Available online at www.sciencedirect.com
SCIENCE DIRECT
International Journal of Mass Spectrometry 251 (2006) 173–178
International Journal of Mass Spectrometry
www.elsevier.com/locate/ijms

The Q-value of tritium β-decay and the neutrino mass

E.W. Otten [a,*], J. Bonn [a], Ch. Weinheimer [b]

[a] *Institut für Physik, Johannes Gutenberg Universität Mainz, D-55099 Mainz, Germany*
[b] *Institut für Kernphysik, Westfälische Wilhelms-Universität, D-48149 Münster, Germany*

Received 12 October 2005; received in revised form 10 January 2006; accepted 19 January 2006

Abstract

The paper discusses the influence of β-endpoint energies and related atomic mass values on the determination of the neutrino mass in present and future β-decay experiments with particular emphasis on the case of tritium decay

PACS: 32.10.Bi, 23.40.-s, 14.60.Pq

Keywords: Atomic masses; Beta decay; Neutrino masses

1. Introduction

The fundamental discovery of neutrino flavour oscillation, which is very likely the result of strong mixing and small mass differences between the three neutrino generations ν_1, ν_2 and ν_3,[1] has re-stimulated the interest in the absolute scale of neutrino masses which is left open in interference experiments. The wave numbers of oscillations are proportional to the differences of the squared masses $\Delta m_{ij}^2 = |m^2(\nu_i) - m^2(\nu_j)|$, of which two have been determined to be $\Delta m_{12}^2 = 7.92(1 \pm 0.09) \times 10^{-5}\,\mathrm{eV}^2/c^4$ and $\Delta m_{23}^2 = 2.4(1^{+0.21}_{-0.26}) \times 10^{-3}\,\mathrm{eV}^2/c^4$, respectively [1]. Hence, the absolute mass scale could range from a hierarchical ordering with m_1^2 or m_3^2 being much smaller than either of the measured Δm_{ij}^2 values to a quasi-degenerate situation where these differences are sitting on a much higher pedestal $m^2 \gg \Delta m_{ij}^2$. Assuming the former case, either m_1 and m_2 or m_3 would be the heavier ones reaching a mass of about $(\Delta m_{23}^2)^{1/2} \cong 0.05\,\mathrm{eV}/c^2$. An experimental hint towards a degenerate solution, however, came recently from a reanalysis [2,3] of earlier data and from new data of the Heidelberg Moscow experiment on neutrinoless double β-decay of ^{76}Ge. If due to virtual emission and reabsorption of Majorana neutrinos the observed rate would correspond to a so-called effective neutrino mass

$$m_{\mathrm{ee}} = \left| \sum_j m(\nu_j) |\tilde{U}_{\mathrm{e}j}|^2 \,\mathrm{e}^{i\Phi_j} \right| . \tag{1}$$

in the limits $0.1\,\mathrm{eV} \le m_{\mathrm{ee}}\ c^2 \le 0.9\,\mathrm{eV}$ [3]. The Φ_j are phase factors of the mixing matrix $\tilde{U}_{\mathrm{e}j}$ which connects the mass eigenstates ν_1, ν_2 and ν_3, to the flavour eigenstates ν_e, ν_μ and ν_τ; the latter transform by the charged current weak interaction into electron, muon or tau, respectively. Combined analyses of recent surveys of the cosmic microwave background and of the present granulation of clusters of galaxies yield mass limits of a few tenth of an eV/c^2 for the relic neutrinos left over from the big bang [4,5]. Another analysis quotes a finite value of about $0.2\,\mathrm{eV}/c^2$ [6]. The most sensitive direct measurements of the neutrino mass stem from the investigation of the β-spectrum of tritium decay near its endpoint at 18.6 keV. The latest generation of these experiments was performed at Mainz [7] and Troitsk [8] using electrostatic filters which played the trick of magnetic adiabatic collimation of the β-particles (MAC-E-filter). Thereby they could accept the major part of the forward emitted particles with a filter width of a few eV only. Both experiments have yielded upper limits of $m(\nu_\mathrm{e}) \le 2.3\,\mathrm{eV}/c^2$ at which point they have reached the limit of their sensitivity. These limits have been derived from measured squared

* Corresponding author.
E-mail address: ernst.otten@uni-mainz.de (E.W. Otten).

[1] The observed spectral distortions of atmospheric [24] and reactor [25] neutrino spectra clearly disfavour other explanations (neutrino decay [26] and neutrino decoherence [27]) than neutrino oscillation due to neutrino mass splittings. Furthermore, this statement is supported by the confirmation of the parameters of the matter-affected neutrino oscillation of solar neutrinos through the vacuum oscillation parameters of reactor neutrinos [25].

