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The Mainz measurement in 1994 is discussed in the view of the problem of "negative m_ν^2" obtained in the analysis for larger energy intervals below the endpoint of the β spectrum. A possible explanation due to a roughening transition of the T_2 film is given. The very recent improvement of the Mainz setup and a first 4 weeks measurement is presented. An outlook to the perspectives of the present setup and into the future is given.

1 Introduction

Whether neutrinos have a non-vanishing mass or not is still one of the most interesting questions of particle physics and cosmology.

In contrast to the methods like the searches for neutrino oscillations or for neutrino-less double β decay, which request neutrino mixing or majorana type neutrinos respectively, the study of the shape of a β spectrum close to its endpoint is the most direct way to search for a non-vanishing mass of the electron antineutrino as this signature is independent on assumptions of the nature of neutrinos. Although facing some problems in fully understanding the recently measured tritium β spectra, the sensitivity of this method is currently reaching a few eV/c^2, which is most relevant for a possible contribution of neutrinos to the dark matter in the universe. Neutrino masses of a few eV/c^2 are also favoured by the LSND experiment, which claims the observation of neutrino oscillations, for which at least one participating mass eigenstate should be as heavy as 0.5 eV/c^2[1].

At present two experiments are investigating tritium β decay, one at the Institute for Nuclear Research of the Russian Academy of Sciences (INR) the other one at Mainz University. The latter is presented in this contribution, the former by V.M. Lobashev [2].

The Mainz experiment published first results in 1993 [3] and was reviewed in the proceedings of the Erice school on neutrino physics in 1993 [4]. In this paper we will briefly repeat the principle of the spectrometer in section 2. In section 3 the problem of negative values of m_ν^2 will be discussed in connection with our 1994 measurement and related investigations on systematic uncertainties. The upgrade of the Mainz setup in the years 1995 to early 1997 will be described in section 4. The first measurement with the improved Mainz experiment will be presented in section 5. On the basis of a

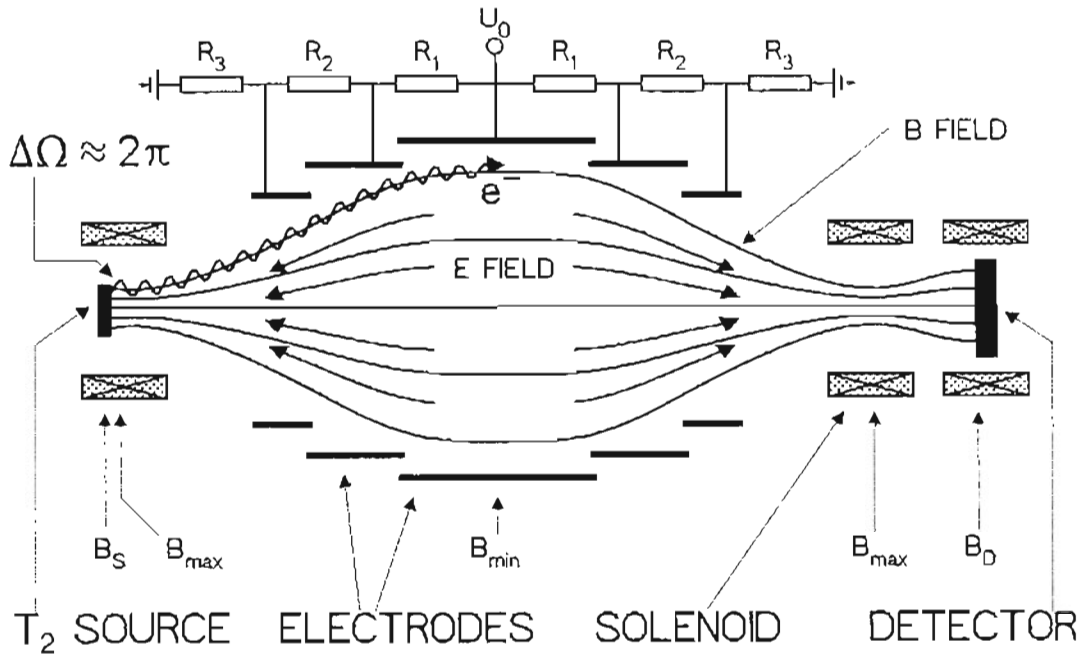

Figure 1: Sketch of the Mainz Solenoid Retarding Spectrometer

preliminary evaluation of the data an estimate of the sensitivity limit of the Mainz setup will be given in section 6. The conclusions will be drawn in section 7.

2 The Mainz setup

To be able to push the sensitivity limit into the region of a few eV the spectrometer used to investigate the β spectrum of tritium have to fulfil stringent requirements. The signal has to emerge from background very close to the endpoint where the spectrum is most sensitive to the neutrino mass. The resolution should be comparable to the sensitivity aspired on the neutrino mass and there should be no tails in the resolution function extending to lower energies. It would be ideal to be able to measure the neutrino mass induced modification of the shape of the tritium β spectrum in the last 10 eV below the endpoint. In this region, which contain only $2 \cdot 10^{-10}$ of the total decay rate, all known systematic uncertainties nearly vanish.

2.1 The Solenoid Retarding Spectrometer

To come close to the ideal spectrometer mentioned above the concept of the so-called Solenoid Retarding Spectrometer was realized in Mainz and Troitsk [5, 6]. The principle of its combination of a magnetic guiding and focusing field and an electrostatic filter is illustrated in figure 1.

Let us assume that the motion of the electron from the source through the analyser to the detector is adiabatic with respect to any local change of the guiding field. This holds under the condition that the relative change of the strength and direction of the guiding field is small within one cyclotron orbit. In this case the electron spirals around one and the same magnetic field line which acts as guiding centre. Moreover, the angular momentum of the electron with respect to the guiding centre or, in other words, the magnetic moment μ of its cyclotron orbit is a constant of the motion. As an important consequence of this invariance the transverse energy $E_\perp$ (which is the cyclotron energy)

$$E_\perp \;=\; E_{cycl.} \;=\; -\vec{\mu}\;\vec{B} \tag{1}$$

scales as the magnetic field B. Moving through an inhomogeneous field the particle transforms $E_\perp$, into longitudinal energy $E_\parallel$ parallel to the field line and vice versa. This effect is well known as magnetic mirroring. The transformation is performed by a component of the Lorentz force in direction of the field gradient. It may be written as a gradient force

$$\vec{F} \;=\; \vec{\nabla}(\vec{\mu}\;\vec{B}) \tag{2}$$

In adiabatic approximation an additional electric field $\vec{E}$ acts only on the longitudinal energy $E_\parallel = m\vec{u}_\parallel^{\,2}/2$. Including this action one obtains the complete adiabatic equation of longitudinal motion.

$$\frac{d}{dt}\left(\frac{1}{2}mu_\parallel^2 - \vec{\mu}\vec{B}\right) + e\vec{E}\vec{u}_\parallel \;=\; \vec{u}_\parallel\left(m\dot{\vec{u}}_\parallel - (\vec{\mu}\vec{\nabla})\vec{B} + e\vec{E}\right) \;=\; 0 \tag{3}$$

2.2 Realization and parameters of the spectrometer

With this idea of parallelising the trajectories in mind, the so called solenoid retarding spectrometer SRS is conceived as follows: The source and the detector are placed in the centre of two solenoids at fields $B_s \approx 2.4$ T and $B_d \approx 0.8$ T, respectively. In the stray field between the solenoids a series of electrodes provides an electrostatic potential which reaches its maximum $-eU_0$ in the analysing plane which is placed at the minimum of the stray field $B_{min} \approx 8 \cdot 10^{-4}$ T. Electrons which cross the barrier are reaccelerated on the down hill slope and refocused by the guiding field onto the detector. In the analysing plane the residual energy in the cyclotron motion (which is not analysed) has decreased by a factor of

$$\frac{B_s}{B_{min}} \;\approx\; 3000 \tag{4}$$

from its original value. Therefore, the whole forward solid angle of emission is analysed by a filter whose width is

$$\Delta E \;=\; E\,\frac{B_{min}}{B_s} \tag{5}$$

within which the transmission rises from zero to one (see Fig. 2). For an electron of 18 keV and the settings given above this amounts to 6 eV.

Actually, the field B_{max} is reached somewhat in front of the source in order to reflect magnetically electrons which are emitted under a polar angle $\theta > 78.5°$ in 1991 and 1994 or $\theta > 45°$ in 1997. This provision serves to limit the ratio of backscattered electrons and the amount of ionisation losses. (B_{max} then replaces B_s in equations 4 and 5). For similar reasons the silicon detector is placed in the weaker field B_d in the centre of the third solenoid shown at the right end of Fig. 1 which limits the angle of incidence to about 35°. The second solenoid inbetween is set at B_{max} to provide symmetry in the electron optics of the spectrometer.

