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SATURNE: Current status and physics potential

M. Cadeddu and F. Dordei

Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari,
Complesso Universitario di Monserrato S. P. per Sestu Km 0.700
09042 Monserrato (Cagliari), Italy

C. Giunti

Istituto Nazionale di Fisica Nucleare,
Sezione di Torino — Via P. Giuria 1
10125 Torino, Italy

A. P. Ivashkin[*], K. A. Kouzakov[†,‡] and F. M. Lazarev[†]

[*]*Institute for Nuclear Research, Russian Academy of Sciences,*
Prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia

[†]*Faculty of Physics, Lomonosov Moscow State University,*
Leninskie Gory, Moscow 119991, Russia
[‡]*kouzakov@gmail.com*

O. A. Moskalev

Russian Federal Nuclear Center – All-Russian Scientific Research
Institute of Experimental Physics, Mira Ave 37
Sarov 607188, Nizhny Novgorod region, Russia

I. S. Stepantsov and A. I. Studenikin

Faculty of Physics, Lomonosov Moscow State University,
Leninskie Gory, Moscow 119991, Russia

I. I. Tkachev

Institute for Nuclear Research, Russian Academy of Sciences,
Prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia

V. N. Trofimov

Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Research,
6 Joliot-Curie St., Dubna 607188, Moscow region, Russia

M. A. Verkhovtsev and M. M. Vyalkov

Branch of Lomonosov Moscow State University in Sarov
Sarov, Nizhny Novgorod region, Russia

[‡]Corresponding author.

A. A. Yukhimchuk
Russian Federal Nuclear Center – All-Russian Scientific Research Institute of Experimental Physics, Mira Ave 37 Sarov 607188, Nizhny Novgorod region, Russia

E. F. Zagirdinova
Faculty of Physics, Lomonosov Moscow State University, Leninskie Gory, Moscow 119991, Russia

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The SArov Tritium Neutrino Experiment (SATURNE), will study neutrino–atom collisions at unprecedentedly low energies for neutrino scattering experiments. A high-intensity tritium source of electron antineutrinos will be employed, with a total tritium mass of at least 1 kg (about 10 MCi) and possibly up to 4 kg (about 40 MCi). The goal of SATURNE is to provide the first experimental evidence of coherent elastic neutrino-atom scattering and to search for the neutrino magnetic moment. It is expected that the detection and measurement of the elastic neutrino–atom interaction channel will be achieved using a 1–m^3 liquid He-4 detector in a superfluid state. With five-year data from this detector, one will be able to probe the neutrino magnetic moment at a level of $\mu_\nu \sim 10^{-13}\,\mu_B$, which is an order of magnitude better than the world-leading upper limits. SATURNE will also study the ionization channel of neutrino-atom scattering. To this end, a cryogenic 4-kg Si crystal detector and a low-temperature 14-kg SrI_2(Eu) scintillation detector are being developed. Both detectors will have record low energy thresholds for their respective detector types. They are expected to achieve a sensitivity to the electron-antineutrino μ_ν value of the order of $\sim 10^{-12}\,\mu_B$ already after one year of taking data.

Keywords: SATURNE; coherent elastic neutrino-atom scattering; neutrino magnetic moment; tritium.

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1. Introduction

The SArov Tritium Neutrino Experiment (SATURNE) experiment is in preparation at the National Center for Physics and Mathematics (NCPM) in Sarov, Russia. It will search for neutrino electromagnetic interactions in elastic and ionizing neutrino-atom scattering. For these purposes, 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 scattering at unprecedentedly low energies.

According to the Standard Model (SM), neutrinos have zero mass and are coupled only to the Z^0 and $W^\pm$ gauge bosons. The nonzero neutrino masses pave the way for neutrinos to have properties beyond the SM. In particular, neutrinos can have electromagnetic characteristics,[1] which include the electric charge (millicharge), charge radius, magnetic, electric and anapole moments.

The most theoretically and experimentally studied neutrino electromagnetic characteristic is the neutrino magnetic moment μ_ν. A nonzero value of μ_ν is predicted already by the minimal SM extension with addition of the right-handed Dirac massive neutrinos[2]:

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

Here 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 μ_ν values compared to (1) (see the review paper 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, which are obtained in laboratory experiments and astrophysics.

By studying the ionization of atoms by tritium neutrinos, SATURNE has a potential to improve the strongest laboratory limits[3,4] to a level that makes them competitive or even better than the world-leading upper limits, which are obtained in astrophysics (see Ref. 5 and references therein). It has an even greater potential with studying coherent elastic neutrino-atom scattering (CEνAS).[6,7] 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. Low-Background Neutrino Laboratory in Sarov

For conducting the SATURNE measurements, a low-background neutrino laboratory is being created at the NCPM. 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.w.e., which is enough to sufficiently suppress the soft and hadronic components of cosmic radiation for acceptable background conditions.

