Prospect of undoped inorganic crystals at 40 Kelvin for low-mass dark matter search at Spallation Neutron Source

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Abstract A light yield of $26.0 \pm 0.4$ photoelectrons per keV electron-equivalent was achieved with a cylindrical 1 kg undoped CsI crystal coupled directly to two photomultiplier tubes at 80 K, which eliminates the concern of self light absorption in large crystals raised in some of the early studies. Also discussed are the sensitivities of a 10-kg prototype detector with SiPM arrays at light sensors operated at 40 K for the detection of low-mass dark matter particles produced at the Spallation Neutron Source at the Oak Ridge National Laboratory after two years of data taking.

1 Introduction

The DAMA/LIBRA experiment observed an annual modulation signal with a very high significance in the 2 to 6 keV electron-equivalent (keVee) region in their thallium-doped sodium iodide, NaI(Tl), scintillation crystals [1]. If it is interpreted with the standard dark matter theory, the observation conflicts with results from experiments using different target materials [2–5]. In different places in the world, including PICO-LON [6], DM-Ice [7], ANAIS [8], COSINE [9] and SABRE [10], many experiments have been built or are under construction to verify the DAMA result using the same material. No annual modulation signal similar to that in DAMA has been observed yet in these experiments due to mainly two difficulties: first, to lower the energy threshold, and second, to reduce radioactive contamination inside or on surface of scintillation crystals.

The second task has been a focus of all the NaI(Tl)-based experiments mentioned so far due to the simple fact that the energy threshold of the DAMA experiment is not extremely low, while the radio-purity of the DAMA crystals is still the best to date. To verify the DAMA results in the same energy region with the same crystal is certainly important. However, equally important is to explore the potential of alkali halide scintillation crystals in detecting other possible dark matter candidates, such as the ones that are light enough to be produced in particle accelerators [11]. The single request that signals must appear in the time window when a short pulsed particle beam hits another or a fixed target reduces by orders of magnitudes background events from radioactive contamination, which appear randomly in time. The stringent requirement on the radio-purity of scintillation crystals can be loosened to some degree in such an experimental setup.

A great evidence of the concept is the observation of coherent elastic neutrino-nuclear scatterings in a $\sim 14$ kg CsI(Na) crystal in the COHERENT experiment in 2017 utilizing neutrinos produced in the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL), TN, USA [12]. The SNS is the world’s premier neutron-scattering research facility. At full beam power, about $1.5 \times 10^{14}$ 1 GeV protons bombard a liquid mercury target in 600 ns bursts at a rate of 60 Hz. Neutrons are produced in spallation reactions in the mercury target. Interactions of the proton beam in the mercury target produce $\pi^+$ and $\pi^-$ in addition to neutrons. These pions quickly stop inside the dense mercury target. Most of $\pi^-$ are absorbed. In contrast, the subsequent $\pi^+$ decay-at-rest (DAR) produces neutrinos of three flavors. The sharp SNS beam timing structure is highly beneficial for background rejection and precise characterization of those backgrounds not associated with the beam [13], such as those from radioactive impurities in the crystal. Looking for beam-related signals only in the 10 µs window after a beam spill imposes a factor-of-2000 reduction in those backgrounds.

In addition to neutrons and neutrinos, the so-called dark portal particles, $V$, could also be produced at the SNS in the decay of mesons produced by the interactions between the 1 GeV proton beam and the mercury target. Those portal particles are predicted in sub-GeV dark matter models.
to mediate interactions between the relic dark matter candidates and the Standard Model particles in order to satisfy the Lee-Weinberg bound for the WIMP mass [14]. Close to the beam direction, the dominant production channel is the decay of $\pi^0/\eta^0$ particles on the fly, while the nuclear absorption of $\pi^-$ particles may produce portal particles isotropically. The portal particle would subsequently decay to a pair of light dark matter particles, $\chi^+\chi^-$, either of which may interact with a detector located near the SNS target.