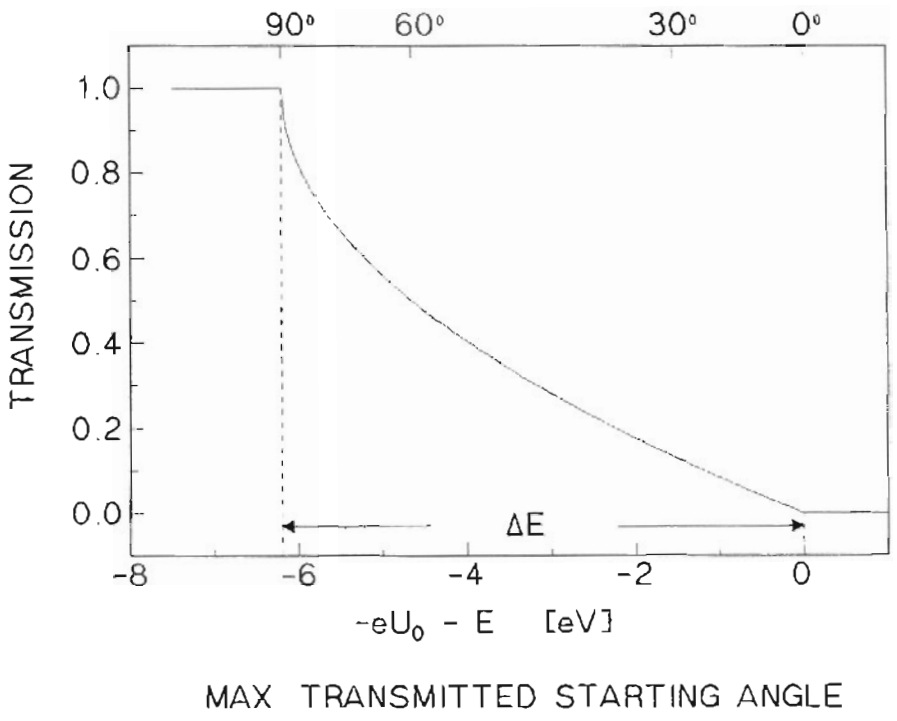

Figure 2: Transmission of the solenoid retarding spectrometer as function of the residual energy of the electrons in the analysing plane. Within the interval $0 \leq E + eU_0 \leq E\ B_{min}/B_{max}$ it rises like $T(E,U) = 1-(1-(E+eU_0)/E \cdot B_{max}/B_{min})^{1/2}$. The formula holds for an isotropically emitting source placed in the field $B_s = B_{max}$. For the case $B_s < B_{max}$ see a more detailed publication [5].

It is very important that we need to consider in adiabatic approximation only longitudinal forces acting along the B-lines. Transverse forces affect the motion only in second order. They cause a drift velocity $u_\perp$ of the guiding centre which is perpendicular to the transverse force and the guiding field

$$\vec{u}_\perp = \frac{\vec{E} \times \vec{B}}{B^2} - \left(\frac{\mu}{e} + \frac{mu_\parallel^2}{eB}\right) \frac{\vec{B} \times \vec{\nabla}_\perp B}{B^2} \tag{6}$$

The energy contained in this transverse drift motion cannot be analysed by the cylindrically symmetric SRS. However, it can be kept small under certain provisions. For instance, the drift energy due to the first term in eq. 6 caused by the transverse electric field, is given as the residual cyclotron energy multiplied by the square of the ratio of the transverse electric force over the Lorentz force

$$E_{drift} = E_\perp \left(\frac{F_{el\perp}}{F_{Lorentz}}\right)^2 \tag{7}$$

It can be kept small enough in the SRS to be neglected safely. Regarding the energy resolution similar arguments can be given with respect to the two other terms in eq. 6 which account for the transverse part of the gradient force (2) and the centrifugal force resulting from the curvature of the guiding field. However, centrifugal forces start to diminish the transmission of the spectrometer when the residual longitudinal electron energy exceeds about 500 eV in the central region of the spectrometer where the guiding field is not strong enough anymore to guide the trajectory adiabatically.

Similar considerations apply to the background stemming from electrons injected from the surface of the electrodes. If their energy is sufficiently low they are guided along peripheral magnetic field lines which do not hit the detector and hence provide a perfect magnetic background shielding. If the electron energy exceeds the adiabatic limit, on the other hand its trajectory is getting very complicated

and chaotic and has a finite chance to hit the detector eventually. Fortunately, this background peaks several keV above the filter energy, i.e. beyond the endpoint E_0. Hence, it can be discriminated by the detector.

For reasons of background suppression the spectrometer has to be run at ultra high vacuum with a residual gas pressure of about 10^{-10} mbar. Otherwise, it slowly develops and sustains a plasma discharge as it is a kind of huge penning vacuum gauge. Even at the very best vacuum this effect could not be suppressed for fields $B_s > 3$ T. Details on the design and the performance of the spectrometer may be found in an earlier publication [5].

2.3 T_2 source

The source realized at the Mainz Solenoid Retarding Spectrometer is a condensed film of molecular tritium. T_2 is evaporated via a capillary onto the cold substrate, while the thickness of the growing Van-de-Waals crystal is monitored optically with ellipsometry.

The thickness is measured with a resolution of about 2 monolayers for the T_2 films of a total thickness between 20 and 40 monolayers used in 1991 and 1994, or 282 monolayers used in 1997 respectively.

In 1991 the substrate used was aluminium, from which two problems arose:

- Investigations with a field emission electron microscope show a roughness of the aluminium surface causing an enhanced inelastic scattering fraction, when working with large accepted solid angles.
- During baking the aluminium surface it may develop a thick oxide layer which deteriorates the resolution of the system by undefined surface structure and potential.

To avoid these problems a substrate of highly oriented pyrolytic graphite (HOPG) was installed from 1994 on.

3 The problem of "negative m_ν^2"

3.1 The 1994 measurement

With this setup the tritium β spectrum was investigated in 1994 over a period of 16 days. Figure 3 shows the count rate in dependence on the retarding energy. The interesting region around the endpoint E_0 is enlarged in the insert. The experimental data with their statistical uncertainties as well as fits to the data for several hypothetical values for the neutrino mass are presented. The fit for 0 matches best, whereas the ones for 10 eV/$c^2$and 15 eV/c^2 are fitting less and less. The best fit for a free m_ν^2, which is the relevant parameter describing the shape of the β spectrum, gives

$$m_\nu^2 = -22 \pm 17_{\text{stat}} \quad \left(\frac{\text{eV}}{\text{c}}\right)^2 \quad . \tag{8}$$

Considering the systematic uncertainties of $\pm 14 \text{eV}/c^2$, which mainly contain uncertainties of the energy loss by inelastic scattering in the tritium film, an upper limit of

$$m_\nu < 5.6 \text{eV}/c^2 \quad (95\ \%\ \text{CL, Bayesian method}) \tag{9}$$

can be given for the neutrino mass [7].

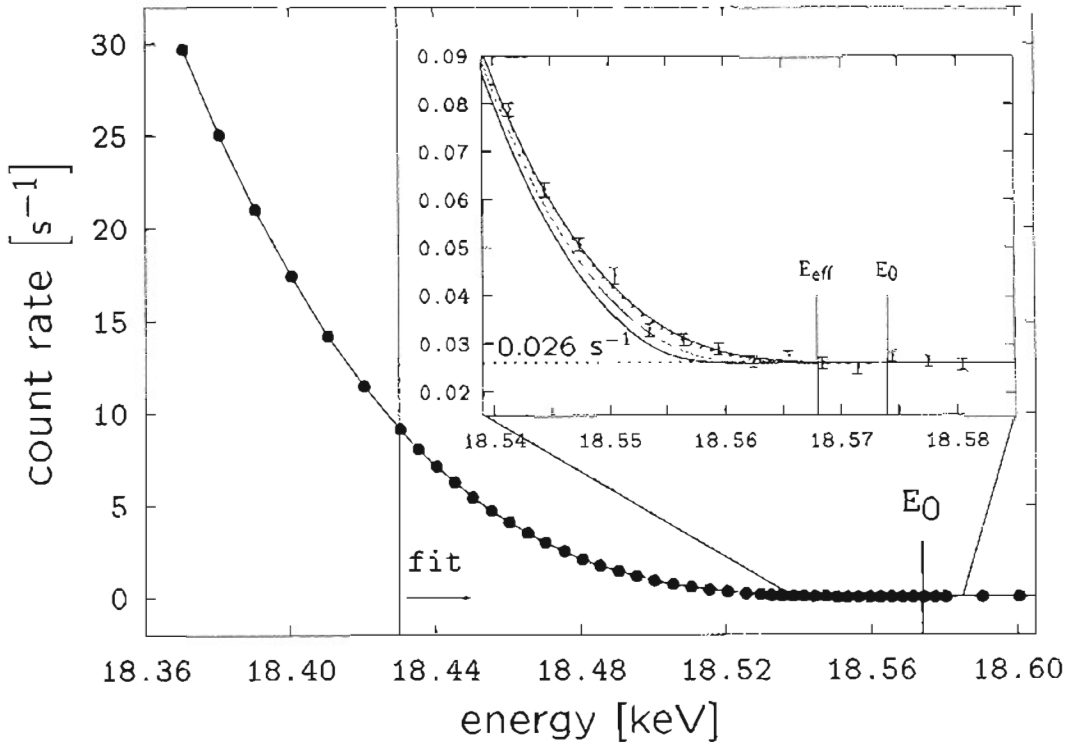

Figure 3: β spectrum measured at Mainz in 1994. In the insert the region around the endpoint E_0 is enlarged. Fits to the data for with hypothetical neutrino masses of 15 eV/c^2 (black), 10 eV/c^2 (grey) and 0 (dots) are shown as well as a fit with free m_ν^2 parameter resulting in $m_\nu^2 = -22 \pm 17_{stat}$eV^2/c^4 (black line close to dots). All fits are using the data points above a truncation point of 18430 eV, *i.e.* of the last 140 eV of the β spectrum.

These fits and the results were obtained truncating the β spectrum 140 eV below the β endpoint E_0, disregarding the data points recorded at retarding energies below 18430 eV. Taking them into account the best fit gives a result for m_ν^2, which depends on the data interval used. Figure 4 shows the values of m_ν^2 from the fits versus the truncation point of the β spectrum: For small intervals below the endpoint the statistical uncertainty is relatively large and m_ν^2 is compatible with zero within the uncertainties. Adding more and more data points from further below the endpoint, the statistical uncertainties are getting smaller but from about 140 eV below the endpoint E_0 a significant trend towards negative fit results for m_ν^2 is visible. This unphysical behaviour is very similar to the one which was observed in 1991 [3]. It cannot be explained by the estimated systematic uncertainties (see fig. 4).

