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The role of electron scattering from registration detector in the "Troitsk nu-mass" MAC-E type spectrometer

P.V. Grigorieva [a,b], A.A. Nozik [a,b,*], V.S. Pantuev [a], A.K. Skasyrskaya [a]

[a] Institute for Nuclear Research of Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russian Federation
[b] Moscow Institute of Physics and Technology, 9 Institutskiy per., Dolgoprudny, Moscow Region, 141700, Russian Federation

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ABSTRACT

There is a proposal to search for a sterile neutrino in a few keV mass range by the "Troitsk nu-mass" facility. In order to estimate sterile neutrino mixing one needs to make precision spectrum measurements well below the endpoint using the existing electrostatic spectrometer with a magnetic adiabatic collimation, or MAC-E filter. The expected signature will be a kink in the electron energy spectrum in tritium beta-decay. In this paper we consider the systematic effect of electron backscattering on the detector used in the spectrometer. For this purpose we provide a set of Monte-Carlo simulation results of electron backscattering on a silicon detector with a thin golden window with realistic electric and magnetic fields in the spectrometer. We have found that the probability of such an effect reaches up to 20–30%. The scattered electron could be reflected backwards to the detector by electrostatic field or by magnetic mirror. There is also a few percent probability to escape from the spectrometer through its entrance. A time delay between the scattering on the detector and the return of the reflected electron can reach a couple of microseconds in the Troitsk spectrometer. Such estimations are critical for the planning upgrades of the detector and the registration electronics. All considered effects are relevant to any MAC-E type spectrometer with solid detector.

1. Introduction

The "Troitsk nu-mass" program is conducted by the Institute for Nuclear Research of the Russian Academy of Sciences. The original measurement to set the limit on mass of electron anti-neutrino by analyzing the tritium beta-decay spectrum was completed and the final results of these efforts were published in [1]. Currently we are expanding the energy range of measurements up to 5 keV from the endpoint with a goal to probe sterile neutrinos with masses up to 4 keV [2].

At the first stage of the new program the "Troitsk nu-mass" experiment will utilize the same layout as in the past measurements [1] but with a new spectrometer. Compared to the old one, the spectrometer has a vessel with a diameter twice as big, volume 10 times larger and magnetic field of the main magnet stronger by about 20%. There are some options of what kind of detector and readout electronics are needed to meet our requirements. Before making decision, we simulate response of the whole spectrometer system concerning tritium beta-spectrum measurement far from its end point. In this work we present the details of our spectrometer, then describe steps and results of electron scattering calculation and finally make conclusions. We have to mention that all our results described here are relevant to future experiments using a MAC-E filter spectrometer, like the KATRIN [3] extended program on search for a sterile neutrino, or PTOLEMY experiment with the goal to detect relic neutrinos [4]. While in this paper we considered only "Troitsk nu-mass" detector, back scattering effect also exists for any type of solid detector which could be used in MAC-E filter, is it silicon or cryo-bolometer or something else.

2. Troitsk nu-mass MAC-E filter

The spectrometer itself consists of a central vessel and two removable side caps, Fig. 1. The vessel is a stainless steel cylinder with a conical taper at its ends for providing transition from the diameter of the cup to the diameter of the housing central part. The sectional high voltage electrode is kept under common high voltage and is mounted on insulators.

The energy spectrum of β-electrons is measured in the spectrometer by varying the electrostatic potential applied. The electrons with energy smaller than this potential are reflected. The electrons with higher energy pass the electrostatic barrier and hit

* Corresponding author at: Institute for Nuclear Research of Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russian Federation.
E-mail addresses: nozik@inr.ru (A.A. Nozik), pantuev@inr.ru (V.S. Pantuev).

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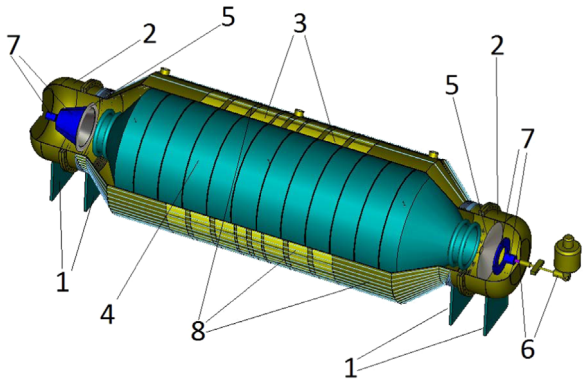

Fig. 1. General view of the spectrometer: 1 – supports, 2 – side cups, 3 – axial winding, 4 – main high voltage electrode, 5 – additional ground electrodes, 6 – detector with liquid N_2 dewar, 7 – superconducting solenoids, and 8 – correction coils.