1387-3806/$ – see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.ijms.2006.01.035

mass values $m^2(\nu_e) = (-0.6 \pm 2.2_{stat} \pm 2.1_{syst})\,eV^2/c^4$ [9] and $m^2(\nu_e) = (-2.3 \pm 2.5_{stat} \pm 2.0_{syst})\,eV^2/c^4$ [10]. (The latter contains a correction for a so far unexplained step like anomaly in the spectrum close to the endpoint.)

In this situation one obviously asks for a new experiment with the capability to push the upper limit of the neutrino mass

(i) below the $1\,eV/c^2$ limit;
(ii) preferably to a $0.2\,eV/c^2$ limit in order to match the recent and forthcoming results from neutrinoless double β-decay and cosmology;
(iii) ideally to a $0.05\,eV/c^2$ limit in order to reach the scale set by neutrino oscillations.

Is any of these steps realistic and which way?

1) By rigorously scaling up the MAC-E-filter method?
2) By choosing a different decay?
3) Or can we hope for a breakthrough by a radically different experimental approach?

In this paper, we like to take a look at these problems and – in order to meet the theme of this Festschrift – we will pay special attention to the impact of improved values of atomic masses involved in the decay.[2]

2. Different looks at tritium β-decay

Quite naturally, the most ambitious goal (iii) pushes itself into the foreground of attention. If atomic masses got to play a role here, then it seems that a so far unequalled precision of $\Delta m{\cdot}c^2 \approx 50\,meV$ should be achieved. The most precise direct determination of the $T - {}^3He$ mass difference has yielded the value $(18590.1 \pm 1.7)\,eV/c^2$ corresponding to a relative uncertainty of about 6×10^{-10} with respect to the total mass of about $2.8\,GeV/c^2$ [13]. But this measurement in a penning trap dates 13 years back already. The relative precision achieved so far in this type of experiments ranges around 10^{-10} (see, e.g., [14]). A further improvement by one order of magnitude seems not to be an unrealistic challenge for a next generation experiment and is discussed in the community. For example, we quote here a particular proposal [15] which involves a tandem of Penning traps each loaded with a single T- or ^{3}He-ion, cooled down resistively to cryogenic temperatures. The mass difference will be determined from the integrated phase difference of their cyclotron orbits measured non-destructively in interchanged positions.

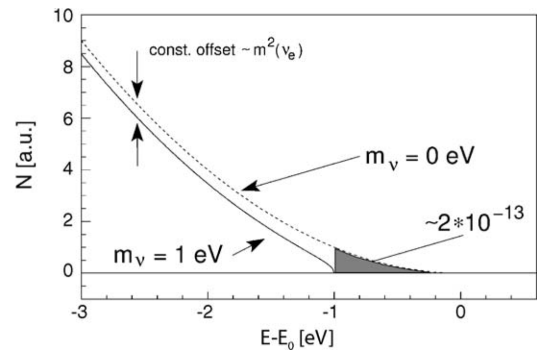

Fig. 1. Expanded tritium β-spectrum around its endpoint E_0 for $m(\nu_e) = 0$ (dashed line) and for an arbitrarily chosen neutrino mass of $1\,eV/c^2$ (solid line). The grey shaded area corresponds to a fraction of 2×10^{-13} of all tritium β-decays for $(E - E_0) \geq 1\,eV$ and decreases with third power of $E - E_0$. The difference between the two curves is proportional to our observable $m^2(\nu_e)$; this is the sum of the squared mass eigenvalues m_j^2 weighted with the probabilities $|\tilde{U}_{ej}|^2$ occurring in β-decay.

Once backed by the input parameter of a such a precise Q-value of tritium β-decay one could naively ask for a β-spectrometer of 50 meV total (that is $\approx 2 \times 10^{-6}$ relative) precision and simply look whether the spectrum approaches the endpoint so closely or not. However, the β-spectrum vanishes quadratically towards the endpoint such that only 4 out of 10^{17} tritium decays would fall into this last 50 meV interval (for $m(\nu_e) = 0$; see Fig. 1). Obviously, this fact forces one to give a second thought to this kind of experiment which we will do below in the course of discussing the forthcoming KATRIN-experiment [16].