In the fit only the parameters A (strength of the source), E_0 (endpoint), BG (background rate) and m_ν^2 are free. All other input is taken from literature (as the distribution of the final states) or determined by independent measurements (as the functions describing the inelastic scattering and backscattering and the spectrometer transmission). If one of these functions deviates more than expected from the assumed value or if another effect was forgotten in the description of the fit it abuses one or more of the four fit parameters to compensate the discrepancies between the measured count rate and its description in the fit. Very sensitive to such a mistake is the fit parameter m_ν^2, because is it the only free parameter, which can change the shape of the spectrum. Such a mistake is obviously the reason for the trend towards negative values of m_ν^2 as shown in figure 4, but what could be its origin?

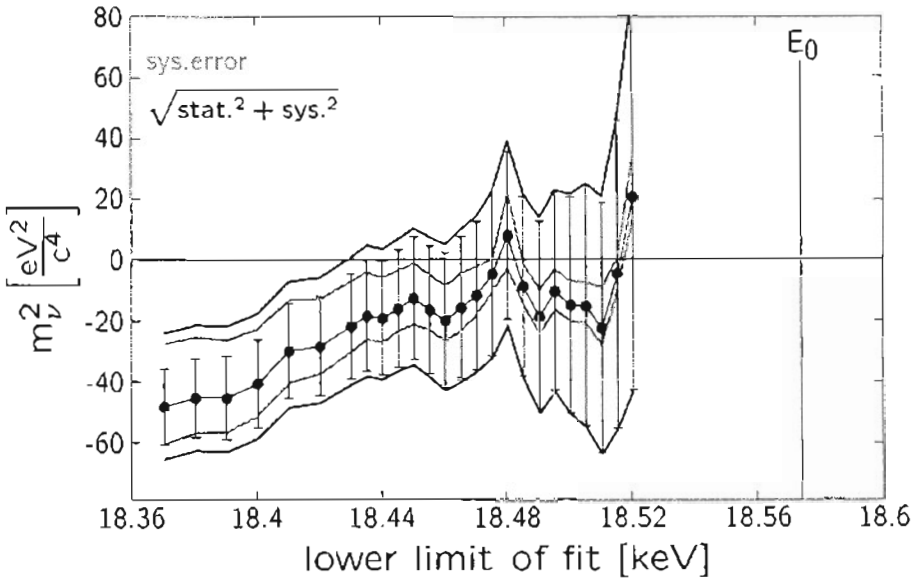

Figure 4: Dependence of the best fit for m_ν^2 on the truncation point of the β spectrum. The error bars represent the statistical uncertainties, the gray envelopes the systematic uncertainties and the black envelopes the total uncertainties calculated by the quadratic sum of the statistical and the systematic uncertainties. The systematic uncertainties contain the uncertainties of the energy loss by inelastic scattering (uncertainties of the mean free path, of the thickness of the T_2 film, and of the condensation rate of H_2 on top of the T_2film of ≤ 1 layer per day) and some other smaller contributions like backscattering of electrons in the graphite substrate, uncertainties in the transmission function of the spectrometer, of the energy dependence of the detector efficiency and of the calculations of the distribution of electronic final states.

3.2 Possible origins of the negative m_ν^2 problem

Figure 5a shows the differences of the experimental count rates and the fit over the last 140 eV for m_ν^2 fixed to 0 and its extrapolation further downwards into the spectrum. Below the fitted interval the data clearly exceed the extrapolated fit. In the third root plot[1] this excess looks like a straight line intercepting the abscissa about 90 eV below E_0, like an additional β spectrum with an endpoint $E_0' \approx E_0 - 90$ eV and a β strength of about 4 % would do. An obvious explanation of this excess would be, that an additional final state with an excitation energy of 90 eV has to be added to the description of the electronic final states. Figure 5 b shows that the residues for the fit allowing for an additional free final state are looking very good ($\chi^2 = 40$, d.o.f. $= 52$).

This explanation was even more favoured by the fact, that some previous experiments [8, 9], which could only analyse larger intervals below the endpoint also obtained significantly negative values for m_ν^2 as best fits. Additionally the first measurements from the Troitsk tritium β experiment got a similar trend towards negative values for m_ν^2 with larger data intervals [10].

This problem evoked a big effort from the theoretical groups to check the calculation of the distribution of the electronic final states, which unfortunately could never been checked experimentally. But no significant deviation from previous calculations were found.

As seen from figure 5 an additional electronic final state is not the only possible explanation for the excess count rate. Figure 5 c,d, and e show the residues of the fits for m_ν^2 fixed to 0 for a free inelastic

[1] Plotting the third root of the measured count rate is a Kurie-like representation of the endpoint region for data taken with an integrating spectrometer

tering in the substrate or of the transmission function of the spectrometer. In all these experiments [11, 12] no significant deviation from the expectations were found, except for one open question: Have the T_2 films undergone a transition from a homogenous quench condensed film into a rough inhomogeneous one (see figure 6). This roughening transition, which was investigated for stable hydrogen isotopes by the group of P. Leiderer/Konstanz [13], would increase the fraction of inelastic scattering in the T_2 film as being looked for (see fig. 5 c).

3.3 Roughening transition of hydrogen films

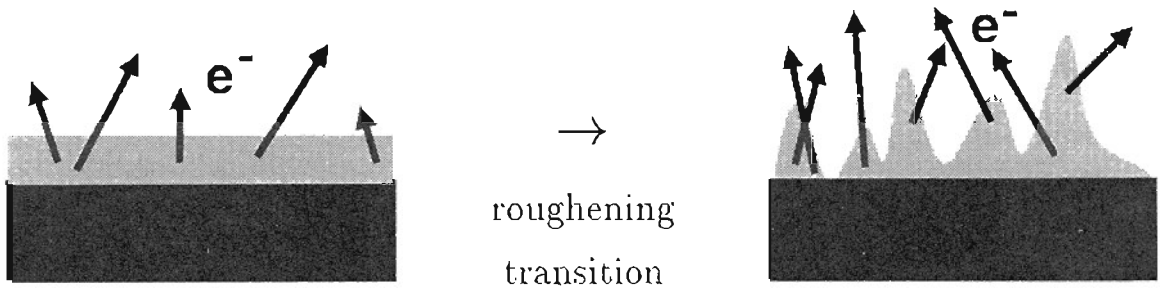

Figure 6: Roughening transition of a T_2 film (gray) quench condensed on a substrate (black). The emitted electrons undergo a larger amount of inelastic scattering within the rough film.

To answer the question, whether roughening transitions of hydrogen films can be suppressed by proper choices of the backing[2] or whether it can be sufficiently slowed down not to disturb the tritium β spectrum a series of investigations was done at Mainz in collaboration with the Konstanz group. H_2, HD and D_2 were used to study systematically the behaviour of the hydrogen isotopes and to be able to extrapolate the results to T_2. Thin films were quench condensed on graphite at temperatures below 2 K and annealed at higher temperatures (at *e.g.* ≈ 4 K in the case of D_2.) The dynamics of the roughening transition was studied during annealing by detecting the increase of light scattering from the film surface (see figure 7). The results of these investigations[3] are: We did not found any backing, which suppresses the roughening transition, but the transition speed is slowed down drastically for the heavier isotopes (like T_2) and by going to lower temperatures. This is understood from the fact that the speed of the roughening transition is determined by the activation energy for surface diffusion for the given isotope compared to the kinetic energy at a given temperature.

The extrapolating from the results obtained for the stable isotopes and from a few measurements done with T_2 leads to a time constant for the roughening transition of a T_2 film at 2.5 K of many years. This extrapolation is valid, as long as the β decay of tritium with its energy depositing processes (recoil of the nucleus and excitation of electron shell by the β decay, inelastic scattering of β electrons) does not play a significant role for the transition process. A first test with a T_2 film, kept over 4 days at 1.8 K, gave no indication for roughening.

[2]The parameters of the backing can be influenced by condensing layers of other gases (*e.g.* noble gases) between the graphite substrate and the hydrogen film.

[3]Additionally to the mentioned investigations done by scattered light technique the roughening transition were confirmed as well by energy loss measurements of ^{83m}Kr conversion electrons within D_2 films at different temperatures.

