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NEUTRINO PHYSICS

Sensitivity and Systematics of KATRIN Experiment*

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Abstract—The KArlsruhe TRItium Neutrino experiment (KATRIN) will measure a "kinematical" electron antineutrino mass upper limit up to 0.2 eV/c^2. The experimental setup based on an electrostatic spectrometer with adiabatic magnetic collimation and windowless gaseous tritium source is briefly described. This sensitivity to the neutrino mass could be reached with a 10-m-diameter spectrometer after three years of data taking. Several major sources of the systematic errors are discussed. *© 2004 MAIK "Nauka/Interperiodica".*

A neutrino oscillation is a well-established fact that implies a nonzero neutrino mass [1]. Oscillation data provide us with a neutrino mass spectral pattern, but not the absolute mass values. It is only possible to deduce that at least one neutrino mass eigenstate is heavier than 0.03 eV/c^2. A "kinematical" experiment based on analysis of kinematics of a weak decay is the only laboratory experiment suitable to provide an absolute neutrino mass value. Particularly, the proposed KATRIN setup will be able to set an electron-antineutrino mass upper limit at the level of 0.2 eV/c^2. Such a study makes sense because there are two neutrino mass schemes: hierarchical and quasidegenerate (Fig. 1). In the hierarchical scheme, the mass eigenstates have a different scale determined by Δm^2_{atm} and Δm^2_{sol} and the heaviest mass is about 0.05 eV/c^2. In the quasidegenerate scheme, all neutrinos have about the same mass, much larger than the mass splitting. The latter scheme is somewhat favored by the observed large mixing angles of different mass eigenstates $\sin\theta_{ij} \approx 1$ [1]. The neutrino mass in the quasidegenerate scheme has a chance to be detected in the tritium experiment (otherwise this scheme will be mostly excluded).

The tritium β decay is a superallowed transition. In the quasidegenerate regime, neutrino mass splitting can be neglected and the electron spectrum is described by the well-known formula

$$dN/dE = KF(Z,E)pE_{\text{tot}} \times (E_0 - E)^2\sqrt{(E_0 - E)^2 - m_\nu^2}. \qquad (1)$$

Almost all of the spectrum data points have $(E_0 - E)^2 \gg m_\nu^2$, and the neutrino mass signature is a negative constant shift of the parabolic spectrum with respect to the background level (Fig. 2):

$$dN/dE \sim (E_0 - E)^2 - m_\nu^2/2. \qquad (2)$$

The absolute value of the statistical error bar is a linear function of the distance from the endpoint $(E_0 - E)$. The sensitivity to nonzero neutrino mass is steadily vanishing far from the spectrum endpoint, as is shown in the inset in Fig. 2.

A real experimental parameter in the tritium-decay experiment is a neutrino mass square [see (1)]. During the last 10–15 years, the experimental sensitivity to neutrino mass square was improved by about two orders of magnitude (Fig. 3). This improvement was achieved by invention of an electrostatic spectrometer with an adiabatic magnetic col-

Table 1. KATRIN parameters

WGTS	Spectrometer	Measurements
Tritium column density 5×10^{17} mol/cm²	Diameter 10 m (effective 9 m)	Three years of data taking
Diameter 90 mm (effective 81 mm)	Resolution $\Delta E = 0.93$ eV	Optimized set of data points
Acceptance angle 51°		
Tritium purity 95%		

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[*] This article was submitted by the author in English.

