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Latest results of the Mainz Neutrino Mass Experiment

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Abstract. The Mainz Neutrino Mass Experiment investigates the endpoint region of the tritium β decay spectrum very precisely to extract the rest mass of the electron antineutrino. The measurements are performed with a MAC-E-Filter, combining Magnetic Adiabatic Collimation and an Electrostatic high pass Filter. After optimal preparation of the apparatus very stable and high quality data have been taken in 2001, which do not show any residual problem. A combined analysis of data from 1998/1999 and 2001 lead to the final value of $m_\nu^2 = -0.7 \pm 2.2_{stat} \pm 2.1_{sys}$ eV^2/c^4, leading to an upper limit $m_\nu \leq 2.3$eV/c^2 (95% C.L.).

PACS. 14.60.P Neutrinos, mass and mixing – 23.40 β decay

1 Introduction

Recent results from atmospheric, solar and reactor neutrinos have proven that neutrinos oscillate from one flavor state into another. However ν-oscillation experiments do not yield absolute neutrino masses, but differences between squared Δm_{ij}^2 and this gives lower limits on the masses themselves [1,2,3]. The kinematics of weak decays on the other hand, yield the square of the involved neutrino $m_{\nu_e}^2$ directly. The Mainz Neutrino Mass Experiment is based on the principle MAC-E-Filter [4], which combines high luminosity and high energy resolution at low background. These features are of decisive importance for the experimental sensitivity to $m_{\nu_e}^2$ in the endpoint region of a β spectrum. The principle of the MAC-E-Filter is illustrated in Fig. 1. Two superconducting solenoids create a magnetic guiding field. The β electrons, starting from a tritium source inside the left solenoid into the forward hemisphere, are guided on a cyclotron spiral along the magnetic field lines into the spectrometer with an accepted solid angle of nearly 2π. The magnetic field strength drops from the center of the solenoid to the center of the spectrometer by several orders of magnitude. This leads to a transformation of the transverse cyclotron energy $E_\perp$ into longitudinal one $E_\parallel$ by the magnetic gradient force. In the center of the spectrometer, the analyzing plane, the electron moments are almost perfectly aligned in the direction of the magnetic field lines. There $E_\parallel$ is analyzed energetically by applying an electrostatic retarding potential formed by a system of cylindrical electrodes. All electrons with enough energy to pass the barrier are reaccelerated onto the detector (in the right solenoid). Therefore the spectrometer works as an integrating high pass filter. The relative energy resolution of the MAC-E-filter is given by the ratio of the minimal magnetic field B_{min} in the analyzing plane and the maximal magnetic field B_{max} between source and spectrometer being in our case:

$$\Delta E \;=\; E\,\frac{B_{min}}{B_{max}} \;=\; 18600 \text{ eV}\,\frac{5.6^{-4}\text{ T}}{2.2\text{ T}} \;\approx\; 4.8 \text{ eV} \quad (1)$$

By changing the retarding potential the integral β spectrum can be scanned. The Mainz setup uses a solid state source realized by a film of molecular tritium, quench-condensed onto a graphite substrate (HOPG). Typical source parameters are: diameter 17 mm, thickness 45 nm (measured by laser ellipsometry), activity 1 GBq.

2 The measurements of 2001

The improved Mainz II setup has a source solenoid consisting of two coils. The first coil houses the tritium film and the second one follows after a bent, so that tritium molecules evaporating from the source are trapped on the LHe cold tube. This eliminated source correlated background and allowed to use a stronger source. Data from 1998 and 1999 in comparison with former data from 1994 are shown in Fig. 2. The signal to background ratio was improved by a factor of 10. Also shown are the latest data of 2001, which have a third of the statistics of the 98/99 data and an even lower background level. This further improvement is due to very careful preparation of the whole system.

