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NEUTRINO MASS FROM TRITIUM β DECAY — PRESENT LIMITS AND PERSPECTIVES*

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Tritium β decay experiments are currently running in Mainz and Troitsk. Both experiments are investigating the endpoint region of the tritium β decay spectrum with a MAC-E spectrometer to determine the mass of the electron antineutrino. By the recent upgrade at Mainz the former problem of dewetting T_2 films has been solved and the signal-to-background-ratio was improved by a factor of 10, resulting in a sensitivity similar to Troitsk. The latest Mainz measurement in 1998 leads to $m_\nu^2 = -3.7 \pm 5.3_{\rm stat} \pm 2.1_{\rm sys}$ eV$^2/c^4$, from which an upper limit of $m_\nu < 2.8$ eV$/c^2$ (95% C.L.) is derived. Some indication for the anomaly, reported by the Troitsk group, was found by the Mainz group, but the postulated half year period of the anomaly is contradicted by Mainz. To push the sensitivity on the neutrino mass below 1 eV$/c^2$ a new larger MAC-E spectrometer is proposed. Besides its integrating mode it could run in a new non-integrating operation MAC-E-TOF mode.

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1. Introduction

The recent 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 determine differences of neutrino mass squares not absolute mass values. The latter are accessible via the kinematics of weak decays. The investigation of the tritium β spectrum near its endpoint is the most sensitive of these so-called direct methods[1]. If the differences between the different neutrino mass eigenvalues are as small

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[1] The search for neutrinoless double β decay is not fully direct, since it is only sensitive to Majorana-type neutrinos and it depends on the neutrino mixing matrix.

as indicated by the solar and atmospheric neutrino experiments, not only hierarchical neutrino mass scenarios but also degenerate masses become very interesting. If the degenerated masses are in the eV/c^2 range they would contribute significantly to the missing dark matter in the universe [3].

Tritium β decay experiments are currently running at Mainz and Troitsk [4, 5]. The principle of the spectrometers used in both experiments [6, 7], Magnetic Adiabatic Collimation followed by a retarding Electrostatic Filter (MAC-E-Filter, also called Solenoid Retarding Spectrometer), combines both a very high energy resolution[2] ($\Delta E = 2$–6 eV at 20 keV) and a large acceptance ($\Delta\Omega/2\pi = 0.2$–0.8).

The Troitsk results are described in Section 2. The recent Mainz upgrade and first data are presented in Section 3. A check by the Mainz data of the anomaly, which was reported by the Troitsk group, is given in Section 4. Upper limits on the neutrino mass from the Mainz 1998 data are presented in Section 5. A conclusion and an outlook on a much larger experiment with sub eV sensitivity on the neutrino mass is given in Section 6.

2. Troitsk results

The Troitsk group has reported an unexpected structure close to the endpoint of the tritium β spectrum which is described as a monoenergetic line added to the β spectrum or equivalently as a step in the data recorded with the integrating spectrometer [5, 8]. If not considered in the data analysis, this anomaly gives rise to negative values of m_ν^2 in the fit in the range of -10 eV$^2/c^4$ to -20 eV$^2/c^4$. The relative intensity of this anomaly is about 10^{-10} of the total decay rate, too small to be checked by the Mainz data of 1991 and 1994. From 1998 on 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 the β endpoint E_0 [5, 9]. The origin of such a monoenergetic line as addition to the primary β-spectrum is not clear within standard physics. An independent experimental check is mandatory.

To obtain a result on the neutrino mass the Troitsk group fits a free monoenergetic line added to the β spectrum to their different data sets. Combining their results they obtain [5]

$$m_\nu^2 = -1.9 \pm 3.4_{\rm stat} \pm 2.2_{\rm sys}\ {\rm eV}^2/c^4$$

which corresponds to an upper limit of

$$m_\nu \leq 2.5\ {\rm eV}/c^2 \quad (95\%\ \text{C.L., unified approach})\,.$$

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

3. The improved Mainz setup and the 1997 and 1998 runs

The motivation of the recent upgrade of the Mainz neutrino mass experiment was not only to improve the sensitivity to m_ν down to an ultimate limit of 2 eV/c^2 but also to check the anomalous excess in the spectrum close to the endpoint which was communicated by the Troitsk group [5, 8].

