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MEMORANDUM

To: Roy Schwitters

From: Peter Fisher

Subject: Detecting neutrinos from a research reactor using Coherent Elastic Neutrino Nuclear Scattering (CENNS)

Date: October 19, 2017

The recent successful detection[1] of Coherent Elastic Neutrino Nuclear Scattering (CENNS) at the Spallation Neutrino Source (SNS) has brought up the question of detecting anti-neutrinos from a research reactor like MITR (25 MW) using the CENNS method. This note shows detecting neutrinos in this way is essentially impossible at any distance.

The COHERENT detector is a 15 kg CsI scintillator detector containing 58 moles each of Cs and I. The SNS delivery 5×10^{20} protons per day onto a mercury target, generating 0.08 neutrinos per proton, giving a flux of $\Phi_{\rm SNS} = 5 \times 10^{14}\nu/{\rm s}$. The average neutrino energy was 25 MeV.

The COHERENT detector was located 19 m from the isotropic neutrino source and Fig. 1 of [1] gives a cross section of $\sigma \sim 2 \times 10^{-38}$ cm^2 for nuclear recoils above 4.5 keV. The maximum nuclear recoil energy from a 25 MeV neutrino is about 5.5 keV. Above this energy, coherence is lost and the A^2 scaling is lost.

The recoil rate is then,

$$\begin{aligned} R_{\rm CENNS} &= \sigma N_{targets}\frac{\Phi}{4\pi D^2} \\ &= 1.6 \times 10^{-5}/{\rm s} = 1.4/{\rm day}. \end{aligned}$$

COHERENT reported about 150 events in 171 days of operation or about 0.9 events per day, consistent with the number above. A key element to the success of COHERENT is the 5% duty cycle of the SNS 1 GeV proton beam. The accelerator sends a 1 μs "spill" of protons to the target every 19 μs and the neutrinos are emitted from the target only during the spill. Data from the COHERENT detector is only recorded during the spill, resulting in a factor of ten reduction in background.

We can estimate the signal rate for the COHERENT detector at the 20 MW MITR. The neutrino flux is 400 times larger, the cross section is 100 times smaller, so the singal rate would be about 4 counts/day at 19 m. At 1 km, the signal rate would be 0.001/day. To get a signal rate of 1 count/hour would require a 10 ton detector.

There are three reasons why the CENNS technique will not work at a reactor.

[1] Akimov, D. et al.,"Observation of coherent elastic neutirno-nucleus scattering," Science, (2017)10.1126, referred to as Ref. 1. Unless otherwise indicated, all numbers in this report from from Ref. 1.

1. The reactor neutrino energy too low. The average reactor neutrino energy is 2 MeV, so the maximum nuclear recoil energy will be about 440 eV, well below what is currently technically in a large detector. Gamma ray nucleus scattering becomes a serious background in this energy range, so the backgrounds would be much higher in this energy region that for COHERENT. Super-conducting detectors can reach this threshold.
2. The reactor neutrino flux is continuous. A key to the success of the COHERENT experiment is the 1 μs pulse structure of the SNS proton beam, so the detector was only active when the neutrinos were known to be coming, see Fig. S3. At a reactor, this is simply not possible and SNR would be one tenth of COHERENT's.
3. The cross section is a factor of 100 smaller at a reactor than at SNS.

Following on the second point, even taking into account the known neutrino arrival time, COHERENT still suffers from significant backgrounds. These backgrounds are pervasive, even after extreme and expensive precautions are taken to eliminate them from the the detector.

What technical breakthroughs would be needed for CENNS to become useful for detecting reactor neutrinos?

