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The search for the neutrino mass by direct method in the tritium beta-decay and perspectives of study it in the project KATRIN

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The updated results of the search for neutrino mass in the tritium beta-decay on the Troitsk nu-mass and Neutrino Mainz set-ups are presented. Both groups give an upper limit for the neutrino mass at 95% $m_\nu < 2.05\ eV/c^2$ in Troitsk and $m_\nu < 2.2\ eV/c^2$ in Mainz. Further improvement is limited both by statistic and systematic errors. In order to enter in the cosmologically important sub-electronvolt area the collaboration of groups from Karlsruhe Forschungszentrum, Mainz, Troitsk et al. proposed a new advanced project KATRIN. The status of the project is presented.

1. INTRODUCTION

Recent results from atmospheric and solar neutrino oscillation experiments as Superkamiokande, SNO, SAGE and Gallex give very strong evidence that the neutrino oscillate from one flavor state into another. It means as it was shown by V. Gribov and B.Pontecorvo [1], that at least two neutrinos have nonzero masses.

The very unexpected result proved to be that oscillation parameters correspond to a small squared mass difference and large (almost 100%) mixing. Oscillation experiments do not yield the values of the neutrino masses.

Large mixing of different flavors may mean that properties of different neutrinos are similar and it is very likely that they have almost the same mass. This absolute mass cannot be deduced from most sensitive oscillation experiments and requires a method which does not depend on flavour. Such information may be obtained by astrophysical observation of the relic photon background or time-of-flight measurement of neutrinos emitted in a supernova. First includes some model dependence and the second both model dependence and unpredictability of the event. Important complementary information may be obtained from study of the double beta-decay which involves only Majorana neutrino. Thus the most straightforward method is the so-called "direct or kinematic mass measurement". It is based on the investigation of weak decay kinematics. Measuring the charged decay products, and using energy and momentum conservation, missing neutrino mass can be reconstructed from the kinematics of charged particles. The most appropriate for this aim is beta-decay of tritium. It has lowest (besides ^{187}Re) decay energy, appears as a super-allowed decay, it may be used with high specific activity, the Final State Spectrum of its daughter molecules may be precisely calculated.

During the many years before the appearance of the oscillation hypothesis [2] and [3]

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study of tritium beta-spectrum provided the most precise data of neutrino mass upper limit. Although tritium emits only electronic antineutrino, the results of recent oscillation experiments, which discovered almost total mixing of all flavor at small ($< 10^{-3}\,eV^2$) squared mass differences, makes very probable that all neutrino are degenerated and study of one type of neutrino gives data about other types. The lowest direct upper limit on a neutrino mass now is obtained in the study of tritium beta-decay by two groups: "Troitsk ν -mass" ($m_\nu < 2.05\,eV$), and "Mainz Neutrino" ($m_\nu < 2.2\,eV$) both at 95% C.L.

2. TROITSK ν-MASS SET-UP

The set-up consists of an integral electrostatic beta-spectrometer with a bottle–like magnetic field, adiabatically guiding electrons from the source of molecular tritium to the spectrometer [4]. A schematic view of the Troitsk set-up is given in Fig.1. The cylindrical electrode in the middle of the magnetic bottle serves as an integral spectrometer. Electrons come to the left side of the bottle, guided adiabatically in strong magnetic field.

