NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

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The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross section is by far the largest of all low-energy neutrino couplings. This mode of interaction offers new opportunities to study neutrino properties and leads to a miniaturization of detector size, with potential technological applications. We observed this process at a 6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the standard model for this process, were observed in high signal-to-background conditions. Improved constraints on nonstandard neutrino interactions with quarks are derived from this initial data set.

The characteristic most often associated with neutrinos is a very small probability of interaction with other forms of matter, allowing them to traverse astronomical objects while undergoing no energy loss. As a result, large targets (tons to tens of kilotons) are used for their detection. The discovery of a weak neutral current in neutrino interactions (*1*) implied that neutrinos were capable of coupling to quarks through the exchange of neutral Z bosons. Soon thereafter, it was suggested that this mechanism should also lead to coherent interactions between neutrinos and all nucleons present in an atomic nucleus (*2*). This possibility would exist only as long as the momentum exchanged remained smaller than the inverse of the nuclear size (Fig. 1A), effectively restricting the process to neutrino energies below a few tens of MeV. The enhancement to the probability of interaction (scattering cross section) would, however, be very large relative to interactions with isolated nucleons, approximately scaling with the square of the number of neutrons in the nucleus (*2*, *3*). For heavy nuclei and sufficiently intense neutrino sources, this can lead to a marked reduction in detector mass, down to a few kilograms.

Coherent elastic neutrino-nucleus scattering (CEvNS) has evaded experimental demonstration in the 43 years since its first theoretical description. This is somewhat surprising, in view of the magnitude of its expected cross section relative to other tried-and-tested neutrino couplings (Fig. 1B) and of the availability of suitable neutrino sources: solar, atmospheric, and terrestrial sources as well as supernova bursts, nuclear reactors, spallation facilities, and certain radioisotopes (*3*). This delay stems from the difficulty in detecting the low-energy (few keV) nuclear recoil produced as the single outcome of the interaction. Relative to a minimum ionizing particle of the same energy, a recoiling nucleus has a diminished ability to generate measurable scintillation or ionization in common radiation detector materials. This is exacerbated by a trade-off between the enhancement to the CEvNS cross section (brought about by a large nuclear mass) and the smaller maximum recoil energy of a heavy target nucleus.

The interest in CEvNS detection goes beyond completing the picture of neutrino couplings predicted by the standard model of particle interactions. In the time since its description, CEvNS has been suggested as a tool to expand our knowledge of neutrino properties. These studies include searches for sterile neutrinos (*4*–*6*), a neutrino magnetic moment (*7*, *8*), nonstandard interactions mediated by new particles (*9*–*11*), probes of nuclear structure (*12*), and improved constraints on the value of the weak nuclear charge (*13*). In addition to these, the reduction in neutrino detector mass may lead to a number of technological applications (*14*), such as nonintrusive nuclear reactor monitoring (*15*). CEvNS is also expected to dominate neutrino transport in neutron stars and during stellar collapse (*16*–*18*). Direct searches for weakly interacting massive particles (WIMPs)—the dark matter candidates most favored at present—rely on the same untested coherent enhancement to the WIMP-nucleus scattering cross section, and will soon be limited by an irreducible CEvNS background from solar and atmospheric neutrinos (*19*). The importance of this process has generated a broad array of proposals for potential CEvNS detectors: superconducting devices (*3*), cryogenic detectors (*20*–*22*), modified semiconductors (*23*–*25*), noble liquids (*26*–*30*), and inorganic scintillators (*31*), among others.

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory generates the most intense pulsed neutron beams in the world, produced by the interactions of accelerator-driven high-energy (~1 GeV) protons striking a mercury target. These beams serve an array of neutron-scattering instruments and a cross-disciplinary community of users. Spallation sources are known to simultaneously create a large yield of neutrinos, generated when pions, themselves a by-product of proton interactions in the target, decay at rest. The resulting low neutrino energies are favorable for CEvNS detection (*3*, *32*, *33*). Three neutrino flavors are produced—prompt muon neutrinos ν_μ, delayed electron neutrinos ν_e, and

