LABORATORY NEUTRINO MASS EXPERIMENTS

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ABSTRACT

Current experiments yield convincing evidence for neutrino mass differences $|\Delta m_{\rm i}^2|$ and mixing. The results are discussed in this SSI. The question of the masses themselves, however, is the domain of laboratory neutrino mass experiments. The "mass' of a weak interaction eigenstate, determined by investigating the kinematics of weak decays, is given by $m_{\rm w}^2 = \sum_{\rm i} |U_{\rm wi}|^2 m_{\rm i}^2$ with $m_{\rm i}$ = mass eigenstates and $U_{\rm wi}$ elements of the mixing matrix.
The second approach to the investigation of neutrino masses, neutrinoless double β decay, is sensitive to an effective mass $m_{\rm ee} = |\sum {\rm e}^{i\phi_{\rm i}} U_{\rm ei}^2 \cdot m_{\rm i}|$ with ${\rm e}^{i\phi_{\rm i}}$ = Majorana phases. The mixing matrix elements $U_{\rm ei}^2$ are complex in general, so cancellation can occur and $m_{\rm ee}$ can become zero or close to it even when the mass values $m_{\rm i}$ are non-zero. Therefore this parameter is complementary to $m_{\rm w}^2$ as detected in weak decays.
The main task of laboratory neutrino mass experiments is to fix the mass scale. This is very important information for elementary particle physics and cosmology which is not accessible by other means.

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1 Introduction

The lectures summarized below describe laboratory experiments to gain information on neutrino masses from neutrino sources specific to the experiment. The alternative approach to look for oscillations of neutrinos produced outside the laboratory is covered by other lectures. The access to neutrino masses is provided by a weak decay emitting the neutrino in question.

Limits on the mass of the tau neutrino are derived from tau decays into 5 pions, in order to carry as much energy away as possible and facilitate the determination of the missing mass associated with the unobserved neutrino. Limits on the mass of the muon neutrino are derived from the 2 body decay of the pion into a muon and a muon neutrino. To derive a limit on the neutrino mass the masses of the muon and the pion, as well as the momentum of the muon from pion decay at rest, have to be precisely known. At present the main contribution to the uncertainty in the ν_μ mass stems from the uncertainty in the pion mass. A new experiment to reduce this uncertainty will be presented. Limits on the electron neutrino mass are derived from nuclear β decays. Different approaches will be presented: the investigation of the decay of rhenium with cryogenic detectors, and the investigation of tritium beta decay with dedicated spectrometers.

If neutrinos are identical to their antiparticles (Majorana particles), which is possible for neutral elementary particles, then neutrinoless double β decay is a very sensitive probe for an effective electron neutrino mass. Proposals for new experiments in double β decay and in tritium decay will be presented.

1.1 Present Knowledge of Neutrino Masses

In the Standard Model neutrinos are assumed to be massless. We have however learned in the lectures on solar and especially on atmospheric neutrinos that there is very strong evidence for neutrino oscillations, from which differences in the squared neutrino masses and mixing parameters can be derived. Therefore neutrinos are not massless and the neutrinos observed, directly or indirectly, are combinations of different mass eigenstates. The different mass eigenstates are linked together by the small mass squared differences derived from the oscillation experiments. The lowest bound on a neutrino mass is of special interest as, in combination with the differences in the squared masses, it limits the sum of all masses. The lowest bound for a neutrino mass adopted by the Particle Data Group is the limit on the mass of the electron anti-neutrino from tritium β decay.

1.2 Aims of the Experiments and Implications of Possible Results

The analysis of experimental data in search for a signature of the masses of ν_μ and ν_τ are predominantly motivated by the fact that there is no firm evidence that these neutrinos are stable. In addition, solar and atmospheric neutrino experiments are disappearance experiments and until recently there was no experimental evidence that the neutrinos oscillate into each other and not into some sterile neutrino. Experiments in search for the mass of the electron neutrino are dedicated experiments, the main task of which is to set the mass scale. This can not be achieved by oscillation experiments as a difference in the square of the mass is not experimental evidence for a small mass, as demonstrated in the K $\bar{\text{K}}$ system.

The most direct approach is nuclear β decay. Double β decay is less direct as it asks for nontrivial properties of the neutrino, namely that it is a Majorana particle. In addition the interpretation of a $\beta\beta0\nu$ result would not be straightforward. The aim of the next generation experiments is to reach a sub-eV sensitivity to be able to discriminate between different models for neutrino masses and to contribute to the question of dark matter in the universe. The determination of the contributions of the different mass eigenstates to the electron neutrino weak eigenstate is beyond present-day proposals. The lectures given at the 2000 SLAC Summer Institute, and this contribution, reflect the status of the experiments described. To update their knowledges the readers are referred to the homepages of the experiments:

`http://www.hep.anl.gov/ndk/hypertext/nuindustry.html`

and links therein. For details of the transparencies shown see:

`www.slac.stanford.edu/gen/meeting/ssi/2000/video.html`

2 Limits on the Mass of ν_τ

Experiments to set limits on m_{ν_τ} are special in the sense that the decay involved has an extraordinary signature. To be able to determine the fraction of energy and momentum carried away by the neutrino it is necessary to study decays into 5 pions and a τ

neutrino,

$$\tau \rightarrow 5\pi(+\pi^0) + \nu_\tau, \qquad \mathrm{BR} = 10^{-3}. \tag{1}$$

This mode is essentially free of background and the information on m_{ν_τ} can be derived from only a few events. Each event can be fully reconstructed and the neutrino mass can be calculated by using the invariant mass of the 'visible' 5(6) π's:

$$M_{5\pi}^2 = \left(\sum E_{\mathrm{i}}, \sum \vec{p}_{\mathrm{i}}\right)^2 \tag{2}$$

The drawback is that the accuracy achievable is rather poor due to low statistics and a still very high energy available. The present best limit, from ALEPH,[1] is $m_{\nu_\tau} \leq 18.2$ MeV/c^2. The ultimate limits attainable at BaBar and BELLE are expected to be about 3 MeV/c^2.

3 High Precision Measurement of the Pion Mass, and Implications for m_{ν_μ}

The limits on m_{ν_μ} are extracted from the two body decay of a pion at rest into a muon and a muon neutrino.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{3}$$

From kinematics one easily derives the formula for the neutrio mass and its uncertainty:

$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2 \cdot m_\pi \cdot \sqrt{p_\mu^2 + \pi_\mu^2} \tag{4}$$

$$\Delta m_\nu^2 = 2p_\mu \sqrt{(\Delta m_\pi)^2 + 1.6(\Delta p_\mu)^2 + 0.9(\Delta m_\mu)^2} \tag{5}$$

The values for the masses of the muon and pion, and for the momentum of the muon, are determined in individual experiments. Using the values adopted by the Particle Data Group[2]:

Mass of the pion: m_π = 139.570180(350) MeV/c^2,
Mass of the muon: m_μ = 105.658357(5) MeV/c^2,
Muon momentum: p_μ = 29.791998(110) MeV/c,

one immediately recognises that the uncertainty is mostly due to the error in the pion mass. A redetermination of this value with lower uncertainties would hence significantly reduce the uncertainty in the mass of the muon neutrino.