1. A target medium with readout that operates at a 300 eV threshold in a multi-ton scale detector. This threshold has been achieved in few hundred gram sized detectors or in superconducting detector with masses of up to 1 kg.
2. Radio-purity at the level of 0.1 counts/day above 300 eV in a multi-ton scale detector. COHERENT has achieved a level of radio-purity of 4 counts/day in at 15 kg detector above a 4 keV.
3. Affordable detector medium at the kiloton scale. An example of a large CsI detector is the BaBar electromagnetic calorimeter, which had a mass of 50 tons and cost $25M for the CsI alone.[2] This detector did not meet either the threshold requirements or the background requirements by several orders of magnitude.

The inverse beta decay technique provides much easier approach to detecting reactor neutrinos. It is true the CENNS cross section is much larger, but you pay for it in much great complexity and radio-purity requirements owing the difficulty in detecting a recoiling nucleus.

[2] See www.hep.ph.ic.ac.uk/ñashja/cal_lect.ps

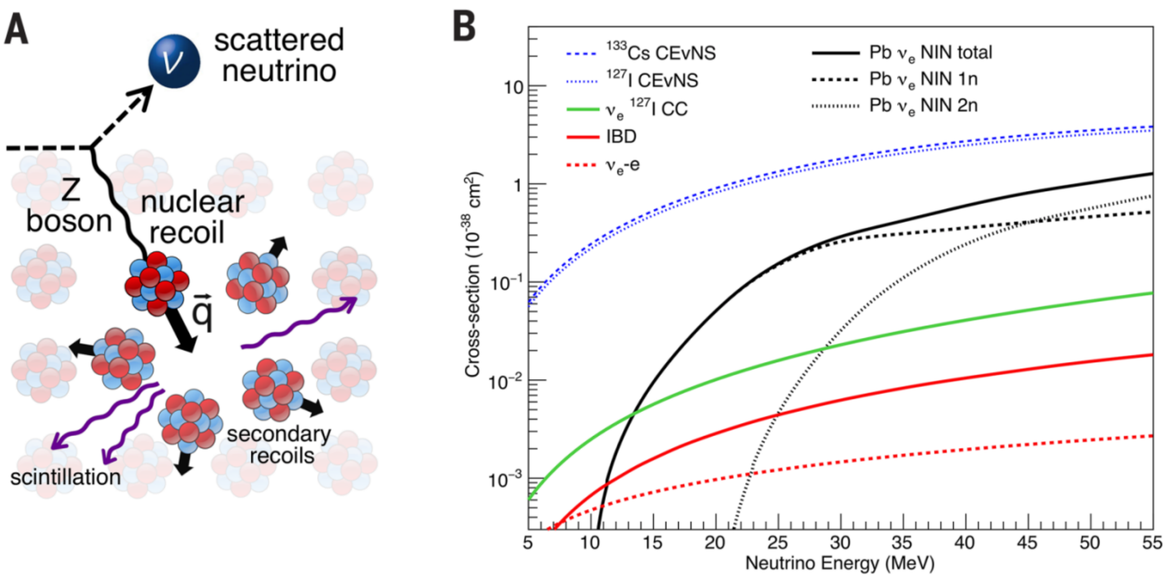

Fig. 1. Neutrino interactions. (**A**) Coherent Elastic Neutrino-Nucleus Scattering. For a sufficiently small momentum exchange (q) during neutral-current neutrino scattering ($qR < 1$, where R is the nuclear radius in natural units), a long-wavelength Z boson can probe the entire nucleus, and interact with it as a whole. An inconspicuous low-energy nuclear recoil is the only observable. However, the probability of neutrino interaction increases dramatically with the square of the number of neutrons in the target nucleus. In scintillating materials, the ensuing dense cascade of secondary recoils dissipates a fraction of its energy as detectable light. (**B**) Total cross-sections from CEνNS and some known neutrino couplings. Included are neutrino-electron scattering, charged-current (CC) interaction with iodine, and inverse beta decay (IBD). Because of their similar nuclear masses, cesium and iodine respond to CEνNS almost identically. The present CEνNS measurement involves neutrino energies in the range ~16-53 MeV, the lower bound defined by the lowest nuclear recoil energy measured (fig. S9), the upper bound by SNS neutrino emissions (fig. S2). The cross-section for neutrino-induced neutron (NIN) generation following $^{208}Pb(\nu_e, e^- \, xn)$ is also shown. This reaction, originating in lead shielding around the detectors, can generate a potential beam-related background affecting CEνNS searches. The cross-section for CEνNS is more than two orders of magnitude larger than for IBD, the mechanism employed for neutrino discovery (*35*).

