PROBING OF THE NEUTRINO MAGNETIC MOMENT AT THE LEVEL OF 10^{-12} μ_B WITH AN INTENSE TRITIUM SOURCE OF (ANTI)NEUTRINO AND HELIUM TARGET (PROJECT)

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We present R&D results of the preparation project for the experimental measurement of the (anti)neutrino magnetic moment at the level of $10^{-12}\mu_B$ using an intense tritium source of antineutrinos and liquid helium target.

I. INTRODUCTION

Minimal Extended Standard Model predicts a small value for the massive neutrino magnetic moment $\mu_\nu \sim 10^{-19}$ μ_B (Bohr magnetons), which is impossible to observe experimentally. In some extensions of the Standard Model, the neutrino magnetic moment (NMM) can reach values of about ~ $10^{-(11\div12)}$ μ_B (Ref. 1) for Majorana neutrinos. At the same time, it follows from general considerations[2] that the magnetic moment of Dirac neutrino cannot exceed $\mu_\nu \sim 10^{-14}$ μ_B. Discovery of the NMM larger than 10^{-14} μ_B would be an evidence of new physics and uniquely prove that neutrinos are Majorana particle (Majorana fermion).[3] So far the task to measure NMM with a sensitivity of $\approx 10^{-(11\div12)}$ μ_B remains a challenge.

It was suggested in Ref. 4 to probe the NMM at the level of 10^{-12} μ_B using an intense tritium source of antineutrinos (ITS) of a 1480 PBq activity and detectors of two types. These detectors – a silicon cryogenic detector based on the ionization-to-heat-conversion effect[5] and a strip avalanche germanium detector with internal signal amplification[6] – should be capable of registering electrons of an energy ~10÷30 eV from neutrino-electron scattering. However, necessary detector parameters were not attained.

It was suggested in[7] to make use of neutrino scattering on helium atom electrons. According to estimations the electromagnetic cross section is significantly enhanced at E < 1 keV compared to the cross section of the elastic scattering on a free electron. For detector with 10 kg of liquid helium and ITS of 1480 PBq activity it is possible to obtain a limit for the NMM at the level of 10^{-12} μ_B (ten times lower than existing limits).

With a perspective of using liquid helium detector we restarted works on creation of 1480 PBq ITS. It is necessary to adapt it for working with a new detector, to solve all questions of handling it at all stages of its life-cycle, of standard legal support and choice of the experiment site. It is necessary to create an ITS element prototype and demonstrate the safety of working with a source of 1480 PBq actitvity.

II. THEORETICAL BACKGROUND OF USING A HELIUM DETECTOR

In view of extremely small cross sections of antineutrino interaction with matter, the key problem in the study of the neutrino properties is that of making sensitive detectors. Differential cross sections of the inelastic interaction of antineutrinos with helium atoms were calculated in NRC "Kurchatov Institute".[7] In the energy interval below 1 keV the electromagnetic cross section is significantly enhanced compared to cross section of the elastic scattering on a free electron. Calculated cross sections are shown farther for comparison. Figure1 presents results for cross sections of neutrino-ionization of helium atoms for energies 125 eV, 10 keV and 500 keV and NMM value of 10^{-12} μ_B.

Contrary to "magnetic" ionization of germanium atom, cross sections for helium significantly exceed cross sections of scattering on a free electron. Figure 2 shows differential cross sections at small energy T transferred to electron for helium atom *He*, free electron *FE* and hydrogen-like germanium ion Ge^{+31}. Cross sections are calculated for neutrinos with an energy significantly larger than the binding energies of *K*-electrons (I = 24.6 eV for helium and I = 14 keV for germanium).

In view of these dependencies the registration of events with E < 1 keV is of practical interest. Despite larger calculated cross sections of reactor antineutrinos, the usage of an ITS with maximum antineutrino energy 18.6 keV can be a good alternative to the reactor experiment. In this case the experiment can be run in the underground laboratory allowing work with a tritium source, while the absence of gamma and neutron radiation correlated with neutrino flux facilitates solving problems with the background. In the reactor experiment the correlated neutrino background from events in the weak interaction channel should be taken into account.