The principle of the new experiment is to determine the pion mass from a gaseous source of a mixture of oxygen and nitrogen in which pionic and muonic atoms are formed simultaneously in the same volume. In a gas the captured muon or pion will blow off the electronic shell and create a hydrogen-like atom with no electrons present as the refilling of the electronic levels will be too slow. Because of this fact, one of the major sources of systematic uncertainties of the former experiment will be avoided.

The wavelength of a photon emitted from such an H like exotic atom is given by

$$\lambda = \frac{1}{R_\infty Z^2} \cdot \frac{m_{\mathrm{e}}}{m_\pi} \cdot \left(1 + \frac{m_\pi}{M}\right) \cdot L \tag{6}$$

with R_∞: Rydberg constant,
L : contains information about the transition,
M : atomic mass.

Inserting the masses and charges for muonic oxygen and pionic nitrogen we find that the ratio of the wavelengths is extremely close to unity (1.0083). One can therefore record both lines simultaneously and thus relate the pion mass to the muon mass which is extremely well known. The pions are stopped in the cyclotron trap at PSI[3]; the muons are created from pion decay in flight. At a mixture of 90% of oxygen and 10% of nitrogen, equal source strength for both lines is achieved. By avoiding two major sources of systematic uncertainties of the former experiments, refilling of the K shell and calibration uncertainties, it should be possible to considerably reduce the uncertainty of the pion mass.

4 Approaches for Determining the Mass of ν_e

4.1 Neutrinoless Double β Decay

4.1.1 Principle of Double β Decay

Double β decay is a rare second order decay connecting two nuclei which differ in neutron and proton number by two units. It can be observed if the sequential decay is forbidden or strongly suppressed. Starting from a nucleus with even numbers of protons and neutrons (even-even nucleus), a β decay leads to a daughter nucleus with

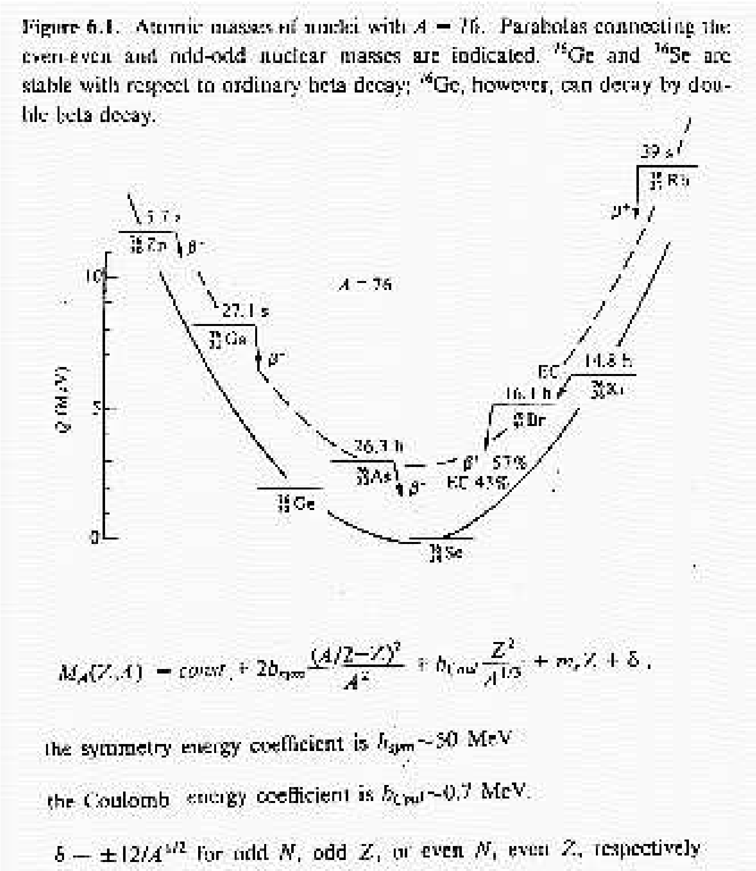


Fig. 1: Atomic masses of nuclei with A=76.

odd numbers of protons and neutrons (odd-odd nucleus). The subsequent decay again results in an even-even nucleus. Due to the pairing of nucleons, even-even nuclei are more bound than odd-odd nuclei. As a result the first decay may be energetically forbidden although the minimum of the energy in the isobaric chain is not reached and the decay from the even-even mother nucleus into the even-even daughter by double β decay is possible (fig. 1).

As shown in fig. 2 there exist two possibilities for double β decay, the allowed 2nd order process in which two electrons and two neutrinos are emitted ($\beta\beta 2\nu$) and neutrinoless double β decay ($\beta\beta 0\nu$) in which the neutrino emitted in one vertex is absorbed at the other vertex. The latter requires physics beyond the Standard Model (SM).

One possibility to allow such a scenario is to require the neutrino to be its own antiparticle (a Majorana particle) and to have a finite mass, because the right-handed antineutrino emitted at the first vertex has to be left-handed at the second vertex to be

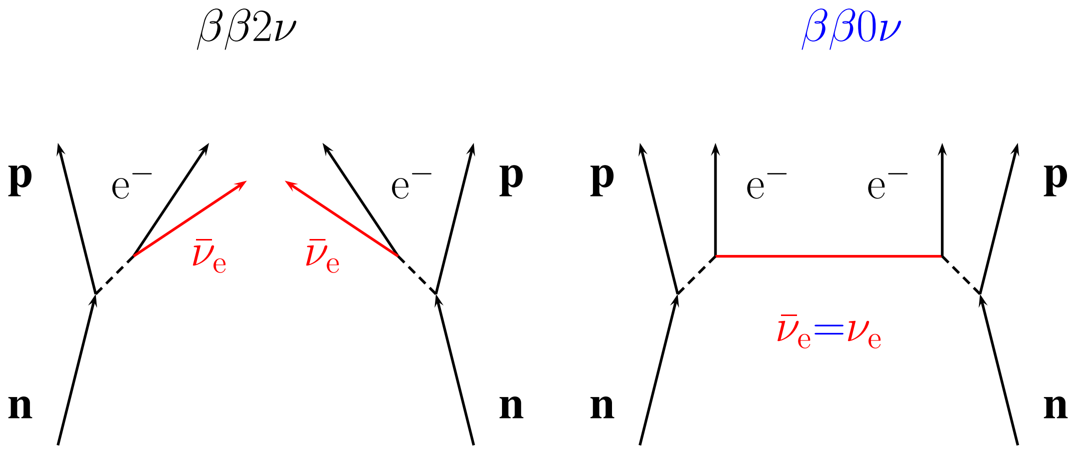


Fig. 2: Double β Decay. Displayed are the two possibilities for double β decay, the allowed 2nd order process ($\beta\beta 2\nu$) and the neutrinoless double β decay ($\beta\beta 0\nu$). Further explainations are given in the text.

absorbed as a neutrino. Via this mechanism neutrinoless double β decay is sensitive to neutrino masses. Although this is a complicated process involving assumptions about the nature of the neutrino, it is attractive for experimental tests as it has a clear signature. One can either reconstruct the two electrons emerging from the same point or look for the monoenergetic line at the high energy end of the allowed double β decay spectrum.