The very nice features of the Mainz spectrometer, high luminosity and high energy resolution, could not been fully explored in the previous measurements [10, 11]. The main limitations of the data taking in 1991 and 1994 came from the T_2 source. The source cryostat did not allow temperatures low enough to avoid safely the dewetting of the T_2 film. Moreover, the signal-to-background-ratio was limited by T_2 gas evaporating from the source into the spectrometer causing background there. These and other short-comings were overcome by the following measures (see figure 1 and compare Ref. [12]):

- A new source cryostat, running stable at 1.86 ± 0.03 K, suppresses effectively the dewetting of the T_2 film [12].
- A pair of superconducting solenoids, tilted by 20° to each other, was installed between source and spectrometer. Consequently β 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.
- 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 the 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_2.

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 much thicker T_2 films of 973 Å (Q2) and 490 Å (Q3–Q5), respectively, compared to 126 Å in 1994 were used. The increase of electron scattering within the T_2 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. 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

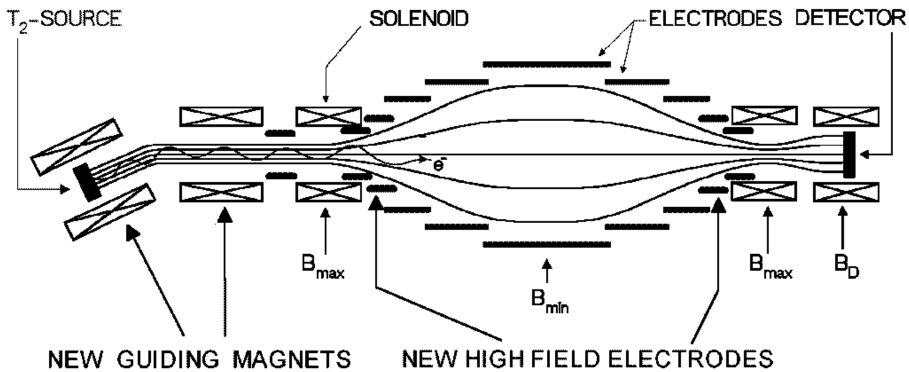

Fig. 1. The improved and enhanced Mainz setup schematically, not in realistic scale. The outer diameter amounts to 1m, the distance from source to detector is 6m.

failures or large sparks in the high voltage system, no other filtering was applied to the data.

Figure 2 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 the daughter molecule of amplitude W_i and excitation energy V_i [13, 14]. This spectrum is then convoluted with the potential distribution within the tritium film [12], the functions describing the backscattering from the substrate, the inelastic processes within the T_2 film, the spectrometer transmission, and the energy dependence of the detection efficiency. Fitting parameters were a free amplitude A, the endpoint E_0, m_ν^2, and an energy independent background B.

Systematic uncertainties were taken into account as follows (the percentages in brackets illustrate their contribution to the total systematic uncertainty on m_ν^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 [15] the energy loss function $f_{\rm eloss}$ of 17.8 keV K-32 conversion electrons of $^{83\rm m}$Kr in D_2 films has been measured at Mainz. The mean free path was found to be $\lambda_{\rm free} = 1204 \pm 63$ Å, 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 repulsive electrostatic inter-

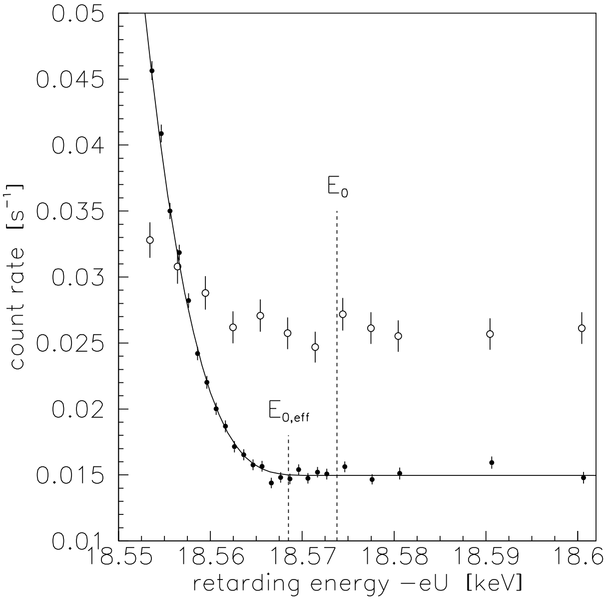

Fig. 2. Averaged count rate of runs Q3, Q4 and Q5 of 1998 (filled circles) compared with the 1994 Mainz data (open circles) near the endpoint E_0, and effective endpoint $E_{0,\mathrm{eff}}$, which considers the convolution with the experimental response function and the mean rotation–vibration excitation energy of the electronic ground state of the $^3\mathrm{HeT}^+$ daughter molecule. The line shows a fit to the data for $m_\nu^2 = 0$ over the interval shown.