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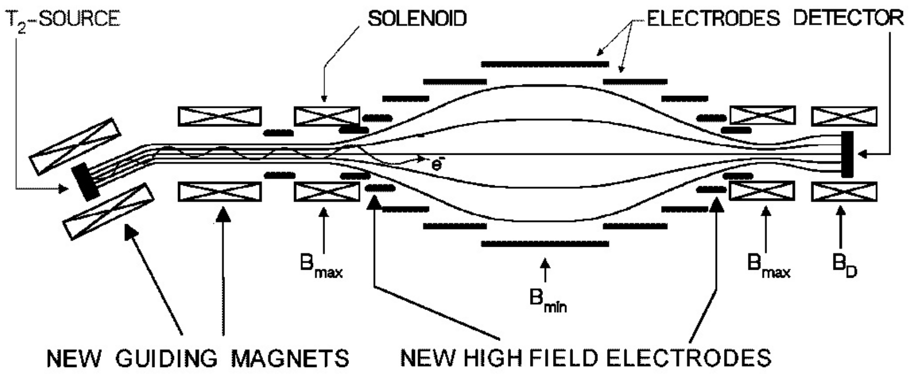

Fig. 1. The setup of Mainz II is shown schematically. The distance between source and detector is about 6 m and the diameter of the spectrometer vessel is 1 m

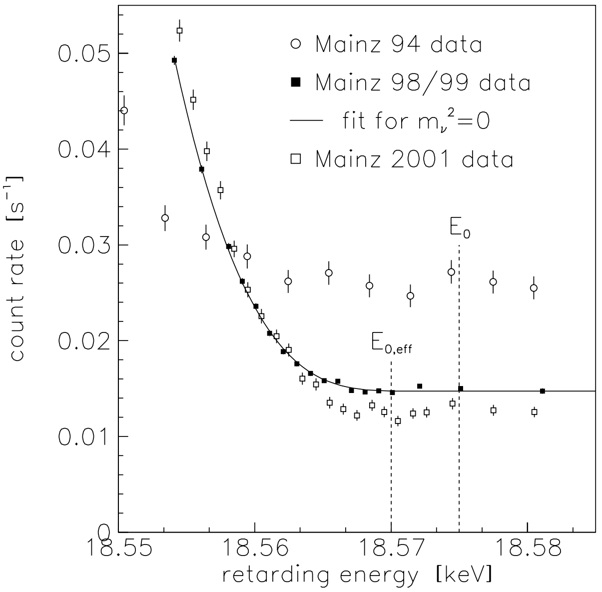

Fig. 2. Averaged count rate of the 98/99 data (filled squares) with fit (line) and the 2001 data (open squares) in comparison with previous Mainz data from 94 (open circles) as function of retarding energy near the endpoint E_0. The position of effective endpoint $E_{0,eff}$ takes into account the rot-vibrational excitation of the ground state, the width of the resolution function and the potential drop across the source