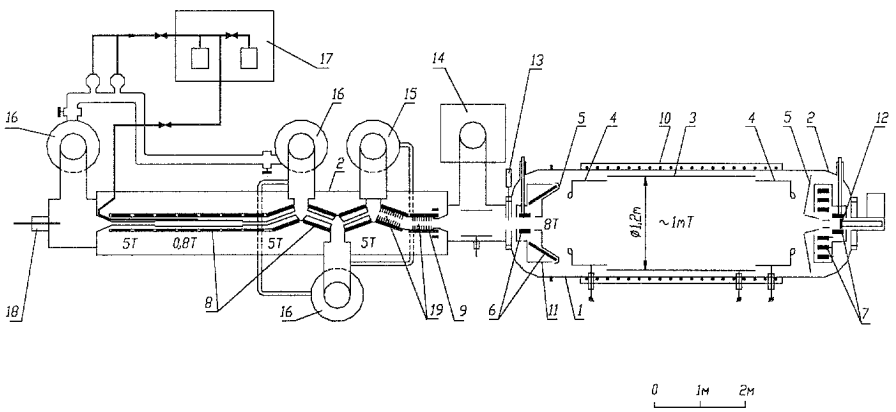

Figure 1. Schematic view of Troitsk nu-mass set up. 1, 2 vacuum tank; 3, 4 electrostatic analyzer; 5 grounded electrode; 6, 7, 8, 9 superconducting coils; 10 warm coil; 11 N2 jacket; 12 Si(Li) detector; 13 fast shutter; 14 Ti-pump; 15, 16 Hg diffusion pump; 17 T2 purification system; 18 electron gun; 19 argon pump.

Electrons, moving adiabatically in decreasing spectrometer magnetic field, transform the transverse component of their energy into longitudinal one. Simultaneously the increasing negative potential acts on the longitudinal component, decreasing it, so that if it reaches zero in the center of the bottle the maximum transverse component becomes

$$\Delta E = E \cdot (H_m/H_0) \qquad (1)$$

Here E is the electron energy, H_m and H_0 are magnetic field intensities in the middle of the spectrometer and in the left bottleneck.

"Troitsk ν-mass"set-up has a gaseous windowless tritium source(WGTS). It represents a tube inside of a chain of superconducting solenoids producing continuous longitudinal magnetic field transporting electrons. Gaseous tritium is injected into a 3 meter tube and expands in both directions. A chain of solenoids in the direction of the spectrometer has gaps which are used for pumping up tritium. Each pump output is connected to a previous pump input, thus all the tritium after additional compression returns to the injection point providing continuous circulation. Extinction factor of the pumping section of the source is about 10^7. Further suppression of tritium is produced by cryopumps consisting of argon on cold surfaces of cryostats.

As a result of all the actions for suppression of tritium, its partial pressure in the spectrometer amounted to about $10^{-18}\,mbar$. Nontritium vacuum in the spectrometer was $0.6 \cdot 10^{-9}\,mbar$.

Electrons with energy exceeding the potential created by the central electrode proceed to the right half of the spectrometer getting acceleration in the decreasing electrostatic field and are detected by the Si(Li) semiconductor detector with a thin window.

The transmission function of the set up for a single monochromatic line is a step with almost a linear slope. The width of the slope is equal to ΔE from equation (1). A relative homogeneity of the electric field in the middle of the spectrometer amounts to $2 \cdot 10^{-5}$ and does not spoil the resolution function which usually was set at $3.5\,eV$ (FW). The adiabatic electron movement in the spectrometer and source makes it possible that the detector sees only the electrons, which appear on the magnetic force lines crossing the sensitive surface of the detector. Thus if the flux tube of magnetic force lines does not touch the walls, the detector does not see electrons which appeared on the walls. It is worth mentioning that a proposal to use a magnetic bottle with an electrostatic analyzer in the center for spectroscopy of low energy $(10 - 100\,eV)$ electrons has been made in [5]. The authors of this paper did not consider the possibility to keep adiabaticity for $20\,keV$ electrons, which proved to be possible in our case due to simultaneous impact of both magnetic and electric fields proposed in [6]. Thus main features of such spectrometer were rediscovered in [7] and independently in [8].

The most important feature of the tritium source in comparison with [9] is the use of a strong magnetic field which allows to make gaps for differential pumping of tritium between solenoids without loss of adiabaticity.

3. THE "NEUTRINO-MAINZ" EXPERIMENT

This experiment uses a similar spectrometer, but twice as short in comparison with the Troitsk one [10]. The small length of the spectrometer forced the Mainz group to make the central electrode as a multielectrode system which proved to be a cause of some background instabilities, which were partially compensated by a better vacuum in comparison with the Troitsk device amounting ($10^{-10}\,mbar$). The main distinction of the Mainz set-up is the use of the tritium source frozen on graphite substrate at a temperature 1.6 K. At such temperature stability of the source is satisfactory, but such frozen matter gives significant difficulties in the analysis of the experimental spectrum due to uncertainty

of spectrum corrections in condensed source. Another problem with the frozen tritium source is selfcharging of the source up to the value of a few volts. A distribution of the potential in the source may depend on the occasional inclusion and strong widening of the energy resolution function. Typical resolution was $4.8\,eV$ instead of $3.5\,eV$.

