

A METHOD FOR MEASURING THE ELECTRON ANTINEUTRINO REST MASS

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Received 13 June 1984 and in revised form 6 May 1985

A method is proposed for measuring the tritium beta spectrum in order to determine the electron antineutrino rest mass. This method includes an electrostatic integral spectrometer with adiabatic collimation. The use of a source in the form of atomic polarized tritium in a strong magnetic field or of a gaseous molecular source is considered.

1. Introduction

The possibility of the existence of a nonzero rest mass of an electron neutrino is one of the most intriguing problems of modern physics. A recent report by a group of the Institute of Theoretical and Experimental Physics [1] on the observation of anomaly in the tritium beta spectrum, which is indicative for a neutrino (anti-neutrino) rest mass of about 30 eV, extremely revived experimental efforts in this area. In spite of the carefulness with which this experiment has been carried out, the interpretation of the results does not seem to be sufficiently simple, owing to the use of tritium-labelled valine as a radioactive source. Decay of tritium in ^3He , occurring in such a complicated system, has a large uncertainty which is associated with the final state energy spectrum and which, as may be supposed, in combination with other factors, can simulate the neutrino nonzero rest mass effect.

In any case the enhancement of the accuracy and reliability on establishing the existence of the neutrino nonzero rest mass is of utmost importance for elementary particle physics and cosmology; therefore it is urgent to develop new approaches to this problem.

The tritium beta decay remains the all-important subject of experimental investigations although most recently another method has been proposed for determining the neutrino mass [2]. This method involves the measurement of the spectrum of inner bremsstrahlung photons through the electron capture from outer shells. The measurement of the photon spectrum has, in principle, a number of advantages over the measurement of the beta spectrum, but the sensitivity of the method proposed in ref. [2] depends on that accidental

circumstance with what accuracy the energy of the X-ray transition in a daughter nucleus will be found to be near the boundary of the bremsstrahlung spectrum. Apparently the available radioactive isotopes (e.g. ^{163}Ho) are not quite fit for the experiment proposed, although it is not unlikely that further searches will reveal a more suitable isotope.

As regards to the measurements of the tritium beta spectrum, it is possible to distinguish several variants of this experimental approach, realized in the previous studies or being discussed in the literature:

- a magnetic spectrometer with a surface ^3H source [1,3];
- an electrostatic integral spectrometer with a surface source [4];
- a magnetic spectrometer of the type used in ref. [1] with an atomic tritium source based on a cooled trap with pyrex walls and with transportation of electrons by a longitudinal magnetic field [5];
- a tritium-implanted semiconductor Si (Li) detector [6]. This method seems to have a limited sensitivity to the neutrino mass.

Most recently the possibility has been discussed of using a combination of a large-area source, a longitudinal magnetic field and an electrostatic spectrometer [7].

The main characteristics of any of these setups are the following:

- (i) Energy resolution.
- (ii) Luminosity, $L = S\Omega/4\pi$, where S is the source area and Ω is the solid angle within the electrons emitted by a source are detected.
- (iii) Detector background.
- (iv) Distortions of the beta spectrum which are introduced by a source and a spectrometer and which may

simulate the neutrino mass.

The first three listed factors determine the sensitivity, that can be attained in principle, to the neutrino mass.

It is very important to eliminate, as far as possible, the distortions of the shape of the beta spectrum in the source and in the instrument since ultimately the problem is divided into the measurement of the spectrum shape at some distance from the end point of the beta spectrum, the extrapolation of the beta spectrum to the end point, and the determination of the difference between the extrapolated and really measured beta spectrum near the end point.

Recently the results of the precision (~ 3 eV) measurement of the mass difference of ${}^3\text{He}$ and ${}^3\text{T}$ by the cyclotron resonance method have appeared, which could make it possible to avoid the measurement of the beta spectrum far from the end point. Nevertheless a knowledge of the final energy of the beta spectrum does not exclude the need to fulfil the abovementioned condition.