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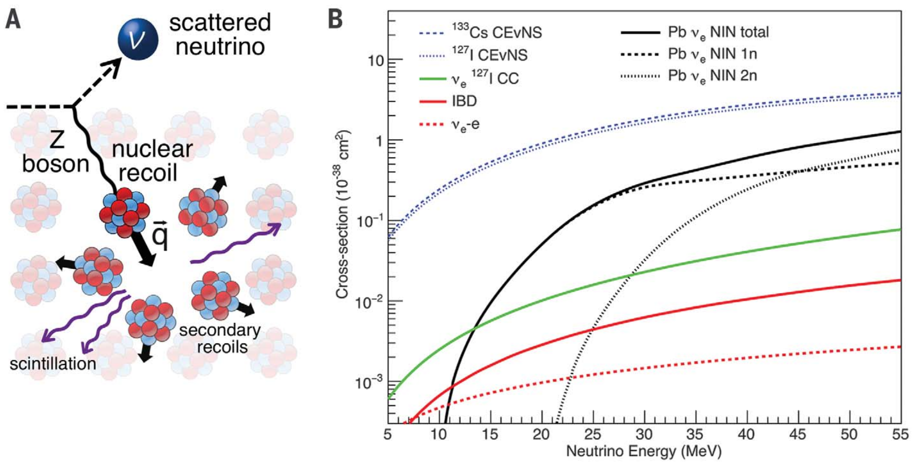

Fig. 1. Neutrino interactions. (**A**) Coherent elastic neutrino-nucleus scattering. For a sufficiently small momentum exchange (q) during neutral-current neutrino scattering ($qR < 1$, where R is the nuclear radius in natural units), a long-wavelength Z boson can probe the entire nucleus and interact with it as a whole. An inconspicuous low-energy nuclear recoil is the only observable. However, the probability of neutrino interaction increases substantially 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 CEvNS 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 CEvNS almost identically. The present CEvNS measurement involves neutrino energies in the range ~16 to 53 MeV, with the lower bound defined by the lowest nuclear recoil energy measured (fig. S9) and the upper bound by SNS neutrino emissions (fig. S2). The cross section for neutrino-induced neutron (NIN) generation following ^{208}Pb(ν_e, e^- xn) is also shown, for single and double neutron production. This reaction, originating in lead shielding around the detectors, can generate a potential beam-related background affecting CEvNS searches. The cross section for CEvNS is more than two orders of magnitude larger than for IBD, the mechanism used for neutrino discovery (*35*).

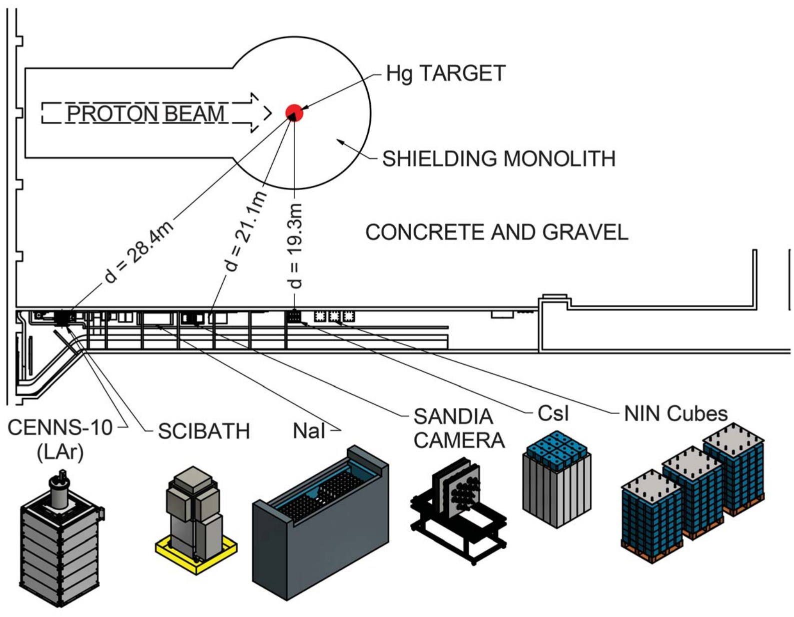

Fig. 2. COHERENT detectors populating the "neutrino alley" at the SNS. Locations in this basement corridor profit from more than 19 m of continuous shielding against beam-related neutrons and a modest 8 m.w.e. overburden able to reduce cosmic ray–induced backgrounds, while sustaining an instantaneous neutrino flux as high as 1.7×10^{11} ν_μ cm^{-2} s^{-1}.

delayed muon antineutrinos $\bar{\nu}_\mu$—each with characteristic energy and time distributions (fig. S2), and all having a similar CEvNS cross section for a given energy. During beam operation, approximately 5×10^{20} protons-on-target (POT) are delivered per day, each proton returning ~0.08 isotropically emitted neutrinos per flavor. An attractive feature is the pulsed nature of the emission: 60 Hz of ~1 μs–wide POT spills. This allows us to isolate the steady-state environmental backgrounds affecting a CEvNS detector from the neutrino-induced signals, which should occur within ~10-μs windows after POT triggers. Similar time windows preceding the triggers can be inspected to obtain information about the nature and rate of steady-state backgrounds, which can then be subtracted (*31*, *34*). A facility-wide 60-Hz trigger signal is provided by the SNS at all times.

