

ELEMENTARY PARTICLES AND FIELDS

Experiment

Status and Physics Potential of SATURNE

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Abstract—The Sarov Tritium Neutrino Experiment (SATURNE) is designed to study coherent elastic neutrino–atom scattering (CE ν AS) and to search for the neutrino magnetic moment. The measurements will be performed in a low-background laboratory in Sarov using a liquid He-4 detector in a superfluid state and a high-intensity tritium source of electron antineutrinos. The He-4 detector with a total volume of 1000 liters will operate at a temperature between 40 and 60 mK and will be sensitive to energy signals of the order of a few meV due to the quantum evaporation channel. The tritium source will have an activity of about at least 10 MCi and possibly up to 40 MCi. It is expected that after five years of data collection, SATURNE will be able to report the first observation of the CE ν AS process. By measuring this neutrino interaction channel, it will achieve sensitivity to the neutrino magnetic moment μ_ν at a level of $\sim 10^{-13} \mu_B$, which is about an order of magnitude better than the current world-leading constraints.

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1. AN OVERVIEW OF THE SATURNE PROJECT

The Sarov tritium neutrino experiment (SATURNE) is in preparation within the framework of the scientific program of the National Center for Physics and Mathematics [1]. The key feature of SATURNE is the use of a high-intensity tritium source of electron antineutrinos with a total tritium mass of at least 1 kg (approximately 10 MCi) and possibly up to 4 kg (about 40 MCi). The principal design of the tritium neutrino source assumes a set of tubular elements, in which tritium is chemically bound to titanium (TiT₂) [2]. The mass of tritium in each tubular element does not exceed 50 g (about 0.5 MCi) and is therefore permissible for safe handling during transportation and operation, in accordance with current national and international standards.

A 1-m³ liquid He-4 detector in a superfluid state operating at a temperature between 40 and 60 mK is being developed for the first observation and study of coherent elastic neutrino–atom scattering (CE ν AS) [3, 4]. The detection method is schematically shown in Fig. 1 and is based on measuring quantum evaporation from the free surface of a He-4 liquid (see, for instance, [5] and references therein), which is induced by elastic interactions of

tritium electron antineutrinos with He-4 atoms in a superfluid. The evaporated atoms are supposed to be registered by an array of transition edge sensors (TESs) [6] suspended in vacuum above the free surface. In this way, even neutrino-induced energy signals on the meV scale can be measured.

In addition, a 4-kg cryogenic Si crystal detector and a 14-kg low-temperature SrI₂(Eu) scintillation detector are being developed. These detectors will be used in combination with the tritium source to search for the neutrino magnetic moment in elastic neutrino–electron scattering before the completion of the He-4 detector. They are designed to have the record low-energy thresholds (~ 10 eV or even ~ 1 eV for Si [7–9] and ~ 100 eV for SrI₂(Eu) [10]) in terms of electron recoil for the corresponding detector systems. This allows one to expect improving the most stringent laboratory upper limits on the neutrino magnetic moment value, which are obtained from the elastic neutrino–electron scattering data.

For conducting the SATURNE measurements, a low-background neutrino laboratory is being created at the National Center for Physics and Mathematics (see [1] for details). For this purpose, an existing shallow underground facility in Sarov is used. It is equipped with a service lift, waterproofed and meets the necessary requirements for working with a high-intensity tritium source. The facility has an overburden of about 20–25 meters of water equivalent, which is enough to sufficiently suppress the soft and hadronic components of cosmic radiation for acceptable background conditions.

