SATURNE: The Sarov Tritium Neutrino Experiment for Probing Coherent Elastic Neutrino-Atom Scattering and Neutrino Electromagnetic Interactions

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1 Introduction

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

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electric and anapole moments. The discovery of the indicated neutrino properties will literally open a window to new physics [1].

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 addition of the right-handed Dirac massive neutrinos. The predicted value is [2]

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

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. There are various theoretical scenarios beyond the minimally extended SM which predict much greater neutrino magnetic moment values compared to (1) (see the review article [1] 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. Such constraints are obtained in laboratory experiments and astrophysics (see [3] and references therein).

SATURNE will search for neutrino electromagnetic interactions in elastic and ionizing neutrino-atom collisions. A high-intensity tritium neutrino source will be employed in combination with the He-4, Si and SrI_2(Eu) targets in order to study the elastic and ionization channels of neutrino-atom collisions at unprecedentedly low energies. With studying the ionization of atoms by tritium neutrinos, SATURNE has a potential to improve the strongest laboratory limits [4] to a level that makes them competitive or even better than the world-leading upper limits [3]. It has an even greater potential with studying coherent elastic neutrino-atom scattering (CEνAS) [5, 6]. In such a case, the sensitivity to the μ_ν value can be almost an order of magnitude better than the world-leading upper limits.

2 Overview of SATURNE

SATURNE is a part of the scientific program of the National Center for Physics and Mathematics (NCPhM) that was founded in Sarov in 2021. The experiment is under preparation, with the first taking of data anticipated to begin in 2025 and the data

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collection expected to be completed by 2032. A marked feature of the experiment is the use of a high-intensity tritium neutrino source, with initial activity of at least 10 MCi and possibly up to 40 MCi. The Si and SrI_2(Eu) detectors with record low-energy thresholds for such detector types will measure the ionization channel of neutrino-atom collisions, namely

$$\bar{\nu}_e + \mathcal{A} \to \mathcal{A}^+ + e^- + \bar{\nu}_\ell, \tag{2}$$

where $\mathcal{A}$ is the atomic target, and the final antineutrino flavor ℓ may differ from the electron flavor if neutrino electromagnetic interactions are present. In its turn, the measurements with the liquid He-4 detector in a superfluid state are expected to provide the first observation of the CEνAS process

$$\bar{\nu}_e + \mathcal{A} \to \mathcal{A} + \bar{\nu}_\ell. \tag{3}$$

This will bring the experimental studies of coherent elastic neutrino-nucleus scattering (CEνNS) [7] to a qualitatively new level, namely when one will be able to explore the neutrino elastic scattering not only on a nucleus as a whole, but also on an atom as a whole.

Low-Background Neutrino Laboratory For conducting the SATURNE measurements, a low-background neutrino laboratory is being created at the NCPhM. 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 consisting of 4-m thick reinforced concrete, manufactured before the Atomic Age and in this regard pure in terms of uranium series elements, 5-m thick sand and a layer of soil, which is more than 0.5-m thick. The overburden is about 20-25 m of water equivalent, which is enough to sufficiently suppress the soft and hadronic components of cosmic radiation for acceptable background conditions.

Tritium Neutrino Source Tritium is an unstable hydrogen isotope with a half-life of 12.3 years. The tritium β^- decay,

$$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e, \tag{4}$$

produces electron antineutrinos in the energy range from 0 to 18.6 keV, with an average energy of about 13 keV. A tritium neutrino source is thus well suited for studying CEνAS that requires neutrino energies $E_\nu \lesssim 10$ keV [5].

The principal design of a tritium neutrino source was worked out in [8]: it is a set of tubular elements, in which tritium is in a chemically bound state on titanium. Titanium powder in bulk form is placed in the tubular element. Then the titanium powder is thermally activated and saturated with tritium, after which the tubular element is sealed. This tubular element design will be classified as a “closed radionuclide source”: the design of the tubular element is made in such a way that it is possible to extract tritium from it only under special factory conditions.