4. MEASUREMENT PROCEDURE

In the Troitsk experiment the beta-spectrum is measured by changing potential on the central electrode. This was possible due to constancy of the background of this potential, that was checked experimentally. The spectrum was measured from energy 18 keV to 18.770 keV. Background was measured up to 20 keV. One scan of spectrum took about 2 hours. Each measurement run lasted 0.5-1.5 month. Altogether from 1994 to 2002 there were 17 runs including about 290 day of data taking.

Experimental spectrum must be corrected for many factors. Among them are those introduced in the experimental spectrum:

- Dead time correction
- Correction for source intensity drift
- Correction for width of amplitude window in the detector signal spectrum.
- Search and elimination of events of tritium decay in the spectrometer volume seen by the detector. Decay electrons are partially trapped in the bottle-like magnetic field of the spectrometer and gradually are stopped loosing energy by ionization of residual gas. Such events are recognized by the sudden increase of counting rate in short intervals ($20 - 40$ *sec*) depending on the vacuum in the spectrometer.

Correction of electron energy losses are measured experimentally by means of a special electron gun with monochromaticity better than 0.5 eV. The beam of electron is injected in the rear part of the source with the energy somewhat higher than the end point of the tritium spectrum. The spectrum of electrons passed through all the source was measured by the spectrometer [11]. These data permit to calculate with great precision the corrections to the experimental beta-spectrum taking into account multiple scattering, electron track in the source and so on.

A more difficult problem is accounting for the Final State Spectrum (FSS) correction. The decay of initial molecules T_2 or TH leads to daughter ionic molecules $^3HeT^+$ or $^3HeH^+$. The excitation spectrum of these molecules is complicated and the resulting beta-spectrum presents a sum of partial spectra with endpoint energies $E_0 - E^i_{ex}$, here E_0 is the end point energy and E^i_{ex} is the excitation energy. Recently the FSS spectrum was calculated theoretically. Whereas for isolated molecules these calculations are considered reliable, the solid state corrections for frozen tritium are much less certain, because they are done in perturbation approach without taking into account many solid state effects. Unfortunately an experimental verification of these calculations is at the moment impossible. The use of these correction functions for direct deconvolution of the experimental spectrum is extremely difficult. For these reasons analysis of the spectra is

carried out by construction of a theoretical spectrum convoluted with all the correction function and summed over FSS. Then it is fitted to experimental spectra by means of a χ^2 minimization procedure using free parameters and Minuit program. As a basic set of variable parameters we used four

- A - normalization
- B - background (supposed as constant over spectrum)
- E_0 - end point energy or maximum electron energy.
- m_ν^2 - squared mass of neutrino (the lightest one).

These parameters of the fit demonstrate a strong correlation, which increase the final error of m_ν^2. Especially important is the correlation between E_0 and other parameters. Unfortunately this value cannot be obtained from outside experiment like mass-spectral difference of ^3He and ^3T because for suppression of the correlation it is necessary to have an accuracy of mass difference of a few times $10^{-2}\,eV$, whereas the present accuracy is of order $1\,eV$. The strong correlation also exists between the spectrum of inelastic energy losses of the electron in the gas and other parameters. The same is true for FSS. Each error of correction factors may imitate nonzero m_ν^2, negative or positive. Combination of correction errors may even compensate the real m_ν^2 effect.

5. RESULTS OF THE MEASUREMENT

Very first results of the tritium measurement in Troitsk revealed that the simplest set of parameters gives a negative value of m_ν^2 within $-(10-20)\,eV^2$. Such anomaly is impossible to explain by any reasonable phenomenon, besides very exotic ones. A feature of the spectrum is some excess of intensity, which starts below the endpoint energy. The most adequate shape of anomaly proves to be a step-like function superimposed on the regular beta-spectrum. Position and intensity of the step may be introduced in the fit in the simplest case as two additional free parameters. The differential spectrum step function appears as a single bump and a procedure to fit with such free parameters appears as a cut-off of the bump. The step function in this case serves as systematics, which increases the fitting error by $1.5-2$ times.