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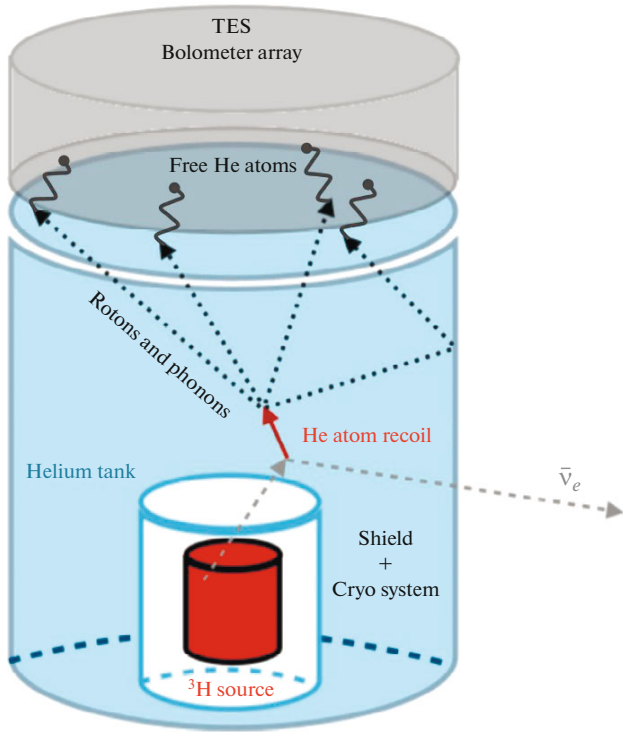


Fig. 1. The He-4 detector layout.

2. PHYSICS GOALS

The major goal of SATURNE is the first experimental study of the $\text{CE}\nu\text{AS}$ process in order (i) to test the Standard Model (SM) interactions of neutrinos at unprecedentedly low energies and (ii) to search for the neutrino magnetic moment [11, 12]. As indicated in the introduction, for the latter purpose, the inelastic neutrino–electron scattering also will be studied (while the $\text{CE}\nu\text{AS}$ measurements are being prepared).

2.1. $\text{CE}\nu\text{AS}$

The process of coherent elastic neutrino–atom scattering was predicted many decades ago by Gaponov and Tikhonov [3]. On the basis of the $V - A$ theory of weak interaction, they showed that at neutrino energies $E_\nu \lesssim 10$ keV a region of coherent optical neutrino phenomena exists where the neutrino elastic scattering by an atom as a whole dominates.

Almost half a century has passed since $\text{CE}\nu\text{AS}$ was predicted, but there are still no experimental observations. The difficulty of studying $\text{CE}\nu\text{AS}$ experimentally is largely related to the necessity of measuring very small values of transferred energy T , satisfying the coherence condition $qR_a \lesssim 1$, where $q = \sqrt{2m_a T}$ is the momentum transfer value, R_a is the atomic radius and m_a is the atomic mass. Already for light atoms ($R_a \sim 0.1$ nm and $m_a \sim$ few GeV)

such T values appear not to exceed several hundreds of meV (see below). In addition, an intense neutrino source with $E_\nu \lesssim 10$ keV is needed. The latter requirement, in particular, hinders the observation of $\text{CE}\nu\text{AS}$ in the experiments on coherent elastic neutrino–nucleus scattering ($\text{CE}\nu\text{NS}$) [13], which employ reactor and accelerator sources with typical (anti)neutrino energies of the order of a few MeV and tens of MeV, respectively.

In the case of the tritium neutrino source, the atomic recoil energy, which amounts to the energy transfer T in $\text{CE}\nu\text{AS}$, is restricted to

$$T \leq \frac{2E_{\nu,\text{max}}^2}{2E_{\nu,\text{max}} + m_a} \simeq \frac{743}{A} \text{ meV}, \quad (1)$$

where A is the atomic mass number. SATURNE will study the process of elastic scattering of a tritium $\bar{\nu}_e$ on a He-4 atom ($A = 4$),

$$\bar{\nu}_e + \text{He} \rightarrow \text{He} + \bar{\nu}_\ell, \quad (2)$$

where the final flavor ℓ can differ from the electron flavor if neutrino electromagnetic interactions are present. The expected average number of $\text{CE}\nu\text{AS}$ events within the SM after five years of collecting data with the He-4 detector in SATURNE is $N_{\text{SM}}^{\text{CE}\nu\text{AS}} = 59$ and $N_{\text{SM}}^{\text{CE}\nu\text{AS}} = 195$ for minimal (1 kg) and maximal (4 kg) anticipated amount of tritium, respectively. As was shown in [4], the footprints of the $\text{CE}\nu\text{AS}$ process within the SM can be clearly identified as a zero in the atomic recoil spectrum at $T \simeq 9$ meV. Such a marked feature is due to a complete screening of the weak nuclear charge by the weak electron charge in the He-4 atom and leads to the suppression of the $\text{CE}\nu\text{AS}$ cross section relative to the $\text{CE}\nu\text{NS}$ one. Thus, in terms of the least squares function