3. Tritium Neutrino Source

One of the key ingredients of SATURNE is a high-intensity tritium neutrino source, with initial activity of at least 10 MCi and possibly up to 40 MCi.

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

$$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e, \tag{2}$$

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 $E_\nu \lesssim 10\,\mathrm{keV}$.[6]

The principal design of a tritium neutrino source was worked out in Ref. 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, and after that 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.

4. Si and SrI_2(Eu) Detectors

At present, the most sensitive and widely used method for the experimental investigation of the neutrino magnetic moment is provided by direct laboratory measurements of low-energy elastic scattering of neutrinos and antineutrinos with electrons in reactor, accelerator and solar experiments.[9–11] Since in such measurements the initial electrons are typically bound in target atoms, the neutrino-electron collision results in atomic ionization. The Si and SrI_2(Eu) detectors in SATURNE with record low-energy thresholds for respective detector types will measure the ionization channel of neutrino-atom collisions, namely,

$$\bar{\nu}_e + \mathcal{A} \to \mathcal{A}^+ + e^- + \bar{\nu}_\ell, \tag{3}$$

where $\mathcal{A}$ is the atomic target, and the final antineutrino flavor ℓ may differ from the initial electron flavor if neutrino electromagnetic interactions are present.

Let us consider the process

$$\bar{\nu}_e + e^- \to \bar{\nu}_\ell + e^-, \tag{4}$$

where an electron antineutrino with energy E_ν elastically scatters off a free electron at rest in the laboratory frame. Experimentally, one usually measures the energy transfer T. In the free-electron case, it amounts to the kinetic energy of the recoil electron, which is constrained from the energy-momentum conservation by

$$T \leq \frac{2E_\nu^2}{2E_\nu + m_e}, \tag{5}$$

where m_e is the electron mass. For tritium $\bar{\nu}_e$'s the maximal energy is $E_{\nu,\max} = 18.6\,\text{keV}$, so that $T \leq 1.26\,\text{keV}$.

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,[12,13] that is, when the conversion of ionization energy into heat is amplified by a (high) bias voltage.[14] The heat is measured by microcalorimeters, for example, such as Transition Edge Sensors (TESs),[15] 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.[16]

Table 1. The expected number of SM events $N_{\rm SM}^{\bar{\nu}_e e^-}$ and sensitivity to $\mu_{\bar{\nu}_e}$ after one year of collecting the $\bar{\nu}_e e^-$-scattering data with the Si detector in the case of 10-MCi tritium activity.

$E_{\rm th}$, eV	$N_{\rm SM}^{\bar{\nu}_e e^-}$	Sensitivity to $\mu_{\bar{\nu}_e}$ at 90% C.L.
1	10.8	$1.6\times10^{-12}\,\mu_B$
10	10.8	$1.9\times10^{-12}\,\mu_B$

Table 2. The same as in Table 1, but in the case of the SrI_2(Eu) scintillation detector.

$E_{\rm th}$, eV	$N_{\rm SM}^{\bar{\nu}_e e^-}$	Sensitivity to $\mu_{\bar{\nu}_e}$ at 90% C.L.
100	24.3	$2.0\times10^{-12}\,\mu_B$
200	22.2	$2.3\times10^{-12}\,\mu_B$
300	19.5	$2.7\times10^{-12}\,\mu_B$
400	16.6	$3.1\times10^{-12}\,\mu_B$

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 $15 \times 15 \times 25\,\mathrm{mm}^3$ and a mass of 25 g, are combined into modules with four elements per module. The operating temperature of the detector is in the range from -60 to -40°C. 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.

Tables 1 and 2 show the projected number of the SM $\bar{\nu}_e e^-$-scattering events $N_{\rm SM}^{\bar{\nu}_e e^-}$ and the μ_ν-sensitivity after one year of data collection in SATURNE using a tritium neutrino source with an activity of 10 MCi and respectively the Si and SrI_2(Eu) detectors. The projected sensitivity to the neutrino magnetic moment is presented depending on the detector's energy threshold $E_{\rm th}$ that can be achieved. It is estimated in terms of the least-square function $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$, with

$$\chi^2(\mu_{\bar{\nu}_e}) = \left(\frac{N_{\rm SM}^{\bar{\nu}_e e^-} - N^{\bar{\nu}_e e^-}(\mu_{\bar{\nu}_e})}{\sqrt{N_{\rm SM}^{\bar{\nu}_e e^-}}} \right)^2, \tag{6}$$

where $N^{\bar{\nu}_e e^-}(\mu_{\bar{\nu}_e})$ is the number of the $\bar{\nu}_e e^-$-scattering events for a given value of $\mu_{\bar{\nu}_e}$.

