Annual modulation results from three-year exposure of ANAIS-112

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Abstract. ANAIS-112 is a dark matter direct detection experiment that operates 112 kg of NaI(Tl) scintillators at the Canfranc Underground Laboratory (LSC, Spain). Its main goal is to test in a model independent way one of the most puzzling results in the present particle physics scenario: the DAMA/LIBRA observation of an annual modulation in the detection rate compatible with that expected for dark matter. This signal is in strong tension with the negative results of other very sensitive experiments. However, until recently a direct comparison using the same target material (NaI(Tl)) was lacking. ANAIS-112 has been taking data since August 2017 in stable conditions with excellent performance. Results from the first three years are compatible with the absence of modulation and incompatible with the DAMA/LIBRA measured modulation at more than 2.5σ C.L. This result supports the projected goal of reaching a 3σ sensitivity to the DAMA/LIBRA result for the scheduled five-year operation.

1. Introduction

The evidence for dark matter (DM) is overwhelming from astrophysical and cosmological observations at all scales. Yet, its existence is inferred indirectly through gravitational effects, but its nature is still unknown. Among the preferred DM particle candidates are Weakly Interacting Massive Particles (WIMPs), new particles beyond the standard model (SM) with weak-scale couplings to SM particles [1, 2].

WIMPs in the Milky Way halo are expected to scatter off the nuclei of a particle detector located in the Earth, with an interaction rate that depends on their relative velocity. As a consequence of the Earth rotation around the Sun, this velocity varies with 1 year periodicity, and so does the expected interaction rate (annual modulation) [3, 4]. For more than 20 years [5], the DAMA/LIBRA experiment at the Gran Sasso Underground Laboratory (Italy) has claimed a positive dark matter detection: an annual modulation in the low-energy detection rate compatible with the expected signal induced by dark matter particles [6]. This signal is

in strong tension with the negative results of other experiments [7]. However, until recently a direct comparison using the same target material (NaI(Tl)) was lacking. This is the goal of the ANAIS-112 experiment [8, 9], and others like COSINE [10, 11], SABRE [12, 13] and COSINUS [14, 15].

2. ANAIS-112 experimental setup

The ANAIS-112 experiment is taking data at the Canfranc Underground Laboratory in Spain since August 2017. It consists of 112.5 kg of NaI(Tl) detectors, arranged in a 3x3 array of modules, 12.5 kg each and built by Alpha Spectra Inc. Among their most relevant features we can mention their outstanding optical quality, which added to the high quantum efficiency of the Hamamatsu photomultipliers (PMTs) results in a very high light collection, at the level of 15 photoelectrons (phe) per keV. Another interesting feature is a mylar window in the lateral face of the detectors, which allow us to calibrate the modules with external sources of energies just few keV above the region of interest (ROI) for testing the DAMA/LIBRA result ([1-6] keV). We have measured the quenching factor of nuclear recoils in crystals of the same batch as the ANAIS-112 detectors. Preliminary results can be found in [16].

The ANAIS-112 shielding consists of 10 cm of archaeological lead, 20 cm of low activity lead, an anti-radon box (kept under overpressure with radon-free nitrogen gas) and 40 cm of a combination of water tanks and polyethylene bricks. An active muon veto made up of 16 plastic scintillators covers the top and sides of the set-up [17]. The signals from the two PMTs coupled to each module are digitized at 2 GS/s with high resolution. The trigger is done by the coincidence of the two PMT trigger signals in a 200 ns window, while the trigger of each PMT is at phe level. ^{109}Cd sources are used every two weeks to calibrate the experiment and correct the small gain drifts. The energy calibration is performed with the ^{109}Cd lines plus the energy depositions at very low energy (3.2 and 0.87 keV) associated to the decay of ^{40}K and ^{22}Na crystal contaminations, respectively, that can be tagged by coincidences with high energy gammas. This procedure allows us to perform a reliable calibration of the ANAIS-112 data down to the threshold. The background in the ROI is dominated by non-bulk scintillation events, so we apply strong filtering protocols based on the pulse shape and light sharing among the two PMTs. The efficiency of the event selection criteria is calculated with scintillation populations (^{109}Cd, ^{40}K, ^{22}Na) and is very close to one down to 2 keV, and then decreases steeply to about 15% at 1 keV, where we set the analysis threshold.