Let us first try to escape this complication and consider to measure the decay kinematics with a 50 meV precision somewhere else in the spectrum where the differential decay rate dN/dE looks more favourable, for instance at its peak around 4 keV in T-decay. Analyzing the situation shows that the necessary reconstruction of the neutrino momentum requires a measurement of the momenta of the β-particle and of the recoiling nucleus to a precision which is unrealistic. The situation becomes clearer at the opposite end of the spectrum where the β-particle is not emitted at all but bound to the daughter nucleus ^{3}He in some s-orbit. This occurs with a probability of the order of 1%. Then the neutrino carries away almost all of the decay energy and transfers a corresponding recoil momentum of about $18590\,eV/c$ to the daughter atom. Let us assume that we measure this momentum with the same precision as the Q-value, i.e., $\Delta p_\nu \approx 50\,meV/c$ by a time of flight measurement on the daughter atom.[3] Then, we could determine the missing rest mass of

[2] In this context, we recall two recent contributions of precision mass measurements to fundamental problems in weak interactions: (a) the redetermination of the ${}^{76}Ge - {}^{76}Se$ mass difference [11] was a cornerstone in fixing the exact position of the narrow (2β, 0ν)-line searched for in ^{76}Ge-decay [2,3]; (b) the precise determination of the Cabbibo angle (and hence a check of the unitarity of the Cabbibo–Kobayashi–Maskawa-matrix) from the chain of superallowed Fermi-transitions requires first of all the input of precise Q-values. The heaviest nucleus involved so far in this systematics is the self-conjugate ^{74}Rb; the Q-value of β-decay has been recently determined by absolute mass measurement [12].

[3] For a flight path of $x = 10\,m$ this demand would limit the extension of the source to $\Delta x \approx 30\,\mu m$. Hence, the product of uncertainties would have to be as small as $\Delta x{\cdot}\Delta p \approx 30\,\mu m{\cdot}50\,meV/c \approx 4h/\pi$, which can be reached but in a Bose–Einstein condensate of the tritium atoms. The time of flight would be 5 ms requiring a time resolution of about 10^{-8} s. The start signal could come, e.g., from a fluorescence photon following prompt laser excitation from the metastable ${}^3S_1$-state of the ^{3}He-daughter, the stop signal from an Auger-electron emitted from a multiplier cathode upon the impact of the metastable atom. The fight for signal rate would be very hard. All together, a tremendous effort would be required to turn this idea from a Gedanken—to a real experiment.

the neutrino from Einstein's relation

$$m^2 = \frac{E^2}{c^4} - \frac{p^2}{c^2}. \tag{2}$$

Inserting the above numbers and calculating the resulting mass uncertainty, however, will disillusion us:

$$\Delta m^2(\nu_e) = \frac{2E_\nu\,\Delta E_\nu}{c^4} + \frac{2p_\nu\,\Delta p_\nu}{c^2} \approx \frac{4E_\nu\,\Delta E_\nu}{c^4} \approx \frac{4000\,\mathrm{eV}^2}{c^4} \tag{3}$$

It misses the present limit by as much as 3 orders of magnitude for the simple reason that in relativistic kinematics this uncertainty scales with the energy of the particle, and that is maximal in the envisaged p_ν-measurement. Hence, it would serve but for an alternative measurement of the Q-value.

Since a relativistic particle is hiding away its restmass through (3) we are pushed back to square 1 in any search for a kinematical neutrino mass, i.e., to β-spectroscopy near the endpoint at small neutrino energy. Hence, we have to face inevitably the handicap of small decay rates fading out with the phase space of the neutrino $E_\nu \cdot p_\nu$ which governs the β-spectrum

$$\frac{\mathrm{d}N}{\mathrm{d}E_\mathrm{k}} \propto p(E_\mathrm{k} + mc^2) \times \sum_{i,j} P_i |\tilde{U}_{\mathrm{e}j}|^2 (E_0 - V_i - E_\mathrm{k}) \sqrt{(E_0 - V_i - E_\mathrm{k})^2 - m^2(\nu_j)c^4} \tag{4}$$

near its endpoint E_0. Here p, E_k, m are the momentum, kinetic energy, and mass of the β-particle, and P_i and V_i are the probability and excitation energy of final states of the daughter, respectively. The two last terms represent the neutrino phase space.

For molecular tritium T_2, onto which we will focus the further discussion, one calculates from the atomic masses given in Ref. [13] an endpoint energy of $E_0 = 18571.9 \pm 1.7$ eV, which is in good agreement with a direct measurement from tritium β-decay yielding $E_0 = 18572.6 \pm 3.0$ eV [17] (including the corrections for the polarisation shift in the T_2 film and electrical potentials of the Mainz experiment). The excitation spectrum of the daughter, the molecular ion $(^3\mathrm{HeT})^+$, is shown in Fig. 2 [9,18]. The first group concerns rotational and vibrational excitation of the daughter in its electronic ground state; it comprises a fraction of $P_\mathrm{g} = 57.4\%$ of the total rate. Its mean excitation energy is 1.73 eV for a β-energy close to the endpoint. The same amount of recoil energy goes into the centre of mass motion of the molecule and is considered already in the E_0 value given above. After this first so-called elastic group we observe an important gap in the spectrum up to the first excited electronic state of $(^3\mathrm{HeT})^+$ at 24 eV, followed by further resonances in the continuum. The external energy loss on other T_2-molecules in the source starts already at 10 eV. Still the short interval below the endpoint which is most sensitive to $m^2(\nu_e)$ is dominated by the elastic component of the spectrum. That is fortunate with respect to systematic uncertainties of the result (see the extensive discussion in [9,16]).

