  $2.5 \times 10^{-3}$ ), restricted to a region of about 20 eV width. The data sets Q3 and Q5 show good agreement concerning this test<sup>10</sup>. Excluding the range [18.538

<sup>8</sup> We mention that although we have taken data set Q5 under nearly the same conditions as Q3 and Q4 concerning  $T_2$  film thickness, retarding voltage and magnetic field settings, we have put a voltage of  $\pm 20$  V with 1 MHz frequency at one of the electrodes at the detector side of our spectrometer during the 2 s measurement pauses every 20 s to destroy the storage conditions for charged particles to reduce the rate and fluctuations of the background.

<sup>9</sup>  $d\dot{N}(-eU_\alpha)/dE_0$  was derived from a fit of Eq. (1) to the data set Q5 for  $m_\nu^2 = 0$ .

<sup>10</sup> It should be mentioned that the obvious disagreement between the results on  $m_\nu^2$  of data set Q3 and Q5 at the  $2\sigma$  level (see Fig. 3) is not a contradiction to this statement, since a  $2\sigma$  change in  $m_\nu^2$  increases  $\chi^2$  only by 4, to which this test is not sensitive.

keV, 18.557 keV] the  $\chi^2$  values become reasonably good for all pairs of data sets, which indicates again that the discrepancies between them seem to be local. But even if the data set Q4 is omitted, the negative values of  $m_\nu^2$  shown in Fig. 3 indicate that still some very small distortion is left over in the data, which is not described by Eq. (1).

The local distortion of data set Q4 visible in Fig. 4 is similar to what the so-called ‘‘Troitsk anomaly’’ could cause. Following Ref. [6] we checked this possibility by adding for the fit a monoenergetic line with free amplitude and position to the  $\beta$  spectrum in Eq. (1) (a line results in a step after convolution with the spectrometer transmission function  $f_{\text{trans}}$ ). Fig. 5 shows for all 4 data sets the reduction of  $\chi^2$  as function of line position  $E_{\text{anomaly}}$  relative to  $E_0$  with  $m_\nu^2$  fixed to 0. The line positions predicted by the Troitsk 0.5 year oscillation hypothesis [13] are marked as well. The improvement of  $\chi^2$  by the free line is not significant for Q2 and Q5, it is clearly significant for Q4 and less significant for Q3. Whereas the line position in Q4 agrees with the prediction and, moreover, has a reasonable amplitude of 6 mHz, which corresponds to a fraction of  $0.9 \cdot 10^{-10}$  from all  $\beta$  decays, the data set Q5 clearly

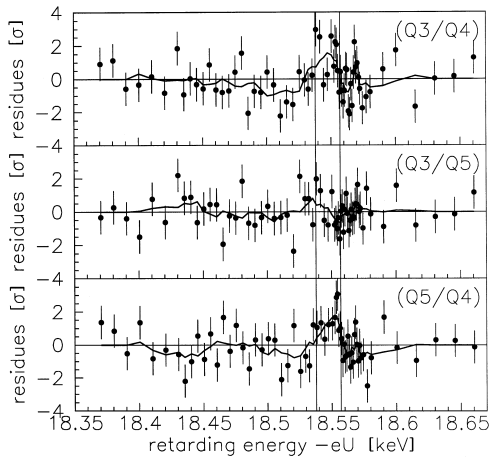


Fig. 4. Residues  $R(-eU_\alpha)$  (circles, normalised to  $\sigma$ ) of the raw data comparisons according to Eq. (2) for every pair of 1998 runs. The lines show smoothed residues  $R(-eU_\alpha) = (\sum_{\beta=-3}^3 R(-eU_{\alpha+\beta}))/7$ . The corresponding values of  $\chi^2$  according Eq. (2) are 95.4 (Q3/Q4), 60.4 (Q3/Q5), 84.0 (Q5/Q4) for the full range (d.o.f. = 61), and 56.4 (Q3/Q4), 47.6 (Q3/Q5), 50.4 (Q5/Q4) if excluding the range [18.538 keV, 18.557 keV] (d.o.f. = 50), which is marked by the vertical lines.