As a historical remark it should be added that the detection of the decay product, e.g. by geochemical methods, cannot distinguish between the two modes of double β decay and thus does not yield any information on neutrino masses.

An example for an energy spectrum from double β decay is depicted in fig.3, showing a clear $\beta\beta 2\nu$ spectrum of the decay of ^{76}Ge into ^{76}Se but no indication of a peak at the position expected for the $\beta\beta 0\nu$ mode. As the position is well known from the mass difference of ^{76}Ge and ^{76}Se one can set a rather narrow window on the energy spectrum and compare the count rate in this window with the background given by the count rate outside the window. In the absence of a signal this difference has a 50% probability to be negative. The statistical treatment of such a "negative count rate" is a problem similar to the problem of negative neutrino mass parameters arising from fits to spectra of e.g. tritium β decay.

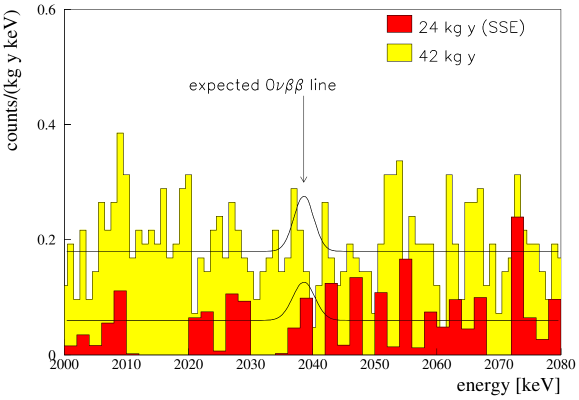


Fig. 3: $\beta\beta 2\nu$ energy spectrum of ^{76}Ge.

4.1.2 Present Limits from $\beta\beta 0\nu$ Experiments

The current status of the different double β decay experiments is given on the homepages of the groups involved. The following data are taken from the homepage of the Heidelberg-Moscow experiment on ^{76}Ge. This experiment claims the present lowest limit; the result of other experiments on different nuclear systems are also given. The half-life reported for the allowed $\beta\beta 2\nu$ decay is[4]

$$T_{1/2} = 1.77 \pm 0.01^{+0.13}_{-0.11} \cdot 10^{21} \text{ y},$$

and the limit for $\beta\beta 0\nu$ derived from the null result is[5]

$$T_{1/2} > 5.7 \cdot 10^{25} \text{ y}.$$

The interpretation of the limit on the partial half-life, in terms of a neutrino mass, more precisely a Majorana neutrino mass, requires knowledge about the structure of the intermediate nucleus. The neutrinos involved are not real, but imaginary particles probing the intermediate nucleus up to very high excitation energies. The relevant nuclear matrix elements are therefore subject to uncertainties. The mass limits deduced from a given set of experimental data using different nuclear matrix elements may differ by about a factor of three.[6–8]

The value derived from the Heidelberg-Moscow collaboration is[9]

$$\langle m_\nu \rangle \ \leq \ 0.35 \text{ eV/c}^2, \ \ 90\% \text{ C.L.}$$

The discussion of the parameter deduced from double β decay and its comparison with the parameters from weak decays will be given in the section on tritium β decay and its interpretation.

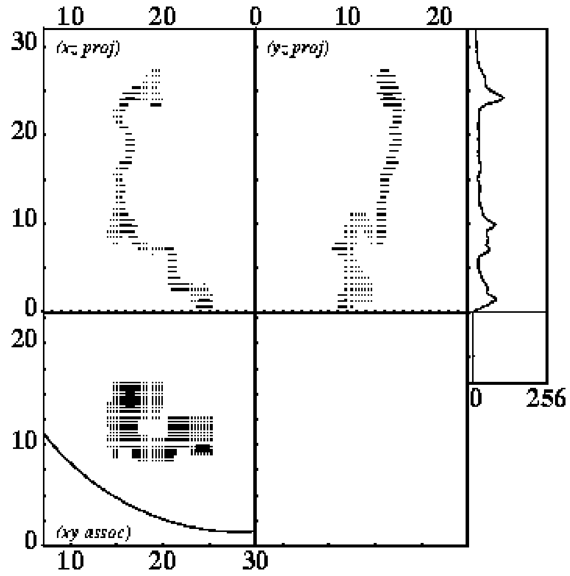
4.1.3 Proposals for Next Generation Double β Decay Experiments

There are eight nuclei which decay via double β decay with electron emission: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd. An optimum candidate should have a well understood intermediate nucleus to reduce uncertainties in the nuclear matrix element, a high isotopic abundance to have as much active material as possible, and a high Q value to have a relatively short half-life. From the experimental point of view it is important to couple source and detector as close as possible. I will briefly present three proposals for next generation $\beta\beta$ decay experiments.

GENIUS, the large scale version of the Heidelberg-Moscow experiment with isotopically enriched ^{76}Ge.
Germanium is not a good candidate except for its superb properties as a detector. The high quality of Ge detectors compensate the low Q value (2.0 MeV) and the low natural abundance (7.8%), asking for isotopic enrichment. To reduce background to the extremely low values needed to improve the present limit a detector array shall be operated in a huge dewar filled with ultra clean liquid nitrogen. The concept of these naked Ge crystals relies on the fact that liquid nitrogen is one of the materials with the lowest radioactive impurities and that the necessary cables can be reduced to a minimum e.g. 3 g of Kevlar and electrical contacts for a test crystal. The whole collection of detectors shall reach a total active mass of about 1 ton and be housed in an underground laboratory such as the Gran Sasso Laboratory.

CUORICINO and **CUORE**
An alternative concept for detecting the decay electrons are cryogenic detectors as used in the CUORICINO test set up, a precursor of a very large array of TeO_2 crystals coupled to bolometric detectors. As the specific heat capacity is extremely low at temperatures in the 1 K range and below, the energy released in $\beta\beta0\nu$ decay would produce a detectable temperature rise in a large crystal. The system developed for $\beta\beta$ decay consists of TeO_2 crystals of about 200 g each coupled to Si-thermometers. The energy resolution reached in a calibration experiment is 3 keV at 5.4 MeV.

The relatively slow response of cryogenic detectors is of no concern in this experiment.



Typical double beta decay candidate. The x−z and y−z projections are measured, as well as the anode signal to the right. The x−y projection is reconstructed. Lengths are in cm.

Fig. 4: Operational TPC from Gotthard experiment[10]

Tellurium is a relatively good candidate with a high Q value of 2533 keV and the highest natural abundance (33.8%) of all $\beta\beta$ decay candidates. Te can therefore be used without isotopic enrichment. A first test set up, called CUORICINO with 14 planes and 4 detectors per plane will be built and operated to find the best conditions for the final set up, CUORE with a total of $17 \cdot 60$ crystals. The site to house CUORE will be the Gran Sasso underground laboratory.

EXO

A third proposal is to use several tons of isotopically enriched ^{136}Xe ($Q = 2.5$ MeV) to operate a large time projection chamber (TPC). In addition it is planned to extract the decay product, a single Ba ion or atom and to identify it by laser spectroscopy. As can be seen from fig. 4 taken from the operational TPC from the Gotthard experiment[10] the tracks of the two electrons can be clearly identified. This is a clear advantage. The disadvantage is the relatively poor energy resolution especially of the proposed huge EXO set up. An identification of the Ba ion at the $\beta\beta$ decay vertex would certainly help to reduce background. At present many technical aspects of EXO are still under discussion.