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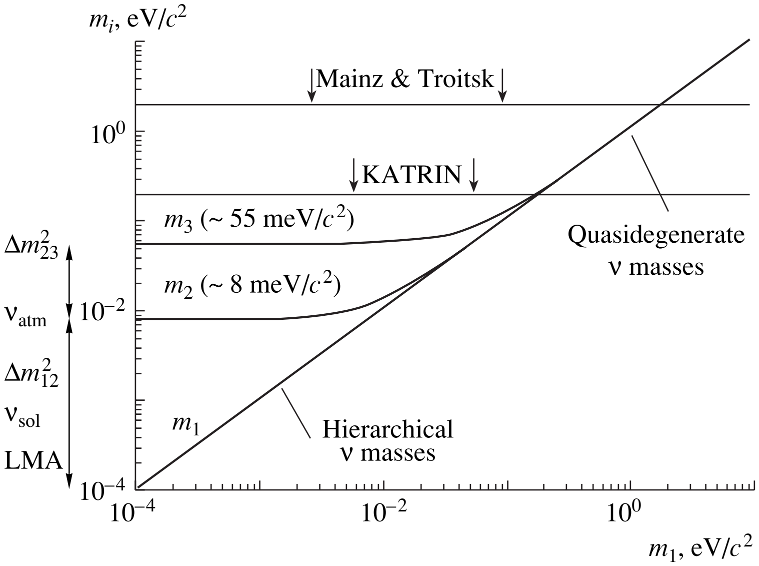

Fig. 1. Neutrino mass scheme. Hierarchical and quasidegenerate parts are shown. The current experimental mass limit [2] and that of KATRIN [3] are shown.

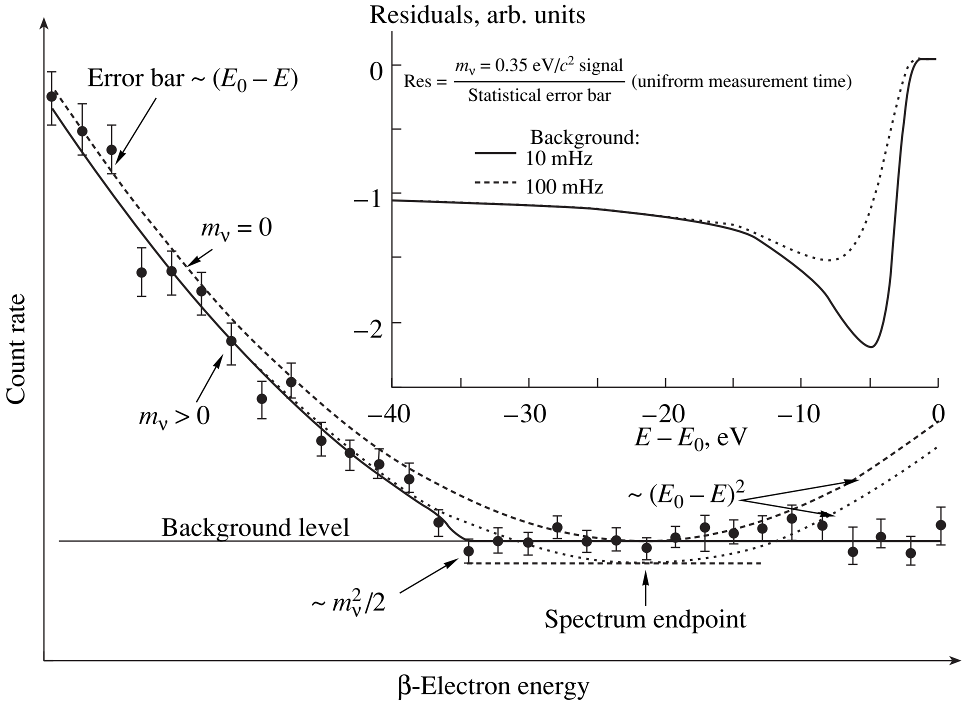

Fig. 2. The exact tritium β-electron energy spectrum and its parabolic approximation. The neutrino mass signature is a shift of the parabolic part of the spectrum. The absolute data error bar increases for high-intensity points. In the inset, the signal-to-error bar ratio is presented for different background levels.

limation (AMC). The AMC allows high-resolution and high-luminosity requirements to be decoupled. This idea was independently developed by several researchers [2]. The AMC is based on conservation (as an adiabatic invariant) of the ratio of transversal kinetic energy to magnetic field strength

$$\mu = E_t/B \qquad (3)$$

for a charged particle moving through the magnetic field. For the conservation of the adiabatic invariant, it is only required that, along the trajectory of a

