Journal of Physics: Conference Series **2156** (2022) 012212 doi:10.1088/1742-6596/2156/1/012212

Influence of NaI background and mass on testing the DAMA modulation

Madeleine J. Zurowski and Elisabetta Barberio

School of Physics, University of Melbourne, Victoria, Australia
ARC Centre of Excellence for Dark Matter Particle Physics

E-mail: madeleine.zurowski@unimelb.edu.au

Abstract. NaI experiments should be sensitive to the same DM-SM interactions proposed to explain the observed DAMA modulation. As such, they are often called a 'model independent' test of the signal. While the same signal will be produced at all NaI detectors, the ability to observe it is strongly dependent on the experimental set up – in particular the mass and background of the target. We present here a study on how changes to these values influence the ability of a detector to observe a characteristic DM modulation. We consider both the standard elastic, spin independent WIMP and a model independent analysis assuming exactly the modulation signal observed by DAMA (i.e., making no assumptions about the particle interaction model producing this signal), and find that in both cases a lower background is favoured over a higher exposure mass (based on currently achievable levels).

1. Introduction

For almost 30 years the DAMA experiment has observed a modulating signal consistent with that expected from WIMP dark matter (DM) with a NaI target [1]. Taken by itself, this is compelling evidence for the direct detection of DM, but this observation is in increasing tension with results from a large number of other DM detectors [2]. However, the experiments constraining DAMA use a different scattering target, and as such require the assumption of a particular model for comparative analysis. Thus, instead of conclusively dismissing the DAMA modulation as having a DM origin, this has strongly constrained the standard WIMP assumptions, and pushed to more and more tailored models to explain these null results consistently.

To test DAMA in a model independent manner, another NaI based experiment is required. As of the end of 2020, three such detectors are planned or already in the data taking stage: ANAIS, COSINE, and SABRE [3–5]. As these all use the same target as DAMA, under the assumption that all the experiments have a similar threshold efficiency and detector resolution, they are expected to be able to observe the same modulation signal. The only thing that will change between the detectors is the run time required for statistical significance, which depends on the background and mass. Based on this, we present the evolving model independent (no assumptions made for particle interaction models) exclusion and discovery power of these experiments for the modulating signal reported by DAMA.

2. Analysis procedure

In general, an experiment will be sensitive to a DM modulating signal if the signature modulation is observable over the detector's background. In this case, the apparent modulation of the background signal due to statistical fluctuations is more problematic than the background rate itself, as analysis of the modulation signature typically involves the subtraction of the constant signal component. As such, to assess the sensitivity of a detector these fluctuations should be modelled over its live time and fit to a cosine function to find the probability of this masking or mimicking the DM signal. These event rates are simulated by randomly sampling from a Poissonian centred on N_{s+b} for the signal + background model and N_b for the background only model:

$$N_{s+b} = M_E \times \Delta T \times \Delta E \times (R_b + R_0 + R_m \cos \omega t)\,, \tag{1}$$

$$N_b = M_E \times \Delta T \times \Delta E \times R_b, \tag{2}$$

where

- M_E is the detector exposure mass in kg
- ΔT is the data taking time period in days (we assume bins of 1 month)
- ΔE is the energy bin of interest in keV (for simplicity we assume a single bin from 2-6 keV)
- R_b is the background rate in cpd/kg/keV
- R_0 is the constant signal rate in cpd/kg/keV
- R_m is the modulating signal rate in cpd/kg/keV

The full experimental live time is simulated and fit to a cosine function hundreds of times to find the distribution of modulation rates observed in the background only and signal + background cases. This distribution is then fit to a gaussian, where the mean and standard deviation values are interpreted as the observed modulation and its uncertainty for a given model, and used to construct the test statistics used for analysis.
We use two test statistics to assess the power of these NaI experiments:

(i) $n\sigma$ confidence level of exclusion: how well the pseudo data from the background only model fits the signal + background hypothesis. This depends on the uncertainty in signal + background:

$$n = \frac{\mu_{sb} - \mu_b}{\sigma_{sb}}. \tag{3}$$

(ii) $n\sigma$ confidence level of discovery: how well the pseudo data from the signal + background model fits the background only hypothesis. This depends on the uncertainty in background only:

$$n = \frac{\mu_{sb} - \mu_b}{\sigma_b}. \tag{4}$$

This methodology is detailed further in Ref. [6].