action of the excited electrons with the neighbour ones and Pauli blocking. However, an increase of 17% of λ_{free} is due to pores within the tritium film, determined by the ellipsometry measurement of its index of refraction giving $n = 1.14$, which is about the same as for the D_2 films. For the systematics the uncertainties of λ_{free} and of the film thickness measurement, which varies between 1% and 7%, depending on the substrate quality, were considered.
Neighbour excitation (26%): The observed peak position shift was considered also for the energy loss caused by the sudden excitation of neighbours of the β decaying molecule. The probability of such an event has been calculated to be 5.9% [14]. The observed increase of λ_{free} leads to an estimated reduction down to 4.6%. The two corrections were added with full amount to the systematic uncertainty for safety.
Final States (11%): Electronic repulsion and Pauli blocking effects are also expected for the excited levels of the 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 [16]. For safety these shifts are fully taken into account as systematic uncertainty.

Charging up of the T_2 film (14%): For the thick T_2 films used in 1997 and 1998 a charging up of the films by several volts due to the β emission was observed. By measuring the energy shift of the K-32 conversion line of ^{83m}Kr positioned in different depths of the T_2 film it was proven, that the potential within the film increases linearly with the distance to the substrate at a slope of 6 mV/Å [12]. 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%): The uncertainties of the transmission, backscattering, and detector efficiency functions was also considered, but their influence on m_ν^2 is small compared to the other effects.

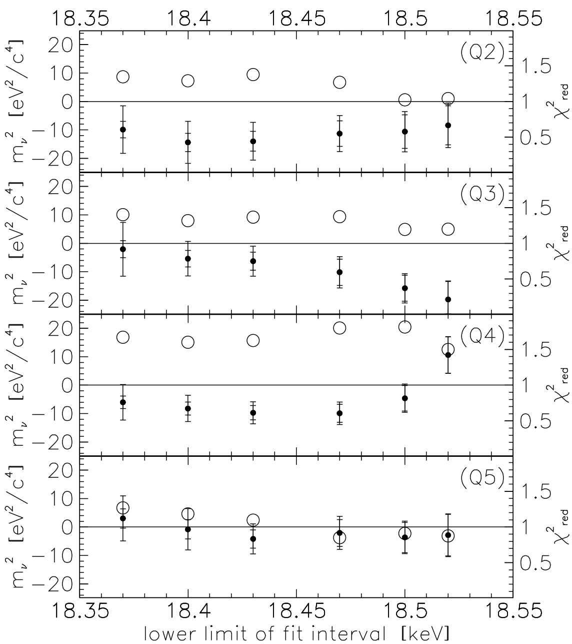

Fig. 3. Fit results on m_ν^2 (left scale, filled circles) for the 4 different Mainz runs with statistical uncertainties (inner bars) and total uncertainties (outer bar) in dependence on the lower limit of the fit interval. The upper limit of the fits is always 18.660 keV, well above the endpoint E_0. The corresponding values of $\chi^2_{\rm red} = \chi^2/$ d.o.f. of the fits (open circles) can be read from the right scale. Please note that the different fit results for one run are statistically not independent but highly correlated, since going to smaller lower limits of the fit interval only a few additional data points are added.

Figure 3 shows the fit results on m_ν^2 with statistical and total uncertainties (statistical and systematic uncertainties 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_ν^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_ν^2 are still significantly negative and the χ^2 values are partly too large for reasonable fits. The data suffer from a small spectral anomaly which cannot be attributed anymore to a mistaken energy loss correction, as before, since such effects matter only further from the endpoint.

4. Check of the "Troitsk anomaly" by the Mainz data

As a first explanation for the still partly negative values of m_ν^2 fitted from their data, the Mainz group tested, whether the data could be described by a "Troitsk anomaly". Following reference [8] this possibility was checked by adding for the fit a monoenergetic line with free amplitude and position to the β spectrum (a line results in a step after convolution with the spectrometer transmission function). Fig. 4 shows for all 4 Mainz data sets the reduction of χ^2 as function of line position E_{anomaly} relative to E_0 with m_ν^2 fixed to 0. The line positions predicted by the Troitsk 0.5 year oscillation hypothesis [9] are marked as well. The improvement of χ^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 β decays, the data set Q5 clearly excludes a line with sizeable amplitude[3]. Summarising this analysis: clear support for the "Troitsk anomaly" comes only by the Mainz 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.