As large as this neutrino yield may seem, prompt neutrons escaping the iron and steel shielding monolith surrounding the mercury target (Fig. 2) would swamp a CEvNS detector sited at the SNS instrument bay. Neutron-induced nuclear recoils would largely dominate over neutrino-induced recoils, making experimentation impossible. This led to a systematic investigation of prompt neutron fluxes within the SNS facility (*34*). A basement corridor, now dubbed the "neutrino alley," was found to offer locations with more than 12 m of additional void-free neutron-moderating materials (concrete, gravel) in the line of sight to the SNS target monolith. An overburden of 8 m of water equivalent (m.w.e.) provides an additional reduction in backgrounds associated with cosmic rays. The CsI[Na] CEvNS detector and shielding described next were installed in the corridor location nearest to the SNS target (Fig. 2).

The advantages of sodium-doped CsI as a CEvNS detection material, its characterization for this application, and background studies using a 2-kg prototype are described in (*31*). Heavy cesium and iodine nuclei provide large cross sections and nearly identical response to CEvNS (Fig. 1B) while generating sufficient scintillation for the detection of nuclear recoil energies down to a few keV. We performed supplementary calibrations of the final 14.6-kg CsI[Na] crystal before its installation at the SNS, as well as studies of the scintillation response to nuclear recoils in the relevant energy region (*34*). In addition to these, an initial dedicated experiment was performed at the chosen detector location, measuring the very small flux of prompt neutrons able to reach this position and constraining the maximum contribution from the neutrino-induced neutron (NIN) background that can originate in lead shielding surrounding the detector (Fig. 1B) (*34*). The conclusion from this measurement was that a CEvNS signal should largely dominate over beam-related backgrounds. The level of steady-state environmental backgrounds achieved in the final crystal slightly improved on expectations based on the prototype in (*31*), mostly because of refinements in data analysis and the presence of additional shielding. Further information about the experimental setup is provided in (*34*).

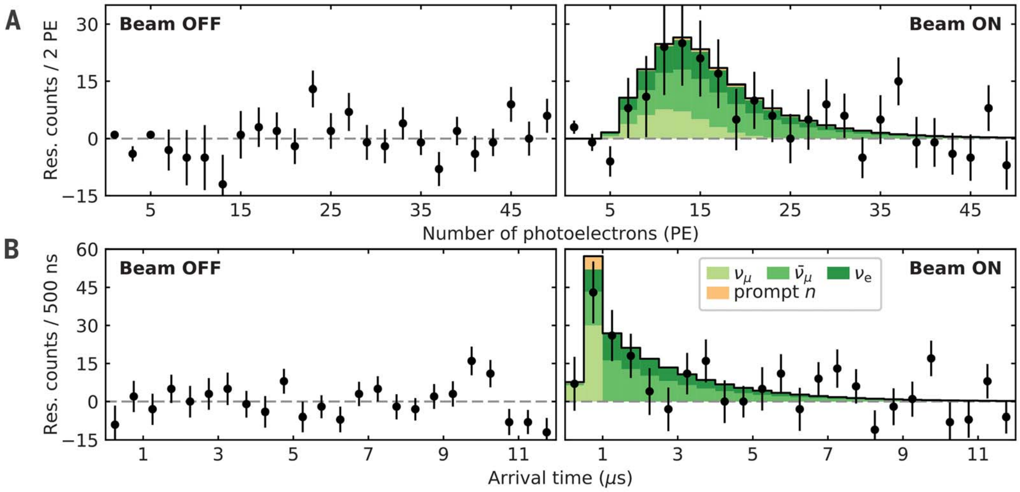

Fig. 3. Observation of coherent elastic neutrino-nucleus scattering. (**A** and **B**) Residual differences (data points) between CsI[Na] signals in the 12 μs after POT triggers and those in a 12-μs window before, as a function of (A) their energy (number of photoelectrons detected) and (B) event arrival time (onset of scintillation). Steady-state environmental backgrounds contribute to both groups of signals equally, vanishing in the subtraction. Error bars denote SD. These residuals are shown for 153.5 live days of SNS inactivity ("Beam OFF") and 308.1 live days of neutrino production ("Beam ON"), over which 7.48 GWh of energy (~1.76×10^{23} protons) was delivered to the mercury target. Approximately 1.17 photoelectrons are expected per keV of cesium or iodine nuclear recoil energy (*34*). Characteristic excesses closely following the standard model CEνNS prediction (histograms) are observed for periods of neutrino production only, with a rate correlated to instantaneous beam power (fig. S14).

