First Probe of Sub-GeV Dark Matter Beyond the Cosmological Expectation with the COHERENT CsI Detector at the SNS

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The COHERENT collaboration searched for scalar dark matter particles produced at the Spallation Neutron Source with masses between 1 and 220 MeV/c^2 using a CsI[Na] scintillation detector sensitive to nuclear recoils above 9 keV$_{\mathrm{nr}}$. No evidence for dark matter is found and we thus place limits on allowed parameter space. With this low-threshold detector, we are sensitive to coherent elastic scattering between dark matter and nuclei. The cross section for this process is orders of magnitude higher than for other processes historically used for accelerator-based direct-detection searches so that our small, 14.6 kg detector significantly improves on past constraints. At peak sensitivity, we reject the flux consistent with the cosmologically observed dark-matter concentration for all coupling constants $\alpha_D < 0.64$, assuming a scalar dark-matter particle. We also calculate the sensitivity of future COHERENT detectors to dark-matter signals which will ambitiously test multiple dark-matter spin scenarios.

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1. INTRODUCTION

Standard model (SM) fermions only account for ≈20% of cosmologically observed matter [1]. Despite the well-understood gravitational effects of the remaining matter, the particle nature of dark matter (DM) has not been determined. Searches for traditional weakly interacting massive particle (WIMP) DM have not yet found a positive signature [2–4]. Further, experimental sensitivity is rapidly approaching a "neutrino floor" [5] of background from coherent elastic neutrino-nucleus scattering (CEvNS) [6] events from astrophysical neutrino sources which will hinder progress.

In response, the interest in sub-GeV DM particles, too light to be observed in many conventional WIMP detectors, has increased recently. Cosmological observations suggest that such DM could not interact with SM matter through the weak force [7]. However, sub-GeV hidden-sector DM particles could interact with standard-model fermions mediated by a "portal" particle [8–11]. These proposed hidden sector particles are viable DM candidates.

If sub-GeV DM exists, these particles would be produced at accelerators. Beam-dump experiments have already begun to survey the possible parameter space [12–18] with more experiments planned [19, 20]. Searches for accelerator-produced DM are of particular interest as the DM particles are relativistic so that the scattering cross section is relatively spin-independent [21].

Experiments capable of seeing low-energy nuclear recoils associated with CEvNS can search for an analogous coherent elastic DM-nucleus scattering process [22, 23]. As the cross section scales according to the square of the proton number Z^2, such an experiment can achieve competitive sensitivity with relatively low mass.

In this paper, we present the first search by COHERENT for accelerator-produced DM particles. This uses data collected by our CsI detector which measured CEvNS [24, 25] at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory [26]. We focus on a single benchmark model of scalar DM particle, χ, mediated by a vector portal particle, V, [11] with masses m_χ and m_V, respectively. In this model, V kinetically mixes with the SM photon with a coupling ε. DM particles can then be produced through $V \to \chi\bar{\chi}$ decay with a coupling α_D. The thermal DM abundance depends on the single parameter, Y [27], defined as

$$Y = \varepsilon^2 \alpha_D \left(\frac{m_\chi}{m_V}\right)^4 . \tag{1}$$

We thus adopt this parameter when presenting our results for convenient comparison to other measurements. Our analysis is restricted to the mass range $1 < m_\chi < 220$ MeV/c^2. We assume $\alpha_D = 0.5$ with lower values of α_D giving more strict constraints. We consider parameters for which the model remains perturbative, $\alpha_D < 1$. We also assume $m_V/m_\chi = 3$ throughout, again a conservative choice [22]. A spin $\frac{1}{2}$ particle is also viable as a DM candidate, though these scenarios would require lower couplings to match the cosmologically observed concentration. With improved sensitivity in the future, we will explore constraints on Majorana and pseudo-Dirac fermion DM, but currently focus on scalar DM.