$$\chi^2 = \left(\frac{N_{\text{SM}}^{\text{CE}\nu\text{AS}} - N_{\text{SM}}^{\text{CE}\nu\text{NS}}}{\sqrt{N_{\text{SM}}^{\text{CE}\nu\text{AS}}}} \right)^2, \quad (3)$$

where $N_{\text{SM}}^{\text{CE}\nu\text{NS}}$ is the expected average number of elastic neutrino scattering events within SM in the He-4 detector if completely ignoring atomic electrons, SATURNE will reach the sensitivity of more than 5σ to $\text{CE}\nu\text{AS}$ after five years of taking data.

2.2. Neutrino Magnetic Moment

In the Standard Model, the neutrinos are massless particles coupled only to the Z^0 and $W^\pm$ gauge bosons. The established existence of nonzero neutrino masses opens up the possibility for neutrinos to have other beyond-SM properties. Of particular interest is the possibility for neutrinos to have electromagnetic characteristics, such as the electric charge (millicharge), charge radius, magnetic, electric and

anapole moments. The discovery of neutrino electromagnetic properties will literally open a window to new physics [11].

So far, the most studied neutrino electromagnetic characteristic, both theoretically and experimentally, is the neutrino magnetic moment. A nonzero magnetic moment for neutrinos arises already in the minimal SM extension with the addition of the right-handed Dirac massive neutrinos. The predicted value is [14]

$$\mu_\nu = \frac{3\sqrt{\alpha}G_F m_\nu}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1 \text{ eV}} \right) \mu_B, \quad (4)$$

where G_F is the Fermi constant, α is the fine-structure constant, m_ν is the neutrino mass, and μ_B is the Bohr magneton. Given the direct constraint on the neutrino mass $m_\nu < 0.45$ eV (at 90% C.L.) from the KATRIN experiment [15], the μ_ν value (4) does not exceed $10^{-19} \mu_B$ in the order of magnitude.

There are various theoretical scenarios beyond the minimally extended SM, which predict much greater μ_ν values than Eq. (4) (see [11] and references therein). Moreover, some of such theoretical predictions have been already ruled out by the world leading experimental constraints on the neutrino magnetic moment, which are obtained in laboratory experiments and astrophysics.

The strongest laboratory constraints are from the data on elastic neutrino–electron scattering. For solar neutrinos the most stringent upper bound is [16]

$$\mu_{\nu_\odot} < 6.3 \times 10^{-12} \mu_B. \quad (5)$$

It was obtained from the analysis of the data of the XENONnT experiment at Gran Sasso, Italy [17]. The most stringent upper bound for reactor neutrinos is due to the GEMMA experiment at the Kalinin Nuclear Power Plant, Russia [18]:

$$\mu_{\bar{\nu}_e} < 2.9 \times 10^{-11} \mu_B. \quad (6)$$

The most stringent astrophysical upper bounds on the μ_ν value were derived from the data on the luminosity of globular clusters [19–21]:

$$\mu_\nu < (1.2\text{--}2.6) \times 10^{-12} \mu_B. \quad (7)$$

Though these constraints are stronger than (5) and (6), they are indirect as opposed to the laboratory ones.

In the case of five-year measurements using the He-4 detector, SATURNE can achieve the sensitivity to the $\mu_{\bar{\nu}_e}$ value as high as about $(2.5\text{--}3.5) \times 10^{-13} \mu_B$ at 90% C.L., depending on the initial activity of the tritium source (the higher the intensity, the better the sensitivity). After one year of data collection with the Si (SrI₂(Eu)) detector using a tritium neutrino source with an activity of about 10 MCi, SATURNE

can achieve the $\mu_{\bar{\nu}_e}$ sensitivity of $1.6 \times 10^{-12} \mu_B$ ($2 \times 10^{-12} \mu_B$) at 90% C.L.