[3] Fitting with free m_ν^2 a line at the predicted position 15.5 eV below E_0 the line amplitude becomes -2.2 ± 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 amplitude about as large as the 6 mHz observed for Q4.

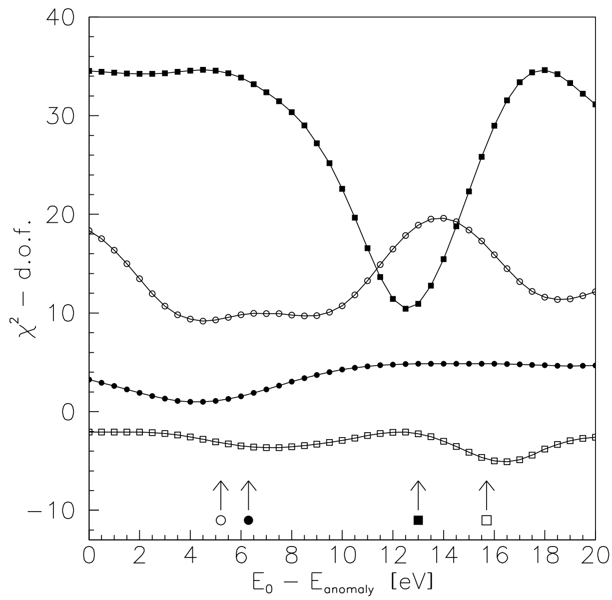

Fig. 4. Mainz data: χ^2 in dependence on the position E_{anomaly} of a Troitsk-like anomaly, which was fitted in addition to the β spectrum for $m_\nu^2 = 0$ fixed to the last 70 eV of the β spectrum: Q2 (filled circles), Q3 (open circles), Q4 (filled squares), Q5 (open squares), with d.o.f. = 29 (Q2) 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.

5. Upper limit on m_ν by the Mainz 1998 data

The faking of m_ν^2 by the local, fluctuating spectral distortion through fitting can be circumvented by the following alternative procedures (all limits are calculated by using the unified approach):

1. The combined data set of all runs of 1998 Q3, Q4 and Q5, which were taken under nearly the same conditions[4], is fitted over the last 15 eV of the β spectrum only (see Fig. 2). Due to the thresholds 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

[4] It should be mentioned that although set Q5 has been taken under nearly the same conditions as Q3 and Q4 concerning T_2 film thickness, retarding voltage and magnetic field settings, a voltage of ± 20 V with 1 MHz frequency was put at one of the electrodes at the detector side of the Mainz 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.

last 15 eV of the β spectrum. Even an anomaly with the shape of a monoenergetic line at the position compatible with the measurement Q4 does not influence the β spectrum in this energy range after having been convoluted with spectrometer response function. To decorrelate m_ν^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 β spectrum). Adding only two points to the last 15 eV of the β spectrum introduces a smaller influence on m_ν^2 by systematic effects and Troitsk-like anomalies. This fit results in

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

which corresponds to an upper limit of

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

2. If we accept the "Troitsk anomaly" as phenomenon the β spectrum can be fitted together with a monoenergetic line of free position and amplitude, usually done by the Troitsk group for their data (compare Section 2). Fitting the last 70 eV of the β spectrum of data set Q4 the following result is obtained[5]:

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

which corresponds to an upper limit of

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

3. If it is accepted that there are variations in the Mainz data, either due to unknown experimental effects or due to an anomaly varying with time like the "Troitsk anomaly", the analysis can be restricted to the data set Q5 alone, the only one which is fitted well over the entire range with a satisfying $\chi^2/\mathrm{d.o.f.} \approx 1.0$ and does not show any anomaly. The fit over the last 70 eV of the β spectrum gives (see Fig. 3)

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

which corresponds to an upper limit of

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

[5] 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.

6. Conclusion and outlook

The Troitsk group report an excess count rate close below the endpoint at an energy which oscillates with a period of 0.5 years. Describing this effect phenomenologically by a step in their integral data they obtain as combined result of their data a limit on the neutrino mass of $m_\nu < 2.5$ eV$/c^2$.

The improved Mainz setup allowed from 1997 on to carry out long term measurements with a signal-to-background-ratio enhanced by a factor of 10 compared to the Mainz 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 [5]. Studies on quench condensed T_2 films clarified their energy loss function, their charging up, and their dewetting as function of temperature. In particular the suppression of the latter effect has removed the trend towards large negative values of m_ν^2 for wide data intervals from which the 1991 and 1994 Mainz data suffered. But still the new Mainz data partly disagree with a pure β spectrum. Small negative values of m_ν^2 and poor values of χ^2 indicate that a small residual effect is not described by the Mainz fit function.