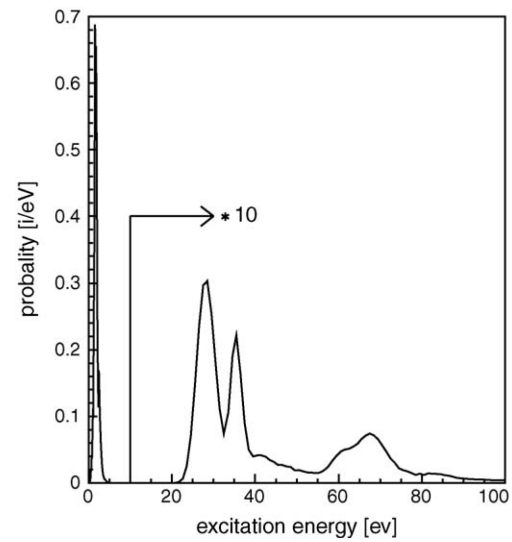

Fig. 2. Excitation spectrum of the daughter $(^3\mathrm{HeT})^+$ in β-decay of molecular tritium [9,18].

The enormous background from the useless β-particles at lower energies is rejected most safely by an electrostatic filter which is passed only by those with $E_\mathrm{k} \geq eU$, where U is the potential difference between the source and the filter and e is the elementary charge. Their integral is the signal S which may sit on top of a (constant) background b. Keeping only the elastic component and treating the two first terms in (4) as constants we obtain for the observed count rate on some detector downstream of the (sharp) filter the approximate rate

$$R(U) = S(U) + b = \int_{E_\mathrm{k} \geq eU} \frac{\mathrm{d}N}{\mathrm{d}E_\mathrm{k}}\,\mathrm{d}E_\mathrm{k} + b \cong C_R \sum_j |\tilde{U}_{\mathrm{e}j}|^2 ((E_0 - eU)^2 - m^2(\nu_j)c^4)^{3/2} + b \tag{5}$$

where C_R is a specific rate constant given by the parameters of the experiment. Under practical conditions the signal rate S integrated over the measurement time t separates from the background noise $(bt)^{1/2}$ only at distances $E_0 - eU$ considerably larger than the sensitivity limit on the mass. Therefore, we may develop (5) to first order

$$R(U) = C_R \left((E_0 - eU)^3 - \frac{3}{2}(E_0 - eU) \sum_j |\tilde{U}_{\mathrm{e}j}|^2 m^2(\nu_j)c^4 \right) + b. \tag{6}$$

Besides the leading cubic term this approximate integral spectrum displays a product of the width of the measured spectral interval $(E_0 - eU)$ and a weighted squared mass

$$m^2(\nu_e) = \sum_j |\tilde{U}_{\mathrm{e}j}|^2 m^2(\nu_j), \tag{7}$$

which is our observable (see also [19]). Hence, we call the square root of (7) the electron antineutrino mass $m(\nu_e)$.

The statistical noise $N^{1/2}$ on the number of counts $N=(S+b)t$ after a measuring time t will be dominated near E_0 by the background and further below by the cubic term in (6). The noise of the latter rises like $(E_0-eU)^{3/2}$ and hence faster than the mass dependent signal, namely the second term in (6) which increases in proportion with the distance from E_0. In between there must be a point with optimal sensitivity on $m^2(\nu_e)$; it is found at

$$S(U)=2b \tag{8}$$

i.e., the closer to the endpoint the smaller the background is. On the other hand, at a particular point of measurement U an endpoint uncertainty ΔE_0 will correlate with a mass uncertainty $\Delta m^2(\nu_e)$ through (6) as

$$\Delta m^2(\nu_e)=\frac{\partial R/\partial E_0}{\partial R/\partial m^2(\nu_e)}\,\Delta E_0=\frac{2(E_0-eU)\,\Delta E_0}{c^4}. \tag{9}$$

Hence, it rises in proportion with the distance from the endpoint as we have learned already from the general relation (3).