2. THE COHERENT CSI DETECTOR AT THE SNS

The SNS operates a 1.4 MW proton beam incident on a mercury target running at 60 Hz. For our detector operations, the SNS maintained a beam-pulse width of 378 ns FWHM and an average proton energy of 0.984 GeV. With its high beam power, the SNS could produce an enormous flux of DM particles through proton bremsstrahlung and hidden-sector decays of π^0 and η^0 mesons produced in the target. Neutrinos from the accelerator, produced by the decay of π^+ particles which formed as protons stop in the target, induce CEvNS in our detectors, one of our principal backgrounds to dark-matter detection. This neutrino flux includes a prompt component from $\pi^+ \to \mu^+\nu_\mu$ and a delayed component, $\tau = 2.2\mu$s, from $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay.

We operate several detectors in "Neutrino Alley" at the SNS, a basement hallway with sufficiently low backgrounds to allow for neutrino measurements. One of our detectors was a 14.6 kg CsI[Na] scintillating crystal [28, 29], commissioned in 2015, which made the first observation of CEvNS [24]. This detector was decommissioned in 2019. During its run, this detector collected 13.99 GWhr, 3.20×10^{23} POT, of beam data. The detector was situated 19.3 m from the beam target, 90° off-axis from the beam direction. The light was collected by a single Hamamatsu R877-100 photomultiplier (PMT) sampled at a rate of 500 MS/s. We assembled shielding with multiple materials to moderate both environmental γ and neutron activity.

3. DARK MATTER EVENTS IN THE CSI DETECTOR

We use the BdNMC [30] simulation package to predict the DM flux in Neutrino Alley along with the scattering rate and kinematics within our detectors. BdNMC is versatile, calculating DM production and detection through several channels. Coherent elastic DM-nucleus scattering has been implemented specifically for CEvNS experiments. To lowest order, the differential cross section in recoil energy, E_r, is

$$\frac{d\sigma}{dE_r} = 4\pi\alpha_D\alpha\varepsilon^2 Z^2 \frac{2m_N E_\chi^2}{p_\chi^2(m_V^2 + 2m_N E_r)^2} \qquad (2)$$

where α is the electromagnetic fine structure constant, m_N is the nuclear mass, and p_χ and E_χ are the incident DM momentum and energy. The scattering model used for our sensitivity estimates presented in [31] had a calculation error with the definition of $Q^2 = 2m_N E_r$, described in [22], that has now been fixed. This improvement on the theory front has a significant impact on our DM sensitivity so that we also now present updated DM sensitivities for our future CEvNS detectors. We have confirmed event rates predicted by BdNMC using this new model with an independent, cross-check calculation from COHERENT.

The dominant production channels for portal particles at the SNS are $\pi^0 \to \gamma + V$ decay, $\eta^0 \to \gamma + V$ decay, and $p + N \to p + N + V$ bremsstrahlung. Production from π^0 decay, η^0 decay, and proton bremsstrahlung dominate for DM masses, below 40 MeV/c^2, between 40 and 130 MeV/c^2, and above 130 MeV/c^2, respectively. We do not have sensitivity for $m_\chi > 220$ MeV/c^2, beyond which bremsstrahlung is kinematically forbidden. With a GEANT4 [32] simulation, we predict 0.107 ±10% π^0/p produced in the target [33]. Though the beam energy at the SNS, $T_p \approx 0.98$ GeV, is slightly lower than the production threshold for $p+p \to p+p+\eta^0$ production, there are η mesons produced in the target due to the Fermi momentum of mercury [34]. A calculation of this sub-threshold production [35] suggests that about 0.002 ±30% η^0/π^0 are produced at the SNS. BdNMC predicts the timing of scattering events which typically scatter within a few ns of the speed-of-light-delayed DM production in the target. As this is a small delay, we assume all DM we study travels at the speed of light.

For $m_\chi = 25$ MeV/c^2, the expected average recoil energy is 9 keV, just at our analysis threshold. The spectra of interacting and selected DM in our CsI detector are shown in Fig. 1 for the DM mass at our peak sensitivity, $m_\chi = 25$ MeV/c^2. The average selection efficiency is 21% at this mass.

