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New process in superfluid ^{4}He detectors: The coherent elastic neutrino-atom scattering

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We propose an experimental setup to observe coherent elastic neutrino-atom scattering (CEνAS) using electron antineutrinos from tritium β^- decay and a liquid helium 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. The interference between the nucleus and the electron cloud produces a sharp dip in the recoil spectrum at atomic recoil energies of about 9 meV, reducing sizably the number of expected events with respect to the coherent elastic neutrino-nucleus scattering case. This technique allows, in principle, to measure the weak mixing angle at energy scales never reached before. In addition, such a low-energy experiment could provide a sensitive test of the neutrino magnetic moment, setting, potentially, a stronger limit than the current ones.

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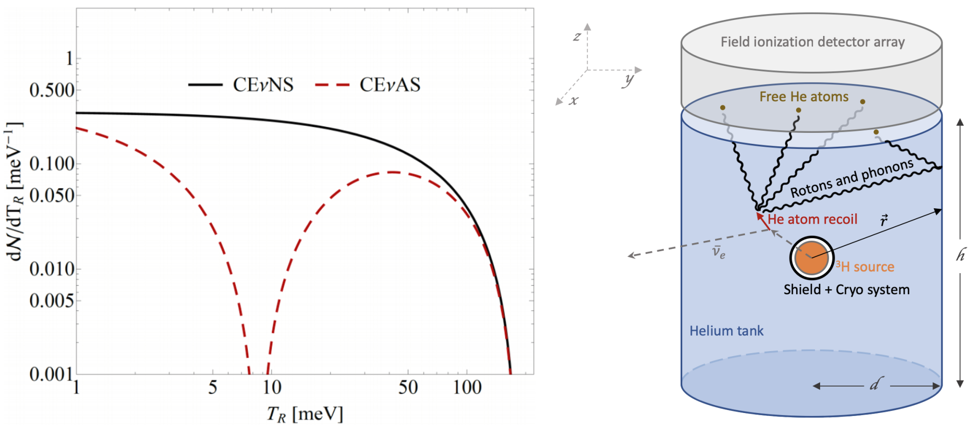
1. Coherent Elastic Neutrino Atom Scattering

A very important breakthrough within neutrino physics has been obtained in 2017 with the first observation of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) by COHERENT Collaboration with a CsI detector [1] and in 2020 with a liquid argon detector [2], forty years after its prediction [3]. These observations opened a very promising window for new physics investigations and measurements of neutron distributions radii [4, 8], weak interaction parameters [5, 8], neutrino-electromagnetic properties [6–8] and physics beyond the Standard Model [9, 10]. These analyses have very unique characteristics because of the low momentum transfer involved in the process. Indeed, CEνNS interaction requires a neutrino scattering off a nucleus at an energy scale low enough to guarantee the coherence of the process. Under this consideration, one could think about the neutrino probing a given size of the target depending on the momentum transfer, information quantitatively embedded in the so-called form factors $F(q^2)$. At very low momentum transfers, such that $qR_{\text{atom}} \ll 1$, where R_{atom} is the radius of the target atom including the electron shells, the reaction can be viewed as taking place on the atom as a whole [11]. Satisfying this condition is translated into the condition of $q \ll 2\,\text{keV}/R_{\text{atom}}[\text{Å}]$, where $R_{\text{atom}}[\text{Å}]$ is the atomic radius in angstroms. Choosing a target of helium, the atomic size is $R_{\text{atom}} \sim 0.5$ Å, meaning that this effect is expected to be important for atomic recoil energies of $O(\text{meV})$. The detection of this process, called Coherent Elastic Neutrino-Atom Scattering (CEνAS), might unlock a door for the looking at weak-interaction neutrino physics at scales never reached before, of the order of $\langle q \rangle \simeq 20$ keV. The differential cross section of CEνAS for a spin-zero target is proportional to the square of the q^2-dependent matrix element of the vector neutral-current charge for atomic processes: $C_V^{\text{Atom}} = \frac{1}{2}[(1-4\sin^2\vartheta_W)Z\,F_{\text{Z}}(q^2) - N\,F_{\text{N}}(q^2) + (\pm 1 + 4\sin^2\vartheta_W)Z\,F_{\text{e}}(q^2)]$, where ϑ_W is the weak mixing angle, Z and N are the number of protons and neutrons in the atom, $F_{\text{N}}(q^2)$, $F_{\text{Z}}(q^2)$ and $F_{\text{e}}(q^2)$ are the neutron, proton and electron form factors, respectively. The minus sign applies to ν_e and $\bar{\nu}_e$ giving rise to the destructive interference between the electron and nuclear contributions at atomic recoil energies around $T_R \simeq 9$ meV (Fig. 1(a)), while the minus sign applies to all the other neutrino species. Such a process could be very suitable for the investigation of neutrino physics. Unfortunately, the downside arises from the detection point of view, since detecting such a small energy is very challenging. In the next section we will describe a possible solution to overcome this issue.

2. Experimental setup for CEνAS detection

In Fig. 1(b), we propose a future experiment that would allow the observation of CEνAS. In order to achieve a sufficient number of low-energy CEνAS events, electron neutrinos with energies of few keV need to be exploited. One promising source producing such low-energy neutrinos is tritium β-decay source, that is characterized by a Q-value of 18.58 keV. The small recoils produced by CEνAS are well below the thresholds of currently available detectors. However, a new promising technology based on the evaporation of helium atoms from a cold surface and their subsequent detection using field ionization is taking place. Nuclear recoils produce elementary excitations (phonons and rotons) in the target that can result in the evaporation of helium atoms, with a threshold of about 1 meV, representing an ideal experimental setup to observe neutrino-atom



(a) (b)

Figure 1: (a) Differential number of neutrino-induced events on helium atoms as a function of the atomic recoil energy T_R, for CEνNS (black solid line) and CEνAS (dashed red line). (b) Schematic representation of the detector proposed to observe CEνAS. The recoil of a helium atom after the scattering with an electron antineutrino coming from the tritium source produces phonons and rotons which cause quantum evaporation.

effects. We estimated that to observe at 3σ CEνAS processes it is necessary to use a tritium source of about 60 g, a tank filled with about 500 kg of liquid helium (contained in a cylinder of height 160 cm and radius 90 cm) and a data-taking period of about 5 years. Some of the possible and unique measurements exploiting this process are better described in [12].

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