Measurement of the Coherent Elastic Neutrino-Nucleus Scattering Cross Section on CsI by COHERENT

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We measured the cross section of coherent elastic neutrino-nucleus scattering (CEvNS) using a CsI[Na] scintillating crystal in a high flux of neutrinos produced at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. New data collected before detector decommissioning have more than doubled the dataset since the first observation of CEvNS, achieved with this detector. Systematic uncertainties have also been reduced with an updated quenching model, allowing for improved precision. With these analysis improvements, the COHERENT collaboration determined the cross section to be \((165^{+30}_{-25}) \times 10^{-40} \text{ cm}^2\), consistent with the standard model, giving the most precise measurement of CEvNS yet. The timing structure of the neutrino beam has been exploited to compare the CEvNS cross section from scattering of different neutrino flavors. This result places leading constraints on neutrino non-standard interactions while testing lepton flavor universality and measures the weak mixing angle as \(\sin^2 \theta_W = 0.220^{+0.028}_{-0.026} \) at \(Q^2 \approx (50 \text{ MeV})^2\).

Introduction: Coherent elastic neutrino-nucleus scattering (CEvNS) is a neutral current process \([1,2]\) with low momentum transfer, \((Q^2)\), where the neutrino interacts coherently with the nucleus. The re-
coil energy transferred to the nucleus is observable, though typical recoil energies are low, tens of keV for neutrino energies in the tens of MeV range. Thus, detectors with low-energy thresholds are required for CEvNS measurement.

CEvNS has the largest cross section among neutrino scattering channels for $E_\nu < 100$ MeV for most target nuclei. The standard-model (SM) prediction depends on the nuclear weak charge, $Q_W^2 = (N - (1 - 4 \sin^2 \theta_W)Z)^2 \approx N^2$, where $N$ and $Z$ are the neutron and proton numbers of the target nucleus, and $\theta_W$ is the weak mixing angle [3].

CEvNS was first measured using the COHERENT CsI[Na] detector in an intense, pulsed source of neutrinos produced at the Spallation Neutron Source (SNS) [4, 5] at Oak Ridge National Laboratory [6].

The COHERENT experiment deploys several detectors to measure CEvNS and other low-energy scattering processes using the $\pi^+$ decay-at-rest (πDAR) neutrino flux at the SNS, attractive for CEvNS measurements [7]. The detectors are situated in “Neutrino Alley” (NA), a basement hallway where background neutrons from the facility are heavily suppressed. CEvNS was first observed in NA, 19.3 m from the neutrino source using a 14.6 kg CsI[Na] scintillating detector [6] 43 years after its theoretical prediction [1]. COHERENT also made the first detection of CEvNS on argon [8], which, together with the initial CsI[Na] measurement, agrees with the $N^2$ scaling of the cross section. While these campaigns were highly successful, they suffer from large statistical and systematic uncertainties, which limit their sensitivity to searches for new physical phenomena.

CEvNS is a precisely predicted neutrino interaction within the SM. The theoretical uncertainty is dominated by understanding of the spatial distribution of the weak charge in the nucleus. As a result, CEvNS is a process well suited for probing physics beyond the SM (BSM). A precision measurement of CEvNS is sensitive to new particles, such as a dark photon that interferes with $Z$ exchange in the low-$Q^2$ regime [9, 10] and may explain the $g$-2 anomaly [11]. Similarly, through the reliance of $Q_W^2$ on $\sin^2 \theta_W$, CEvNS may identify new physics through an unexpected value of the weak mixing angle at $Q^2 \approx (50 \text{ MeV})^2$ [11]. It can shed light on new forces at high mass scales through non-standard interactions (NSI) searches [12], the understanding of which is crucial for interpreting neutrino oscillation measurements, as NSI scenarios can obfuscate the interpretation of results [13, 14].

Detectors that measure CEvNS are also sensitive to sub-GeV, accelerator-produced dark matter particles [15, 16]. Further, CEvNS from solar and atmospheric neutrinos are a background for dark matter direct detection experiments [17, 18], making up the so-called neutrino floor, so that a clear understanding of their interaction will soon become paramount.

CEvNS will also contribute to measuring a future supernova neutrino burst [19, 20]. As a neutrino-current process, CEvNS is sensitive to the total neutrino flux, which is of particular interest as other detection channels are most sensitive to the $\nu_e$ [21] or $\bar{\nu}_e$ [22] flux. CEvNS is also understood to play an important role in energy transport driving the core-collapse mechanism in the supernova [23, 24].