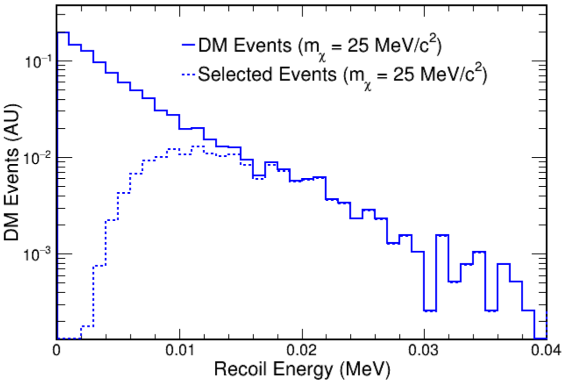

Figure 1. The simulated spectrum of interacting and selected events 25 MeV/c^2 DM, near our optimal sensitivity.

The detector response for DM recoil events is assumed to be the same as for CEvNS, described in [25], apart from quenching at high recoil energies. All data used to fit our quenching model were taken at $E_{\rm rec} < 70$ keV$_{\rm nr}$. This is sufficient to cover all CEvNS recoils; however a small percentage of DM-induced recoils lie beyond this point. For recoil energies above 70 keV$_{\rm nr}$, we assume a constant quenching factor, $(9.8 \pm 1.8)\%$, which is the quenching and uncertainty implied by our fit at 70 keV$_{\rm nr}$.

4. DATA ANALYSIS

We performed a search for light DM particles in our CsI data collected during SNS operations. The analysis was blinded, defining all selection cuts, uncertainties, and fitting methods before determining the observed data spectrum. The DM scattering model, however, was updated after box-opening to correct the error discovered in the coherent cross section, described in Sect. 3. The corrected version is given by Eqn. 2.

We used the same event reconstruction used to determine the CEvNS cross section [25]. We also applied the same event selection, except that the highest recoil energy analyzed was increased from 60 PE to 250 PE to capture the most energetic recoils expected from high-mass DM interactions. The recoil energy binning was also re-optimized for ideal DM separation from the backgrounds. The analysis binning was not reoptimized after box opening and updating the cross section model. Steady-state accidentals (SSBkg) and CEvNS interactions are the dominant backgrounds. A small number of beam-related neutron (BRN) and neutrino-induced neutron (NIN) events were also accounted for. Neutron rates and uncertainties were determined from EJ-301 [36] liquid scintillator data collected before detector commissioning [25].

The CEvNS cross section was fixed to the standard-model prediction and allowed to float within the form-factor uncertainty, 3.4%. We also included systematic uncertainties from neutrino flux, background normalization, threshold, and quenching that are calculated as described in [25] and propagated to the DM signal prediction when appropriate.

Our DM prediction, parameterized by DM mass, m_χ, and coupling, Y, was added to our expected SSBkg, BRN, NIN, and CEvNS backgrounds. We tested DM masses between 1 and 220 MeV/c^2 which covers the range where COHERENT has competitive sensitivity.

The timing of observed events, $t_{\rm rec}$ is critical for this result. The DM region of interest (ROI) is defined as $0.25 \leq t_{\rm rec} < 0.75\ \mu$s. Over 92% of DM recoils but only 25% of CEvNS are expected in this interval. Most neutrino events are delayed relative to the DM events by $\tau_\mu = 2.2\ \mu$s. These delayed events can be used to constrain systematic uncertainties in situ to improve the precision of background estimates within the DM ROI.

The data was binned in two dimensions: recoil energy and recoil time. For each DM mass and coupling, we performed a log-likelihood fit profiling over nuisance parameters relating to systematic uncertainties. For a given value of m_χ, we calculate the $\Delta\chi^2(Y)$ curve relative to the best-fit DM coupling. Allowed values of Y are determined according to the Feldman-Cousins prescription [37] with 90% confidence.

5. RESULTS

We selected 5142 events in the analysis region of $0 \leq E_{\rm rec} < 250$ PE and $0 \leq t_{\rm rec} < 6\ \mu$s. For each DM mass tested, the best-fit was identical, preferring no DM events in each case with a fit $\chi^2/\text{dof} = 103.0/120$. Our observed best-fit, SSBkg-subtracted spectra, both in the DM timing ROI and the CEvNS background timing region, are shown in Fig. 2 with our 90% limit on DM events. A summary of background counts in the sample is shown in Tab. I.

