

Search for Neutrino Magnetic Moment with Coherent Elastic Neutrino–Atom Scattering: The Experimental Concept

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Abstract—A description of an experimental scheme for the study of coherent elastic neutrino–atom scattering using a tritium neutrino source and superfluid He-4 detector is given. The basic concept was originally proposed in our paper in 2019 and its realization has a potential to provide a new record upper limit on the neutrino magnetic moment at a level of below $10^{-12}\mu_B$. It is currently implemented in the Sarov tritium neutrino experiment (SATURNE), which is under preparation and will employ a high-intensity tritium neutrino source with activity of 10 MCi or even 40 MCi.

Keywords: neutrino magnetic moment, coherent elastic neutrino–atom scattering, tritium neutrino source, liquid He-4 detector, SATURNE

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INTRODUCTION

The studies of neutrino electromagnetic properties can open a window to new physics [1]. This is because the neutrino magnetic moments, the most well understood and studied among neutrino electromagnetic characteristics, are zero in the Standard Model with massless neutrinos. In a minimal extension of the Standard Model the diagonal magnetic moment of a massive Dirac neutrino ν_i with mass m_i is given by [2]

$$\mu_{ii}^D = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left(\frac{m_i}{1 \text{ eV}} \right) \mu_B,$$

where e is the elementary charge, G_F is the Fermi constant, and μ_B is the Bohr magneton. The strongest upper bounds for the neutrino magnetic

moments in laboratory experiments are obtained with reactor neutrinos: $\mu_\nu \leq 2.9 \times 10^{-11}\mu_B$ (GEMMA Collaboration [3]), and solar neutrinos: $\mu_\nu \leq 2.8 \times 10^{-11}\mu_B$ (Borexino Collaboration [4]). Recently, the strongest upper bounds for solar neutrino magnetic moments have been obtained by XENON Collaboration, $\mu_\nu \leq 6.4 \times 10^{-12}\mu_B$ [5], and LZ Collaboration, $\mu_\nu \leq 1.1 \times 10^{-11}\mu_B$ [6]. Stronger constraints, at a level of $\mu_\nu \lesssim 10^{-12}\mu_B$ are provided by studies of astrophysical neutrinos (see, for example, [1]). Thus, it is an important goal of the present fundamental physics research to fill the gap between the present experimental limits and the theoretical predictions for the neutrino magnetic moments.

In our recent paper [7] we have proposed to observe coherent elastic neutrino–atom scattering (CE ν AS) using electron antineutrinos from tritium decay and a

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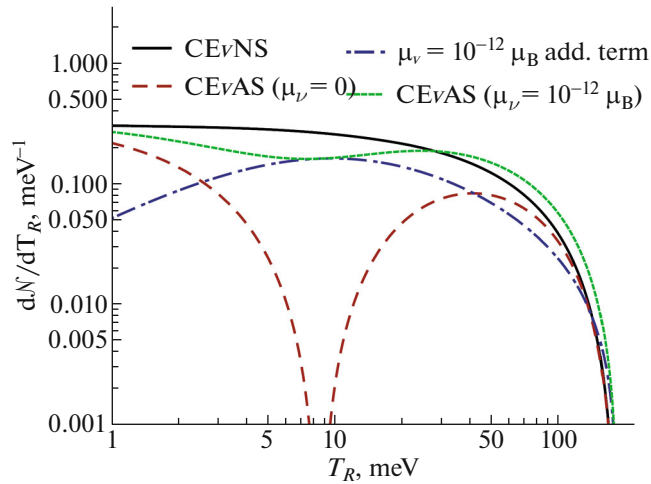


Fig. 1. Atomic recoil spectrum in CEνAS with tritium antineutrinos and liquid He-4 [7].

superfluid ^4He target. In this scattering process with the whole atom, that has not been observed so far, the electrons tend to screen the weak charge of the nucleus as seen by the electron antineutrino probe. Figure 1 shows the differential number of neutrino-induced elastic-scattering events in superfluid He-4 as a function of the atomic recoil energy T_R on a logarithmic scale [7]. The coherent elastic neutrino nucleus scattering (CEνNS) differential number is shown by the black solid line while the CEνAS one is shown by the dashed red line. The dashed-dotted blue line represents the additional term appearing in the CEνAS differential number of events assuming a neutrino magnetic moment of $\mu_\nu = 10^{-12}\mu_B$ while the dotted green line represents the total differential number of CEνAS for the same value of μ_ν . We found that it is possible to set an upper limit that is about two orders of magnitude smaller than the current experimental limits from GEMMA and Borexino. Such an experiment, SATURNE [8–10], involving an intense tritium neutrino source is already being prepared in the framework of the research program of the National Center for Physics and Mathematics in Sarov (Russia).