3. Uncertainties of E_0 and $m^2(\nu_e)$ in recent and forthcoming experiments

The important analytical results (8) and (9) govern also numerical calculations of sensitivity and uncertainties on measured [9] and simulated spectra [16] and hence will be in the foreground of our further discussion. In [9] the mass sensitivity was found to peak according to (8) about 15 eV below E_0 (see Fig. 3). This value may be inserted into (9) as the characteristic one for estimating the mass-endpoint correlation of this particular data set. Using the endpoint from [11] as input parameter for the data analysis would have introduced an external uncertainty of at least $\Delta E_0=1.7$ eV resulting through (9) in a systematic mass uncertainty of $\Delta m^2(\nu_e)\approx 50\,\mathrm{eV}^2/c^4$. This is 25 times higher than the one quoted in [9], which was determined from a joint fit of $m^2(\nu_e)$, E_0, b and C_R from a spectral interval including data down to 70 eV below E_0. The joint fit is sensitive only to the much more easily measured small voltage differences within this interval rather than to the absolute energy scale.

Moreover, we learn from (9) that a joint fit of the endpoint should include also data obtained at somewhat larger distances from E_0, since its uncertainty ΔE_0 decorrelates from $\Delta m^2(\nu_e)$ like 1/2 (E_0-eU). Altogether, there are in principle three spectral regions from which the basic parameters $m^2(\nu_e)$, E_0 and b are fitted most sensitively and with a minimum of correlations:

- a region beyond E_0 fixing b,
- a region just below E_0 fixing $m^2(\nu_e)$,
- a region further below E_0 fixing E_0.

In the latter region, however, the inelastic components of the spectrum and their uncertainties start to matter, in particular the energy loss in a thick source, which finally dominates the systematic error. Hence, there exists an optimal length of the measuring interval at which one meets a proper balance between the systematic and statistical uncertainties of the result.

However, if an external endpoint with an uncertainty as small as 50 meV could have been inserted in the data analysis of [9], it would have contributed to $\Delta m^2(\nu_e)$ through (9) by only $1.5\,\mathrm{eV}^2/c^4$. In addition the measurements could have been restricted to a still shorter spectral interval, and statistical accuracy in the most sensitive region could have been gained. Honestly speaking, one has to admit that the uncertainty of the absolute filter potential ranged rather at the order of 1 eV in this experiment (compare [20]) such that it would not have profited from an improved Q-value.

How will matters change at the KArlsruhe TRItium Neutrino experiment KATRIN currently being setup at the Forschungszentrum Karlsruhe/Germany? In short KATRIN will be modelled after the Mainz/Troitsk-design with linear dimensions increased by a factor of 10, thereby gaining a factor of 100 in signal at hopefully the same or even diminished background [16] (see Fig. 4). As calculated from (6) and (8) the highest mass sensitivity would then be reached already at 3 eV (instead of 15 eV [9]) below E_0 or still closer to it. Accordingly an uncertainty of 50 meV of E_0 as external input parameter would cause through (9) a correlated uncertainty of still

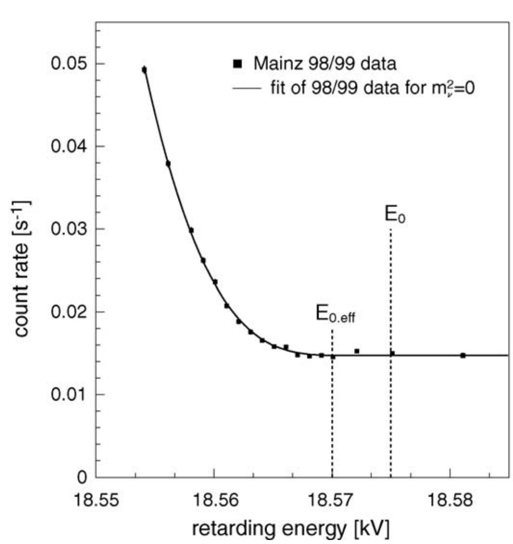

Fig. 3. Averaged count rate of the Mainz 98/99 data (filled squares) with fit for $m(\nu_e)=0$ (line) plotted as function of the retarding potential near the endpoint E_0 [9]. The effective endpoint $E_{0,\mathrm{eff}}$ considers the mean rotation–vibration excitation of the $(^3\mathrm{HeT})^+$ daughter ion and the width of the spectrometer transmission function.

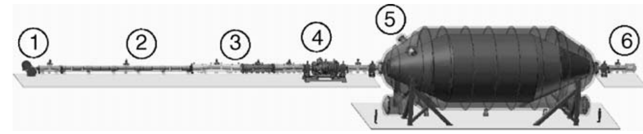

Fig. 4. Schematic view of the KATRIN-experiment with the rear monitoring and calibration system (1), the windowless gaseous tritium source (2), the differential and cryopumping electron transport section (3), the pre-spectrometer (4), the main spectrometer (5) and the electron detector array (6). The main spectrometer has a length of ∼23 m and a diameter of ∼10 m, the overall length over the experimental setup amounts to ∼70 m.