	Prior Prediction	Best-Fit Total
SSBkg	4893 ± 70	4857 ± 62
BRN	27.6 ± 6.9	25.8 ± 6.7
NIN	7.6 ± 2.7	7.4 ± 2.7
CEvNS	341 ± 36	320 ± 32
DM	–	< 15.8

Table I. A summary of prior prediction and best-fit event rates each background and the 90% limit for 25 MeV/c^2 DM.

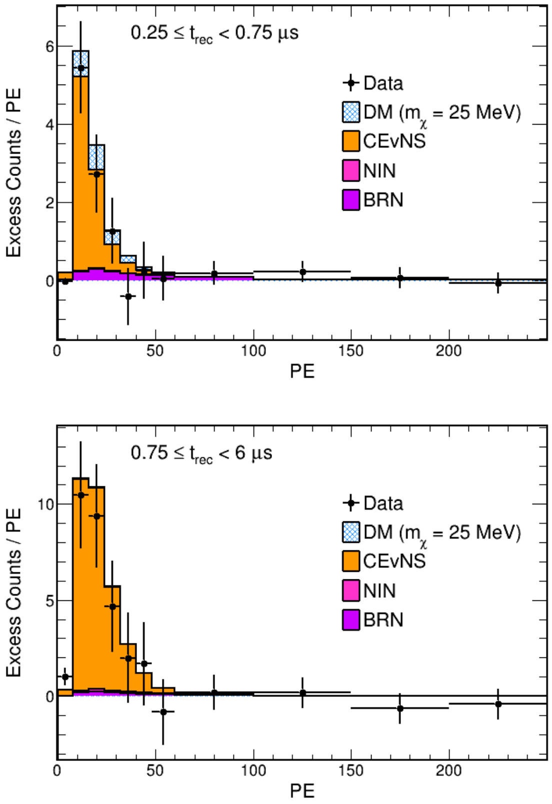

Figure 2. The observed, SSBkg-subtracted recoil spectra in the DM timing ROI (top) and the background control sample (bottom) compared to the best-fit prediction with no DM. The expected DM distribution at the 90% limit is stacked on the standard model prediction for $m_\chi = 25$ MeV/c^2.

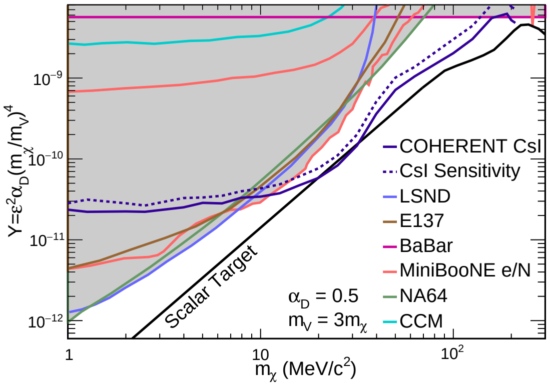

Figure 3. Constraint of DM parameter space for COHERENT CsI data compared to other experimental data, assuming $\alpha_D = 0.5$. The thermal target line for scalar DM is also shown.

The fit prefers slightly fewer CEvNS events than predicted after profiling over nuisance parameters. This is consistent with our CEvNS measurement using the same dataset [25]. Our critical $\Delta\chi^2$ values used to construct 90% confidence intervals on $N_{\rm DM}$ are $2.1 - 2.3$ depending on m_χ. These are slightly lower than those expected from Gaussian statistics