3. Annual modulation analysis

We keep the single-hit events in the ROI blinded during the event selection and efficiency calculation. Up to now, we have carried out three unblindings of our data: at 1.5 years (corresponding to an exposure of 157.55 kg×y) [8], at 2 years (exposure of 220.69 kg×y) [18], and the present one [9], which corresponds to an exposure of 313.95 kg×y. We look for an annual modulation in the same energy regions as DAMA/LIBRA does: [1-6] keV and [2-6] keV. In a first search, we add together data from the nine modules, grouped in 10-days time bins, and minimize $\chi^2 = \sum_i (n_i - \mu_i)^2/\sigma_i^2$, where n_i is the number of events in the time bin t_i (corrected by live time and detector efficiency), σ_i is the corresponding Poisson uncertainty, accordingly corrected, and μ_i is the expected number of events at that time bin, that can be written as:

$$\mu_i = [R_0\phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))]M\Delta E\Delta t. \tag{1}$$

Here, R_0 is a free parameter that represents the unmodulated rate in the detector, ϕ_{bkg} is the probability distribution function (PDF) in time of any unmodulated component, S_m is the modulation amplitude, ω is fixed to $2\pi/365\,\mathrm{d} = 0.01721\,\mathrm{rad\,d^{-1}}$, t_0 to $-62.2\,\mathrm{d}$ (corresponding the cosine maximum to 2nd June, when taking as time origin 3rd August), M is the total detector

mass, ΔE is the energy interval width, and Δt the time bin width. S_m is fixed to 0 for the null hypothesis and left unconstrained (positive or negative) for the modulation hypothesis.

We follow two different approaches to model the experimental background: (1) following our previous analysis [8, 18], we approximate the background evolution to an exponential decay: $\phi_{bkg}(t_i) = 1 + f e^{-t_i/\tau}$, where f and τ are free parameters; (2) we use our Monte Carlo background model [19, 20] in order to compute the background evolution in time and convert into a PDF, so $\phi_{bkg}(t_i) = 1 + f \phi_{bkg}^{MC}(t_i)$. Finally, in order to account for systematic effects related to the differences in background and efficiency among detectors, we apply a third approach: (3) we considered the nine modules independently, so the χ^2 summation is also performed over detectors and the expected number of events for every time bin t_i and detector d is written as

$$\mu_{i,d} = [R_{0,d}(1 + f_d \phi_{bkg,d}^{MC}(t_i)) + S_m \cos(\omega(t_i - t_0))] M_d \Delta E \Delta t, \tag{2}$$

where M_d is the mass of every module, $\phi_{bkg,d}^{MC}$ is the PDF sampled from the MC background evolution in time calculated independently for every module, and $R_{0,d}$ and f_d are free parameters.