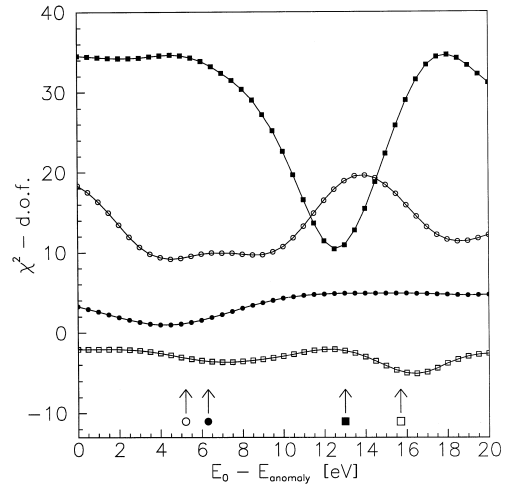


Fig. 5.  $\chi^2$  in dependence on the position of a Troitsk-like anomaly  $E_{\text{anomaly}}$ , which was fitted in addition to Eq. (1) for  $m_\nu^2 = 0$  fixed to the last 70 eV of the  $\beta$  spectrum of the Mainz data: Q2 (filled circles), Q3 (open circles), Q4 (filled squares), Q5 (open squares), with d.o.f. = 29 (Q2) and d.o.f. = 39 (Q3,Q4,Q5), respectively. The arrows indicate the Troitsk predictions. Dates of the Mainz data takings: Q2: 26.07.97 – 08.08.97, Q3: 25.02.98 – 16.03.98, Q4: 07.06.98 – 13.07.98, Q5: 07.11.98 – 14.12.98

excludes a line with sizeable amplitude<sup>11</sup>. Summarising this analysis: clear support for the ‘‘Troitsk anomaly’’ comes only by our data set Q4, whereas data set Q5 is at variance. Either the time structure of the anomaly is more complicated or the effects do not arise from a common origin.

## 6. Upper limit on $m_\nu$

The faking of  $m_\nu^2$  by the local, fluctuating spectral distortion through fitting with Eq. (1) can be circumvented by the following alternative procedures:

1. The combined data set of all runs of 1998 Q3, Q4 and Q5 is fitted over the last 15 eV of the  $\beta$  spectrum only (see Fig. 1). Due to the thresholds

<sup>11</sup> Fitting with free  $m_\nu^2$  a line at the predicted position 15.5 eV below  $E_0$  the line amplitude becomes  $-2.2 \pm 1.4$  mHz, from which an amplitude larger than 1.1 mHz can be excluded at the 95% C.L., whereas the Troitsk prediction would indicate an even larger amplitude than the 6 mHz observed for Q4.

for excitation of the electron shell of  $T_2$  or the daughter  $THe^+$ , respectively, uncertainties from energy loss, final states, etc., could not affect these last 15 eV of the  $\beta$  spectrum. Even an anomaly with the shape of a monoenergetic line at the position compatible with our measurement Q4 does not influence the  $\beta$  spectrum in this energy range after having been convoluted with  $f_{\text{charge}}$  and  $f_{\text{trans}}$ . To decorrelate  $m_\nu^2$  from the endpoint position  $E_0$  and amplitude  $A$  the two data points at 18.470 keV and at 18.500 keV have been added for this fit to the data above 18.559 keV (last 15 eV of the  $\beta$  spectrum). For the following two reasons these additional data points could not be affected by a Troitsk-like anomaly: the statistical uncertainties of the auxiliary points are larger than the anomalies discussed above and the range of the local disagreement of the data sets (compare Fig. 4) is left out. This fit results in

$$m_\nu^2 = -0.1 \pm 3.8_{\text{stat}} \pm 1.8_{\text{sys}} \text{ eV}^2/c^4$$

which corresponds to an upper limit of

$$m_\nu \leq 2.9 \text{ eV}/c^2 \quad (95\% \text{ C.L., unified approach})$$

2. If we accept the ‘‘Troitsk anomaly’’ as phenomenon we can fit the  $\beta$  spectrum together with a monoenergetic line of free position and amplitude, usually done by the Troitsk group for their data. From fitting the last 70 eV of the  $\beta$  spectrum of data set Q4, for instance, we obtain<sup>12</sup>:

$$m_\nu^2 = -1.8 \pm 5.1_{\text{stat}} \pm 2.0_{\text{sys}} \text{ eV}^2/c^4$$

which corresponds to an upper limit of

$$m_\nu \leq 3.0 \text{ eV}/c^2 \quad (95\% \text{ C.L., unified approach})$$

3. If we accept as result of Section 5 that there are variations in our data, either due to unknown experimental effects or due to an anomaly varying with time like the ‘‘Troitsk anomaly’’, we can restrict the analysis to the data set Q5 alone, the only one which is fitted well by Eq. (1) over the entire range with a satisfying  $\chi^2/\text{d.o.f.} \approx 1.0$  and

does not show any anomaly. The fit over the last 70 eV of the  $\beta$  spectrum gives (see Fig. 3)