4.2 Nuclear β Decay

Nuclear β decay is the historical ground of neutrino physics. It was in β decay where the neutrino had to be introduced by Wolfgang Pauli to be able to find a description that did not violate the conservation of energy. Up to now the influence of the neutrino mass onto the shape of the β spectrum however could not be measured with high enough precision to find a non-zero value. The most stringent limits from kinematics, however, are derived from tritium β decay. Close to the end point the modification of the spectrum caused by a finite neutrino mass is given by

$$(E_0 - E)^2 \sqrt{1 - \frac{m_\nu^2 c^4}{(E_0 - E)^2}} \, . \qquad (7)$$

4.2.1 Criteria for Selecting a Candidate for Neutrino Mass Determination from β Decay

From the above formula it can be seen that a detectable modification of the β spectrum can only be expected very close to its endpoint. It is therefore mandatory to select a decay with a low Q value to have a high fraction of the count rate in the interesting area. A low energy of the electrons to analyse is very helpful to achieve a high resolution $\Delta E/E_0$. To work with a well known β decay spectrum, it is preferable to use a superallowed transition.

If the radioactive source is identical with the detector or at least part of this, the above-mentioned points may be the only relevant criteria. In the case that a spectrometer is used to analyse the energy the following additional criteria apply:

- Precise knowledge of the final state spectrum.
- Low energy loss in the source.
- Low backscattering fraction.
- Short half-life to achieve a high specific activity.

At present two experimental approaches are realised: the investigation of ^{187}Re by bolometric cryo detectors and the investigation of the β decay of molecular tritium (T_2) by dedicated spectrometers.

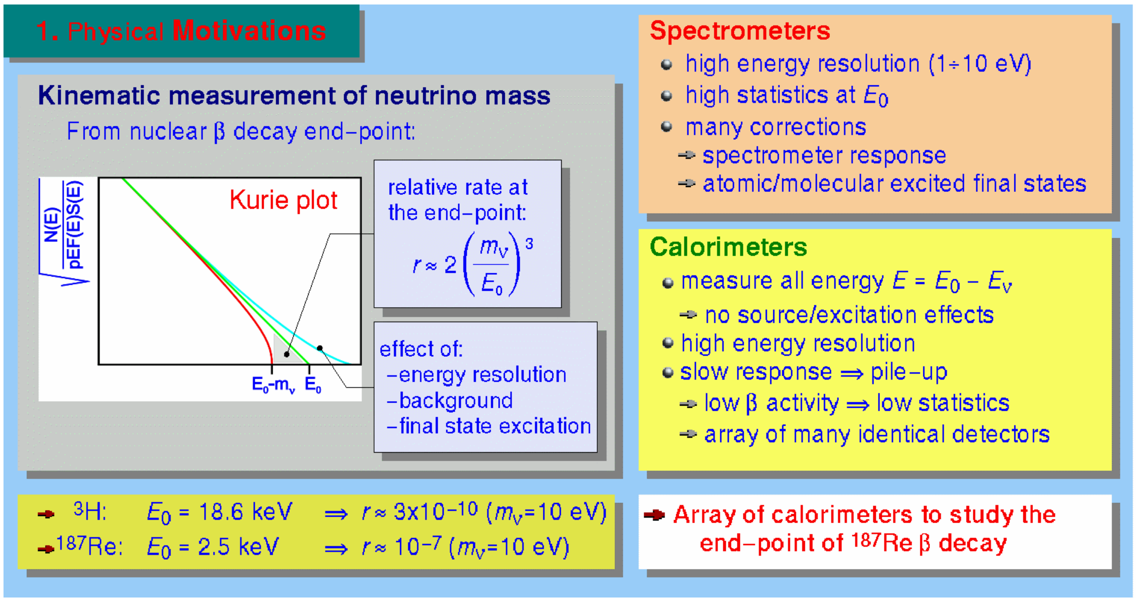


Fig. 5: Milano experiment.

4.2.2 Neutrino mass limit from Re β decay with cryo detectors

At NEUTRINO 2000 the status of the Milano experiment to determine the neutrino mass from ^{187}Re decay was presented and some comments were given to compare this experiment with the experiments with dedicated spectrometers to investigate tritium β decay. Let me comment on the figure given[11] at Neutrino 2000 (fig. 5). In fig. 5 the authors claim an extension of the observed β-spectrum into the region above the endpoint caused by energy resolution, final state excitations and background. It is true that background is present above the endpoint, and it is there that the background can be determined without correlations to the parameters of the β spectrum. In the energy analysing MAC-E filters used to study tritium decay, however, there is no count rate from the β spectrum scattered into the region above endpoint. More generally, no electron will be detected at an energy higher than its real energy. The electrons can only lose energy and, unlike momentum analysing magnetic spectrometers, there is no way to get a misinterpretation caused by scattering inside the spectrometer. This is an important point as one is bound to detect very small changes of the spectral shape in the endpoint region.

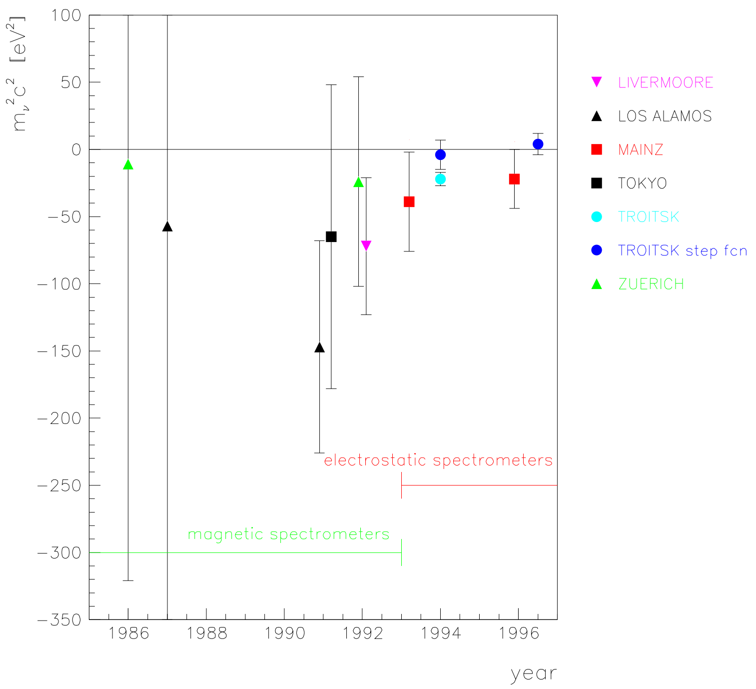


Fig. 6: Results of all tritium-β-experiments since 1986.[12–20]

4.2.3 Neutrino Mass Limit from Tritium β Decay

Another point claimed as being in favor of the Re experiment is the relatively high rate close to the endpoint. This is certainly true. In the real experiments it is however more than compensated by the fact that in the Re experiment all decays have to be analysed with a slow detector of moderate resolution. In the tritium experiments the overwhelming part of the spectrum is not passing the analysing filter such that at 10 eV below endpoint only $3 \cdot 10^{-10}$ of the total activity have to be counted with a fast detector.