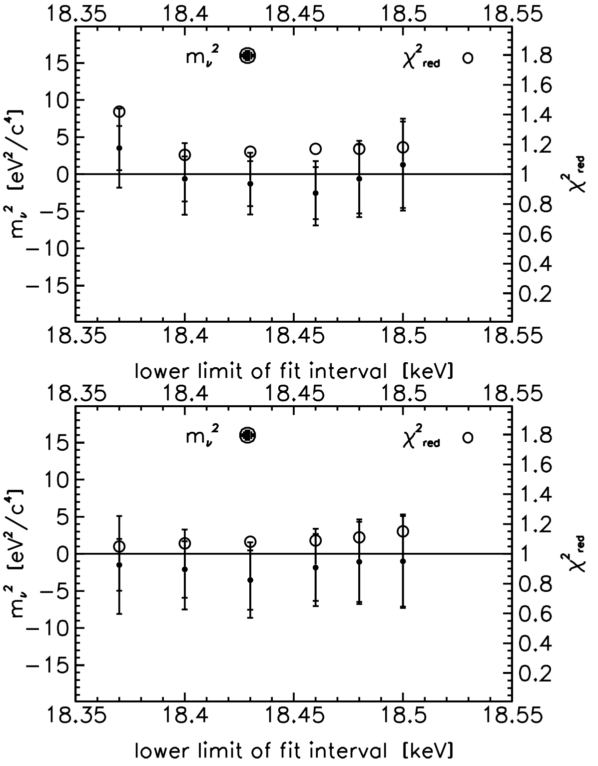

Fig. 3. Fit results on $m^2_{\nu_e}$ (filled circles, left scale) as a function of the lower limit of fit interval for the two different tritium runs of 2001 (the upper bound is fixed at 18.66 keV, well above E_0). The errorbars show the statistical uncertainties (inner bar) and the total uncertainties (outer bar). The corresponding values for the χ^2_{red}=$\chi^2/d.o.f.$ (open circles) is given on the right scale

Especially all parts which need refreshment from time to time were replaced, in particular: The graphite substrate of the tritium source, the oil for the high voltage divider. Additionally the non-evaporable getter pumps were reactivated by baking of all vacuum systems. All these measures led to the most stable operation ever had. The background rate was about 12 mHz during the whole 2001 period (2 months) without the necessity of high voltage conditioning during the run. The results of fitting $m^2_{\nu_e}$ to the 2001 data as a function of the lower limit of fit interval are shown in Fig. 3. Within the errorbars all values are fully compatible with each other and with the physically allowed range $m^2_{\nu_e} \geq 0$. To extract an upper limit on the neutrino mass the interval which leads to the smallest combined statistical and systematical uncertainty (last 70 eV below endpoint) was chosen, giving:

$$m^2_{\nu_e}c^4 = +0.2 \pm 4.2_{stat} \pm 2.0_{sys}\ \mathrm{eV}^2 \quad \chi^2/d.o.f. = 83/73 \tag{2}$$

Combining these measurements with the previous measurements from 98/99 [5] one gets:

$$m^2_{\nu_e}c^4 = -1.2 \pm 2.2_{stat} \pm 2.1_{sys}\ \mathrm{eV}^2 \quad \chi^2/d.o.f. = 208/195 \tag{3}$$

which is compatible with a zero neutrino mass. This value corresponds to an upper limit on the electron neutrino mass of:

$$m_{\nu_e} c^2 \leq 2.2 \text{ eV} \qquad (95\% \ C.L., \ unif. \ appr.) \qquad (4)$$

The limit on m_ν for 98/99 is the same, but it is slightly pushed down by the negative mean value.

3 Refined analysis

Up to now data were analyzed in the standard way [6]. There the contribution of the final state spectrum of the daughter molecule $(^3\text{HeT})^+$ certainly were based on a number of stringent numerical calculations [7]. In addition W. Kolos [8] has estimated that in a_{nex} = 5.9% of T_2 decays within a solid closely packed T_2 crystal a neighbor molecule is promptly excited at a mean energy of ϵ = 14.6 eV as a consequence of the local lattice relaxation. In our standard analysis we have reduced a_{nex} to 4.6% considering the apparent 20% porosity of the quench condensed film and the measured differences between electron energy losses in condensed T_2 compared to the ones in gaseous T_2 [9]. Furthermore, we have increased ϵ to 16.1 eV according to the same differences. We have let both changes fully enter the systematic uncertainty. The energy loss spectrum and the mean free path λ of the β particles within the source are taken from a separate experiment [9]. By now, however, the statistic over the full data set in the full measuring interval (170 eV) is high enough as to allow a_{nex} to be an additional fit parameter. Figure 4a shows its correlation to $m^2_{\nu_e}$ in a contour plot centered at a_{nex} = (5.0 ± 1.6)% and $m^2_{\nu_e}$ = (0 ± 3) eV^2/c^4, the former being in good agreement with the formerly used value. If we now vary the input value of λ in the fit within its experimental uncertainty [9] λ = (124 ± 7) nm, than the fit result of a_{nex} varies accordingly by ±2.2% (Fig. 4b) in order to keep the total energy loss constant, whereas the fit value of $m^2_{\nu_e}$ is barely affected by this interchange. We can now use this empirical value a_{nex} = (5.0 ± 2.7)% instead of the theoretical estimate as an input parameter again to fit the optimal 70 eV interval and get a refined and slightly towards zero shifted result for $m^2_{\nu_e}$:

$$m^2_{\nu_e} c^4 = -0.7 \pm 2.2_{stat} \pm 2.1_{sys} \ \text{eV}^2 \chi^2/d.o.f. = 208/194 \qquad (5)$$

This value corresponds to an upper limit on the electron neutrino mass of:

$$m_{\nu_e} c^2 \leq 2.3 \text{ eV} \qquad (95\% \ C.L., \ unif. \ appr.) \qquad (6)$$

Concluding remark

As the Mainz Experiment has almost reached its sensitivity limit it has been shut down and the spectrometer was changed for test experiments in view of KATRIN [10]. Based on the forerunners at Mainz and Troitsk the forthcoming KATRIN experiment aims at 100 times increase $m^2_{\nu_e}$ sensitivity with a 10 times larger MAC-E spectrometer.

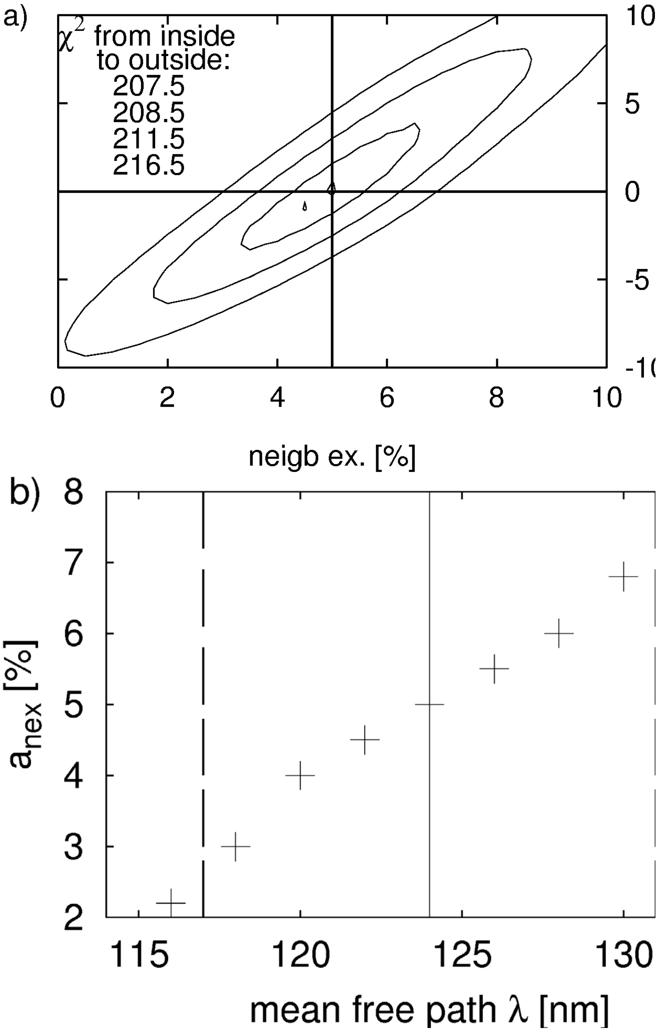

Fig. 4. The upper part of the picture shows the contour plot for fixed λ=124 nm for the parameters $m^2_{\nu_e}$ over a_{nex}. The value of χ^2 rises from the inside to the outside. In the lower plot the correlation of all mean values for a_{nex} and λ is shown. The perpendicular lines gives the value for λ and its uncertainty as given by the energy loss measurements

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