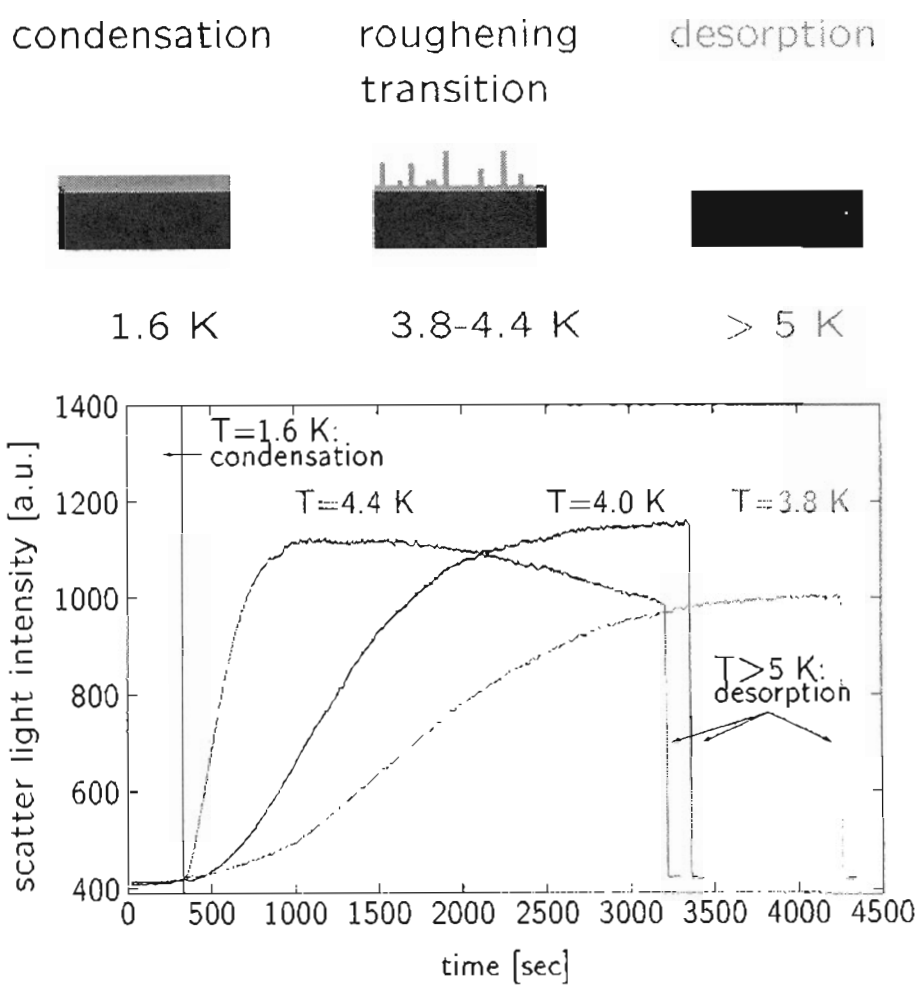

Figure 7: Investigation of roughening transition by the measurement of light scattered from D_2 films. A D_2 film was quench condensed at 1.8 K. Afterwards the film was kept over a period of about 3000 s at a temperature of 3.8 K, 4.0 K or 4.4 K respectively while measuring the intensity enhancement of the scatter light due to the starting roughening transition. To check the background light intensity the D_2 films were desorbed at a temperature of about 5 K later on. (The desorption rate at 4.4 K was already not negligible as the decreasing scatter light intensity curve shows.)

3.4 The current status of the negative m_ν^2 problem

Our investigations show, that the roughening transition of the T_2 film can be avoided in future measurements by going to very low temperatures. But it may have taken place for the much warmer T_2 films of the Mainz measurements in 1991 (T_2 film preparation at $T \approx 4.2$ K, β spectrum measurement at $T > 2.9$ K) and in 1994 ($T > 2.9$ K), probably causing the problem of negative values of m_ν^2 for larger energy intervals.

The Troitsk collaboration recently found, that their trend towards negative values of m_ν^2 for larger energy intervals was caused by underestimating the fraction of electrons trapped in the tritium source, which escape by large angle scattering into the spectrometer [2].

In view of the results quoted above, it seems to be likely that the problem of negative values of m_ν^2 is at least in part due to unaccounted or underestimated systematic uncertainties of the experiments.

Having solved or at least found some possible explanations for the "old problem" of negative values of m_ν^2 a new puzzle arose [2]: In all Troitsk measurements starting in 1994 an excess count rate was reported to appear close below the tritium endpoint. This excess seem to be a monoenergetic

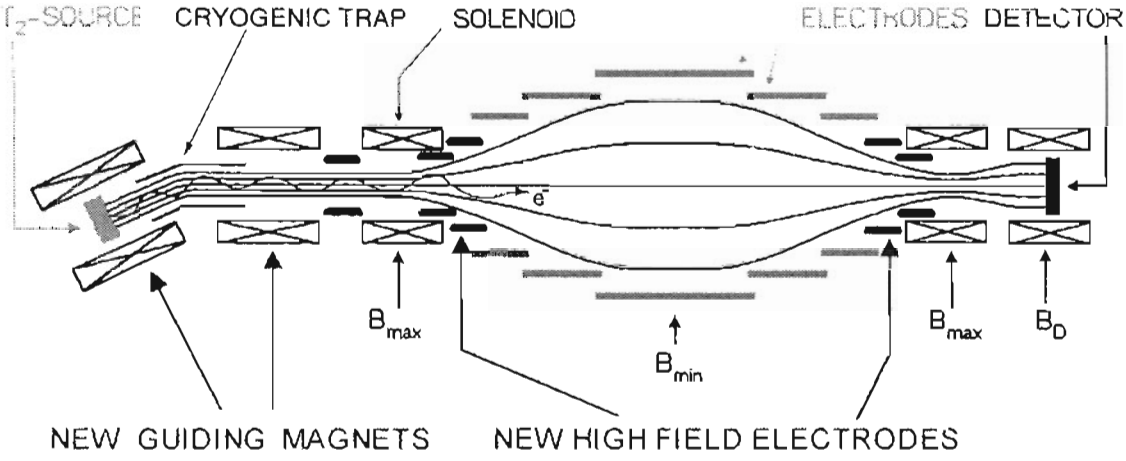

Figure 8: The improved and extended Mainz setup

line with a relative fraction of less than 10^{-10} of all tritium β decays. Its position and amplitude varies from measurement to measurement. There is no explanation by experimental errors or within standard physics. This excess is to small to be checked by the Mainz data of 1991 and 1994.

4 The extended Mainz setup

Looking for a non-zero neutrino mass in the range of a few eV/c^2 is more and more important for the reasons mentioned in section 1. Additionally we like to test the hypothesis that the excess count rate further below the endpoint observed at Mainz was due to roughening transition of the T_2 film. And moreover the monoenergetic anomaly just below the endpoint reported by the Troitsk experiment[2] clearly need an independent experimental check.[4]

To fulfil these expectations the Mainz experiment had to solve the following problems:

- to decrease the background
- to increase the signal
- to increase the energy resolution of the spectrometer
- to make long term runs feasible
- to avoid the T_2 film roughening transition
- to avoid the condensation of H_2 on the T_2 film

For these reasons the Mainz experiment has improved its setup substantially (see figure 8) by the following items:

- A new, automatically controlled source cryostat was installed to slow down the T_2 film roughening transition to a negligible speed by working at temperatures down to 1.6 K.

  Its about 3 times larger source area allows to optimise the source strength and the maximum starting angle of β electrons accepted by the spectrometer.[5] This enables us to increase the

[4]The last two statements are strongly supported by the fact, that the Particle Data Group renounced in their last edition to extract an upper limit on m_ν from the tritium β decay experiments due to the unsolved problems.

[5]The ratio of the maximum magnetic field B_{max} and the field at the detector B_d defines the size of a virtual electron source placed at the maximum field B_{max}. By moving the source to a position at a lower field in front of this field maximum, electrons from a larger source area are accepted by the spectrometer at the expense of a decrease of the

signal rate with respect to the uncertainties of the inelastic scattering.

- A new doublet of superconducting solenoids, rotated by 20° to each other, was installed. The source is now placed in the leftmost solenoid. β decay electrons are guided into the spectrometer without losses as before, whereas tritium molecules evaporating from the source are prohibited from contaminating the spectrometer as well as residual gas molecules of the spectrometer from condensing on top of the T_2 film. These two problems were the biggest sources of background and of systematic uncertainty for the 1994 run.
  Additionally the spatial separation of the source and the spectrometer allows a valve to be closed by a control system in case of any problems, which is an essential feature for automatic running.
- The electrodes in the high magnetic field were redesigned to lower the background contribution from the spectrometer itself. The number of electrodes was increased from 23 to 27 resulting in a reduction of the potential differences between them in order to improve the high voltage stability. A small change in geometry prohibits high energy electrons from the electrode surface to be guided onto the detector, which was a problem for the old setup (see section 2.2).
- An experiment control system was setup in order to run the experiment fully automatically except the necessary LHe and LN_2 fillings. This was a very important improvement because the potential of the Mainz experiment has never fully been exploited in the past since the lack of human power in the small collaboration did not allow longer measurements than periods of a few weeks. The old cryostat as well as the missing possibility to prevent the spectrometer from a tritium contamination in case of emergency prohibited to run the experiment without permanent human control.

5 First measurement with the improved Mainz setup

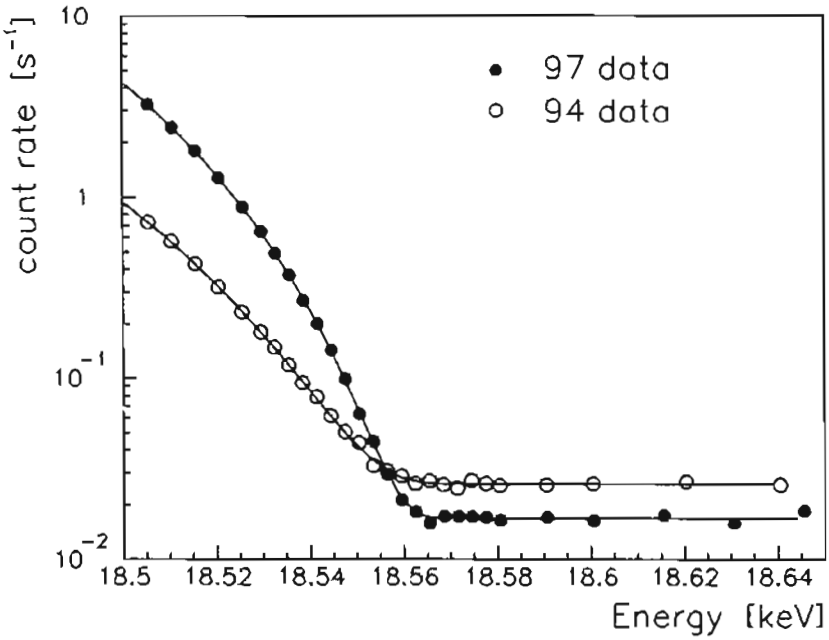

Figure 9: Mainz tritium β spectra close to the endpoint

maximum accepted starting angle. Thereby the effective source strength can be chosen but at the same time the fraction of inelastically scattered electrons which depend strongly on the path length within T_2 film varies as well. The 3 times larger source area allows this variation and an optimisation in a much bigger range.