In spite of the presently large gap in the performance of Re bolometers and tritium β decay spectrometers the Re detectors may have a chance to contribute substantially to the field. Bolometric detectors are used in many applications, so their technical development and improvement does not depend on experiments on the neutrino mass only. These detectors are very inexpensive compared to spectrometers and it may be possible to operate large arrays once a proof-of-principle experiment is successful. Microbolometers and spectrometers have completely different systematics.

As already indicated the present lowest limits on neutrino masses from the kinematics of weak decays are derived from tritium β decay.

The limits on the mass of the electron neutrino from tritium β decay experiments have been considerably improved and the former trend to unphysically negative values of the mass-squared seems to have vanished. This breakthrough is clearly seen in fig. 6. It is to a large extent based on the properties of a new type of spectrometer. This instrument, dedicated to the investigation of the tritium β spectrum close to its endpoint, is the MAC-E filter containing Magnetic Adiabatic Collimation with an electrostatic Energy analysis.[21,22] It was developed independenly by the groups in Mainz[21] and in Troitsk.[23]

The principle of the spectrometer will be briefly explained and the choice of tritium will be motivated. For details I refer the reader to the literature. For convenience a recent summary of the status of the Mainz experiment is attached to this paper. A description of the joint effort of a new international collaboration to build a new spectrometer to push the sensitivity on the neutrino mass below 0.5 eV/c^2 can be found on the homepage of the collaboration[24] called Karlsruhe Tritium Neutrinomass Experiment KATRIN.

Basic properties of a MAC-E-filter

Fig. 7 shows the principal setup of a MAC-E filter (or solenoid retarding spectrometer). It basically consists of a magnetic guiding field with a strong variation in its field strength and an electric analysing potential in the minimum of the magnetic field. The source is placed close to one of the magnetic field maxima and the detector close to the other one. Electrons starting from the source into the forward hemisphere are guided by magnetic field lines of the superconducting solenoids onto the detector. In between the two solenoids the fringing field gets rather weak and the electron beam expands accordingly. When passing from high to low magnetic field the electrons experience a gradient force acting on the orbital motion around the field line and transforming the energy in this motion into energy in the longitudinal motion. In the case of adiabatic conditions the resulting quasi-parallel electron beam in the center of the spectrometer has the same emittance as the source.

The energy of the electrons in this quasi-parallel beam is analysed by an electrostatic filter. Electrons with an energy large enough to pass the filter potential are transmitted and counted by the detector. The relative width of the filter is given by the ratio of the magnetic fields in the center of the solenoid and in the analysing plane. It is typically 5000 at the present spectrometer. For KATRIN it is planned to work with a resolution $E/\Delta E$ of up to 20000.

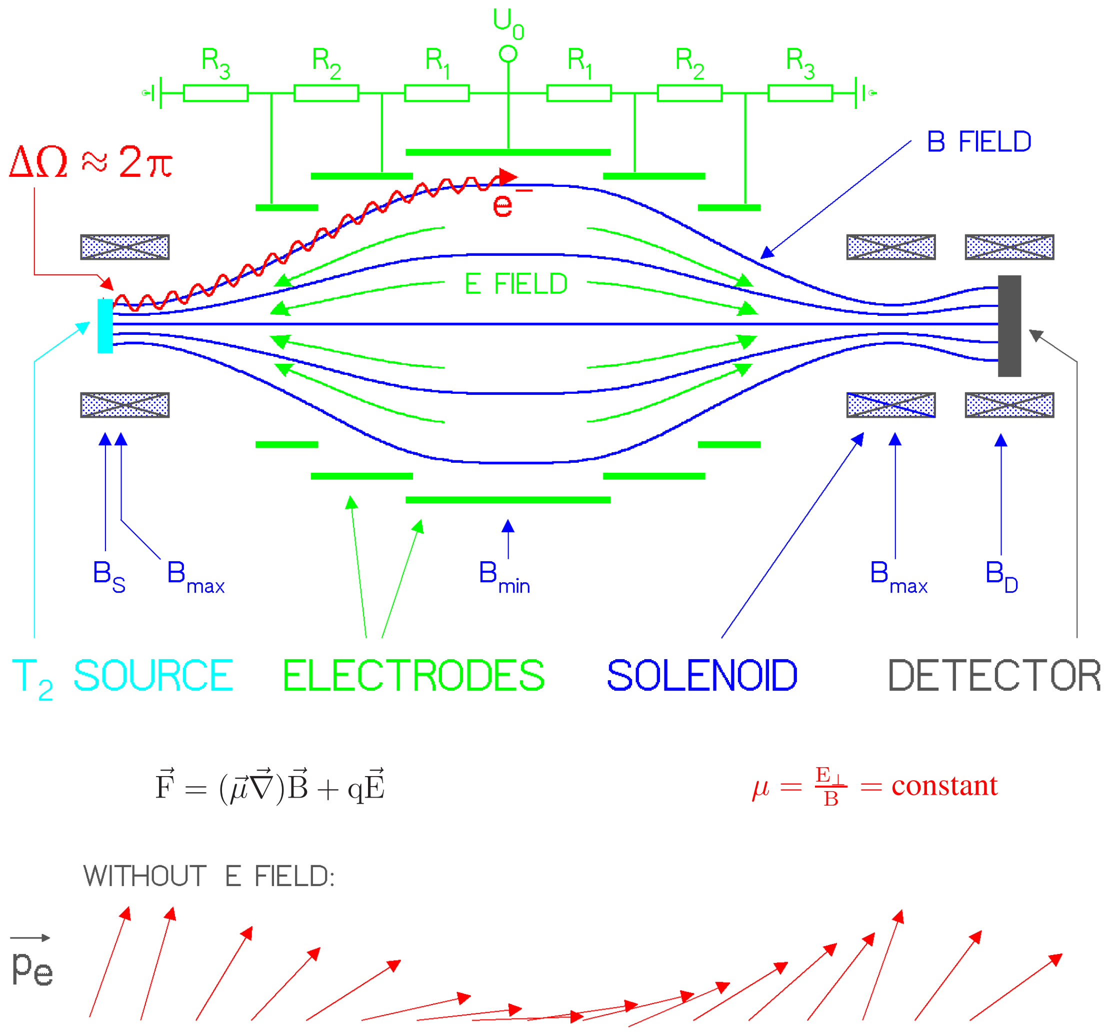


Fig. 7: Principle of the Mainz MAC-E Filter.