Figure 1: Fig. 1 from Ref. 1.

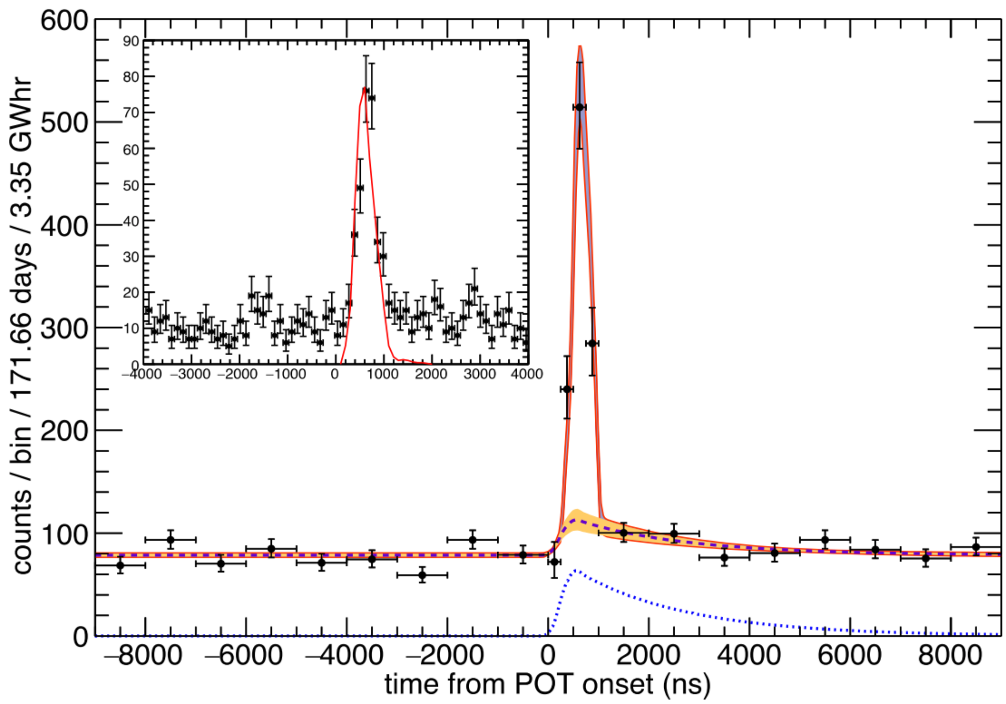

Fig. S3. Three-component unbinned fit to the arrival time of neutron-like events in EJ-301 scintillator cells (see text). Red lines delimit the one-sigma contour of the best-fit model. A dashed line indicates the best fit to NIN and environmental background components, a yellow band their one-sigma uncertainty. The presence of a non-zero NIN component is favored at the 2.9-sigma confidence level. However, the magnitude of this background is found to be negligible for a CEνNS search. A dotted line represents the predicted NIN component using the production rate calculated in (*57,58*). *Inset:* zoom-in using 100 ns bins. The red line is a normalized probability distribution function predicted by Geant4 for the arrival time of prompt neutrons contributing to the available 30-300 keV ionization energy region (Fig. S4). The simulation includes the time-profile of POT, provided by the SNS, and subsequent neutron production, moderation, and time-of-flight through 19.3 m of intermediate moderating materials (see text). This PDF is used to represent the prompt neutron component in our fits. The best-fit to its position agrees within errors (±168 ns) with the Geant4 prediction shown.

Figure 2: Fig. S3 from Ref. 1.