With this improved setup a first measurement of the tritium β spectrum was performed in July and August 1997 over 4 weeks. The requirements mentioned above for the current goals of the Mainz experiment could be satisfied very nicely as illustrated by the following items:

- The full setup, especially the new cryostat running at a temperature of 1.83 K within a range of ± 0.03 K, the new solenoids and the improved electrode system of the spectrometer were working stable over 4 weeks. This behaviour allowed to do the whole run fully automatically, human intervention was needed only for filling of LHe and LN_2.
- Although the T_2 film of about 282 monolayers was about 7 times thicker than in 1994 the background was even lower (see figure 9). The background rate of 0.016 s^{-1} was only 50 % larger than the rate without any tritium source. This demonstrates that the cryotrap in the bending magnets prohibits nearly completely the tritium contamination of the spectrometer. Therefore the signal to background ratio was increased by a factor of 10 compared to the measurement in 1994.
- The thickness of the T_2 film was measured before and after the runs with ellipsometry. Within the precision of a few percent the film thickness was reduced by the same amount as the source strength decreased.[6] Therefore no significant signal of condensing residual molecules were found, demonstrating again the performance of the cryotrap.
- The cryostat was running a temperature of 1.83 K, but the T_2 film itself was at a temperature of 2.5 K due to a temperature gradient between the copper head of the cryostat and the graphite substrate. This gradient was determined by measuring the temperature dependence of desorption rates of D_2 film condensed on the graphite substrate. This T_2 film temperature should be still low enough to slow down the roughening transition strongly as stated above and was significant lower than in 1994.[7]
- Due to a better alignment of the whole system the spectrometer could run at a higher energy resolution of 4.4 eV compared to 6.3 eV in 1994 (these widths correspond to the 0 to 100 % rise of the transmission function of the spectrometer, see figure 2).

5.1 Statistical sensitivity of the data

The tritium β spectrum was investigated by taking measurements at a fixed retarding potential over 10 s to 60 s. The retarding potential was changed in steps of 1 eV to 10 eV by changing the electric potential of the tritium source. A whole cycle running over the last 200 eV of the β spectrum took 40 min (or 2 hours using different settings respectively). Within the 4 weeks of data taking the measurement at each retarding potential was repeated about 1400 times.

The data taking was suffering from instabilities due to micro sparking of the high voltage electrodes of the spectrometer. The data were cleaned from these disturbances in two steps:

- Large discharges are clearly visible in the data by a significant increase of the count rate over

[6] Measured by the time dependence of the β electron count rate the T_2 film had an effective half life of about 320 days, which is about one order of magnitude shorter than the half life of tritium. This loss of tritium is likely due to the fact, that the recoil energy given by the β decay to a nucleus is about two orders of magnitude larger than the binding energy of the T_2 crystal enabling tritium molecules to be sputtered off the film.

[7] The cryostat temperature in 1994 was about 2.9 K, but a temperature gradient between the cryostat and the graphite substrate was very likely existing similar to the one in 1997.

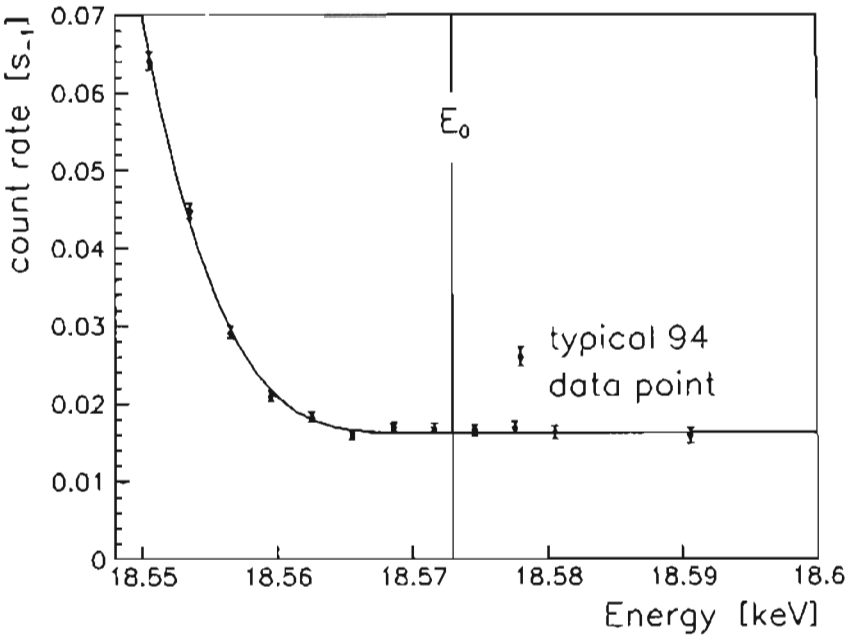

Figure 10: β spectrum of the 1997 measurement close to the endpoint after cleaning from events by micro sparks. The line is a preliminary fit.

several minutes. This happens about once a day. In such a case the data of a whole cycle were rejected.

- In order to detect also very small instabilities a Poisson distribution was fitted by the maximum likelihood method to the distribution of counts recorded at the same retarding potential of the different cycles. High count measurements with a probability level less than 10^{-3} were rejected.

The spectrum after cleaning is shown close to its endpoint in figure 10 together with a preliminary fit. The residuals of this preliminary fit over the last 70 eV of the β spectrum (see figure 11) show no indication of remaining unstatistical disturbances in the cleaned data.

This preliminary fit with the free fit parameters A, E_0, BG and m_ν^2 (as described in section 3 and more detailed in reference [3]) was repeated for different truncation points of the energy intervals of the data contributing to the fit. Figure 12 shows the 1σ uncertainties for m_ν^2 obtained by these fits compared to the same numbers for the 1994 data. The longer data taking period and moreover the 10 times higher signal to background ratio of the 1997 data result in an improvement of the statistical sensitivity on m_ν^2 by about a factor 5.

5.2 Systematic uncertainties

Since the study of the systematic uncertainties of the July/August 1997 measurement is not completed yet, only preliminary results are given here, as they were presented at the Erice school.

The main systematic uncertainties are caused by the inelastic scattering of β electrons within the T_2 film due to the large thickness of the film compared to previous measurements. A second source of uncertainty is the charging up of the T_2 film. This new effect has never been noticed before because it has not been important for previous measurements. The charging is not uniform over the film and therefore decreases the energy resolution, but it might give a handle to monitor a possible roughening

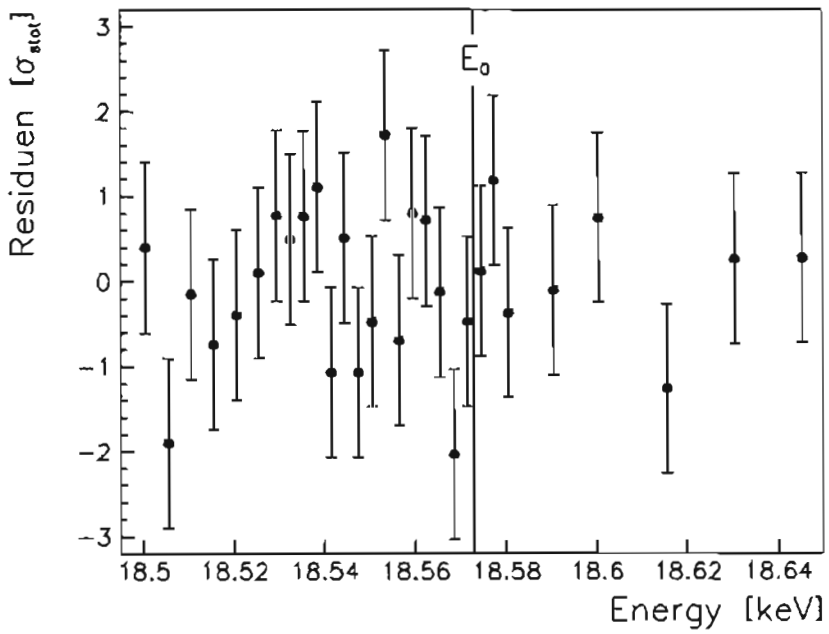

Figure 11: Residuals of a preliminary fit to the data after cleaning from micro instabilities ($\chi^2 = 23$, d.o.f. $= 25$).

transition. All other sources of uncertainties are small and will not be discussed here further.

5.2.1 Inelastic scattering

The T_2 film thickness of $d_{T_2} = 282$ monolayers was 7 times larger than in the 1994 measurement and corresponds to about 90 % of the mean free path for 18.6 keV electrons. But the increase of systematic uncertainties is modest since 3 items are partly compensating the larger film thickness:

- The maximum starting angle for electrons accepted by the spectrometer was set to $\theta_{max} = 45°$ by the choice of the magnetic field at the source ($\rightarrow$ maximum path in the T_2film: $1.4 \cdot d_{T_2}$) compared to $\theta_{max} = 78.5°$ in 1994 ($\rightarrow$ maximum path in the T_2film: $5 \cdot d_{T_2}$)
- The much higher signal to background ratio allows to use much smaller energy intervals below the endpoint for the final analysis. This reduces the fraction of inelastically scattered electrons in the fitted data, since they appear at energies reduced by their energy loss. In the ideal case the last 9 eV of the β spectrum should be analysed. This interval is completely free of any contribution from inelastically scattered β electrons, since the minimum energy loss possible in T_2 is about 9 eV.[8]
- Avoiding the condensation of H_2 on top of the T_2 film in 1997 by the cryotrap in the bending solenoids eliminates for 1997 the biggest contribution to the inelastic scattering uncertainties of the 1994 measurement.