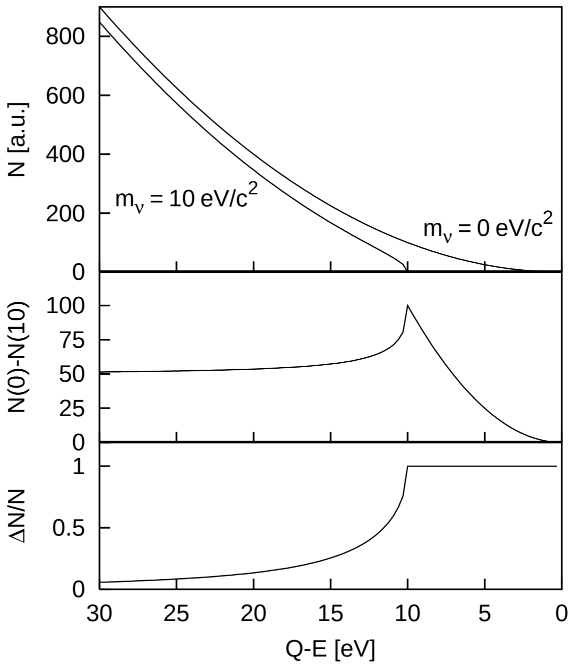


Fig. 8: Signature of a non-zero neutrino mass. In the upper part the endpoint region of the tritium β-spectrum is displayed for two neutrino masses, 0 eV/c^2 and 10 eV/c^2. In the middle part the absolute difference of the spectra is shown, and in the lower part the relative difference. The strongest signature for a non-zero neutrino mass can be found in the region close to the β endpoint.

Consideration that led to the choice of tritium to be studied with a MAC-E filter. To detect the change of the shape of the β-spectrum due to a non-zero neutrino mass several considerations are important.

1. The signal is given by a correction factor to the standard β-spectrum,

$$\frac{dN}{dE} = const \cdot |M|^2 \; F(Z,E) \; p \; (E + m_{\rm e}c^2) \; \sum_{\rm n} W_{\rm i \to f_n} \varepsilon_{\rm n} \sqrt{\varepsilon_{\rm n}^2 - m_\nu^2 c^4} \qquad (8)$$

   with $|M|$: matrix element of β decay,
   $F(Z,E)$: Fermi function,
   $W_{\rm i \to f_n}$: transition probability in the nth final state,
   $\varepsilon_{\rm n}$: $E_0 - V_{\rm n} - E$,
   $V_{\rm n}$: energy of nth final state.

   For values of $\varepsilon >> m_\nu c^2$ the correction approaches a constant (see fig. 8). As we are looking for an effect of a neutrino mass in the range of 1 eV/c^2 or even below, $\Delta\dot{N}$ is in the order of $10^{-13} \cdot I_0$ eV/c^2 (I_0 = total accepted decay intensity under investigation) * . In the case of an integrating spectrometer the influence of m_ν will increase linearly with the distance from the endpoint, the slope being $\Delta\dot{N}_{\rm diff}$.

2. A constant background (in a differential spectrum) or a slope in the background (in an integrating spectrum) directly correlate with the neutrino mass. It is therefore extremely important to be able to gain information on the background. In the MAC-E spectrometers the recorded β-spectrum definitively ends at its endpoint. There is no tail to the high energy side. This allows one to extract the background, and its possible dependence on the effective retarding voltage, undisturbed by the β-spectrum.

3. As the relative change of the β-spectrum is very small, a high total decay rate and a high accepted solid angle are necessary to achieve the statistics needed to emerge from background. In this respect the MAC-E filter spectrometers win by orders of magnitudes over the previously used magnetic spectrometers.

4. The arguments 1) to 3) are technical and apply to any β-spectrum. The choice of tritium is governed by

   - its high specific activity, i.e. by the fact that a thin source within a limited energy loss fraction of the β-particles results in a relatively high count rate.

*In the case of tritium β decay with $E_0 = 18.6$ keV.

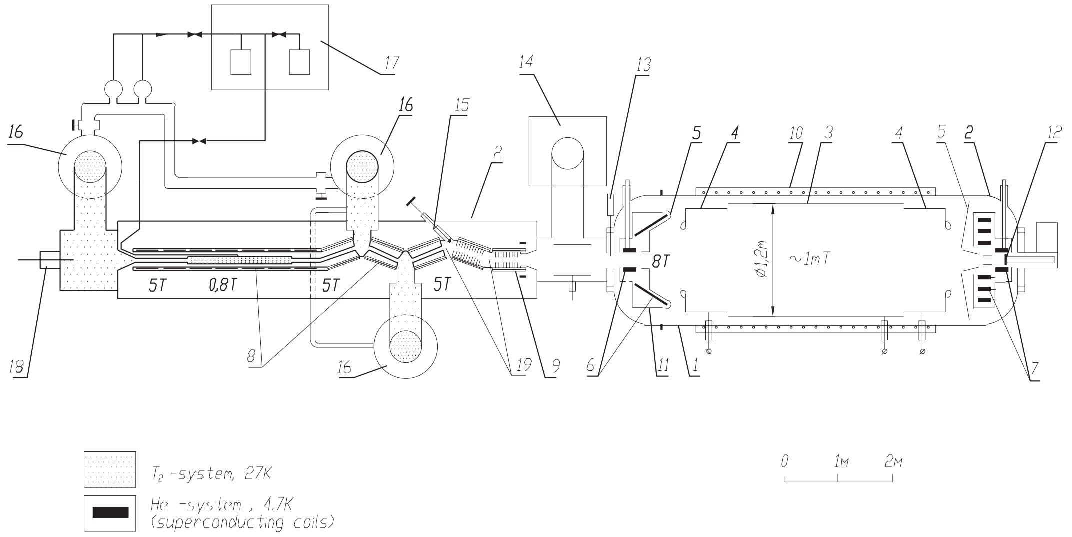


Fig. 9: Schematic view of the Troitsk experimental setup.

- its well-known slope as a superallowed mirror transition.
- the fact that the spectrum of molecular final states is rather well understood.

In spite of the fact that tritium is the easiest and best understood candidate, the systematic uncertainties are serious and will grow with the attempt to detect smaller neutrino masses. Really helpful is that the extreme end of the β-spectrum, i.e. $(E - E_0)$, is smaller than the excitation energy of the first excited state in T_2, and therefore is free of energy loss and corresponding systematic uncertainties.

4.2.4 The Mainz and the Troitsk experiments

The experiments at Troitsk[25] and Mainz[26] use similar MAC-E-Filters differing slightly in size: The diameter and length of the Mainz (Troitsk) spectrometers are 1 m (1.5 m) and 4 m (7 m). The major differences between the two setups are the tritium sources.

The Troitsk experiment uses a windowless gaseous tritium source (WGTS) which is based on adiabatic transportation of electrons in a strong longitudinal magnetic field and circulation of tritium gas at low pressure by means of a differential pumping system[23] (see fig. 9). This approach was first pioneered in an experiment at Los Alamos.[14] An essential refinement made at Troitsk was the use of the strong magnetic field for transportation, which permits the use of multiple bends of the transportation channel

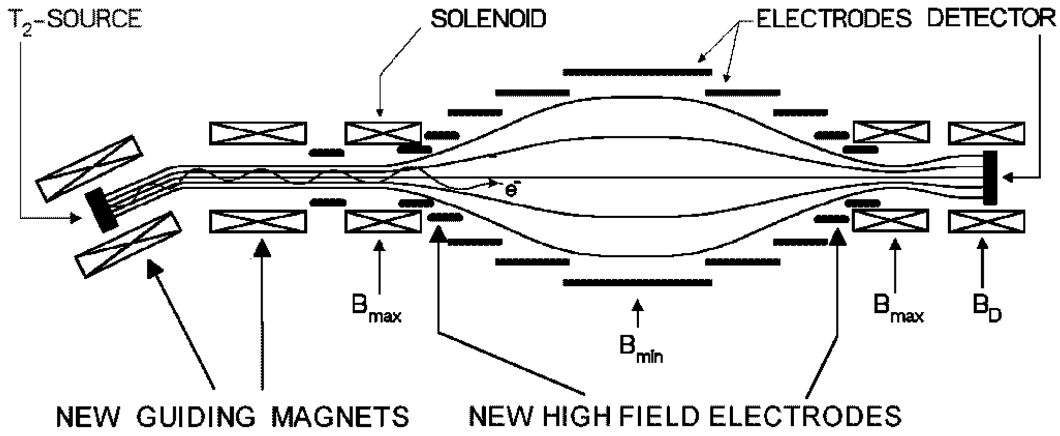


Fig. 10: The upgraded and improved Mainz setup (schematically, not in realistic scale). The outer diameter amounts to 1 m, the distance from the source to the detector is 6 m.

