Coherent elastic neutrino-nucleus scattering

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Abstract. I describe physics potential and experimental prospects for coherent elastic neutrino-nucleus scattering (CEvNS), a process which has not yet been observed. Germanium-based detectors represent a promising technology for CEvNS experiments. I focus primarily on stopped-pion neutrino sources.

1. Coherent elastic neutrino-nucleus scattering
Coherent elastic neutrino-nucleus scattering ("CEvNS\(^1\)) is a process involving the neutral-current scattering of a neutrino with an entire nucleus \([1, 2]\). It has a well-defined rate in the standard model, given by (for a spin-zero nucleus and neglecting radiative corrections):

\[
\frac{d\sigma}{dT}(E, T) = \frac{G_F^2}{2\pi} M \left[ 2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2} \right] \frac{Q_w^2}{4} F^2(Q^2). \tag{1}
\]

where \(E\) is the incident neutrino energy, \(T\) is the nuclear recoil energy, \(M\) is the nuclear mass, \(F\) is the ground-state elastic form factor, \(Q_w\) is the weak nuclear charge, and \(G_F\) is the Fermi constant. For nuclei in the medium-\(A\) range, the process remains largely coherent (i.e., all nucleon wavefunctions in phase) for neutrino energies up to a few tens of MeV. The cross section is relatively high, boosted by an \(\sim N^2\) enhancement, compared to other charged- and neutral-current processes in the same energy range. It potentially even has practical applications \([3, 4]\), thanks to the large cross section.

Although observation of this process has been sought for decades, the experimental signature—very low energy nuclear recoils in the tens-of-keV or less regime—is a challenging one. Only with recent detector developments has good sensitivity to very-low-energy nuclear recoils been feasible. In particular, the experimental search for WIMP dark matter, which has a similar nuclear recoil signature (and in fact for which neutrinos represent a background floor \([5, 6]\)), has driven detector development to enable CEvNS observation.

\(^1\) Note there exist a number of abbreviations for this process in the literature, e.g., CNS, CNNS, CENNS. I favor a version with "E" for "elastic" to distinguish the process from inelastic coherent pion production, which is commonly confused with CEvNS by members of the high energy physics community. I prefer to replace the first "N" with "ν", for "neutrino", for two reasons: first, "NN" means "nucleon-nucleon" to many in the nuclear physics community. Second, this disambiguates from CENNS, which is the name of an experimental collaboration. Finally, the Roman letter "ν" is less cumbersome than the Greek letter "\(\nu\)".
2. Sources and detectors

The CEvNS cross section increases with energy, so in general to detect CEvNS, one wants a relatively high-energy neutrino source. Moreover, the maximum nuclear recoil energy is given by $E_{\text{max}} = \frac{2E_{\nu}^2}{M}$ (see Fig. 1), and the higher the recoil energy of the nucleus, the easier it is in general to detect. Figure 1 shows an example recoil spectrum for 3 and 30 MeV neutrinos, given the same flux, demonstrating both the higher rate and higher recoil energies for higher neutrino energy. However, the neutrino incident energy must not be too high, or else inelastic interactions will begin to dominate (i.e., neutrinos will scatter off individual nucleons inside the nucleus, rather than with the nucleus as a whole— the neutrino wavelength shrinks with increasing energy, and the coherence condition is $Q \sim< 1/R$). For germanium, neutrino energies must be less than about 50 MeV to ensure coherence.

Desirables for a neutrino source for CEvNS detection include:

- High flux
- Well-understood spectrum
- Multiple flavors (helpful for testing new physics)
- A pulsed source if possible, for background rejection
- Ability to get close to the source; flux increases as inverse square of distance
- Practical aspects, such as access and control.

Natural sources of neutrinos suitable for CEvNS detection exist: a nearby core-collapse supernova will create an intense burst, feasibly visible over background, in dark matter detectors (e.g., [7]). Diffuse supernova background neutrinos, solar neutrinos, and the low-energy end of the atmospheric neutrino flux are also in principle observable (geoneutrinos are in principle observable also, but their energies are so low as to produce extremely low-energy recoils). However such steady-state fluxes of natural neutrinos are relatively small and would require enormous detectors, and subject to large backgrounds (perhaps including dark matter!)
Supernova burst neutrinos come in a high-flux pulse, but unfortunately, not on demand. That leaves us with artificial sources for near-term prospects.

There are several candidates for artificial neutrino sources for CEvNS detection. Reactors are among the most promising, producing enormous fluxes of $\bar{\nu}_e$ (and CEvNS has possible practical use for reactor monitoring [3, 4]). However, reactor neutrino energies range only up to $\sim 7$ MeV, presenting the experimentalist with the significant challenge of detecting mostly sub-keV recoils (see Fig. 1). Furthermore, these are steady-state sources and backgrounds must therefore be kept well under control. Radioactive sources can also be made quite intense; however these have typically even lower energies than reactor neutrinos. Beam-induced radioactive sources, such as IsoDAR [8], are under development; neutrino energies are still lower than 15 MeV and neutrino production steady-state; nevertheless they are interesting. Storage rings of boosted decaying nuclei, the so-called “beta beams”, which have tunable energy, could also be very interesting [9]. These, too, are steady-state sources and so require excellent background rejection. These latter two kinds of sources, while possibly interesting for the future, do not yet exist.