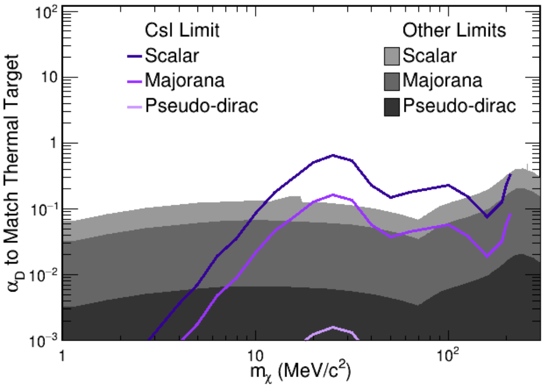

Figure 4. The values of α_D for which we can reject the cosmologically observed DM concentration as a function of DM mass compared to constraints shown in Fig. 3. We include scenarios where DM is scalar, a Majorana fermion, or a pseudo-Dirac fermion.

due to the proximity to the boundary $N_{\rm DM} \geq 0$. At our peak sensitivity, $m_\chi = 25$ MeV/c^2, we determined there are < 15.8 DM events in our sample to 90% CL, though the constraint on the number of DM scatters in our dataset depends on the mass assumption.

Our constraint on DM parameters for $\alpha_D = 0.5$ is shown in Fig. 3 along with our projected sensitivity and other current constraints. The thermal target line for scalar DM [38], which gives the model parameters needed to match the cosmologically observed DM concentration, is also shown. With a small 14.6 kg detector, we improve constraints on Y for $11 < m_\chi < 165$ MeV/c^2 by up to 5× suggesting that future, large-scale CEvNS detectors will be successful in ambitiously limiting light DM models. With the current dataset, we can reject coupling parameters consistent with cosmological DM for masses between 20 and 33 MeV/c^2 assuming $\alpha_D = 0.5$. The constraint is strongest at $m_\chi = 25$ MeV/c^2 where we can eliminate the scalar target for all $\alpha_D < 0.64$.

As our constraint depends on our particular choice of α_D, we can explore this parameter by constraining the values of α_D for which we reject the cosmological concentration at 90%, as shown in Fig. 4. For scalar DM, we constrain the cosmological abundance with very conservative choices of α_D. However, if DM is a Majorana or a pseudo-Dirac fermion, significant parameter space remains. In the future, with larger detectors sensitive to lower nuclear recoils, CEvNS data can probe fermion DM models at conservative choices of α_D, which favor Y values up to 20× lower.

6. FUTURE COHERENT SENSITIVITY

With the significant changes to the DM scattering model used, we also calculate our future sensitivity similar to the procedure described in [31]. Five scenarios are considered with Ge, Ar, and CsI nuclear targets. We consider detectors deployed both in Neutrino Alley and in a new detector hall at the planned second target station (STS) [39]. The STS will run 1.3 GeV protons on tungsten at 0.7 MW at a rate of 15 Hz which doubles the instantaneous neutrino flux at both the STS and first target state (FTS) compared to current operations at the FTS. The increase in beam energy will allow DM production through proton bremsstrahlung up to $m_\chi = 280$ MeV/c^2. This is high enough to access the ρ resonance which would enhance the DM production at masses around 250 MeV/c^2 [30], assuming $m_V = 3m_\chi$. We are currently working with ORNL to design a space suitable to accomplish our experimental goals.

First, we consider DM scattering in our COH-Ge-1 detector, a roughly 18-kg PPC detector fabricated by Mirion Technologies [40]. Detectors have been delivered and are being characterized and prepared for deployment perpendicular to the SNS beam near the former CsI location. We expect a roughly 1.4 keV$_{\rm nr}$ nuclear recoil threshold, low enough to extend sensitivity beyond our CsI constraint for low DM masses. Though offering a low threshold and excellent energy resolution, the timing resolution is poor in this detector compared to the SNS beam width, complicating the analysis. The sensitivity is calculated for three years of detector running at the FTS.