The benefit of less stringent requirement on radio-purity of scintillation crystals in such a setup is accompanied with a desire for a lower energy threshold, since lighter dark matter particles are less efficient than heavier ones in transferring momentum to nuclei, resulting in less energetic nuclear recoils. Lowing the energy threshold involves reducing radioactive backgrounds and instrumental noises from light sensors and crystals near the threshold, as well as increasing the detection efficiency of the system and the light yield of the crystal. In this work, we focus on the possibility of increasing light yields of NaI and CsI crystals at cryogenic temperatures.

The light yields of undoped NaI and CsI crystals increase rapidly when temperature goes down, and reach the highest point around 40 K [15–17] was observed. The light yields at liquid nitrogen temperature (77 K at one atmospheric pressure) are slightly lower, but for convenience, most experiments were done at about 77 K. The observed number of photons varied with the purity of crystals and light readout methods [11, 18–40]. Nevertheless, all measurements gave similar or higher yields than those of Tl-doped NaI and CsI crystals at room temperature. The highest ones [11, 18, 21, 33, 35] almost reached the theoretical limit deduced from the band gap energy.

In 2016, one of the authors of this work measured the light yield of a small undoped CsI crystal directly coupled to a 2 inch Hamamatsu PMT R8778MODAY(AR) [41] at 80 K and achieved a yield of $20.4 \pm 0.8$ photoelectrons (PE) per keVee [40]. The cylindrical crystal used in that study had a diameter of 2 inches and a thickness of 1 cm, corresponding to a mass of only 91.4 gram. Mentioned in the literature [15], there was a concern about strong self absorption of the intrinsic scintillation light in undoped crystals, which might prevent the usage of crystals thicker than 1/2 inch from practical uses. However, later investigations revealed that the scintillation mechanism of undoped crystals [16, 39] should be transparent to their own scintillation light. Strong absorptions mentioned in early literature may have been due to impurities in their crystals.

A cylindrical undoped CsI crystal of more than 1 kg was used to test whether the light yield would reduce as the size of the crystal increases. The experimental setup is described first. The light yield achieved with two Hamamatsu R11065 PMTs is reported secondly. After that, the scintillation mechanism of undoped crystals is summarized briefly to support the high light yield observed with the large crystal. Using a 10-kg cryogenic detector located 19.3 meters away from the SNS target to detect the sensitivity of low-mass dark matter particles is discussed last.

Due to mechanical difficulties in operating NaI crystals in cryogenic environment, the experimental investigation was done using only undoped CsI. The discussion, however, was kept generic, involving both CsI and NaI given similar scintillation properties of the two from 4 to 300 K [15–17].

2 Experimental setup

The right picture in Fig. 1 shows an open liquid nitrogen (LN2) dewar used to cool a 50 cm long stainless steel tube placed inside. The inner diameter of the tube was $\sim$ 10 cm. The tube was vacuum sealed on both ends by two 6-inch ConFlat (CF) flanges. The bottom flange was blank and attached to the tube with a copper gasket in between. The top flange was attached to the tube with a fluorocarbon CF gasket in between for multiple operations. Vacuum welded to the top flange were five BNC, two SHV, one 19-pin electronic feedthroughs and two 1/4-inch VCR connectors.

![Fig. 1 A sketch (left) and a picture (right) of the experimental setup.](image)

The left sketch in Fig. 1 shows the internal structure of the experimental setup. The undoped cylindrical CsI crystal was purchased from the Shanghai Institute of Ceramics, Chinese Academy of Sciences. It had a diameter of 3 inches, a height of 5 cm and a mass of 1.028 kg. All surfaces were mirror polished. The side surface was wrapped with multiple layers of Teflon tapes. Two 3-inch Hamamatsu R11065-ASSY PMTs were attached to the two end surfaces without optical grease. To ensure a good optical contact, the PMTs were pushed against the crystal by springs, as shown
in Fig. 2. The assembly was done in a glove bag flushed with dry nitrogen gas to minimize exposure of the crystal to atmospheric moisture. The relative humidity was kept below 5% at 22°C during the assembly process.

The detector assembly in a glove bag.