The remaining near-term possibility for an artificial neutrino source for CEvNS detection is a pion decay at rest (stopped-pion) source. Such sources have previously been used successfully for neutrino physics [10, 11]. The idea is to irradiate a dense target with a proton beam (preferably with proton energies below kaon production threshold). The resulting pions decay at rest, producing neutrinos of muon, electron, and muon antineutrino flavor with well understood spectra, as shown in Fig. 2. These neutrinos have high enough energy to produce promising-to-detect recoils, yet have energies low enough to result in a high fraction of coherent interactions in most detector targets.

Table 1 contrasts the pros and cons of reactor and stopped-pion neutrinos for CEvNS detection.

| Source         | Flux $\nu$'s per second | Flavor | Energy        | Pros                        | Cons                          |
|----------------|-------------------------|--------|---------------|-----------------------------|-------------------------------|
| Reactor        | $2 \times 10^{20}$ per GW | $\bar{\nu}_e$ | few MeV       | huge flux                   | lower cross section           |
|                |                         |        |               |                             | low energy recoils            |
|                |                         |        |               |                             | steady-state                  |
| Stopped-pion   | $1 \times 10^{15}$      | $\nu_\mu$ | 0-50 MeV      | higher cross section        | lower flux                    |
|                |                         | $\nu_e$ |               | higher energy recoils       | in-time neutrons              |
|                |                         | $\bar{\nu}_\mu$ |         | pulsed beam                |                               |
|                |                         |        |               | multiple flavors            |                               |

Table 2 summarizes properties of past, existing and future stopped-pion sources worldwide. Figure 4 plots these in a figure-of-merit space. Neutrino flux is roughly proportional to power, so higher power is better. The larger the reciprocal duty factor, the better for background rejection (although beam time windows smaller than the muon decay timescale provide only marginal improvement for the delayed flux).

Of these, the Spallation Neutron Source (SNS) in Oak Ridge, TN, provides an excellent prospect [15]. The SNS uses a proton beam energy of about 1 GeV incident on a liquid mercury target, for total power up to 1.4 MW, and resulting in about $8 \times 10^{14}$ neutrinos per flavor per second produced at the source. The repetition rate is 60 Hz, and pulse width is about 700 ns, resulting in a background rejection factor of $10^{-3}$ to $10^{-4}$. Because the proton energy is not
Figure 2. Top: SNS neutrino production mechanism [12]. Bottom: resulting neutrino spectrum (flux in arbitrary units) from pion decay at rest.

Table 2. Characteristics of past, current and planned stopped-pion neutrino sources worldwide.

| Facility   | Location           | Proton Energy (GeV) | Power (MW) | Bunch Structure | Rate (Hz) |
|------------|--------------------|---------------------|------------|-----------------|-----------|
| LAMPF      | USA (LANL)         | 0.8                 | 0.8        | 600 μs          | 120       |
| ISIS       | UK (RAL)           | 0.8                 | 0.16       | 2 × 200 ns      | 50        |
| BNB        | USA (FNAL)         | 8                   | 0.032      | 1.6 μs          | 5-11      |
| SNS        | USA (ORNL)         | 1.3                 | 1.4        | 700 ns          | 60        |
| MLF        | Japan (J-PARC)     | 3                   | 1          | 2 × 60-100 ns   | 25        |
| CSNS       | China (planned)    | 1.6                 | 0.1        | <500 ns         | 25        |
| ESS        | Sweden (planned)   | 1.3                 | 5          | 2 ms            | 17        |
| DAE9ALUS   | TBD (planned)      | 0.7                 | ∼ 7 × 1    | 100 ms          | 2         |
Figure 3. Time and energy distributions (arbitrary units) for the different neutrino flavors produced at the SNS. The top plots are from a 2003 study [13]; the bottom plot shows proton beam structure on target from recent SNS running [14]. The prompt (pion-decay) component of the neutrino flux should closely follow the proton time structure.

too high (below kaon production threshold), the contamination from non-DAR-pion neutrinos should be small. This neutrino source is of extremely high quality.

Expected event rates for CEvNS in various targets are shown in Fig. 5. The effect of kinematics is seen here: the heavier the target, the more events are expected, but fewer are kicked to high recoil energy. Germanium rates are promising for detection thresholds less than a few tens of keV.

