Sensitivity of sodium iodide cryogenic scintillation-phonon detectors to WIMP signals

M Clark¹, P Nadeau¹, P C F Di Stefano¹, J-C Lanfranchi², S Roth¹, M von Sivers³ and I Yavin⁴

¹ Department of Physics, Engineering Physics & Astronomy, Queens University, Kingston, Ontario, Canada, K7L 3N6
² Physik-Department E15, Technische Universität München, Garching, Germany 85748
³ Albert Einstein Center for Fundamental Physics, University of Bern, 3012 Bern, Switzerland
⁴ Perimeter Institute for Theoretical Physics, 31 Caroline St. N, Waterloo, Ontario, Canada N2L 2Y5

E-mail: clarkmt@owl.phy.queensu.ca

Abstract. There is great interest in performing dark matter direct detection experiments using alkali halides such as NaI to test the DAMA/LIBRA claim. Cryogenic scintillation-phonon detectors measure both scintillation light and phonons to provide event-by-event discrimination between particles interacting with nuclei and particles interacting with electrons. An alkali halide scintillation-phonon detector could test the DAMA/LIBRA claim in a model-independent way using a similar material with added background discrimination. We present simulations of such detectors to determine their possible sensitivity to both annual modulation and particle interaction signals. We find that a 5 kg detector array could test the modulation reported by DAMA/LIBRA within 2 years using a likelihood-ratio test.

1. Introduction

The DAMA/LIBRA experiment reports a positive signal for detection of dark matter [1], which is not corroborated by other experiments using different detector materials or technology under standard astrophysical assumptions [2]. DAMA/LIBRA is composed of 250 kg of NaI(Tl) scintillating crystals, operating at room temperature in the Gran Sasso Underground Laboratory, shielded from cosmic ray backgrounds and constructed of low radiation materials. The reported signal is in the form of an annual modulation in their measured interaction rate with a phase and period consistent with the Earth passing through the Dark Matter halo of the galaxy [1].

The DAMA experiment observes only the scintillation light from particle interactions, without a background discrimination method to determine whether a single measurement is based on a nuclear recoil, expected from dark matter WIMP particles, or an electron recoil, characteristic of electrically charged particles or gamma rays from radioactive or cosmic ray background events [3].

We have argued previously [4] that a cryogenic scintillation-phonon detector would provide the possibility to directly measure the vibrational energy imparted into the crystal in addition to the scintillation light for each individual particle interaction. Nuclear recoils produce a smaller fraction of scintillation light to phonon energy when compared to electron recoils, so this measurement scheme could allow for a mode of background discrimination. The CRESST
experiment operates CaWO$_4$ scintillating crystals using this background discrimination scheme, and are currently performing WIMP search experiments [5].

If the DAMA modulation signal is truly a result of interactions with standard WIMP particles, they should be able to be clearly determined as nuclear recoils by a scintillation-phonon detector. This would allow a model-independent test of the DAMA claim in a complementary way to other NaI-based scintillation-only experiments that are beginning operation in the near future, such as SABRE [6] and ANAIS [7], which will use lower background crystals than DAMA and a muon-veto system [6], KIMS [8], which will utilize pulse-shape discrimination, and DM-Ice [9], which will be operated at the South Pole to evaluate seasonal backgrounds.

2. Expected sensitivity of alkali halide calorimeters

Alkali halide scintillators such as NaI(Tl) are traditionally operated at room temperature, and have been tested down to cryogenic temperatures. We performed light yield measurements to determine the scintillation performance of alkali halides at low temperatures using an optical cryostat at Queen’s University [10]. Small samples of the scintillators were irradiated with $\alpha$-particles and $\gamma$-rays from an Am-241 source and the light emitted was observed using two photomultiplier tubes in coincidence. The light-detection apparatus is kept at room temperature, so a change in measured light is interpreted as a change in light being produced in the crystal. We can then compare our measured relative light yield change to a reference absolute light yield at room temperature to determine our absolute light yield at cryogenic temperature. Light yield measurements from 300 K down to 3.4 K were carried out for three alkali halides: NaI, NaI(Tl) and CsI (not discussed here). The results of scaling our relative light yield measurements to absolute light yield measurements [4] are reproduced in Table 1. We use the $\gamma$-radiation light yield as we are assuming our backgrounds are coming from electron recoils, which should behave similarly to $\gamma$-rays. The light yield appears to remain relatively constant at lower temperatures, and thus we assume that the light yield at millikelvin temperatures required for the use of phonon sensors is similar to what we measured at our base temperature.