Figures 3 and 4 show differential and integral cross sections of "magnetic" (solid lines) and "weak" (dashed lines) ionization of helium atoms averaged over the corresponding spectra of antineutrinos from tritium source and reactor.

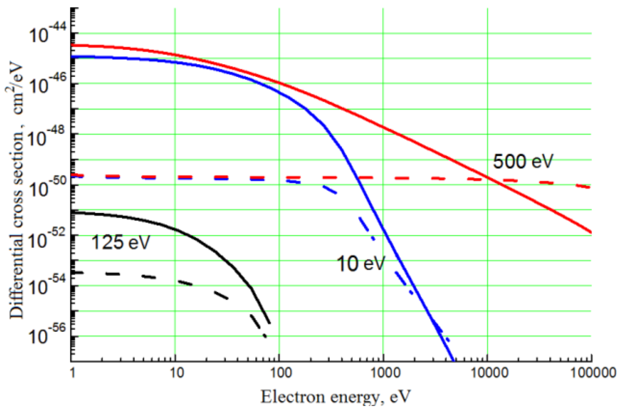

Fig. 1. Differential ($d\sigma/dT$) cross sections of "magnetic" (solid lines) and "weak" (dashed lines) neutrino-ionization of helium atoms.

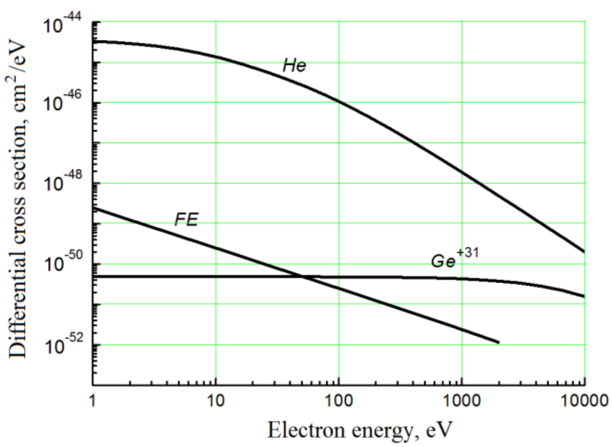

Fig. 2. Differential cross sections for helium, free electron and germanium ion.

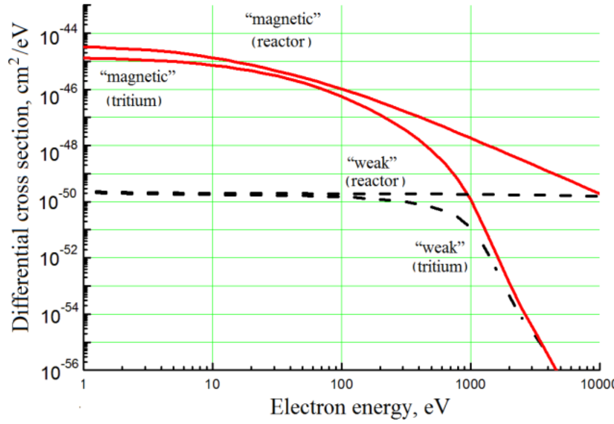

Fig. 3. Differential cross sections of "magnetic" (solid lines) and "weak" (dashed lines) scattering of reactor antineutrino.

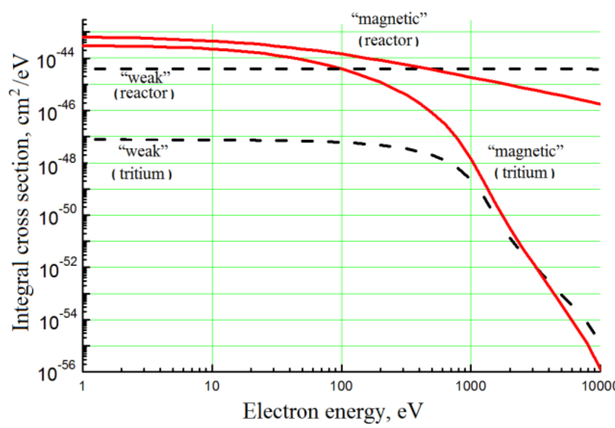

Fig. 4. Integral cross sections of "magnetic" (solid lines) and "weak" (dashed lines) scattering of reactor antineutrino.