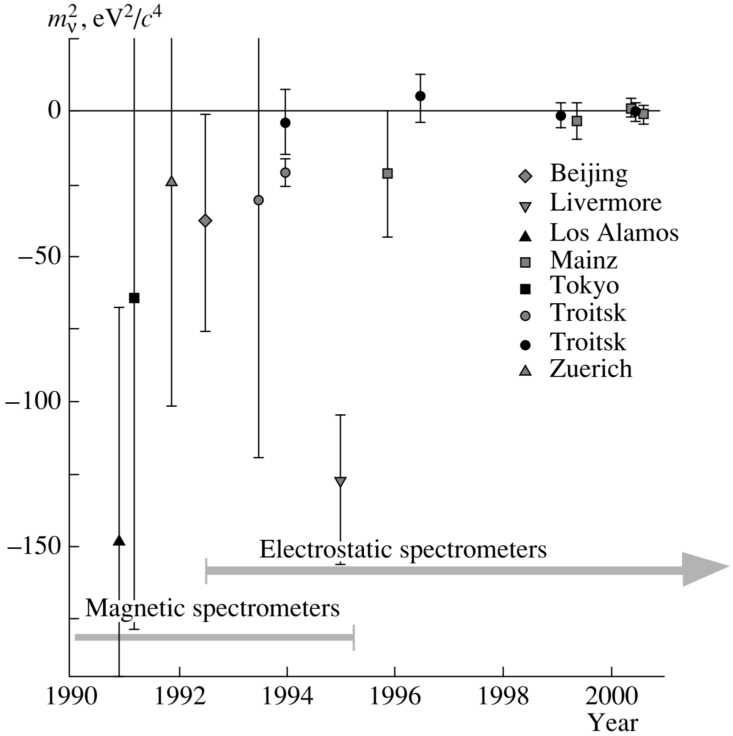

Fig. 3. The electron-antineutrino mass-square measurement summary for the previous decade.

moving particle, the magnetic field variation should be small on the time scale of one gyration. The idea of the AMS is that a tritium β decay takes place in a strong magnetic field within a large solid angle (Fig. 4). When electrons are transported to the low-magnetic-field region, their moments become aligned along the magnetic field due to the conservation of the adiabatic invariant. The aligned electron energy can be analyzed with an electrostatic spectrometer. To define the tritium decay solid angle, electrons should pass the region with magnetic field $B_{\max}$ somewhat stronger than the one in the decay region. Finally, one obtains an integral spectrometer—a high-pass filter at an electrostatic mirror potential U_0 with a full width resolution:

$$\Delta E = |eU_0|\frac{B_{\text{analys}}}{B_{\max}}. \tag{4}$$

Thus, the spectrometer resolution is only determined by the magnetic field ratio with an acceptance solid angle of the order of 1 sr and an arbitrary source diameter.

The second important invention is a windowless gaseous tritium source (WGTS), first used in the LANL experiment [4] and significantly modified later at Troitsk [5]. The WGTS provides an excellent intensity of β electrons and has high uniformity and well-controlled energy losses.

The KATRIN project united almost all experts in the field with the aim to get ultimate sensitivity to m_ν using an electrostatic spectrometer with AMC and the WGTS. The KATRIN setup is given in Fig. 5. The tritium β decay takes place inside the WGTS, surrounded by differential pumping stations. The outgoing tritium is collected, purified, and reinjected in the center of the WGTS. The decay electrons are guided by the magnetic field through the WGTS and the cryotrapping section toward the pre- and main spectrometer. In order to have a low spectrometer background, the multiple differential pumping stations and cryotrapping sections have to reduce the tritium partial pressure in the spectrometer compared

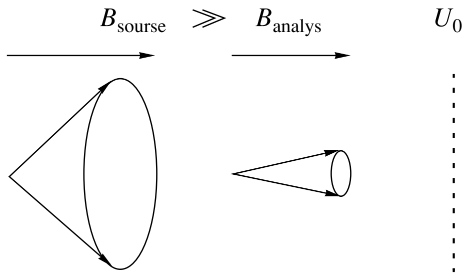

Fig. 4. The operational principle of the electrostatic spectrometer with an adiabatic magnetic collimation. Electron moments are aligned along the guiding magnetic field after transition into the low-field region and are analyzed with electrostatic barrier.