Fig. 2

The assembled crystal and PMTs were lowered into the stainless steel chamber from the top. After all cables were fixed beneath it, the top flange was closed. The chamber was then pumped with a Pfeiffer Vacuum HiCube 80 Eco to \( \sim 1 \times 10^{-4} \) mbar. Afterward, it was refilled with dry nitrogen gas to 0.17 MPa above the atmospheric pressure and placed inside the open dewar. Finally, the chamber was cooled by filling the dewar with LN2. After cooling, the chamber pressure was reduced to slightly above the atmospheric pressure.

A few Heraeus C 220 platinum resistance temperature sensors were used to monitor the cooling process. They were attached to the side surface of the crystal, the PMTs, and the top flange to obtain the temperature profile of the long chamber. A Raspberry Pi 2 computer with custom software [42] was used to read out the sensors. The cooling process could be done within about 30 minutes. Most measurements, however, were done after about an hour of waiting to let the system reach thermal equilibrium. The temperature of the crystal during measurements was about 3 K higher than the LN2 temperature.

The PMTs were powered by a 2-channel CAEN N1470A high voltage power supply NIM module. Their signals were fed into a 4-channel CAEN DT5751 waveform digitizer, which had a 1 GHz sampling rate, a 1 V dynamic range and a 10-bit resolution. Custom-developed software was used for data recording [43]. The recorded binary data files were converted to CERN ROOT files for analysis [44].

3 Single-photoelectron response of PMTs

The single-photoelectron response of PMTs was measured using light pulses from an ultraviolet LED from Thorlabs, LED370E. Its output spectrum peaked at 375 nm with a width of 10 nm, which was within the 200-650 nm spectral response range of the PMTs. Light pulses with a \( \sim 50 \) ns duration and a rate of 10 kHz were generated using an RIGOL DG1022 arbitrary function generator. The intensity of light pulses was tuned by varying the output voltage of the function generator so that only one or zero photon hit one of the PMTs during the LED lit window most of the time. A TTL trigger signal was emitted from the function generator simultaneously with each output pulse. It was used to trigger the digitizer to record the PMT response. The trigger logic is shown in the left flow chart in Fig. 3.

A typical single-photoelectron (PE) pulse from an R11065 working at its recommended operational voltage, 1500 V, is well above the pedestal noise. However, the two PMTs were operated at about 1300 V to avoid saturation of electronic signals induced by 2.6 MeV \( \gamma \)-rays from environmental \( ^{208} \)Tl. The consequent small single-PE pulses hence had to be amplified by a factor of ten using a Phillips Scientific Quad Bipolar Amplifier Model 771 before being fed into the digitizer in order to separate them from the pedestal noise.

Fig. 4 shows two hundred consecutive waveforms from the bottom PMT overlapped with each other.

Fig. 4

Fig. 3 Trigger logics for single-photoelectron response (left) and energy calibration (right) measurements.
sulting single-PE spectra for the top and bottom PMTs are presented in Fig. 5 and Fig. 6, respectively.

The spectra were fitted in the same way as described in Ref. [45] with a function,

\[ F(x) = H \sum_n P(n, \lambda) f_n(x), \]

where \( H \) is a constant to match fit function to spectra counting rate, \( P(n, \lambda) \) is a Poisson distribution with mean \( \lambda \), which represents the average number of PE in the time window, \( f_n(x) \) represents the \( n \)-PE response, and can be expressed as

\[ f_n(x) = f_0(x) * f_1^n(x), \]

where \( f_0(x) \) is a Gaussian function representing the pedestal noise distribution, \( * \) denotes a mathematical convolution of two functions, and \( f_1^n(x) \) is a \( n \)-fold convolution of the PMT single-PE response function, \( f_1(x) \), with itself. The single-PE response function \( f_1(x) \) was modeled as:

\[ f_1(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma} e^{-x^2/(2\sigma^2)} & x > 0; \\ 0 & x \leq 0, \end{cases} \]

where \( R \) is the ratio between an exponential decay with a decay constant \( x_0 \), and a Gaussian distribution \( G(x; \bar{x}, \sigma) \) with a mean of \( \bar{x} \) and a width of \( \sigma \). The former corresponds to the incomplete dynode multiplication of secondary electrons in a PMT. The latter corresponds to the full charge collection in a PMT.

\[ \text{Eq. 3} \]

Due to technical difficulties in realizing multiple function convolutions in the fitting ROOT script, the three-PE distribution, \( f_3^n(x) \), was approximated by a Gaussian function with its mean and variance three times that of the single-PE response.