It is also very important to eliminate a high-energy tail of the energy resolution function of the spectrometer. In case of the focussing magnetic spectrometers this tail may appear due to the scattering of the electrons on the aperture diaphragms and some other parts of the spectrometer. The presence of such a tail strongly limits the sensitivity to the neutrino mass near the very end of the beta spectra.

2. The method proposed

In the present paper we consider a new experimental approach to the measurement of the electron antineutrino mass by measuring the tritium beta spectrum using an integral electrostatic beta spectrometer with

magnetic adiabatic collimation. The latter term seems to be introduced for the first time and its meaning will be clear from the following.

The experimental arrangement is illustrated in fig. 1.

The specific feature of the spectrometer is a longitudinal magnetic field which forms a configuration of the type of a magnetic bottle with a bottleneck ratio, i.e. the ratio of the field in the bottleneck (region A) to that in the median plane (region B), of about 10^3 . The tritium source is located either in the neck A itself or in region A' with a somewhat weaker magnetic field.

In the median part of the bottle in the region of a uniform magnetic field there is an integral electrostatic analyzer which for simplicity is at first represented by a cylindrical electrode, which is held at a voltage V_0 such that no electrons having energies less than eV_0 are transmitted.

An electron detector (it may be a semiconductor Si (Li) with a very thin entrance window) is located in region C with a somewhat weaker field in comparison with that in region A. Various variants of a source are under consideration. The most appealing is a variant with atomic polarized tritium in a magnetic trap formed by a strong 10 T field with the use of the technique developed in the studies on the confinement of atomic hydrogen [8]. Although the solution of the problem of confinement of atomic tritium involves a number of presently unknown factors, yet the development of an atomic tritium source with a number of atoms of 10^{15} – 10^{16} appears to be fairly real.

The tritium beta decay electrons in a strong magnetic field will move on a spiral path along magnetic force lines, in which case the condition of conservation of the adiabatic invariant $\sin^2\alpha/H = \text{const.}$, where α is the angle between the electron momentum and the direction of a magnetic force line, and H is the magnetic field strength, must be fulfilled. If in the neck the angle α