1. EXPERIMENTAL SCHEME

We consider a detector setup such that the tritium source is surrounded with a cylindrical superfluid-helium tank, as depicted in Fig. 2. The superfluid helium must be cryoprotected from the tritium source due to unacceptable heat production (0.328 W/g) [11]. This configuration allows us to maximize the geometrical acceptance, while allowing us to have a top flat surface where helium atoms could evaporate after a recoil. The concept of the detection method is as follows. The recoil of a helium atom after the scattering with an electron antineutrino coming from the

tritium source produces phonons and rotons which, upon arrival at the top surface, cause helium atoms to be released by quantum evaporation. An array of bolometers on the top surface detects the number of helium atoms evaporated.

The source and tank dimensions depend on the tritium source activity. For illustrative purposes, we consider the parameters specific for SATURNE, namely the tank's volume of about 1 m^3 and two values of the tritium source activity: 10 MCi (minimally expected) and 40 MCi (maximally expected).

The expected number of the CEνAS events for five years of data taking are $N^{\text{CEνAS}} = 58.9$ and 195.2 for the tritium source activity of 10 and 40 MCi, respectively. These numbers allow one to reach the sensitivity to CEνAS of at least 5σ . A successful implementation of such scheme will also allow one to test the neutrino magnetic moment at the level of $3.8 \times 10^{-13}\mu_B$ and $2.3 \times 10^{-13}\mu_B$ at 90% C.L. for 10 MCi and 40 MCi tritium source, respectively.

2. PROSPECTS

The proposed experimental scheme with a superfluid ^4He target and a tritium neutrino source will allow one to study for the first time the CEνAS process and to test the neutrino magnetic moment and other neutrino electromagnetic properties (millicharge and charge radius) at an unprecedentedly high level of sensitivity. The SATURNE Collaboration plans to start the corresponding measurements in 2027 in a low-background neutrino laboratory that will be established in Sarov for this purpose [8–10]. It is expected to use the tritium source with the activity of at least 10 MCi (1 kg of tritium) and the amount of tritium can be increased to reach 40 MCi (4 kg of tritium).

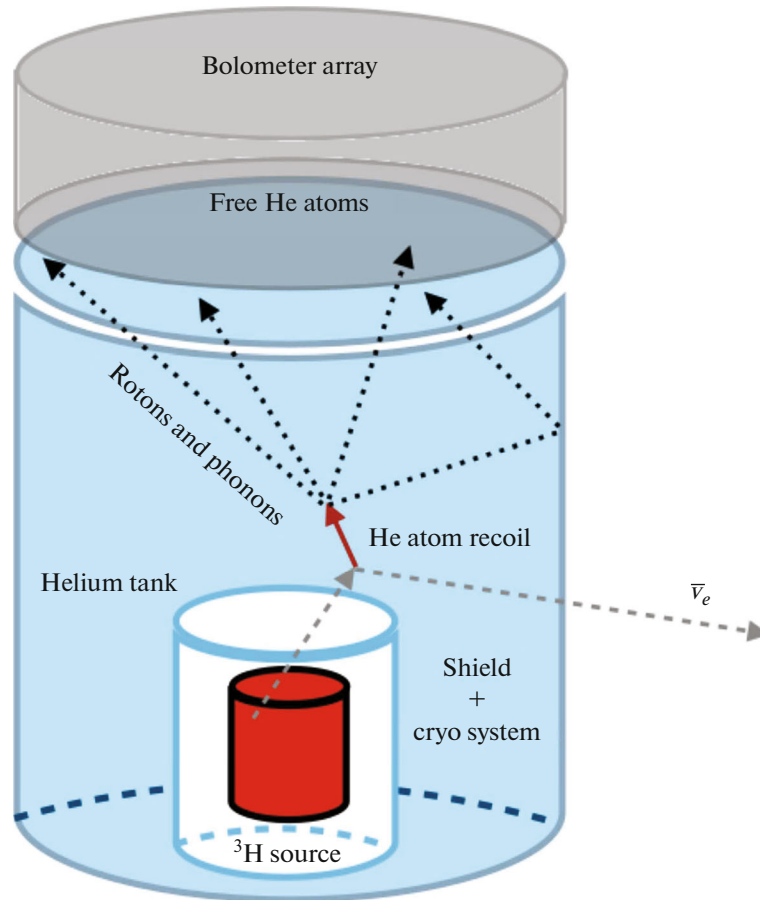


Fig. 2. Schematic representation of the detector proposed to observe the CEνAS processes.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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