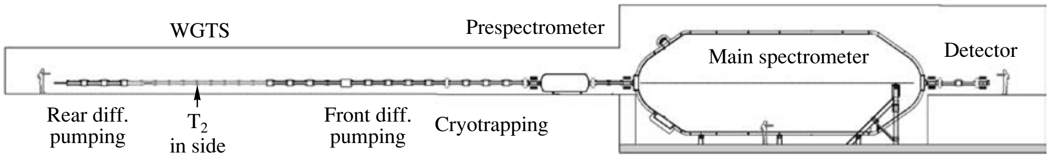

Fig. 5. The KATRIN setup general view. The tritium β decay takes place inside the windowless gaseous tritium source, surrounded by differential pumping stations. Decay electrons are guided by the magnetic field through the cryotrapping section toward the pre- and main spectrometer. After being analyzed by an electrostatic mirror, the decay electrons are recorded by a semiconductor detector.

with the WGTS by a factor of 10^{16}. Inside the pre- and main spectrometers, the decay electron energies are analyzed by the electrostatic mirror formed by a set of electrodes. After being analyzed, the decay electrons are recorded by a segmented semiconductor detector. The total setup length is up to 90 m long. Magnetic field values are 3.6 (WGTS), 6 (maximal field), and 0.0003 T (analyzing plane). The WGTS diameter is 90 mm, the main spectrometer diameter is 10 m, and the spectrometer vacuum is up to 10^{-12} mbar.

To evaluate the statistical sensitivity of the KATRIN setup, one should take into account the fact that several parameters can be further optimized but others are interrelated. The spectrometer resolution and acceptance define the magnetic field ratios and geometry of the vessels. Technical limitations are a maximal diameter of the extrahigh-vacuum spectrometer vessel (10 m) and a maximal field in the superconducting magnets (6 T). For the ultimate accuracy, only the electrons leaving the WGTS without inelastic scattering are useful (see below). The source column density and acceptance angle are selected in such a way that the nonscattering fraction of outgoing decay electrons is near saturation. The spectrometer resolution improvement below 1 eV provides no increase in sensitivity, because the effective resolution is limited by rotovibrational excitation of a recoil molecular ion $(^3\mathrm{HeT})^+$. Finally, a data point distribution was optimized to reach maximal sensitivity. A set of parameters for the sensitivity calculations is presented in Table 1. Assuming $\sigma_{\mathrm{syst}} \approx \sigma_{\mathrm{stat}}$ and a background level of 10 mHz with parameters from Table 1, one obtains the KATRIN neutrino mass upper limit to be 0.2 eV/c^2 (90% C.L.).

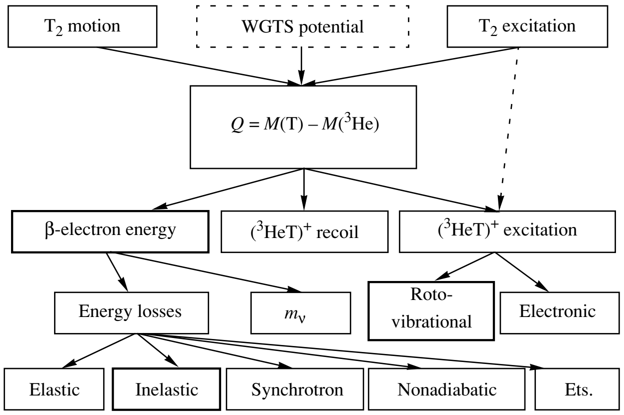

Fig. 6. Energy flow chart. First line—corrections to the released energy. Second line—the nuclear mass difference is the main source of released energy. Other lines—different energy drains.