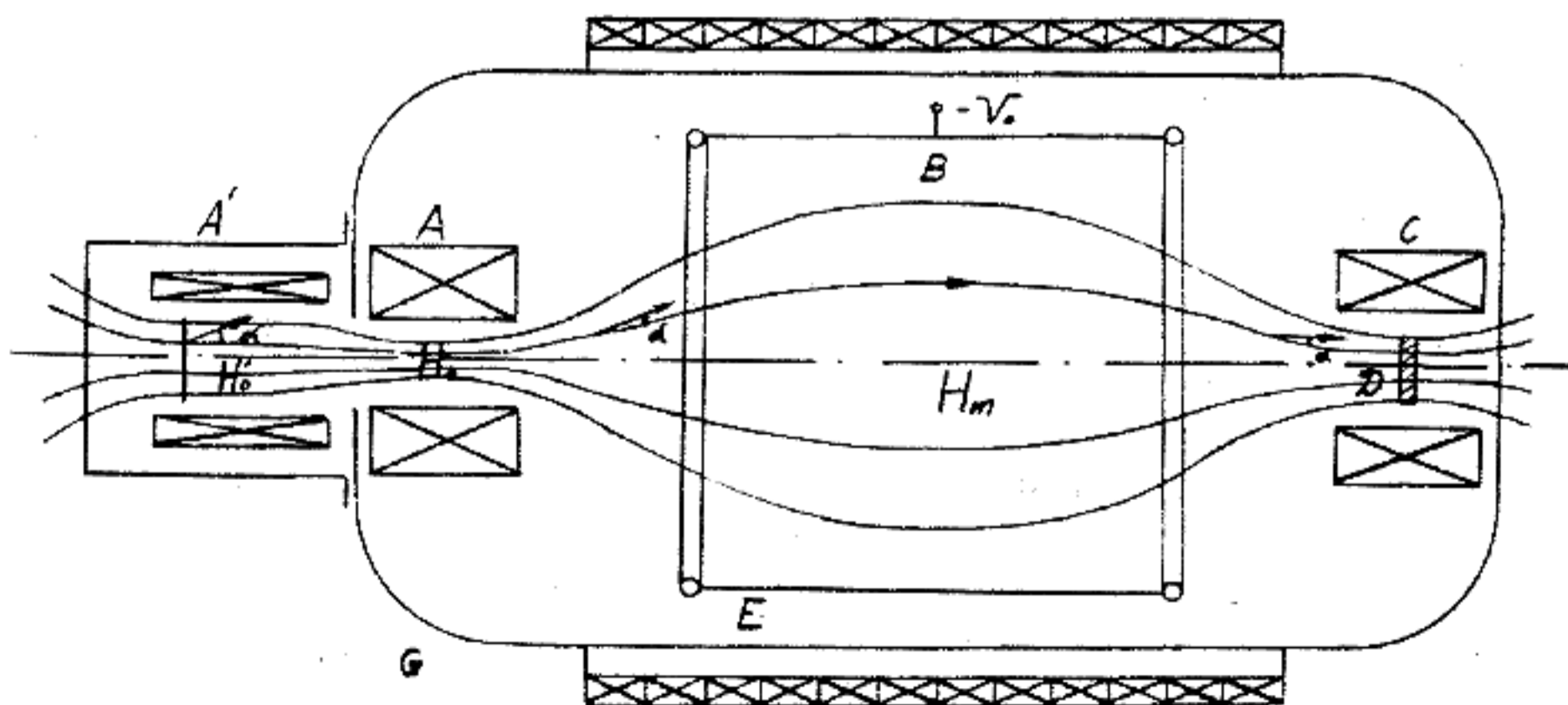


Fig. 1. Schematic diagram of the spectrometer and configuration of the magnetic field. H'_0 , H_0 and H_m are the magnetic field strengths. D is the detector; E is the electrostatic analyzer. Only some of the solenoids setting up a magnetic field are shown.

ranges from 0 to $\pi/2$ then, subject to the condition of a sufficiently smooth falloff of the magnetic field, in the median plane the maximum angle is determined as $\sin \alpha_m = \sqrt{H_m/H_0} \approx \alpha_m$. In the electrostatic stopping field directed along a force line, the transverse component of the electron momentum is conserved. If the energy of the electrons is such that the longitudinal component of the momentum is fully cancelled when approaching the central grid, then the energy related to the transverse momentum is

$$\Delta E = E_0 \sin^2 \alpha_m = E_0 \frac{H_m}{H_0}.$$

Thus, the spectrometer transmission function for a strictly monochromatic line with a change in the stopping potential will represent a step whose edge is smeared by the value ΔE which determines the spectrometer energy resolution.

After the transit through the median plane the electrons are accelerated to their initial energy and, moving along force lines with increasing of an angle α , arrive at the second neck C where the Si (Li) detector is located. The resolution of such a detector can be made sufficiently high in a field of up to 3 T and can amount to 300–400 eV.

The electrons that have lost in the detector only some of their energies and have been scattered backward at any angle, move in the magnetic field to the median plane, and on getting into the electrostatic field, turn back (since their energy is much less than the initial one close to the potential of the spectrometer central electrode) and again return to the detector. After several such oscillations practically the whole of the electron energy will be released in the detector so that its efficiency at a detector resolving time $\tau > 0.1 \mu\text{s}$ must be close to 100%.