3. Physics sensitivity
The cross section for CEvNS is very cleanly predicted in the standard model; hence, a deviation could be the signature of beyond-the-SM physics. Because of the dependence of the cross section on the weak mixing angle, in the context of the standard model, it represents a new channel for measuring $\sin^2 \theta_W$— so a deviation from prediction would mean potentially new physics. The weak mixing angle measurement in a first-generation experiment would not likely have better precision than other current experiments [16]. However, certain new physics that is not probed by the existing weak mixing angle measurements — in particular, non-standard interactions (NSI) of neutrinos with quarks — would result in an anomalous interaction rates. Even a first-generation measurement would provide constraints an order of magnitude better than existing ones [17, 18, 19]. Multiple types of targets, with different $N$ and $Z$, will be advantageous for cancelling systematics. Other possibilities are neutrino magnetic moment searches [17].
the longer term, after experimental precision exceeds that of the current knowledge of nuclear form factors [20, 21, 22], a CEvNS measurement can in principle probe these nuclear form factors via precision spectral shape measurements. Another potentially interesting far-future prospect is the sensitivity to sterile neutrino oscillations; because the channel is neutral current, and hence flavor-blind, a disappearance experiment could probe parameter-space regions of current interest [23]. Note that because the CEvNS process represents a background “floor” for dark matter detection experiments [5, 6], it is essential to measure it to confirm predictions. The CEvNS process is astrophysically important, playing a role in supernova processes and detection [7], and may even potentially be used for solar neutrino physics [24].

A first measurement could in principle be made at a pion decay-at-rest neutrino source with a few to a few tens of kilograms of detector material. For such a “first light” experiment, precision understanding of flux and stringent control of systematic uncertainties is not needed. A next-phase experiment, up to a few hundred kilograms, could provide new constraints on NSI of neutrinos with quarks, and will start to become limited by systematic uncertainties. An eventual tonne- or multi-tonne-scale experiment could probe nuclear physics, and with low enough energy threshold, also potentially search for large neutrino magnetic moment. Exacting control of systematics will be required at this stage.
Figure 5. CEvNS events from the muon-decay component of the pion decay-at-rest flux over recoil energy threshold for different materials for a location 20 m from the SNS target. The rates are for spin-zero isotopes $^{20}\text{Ne}$, $^{40}\text{Ar}$, $^{76}\text{Ge}$, $^{132}\text{Xe}$, but should be similar for other isotopes.

4. Prospects for near-future measurements

While there are several very interesting proposals for measuring CEvNS at reactors with various technologies, including germanium-based (e.g., [25, 26, 27]), I will focus here on proposals to use pion decay-at-rest neutrinos.

4.1. COHERENT

The COHERENT collaboration is newly formed and aims to use the SNS at Oak Ridge National Laboratory [28]. The aim is to make a CEvNS measurement with as many different detector targets as resources permit. Three technologies are currently under consideration: two-phase liquid xenon, CsI[Na], and germanium. The germanium-based detectors under consideration are high-purity PPC technology, deployed as MAJORANA Demonstrator-like strings [29]; see Figs. 6 and 7. An initial deployment of a few kg could be increased to a few tens of kg. Fig. 8 shows the expected differential recoil spectrum.

Neutron-induced nuclear recoils are the most significant background. While cosmic neutrons and other cosmogenic and ambient backgrounds can be well understood from data outside of the beam pulse window and subtracted, beam-related neutrons are more worrisome. A background campaign over 2013-2014 using scintillator neutron detectors has found some promising sites at the SNS, including one with some overburden in the basement. Neutrino-induced neutrons from charged- and neutral-current interactions in a lead shield surrounding the detectors may cause some non-negligible background [30].

2 These neutrino-induced neutrons are interesting in themselves, for e.g., supernova detection [31], and measurements are underway.
Figure 6. Canberra Broad-Energy Germanium (BEGe) PPC-type detectors in the Majorana Demonstrator detector mounting hardware. Left: a single mounted detector with low-mass front end electronics. Right: A string of 5 detectors with total mass of $\sim 3$ kg (Photo credit: Matthew Kapust, Sanford Underground Research Facility). From reference [28].

Figure 7. A Majorana Demonstrator modular cryostat with capacity of $\sim 20$ kg of germanium detectors, deployed in a potential passive shield of copper and lead. From reference [28].

4.2. CENNS
Another collaboration aiming to exploit stopped-pion neutrinos for CEvNS measurement is the CENNS collaboration [32]. Here the idea is to exploit the Fermilab Booster Neutrino Beam flux at a far off-axis location, where the flux is dominated by pion decay-at-rest neutrinos. The detector concept is a single-phase argon detector in a water shield, similar to the proposed CLEAR detector [33]. Background measurements using the SciBath detector [34] have characterized the beam-related neutron background, to determine required levels of shielding for a measurement. The background rejection factor is quite good, although flux is relatively low (see Fig. 4).
5. Summary

In summary, CEvNS measurements offer a number of interesting physics prospects. The low-hanging fruit is NSI, for which significant constraints can be set even in a first-generation program. Future-generation experiments will have a broad physics program. For the first measurements, requirements are not terribly stringent; however in the long term, multiple targets and well understood systematics will be necessary. Pion decay at rest sources are particularly attractive, thanks to high cross sections and recoil energies, as well as good background rejection. Reactor sources are attractive for high fluxes. Many interesting detector strategies have been proposed, including germanium, such as for the COHERENT proposal. Prospects are good for near-term measurements.

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