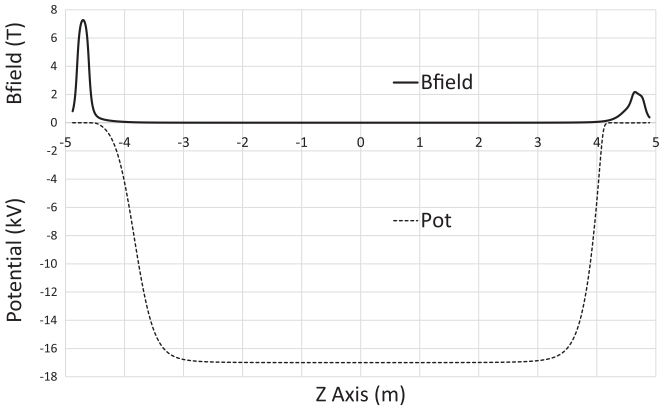

Fig. 2. The strength of magnetic and electrostatic fields in the spectrometer at its *Z*-axis. Zero *Z* is in the center of the spectrometer, the entrance – on the left, the detector – on the right.

the detector. This is the way the integral spectrum of electrons is measured. However, the retarding potential changes only the longitudinal component of the energy, $E_{\parallel} \propto v_{\parallel}^2$. Therefore, in order to get a good energy resolution one has to make the transversal energy of electrons, $E_{\perp} \propto v_{\perp}^2$, as small as possible inside the potential barrier, i.e. in the analyzing plane of the spectrometer. This is achieved by a special configuration of electric and magnetic fields, Fig. 2.

The magnetic field lines of the spectrometer form a "bottle" shape with the highest longitudinal field at the pinch-magnet located near the spectrometer entrance (on the left in Figs. 1 and 2). The field in the pinch-magnet, B_0, is up to 8 T. The lowest longitudinal magnetic field is in the analyzing plane in the center of the spectrometer (Fig. 2). The magnetic moment of a charged particle, $\mu = E_{\perp}/2B$, is an adiabatic invariant when the transversal gradient of the magnetic field is small. In this case we have $E_{\perp m} = E_{\perp 0} \cdot B_m/B_0$, where subscripts m and 0 refer to quantities in the analyzing mid-plane and in the pinch-magnet correspondingly. Therefore, the resolution of the spectrometer (spread of transversal energies of electrons) is $\Delta E_{\perp m} = E_0 \cdot B_m/B_0$, which boils down to ≈ 1.5 eV at the highest energies, $E_0 \approx 18$ keV. More details and an accurate formula are presented in [2]. The overall magnetic and electrostatic fields form the so-called electrostatic spectrometer with a magnetic adiabatic collimation or MAC-E filter. Electrons from beta-decay in the gaseous source are transported by the solenoid field into the spectrometer entrance with a high magnetic field formed by the pinch magnet. Electrons move to the center of the spectrometer following the magnetic lines and reach there a very low magnetic field of the order of 0.6 mT. Particles with energy high enough to pass the retarding electrostatic potential are then collected by another magnet and detected by a surface barrier Si detector.

The magnetic field in the spectrometer is formed by a system of two main electromagnets. Superconducting cryogenic magnets produce a field of up to 8 T at the input of the spectrometer (pinch-magnet) and up to 3 T at the detection side. The magnets are rather small, so the field quickly decreases with distance from the coils and the center of the spectrometer reaches 0.3 mT. Fine tuning of the field to the desired shape in the central part of the spectrometer is controlled by warm electromagnetic coils wound outside the spectrometer vessel. These four coils generate an additional axial field up to 0.4 mT in the central analyzing plane of the spectrometer. The Earth's magnetic field and other external transversal fields are compensated by two warm coils which can form 0.12 mT field in the transverse vertical and horizontal directions.

The additional calculations have shown that the adiabatic approximation for the magnetic moment $\mu = E_{\perp}/2B$ for 18.5 keV electrons is valid down to 13.5 kV on the high voltage electrode, which covers current measurement region. A question remains what the electron behavior will be if it scatters backwards on the detector and there is a big difference between the electron energy and the spectrometer electrostatic potential? To answer this question we have to consider the scattering first.

3. Detector and electron scattering

The current detector is a surface barrier Si(Li), 25 mm in diameter, with a gold plated 20 μg/cm^2 or 10 nm thick entrance window. The entrance window defines about 2 keV threshold. The detector aperture is limited by a copper collimator, 17 mm in diameter. There are a few options to replace this detector and electronics but we use this one as a typical example because backward electron scattering is a common feature for any kind of detectors. To simulate electron passage through the detector window and silicon we used an open Monte Carlo program CASINO v.2.42 [5]. It is designed to simulate a large amount of electron trajectories in a solid. An important feature of the CASINO code is that it allows one to calculate electrons with energies in a keV region. While there are few other software packages used for keV electron simulation (like KESS [6] software developed for KATRIN, or GEANT [7]), we decided that CASINO is suited best for this task since it is well tested in electron microscopy and therefore gives correct results for electron reflection from surfaces.

Our spectrometer as a MAC-E filter is constructed in such a way that an electron moving in variable magnetic field changes its pitch angle relative to the spectrometer axis. This angle at the entrance and at the detector follows the relation $\sin(\theta_{pinch})/\sin(\theta_{detector}) = \sqrt{B_{pinch}/B_{detector}}$. For field configuration of 7.2 T and 2.1 T in pinch and detector magnets, respectively, at the spectrometer entrance the angular range is from 0° to 90°, while at the detector position the range shrinks to 0–33°. In Fig. 3 we show how electrons move inside our detector at two impact angles as it was calculated by CASINO simulation.

There is a quite significant amount of tracks which scatter back from the detector. The probability to escape depends on electron energy and impact angle, see Fig. 4. The 10 nm gold window at the entrance gives a smaller contribution to the scattering, at the level of a few percent from number of primary electrons, Fig. 5. There are rather wide energy and angular distributions of scattered electrons, Fig. 6. The energy spectrum has a specific peak on the right corresponding to scattering on the gold window. If we