We also observed in 3 runs, including the last one (2002), the step with shift value $18-22\,eV$ and with an intensity jump about 2-3 times more than the average value over all the runs. These runs were not used for deduction of m_ν^2. The runs with the shift of the step to lower energy less than $8\,eV$ were also excluded due to strong correlation between step and m_ν^2. Thus only half of the data were taken for analysis of the presence of neutrino mass. Summing all the fit results in quadratures and averaging systematic errors with statistical weight corresponding to the fit error, one obtains:

$$m_\nu^2 = -2.3 \pm 2.5_{fit} \pm 2.0_{syst} eV^2 \tag{2}$$

Using the unified approach to confidence interval in the case of a one-side distribution [12] summing fit and systematic errors in quadrature one obtains:

$$m_\nu < 2.05\,eV \tag{3}$$

Systematic errors of m_ν^2 include the following main components:

1. Uncertainty of electron energy losses in the source - $1.2\,eV^2$,
2. Energy resolution function - $0.5\,eV^2$
3. Uncertainty of FSS (0.1% in the level population) - $0.7\,eV^2$
4. Possible space charge in the source - $1.0\,eV^2$

Sum in quadrature: - $1.8\,eV^2$

Including some small additional error one obtains for systematics $2.0\,eV^2$. Systematics connected with step function may be estimated from the difference of fit error with step (6 free parameters) and 4 parameter fit. The resulting number is 1.5 eV^2.

6. RESULTS OF THE MAINZ NEUTRINO MASS EXPERIMENT

The last reported results of the Mainz Neutrino group embrace data obtained during 1998-2001. In total they conducted 12 runs of data taking. The first 4 runs were considered not suitable for the neutrino mass search, due to low statistics and presence of a step effect in run Q4 and possibly in Q3. The result of the 2001 runs to fit the last 70 eV of the beta-spectrum below end point on m_ν^2 is:

$$m_\nu^2 = +0.1 \pm 4.2_{fit} \pm 2.0_{syst}\, eV^2 \tag{4}$$

Combining this value with the one obtained from the data sets Q5-Q8 from 1998 and 1999 gives:

$$m_\nu^2 = -1.2 \pm 2.2_{fit} \pm 2.1_{syst}\, eV^2 \tag{5}$$

It corresponds to an upper limit of:

$$m_\nu < 2.2eV (95\%\, C.L.) \tag{6}$$

The Mainz group reported that they do not see a step effect in the data of runs of Q5-Q12. At least two runs in Mainz and Troitsk were conducted partially synchronously. Troitsk group again have seen the step in the spectrum and Mainz group have not seen it.

7. TROITSK ANOMALY

The step function being seen in the Troitsk set-up remains to be a very enigmatic phenomenon. Observation demonstrated also strange variations of position and amplitude of the step. The position of it changed about periodically with a period of half year. Last measurement shows more variability of the step. Nevertheless two runs conducted in December 2001 and in April 2002 again show steps at about the same places of seasonal plot. It is obvious that non observation of a step in more than half of Mainz data makes apparatus origin of this effect more plausible, moreover that there is no reasonable explanation of this effect in Troitsk as well as earlier in Mainz. It is worth while to mention however that the Mainz set-up does not possess decisive advantageous features in comparison with the Troitsk set-up. Moreover energy resolution and systematic effects such as charging and FSS problem in frozen source makes fit very dependent on the choice of correction parameters which are difficult to calculate or to measure independently.