Before considering the design of the spectrometer and tritium source let us determine the spectrometer luminosity. By the area of the source we should imply here the area πR_0^2 , where R_0 is the radius of the used part of the neck A which, in turn, is determined by the maximum radius of the boundary force line of the magnetic field of the entire trap, and is mainly limited by the radius of the median part, where

$$R_{\max} = R_0 \sqrt{H_0/H_m}.$$

All electrons produced in the neck within the hemisphere facing the spectrometer can be detected in the spectrometer if their energy exceeds the stopping potential of the electrostatic spectrometer. Thus, the spectrometer luminosity in the present case is $\pi R_0^2/2$.

The relative energy resolution, as is evident from the foregoing, is

$$\Delta E/E = H_m/H_0 \equiv \gamma^{-1}.$$

For the value $\gamma \sim (1-2) \times 10^3$, considered previously,

the energy resolution at a beta-electron energy of 18 keV will be 9–18 eV.

If the tritium source is located not in the neck itself but before it in a weaker magnetic field H'_0 , then the expression for the luminosity is slightly changed. If $H'_0 \ll H_0$ then the solid angle, within which the electrons emitted by the source pass through the neck to be detected by the spectrometer, is limited by the emission angle

$$\alpha' \approx \sqrt{H'_0/H_0},$$

i.e. the solid angle itself is

$$\Omega = \pi \alpha'^2 = \pi H'_0/H_0.$$

The used area of the source, limited by the boundary force line of the magnetic field is $S = \pi R_0^2 H_0/H'_0$. Hence, the luminosity is $S\Omega/4\pi = \pi R_0^2/4$, which is twice as small as in the case of the arrangement of the source in the neck.

In this case, however, it should be kept in mind that except for the case of an atomic source, where the attainable density of the number of atoms per unit volume is sufficiently small, the use of a gaseous molecular source (considered below) or a surface source causes one to limit the electron emission angle, so that the electrons do not move at small angles to the source surface, which may lead to energy losses and scattering. Therefore the decrease in the luminosity is quite justified here.

The basic parameters of the spectrometer – luminosity and relative resolution – are determined by the relation between the magnetic fields in the neck and median plane (the bottle neck ratio), and by the effective radius of the neck. These quantities, subject to the condition of the adiabatic unvariant fulfilment for the most energetic electrons, are independent of the electron energy. The luminosity is determined only by the neck area and the resolution only by the bottle neck ratio.

As a matter of fact the magnetic field acts as a collimator which limits the solid angle used, therefore it is possible to define this method as a method of magnetic adiabatic collimation.

With the given configuration of magnetic fields, the used area of the source and spectrometer as a whole is determined by the boundary force lines which cross the detector. For this reason none of electrons produced outside this volume can be detected by the detector, what is very important for decreasing the background. The electrostatic analyzer may be represented by a distributed electrostatic field set up by a system of ring and cylindrical electrodes. This circumstance is also important for the condition of the adiabatic invariant conservation to be fulfilled.

Table 1 lists the parameters of the spectrometers used previously and proposed for some new experiments.

Table 1
Parameters of some spectrometers for measuring the tritium beta spectrum. Note that the luminosity also depends on the actual size of the instruments.

Luminosity (cm ²)	Resolution (eV)	³ H ₁ source	Reference
0.25	45	Surface, tritium-labelled valine	[1]
1.0	55	Surface, tritium implanted into aluminium	[3]
0.065	10	Tritium frozen onto surface	[4]
0.023	20–40	Atomic tritium, total numbers of ³ H atoms is 5 × 10 ¹³	[5]
0.6–1.5	2–5	Atomic or gaseous molecular source	Present paper