3. BACKGROUND ESTIMATION

Originally the detection method based on a superfluid He-4 target was proposed to study solar neutrinos [22] through their elastic scattering on electrons and nuclei in He II. This scattering will constitute the main source of the irreducible background, which is often called the neutrino “floor” or “fog”, in the He-4 detector in SATURNE. The background events due to solar neutrino–electron and –nucleus collisions in He II can be estimated employing the method of [23]. Using the experimental and theoretical data on solar neutrino fluxes (see, for instance, [24] and references therein), one thus obtains within the SM the rates of 92.5 and 94.2 events per year for respectively electron and nuclear recoils due to solar neutrinos. Though these event rates turn out to be notably larger than the expected CE ν AS event rate due to tritium neutrinos, they practically will not affect the dead time for the He-4 detector. Moreover, the solar neutrino events can be easily discriminated by their recoil energies, since the electron recoil is a threshold process, requiring the minimal energy transfer of about 24 eV (i.e., the ionization potential of the He atom), and the nuclear recoils due to solar neutrinos have an average energy of about 400 eV. Finally, in the case of a nonzero neutrino magnetic moment, the corresponding additional contribution to the solar neutrino event rates will be at the level of only 0.016 and 0.032 events per year for electron and nuclear recoils, respectively, provided the solar μ_ν value is $3 \times 10^{-13} \mu_B$, that is, about the projected μ_ν sensitivity of the He-4 detector in SATURNE.

The cosmic ray muons and associated spallation products, particularly fast neutrons, are expected to generate energy deposits in the He-4 detector that are many orders of magnitude larger than those from CE ν AS with tritium neutrinos. Whereas such background signals are typically discriminated by their energy and applying a muon veto, the corresponding event rate can critically affect the live time of the He-4 detector in terms of the quantum evaporation channel, which is slow by the standards of traditional technologies. In fact, the projected rate of muon events in the He-4 detector for the overburden of the underground facility in Sarov is 150–200 muons per second, thus reducing the live time to zero or practically zero. This means that for measurements using the He-4 detector, a much deeper underground laboratory is necessary to provide acceptable muon-induced backgrounds. For example, in the case of Baksan Neutrino Observatory as a possible alternative location for such an experiment, the projected muon rate is only 1–2 muons per day.

In addition to the cosmogenic background, there is a radiogenic background which depends on the concentration of primordial radionuclides (mainly ^{40}K , ^{238}U and ^{232}Th) and their decay chain products present in the local rock surrounding the underground laboratory. Simulations of these backgrounds performed in [5] for a simplified 100-kg He-4 detector with shielding geometry modeled on the proposed design of the SuperCDMS SNOLAB experiment [25] show that neutrons produced in the rock by spontaneous fission and (α, n) reactions from ^{232}Th and ^{238}U decays do not induce events in a one-year exposure. At the same time, gamma-induced nuclear recoils can notably dominate below the ~ 1 eV recoil energy not only over those due to solar neutrinos, but also over the projected CE ν AS recoils induced by tritium neutrinos. Thus, a much more serious gamma radiation shielding is to be developed for the He-4 detector in SATURNE.

4. OUTLOOK

The beginning of SATURNE measurements using the He-4 detector is scheduled for 2027. By 2032, it should collect enough data to reliably observe the existence of CE ν AS. This will open the next era of CE ν NS experiments, when it will be possible to explore the neutrino elastic scattering not only on an atomic nucleus as a whole, but also on an atom as a whole. With the CE ν AS channel, SATURNE has the potential to, if not discover, then at least set a new upper limit on the neutrino magnetic moment, which is almost an order of magnitude better than the current most stringent constraints.

Before the CE ν AS measurements with the He-4 detector, it is planned to study elastic scattering of tritium electron antineutrinos on electrons in the Si and $\text{SrI}_2(\text{Eu})$ detectors. Both detectors will have record low-energy thresholds for their respective types of detection systems and, upon completion of the measurements, can be used in other areas of fundamental and applied physics. After one year of collecting data in SATURNE using the Si and $\text{SrI}_2(\text{Eu})$ detectors, by 2026 and 2027, respectively, it is expected to achieve a sensitivity to the neutrino magnetic moment that is competitive with or even better than the current world leading constraints.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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