Concerning the inelastic scattering in the T_2 film the following uncertainties are taken into account:

a) 10 % uncertainty of the mean free path

[8]The inelastic scattering cross section would only affect the signal rate by changing the fraction of not scattered electrons contributing to the very end of the β spectrum.

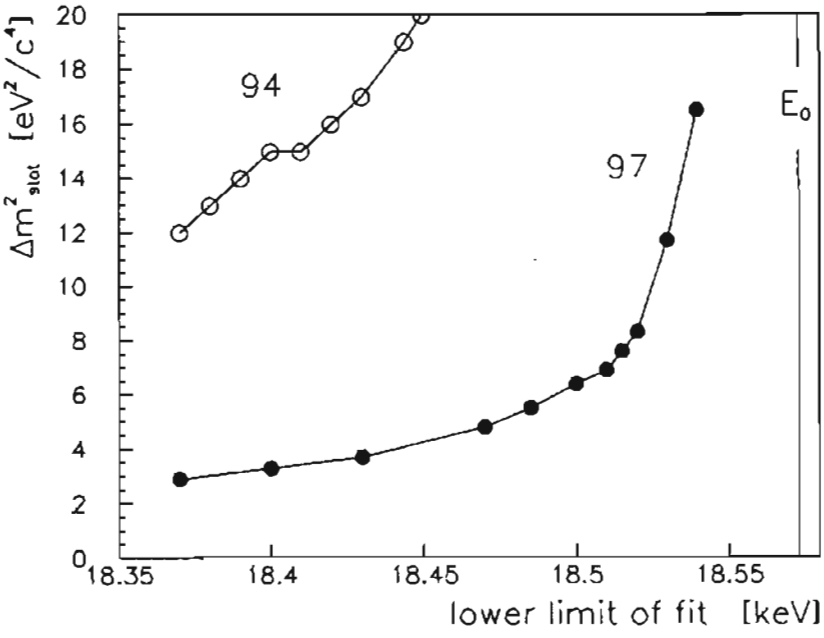

Figure 12: Statistical sensitivity of the 1997 data (filled circles) in comparison with 1994 (open circles). Shown are the 1σ statistcal uncertainties for m_ν^2 obtained by the preliminary fit in dependence on the truncation point of the energy intervals of the data contributing to the fit.

b) 20 % uncertainty of the measured film thickness. Although the thickness determination by ellipsometry is in principle much more precise, there are still some items to be clarified like the question whether there was a significant amount of pores within the T_2 film or how to transfer the results obtained for the previous thin T_2 films to the much thicker one of the 1997 measurement.

c) The new investigations of the shape of the energy differential inelastic cross section recently performed at Troitsk [2] seem to contradict our own measurements [12]. As long as this discrepancy is not clarified the difference between the results on m_ν^2 for both shapes are taken into account as systematic uncertainty.

All three points are currently under investigations at Mainz by energy loss measurements with conversion electrons from ^{83m}Kr and by intensive studies of ellipsometry on thick hydrogen films. Therefore all these results are preliminary and the uncertainties are expected to decrease.

5.2.2 T_2 film charging

The endpoint energy of the β spectrum measured in 1997 is shifted by about 3 eV towards lower energies compared to the previous measurements. This shift is due to a charging of the T_2 film, which is qualitatively understood by the fact that from a T_2 source of about 40 mCi activity more than one billion β electrons per second are leaving the film, whereas the positive daughter nuclei are remaining within the T_2 film. If the charge compensation current is not large enough the film will charge up positively.

We have investigated the surface potential of the T_2 film at the end of the 4 weeks data taking by condensing a sub monolayer of ^{83m}Kr on top of the T_2 film. The shift of the position of K conversion line with respect to a reference measurement using a 240 monolayers thick D_2 film is a measure of the

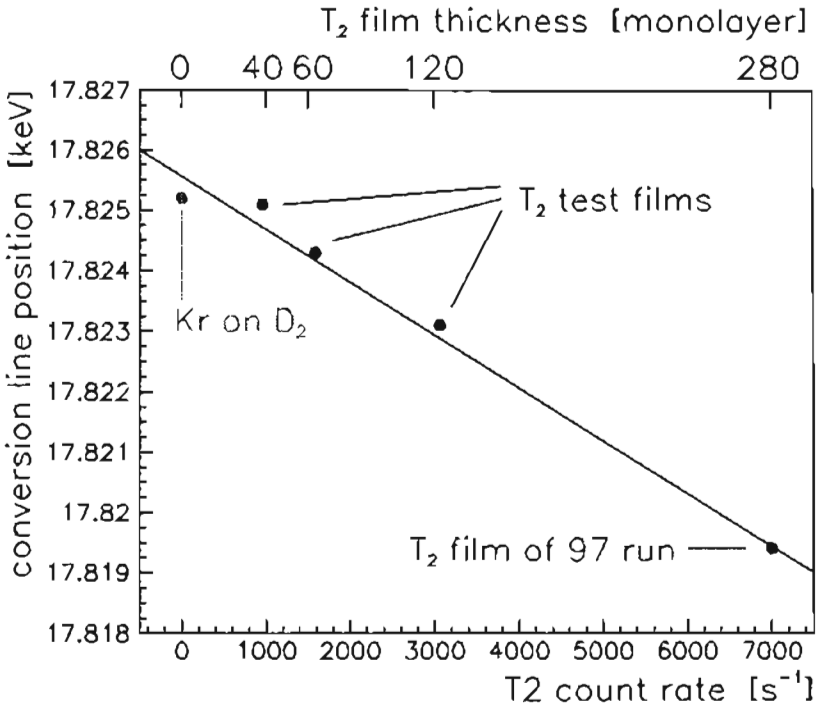

Figure 13: Position of the K conversion line from ^{83m}Kr condensed on T_2 films of different activity or thickness respectively, or on a D_2 film (reference measurement). A straight line is shown to guide the eyes.

surface potential due to the charging up. For several T_2 films of different thicknesses this measurement was repeated. Figure 13 shows the positions of the K conversion line from these measurements. The line positions seem to depend linearly on the T_2 film thickness. More tests with a ^{83m}Kr sub monolayer between 2 T_2 layers show that the shift only depend on the T_2 film thickness between the graphite substrate and the ^{83m}Kr layer, but not on the thickness of the second T_2 layer on top of the ^{83m}Kr.

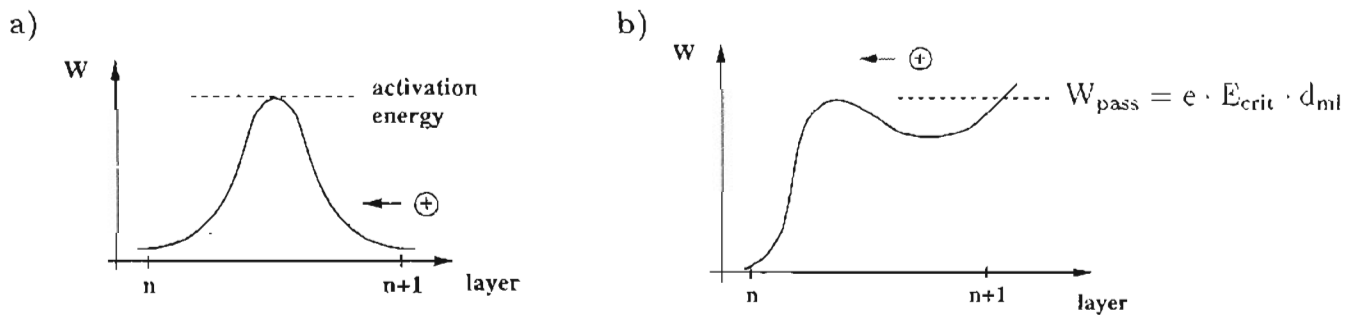

Figure 14: Simple picture of charge transport through one layer of a condensed hydrogen film for the example of positive carriers. a) without E field, b) with a critical E field.

A first description of this effect was given at the Erice school and is repeated here:
It is clear that a quench condensed T_2 film is not regularly arranged in contrast to a real crystal. Nevertheless for simplicity we will use in this description the picture of a T_2 film arranged in monolayers, in which the charge transport takes place by charge carrier moving from one monolayer to the next. This simplification still represents still the fact, that in a quench condensed film the carries move from one place to the next.
The charge mobility inside the condensed T_2 film is much too low for carriers [14] to serve for a

current of 0.2 nA, which is needed to compensate a 40 mCi activity. This holds also for negative carriers, since the charge movement of free electrons is handicapped by the fact, that they build up nanometer sized vacuum bubbles because they occupy space due to the Pauli principle. In a simple pictures there exists an activation energy for carriers of both signs to pass a layer as indicated in figure 14a. Typical activation energies [14] are about 2 orders of magnitude larger than the thermal energies of a particle prohibiting them to pass the barrier. The result of this is a charging up of the T_2 film by the remaining positive ions. The corresponding space charge changes the picture by creating an electric field as indicated in figure 14b. There is not only the barrier which hampers the charge transport through a layer of thickness d_{ml}, but there exists also a driving force from the electric field E, resulting in a energy gain of $W_{ml} = q \cdot E \cdot d_{ml}$ per monolayer. Above a critical field strength E_{crit} this energy gain is large enough to allow the carrier to pass the barrier.[9]

Does this simple picture reflect the reality at least partly?