3. Conservation of the adiabatic invariant

For the case of the tritium beta spectrum for the maximum electron energy of 18.6 keV (magnetic rigidity $H\rho = 460$ G cm) the maximum radius of the Larmor spiral in the neck at a field strength $H_0 \sim 10$ T is $\rho_0 = 0.46 \times 10^{-2}$ cm. The maximum step of the spiral is $2\pi\rho_0 = 2.9 \times 10^{-2}$ cm. Conservation of the adiabatic invariant requires that a change in the particle magnetic moment, determined as $\mu = (v_{\perp}^2 / (2H))$, where v_{\perp} is the particle velocity component perpendicular to the magnetic force line, should be sufficiently small at one step of the Larmor spiral. In most cases it is sufficient to require that $\Delta\mu/\mu = 0.1$. Calculations show that this requirement can readily be fulfilled with a fall-off of the magnetic field to a level of 0.2–0.3 T. In a field of 1–3 T it is possible to bend the middle line of the field practically at any radius. This enables one to prevent tritium atoms or molecules from direct flight to the middle part of the spectrometer and to prevent tritium from getting into the detector. The length of the region of a strong magnetic field at a small radius can be made sufficiently large for tritium to be recaptured by the cooled walls and by differential pumping.

With this method, it is very important to ensure the conservation of the adiabatic invariant with the magnetic field falling off to a level of 100 Oe and below, which is necessary at the bottle neck ratio $\gamma = (1-2) \times 10^3$ with a field of 10 T in the neck. In this case, apart from the requirement of a small $\Delta\mu/\mu$ on the length of the Larmor spiral, it is necessary to take into account the curvature of the boundary magnetic force lines at $\alpha \sim 0.02-0.03$.

Consideration of this problem in general is rather difficult. For some special cases of certain magnetic fields, configuration estimates give a distance from the neck to the median plane of 5 m at $\gamma \sim 10^3$ and 10 m at $\gamma \sim 2 \times 10^3$ and $R_0 = 1$ cm.

Setting up of a smoothly falling-off magnetic field of such a length would make the spectrometer too long.

As a possible solution we propose that the stopping potential should be distributed along the magnetic field

so as to decrease the longitudinal component of the electron momentum even in the region of a sufficiently strong magnetic field (at $\alpha \sim 0.2-0.3$). This should be done so that the effective step of the Larmor spiral is minimum for all the electrons with an energy close to the value of the maximum stopping potential V_0 . Some problems may arise for electrons with an energy significantly greater than eV_0 , i.e. when the shape of the beta spectrum is measured far from the end-point energy. In this case, however, the requirement for the conservation of the adiabatic invariant for the energetic part of the electron spectrum consists in that all the electrons could ultimately reach the detector, located in the neck C, where the magnitude of the magnetic field is at least by an order smaller than that in the neck A (the bottleneck ratio is not over 10^2), so that the electron detection efficiency within the fiducial solid angle remains to be 100%. The latter requirement could be satisfied when the total length of the spectrometer does not exceed 4 m at a middle part diameter of 1 m ($\gamma \sim 2 \times 10^3$, the resolution being $\Delta E/E = 5 \times 10^{-4}$).

Detailed calculations of the required configuration of magnetic fields and electrostatic fields will be published elsewhere.

4. The tritium source

As has already been pointed out, most appealing is the development of a tritium source in the form of atomic polarized tritium confined in a magnetic trap by a strong field, which is the natural part of the method proposed. Reported in the literature is the successful accumulation of atomic hydrogen in a magnetic trap in a cell with the walls coated with superfluid helium at a temperature of about 0.3 K up to a density of 10^{17} atoms/cm³ with a confinement time up to several hours [8,9].

The main problem of this method of accumulation for heavy hydrogen isotopes is a recombination of atomic hydrogen on the walls on the surface of the helium film. Deuterium and tritium have an adsorption energy on

the helium surface which is much higher than that of light hydrogen, which leads to a much higher rate of recombination.

An attempt to employ the technique under consideration for the accumulation of deuterium in ref. [10] has given a maximum density of 10^{14} atoms/cm³ at a confinement time of 10–30 s. As has been pointed out by the authors of that work, the indicated parameters can be improved at least by one order. For tritium the confinement conditions are experimentally unknown, and so far there has been no reliable theory of the processes of recombination and adsorption on the helium surface.