(a 3 m long tube of 50 mm diameter filled with 0.01 mbar of T_2), providing better differential pumping and smooth coupling to the MAC-E-filter spectrometer. The WGTS provides a number of beneficial features for the study of the tritium β spectrum, such as guaranteed homogeneity over the cross section of the source, and reliable on-line control of inelastic energy losses of electrons in the source. It further allows one to use theoretical calculations of free molecular final state corrections and totally suppresses backscattering.

Mainz uses a film of molecular tritium quench-condensed onto a highly oriented graphite substrate (HOPG). The film has a diameter of 17 mm and a typical thickness of 40 nm, which is measured by laser ellipsometry. In the years 1995–1997 the Mainz setup was upgraded to enhance the count rate and to decrease the background rate. As a second substantial improvement, a new cryostat now provides temperatures of the tritium film below 2 K to avoid a roughening transition of the film, which was a source of systematic errors of earlier Mainz measurements. The roughening process is a temperature activated surface diffusion process; therefore low temperatures are necessary to get time constants much longer than the duration of the measurement.[27,28] The full remote control of the apparatus allows one to perform long term measurements of several months per year. Figure 10 gives a sketch of the Mainz setup. Since this upgrade, the count rate, background and energy resolution of the Mainz setup are nearly the same as the ones of the Troitsk experiment.

Results of the Troitsk Neutrino Mass Experiment

The Troitsk experiment has taken 200 days of tritium data from 1994 on. Since the first measurement in 1994, the Troitsk experiment has observed a small anomaly in their experimental spectrum a few eV below the β endpoint E_0, which resembles a sharp step of the count rate. Since a MAC-E-Filter is integrating, a sharp step corresponds to a narrow line in the primary spectrum. The data indicate a relative intensity of about 10^{-10} of the total decay rate. From 1998 on, the Troitsk group reported that the position of this line seems to oscillate with a frequency of 0.5 years between 5 eV and 15 eV below E_0.[25] The cause for such an anomaly is not known. Detailed investigations as well as synchronous measurements with the Mainz experiment are under way and will help to clarify this effect.

Fitting a standard β spectrum to the Troitsk data results in significantly negative values of $m_\nu^2 \approx -10$ to -20 eV^2/c^4. However, describing the anomaly phenomenologically by adding a monoenergetic line with free amplitude and position to a standard β spectrum results in values of m_ν^2 compatible with zero. The average over all Troitsk runs until 1999 then amounts to[29]

$$m_\nu^2 = -1.0 \pm 3.0 \pm 2.5 \text{ eV}^2/\text{c}^4,$$

which corresponds to an upper limit of

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

Results of the Mainz Neutrino Mass Experiment

Figure 11 shows the endpoint region of the Mainz 1998 and 1999 data in comparison with the former Mainz 1994 data. An improvement of the signal-to-background ratio by a factor of 10, as well as a significant enhancement of the statistical quality of the data, is clearly visible. The main systematic uncertainties of the Mainz experiment are originating from the physics and the properties of the quench-condensed tritium film and are the inelastic scattering of the β electron within the tritium film, the excitation of neighbor molecules due to the β decay, and the self-charging of the tritium film due to the radioactivity. As a result of detailed investigations,[30–32] these systematic uncertainties were improved significantly. The data of the last runs of 1998 and 1999 (see fig. 11) neither show a Troitsk-like anomaly nor any residual problem. The most sensitive analysis on the neutrino mass, in which only the last 70 eV of the β spectrum

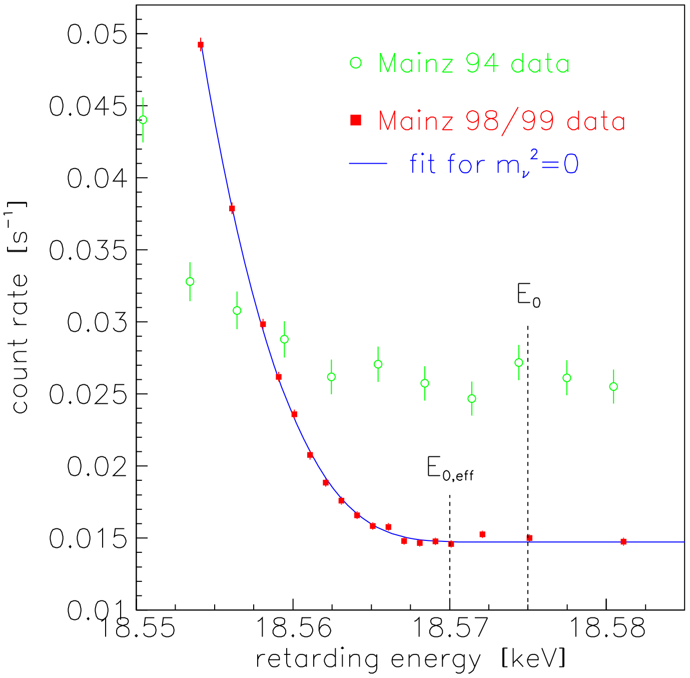


Fig. 11: Averaged count rate of the Mainz 1998 and 1999 data (points) in comparison with previous Mainz data from 1994[20] . Displayed is the count rate as a function of the retarding energy near the endpoint E_0. The line describes the fit and $E_{0,eff}$ the effective endpoint. The position of the latter takes into account the width of response function of the setup and the mean rotation-vibration excitation energy of the electronic ground state of the ^{3}HeT$^+$ daughter molecule.

below the endpoint are used, results in

$$m_\nu^2 = -1.6 \pm 2.5 \pm 2.1 \text{ eV}^2/\text{c}^4,$$

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

$$m_\nu \leq 2.2 \text{ eV/c}^2 \quad (95\ \% \text{ C.L.}).$$

These new Mainz 1998 and 1999 data and analysis,[33] improved the published former upper limit of $m_\nu < 2.8\,\text{eV/c}^2$,[26] which was based on the Mainz 1998 data alone. Together with the Troitsk results, they represent the world's best sensitivity on a neutrino mass in a direct neutrino mass experiment.

5 A next generation tritium β-decay experiment

The present tritium β decay experiments at Troitsk and Mainz have already reached their intrinsic sensitivity limit. One can estimate that future measurements of both experiments will improve the current mass limits only marginally to $m_\nu < 2\,$eV/c^2. This implies that the interesting sub-eV/c^2 neutrino mass region can only be investigated by a new experimental set-up with much higher ν-mass sensitivity.