Table 1 lists means of single-PE distributions for both PMTs measured before and after the energy calibration mentioned in the next section to check the stability of the PMT gains. The average mean for the top and bottom PMT is 28.58 ± 0.51 and 33.08 ± 0.47 ADC counts·ns, respectively.

| PMT  | Temperature of PMT [°C] | Temperature of crystal [°C] | Mean of single-PE [ADC counts·ns] |
|------|-------------------------|-----------------------------|----------------------------------|
| Top  | 28.53 ± 0.51            | 33.08 ± 0.47                |
| Bottom | 28.63 ± 0.45            | 33.18 ± 0.43                |

4 Energy calibration

The energy calibration was performed using \( \gamma \)-rays from a \( ^{137} \text{Cs} \) and a \( ^{60} \text{Co} \) radioactive source, as well as \( ^{40} \text{K} \) within the crystal and \( ^{208} \text{Tl} \) from the environment. The sources were sequentially attached to the outer wall of the dewar as shown in Fig. 1. Background data taking was done before those with a source attached. The digitizer was triggered when both PMTs recorded a pulse above a certain threshold within a time window of 16 ns. The trigger logic is shown in the
right flow chart in Fig. 3. The trigger rate for the background, $^{137}$Cs and $^{60}$Co data taking was 100 Hz, 410 Hz and 520 Hz, respectively, if the threshold was set to 10 ADC counts above the pedestal level.

Each recorded waveform was 8008 ns long. The rising edge of the pulse that triggered the digitizer was set to start at around 1602 ns so that there were enough samples before the pulse to extract the pedestal level of the waveform. After the pedestal level was adjusted to zero the pulse was integrated until its tail fell back to zero. The integration had a unit of ADC counts · ns. It was converted to numbers of PE using the formula:

$$\text{(number of PE)} = \frac{\text{(ADC counts · ns)}}{\bar{x}}$$

where $\bar{x}$ is the mean of the single-PE Gaussian distribution mentioned in Eq. 3. Its unit was also ADC counts · ns. Its value was obtained from the fittings shown in Fig. 5 and 6. The resulting spectra normalized by their event rates recorded by the bottom PMT are shown in Fig. 7. The spectra from the top PMT are very similar.

Fig. 7 Energy spectra of the bottom PMT at 80 K.

The $\gamma$-ray peaks were fitted using one or two Gaussian distributions on top of a 2nd order polynomial. A simultaneous fit for the 1.17 MeV and 1.33 MeV peaks from $^{60}$Co is shown in Fig. 8 as an example. The peaks are clearly separated indicating an energy resolution much better than that of a regular NaI(Tl) detector running at room temperature. The means and sigmas of the fitted Gaussian functions are listed in Table 2 together with those from other $\gamma$-ray peaks.

The obtained light yield at each energy point is shown in Fig. 9. The light yield of the whole system was calculated as a sum of those of the top and bottom PMTs. The uncertainties of light yields are mainly due to the uncertainties of mean values of the single-PE responses used to convert the $x$-axes of the energy spectra from ADC counts to the number of PE. The data points in each category were fitted by a straight line to get an average light yield, which was $15.38 \pm 0.34$ PE/keVee for the top PMT, $10.60 \pm 0.24$ PE/keVee for the bottom one, and $25.99 \pm 0.42$ PE/keVee for the system.

