Physics with Electron Capture Neutrino Sources

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NF Topical Groups:
☐ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
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☐ (NF7) Applications
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■ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors
■ (Other) Cosmic Frontier

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Abstract: Mega-Curie Electron capture sources, like ^{51}Cr, produce monoenergetic beams of electron neutrinos that can be deployed to existing underground sites and paired with existing ton-scale, low-threshold detectors to for an array of interesting physics searches including sterile neutrinos, neutrino magnetic moments and other BSM searches. Further, advances in very low threshold bolometric detectors may soon make it possible to detect electron capture neutrinos via coherent elastic neutrino nucleus scattering. Combining such detectors and sources results in a compelling search for total neutral current disappearance, a model specific prediction of the sterile neutrino hypothesis.

Introduction

Since the 1970's, EC neutrino sources have been proposed as a means to calibrate the detection efficiency of solar radio-chemical detectors. In the mid-90's the gallium experiments, GALLEX [1] and SAGE [2], pioneered the use of mega-Curie (MCi) scale EC sources, producing them on four separate occasions (see table 1). GALLEX made two ^{51}Cr sources [1, 3] while SAGE made one of ^{51}Cr [2] and one of ^{37}Ar [4]. Within the last year, The BEST experiment, a two-zoned radio chemical experiment, which descends from SAGE and is intended to search for sterile neutrino oscillations, has produced the largest EC source yet: a ^{51}Cr source with an initial strength of 3.4 MCi. That the SAGE/BEST group chose ^{51}Cr solidifies its position as the most accessible EC isotope. This is largely due to the fact that ^{37}Ar is made by fast neutron-alpha exchange on ^{40}Ca, which requires a large fast-neutron reactor, but there are no such reactors currently in operation anywhere in the world.

Electron capture (EC) isotopes decay by absorbing an atomic electron and emitting a neutrino. As with a β^+ decay, the Z of the nucleus decreases by one unit. The result is a two body final state of the neutrino and daughter nucleus which emerge back-to-back in the rest frame to conserve momentum. As such, the neutrino carries away nearly all of the decay energy, producing a mono-energetic and isotropic beam of electron neutrinos with typical energies in the range of 0.5 to 1.5 MeV. For most decays the only visible sign is an x-ray that comes from refilling the voided inner-shell electron orbital, although some EC isotopes have a non-zero capture fraction to an excited state of the daughter nucleus, in which case the decay is accompanied by the emission of one or more gammas.

In contrast, ^{51}Cr is made by exposing enriched ^{50}Cr to the high thermal neutron flux in the core of a nuclear reactor. Care must be taken to remove other isotopes that could be activated in the core, which would make the source more difficult to handle and introduce backgrounds in your neutrino detector. There have been at least two studies of MCi scale ^{51}Cr source production at Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR) [6, 7]. The most recent study, conducted in 2017, concluded that a source with an initial strength of 5 MCi should be feasible [7].

The main branching fraction of the ^{51}Cr decay goes straight to the ground state of ^{51}V producing a 750 keV neutrino. This occurs 90% of the time. The remaining 10% of decays go to an excited state and are accompanied by a 320 keV gamma, while producing a 430 keV neutrino.

Future Experimental Concepts Based on EC Sources

Beyond the calibration of radio chemical neutrino detectors, there have been many proposals to use EC source for a wide range of neutrino physics, including sterile neutrino searches, neutrino magnetic moment searches, and searches for a wide range of other beyond standard model (BSM) physics. One of their main advantages, is that unlike nuclear reactors, these source can be transported to existing underground sites and paired with existing detectors that were (or are being) constructed to do other physics, such as WIMP dark matter searches and solar neutrino detection.

Experiment	Isotope	Strength	Production Process
GALLEX [3]	^{51}Cr	1.69 MCi	Thermal neutron capture on ^{50}Cr
SAGE [2]	^{51}Cr	0.517 MCi	Epithermal neutron capture on ^{50}Cr
GALLEX [1]	^{51}Cr	1.87 MCi	Thermal neutron capture on ^{50}Cr
SAGE [4]	^{37}Ar	0.409 MCi	Fast neutron ^{40}Ca$(n, \alpha)^{37}$Ar
BEST [5]	^{51}Cr	3.4 MCi	Thermal neutron capture on ^{50}Cr

Table 1: Mega-Curie-scale electron capture neutrino sources that have been produced.

Several studies have examined their potential for use in sterile neutrino searches via short-baseline oscillations. In this context the mono-energetic nature of the EC beam means that the oscillation will manifest as a pure function of distance from the source (L) which makes it possible to use non-spectral detector technologies, like radio chemical detectors, and non-spectral neutrino scattering processes like electron elastic scattering (ES) and coherent elastic neutrino nucleus scattering (CEvNS). Concepts include:

- LENS-Sterile – utilizing the charged current (CC) interaction on ^{115}In [8],
- Ricochet – a proposal for an array CEvNS detectors at a range of baselines [9],
- BEST – a two zone radio chemical experiment, that is currently underway in Russia [5],
- Pairing with ton-scale liquid xenon (LXe) detectors and using ES with a very low-energy threshold and very high spatial precision [10].

Perhaps the most experimentally challenging approach is based on CEvNS detection, but if the hints of short-baseline oscillations are confirmed in either the CC or ES channels, then a search for total neutral current disappearance will be required to test a central prediction of the sterile neutrino hypothesis. The large CEvNS cross section makes this approach very interesting and goal of achieving the required low-detection threshold is driving advancements in cryogenic detector technology. The challenge comes from the fact that nuclear recoils occur at very low energies, *e.g.* $\mathcal{O}(10)$ eV nuclear recoils for silicon. Quenching factors at these energies have not been measured, but it is possible that they are very low or zero, such that ionization readout is unlikely to be feasible. Measuring the recoil energy through its heat signature (phonons) in cryogenic crystals is being actively studied. A detector needs to have sub-10 eV energy resolution in order to see the CEvNS signal from a ^{51}Cr source. Detectors with energy resolution in this range have been demonstrated [11–13], but the mass of these detectors is still quite small. R&D into scalable low-threshold detector and readout technologies to design an $\mathcal{O}(10)$ kg experiment with thousands of detectors is needed to realize this measurement.

In addition to sterile neutrinos, pairing an EC source with ton-scale LXe detectors such as LZ [14] and XENONnT [15] would open up a range of new physics topics. For example [10], with an order 1 keV electron-equivalent detection threshold, a 6 ton detector and a 5 MCi source, searches for neutrino magnetic moments in the ES channel would have sensitivity that is an order of magnitude better then the best terrestrial limit [16] and comparable to astrophysical limits [17]. Similarly, searches for a wide range of BSM physics from generalized four-fermion interactions to light-boson mediated interactions could be probed with unprecedented sensitivity [18]. Finally [19], an EC source deployment has shown to be an effective way to test the hypothesis that a larger-than-expected neutrino magnetic moment is responsible for the XENON1T low-energy excess [20].

What Should be Done

Given existing world-class facilities like HFIR, we believe that, with a modest investment, the US could develop a MCi ^{51}Cr source capability that would create new physics opportunities for large dark matter detectors like LZ and XENONnT, and continue to drive development in low-threshold detector technologies that will, in turn, enable new physic measurements. We submit that this should be a priority area for small scale experimental investment. We also note that this activity will require high-level cooperation between the **Cosmic Frontier**, which has primary responsibility for large dark matter detectors and related low-threshold detector development, and the **Intensity Frontier**, which is responsible for neutrino sources.

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