It is with precision measurements of CEvNS that these physics searches are realized. In this letter, we present the first such measurement with the final CsI[Na] dataset and improved understanding of systematic uncertainties. Using the time structure of the neutrino flux from πDAR, leading constraints on non-standard neutrino interactions are presented, along with a direct measurement of the weak mixing angle at low $Q^2$.

**Experiment:** We used a 14.6-kg scintillation CsI[Na] crystal [6]. The dopant was selected to reduce the rate of afterglow scintillation following a burst of activity in the detector [25]. The crystal was attached to a single Hamamatsu R877-100 photomultiplier (PMT). The signal was digitized at a rate of 500 MS/s with a dynamic range extending beyond the 60-keV$_{\text{ee}}$ calibration scale. This crystal was shielded with both low-activity lead and low-Z materials to mitigate $\gamma$ and neutron backgrounds [29, 30]. Muon veto panels surrounded the detector which allowed for removal of cosmic-associated activity.

Our dataset includes 13.99 GWhr of integrated beam power that passes lifetime criteria on beam stability, detector condition, and afterglow rate. During data collection, the SNS ran using a mercury target with a mean beam energy of 0.984 GeV yielding $3.2 \times 10^{23}$ protons-on-target (POT). Averaged over beam energies, a pion yield of $0.0848 \pm 10\%$ $\pi^+/\text{POT}$ is expected from a GEANT4 [31] simulation of the SNS beam [32]. The POT timing distribution averaged over the running period is calculated using beam current data from the SNS and has a FWHM of 378 ns. Since this is less than the muon lifetime, the flux separates into two populations: a prompt, predominantly $\nu_\mu$ flux from $\pi^+$ decay followed by a delayed flux of $\nu_e$ and $\bar{\nu}_e$ from subsequent $\mu^+$ decay. Over 99% of the SNS neutrino flux is generated by $\pi^+$ decay-at-rest [32].

The detector was calibrated with the 59.5 keV $\gamma$ decay of an $^{241}$Am source. With a Gaussian fit to calibration data, we found a light yield of 13.35 photoelectrons per keV electron-equivalent (PE/keV$_{\text{ee}}$). Calibration data were taken with the source at nine different locations along the crystal, finding a spatial
spread in light yield less than 3%. This is negligible compared to other identified energy smearing effects. The single PE (SPE) charge was monitored during SNS running by tagging single PMT pulses with little other activity in the crystal.

Data analysis: Our analysis procedure closely parallels the approach described in [6, 33] with improvements to our simulation, re-optimization of our event selection, and a more thorough detector response model. Data coincident with the arrival of beam were blinded until reconstruction, selection, and analysis methods were determined. Event time and energy were reconstructed by analyzing the PMT waveform in the beam window.

The PMT voltage traces were digitized and a 70 μs waveform was saved for every beam spill. We formed a 15 μs region-of-interest (ROI) coincident with the arrival of beam and formed a 3 μs integration time to capture most light given by a dominant scintillation decay constant \( \tau = 0.6 \) μs [29]. We also analyzed a 40 μs pretrace region (PT) immediately preceding the ROI which monitors afterglow activity in the crystal on a spill-by-spill basis. We also analyze an analogous anti-coincident (AC) region preceding the beam to monitor steady-state backgrounds (SSBkg).

We applied two selection cuts to the waveform PT. First, backgrounds producing afterglow contamination in the signal ROI are more likely to have more activity in the PT; we therefore only selected events with five or fewer PT pulses. We also removed events that have a pulse within the last 200 ns of the PT which are typically background events that scatter very late in the PT and then leak into the ROI.

Only events with \( \geq 9 \) pulses reconstructed in the ROI are selected. This mitigates background from coincidence of afterglow pulses. These events are predicted to be biased to early scattering times in the ROI, with approximately exponential shape, \( \tau \approx 4 \) μs. Using this time dependence, we validated this simulation by comparing the rate and time dependence of the afterglow background using AC data and confirm that a negligible afterglow rate, consistent with 0, is expected after the \( \geq 9 \) pulse cut. This cut sets the analysis threshold, at \( \approx 7 \) PE.

We applied nuclear recoil quenching by fitting the scintillation response curve, \( E_{sc} = f(E_{nr}) \), to five datasets collected in CsI[Na] including three taken by COHERENT [31, 33]. The recoil energies in these datasets spanned from 3 to 63 keVee. To account for shape as a function of \( E_{nr} \), we parameterized the scintillation response curve as a fourth degree polynomial, constrained so that \( f(0) = 0 \).