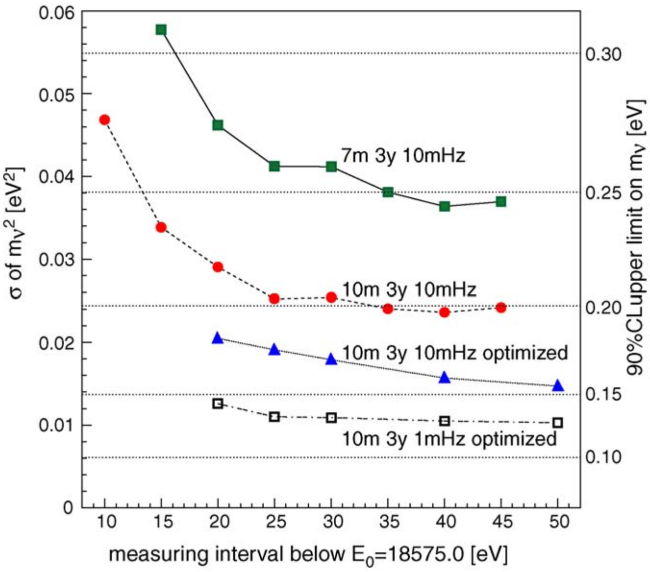

Fig. 5. Statistical uncertainties (3 years measurement time) of the observable $m^2(\nu_e)$ and corresponding 90% C.L. upper limit on $m(\nu_e)$ as a function of the analyzed interval for different configurations and background rates: standard KATRIN setup with a 10 m diameter spectrometer and with uniform (circles) and optimized (triangles) spectral distribution of measurement times. This latter is also shown for the case of a background rate reduced to 10^{-3}/s (open squares).

$\Delta m^2(\nu_e) = 0.3\,\mathrm{eV}^2/c^4$. KATRIN, however, aims at a statistical uncertainty of $\Delta m^2(\nu_e)$ in the range of $0.02\,\mathrm{eV}^2/c^4$ after 3 years of measurement, i.e., in 2012 at the earliest (see Fig. 5). Its slight down sloping for longer data intervals stems from a better fixing of E_0 in a joint fit which reduces the correlated $\Delta m^2(\nu_e)$ as discussed above. But for data intervals larger than about 30 eV systematic uncertainties from energy losses are expected to prevail. Altogether KATRIN aims at goal (ii), namely a mass sensitivity of $m(\nu_e) \approx 0.2\,\mathrm{eV}/c^2$.

We see that for an external Q-value to play a competitive role as external input parameter, still one more order of magnitude in precision seems to be necessary. This estimation from (9) can be also obtained by Monte Carlo calculations simulating the KATRIN-experiment (see Fig. 6). The 2σ uncertainty of $m^2(\nu_e)$

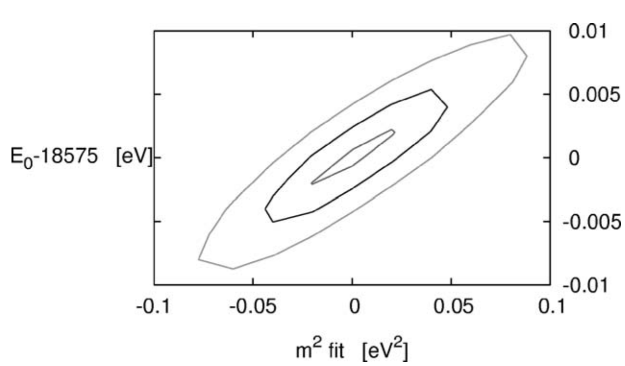

Fig. 6. χ^2 contour plot to illustrate the correlation between the fitted endpoint E_0 and the fitted neutrino mass squared $m^2(\nu_e)/c^4$ from Monte Carlo simulations with conditions similar to the KATRIN-experiment [16] for a measurement interval of 25 eV below the endpoint and uniform spectral distribution of measurement times (compare to the circles in Fig. 5). The ellipses correspond to 1σ, 2σ and 3σ contours.

amounts to about $\pm 0.05\,\mathrm{eV}^2/c^4$ when the endpoint is not known and corresponds to an endpoint uncertainty of $\Delta E_0 = \pm 5$ meV. The ellipses of Fig. 6 show clearly that only when the endpoint is known better than this 5 meV would a sensitivity gain on the neutrino mass be possible. From Fig. 6 one can also read, that with infinite precision of the endpoint energy the uncertainty on the neutrino mass squared could be reduced by almost a factor 2 under the given conditions.