$$m_\nu^2 = -3.7 \pm 5.3_{\text{stat}} \pm 2.1_{\text{sys}} \text{ eV}^2/c^4$$

which corresponds to an upper limit of

$$m_\nu \leq 2.8 \text{ eV}/c^2 \quad (95\% \text{ C.L., unified approach})$$

## 7. Conclusion and outlook

The improved Mainz setup enables us to carry out long term measurements with a signal-to-background-ratio enhanced by a factor of 10 compared to our measurements in 1991 and 1994. The 4 runs of 1997 and 1998 are competitive in sensitivity to the Troitsk measurements and capable of cross checking them [19]. Studies on quench condensed  $T_2$  films clarified their energy loss function, their charging up, and their dewetting as function of the temperature. In particular the suppression of the latter effect has removed the trend towards large negative values of  $m_\nu^2$  for wide data intervals from which our 1991 and 1994 suffered. But still the new Mainz data partly disagree with a pure  $\beta$  spectrum. Small negative values of  $m_\nu^2$  and poor values of  $\chi^2$  indicate that a small residual effect is not described by our fit function. The data comparison of runs performed at different dates but otherwise under identical conditions exhibits fluctuating discrepancies to each other within a narrow interval close to the endpoint.

We tested whether these discrepancies are compatible with the ‘‘Troitsk anomaly’’, which has been described by a monoenergetic line a few eV below the endpoint, whose position and amplitude seemed to vary with a 0.5 year period. Our two best runs concerning statistics, Q4 and Q5, showed different results: Q4, taken in June/July 1998, is supporting the Troitsk hypothesis by a distinct anomaly, but Q5, taken half a year later in November/December 1998, does not show any anomaly at all. This means at least that a simple half year period of the anomaly is contradicted by our data. To check whether the effects observed in Troitsk and partly in Mainz have a common origin the groups plan to take data synchronously in 1999. In addition we will check by our data some other possible modifications of the  $\beta$  spectrum, as predicted, e.g. for tachyonic neutrinos

<sup>12</sup> Applying this procedure to the other 3 data sets Q2, Q3 and Q5 and combining the results decreases the limit further down. However, there remains the question mark that the ‘‘Troitsk anomaly’’ is not established yet.

or the admixture of right handed weak currents. But such effects would hardly oscillate in time. Of course, one must also consider the effect possibly to be an instrumental artefact. In this case it should originate from some critical feedback between  $\beta$  particles and background sources in the spectrometer. It is difficult to imagine such a coupling and how it could produce something like a step.

In spite of these problems we can obtain upper limits on the neutrino mass by various types of analysis. By applying a standard analysis to our data set Q5, which is free of any anomaly, we obtain a limit of  $m_\nu \leq 2.8 \text{ eV}/c^2$ <sup>13</sup>.

By collecting more data a sensitivity on  $m_\nu$  of about  $2 \text{ eV}/c^2$  can be reached. This does not clarify the possibility of a cosmologically relevant amount of neutrino dark matter. For this task further improvement of the sensitivity on  $m_\nu$  down to less than  $1 \text{ eV}/c^2$  is needed.

Moreover, the Troitsk anomaly must be definitely clarified and, if confirmed, precisely and repeatedly measured with short time intervals. This is mandatory in view of the very speculative but so far only explanation under discussion, namely  $\nu_e$ -capture from dense, variable  $\nu_e$ -clouds. (compare Ref. [19] and references therein). Neither of these two tasks can be achieved by the present experiments. A larger spectrometer providing higher signal rate and better energy resolution is needed. In a different paper [14] we have investigated the possibility of a spectrometer based on the same principle but 5 times larger (in linear dimensions) than the present one. By an additional time-of-flight analysis the spectrometer transforms from an integrating high pass filter into a narrow band filter (successfully applied [14] to the present spectrometer) and local anomalies can be decorrelated from the measurement of the neutrino mass. It seems quite feasible to realize such a proposal.

<sup>13</sup> In case of neutrino mixing, see Section 1, the limit on  $m_\nu$  is valid for the following average: If the different neutrino mass eigenstates, which contribute with  $U_{ei}$  to the electron neutrino, are not resolved, the  $\beta$  spectrum is determined by an average electron neutrino square mass  $\overline{m_\nu^2} = \sum_i |U_{ei}|^2 \cdot m_i^2$ .

## Acknowledgements

We like to thank our colleagues from Troitsk and the mechanical and electronic workshops of the Institute of Physics/Mainz for their support during the upgrade of the apparatus. We are grateful to E. Griebel and H. Geibel for their technical support during the runs. We like to thank H. Backe, G. Barenboim, H. Barth, L. Fleischmann, T. Jannakos, G. Kube, P. Leiderer, M. Przyrembel, F. Scheck and E. Yakushev for helpful and stimulating discussions. This work was supported by the Deutsche Forschungsgemeinschaft under contract Ot33/13. A.K. and O.K. are indebted to the Deutsche Forschungsgemeinschaft for funding their stays at Mainz.

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