5. Liquid He-4 Detector

The planned SATURNE measurements using the liquid He-4 detector are expected to provide the first observation of the CEνAS process

$$\bar{\nu}_e + \mathcal{A} \to \mathcal{A} + \bar{\nu}_\ell. \tag{7}$$

This process was predicted many years ago by Gaponov and Tikhonov,[6] using the framework of the $V - A$ theory of weak interaction. They showed that at neutrino energies $E_\nu \lesssim 10\,\mathrm{keV}$ a region of coherent optical neutrino phenomena exists where the neutrino elastic scattering by an atom as a whole dominates.

Although it is almost half a century since CEνAS was predicted, it is still to be observed in experiment. The difficulty of experimental investigation of CEνAS 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 ($R_a \sim 0.1\,\mathrm{nm}$ 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 CEνAS in the experiments on coherent elastic neutrino-nucleus scattering (CEνNS),[17] 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 CEνAS, is restricted to

$$T \leq T_{\max} = \frac{2E_{\nu,\max}^2}{2E_{\nu,\max} + m_a} \simeq \frac{743}{A}\ \mathrm{meV}, \tag{8}$$

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 ($A = 4$),

$$\bar{\nu}_e + \mathrm{He} \rightarrow \mathrm{He} + \bar{\nu}_\ell, \tag{9}$$

where the final flavor ℓ can differ from the electron flavor if neutrino electromagnetic interactions are present.

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.

The $N_{\mathrm{SM}}^{\mathrm{CE}\nu\mathrm{AS}}$ and $N_{\mu_\nu}^{\mathrm{CE}\nu\mathrm{AS}} = N^{\mathrm{CE}\nu\mathrm{AS}}(\mu_{\bar{\nu}_e}) - N_{\mathrm{SM}}^{\mathrm{CE}\nu\mathrm{AS}}$ values, where $N_{\mathrm{SM}}^{\mathrm{CE}\nu\mathrm{AS}}$ and $N^{\mathrm{CE}\nu\mathrm{AS}}(\mu_{\bar{\nu}_e})$ are the expected average numbers of events within SM ($\mu_{\bar{\nu}_e} = 0$) and for a given $\mu_{\bar{\nu}_e}$ value, respectively, after five years of collecting data for minimal and maximal anticipated initial activity of the tritium source in SATURNE are presented in Table 3. SATURNE can achieve the sensitivity to the $\mu_{\bar{\nu}_e}$ value as high as about $(2.5 - 3.5) \times 10^{-13}\,\mu_B$ at 90% C.L., depending on the initial activity of the tritium source: The higher the intensity, the better the sensitivity.

Table 3. The expected number of SM and μ_ν events, $N_{\rm SM}^{\rm CE\nu AS}$ and $N_{\mu_\nu}^{\rm CE\nu AS}$, in the liquid He-4 detector after five years of collecting data.

Tritium activity	$N_{\rm SM}^{\rm CE\nu AS}$	$N_{\mu_\nu}^{\rm CE\nu AS}$	
		$\mu_{\bar{\nu}_e} = 3 \times 10^{-13}\,\mu_B$	$\mu_{\bar{\nu}_e} = 10^{-12}\,\mu_B$
10 MCi	58.9	7.8	90.1
40 MCi	295.2	27.1	298.8

6. Prospects of SATURNE

The tritium neutrino experiment, SATURNE, is under preparation at the NCPM 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. This will bring the experimental studies of coherent elastic neutrino-nucleus scattering 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. After five years of collecting data, by 2032, it is expected to achieve a neutrino magnetic moment sensitivity which is by an order of magnitude better than the current world leading constraints.

Thanks to the study of the ionization of atoms by tritium neutrinos, SATURNE has the potential to improve the laboratory limits. 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 one year of collecting data, by 2026 and 2027, respectively, they are expected to achieve a neutrino magnetic moment sensitivity that is competitive with or even better than the current world leading constraints.

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ORCID

M. Cadeddu https://orcid.org/0000-0002-3974-1995

F. Dordei https://orcid.org/0000-0002-2571-5067
C. Giunti https://orcid.org/0000-0003-2281-4788
A. P. Ivashkin https://orcid.org/0000-0003-4595-5866
K. A. Kouzakov https://orcid.org/0000-0002-4835-2270
F. M. Lazarev https://orcid.org/0009-0002-8376-6142
I. S. Stepantsov https://orcid.org/0000-0002-8620-7672
A. I. Studenikin https://orcid.org/0000-0003-3310-9072
I. I. Tkachev https://orcid.org/0000-0003-1681-8408
M. M. Vyalkov https://orcid.org/0009-0000-6230-7292

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