The selection efficiency for CEvNS recoils depends on observed energy, PE, and recoil time, \( t_{rec} \). We estimated energy dependence of the efficiency and its uncertainty using \(^{133}\)Ba calibration data which gave a sample of Compton-scattered electrons. A coincidence with a backing detector was used to mitigate background and ensure only low-energy forward scattering events were used in the calibration.

There is a 39% chance that there is at least one afterglow pulse in each waveform ROI. Since we reconstructed \( t_{rec} \) as the time of the first pulse in the ROI, it is possible for a CEvNS recoil occurring at late \( t_{rec} \) to be rejected because it follows a random pulse which is accounted for in a time-dependent efficiency, \( \varepsilon_{T} \), estimated with a data-driven simulation. A library of waveforms from AC data was constructed by selecting exactly one waveform for each hour of detector running. A simulated CEvNS waveform was then overlaid on a waveform randomly selected from this library. We took \( \varepsilon_{T} \) as the ratio of events selected when simulated at \( t = t_{rec} \) compared to \( t = 0 \). We also expect signal events that follow a random afterglow pulse but within the 3 μs integration window. These events may be selected, but would have biased recoil energy and time. This background was mitigated by requiring the time difference between the first and second pulse in the ROI be \( < 520 \) ns. This cut rejected a negligible fraction of events with properly reconstructed \( t_{rec} \) but reduced the fraction of biased events sufficiently that the bias does not noticeably affect the measurement. This was validated with large PE inelastic signals in our detector whose onset time was unambiguous.

Our energy resolution is dominated by photon counting. However, the variation in SPE charge is also included in our energy resolution. Combining these two effects, the smearing was modeled with a gamma function which appropriately predicts the asymmetric simulated smeared distribution much better than a Gaussian model.

Over 98% of the background comes from beam-uncorrelated, steady-state background (SSBkg). This background is measured in-situ from AC data. We estimated the PE distribution using all events found in AC data and used an exponential model for the time distribution with \( \tau = 20.2 \pm 2.6 \) μs, consistent with the time dependence of the signal efficiency. Uncertainty in this decay constant had a negligible impact on the measured cross section.

We accounted for two sources of beam-related background: beam-related neutron (BRN) and neutrino-induced neutron (NIN) scatters. Prior to detector installation, the normalization of each of these components was studied by an EJ-301 liquid scintillator detector [33] housed in the CsI[Na] shielding. The neutron-moderating water used in the detector shielding was drained to increase the neutron rate. The BRN and NIN rates were determined from a fit to the time distribution [6]. A MCNPX-FoLLMi [37] simulation was used to estimate
Recoil Energy (keV)

| 5  | 10  | 15  | 20  | 25  | 30  | 35  | 40  | 45  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
| PE| Excess Counts / PE|
| 0  |      |      |      |      |      |      |      |      |
| 10 |      |      |      |      |      |      |      |      |
| 20 |      |      |      |      |      |      |      |      |
| 30 |      |      |      |      |      |      |      |      |
| 40 |      |      |      |      |      |      |      |      |
| 50 |      |      |      |      |      |      |      |      |
| 60 |      |      |      |      |      |      |      |      |

Data Residual

CEvNS
ν\text{ν} CEvNS
µν CEvNS
µνBRN + NIN

Results: After fitting, we observed 306 ± 20 CEvNS events, consistent with the SM prediction of 341 ± 11 (theory) ± 42 (experiment). The best-fit residual CEvNS spectra in PE and \( t_{\text{rec}} \) are shown in Fig. 1. The best-fit prediction models the observed data well with \( \chi^2/\text{dof} = 82.6/98 \). No excess is observed in beam-off data. The cross section averaged over the \( \nu_\mu/\bar{\nu}_\mu \) flux, \( \langle \sigma \rangle_\phi \), was determined to be \( (165^{+30}_{-25}) \times 10^{-40} \) cm\(^2\) by a profiled log-likelihood fit. This is consistent with the SM prediction of \( (189 \pm 6) \times 10^{-40} \) cm\(^2\). The observed data reject the no-CEvNS hypothesis at 11.6 \( \sigma \). See supplemental material at [URL] to see observed data listed along with assumptions required to reproduce this result.