III. DETECTOR SCHEME

Neutrino detection in the proposed scintillation detector[7] is based on the neutrino scattering on electrons of detector material atoms: $e^- + \nu = e^{-\prime} + \nu^\prime$. Thus produced fast electrons ionize and excite detector atoms. Atomic radiation in the relaxation process is detected, its parameters will allow to conclude on the neutrino properties.

Requirements to the detectors: high level of signal from the single act of neutrino scattering, high sensitivity, fast response and low level of the background from intrinsic background (radiation purity of the detector material).

As a neutrino target (liquid scintillator) liquid helium looks perspective. The choice is due to unique properties of liquid helium for registration of useful events by emission of vacuum ultraviolet (VUV) photons accompanying ionization and excitation of liquid helium atoms.[7] For liquid helium, intense scintillations in the UV part of the spectrum under ionizing radiation, transparency to the own scintillation radiation, and low level of radiative admixtures are characteristic.[8]

Scintillations in liquid helium are similar to these in other condensed noble gases. When a fast charged particle passes through the liquid multiple ion-electron pairs and excited atoms are formed. Ions attract neutral atoms and form clusters. After ion cluster recombination with an electron, an excited diatomic molecule is formed. Similarly, a diatomic helium molecule is formed when excited helium atom interacts with surrounding atoms in the ground state. This excited diatomic molecule decays emitting ultra-violet photon with wave-length of approximately 80 nm (Ref. 9). Helium transparency for its own scintillation radiation enables one to construct the detector of the arbitrary volume without signal reduction due to re-absorption.

Scintillations in liquid helium are quite well studied.[10] It is established that about 24% of electron kinetic energy are conversed to UV radiation which corresponds to 15000 photons per 1 MeV of electron initial kinetic energy. UV photons can be effectively converted to the visible part of the spectrum with wavelength shifting films, e.g., with tetraphenylbutadiene which glows blue with an emission spectrum peak wavelength at 430 nm (Ref. 9). Modern photomultipliers have peak efficiency in the blue part of spectrum. Tetraphenylbutadiene has a photon-photon conversion time about 20 ns and UV-to-blue conversion efficiency not less than 70% (Ref. 9).

Existing cryogenic systems allow obtain and support about 10 kg of liquid helium during the experiment, thus we tend using this amount.

IV. INTENSE TRITIUM SOURCE OF ANTINEUTRINO

As a source of antineutrino we suppose to use tritium β-decay. There is a possibility to create a source containing 370÷1480 PBq of tritium. Such amount of tritium should provide high antineutrino flux – at the level of $1\times10^{14}\div4\times10^{14}$ per cm^2 of the source surface per second. This flux density is by three orders of magnitude larger than the solar neutrino flux. This increase of the flux compensates a small detector volume by increasing the number of events in it. According to estimations in Ref. 7 we expect up to 10000 events per day.

Schemes of possible constructions of the liquid helium detector and the source are shown in Fig. 5, only main elements being displayed. Not shown are: cryosystem producing liquid helium, freezing system for ITS elements (total heat release from the radioactive tritium decay in the source of 370÷1480 PBq activity is 336.1 ÷ 1344.4 W) and some other systems.

The main requirements to ITS are:

- safety at all stages of the life-cycle;
- high antineutrino flux density;
- technological effectiveness of construction, storage, transportation and utilization;
- radiation purity of the materials for minimization of the background.

Starting from these requirements and using previous experience[4] we consider the source as a module construction containing an activity up to 1480 PBq in titanium tritide inside tubular elements (modules).