- We expect from this picture a linear dependence of the surface potential $U_{sf} = E_{crit} \cdot d_{T_2}$ on the T_2 film thickness d_{T_2} due to the overall constant critical field strength E_{crit}. This expectation is confirmed by figure 13 and the measurements with T_2- ^{83m}Kr- T_2 sandwiches.
- The slope of the straight line of figure 13 gives the critical field E_{crit} and should correspond to the activation energy as indicated in figure 14b. From the value of the slope $E_{crit} \approx 6$ V / 282 monolayer the energy gain per monolayer can be calculated to be $W_{ml} = q \cdot E_{crit} \cdot d_{ml} = 21$ meV $= 247 \cdot k_B$ K, which agrees very well with activation energies measured in solid hydrogen of $W^-_{act} = 230 \cdot k_B$ K and $W^+_{act} = 215 \cdot k_B$ K [14].

Therefore we state that the charging of the T_2 film seems to be understood. This effect has the consequence of a varying potential for the different layers of the T_2 film which increases linearly with the distance to the substrate. Its existence is bad, because the energy resolution, with which the β spectrum is investigated is smeared out from 3.5 eV width of the spectrometer only (here 10 % to 90 % rise of transmission) to 6.0 eV after convolution with the potential distribution over the 282 monolayers.

We consider the charging effect in the analysis by applying an energy shift for every β electron, which depends on the distance between the layer, where the β decay takes place, and the graphite substrate. The correlation of the inelastic scattering probability for β electrons from a given layer in respect to its distance to the surface of the T_2 film is taken into account in this context as well. Since this picture simplifies probably too much the reality we take into account conservatively 50 % of the whole effect on m_ν^2 as systematic uncertainty.

5.2.3 Film roughness

The disadvantage of the existence of the charging of the T_2 film may also have an advantage. The potential at the surface of the T_2 film could serve as a roughness monitor. If the surface potential depends only on its distance to the graphite substrate then a T_2 film of very inhomogeneous thickness should be recognised by either one of the following two ways:

a) If the charge mobility on the surface is also as small as in the bulk an inhomogeneously thick T_2 film should still have an inhomogeneous surface potential. This should reflect in a broadening

[9] Tunnelling processes will of course reduce the necessary strength of E_{crit} a bit.

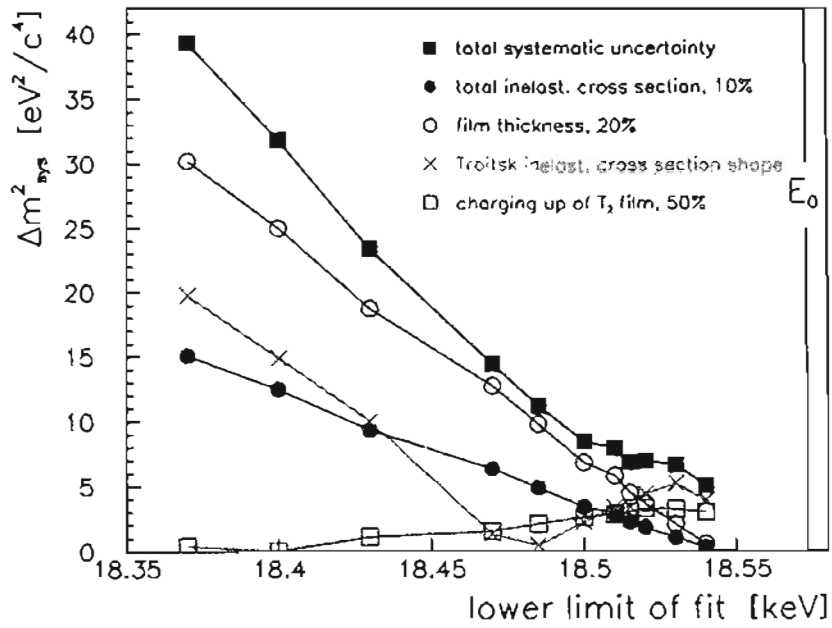

Figure 15: Estimated systematic uncertainties on m_ν^2 for the 1997 measurement from the various sources (preliminary).

of the conversion line. The width of the K conversion line of ^{83m}Kr on the T_2 film after 4 weaks was determined to be 2.94 ± 0.15 eV compared to a natural line width of 2.83 ± 0.12 eV [11]. From these values an inhomogeneity of the surface potential larger than ± 1 eV can be excluded.

b) If the charge mobility on the surface is large compared to the one in the bulk, a T_2 film of inhomogeneous thickness should have an homogeneous surface potential. But the line shift should be smaller because the compensation current could use the smallest distance to the graphite. Such an evidence of a inhomogeneous T_2 film is not favoured by the plot of figure 13 showing that the test measurements with 1 hour old T_2 films lie on the same straight line as the measurement with the 4 weeks old film. This indicates that the time constant for the roughening transition seems to be long compared to the 4 weeks as expected (see section 3).

From these arguments a roughening transition of the T_2 film of the 1997 measurement cannot be ruled out beyond doubt, but they and the investigations presented in section 3 give very good reasons to believe, that the T_2 film was not significantly inhomogeneous.

5.2.4 Comparison of systematic uncertainties

The dependence of the individual systematic uncertainties as well as the total systematic uncertainty are shown in figure 15 in dependence on the truncation point of the β spectrum.

5.3 First interpretation of the data and sensitivity on m_ν

Figure 16 shows the compilation of the statistical, the preliminary systematic, and the total uncertainties on m_ν^2 in dependence of the truncation point of the β spectrum. The total uncertainty, calculated as quadratic sum from the statistical and systematic uncertainties, is dominated by systematics for

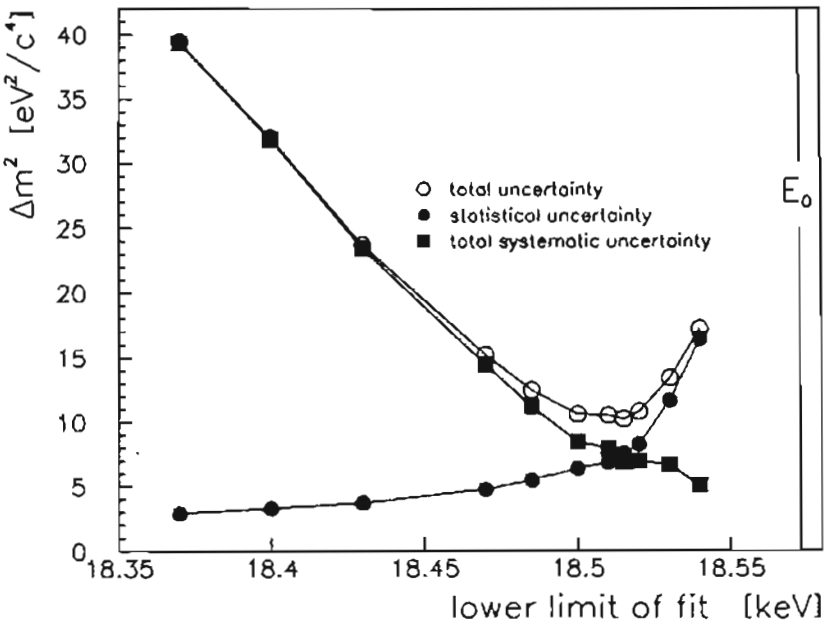

Figure 16: Statistical and estimated systematic 1σ uncertainties and total uncertainty of m_ν^2 for the 1997 measurement (preliminary).

large energy intervals and by statistics for truncation points close to the endpoint E_0. For intermediate truncation points at 50 eV to 70 eV below the endpoint the total uncertainty reaches a flat minimum of about $m_\nu^2 \approx 10\ eV^2/c^4$.

Since the analysis of the systematics, especially of the inelastic scattering within the T_2 film, is not yet completed, the values of m_ν^2 obtained by the fit may change within the preliminary uncertainties given in figure 15. These values of m_ν^2, as presented at the Erice school, are all compatible with zero within 1σ total uncertainty giving no hint for a non-zero neutrino mass, but they are lying in a range of -0.5 to -1 σ in the negative, unphysical region. The values χ^2/d.o.f. of the fits are all about 1. The data give no hint for a non-zero neutrino mass.

Additionally the values of m_ν^2 do not show any trend to more negative values as a function of the decreasing truncation point in contrast to the data shown in figure 4 from 1994. The most probable interpretation of this fact is, that the T_2 film has not undergone a significant roughening transition in 1997, whereas the T_2 film did it in 1994. This explanation would match the results from the investigations on roughening transitions presented in sections 3.3 and 5.2.3. Although following these arguments the roughening transition of the T_2 seems to be responsible for the problem of negative m_ν^2 of the previous Mainz measurements, the preliminary systematic uncertainties are too large to really exclude at present the compatibility of the 1997 results on m_ν^2 with the 1994 results as shown in figure 4. Therefore the exact source of negative m_ν^2 of the previous measurements in 1991 and 1994 cannot be located, until the investigations on the systematics are completed resulting in probably smaller uncertainties. But the general reason, namely enhanced energy loss, should be clear now.

The question whether these slightly negative values of m_ν^2 are a serious problem can only be answered when the current investigations of systematics are completed: Either the energy loss function under investigation with its probably smaller uncertainties will bring m_ν^2 closer to zero, or the discrepancy will exceed the 1σ level and has to be taken seriously. Unfortunately the question, whether this discrepancy is reflecting the monoenergetic anomaly in the β spectrum close below its endpoint

as reported by the Troitsk experiment[2] can be investigated only when the investigations on the systematics have been completed.