The results of the fit in the [1–6] keV energy region are shown in Fig. 1. Results of the three methods in both energy regions are summarized in Table 1.
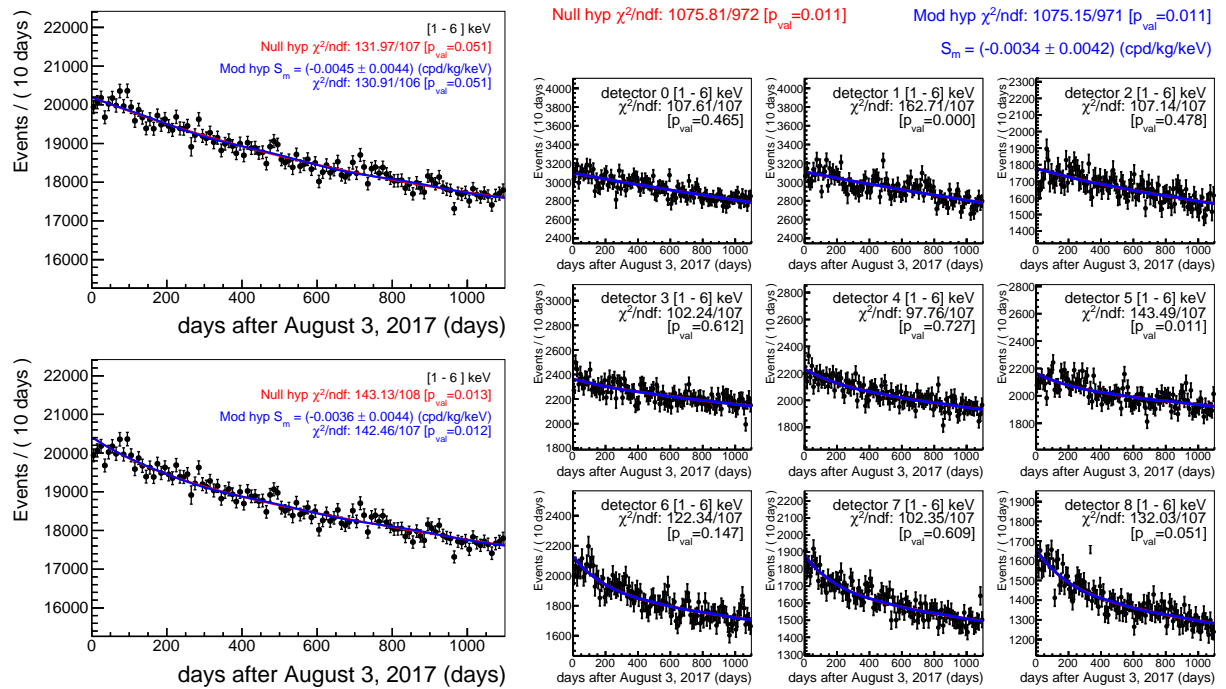

Figure 1. Upper left pannel: fit results for three years of data in the [1-6] keV energy region in the modulation (blue) and null hypothesis (red) when the background is described by approach (1). Lower left panel: same, but for approach (2). Right panel: same, but for approach (3).

In the [2-6] keV region, data is well described by the null hypothesis in the three approaches (p-values of 0.27 and 0.19 and 0.15). Smaller p-values (0.051, 0.013 and 0.011) are obtained in [1-6] keV region. When we calculate individual p-values for every detector, we conclude that only detectors 1 and 5 are responsible of the bad agreement with the null hypothesis in the [1-6] keV region (see right panel in Fig. 1). The anomalous behavior of these two modules could be an indication of noise in the very low energy bin [1-2] keV. We are working on the application of machine learning techniques in order to improve the rejection of non-bulk scintillation events below 2 keV, and preliminary results have been presented in these proceedings [21].

Energy region	Approach	χ^2/NDF	S_m (cpd/kg/keV)	p-value mod	p-value null
$[1-6]$ keV	(1)	132 / 107	-0.0045 ± 0.0044	0.051	0.051
$[1-6]$ keV	(2)	143.1 / 108	-0.0036 ± 0.0044	0.012	0.013
$[1-6]$ keV	(3)	1076 / 972	-0.0034 ± 0.0042	0.011	0.011
$[2-6]$ keV	(1)	115.7 / 107	-0.0008 ± 0.0039	0.25	0.27
$[2-6]$ keV	(2)	120.8 / 108	0.0004 ± 0.0039	0.17	0.19
$[2-6]$ keV	(3)	1018 / 972	0.0003 ± 0.0037	0.14	0.15

Table 1. Summary of the fits searching for an annual modulation with fixed phase in the three years of ANAIS-112 data for different background modelling (see text for more details).