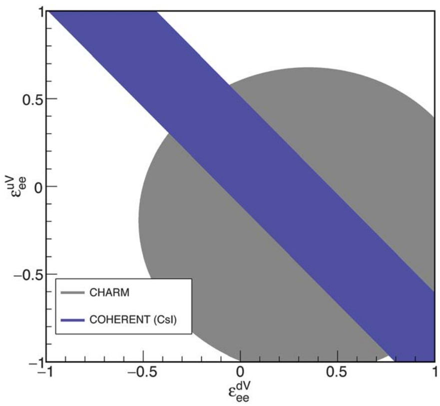

Fig. 4. Constraints on nonstandard neutrino-quark interactions. The blue region represents values allowed by our data set at 90% confidence level ($\chi^2_{min} < 4.6$) in $\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV}$ space. These quantities parameterize a subset of possible nonstandard interactions between neutrinos and quarks, where $\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV}$ = 0,0 corresponds to the standard model of weak interactions, and indices denote quark flavor and type of coupling. The gray region shows an existing constraint from the CHARM experiment (*34*).

Figure 3 displays our main result, derived from 15 months of accumulated live time (fig. S1). When comparing CsI[Na] signals occurring before POT triggers and those taking place immediately after, we observe a high-significance excess in the second group of signals, visible in both the energy spectrum and the distribution of signal arrival times. This excess appears only during times of neutrino production ("Beam ON" in the figure). The excess follows the expected CEνNS signature very closely, containing only a minimal contamination from beam-associated backgrounds (*34*). NINs have a negligible contribution, even smaller than that from prompt neutrons, shown in the figure. The formation of the excess is strongly correlated to the instantaneous power on target (fig. S14). All neutrino flavors emitted by the SNS contribute to reconstructing the excess, as expected from a neutral current process. Stacked histograms in Fig. 3 display the standard model CEνNS predictions for prompt ν_μ and delayed ν_e, $\bar{\nu}_\mu$ emissions. Consistency with the standard model is observed at the 1σ level (134 ± 22 events observed, 173 ± 48 predicted). A two-dimensional (energy, time) profile maximum likelihood fit favors the presence of CEνNS over its absence at the 6.7σ level (fig. S13). Further details and a discussion of uncertainties are provided in (*34*), together with similar results from a parallel analysis (fig. S11).

Figure 4 shows an example of CEνNS applications: improved constraints on nonstandard interactions between neutrinos and quarks, caused by new physics beyond the standard model (*9*–*11*). These are extracted from the maximum deviation from standard model CEνNS predictions allowed by the present data set (*34*), using the parametrization in (*30*, *33*).

As our experiment continues to run, neutrino production is expected to increase in late 2017 by up to 30% relative to the average delivered during this initial period. In addition to CsI[Na], the COHERENT collaboration currently operates a 22-kg single-phase liquid argon (LAr) detector, 185 kg of NaI[Tl] crystals, and three modules dedicated to the study of NIN production in several targets (Fig. 2). Planned expansion includes a ~1-ton LAr detector with nuclear/electron recoil discrimination capability, an already-in-hand 2-ton NaI[Tl] array simultaneously sensitive to sodium CEνNS and charged-current interactions in iodine (Fig. 1B), and p-type point contact germanium detectors (*24*) with sub-keV energy threshold. We intend to pursue the new neutrino physics opportunities provided by CEνNS using this ensemble.

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SUPPLEMENTARY MATERIALS

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Supplementary Text
Figs. S1 to S14
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Nailing down an elusive process

Detecting neutrinos––elementary particles that barely interact with other matter––usually requires detectors of enormous size. A particular interaction of neutrinos with atomic nuclei, called the coherent elastic neutrino-nucleus scattering (CEνNS), is predicted to occur with relatively high probability, and it could be used to drastically reduce the size of neutrino detectors. However, observing this interaction requires a source of low-energy neutrinos and detectors that contain nuclei of optimal mass. Akimov *et al.* observed CEνNS with a 6.7σ confidence by using a comparatively tiny, 14.6-kg sodium-doped CsI scintillator exposed to neutrinos from a spallation neutron facility (see the Perspective by Link). The discovery places tighter bounds on exotic, beyond-the-standard-model interactions involving neutrinos.

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