| Temp. (K) | NaI | NaI(Tl) |
|-----------|-----|---------|
| 300       | 4.16 [11] | 44.8 [12] |
| 3.4       | 19.5 $\pm$ 1.0 | 40.6 $\pm$ 0.8 |

2.1. Background rejection capability

Using our measured light yield values, the sensitivity of a detector composed of these materials to a WIMP signal can be evaluated by simulation of particle interactions as described elsewhere [4]. Particle interaction energies are generated using background spectra reported by DAMA [3] for NaI, NaI(Tl) and KIMS [13] for CsI as the probability density. Poisson statistical fluctuations are applied on the number of photons generated along with light collection efficiency, light channel and phonon channel resolutions based on results from the CRESST CaWO$_4$ scintillation-phonon detectors [14] are applied to each individual event to create a distribution of simulated measurements of light and phonon signal.
Using published measurements of the quenching factor of the light yield between nuclear and electron recoils, and assuming it does not depend on temperature, we can determine where a nuclear recoil event would be expected to lie in the phonon energy vs. light energy parameter space. The ratio of the light energy and phonon energy is taken, known as the Yield, and normalized such that the expected Yield of electron recoils is set to 1 for 122 keV photons [4]. A more detailed description of this simulation process can be found in a previous publication [4].

**Figure 1.** Discrimination band plot [4] for NaI, NaI(Tl) (as well as CsI) using phonon resolution reported by the CRESST collaboration of their CaWO$_4$ crystals. Expected regions for electron and nuclear recoils are shown in black and blue/red respectively. Simulated electron recoil events are shown as grey dots for 10 kgd exposure, and events leaking into the signal region are shown as open circles.

The results of these simulations, using light and phonon resolutions measured by the CRESST collaboration for their CaWO$_4$ crystals [14] are shown in Figure 1. The marked regions are the 10th and 90th percentile of large simulations using the published nuclear recoil quenching factors to determine where nuclear recoils are expected to lie, with the dotted line being the median of those simulations at each phonon energy. In a physical experiment, these regions would be determined using calibration with neutron and gamma ray sources. Simulated background events for 10 kgd of exposure are shown in gray solid dots, and any of these events which pass into the nuclear recoil regions are shown as open circles.

Over the full range of energies considered of 1-20 keV phonon energy, 95% of the simulated background is removed from selecting only events in the nuclear recoil band, so this shows that a scintillation-phonon detector could greatly reduce the amount of background considered in a WIMP search experiment. We have shown [4] that using a standard time-independent analysis, a modest exposure of 10 kg is able to test the DAMA region if the threshold and resolution is low enough. In the 2-6 keV region relevant to the DAMA modulation result [1] and a simulated
exposure of 10 kgd, we reject 27 of the 35 events, achieving a 77.1% background discrimination rate for pure NaI. For NaI(Tl), all of the 34 events seen in this region are rejected, showing a near 100% discrimination power for this exposure.

2.2. Modulation sensitivity

We next use this background discrimination level to determine the sensitivity to an annual modulation signal, to compare with the DAMA result in a WIMP model independent way. In the 2-6 keVee range, DAMA reports a modulation with an amplitude of 0.0448 cpd/kg and phase of 144 days after January 1 [1].

We use the reported DAMA non-modulating (DC) background in the 2-6 keVee region (approx. 4 cpd/kg) [3] and the modulation parameters to create a probability distribution for events in time, and simulate events based on exposure. These data are then used as the basis of two maximum likelihood fits, named the modulation hypothesis and the null hypothesis. The modulation hypothesis is a sinusoidal function with a period fixed to one year, but amplitude and phase are allowed to vary. The null hypothesis is a simple flat distribution in time, with no modulation.