In spite of the preliminary character of the results it might be interesting to raise the question of the sensitivity on m_ν of the Mainz 1997 measurement. In order to consider the fact, that the fit results are not final, the following statements are given under the simplifying assumption that the fit would give a value of $m_\nu^2 \approx 0$. The total 1σ uncertainty of $\Delta m_\nu^2 \approx 10 eV^2/c^4$ would give an upper limit for m_ν with 95 % CL of 4.5 eV/c^2 (using the Bayesian method: $m_\nu < \sqrt{2\sigma}$) or 4.0 eV/c^2 respectively (using the method of confidence intervals: $m_\nu < \sqrt{1.64\sigma}$).[10, 11]

6 Perspectives and outlook

6.1 Obtainable sensitivity of the Mainz setup

Further significant improvements of the sensitivity on m_ν require substantial decreases of both the statistical and systematic uncertainties.

The statistical uncertainty can be decreased by taking data over periods of several months, which seems to be feasible considering the experience obtained for the improved Mainz setup during the 4 weeks measurement.

By using only a small part of the β spectrum below the endpoint E_0 (i.e. to set the truncation point close to E_0) also the systematic uncertainties are reduced, except for the problem originating from the charging up of the T_2 film. Since there is presently no feasible idea how to eliminate this problem the only possible way is to reduce its influence by using thinner T_2 films again. Of course this means a loss of signal rate, but it can be mainly compensated by:

a) enhancing the maximum angle accepted by the spectrometer from currently 45° to 60°, from which a signal gain of 20 % can be expected.[12]

b) improving the tritium content of our source film. Due to exchange processes at the walls of our gas inlet system the source film in 1997 had a tritium content of about 60 % only, the rest of the film consisted of hydrogen. We have already demonstrated that we can reach a tritium content of more than 80 % with a fresh sample of T_2. This improvement will enhance the signal rate by at least 33 % keeping the systematic uncertainties constant.

Therefore we expect to keep 80 % of the signal rate for a source film of half the thickness of the film of 1997. Such a film will have half of the systematic uncertainties caused by the charging of the source film and a little bit more than half of the uncertainties originating from the inelastic scattering.

For the future 2 scenarios have been roughly estimated:

a) Near future:

Without further improvements of the setup except the already demonstrated enhancement of the

[10] In the field of tritium β experiments most often the more conservative Bayesian method is used to give an upper limit.

[11] The systematic uncertainties do not include any correlation to a line-like anomaly, as reported by the Troitsk experiment [2].

[12] When optimising the maximum accepted angle to 45° for the 1997 measurement, the charging effect was not taken into account. Including it also into the considerations the optimum shifts towards larger angles.

tritium content in the source film the following scenario seems to be very realistic: For a period of data taking of 2 months in total with 80 % of the signal rate and the same background rate as in 1997 the statistical 1σ uncertainty would be $\Delta m^2_{stat} \approx 4.5\ eV^2/c^4$ using the last 70 eV of the β spectrum. Expecting conservatively only to improve the uncertainty of the film thickness from 20 % to 10 % by the current investigations the total systematic uncertainty would be $\Delta m^2_{sys} \approx 3.8\ eV^2/c^4$. The total uncertainty of $\Delta m^2_\nu \approx 5.9\ eV^2/c^4$ corresponds for $m^2_\nu \approx 0$ to a limit on the neutrino mass of 3.4 eV/c^2 (Bayesian method) or 3.1 eV/c^2 (method of confidence intervals) at 95 % CL.

b) **Sensitivity limit of the present Mainz setup:**

We consider a period of 6 months of data taking in total to be feasible with present Mainz setup under the same conditions as in scenario a but under the assumption of a background reduction by a factor 2. This background improvement seems not to be unrealistic, because many ideas to reduce the spectrometer background have been not tested yet. Such a long term measurement will give a statistical uncertainty of $\Delta m^2_{stat} \approx 2.0\ eV^2/c^4$ going closer to the endpoint by using the last 50 eV of the β spectrum. Concerning the systematics we also expect the discrepancy between the energy loss functions measured at Troitsk and at Mainz to be clarified, resulting in a total systematic uncertainty of $\Delta m^2_{sys} \approx 1.7\ eV^2/c^4$. The total uncertainty of $\Delta m^2_\nu \approx 2.6\ eV^2/c^4$ corresponds for $m^2_\nu \approx 0$ to a limit on the neutrino mass of 2.3 eV/c^2 (Bayesian method) or 2.1 eV/c^2 (method of confidence intervals) at 95 % CL.

In both cases a) and b) the monoenergetic anomaly reported by the Troitsk group should be detectable.

Scenario b) seems to be the final limit of the present Mainz setup. Any further improvement below a sensitivity of 2 eV/c^2 clearly needs a stronger spectrometer.

6.2 Perspectives for a new experiment

Depending on the outcome of the various puzzles in neutrino physics and due to the importance of neutrino masses in the 1 eV/c^2 region for the dark matter problem the direct test of a non-zero mass of the electron antineutrino by investigation the tritium β decay spectrum should be improved further.

It is the feeling of the Mainz group that we should investigate how far one can push the proven technique of a solenoid retarding spectrometer. As pointed out in section 6.1 the influence of systematic uncertainties can be reduced by determining the neutrino mass from a small part of the spectrum close to its endpoint. In this case the advantage of a differentiating spectrometer against an integrating one, like the solenoid retarding spectrometer, vanishes for the β spectrum at its very end due to the high energy cut off at the endpoint. Progress can be made by increasing luminosity and energy resolution. Both improvements could be achieved by scaling up the apparatus. In view of source questions discussed above, the concept should also consider a gaseous T_2 source.

Without performing a detailed simulation it seems to be rather reasonable that a sub eV/c^2 sensitivity on m_ν can be reached only, if the signal would emerge from background at an energy 1 eV below the endpoint E_0 of the β spectrum investigated with an energy resolution of about 1 eV. This resolution of $\Delta E \approx 1$ eV will be reached according to equation 5 by setting the ratio of magnetic fields to

$$\frac{B_{min}}{B_{max}} = \frac{\Delta E}{E} = 5 \cdot 10^{-5} \qquad (10)$$

This goal can be reached by increasing the diameter of the analysing plane from 1 m to 5 m. The diameter of the virtual source positioned at the maximum field B_{max} would then be 10 cm^2, resulting in a luminosity of $2\pi \cdot 10$ cm^2. The effective source strength is limited by the fact, that electrons contribute only to the very end of the β spectrum if they have not undergone an inelastic scattering process. This means that even in the case of an infinitely thick source only electrons from a thickness equivalent to the mean free path will contribute. Averaging over all starting angles the maximum effective source thickness of the virtual source placed at B_{max} is about 160 monolayers, or the equivalent mass density of a gaseous T_2 source respectively, which corresponds to an effective source strength of $6 \cdot 10^9$ Bq. Considering that the fraction of β electrons which are accepted by the spectrometer within the last 1 eV of the β spectrum amounts to about $1 \cdot 10^{-13}$ of all β decays and taking into account the convolution with the spectrometer transmission function the signal count rate S would be $1.5 \cdot 10^{-4}$ s^{-1} at a retarding energy of 1 eV below the endpoint. The measurement time t necessary to see an excess above a background rate BG at a 2σ level is given by:

$$(S + BG) \cdot t - BG \cdot t > 2 \cdot \sqrt{(S + BG) \cdot t} \tag{11}$$

$$\rightarrow t > 4 \cdot \frac{S + BG}{S^2} \tag{12}$$

Assuming a background rate of the same order as the present background rate[13] of 10^{-2} s^{-1} a measurement time of $t \approx 20$ days would be required to fulfil equation 12. A full measurement covering the last 10 eV of the β spectrum and background would require less than one year.

This rough estimate shows that it seems possible to reach a sub eV/c^2 sensitivity on m_ν by upscaling the proven technology of a solenoid retarding spectrometer by a factor of 5. Of course this short exercise can not replace a full simulation[14] of the problem and a discussion of the systematic uncertainties for such a scenario.

7 Conclusions

The Mainz measurement in 1994 shows a significant trend towards negative values of m_ν^2 for larger intervals of the β spectrum below the endpoint used for the analysis similar to the one reported in 1993. To our understanding this behaviour is due to underestimated or unaccounted energy loss processes. A roughening transition of the T_2 film would explain this situation. Our investigations show, that such a roughening transition can be slowed down to insignificance by keeping the T_2 film at temperatures below 2.5 K.

The Mainz group has improved its setup to run with very high signal to background ratio over longer periods of time fully automatically. The success of this upgrade was demonstrated by a first

[13] It is not obvious how the spectrometer background would scale with the size of the spectrometer. Volume and surfaces increase but, on the other hand the electric gradients decrease, reducing the micro spark induced background. Another source of background, the natural γ background in the detector, will increase by scaling the setup, but advanced detectors could be made thinner and shielded better to compensate this effect. Therefore it seems to be reasonable to estimate for a larger setup about the same background rate as for the present one.

[14] As an indication for the relation between the sensitivity on the neutrino mass and the point at which the count rate clearly exceeds the background level may serve the fact that for the 1991 and the 1994 results, as well as for the sensitivity estimation of the 1997 data the following rule seems to be fulfilled: The upper limit on m_ν is about half of the distance to the endpoint, at which the signal clearly exceeds the background level. This would point to an achievable sensitivity on m_ν of about 0.5 eV/c^2.

measurement over 4 weeks, showing a much better statistical accuracy than in our previous measurements. No indication for a roughening transition of the T_2 film has been observed in the 1997 experiment. The ongoing data analysis will very likely result in a sensitivity on the neutrino mass below 4.5 eV. The apparatus is now ready to check the anomaly in the β spectrum very close to its endpoint reported by the Troitsk group and to reach our final sensitivity limit on m_ν of about 2 eV/c^2. A scale up of this type of spectrometer would open the possibilities to a sub eV/c^2 sensitivity.

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