To understand the origin of the significant light yield difference between the two PMTs, additional measurements were performed. First, the PMT-crystal assembly were pulled from the chamber and reinserted upside down without any other change. The PMTs kept their yields unchanged. Second, the PMT with the lower yield was replaced by another R11065. No significant change could be observed. Last, the crystal was flipped while the PMTs were kept in their original locations. Again, no significant change could be observed. Therefore, the difference in the light yields between the two PMTs was most probably due to the difference in the

5 Light yield

The light yield was calculated for each PMT using the data in Table 2 and the following equation:

$$\text{light yield [PE/keVee]} = \frac{\text{Mean [PE]}}{\text{Energy [keVee]}}.$$
quantum efficiencies of individual PMTs instead of different optical interfaces or temperatures.

There seems to be a systematic increase of the light yield as the energy increases as shown in Fig. 9. This may indicate a slight non-linearity in the energy response of the undoped CsI crystal at 80 K. However, limited by the large uncertainty of each data point, no quantitative conclusion can be drawn. Additional studies with low-energy sources will be performed in the future.

6 Scintillation mechanism

The light yield achieved with this ∼1 kg undoped CsI is even higher than that achieved with the 91.4 gram crystal, which proves that the undoped CsI is at least transparent to its own scintillation light up to a few tens of centimeters. The scintillation mechanism of undoped crystals is summarized here to back up this conclusion.

A scintillation photon must have less energy than the width of the band gap of the host crystal. Otherwise, it can excite an electron from the valence band to the conduction band and be absorbed by the host crystal. This demands the existence of energy levels in between the band gap. Recombinations of electrons and holes in these levels create photons not energetic enough to re-excite electrons up to the conduction band, and hence cannot be re-absorbed. In Tl-doped crystals, there exist these energy levels around the doped ions, which are called scintillation centers. Scintillation centers in undoped crystals are understood to be self-trapped excitons instead of those trapped by doped impurities [46]. Two types of excitons were observed in an undoped CsI [16] as demonstrated in Fig. 10. In both cases, a hole is trapped by two negatively charged iodine ions, it can catch an excited electron and form a so-called exciton that resembles a hydrogen atom. These excitons have less energy than the width of the band gap, photons emitted by the de-excitation of which are not energetic enough to be re-absorbed by the host crystal.

The energy dispersion among phonons and the two types of excitons dictates the temperature dependence of the light yield of undoped crystals (full and empty circles in Fig. 11), which were experimentally verified [16, 39]. It is worth noting that if the operation temperature can be lowered from 80 K to 40 K, the light yield can be further increased.

Due to completely different scintillation mechanisms, the scintillation wavelengths and decay times of undoped NaI/CsI are quite different from those of NaI/CsI(Tl), as summarized in Table 3 and Table 4 for room and liquid nitrogen temperatures, respectively. Undoped NaI is a much faster scintillator than NaI(Tl). It permits a narrower coincidence time window that can further suppress steady-state backgrounds. This allows for precise searches for physics beyond the Standard Model, such as low-mass dark matter particles or non-standard neutrino interactions, depending on their timing relative to the beam.
Table 3  Scintillation wavelength $\lambda$ and decay time $\tau$ of Tl-doped and undoped NaI, CsI crystals at room temperature.

| Crystal   | $\tau$ at $\sim$ 297 K [ns] | $\lambda$ at $\sim$ 297 K [nm] |
|-----------|-----------------------------|---------------------------------|
| NaI(Tl)   | 230 $\sim$ 250 [48–50]     | 420 $\sim$ 430 [21, 38]        |
| CsI(Tl)   | 600 [18]                    | 550 [51]                       |
| undoped NaI | 10 $\sim$ 15 [18, 21, 22]  | 375 [25, 26]                   |
| undoped CsI | 6 $\sim$ 36 [32, 51, 52]  | 305 $\sim$ 310 [29, 32, 51]   |

Table 4  Scintillation wavelength $\lambda$ and decay time $\tau$ of Tl-doped and undoped NaI, CsI crystals at liquid nitrogen temperature.

| Crystal   | $\tau$ at $\sim$ 77 K [ns] | $\lambda$ at $\sim$ 77 K [nm] |
|-----------|-----------------------------|---------------------------------|
| NaI(Tl)   | 736 [38]                    | 420 $\sim$ 430 [21, 38]        |
| CsI(Tl)   | no data                     | no data                         |
| undoped NaI | 30 [15, 22]               | 303 [21, 38]                   |
| undoped CsI | 1000 [16, 32, 40]        | 340 [16, 29, 32]               |