Si Crystal Detector The Si detector is supposed to consist of fourteen 125-cm^3 Si crystal cylinders with a total mass of 4 kg, operating at a temperature between 10 and 50 mK, surrounded with the tubular elements of the tritium neutrino source. The low operating temperature is designed to take advantage of the Neganov–Trofimov–Luke effect [9, 10], that is, when the conversion of ionization energy into heat is amplified by a (high) bias voltage. The heat is measured by microcalorimeters, for example, such as transition edge sensors (TESs) [11], which are mounted on each silicon cylinder. This may allow to achieve the energy threshold of the detector as low as about 10 eV or even 1 eV [12]. In such a case, after 1 year of collecting data with the Si detector using 1 kg of tritium, one can achieve the sensitivity to the $\mu_{\bar{\nu}_e}$ value on the order of $1.6 \times 10^{-12}\ \mu_B$ at 90% C.L.

SrI_2(Eu) Scintillation Detector The scintillation detector is assumed to be an assembly of SrI_2(Eu) crystal elements with a total mass of 14 kg surrounding the tritium neutrino source. The elements, each having dimensions of $15 \times 15 \times 50$ mm^3 and a mass of 50 g, are combined into modules with four elements per module. The operating temperature of the detector is in the range of 80–100 K. At such a temperature the thermal noise of silicon photomultipliers used for signal readout decreases sharply, thus making it possible to detect extremely low light signals (at the level of several photons only). This is expected to provide a record light collection and a detector threshold as low as 100 eV. In the latter case, after 1 year of collecting data with the SrI_2(Eu) detector using 1 kg of tritium, one can achieve the sensitivity to the $\mu_{\bar{\nu}_e}$ value on the order of $2 \times 10^{-12}\ \mu_B$ at 90% C.L.

Liquid He-4 Detector The concept of the liquid He-4 detector assumes that the tritium neutrino source is placed inside the hollow of the cylinder tank filled with a cubic meter of liquid He-4 in a superfluid state. The dilution refrigerator keeps liquid He-4 at a temperature between 40 and 60 mK. An array of about 1000 TES microcalorimeters suspended in vacuum above the helium surface registers the evaporated He-4 atoms, which are induced by scattering of electron antineutrinos from the tritium β-decay on atoms in the superfluid. The signal from the TES microcalorimeters is readout by a SQUID system. In such a way, the He-4 detector is expected to be sensitive to the energy signals below 0.1 eV. After 5 years of collecting data with the He-4 detector, one can achieve the sensitivity to the $\mu_{\bar{\nu}_e}$ value as high as $(2–3) \times 10^{-13}\ \mu_B$ at 90% C.L., depending on the initial activity of the tritium source.

3 Summary and Outlook

The tritium neutrino experiment, SATURNE, is under preparation at the NCPhM in Sarov. Its major goal is the first observation of coherent elastic neutrino-atom scattering, in order to test SM neutrino interactions at unprecedentedly low energies and to search for new physics, in particular, such as the neutrino magnetic moment. For these purposes, a low-background neutrino laboratory is being created and a high-intensity tritium neutrino source is being prepared with a tritium mass of at least 1 kg (10 MCi), and possibly up to 4 kg (40 MCi).

A 1-m^3 superfluid helium-4 detector is being developed for the first observation of coherent elastic neutrino-atom scattering. After 5 years of collecting data, by 2032, it is expected to achieve the neutrino magnetic moment sensitivity which is an order of magnitude better than the current world leading constraints [3, 4].

A 14-kg SrI_2(Eu) scintillation detector and a 4-kg Si crystal detector are being developed for studying atomic ionization by tritium neutrinos. After 1 year of collecting data, by 2026 and 2027, respectively, they are expected to achieve the neutrino magnetic moment sensitivity that is competitive with or even better than the current world leading constraints.

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