For the modulation hypothesis, we obtain in all cases best fit modulation amplitudes compatible with zero at 1σ. The standard deviation $\sigma(S_m)$ is the same for (1) and (2) approaches and slightly lower for the third approach, when detectors are considered independently, as expected from our sensitivity analysis [22]. Therefore, we select this method to quote our final result. Figure 2 shows a graphical representation of our best fits (black dots) and sensitivity (colored bands) in comparison with DAMA/LIBRA results (blue squares).
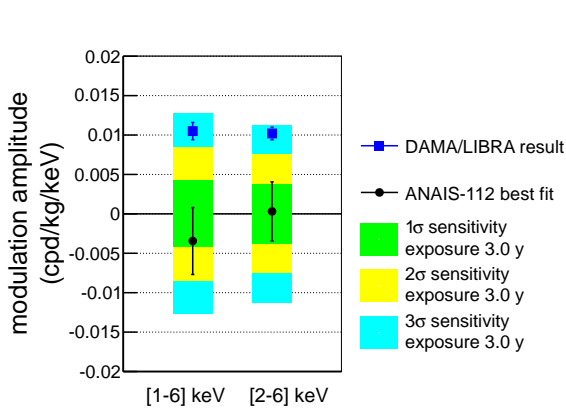
Figure 2. Comparison between ANAIS-112 results on annual modulation using three years of data and DAMA/LIBRA modulation best fit. Estimated sensitivity is shown at different confidence levels as colored bands: green at 1σ, yellow at 2σ, and cyan at 3σ.
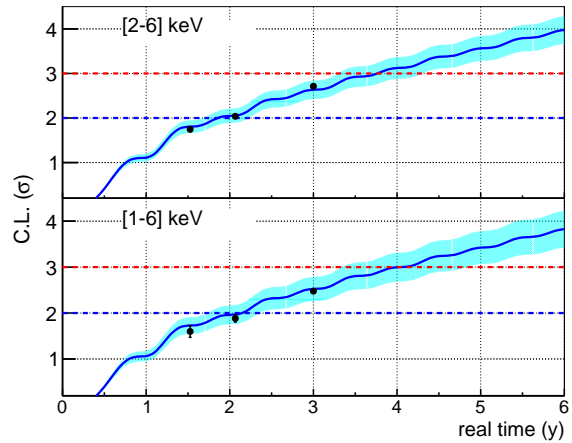
Figure 3. ANAIS-112 sensitivity to the DAMA/LIBRA signal in σ C.L. units (see text) as a function of real time in [1-6] keV (lower panel) and [2-6] keV (upper panel). The black dots are the sensitivities measured experimentally. The blue bands represent the 68% C.L. DAMA/LIBRA uncertainty.

In Fig. 3, we present our sensitivity projection according to our measured background, efficiency and live time, as calculated in [22]. It is given by the ratio $S_m^{DAMA}/\sigma(S_m)$, which directly gives in σ units the C.L. at which we can test the DAMA/LIBRA signal. At present, our result $\sigma(S_m)$ = 0.0042 (0.0037) cpd/kg/keV for [1-6] keV ([2-6] keV) corresponds to a sensitivity of 2.5σ (2.7σ).

We have carried out several consistency checks (changing the number of detectors entering in the fit, considering only first two years, or last two years, or changing time bin size) and we conclude that we do not have any hint supporting relevant systematical uncertainties in our result. Performing a large set of Monte Carlo pseudo-experiments sampled from the background model, we have checked that the fit is not biased. Instead, when we leave the phase t_0

unconstrained, the fit has a bias in absence of modulation equal to $\sqrt{\frac{\pi}{2}}\sigma(S_m)$, where $\sigma(S_m)$ is the standard deviation of the modulation amplitude. Correcting the best fits with the calculated bias, our phase-free results are compatible with no modulation in all the approaches and both energy regions. We have also performed a frequency analysis, looking for a periodic signal at other frequencies in our data, and the conclusion is that there is no statistically significant modulation in the frequency range searched in ANAIS-112 [9].

4. Conclusions

ANAIS-112 results for 3 years of data-taking confirm our previous analysis and support the absence of modulation. The statistical significance of this result increases as expected according to our sensitivity estimates, supporting our prospects of reaching 3σ within the scheduled 5-years operation (see Fig. 3). We obtain for the best fit a modulation amplitude of –0.0034±0.0042 (0.0003±0.0037) cpd/keV/kg in the [1–6] keV ([2–6] keV) energy region, being incompatible with DAMA/LIBRA result at 3.3 (2.6) σ, for a sensitivity of 2.5 (2.7) σ. All the consistency checks we have performed support that no systematic effects are present in our data. The ANAIS-112 experiment will be able to provide 3σ C.L. test on DAMA/LIBRA annual modulation signal soon, and 4σ in six years of data-taking, according to our sensitivity estimates, which are confirmed with the results presented here.

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