Compared to deep-underground dark matter experiments, detectors located at the SNS are much shallower. Afterglows of the crystal induced by energetic cosmic muon events may be a serious concern. As shown in Fig. 11, undoped CsI and NaI suffer from afterglow above $\sim$ 60 K [47]. However, one of the authors of [47], suggests through private communication that at 40 K (near maximal light yield for undoped CsI and NaI), the afterglow rate at the single-photon level is reduced by a Boltzmann factor to a level that is probably much lower than the dark noise of the light sensors. One can thus maximize the light yield and minimize the afterglow of undoped CsI and NaI by operating them near 40 K. One can also require the coincident observation of light signals in at least two light sensors to suppress both the afterglow from the crystal and the dark noise from light sensors at the single photon level.

7 Energy threshold

According to Ref. [40], the quantum efficiency of R11065 at 80 K near 300 nm is about 27%, while the photon detection efficiency of some silicon photomultipliers (SiPM) can already reach 56% at around 420 nm [53]. By replacing PMTs with SiPM arrays coated with some wavelength shifting material that shifts 313 nm [38]/340 nm [16, 29, 32] scintillation light from undoped NaI/CsI to $\sim$430 nm, it is possible to double the light yield from 25.99 $\pm$ 0.42 PE/keVee to about 50 PE/keVee. Such a high yield has recently been almost achieved using a combination of a small undoped CsI and a few large-area avalanche photodiodes (LAAPD) after wavelength shifting [11]. Compared to a SiPM, a LAAPD has generally even higher light detection efficiency (about 90%), but its output signals are too small to be triggered at single-PE level.

To estimate the trigger efficiency of a detector module as shown in the inlet of Fig. 12 that has a light yield of 50 PE/keVee, a toy Monte Carlo simulation was performed as follows:

- $n$ photons were generated.
- 10% of them were thrown away randomly, mimicking a 90% light collection efficiency.
- The remaining photons had an even chance to reach individual SiPM arrays, and 56% of chance to be detected.
- If both arrays recorded at least one PE, this simulated event was regarded as being triggered.

The value of $n$ changed from 0 to 40. For each value, 10,000 events were simulated. The trigger efficiency was calculated as the number of triggered events divided by 10,000.

Fig. 12 shows the simulated 2-PE coincidence trigger efficiency as a function of the number of generated photons. An exponential function (purple curve) with three free parameters was fitted to the simulated results (blue dots). The fitted function was used to convert energy spectra to PE spectra, which is described in detail in the next section.

From Fig. 12, one can read a trigger efficiency of 80 % when there are about 8 photons, which can be converted to about 8 $\times$ 90% $\times$ 54% $\approx$ 4 PE, taking into account the light collection efficiency of 90% and the photon detection efficiency of 56%. This can be further translated to a threshold of 4/50 = 8 eVee, given the 50 PE/keVee light yield.

Assuming a constant quenching factor of 0.08 for NaI and 0.05 for CsI in such a low energy region, the threshold is translated to 1 keV for Na recoils, and 1.6 keV for Cs recoils.

8 Sensitivity to low-mass dark matter produced at SNS

Given the simulated trigger efficiency near the energy threshold, the sensitivity of cryogenic crystals placed 19.3 meters...
away from the SNS target for low-mass dark matter detection was estimated.

Two classes of dark matter portal particles can be constrained by such an experiment: a vector portal particle kinetic mixing with a photon, and a leptophobic portal particle coupling to any Standard Model baryon. In addition to the portal and the dark matter particle masses, $m_V$ and $m_\chi$, the vector portal model has two coupling constants as free parameters, $\epsilon$ and $\alpha'$, while the leptophobic parameter depends on a single $\alpha_B$. The parameters of the vector portal model can be conveniently compared to the cosmological relic density of dark matter through the dimensionless quantity,

$$Y = \frac{\epsilon^2 \alpha'(m_\chi/m_V)^4}{54},$$

which can easily be compared to results from direct detection experiments. The sensitivity to the leptophobic portal of the assumed detector is of great interest compared to beam dump experiments, which are frequently most sensitive to $\nu$-$e$ elastic scattering [55, 56], and are incapable of testing this model.