Since the SM cross section depends on the weak charge, the CEvNS cross section can be interpreted as a constraint on the weak mixing angle at a low momentum exchange, \( Q^2 \approx (50 \text{ MeV})^2 \) consistent with previous results [41]. Our current result implies \( \sin^2 \theta_W = 0.220^{+0.028}_{-0.026} \) compared to the SM prediction 0.23857(5) [42]. Current constraints at low-\( Q^2 \) from atomic parity violation measurements are much more precise, though a percent-level measurement from COHERENT will be possible within the future [43]. Additionally, as \(^{133}\text{Cs}\) is a commonly used atom for these studies [44, 45], CEvNS data can be used to constrain theoretical uncertainties on nuclear structure assumed in these results [3].

The “flavored” CEvNS cross sections, \( \langle \sigma \rangle_\mu \) and \( \langle \sigma \rangle_\nu \), are also measured by exploiting the differences in timing shapes between the CEvNS contributions from \( \nu_\mu, \bar{\nu}_\mu \) and \( \nu_\nu \). This parameter space is a sen-
The best-fit parameters and the SM prediction, along with $\pm 1\,\sigma$ error bands from form-factor uncertainty, are shown as pink markers.

Figure 2. Contours for the flavored CEvNS cross section. The best-fit scales relative to the SM are 0.88 and 0.87 for $\langle \sigma \rangle_\mu$ and $\langle \sigma \rangle_e$, respectively, consistent with the SM.

Neutrino-quark NSI, commonly parameterized as a matrix of $\epsilon_{ij}$ where $i,j = e, \mu, \tau$ and $f = u, d$. Existence of NSI could confuse ongoing efforts to measure the neutrino mixing matrix parameters. Notably, it is possible to reverse the inferred neutrino mass ordering from oscillation data by choosing a suitable set of NSI parameters [14]. Also, NSI allow for additional $CP$-violating phases which may bias constraints on $\delta_{CP}$ [15, 46].

In Fig. 3, we show the constraint on $\epsilon_{ue}$ and $\epsilon_{de}$ with other parameters fixed to 0 compared to CHARM [47] constraints. This marks a significant improvement over the previous CsI[Na] constraint from COHERENT [4] because of an improved precision result and measuring the flavored cross sections. There are also NSI constraints determined from CEvNS data on Ar [8] and Xe [48], though these limits are currently less precise.

Figure 3. The top plot shows the 90% allowed parameter space with $\epsilon_{ue}$ and $\epsilon_{de}$ to float while fixing others at 0, while the bottom shows $1/2/3\sigma$ contours allowing $\epsilon_{ue}$ and $\epsilon_{mu}$ to float fixing others to 0. The bottom also shows parameter space that is compatible with a degeneracy in solar neutrino oscillation data that would flip the inferred neutrino mass ordering.

Conclusion: We measured the CEvNS cross section using the full dataset collected by the CsI[Na] scintillation detector using a blinded analysis approach. With doubled exposure and improved understanding of systematic uncertainties, we have made the most precise measurement of CEvNS to date, observing CEvNS at 11.6 $\sigma$ and finding a flux-
averaged cross section $\langle \sigma \rangle_\Phi = (165^{+30}_{-25}) \times 10^{-40}$ cm$^2$, consistent with the SM prediction to within 1 $\sigma$. The weak mixing angle was measured at low $Q^2$. We also introduced measurements of the flavored CEvNS cross section, which improve CEvNS constraints on neutrino-quark NSI scenarios. Though the CsI[Na] detector has been decommissioned, a planned calibration of the neutrino flux using a heavy-water Cherenkov detector [50] will further improve precision of the CEvNS measurements. COHERENT is currently engaged in ongoing measurements of CEvNS on Ar, Ge, and NaI, while additional targets are possible for the future.

Acknowledgements: The COHERENT collaboration acknowledges the Kavli Institute at the University of Chicago for CsI[Na] detector contributions. The COHERENT collaboration acknowledges the generous resources provided by the ORNL Spallation Neutron Source, a DOE Office of Science User Facility, and thanks Fermilab for the continuing loan of the CENNS-10 detector. We also acknowledge support from the Alfred P. Sloan Foundation, the Consortium for Nonproliferation Enabling Capabilities, the National Science Foundation, the Russian Foundation for Basic Research (proj.# 17-02-01077 A), and the U.S. Department of Energy, Office of Science. Laboratory Directed Research and Development funds from ORNL and Lawrence Livermore National Laboratory also supported this project. This research used the Oak Ridge Leadership Computing Facility, which is a DOE Office of Science User Facility. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525. The work was supported by the Ministry of Science and Higher Education of the Russian Federation, Project Fundamental properties of elementary particles and cosmology No. 0723-2020-0041.

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