8. PROJECT KATRIN

As it was seen from last results of both groups, further improvement is limited by both statistical and systematic errors. At first look the most serious are systematic problems connected with corrections on FSS and possibly the anomaly of Troitsk type. If to ignore the latter in the hope that it will be at last explained by some apparatus effect, the FSS problem nevertheless seems to be difficult to overcome. Fortunately improvement of sensitivity of the set-up by means of enlargement of spectrometer and tritium source may resolve to some extent the FSS problem as well as electron energy losses correction. The solution is in the fact that sensitivity, that is ratio of neutrino mass signal to statistical error has maximum in the spectrum point where the spectrum intensity is equal to the double background rate. Thus if to increase luminosity of the spectrometer and aperture of tritium source (hopefully without significant increase of background) the area of maximum sensitivity will be at a few eV below end point. It allows to confine themselves by the fit area $12 - 15eV$ below end point where FSS are represented only by vibro-rotation excitation spectra and a very small part of energy losses spectra. Luminosity of the set up very crucially depends on the spectrometer size and tritium source aperture. Windowless Gaseous Tritium Source (WGTS) similar to the Troitsk version needs to be much longer in order to suppress penetration of tritium into the spectrometer up to partial pressure below $10^{-20} mbar$.

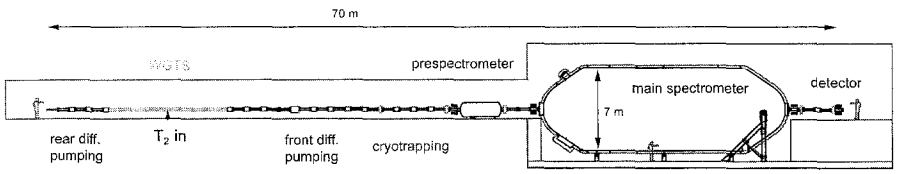

Figure 2. Schematic view of KATRIN set up

A simplified sketch of the set up is shown in Fig.2. Present acute need to know the kinematic mass of neutrino, stimulated proposal to build a new huge set-up for measurement of the tritium beta-spectrum. International collaboration includes both the Mainz and Troitsk group and as a host of the experiment a group from Karlsruhe Forschungzentrum (KFZ). The essential advantage of KFZ is the existence in it of a powerful Tritium Laboratory capable to handle $40\,g$ of tritium. Collaboration now includes other members from USA, Czech Republic, England, Slovak Republic and so on. The collaboration adopted abbreviation KATRIN, (Karlsruhe, Tritium, Neutrino). As the initial dimension of the set-up it was decided to take the diameter of the spectrometer to be 7 meters. The length of it consisted of 20 meters. Similar to Troitsk a chain of superconducting solenoids transports electrons from the source. At the field in the source $6\,T$ diameter of tritium tube

was chosen $70\,mm$. Magnetic pinch which defines initial solid angle of electron emission in the source will be $10\,T$. The field in the spectrometer center is $0.5\,mT$. It gives an energy resolution $0.9\,eV$. Luminosity of the set-up exceeds the Troitsk one by factor 50. On the way to spectrometer, the electron spectrum is cut off at the energy 18.4 keV by a relatively small preliminary spectrometer (prespectrometer). It helps to avoid entering into the main spectrometer about $10^{10}\,e/sec$ from the source. The detector is supposed to be a multiarray of semiconducting $Si(Li)$ detectors with total diameter $100\,mm$.

The source length consists of the $10\,m$ tritium tube and a differential pumping section with 9 gaps in the spectrometer direction and 3-4 gaps to the rear side. Each gap is connected with Turbo Molecular Pumps which provide suppression of tritium by factor $2 \cdot 10^9$. Further suppression will be made by cryopumps on the base of argon frozen on the walls of helium cryostats. Additional pumping will be provided by both spectrometers with their pumping systems. The sensitivity of this experiment may be characterized by a final error of m_ν^2 or upper limit after tree years of measurement. The first is estimated as $0.08\,eV^2$ and the second as $m_\nu < 0.35\,eV$. These estimates were done for background $10\,mHz$. Such low background was achieved in Troitsk and Mainz for a very small detector ($2cm^2$) and at active spectrometer volume almost 500 times less then in KATRIN. There is a hope that better vacuum and some active methods for suppressing background will allow to reach at least to above-mentioned value of $10 - 20\,mHz$. It is also supposed that the fit area will start not more than $25\,eV$ below end point. Of course the Troitsk anomaly should be understood or eliminated.

At the moment intensive studies for the development of methods which will provide optimal condition for neutrino mass search, are in progress.

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