But these statements are rather academic. In practise it would be a tremendous success and help if the E_0 value determined from a joint fit of KATRIN-data would match an independent value from mass spectrometry already at the 50 meV level, because, first of all, the art of metrology can live and develop only on a network of interlinked data. Moreover, a precise external E_0 value would check unambiguously that the electric potentials within the gaseous source and the huge analyzing filter of KATRIN are under sufficient control. Simulations have shown, indeed, that any unidentified drift or scatter of the absolute potential difference U during the full measuring period should not exceed rms values $\sqrt{\langle (U - \langle U \rangle)^2 \rangle}$ in the range of 50–100 mV [16]. This can be seen also directly from another approximate analytical correlation formula

$$\Delta m^2(\nu_e) = -\frac{2e^2 \langle (U - \langle U \rangle)^2 \rangle}{c^4} \tag{10}$$

derived in [21]. Thirdly a precisely known Q-value could help to check the possible influence of other, non-standard model physics modifying the tritium β-spectrum near its endpoint, e.g., right-handed currents. For achieving that level of accuracy and reliability extensive and sophisticated control and calibration mechanisms are performed at KATRIN [16].

Finally one can discuss investigating an alternative β-decay to determine the neutrino mass, e.g., the case of ^{187}Re. Its endpoint is ∼2.5 keV, an order of magnitude below the one of tritium. This allows to relax the demand on the relative accuracy and resolution of the spectrometer accordingly. One can turn this source into a highly resolving cryogenic detector which is insensitive to uncertainties in the final state distribution of the spectrum, presuming that all of the decay energy is transformed into heat. A pilot experiment has reached a mass limit $m(\nu_e) \leq 15\,\mathrm{eV}/c^2$. There is hope for substantial improvement, but not for breaking the $1\,\mathrm{eV}/c^2$ limit by the foreseeable progress of that technology in the near future [22,23]. In our context of discussing the possible input from an external Q-value, determined by mass spectrometry, the Re-case is an unfavourable example, however. Because this heavy nucleus would require raising the relative precision of the mass determination for the Q-value by two more orders of magnitude in order to cope with the tritium case.

We summarize the perspectives in direct, absolute neutrino mass measurement as follows:

- The most ambitious goal (iii) of reaching the mass scale of neutrino oscillations at $50\,\mathrm{meV}/c^2$ seems to be out of reach of next generation experiments.
- Approach (1), namely a scheme for another experiment on tritium β-spectroscopy near the endpoint by a rigorously

scaled-up MAC-E-filter has been worked out by the KATRIN-collaboration [16]; it aims at goal (ii), a sensitivity on the neutrino mass of 0.2 eV/c^2 which is addressed by cosmology and neutrinoless double β-decay.
- We are not aware of any other approach, besides KATRIN, having a realistic chance for a substantial improvement of the present 2.3 eV/c^2 limit, obtained by the KATRIN forerunners at Mainz and Troitsk [9,10].
- The proposed improvement of the $T - {}^3He$ mass difference to a relative precision of 10^{-11} [15] would play an important role in checking systematic uncertainties in the KATRIN-experiment.

Acknowledgement

We would like to thank Jürgen Kluge for many years of exciting and intensive collaboration in various daring experiments and wish him many returns in best personal and scientific circumstances.