The ratio of the results of these two likelihood fits indicates the probability that the data is truly distributed by a modulating probability distribution versus a random fluctuation of a flat distribution. If the simulated data is truly distributed by the null hypothesis, i.e. no modulation is present, then Wilks’s Theorem states that the likelihood ratio will asymptotically follow a $\chi^2$-distribution with degrees of freedom equal to the difference in the number of free parameters between null and modulation hypotheses [15]. We confirmed that our method is compatible with Wilks’ Theorem, by performing the likelihood fits on a set of 5000 simulations containing no modulation, and showing that the distribution of the likelihood ratio follows a $\chi^2$ with 2 degrees of freedom, i.e. $f(x) = e^{x/2}$.

We can evaluate the probability that the data represents a true modulation in the measured interaction rate, known as the p-value, by taking the area of the $\chi^2$ pdf below the likelihood ratio for each simulation. The probability that the data is distributed by the null hypothesis is directly complementary to the confidence level in the detection of a modulation, so a 1% probability of the null hypothesis represents a 99% confidence level in the detected modulation [15].

Figure 2 shows the likelihood that the simulated modulating data was distributed by the null hypothesis as a function of time for a 5 kg detector for different levels of background discrimination. We assume a minimal DC signal contribution equal to the modulation amplitude so that the simulated rate does not drop below zero even with no backgrounds. Each line represents the median of a set of 1000 simulations, while the shaded regions show the area between the 10th and 90th percentile.

From Figure 2 we can see that with the background discrimination level achieved in the pure NaI simulation (77%) assuming a minimal DC signal, a modest 5 kg detector array would have a 50% chance to reach a 90% confidence level in modulation detection within 2 years. With the higher background discrimination of the NaI(Tl) simulation (near 100%), 99% confidence could be reached after only one year.

3. Conclusion

Scintillation-phonon detectors composed of alkali halide crystals could provide a unique way to check the DAMA modulation result in a model-independent way. Using the same or similar materials with another method of background discrimination could confirm the presence of the signal with a relatively small exposure, and provide an avenue of insight into its origin if it is observed. Technical challenges such as the phonon channel resolution and reducing the radiative background must be overcome, though there are active collaborations developing NaI(Tl) crystals with backgrounds even lower than DAMA [6] [7].
Figure 2. Simulated p-values for a 5 kg detector array with: background discrimination, - - - - 100%, · · · · · 77%, and —— 0% DC background discrimination, assuming a minimal DC signal. The lines represents the median and the shaded regions denote the area between the 10th and 90th percentile of 1000 simulated experiments for each background level. 90% and 99% confidence levels are also shown as horizontal lines.

References
[1] Bernabei R et al. 2013 European Physical Journal C 73 2648 (Preprint 1308.5109)
[2] Beringer J et al. (Particle Data Group) 2012 Phys. Rev. D 86(1) 010001
[3] Bernabei R et al. 2008 The European Physical Journal C 56 333–355 ISSN 1434-6044
[4] Nadeau P et al. 2015 Astroparticle Physics 67 62–69 (Preprint 1410.1573)
[5] J Schieck for the CRESST collaboration 2015 ArXiv e-prints (Preprint 1505.03289)
[6] Shields E et al. 2015 Physics Procedia 61 169 – 178 ISSN 1875-3892 13th International Conference on Topics in Astroparticle and Underground Physics, {TAUP} 2013
[7] Amaré J et al. 2015 ArXiv e-prints (Preprint 1501.00104)
[8] Kim K et al. 2015 Astroparticle Physics 62 249 – 257 ISSN 0927-6505
[9] DM-Ice Collaboration, Cherwinka J et al. 2014 Phys. Rev. D 90 092005 (Preprint 1401.4804)
[10] Verdier M A et al. 2009 Review of Scientific Instruments 80 046105
[11] Moszynski M 2003 Nucl Instrum Meth A 505 101 – 110 ISSN 0168-9002 proceedings of the tenth Symposium on Radiation Measurements and Applications
[12] Holl I et al. 1988 A measurement of the light yield of common inorganic scintillators vol 35:1
[13] Kims Collaboration, Lee H S et al. 2006 Physics Letters B 633 201–208 (Preprint astro-ph/0509080)
[14] Lang R et al. 2010 Astroparticle Physics 32 318 – 324 ISSN 0927-6505
[15] Wilks S S 1938 Ann. Math. Statist. 9 60–62