In case the confinement conditions for tritium turn out to be not too different from those for deuterium, one may apparently expect that the density of atoms in a source should reach 10^{14} atoms/cm³ (i.e. 10^{16} atoms in a source) with a continuous feed of 10^{14} atoms/s into the source and with the regeneration of tritium deposited on the helium film in the molecular state. In this case the magnetic trap will decrease the flow of tritium into the spectrometer by 4 or 5 orders of magnitude in comparison with the method proposed in ref. [5].

In case in the near future there appear sufficiently reliable calculations of the final state spectrum for the decay of tritium in the form of T₂ or HT molecules then a molecular gaseous source of tritium can be used in the experiment.

The source in this case is a pipe with gaseous tritium, cooled down to 15–20 K and having a length of several meters and a diameter of 5 cm in a longitudinal magnetic field of 1 or 2 T which transports decay electrons. At the end of the pipe, facing the spectrometer, there are systems of differential pumping and tritium traps cooled down to 4 K, as has already been discussed previously. The transporting field of the source gradually changes to the field of the neck so that the rest of the spectrometer design remains unchanged.

The differential pumping and regeneration of tritium in a closed cycle must maintain the tritium pressure in the pipe of the source at a constant level. If the source length is approximately 3 m then for creating the total thickness of the molecular source of 5 molecular layers (10^{17} atoms/cm²) it is necessary to maintain the tritium pressure at a level of 5×10^{-4} mm Hg at a temperature of 15–20 K.

At the first stage of experimentation it is possible to use a plane surface source located behind the neck in the field H'_0 (fig. 1).

5. The detector background

The own background of a semiconductor Si (Li) detector, associated with radioactive contaminants, is usually negligible. The presence of a strong magnetic

field around the detector screens it against electrons produced on the walls of the instrument.

Only decays of tritium atoms on the detector surface can be detected. Estimates show that if no additional measures are taken then it is possible to let up to 10^6 tritium molecules per second penetrate into the spectrometer during the time of about 10^7 s without significantly increasing the background at the boundary of the beta spectrum.

Some difficulty can be presented by electrons produced in volume A' (fig. 1) on the walls where they cross the magnetic force lines along which electrons are collected. According to the foregoing, this source of the background will give a relative contribution proportional to the ratio of the surface density of tritium on the wall to the equivalent surface density of the source used. This circumstance imposed stringent requirements on the cleanliness of the rear wall since the source used has a density of only several atomic or molecular layers. The problem can be solved by providing an additional magnetic bottleneck with traps for tritium or by applying a positive potential to this wall, which shifts the electron spectrum by 1 or 2 keV.

The presence of adsorbed tritium on the rear wall may mainly be exhibited in a distortion of the spectrum shape rather than the background near the end point of the beta spectrum.

The cosmic ray background in the detector may play some part but can be significantly suppressed by an anticoincidence protection.

It may be anticipated that in such a detector the background could be decreased to a level lower than 10^{-3} I/s.

The backscattering in a variant with a gaseous or molecular source should be insignificant because electrons moving back in region A' (fig. 1) get into the region of a small field and are scattered almost isotropically. The solid angle at which electrons can return to the neck is very small and constitutes $\sim \gamma'^{-1}$, where $\gamma' = H_0/H'_0$. Thus, the correction to the shape of the beta spectrum, due to backscattering, can easily be made sufficiently small ($< 10^{-3}$).

6. Estimation of the attainable sensitivity to the antineutrino mass

The sensitivity to the antineutrino mass, that can be obtained in a real experiment, depends on a variety of parameters and sources of systematic errors. For this reason at the given stage it is necessary to characterize those distinctions from the previous experiments which can make it possible to enhance the reliability and sensitivity to the antineutrino mass. The following features can be pointed out:

- (i) The luminosity of the spectrometer can be made