References

[1] Reviewed, e.g. in G.L. Fogli, E. Lisi, A. Marrone, and A. Pallazzo, hep-ph/0506083, Prog. Part. Nucl. Phys., submitted for publication.
[2] H.V. Klapdor-Kleingrothaus, A. Dietz, H.L. Harney, L.V. Krivosheina, Mod. Phys. Lett. A 16 (2001) 2409.
[3] H.V. Klapdor-Kleingrothaus, L.V. Krivosheina, A. Dietz, O. Chkvorets, Phys. Lett. B 586 (2004) 198.
[4] S. Hannestad, JCAP 0305 (2003) 004, astro-ph/0303076.
[5] U. Seljak, A. Makarov, P. McDonald, S.F. Anderson, N.A. Bahcall, J. Brinkmann, S. Burles, R. Cen, M. Doi, J.E. Gunn, Z. Ivezic, St. Kent, J. Loveday, R.H. Lupton, J.A. Munn, Robert C. Nichol, Jeremiah P. Ostriker, David J. Schlegel, Donald P. Schneider, M. Tegmark, D.E. Vanden Berk, D.H. Weinberg, D.G. York, Phys. Rev. D71 (2005) 103515.
[6] S.W. Allen, A.C. Fabian, S.L. Fridle (2003), astro-ph/0306386.
[7] A. Picard, H. Backe, H. Barth, J. Bonn, B. Degen, Th. Edling, R. Haid, A. Hermanni, P. Leiderer, Th. Loeken, A. Molz, R.B. Moore, A. Osipowicz, E.W. Otten, M. Przyrembel, M. Steininger, Ch. Weinheimer, Nucl. Instrum. Meth. B 63 (1992) 345.
[8] V.M. Lobashev, P.E. Spivac, Phys. Lett. B 460 (1985) 3305.
[9] Ch. Kraus, B. Bornschein, L. Bornschein, J. Bonn, B. Flatt, A. Kovalik, B. Ostrick, E.W. Otten, J.P. Schall, Th. Thümmler, Ch. Weinheimer, Eur. Phys. J. C 40 (2005) 447.
[10] V.M. Lobashev, in: Proceedings of the 17 International Conference on Nuclear Physics in Astrophysics, Debrecen/Hungary, 2002, Nucl. Phys. A 719 (2003) 153c.
[11] G. Douysset, T. Fritioff, C. Carlberg, I. Bergström, M. Björkhage, Phys. Rev. Lett. 86 (2001) 4259.
[12] A. Kellerbauer, G. Audi, D. Beck, K. Blaum, G. Bollen, B.A. Brown, P. Delahaye, C. Guenaut, F. Herfurth, H.J. Kluge, D. Lunney, S. Schwarz, l. Schweickhard, C. Yazidjan, Phys. Rev. Lett. 93 (2004) 072502.
[13] R.S. Van Dyck Jr., D.L. Farnham, P.B. Schwinberg, Phys. Rev. Lett. 70 (1993) 2888.
[14] T. Fritioff, C. Carlberg, G. Douysset, R. Schuch, I. Bergström, Eur. Phys. J. D 15 (2005) 141, and references therein.
[15] Blaum, K., Mainz, Private communication, 2005.
[16] The KATRIN-Collaboration at Forschungszentrum Karlsruhe (Bonn, Fulda, Karlsruhe, Mainz, Moscow, Münster, Prague, Seattle, Swansea), KATRIN Design Report 2004, Wissenschaftliche Berichte FZK 7090 (2004); NPI ASCR Řež EXP-01/2005; MS-KP-0501.
[17] Ch. Weinheimer, M. Przyrembel, H. Backe, H. Barth, J. Bonn, B. Degen, Th. Edling, H. Fischer, L. Fleischmann, J.U. Grooß, R. Haid, A. Hermanni, G. Kube, P. Leiderer, Th. Loeken, A. Molz, R.B. Moore, E.W. Otten, A. Picard, M. Schrader, M. Steininger, Phys. Lett. B300 (1993) 210.
[18] A. Saenz, S. Jonsell, P. Froehlich, Phys. Rev. Lett. 84 (2000) 242.
[19] Ch. Weinheimer, in: G. Altarelli, K. Winter (Eds.), Springer Tracts in Modern Physics, vol. 190, Springer-Verlag, Berlin, Heidelberg, Germany, 2003, p. 25.
[20] A. Picard, H. Backe, J. Bonn, B. Degen, R. Haid, A. Hermanni, P. Leiderer, A. Osipowicz, E.W. Otten, M. Przyrembel, M. Schrader, M. Steininger, Ch. Weinheimer, Z. Phys. A 342 (1992) 71.
[21] R.G.H. Robertson, D.A. Knapp, Ann. Rev. Nucl. Sci. 38 (1988) 185.
[22] M. Sisti, C. Arnaboldi, C. Brofferio, G. Ceruti, O. Cremonesi, E. Fiorini, A. Giuliani, B. Margesin, L. Martensson, A. Nucciotti, M. Pavan, G. Pessina, S. Pirro, E. Previtali, L. Soma, M. Zen, Nucl. Instrum. Meth. A 520 (2004) 125.
[23] M. Galeazzi, F. Fontanelli, F. Gatti, S. Vitale, Phys. Rev. C 23 (2001) 014302.
[24] Y. Ashie, et al., Super-Kamiokande Collaboration, Phys. Rev. Lett. 93 (2004) 101801.
[25] T. Araki, et al., KamLAND Collaboration, Phys. Rev. Lett. 94 (2005) 081801.
[26] V. Barger, J.G. Learned, S. Pakvasa, T.J. Weiler, Phys. Rev. Lett. 82 (1999) 2640.
[27] E. Lisi, A. Marrone, D. Montanino, Phys. Rev. Lett. 85 (2000) 1166.