In the following we present a design study for a next-generation tritium β decay experiment with sub-eV/c^2 sensitivity for the electron neutrino mass. With an estimated sensitivity of $m_\nu = 0.3\,$eV/c^2 (95 % C.L.) the experiment will have the potential to improve the existing limits by a *factor of ten*.

The study is based on the long-term experience with the existing spectrometers of the MAC-E type and has been done in collaboration by groups from Mainz, Troitsk, Karlsruhe and Fulda, following first ideas presented in Refs. 31,22.

5.1 Definition of experimental parameters

The neutrino mass sensitivity of a tritium experiment depends on the design values of two key experimental parameters: the relative energy resolution $R = \Delta E/E$ of the electrostatic spectrometer and the luminosity $\mathcal{L}$. While $\Delta E/E$ is given by the ratio $B_{\mathrm{min}}\,/\,B_{\mathrm{max}}$ of the magnetic field B_{min} in the analyzing plane of the spectrometer and the maximum magnetic field B_{max}, the luminosity $\mathcal{L}$ is proportional to the source area A_{S} and the maximum allowed starting angle θ_{max} of β decay electrons in the tritium source.

To reach a sub-eV/c^2 sensitivity, the energy resolution ΔE of the electrostatic spectrometer at the tritium β decay endpoint at 18.6 keV should be $\Delta E = 1\,$eV, implying a ratio of magnetic fields $B_{\mathrm{min}}\,/\,B_{\mathrm{max}} = 5 \times 10^{-5}$. This resolution requires an improvement by a *factor of about 4* compared to the ΔE values of the experiments in Troitsk and Mainz. With regard to the luminosity $\mathcal{L}$ one has to keep in mind that the relative influence of a finite neutrino mass on the count rate scales with m_ν^2, hence the luminosity should be increased by *nearly two orders of magnitude* relative to present experiments (see also figure 12).

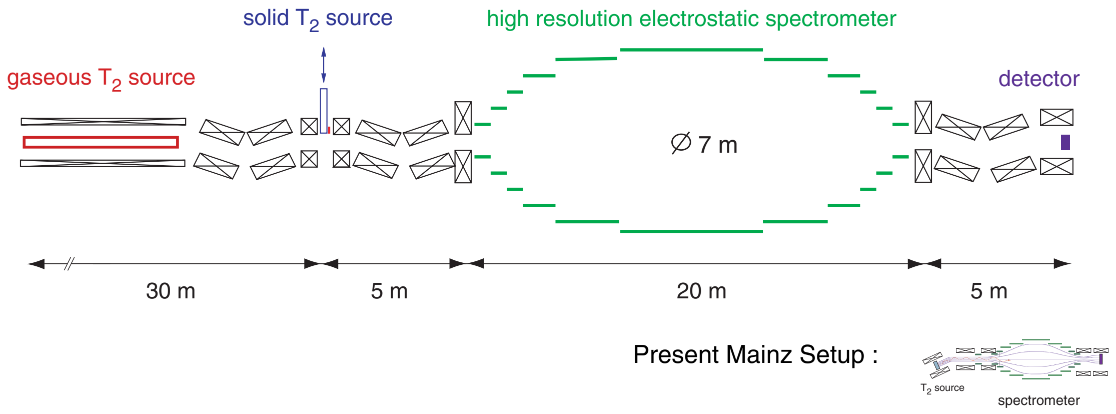


Fig. 12: Schematic view of the proposed next-generation tritium β decay experiment in a linear configuration. The main components of the system comprise a windowless gaseous tritium source (WGTS), a quench condensed tritium source (QCTS), and a large electrostatic spectrometer of 7 m diameter and 20 m length with an energy resolution of 1 eV. Electrons passing the MAC-E filter are recollimated onto a segmented solid state detector. The electron transport section adiabatically guides β decay electrons from the source to the spectrometer (and further on to the detector) while at the same time eliminating all tritium molecules in a two stage process: a first differential (active) pumping part at LN_2 temperature, which is followed by a second (passive) cryotrapping part at LHe temperature. The overall length of this linear set-up amounts to about 60 m. Shown for comparison is the present Mainz setup at same scale.

In this context it is advantageous to define a single overall quality factor Q by the ratio of both parameters with $Q = \mathcal{L}/R$, which can also be expressed as[22]

$$Q = \frac{A_\mathrm{A}}{2 \cdot (1 + \cos\theta_\mathrm{max})} \quad .$$

The quality of a MAC-E filter is proportional to the area of the analyzing plane A_A of the spectrometer and thus will improve quadratically with the up-scaling of its linear dimensions. To meet the improvements on energy resolution and source luminosity defined above, a large electrostatic spectrometer with an analyzing plane of 7 m diameter and a T_2 source with column density of $5 \cdot 10^{17}$ molecules/cm^2 and a maximum accepted starting angle $\theta_\mathrm{max} = 51°$ are considered.

In addition to these requirements, a low background rate at the tritium β-decay endpoint region at 18.6 keV of the order of 10^{-2} counts/sec is essential for a sensitivity to sub-eV neutrino mass effects. This low background rate implies stringent requirements on the vacuum conditions of the electrostatic spectrometer, and it also calls for a state-of-the-art solid state detector with good energy-, time- and spatial resolution for low energy electrons in the keV range.

Finally, it is especially important to control all systematic effects which might influence the measurements. As the most important systematic effects are associated with the properties of the tritium source, the design study proposes to use two different tritium sources with entirely different systematics: a WGTS, following the design of the Troitsk experiment, and QCTS, following the Mainz design. Alternate measurements with both sources will minimize systematic uncertainties. Both sources will have to be calibrated and controlled extensively. Calibration of the properties of the WGTS will be provided by means of an electron gun, while a series of ^{83m}Kr-conversion line test measurements will determine the characteristics of the QCTS.

Apart from the standard integrating (MAC-E) mode of operation, short-term measurements with the differential time-of-flight (MAC-E-TOF) mode pioneered in Mainz[22] will play an important role in the planned measuring program of the new experiment. These additional runs will help to investigate possible systematic effects arising from local distortions of the energy spectrum close to the endpoint. Effects such as the anomaly reported in the Troitsk experiment[19] can thus be investigated in detail. Moreover, as an effect such as the Troitsk anomaly corresponds to a narrow line in the energy spectrum, the resulting distortion in the energy spectrum will stay *local* in the MAC-E-TOF mode. This in turn will allow one to disentangle the effects due to m_ν^2 from any narrow spectral anomaly close to the endpoint. Apart from the search for massive neutrinos, the detailed spectral information to be obtained with the new setup will also allow the search for other non-SM physics like tachyonic neutrinos or small right-handed contributions to the electroweak interactions.

6 Summary

- Tritium is the best candidate for the investigation of a β-spectrum to extract information on the neutrino mass with a β-spectrometer.
- The MAC-E filters used in Mainz and in Troitsk are the best spectrometers ever used to investigate β-spectra close to their endpoint.
- The proposed next generation experiment KATRIN has a chance to detect the neutrino mass if $m_\nu > 0.5$ eV/c^2.

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