The Mainz group has tested whether this effect is compatible with the "Troitsk anomaly"- The 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 the Mainz data.

To check whether the effects observed in Troitsk and partly in Mainz have a common origin the groups have started to take data synchronously in 1999. In addition some other possible modifications of the β spectrum, as predicted, *e.g.* for tachyonic neutrinos or the admixture of right handed weak currents have to be checked by the data. 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 β particles and background sources in the spectrometers. It is difficult to imagine such a coupling and how it could produce something like a step.

In spite of these problems the Mainz group obtains upper limits on the neutrino mass by various types of analysis which gave similar results. By applying a standard analysis to data set Q5, which is free of any anomaly, a limit of $m_\nu \leq 2.8$ eV$/c^2$ is obtained[6]. An alternative method to extract the

[6] In case of neutrino mixing, see Section 1, the limit on m_ν 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 β spectrum is determined by an average electron neutrino square mass $\overline{m_\nu^2} = \sum_i |U_{ei}|^2 \cdot m_i^2$.

neutrino mass is to use the last 15 eV of the β spectrum plus two additional data points further below the endpoint, leading to a limit of $m_\nu < 2.9$ eV$/c^2$ for all Mainz 1998 data (including also half of 1999 data this method yields a preliminary limit of $m_\nu < 2.3$ eV$/c^2$ [17]).

By collecting more data a sensitivity on m_ν of about 2 eV$/c^2$ can be reached by both experiments at Mainz and at Troitsk. 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_ν down to less than 1 eV$/c^2$ is needed. Moreover, the Troitsk anomaly must be definitely clarified and, if confirmed, precisely and repeatedly measured with short time intervals. 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 [18] the possibility of a spectrometer based on the same MAC-E filter principle but 5 times larger (in linear dimensions) than the present one has been investigated. By an additional time-of-flight analysis the spectrometer transforms from an integrating high pass filter into a narrow band filter (MAC-E-Filter mode).

In a first proof of principle experiment for this new method the K-32 conversion line of $^{83\mathrm{m}}$Kr was investigated with the present Mainz spectrometer. A periodical chopping voltage ($t_{\mathrm{on}} = 2.5\mu s, t_{\mathrm{blocking}} = 2.5\mu s, U_{\mathrm{blocking}} = 80V$,) was applied to the conversion electron source and the arrival time of the electrons was measured at the detector. Fig. 5 shows the counts in the de-

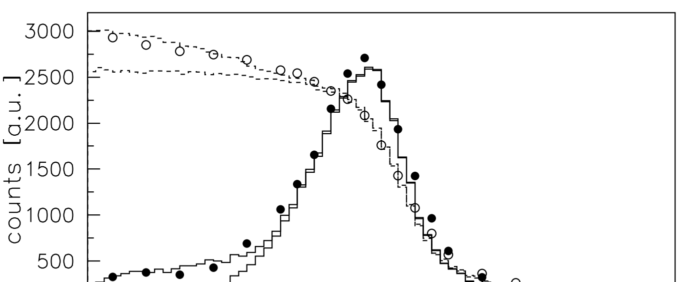

Fig. 5. Measurement of the $^{83\mathrm{m}}$Kr K-32 conversion line with the Mainz spectrometer and time-of-flight analysis. Circles: integral recording over all times, dashed lines: corresponding simulation without N shake and including it; full dots: narrow band recording of the spectral line with time-of-flight selection ($3.5\mu s \le t_{\mathrm{arrival}} \le 5.1\mu s$), lines: corresponding simulation for the conversion line and including its N-shake. Background has been subtracted. The integral data are scaled down by a factor of 4.

tector for all arrival times, which corresponds to the normal integral mode of the spectrometer. Selecting only electrons, which have a certain arrival time (which corresponds to a certain kinetic energy in the spectrometer), shows the K-32 conversion line in a narrow band mode. By this new method a local distortion in the β spectrum will stay local and has a localised correlation to m_ν^2, thus it becomes an ideal instrument to clearly resolve the question of possible anomalies.

Currently the feasibility and the physical prospects of a large tritium β spectrometer with 7 m diameter aiming for a sub eV/c^2 sensitivity to the electron neutrino mass is being discussed by the neutrino groups of Karlsruhe, Mainz and Troitsk.

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