Considering the KATRIN systematic uncertainties, one should keep in mind that the neutrino mass signature is some drain of part of the β-electron kinetic energy to the neutrino rest mass. All other competing sources of the energy drain can mimic the neutrino mass. A chart of the energy flow is presented in Fig. 6. The main source of released energy is a nuclear mass difference. The released energy is modified by the source molecule motion and excitation. A tiny effect is the influence of mother molecule excitation on the recoil ion excitation spectra shown by the dashed arrow [6, 7]. The space charge potential inside the WGTS decelerates the β electron when it leaves the source. Different energy drains are listed at the lower part of the chart. The most significant are the excitation of the recoil ion $(^3\mathrm{HeT})^+$ and the β-electron inelastic energy losses. All of them modify the endpoint energy E_0 in formulas (1) and (2). It is crucial that one should distinguish two cases of the endpoint modification: endpoint shift and endpoint broadening. In all practical cases, the tritium spectrum analysis keeps the endpoint energy as a free parameter and the endpoint shift is accounted for, leaving no damage. On the contrary, the endpoint broadening results in false m_ν^2 without any other signature. If broadening is described with a Gaussian distribution, the false m_ν^2 is determined by the distribution width [8]:

$$\delta m_\nu^2 = -2\sigma^2. \tag{5}$$

The recoil ion $(^3\mathrm{HeT})^+$ final-state spectrum (FSS) is presented in Fig. 7. No method has yet been proposed to measure the FSS and only theoretical calculations [6, 7] are used to take the FSS into account. To reduce the FSS influence, it is proposed to perform the measurements only in the last 20–25 eV of the tritium-decay spectrum. The rotovibrational

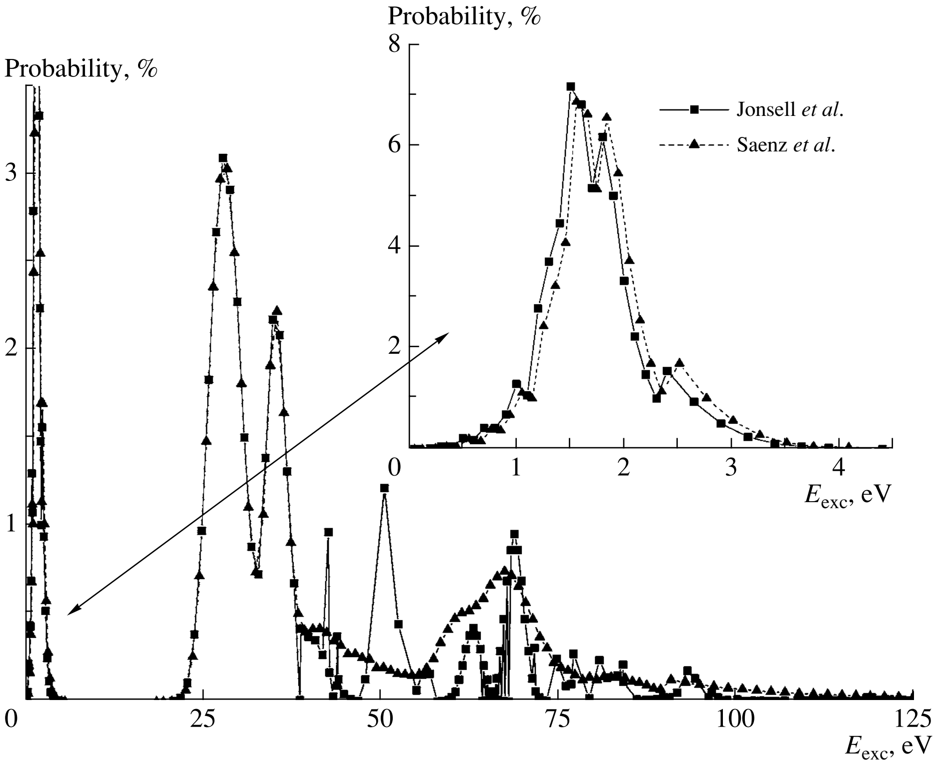

Fig. 7. Molecular ion $(^3\text{HeT})^+$ excitation spectrum calculated by S. Jonsel *et al.* [6] and Saenz *et al.* [7]. In the inset, a rotovibrational part of spectrum is presented.