Two argon scintillating calorimeters are studied based on technology developed for the CENNS-10 detector [41] which recently made the first measurement of CEvNS on argon [42]. A 610-kg fiducial detector concept, COH-Ar-750, is being developed to be deployed in Neutrino Alley, sited 134° from the beam direction, with a three-year run-time. A larger, 10-t detector, COH-Ar-10t, is also planned for the STS with a running time of five years. This detector will be placed roughly 30° off-axis. For both detectors, the sensitivity is calculated using a three-dimensional fit in recoil energy, time, and the pulse-shape discriminator [42]. Backgrounds have been estimated from CENNS-10 data, assuming the steady-state background can be reduced by filling with low-background argon [43, 44]. Neutrons are also expected to be reduced by 20× through additional shielding for both FTS and STS detectors. We adopt the quenching model used for the CENNS-10 CEvNS measurement [42].

Finally, we plan two cryogenic CsI scintillation detectors [45] which can achieve very high light

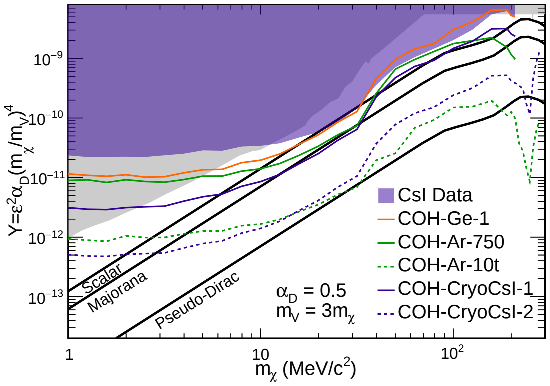

Figure 5. A comparison of DM sensitivity projections for future COHERENT detectors compared to this result and other constraints, shown in gray. Our peak in sensitivity around 250 MeV/c^2 comes from increased DM production through the ρ resonance.

yields suitable for strong constraints of low-mass DM scenarios with a threshold of roughly 0.5 keV$_{\mathrm{nr}}$. We consider COH-CryoCsI-1 with 30 kg×yrs of exposure at the FTS and COH-CryoCsI-2 with 3500 kg×yrs at the STS. Both detectors are expected to be placed perpendicular to the SNS beam.

We calculate the Asimov sensitivity [46] for each detector scenario with a binned likelihood fit. Each fit profiles over neutrino flux, background normalization, quenching, and form factor uncertainties. A comparison of these sensitivities to current constraints is shown in Fig. 5.

Once commissioned, COH-Ge-1 will cover unexplored parameter space with masses between 5 and 20 MeV/c^2 though CsI will continue to dominate at higher masses due to the Z^2 dependence of the scattering cross section. Our other detectors proposed for the FTS, COH-Ar-750 and COH-CryoCsI-1, would improve on constraints at all masses. These detectors would efficiently test fermion DM models, probing the cosmological DM concentration for masses between 12 and 35 MeV/c^2 assuming the DM particle is Majorana.

Detectors at the STS would dramatically improve sensitivities due to increased space for detector mass and improved background rejection due to beam livetime. Both proposed detectors would improve on current constraints and other COHERENT sensitivity estimates throughout the entire mass regime of interest. Detectors at the STS would be particularly sensitive to DM with masses around 250 MeV/c^2 due to increased bremsstrahlung production near the ρ resonance, assuming $m_V = 3m_\chi$. These masses, however, are not accessible with lower proton energies currently used at the FTS. In particular, COH-Ar-10t would probe conservative scenarios for pseudo-Dirac DM, thus testing all viable spin scenarios.

7. CONCLUSION

We have exploited CEvNS data collected by our decommissioned CsI[Na] detector at the SNS to search for hidden-sector DM particles produced in the beam. This dataset, in addition to making the most precise measurement of CEvNS to date, has considerably improved on current constraints for DM particles with masses between 11 and 165 MeV/c^2. In particular, this is the first result to test scalar DM for even the conservative choice of $\alpha_D = 0.5$ in the studied mass range. The data also constrains Majorana and pseudo-Dirac DM, but constraints on these scenarios will not be as exhaustive until future data is collected. We have developed powerful methods for understanding background rates by exploiting timing information. In the future, these techniques will constrain systematic uncertainties in-situ allowing much more stringent searches. In particular, future argon and CsI detectors placed in the STS beam have significant potential to discover an excess of DM scatters in currently unexplored parameter space independent of DM mass and spin phenomenology.

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