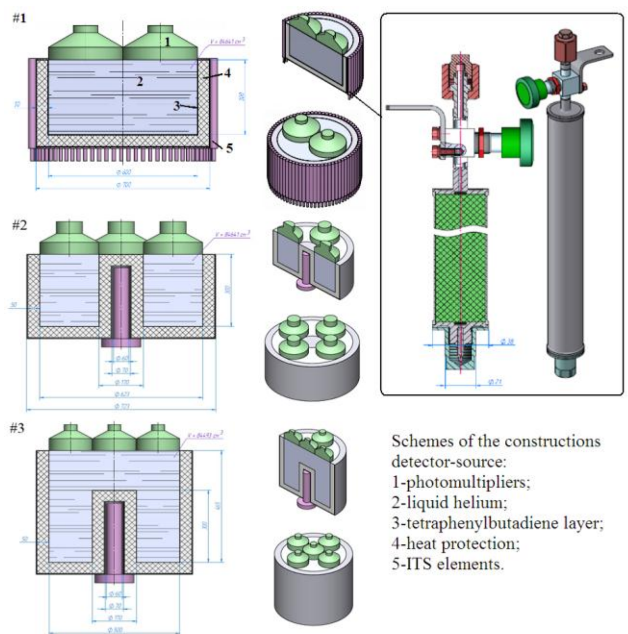

Fig. 5. Schemes of the constructions detector-ITS.

When working out various ITS constructions we performed optimization calculations using methods of imitating modeling. Basing on the obtained results we found analytical dependencies of the main source and detector characteristics versus various parameters (masses of liquid helium and tritium, height and diameter of the detector and source, titanium tritide density). These dependencies enabled an estimation of characteristics and further optimization of the construction.

Main conclusions based on results of calculations:

- Most effective construction is one consisting of co-axial cylinder-shaped source and detector (#2, Fig. 5).
- Height of the source, height and diameter of the detector are equal.
- Source and detector volumes must be coordinated among themselves.

However, in view of simplifying the detector construction, the consumption of pretty large amount of heat from the ITS, decreasing of heat flux through the detector wall, arrangement of detector systems (cryogenic, photomultipliers, etc.) construction 1 is chosen. It consists of modules shown in Fig. 5. Number of neutrino-ionizations is expected to be about 10000 per day for the magnetic moment $\mu_\nu = 4\times10^{-12}\ \mu_B$ (10 times lower than existing experimental limit).

Below we describe the main measures to satisfy the requirements to ITS which were worked during the course of R&D.

1) Safety at all stages of ITS life-cycleis is provided by following factors.

- Tritium is used as titanium tritide, due to low equilibrium tritium pressure over the surface (much less than mbar), the possibility of confining radiogenic helium in the titanium tritide structure, and rather large tritium volume density in the crystal lattice.
- The source is combined from elements (modules), each of them contains up to 50g of tritium (up to 18.5 PBq).
- Elements (modules) of the source are made as closed sources of ionizing radiation, what weakens the safety requirements at all stages of the life-cycle.
- Titanium tritide density is chosen within the interval 1.3-1.7 g/cm^3, in view of storage of radiogenic helium during planned time between manufacturing and utilization 2-3 years.
- Steel like SS316 (12X18H10T) is chosen for manufacturing of modules.
- While manufacturing the checked technologies and construction solutions are used.
- Each element will pass the total scope of tests to provide strength reliability, hermeticity, strength and functional reliability.
- Source elements will be manufactured and utilized in a special facility of the State Atomic Energy Corporation ROSATOM
- Existing technologies do allow to create source elements in existing infrastructure and later utilize tritium and radiogenic helium from the elements down to minimum residual level (0.67% from the initial amount). Special measures will allow to lower the level to 0.0045%.
- Transportation and storage in existing special certified containers of ROSATOM.
- Experiments will be carried out in additionally equipped special underground laboratory at the territory of some ROSATOM site. It must satisfy requirements to experiment site (technical possibility of working even at accidents, low background radiation, necessary infrastructure, availability of physical shield, necessary apparatus and license).
- Dosimetry control at all stages of the source life cycle.
- License for corresponding kinds of works for all participating institutions.

2) High density of antineutrino flux is provided by:

- usage of large amount (up to 1480 PBq) of active tritium;
- high tritium density inside the crystal lattice of titanium tritide;
- compact construction of source elements;
- minimal distance between source elements and detector.

3) Adaptability to manufacturing, storage, transportation, and utilization is provided by using:

- existing worked out technologies in conditions of operating special manufactures;
- certified containers for transportation and storage.

4) Radiation purity of the materials for background minimization is provided by:

- results of performed measurements of radioactive isotope admixtures in materials of various sorts;
- conformity of technical conditions and state standards in material manufacturing.

We performed heat and strength calculations of construction elements, chose main dimensions and parameters of ITS modules. Experimental models are manufactured and developed.

ACKNOWLEDGMENTS

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