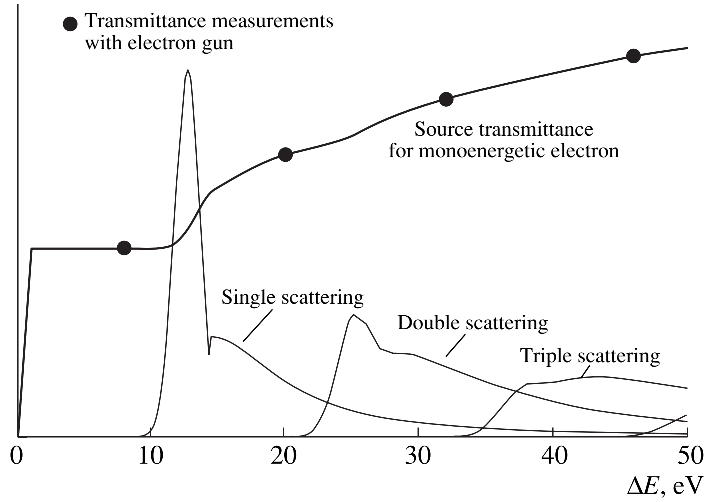

Fig. 8. Monoenergetic electron energy-loss spectra for single, double, and triple scatterings. A gaseous source transmittance function for monoenergetic electrons. Points for transmittance measurements with an electron gun.

part of the FSS cannot be excluded and it should be known very well. The two most sophisticated calculations [6, 7] provide slightly different estimates of the rotovibrational FSS, resulting in m_ν^2 ambiguity of 0.010–0.015 eV^2/c^4.

The β electron undergoes inelastic scattering in the WGTS. When the last 20–25 eV of the tritium-decay spectrum are analyzed, only single and double scattering can be accounted for (Fig. 8). The energy loss spectrum will be measured with a high accuracy with monoenergetic electrons from an electron gun placed at the rear side of the WGTS as in the existing experiments [9]. The relative probability of zero, single, and double scattering is controlled by the source

Table 2. Existing WGTS parameters

Laboratory	Magnetic field, kG	Gas temperature, K	Mean density, 10^{14} mol/cm^{-3}	Storage time, s	Ion–electron pair concentration, 10^6 pair/cm^{-3}
LANL (Los Alamos) [4]	3.1	160	0.19	0.2	0.03
LLNL (Livermore) [11]	6.0	100	1.5	0.5	1.1
INR (Troitsk) [5]	5.6/37.5	30	2.5/1.2	4.9	13/6
KATRIN	36.0	30	5.0	1.3	26

thickness, which should be known with a 0.1% accuracy (including the contribution from the non-tritium hydrogen isotopes). The required source-thickness-measurement accuracy will be achieved using frequent transmittance measurements with the electron gun. Measurements will take place at several points selected in a way to determine the source thickness with a redundancy.

The electric potential inside the WGTS is generated by a positive ion space charge left after the escape of the fast β electrons. The primary space charge value is determined by the decay rate, tritium density, and the mean time of the ion storage. The secondary ionization, electron thermalization, and recombination should be taken into account and turn out to be crucial processes [10]. A simple estimate shows that ions and electrons form a slightly ionized plasma. The comparison of properties of the existing WGTS (Table 2) shows that similar effects were present in all of them. It is expected that ion space charge will be compensated by thermalized electrons ("quasineutrality") with the accuracy limited by the electron temperature: $e(\varphi_{\text{ion}} - \varphi_e) \sim T_e$.

The electron temperature T_e defines both the scale of the potential mean value and its variation in space and time. The LANL group measured a mean WGTS potential with a 17 830-eV intrinsic K-conversion electron line of the ^{83m}Kr γ decay. Krypton was circulated alone and together with the tritium. No line shift was detected: $\Delta(e\varphi) < 0.5$ eV. The Troitsk group measured a mean potential difference for regular WGTS volume and its axial part containing 1/4 of the regular one. A tritium spectrum endpoint shift was evaluated and no difference was found: $\Delta(e\varphi) = 0.1 \pm 0.3$ eV.

The KATRIN specification is much lower and deals with smaller potential variation $\sigma(e\varphi) <$ 75 meV. A special experiment is planned at Troitsk to measure broadening of the ^{83m}Kr 17 830-eV conversion line when ^{83m}Kr is circulated together with T_2 (but at 100 K). A sensitivity to the line broadening at the level of a few hundred meV is expected.

The KATRIN project is now in the R&D phase. The Collaboration is sticking to the schedule to start the first measurements in 2007.

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