The BdNMC event generator [57] was used to determine the energy spectra of Na and I recoils in the assumed detector, parameterized by the dark matter and portal particle masses [58]. Assuming a constant nuclear recoil quenching factor of 0.08, the generated Na and I recoil energy spectra were converted to visible energy spectra in keVee. The 50 PE/keVee system light yield was translated to the crystal’s intrinsic light yield of 50/56%/90% $\approx$ 100 photons/keVee, which was used to convert the visible energy spectra to number-of-photon spectra. A simple Poisson smearing of the number of photons was applied to the latter. At last, the trigger efficiency function fitted to Fig. 12 was applied to convert the number-of-photon spectra to PE spectra, which were summed and shown as the blue histogram stacked on top of others in Fig. 13 labeled as “LDM Signal”. The total number of LDM events integrated over the whole spectrum at $Y = 2.6 \times 10^{-11}$ and $m_\chi = 10$ MeV is about 44.

The largest component in Fig. 13 colored in orange and labeled as “Neutrino Signal” are the calculated CEvNS spectrum with the detector responses folded in. The total number of events is about 218 in the $0 \sim 0.8\mu s$ prompt neutrino window. Additional 663 CEvNS events can be detected in the delay window ($0.8 \sim 6\mu s$), which were used to constrain the uncertainty of the orange spectrum in Fig. 13. The bottom two histograms labeled “Beam Neutrons” and “Steady-State bkg” are the SNS beam related and unrelated background spectra measured by the COHERENT CsI(Na) detector [12]. Since the proposed detector has a much lower threshold, there are no measurement of the two backgrounds below 40 PE. The rates of the two were assumed to be flat below 40 PE.

For each $m_\chi$ and $m_V$, the minimum dark matter coupling constants that are inconsistent with the Asimov prediction [59] was calculated taking into account systematic uncertainties as described in detail in Ref. [58]. The results are shown in Fig. 14 and 15 for an exposure of a 10 kg crystal for 2 years of data taking. The thermal target line indicates the model parameters where dark matter interactions with visible matter in the hot early universe explain the dark matter abundance today.

The nuclear quenching factor of undoped NaI has not been measured. Small or no quenching were observed in undoped CsI for $\alpha$ radiation compared to $\gamma$ radiation [20, 52]. A very preliminary measurement of the nuclear quenching factor of an undoped CsI gives a value of 0.1 [11]. Detailed measurement of the nuclear quenching factors for both undoped NaI and CsI is planned. For the purpose of sensitivity estimation, two extreme cases are considered. The red curves in Fig. 14 and 15 correspond to a constant quenching factor of 0.08. The blue ones are with no quenching at all. The real sensitivity curve should lay in between.

![Fig. 13 Energy spectra of the proposed detector at the SNS in the prompt neutrino window (0 ∼ 6μs) with an exposure of 20 kg-year.](image)

![Fig. 14 Predicated 90% sensitivity to low-mass dark matter production parameters in case of the vector portal theory.](image)
Fig. 15 Predicated 90\% sensitivity to low-amss dark matter production parameters in case of the baryonic portal theory.

9 Conclusions

A light yield of $26.0 \pm 0.4$ PE/keVee was achieved with an undoped CsI crystal directly coupled to two PMTs at 80 K. The cylindrical crystal has a diameter of 3 inches, a height of 5 cm, and a mass of 1.028 kg, which can work as a module of a 10 kg detector for the detection of low-mass dark matter particles produced at the Spallation Neutron Source at the Oak Ridge National Laboratory. The sensitivity of such a detection was investigated assuming a similar setup as the CsI(Na) detector used in the COHERENT experiment where the coherent elastic neutrino-nuclear scattering was first observed. With such a detector, a large amount of phase space that has not been covered by current experiments can be explored given a 20 kg-year exposure.

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