3. Results

The analysis described in Sec. 2 was carried out for both the model dependent (R_0 and R_m computed by assuming a spin independent, elastic WIMP) and independent (R_0 and R_m taken to be the values reported by DAMA) cases for the various NaI detectors. The mass and background assumptions made for each detector are given in Table 1. To verify that this method returns sensible results, we assume all four detectors have the same live time (three years) and present their 90% exclusion limits in Fig. 1. These exclude the usual regions of parameter space ($\sigma \sim 10^{-42} - 10^{-37}$), and as expected the relative power of the experiments scales with $\sqrt{M_E/R_b}$.

The model independent exclusion and discovery power for the planned and running experiments are shown in Fig. 2, with the time required to reach typical benchmark values given in Table 1. This analysis method can also be used to understand allowable mass and

Table 1. Detector mass and background assumptions, the resulting current exclusion power, and years required to reach 3σ exclusion or 5σ discovery.

Experiment	Mass (kg)	R_b (cpd/kg/keV)	Current excl.	For 3σ excl.	For 5σ disc.
ANAIS [3]	112	3.2	2.9σ	3 yrs	7 yrs
COSINE [4]	57.5	2.7	2.2σ	5 yrs	>7 yrs
DAMA [1]	250	0.8	-	-	-
SABRE [5]	50	0.36	0σ	2 yrs	2 yrs

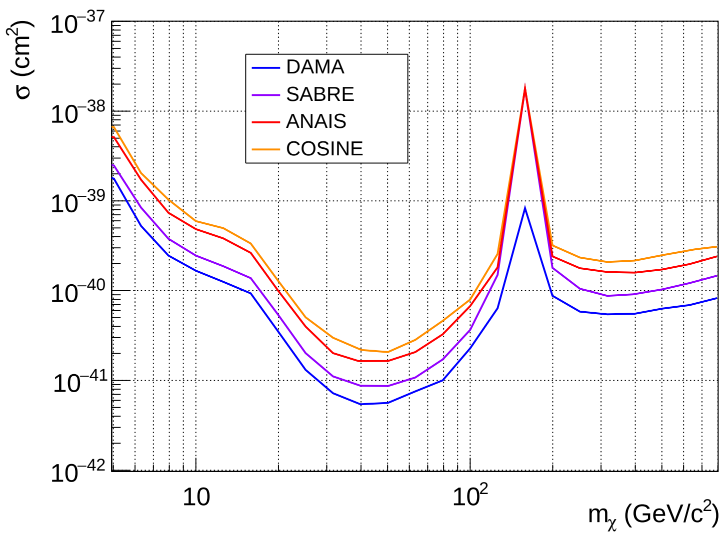

Figure 1. 90% exclusion limits for various detectors under the assumption of a spin independent, elastic WIMP, and three years of live time.

background requirements to achieve certain sensitivity levels to the DAMA signal. In Fig. 3 for example, we plot the combinations that give a 3σ exclusion C.L. after 3 years of operation. Mass and background levels below the line can achieve this sensitivity. This can be useful for the R&D for new detectors, or in the event of upgrades to existing NaI detectors where funding and/or space considerations need to be taken into account during the design.

4. Conclusions

For both model dependent and dependent limits the lowest background (SABRE) has performed the best of the three new experiments, despite having the lowest exposure mass. This makes clear how important a low background is for DM searches in order to observe the small modulation in an already low interaction rate, further motivating the purification and veto techniques presently explored by these collaborations. Based on this analysis, should the projected exposure mass and backgrounds be achieved, and data taking commence in the next 18 months, SABRE will be positioned to provide statistically significant exclusion or discovery of the DAMA signal within 3-4 years. In this event (and even more so in the event of a positive DM-like signal), it will be beneficial to compare the results from the Northern and Southern hemispheres, to further elucidate clues as to nature of the modulating DAMA signal - DM or not.

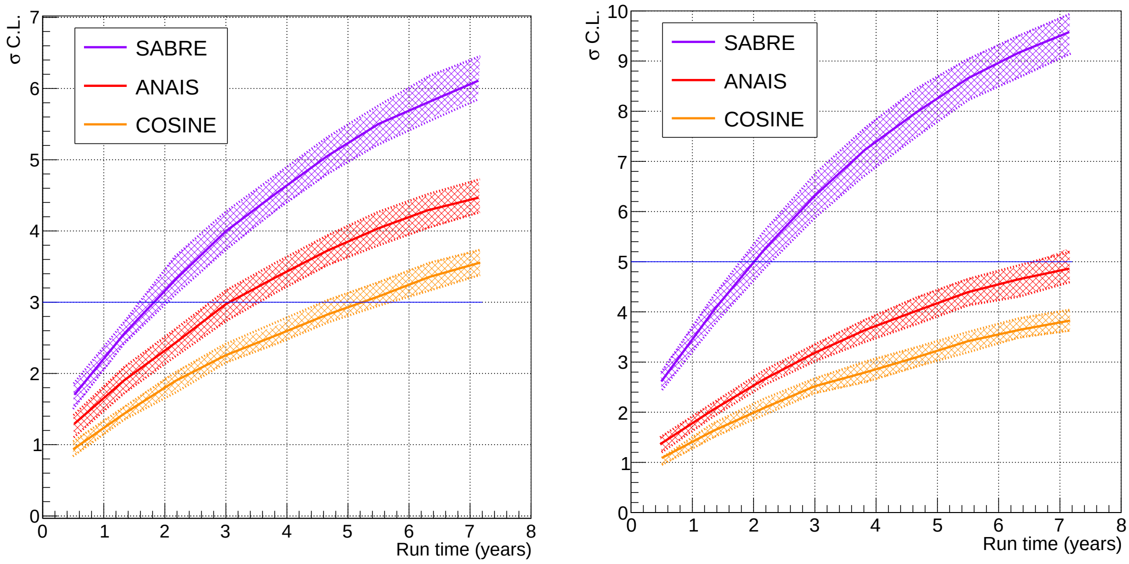

Figure 2. Exclusion (left) and discovery (right) confidence levels as a function of time.

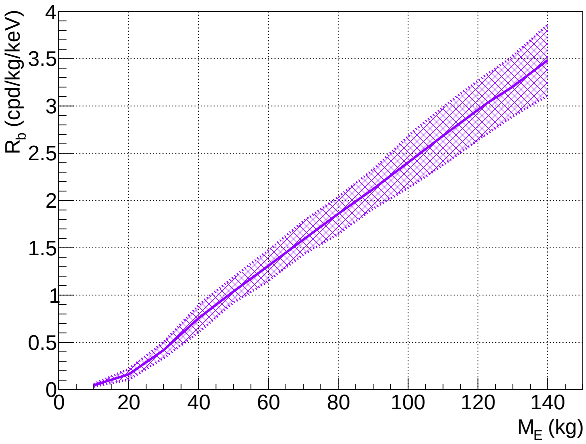

Figure 3. Mass and background combinations for 3σ after 3 years. Detectors with a combination that lies below the line will satisfy the sensitivity requirements in the desired period of time.

Acknowledgements

This work was supported by the ARC Centre of Excellence of Dark Matter Particle Physics through grant CE200100008. MJZ is supported through the Australian Government Research Training Program Scholarship. Both authors are members of the SABRE Collaboration.

References

[1] Bernabei R et al., [The DAMA Collaboration] 2018 *Nucl. Phys. At. Energy* **19** 307-325
[2] Tanabashi M et al., [Particle Data Group] 2018 *Phys. Rev. D* **98** no. 3, 0300
[3] Amare J et al., [The ANAIS Collaboration] 2019 *EPJC* **79** 412
[4] Adhikari G et al., [the COSINE-100 Collaboration] 2019 *Phys. Rev. Lett.* **123** 031302
[5] Antonello M et al., [The SABRE Collaboration] 2019 *Astropart. Phys.* **106** 1
[6] Zurowski M J, Barberio E 2021 Influence of NaI background and mass on testing the DAMA modulation *Preprint* hep-ex/2107.07674