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Proceeding Paper

Dark Matter Annual Modulation Results from the ANAIS-112 Experiment †

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Abstract: An annual modulation in the interaction rate of galactic dark matter particles is foreseen due to Earth's movement around the Sun; the DAMA/LIBRA observation of a modulation signal compatible with expectations has intrigued the community for twenty years. The ANAIS-112 experiment, with a target of 112.5 kg of NaI(Tl), has been running smoothly at the Canfranc Underground Laboratory (Spain) since 2017. It aims to test this observation using the same detection technique and target. Results on the modulation search from two years of data (220.7 kg·y) have been presented and the analysis of three years (313.6 kg·y) is underway. Under the hypothesis of modulation, the deduced amplitudes from best fits are in all cases compatible with zero for the two energy regions at [2–6] and [1–6] keV; the results agree with the expected sensitivity for the considered exposure and fully support the goal of achieving a 3σ sensitivity to explore the DAMA/LIBRA result for a five-year operation. Here, the ANAIS-112 set-up and performance will be briefly recapped and the annual modulation results and prospects will be discussed.

Keywords: dark matter; WIMPs; direct detection; annual modulation; NaI scintillators

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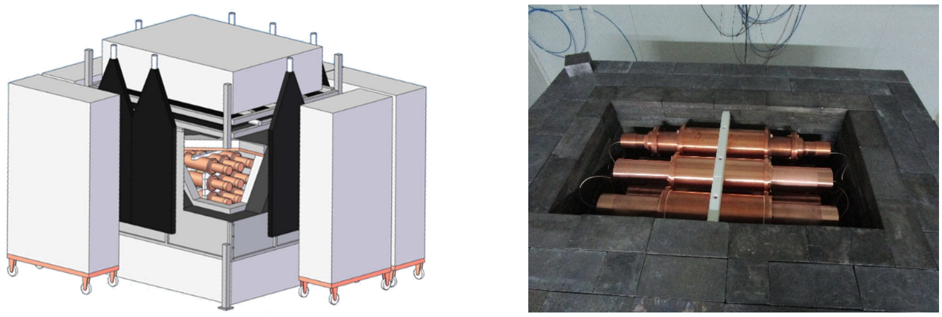
1. Introduction

The direct detection of dark matter particles, such as the so-called weakly interacting massive particles (WIMPs) which could populate the galactic halo, is mainly based on their elastic scattering off target nuclei in suitable detectors [1]. As Earth moves around the Sun, the relative velocity between the detector and the dark matter particles follows a time variation, giving rise to a modulation in the expected rate of interaction with well-defined features [2]. The DAMA/LIBRA experiment, based on data with about 250 kg of NaI(Tl) detectors at the Gran Sasso Underground Laboratory in Italy, has reported the presence of an annual modulation signal with all the expected properties at a confidence level of 12.9σ, from an exposure of 2.46 t·y accumulated over two decades [3,4]. Taking into account the results presented by other direct detection experiments using different targets (see for instance [1]), a tension appears if considering the DAMA/LIBRA signal as due to dark matter, assuming common but also more generic interaction or halo models. In this context, to prove or disprove the DAMA/LIBRA observation in a model-independent way, using the same target and technique would be essential; this is the goal of the ANAIS experiment [5]. Other projects all over the world have undertaken this task too, such as COSINE-100 (which is also taking data with first annual modulation results for an exposure of 97.7 kg·y released [6]) while SABRE [7], PICOLON [8] and COSINUS [9] are in preparation.

2. Experiment

The ANAIS-112 experiment, located at the Canfranc Underground Laboratory (LSC), in Spain, started the data-taking phase in August 2017. A full description of the set-up, shown in Figure 1, can be found in [10]. ANAIS-112 includes an array of 3 × 3 NaI(Tl) scintillators, with a crystal mass of 12.5 kg each and a total mass of 112.5 kg. ANAIS detectors were manufactured by the Alpha Spectra Inc. company in Colorado (US) and two Hamamatsu photomultipliers (PMTs), model R12669SEL2, were coupled to each crystal through quartz windows at the LSC clean room. The copper enclosure has a Mylar window (to perform low-energy calibration using external sources) and detectors showed an outstanding optical quality; together with the high efficiency of the PMTs used, this allowed for the achievement of a light collection of ~15 photoelectrons (phe) per keV for all the detector units [11]. The shielding of ANAIS-112 is made of 10 cm of archaeological lead followed by 20 cm of low-activity lead against the external gamma radiation, a box filled with radon-free N_2 gas to avoid radon intrusion being under overpressure, and 40 cm of polyethylene and water to moderate neutrons. Sixteen plastic scintillators cover the sides and top of the set-up acting as an active veto to tag residual muons. The LSC facilities are placed at a depth of 2450 m.w.e.



(**a**) (**b**)

Figure 1. Set-up of the ANAIS-112 experiment: (**a**) Schematic view showing the nine modules and the full shielding; (**b**) Picture taken during ANAIS-112 commissioning with detectors, lead shielding and calibration system visible.

The ANAIS-112 hardware and software for data acquisition, fine-tuned in the previous operation of several prototypes, were also described in [10]. The PMT electric pulses taken from the detectors are processed for trigger and for signals at both high and low energy. The waveform of the low-energy signal is recorded at 2 GS/s. For each PMT, the trigger is at phe level; the coincidence (logical AND) in a 200 ns window of the two PMT signals from a module gives the acquisition trigger. Every two weeks, measurements with ^{109}Cd sources are made for calibration and correction of potential gain drifts, if necessary. An accurate calibration in the low energy range down to the threshold is performed by considering both the information from the ^{109}Cd calibration measurements and from ^{40}K and ^{22}Na emissions from crystal contaminations corresponding to 3.2 and 0.87 keV (identified by the coincidences with the corresponding high-energy gammas). Even though triggering with virtually 100% efficiency below 1 keV (all the energies given in the paper correspond to electron equivalent energies) is shown by observing ^{22}Na events, the analysis threshold is set at 1 keV due to the selection criteria established for the rejection of non-scintillation events, which then decrease the acceptance efficiencies up to ~15% at 1 keV.

3. Results

In the analysis protocol of ANAIS-112, the energy distribution of single-hit events (those depositing energy at only one detector) in the region of interest is blinded. After the first year of data collection, and before the first annual modulation analysis was performed, 10% of acquired events (randomly chosen) were unblinded in order to perform the final tuning of the procedures for event rejection [10], to make a complete background analysis and characterization [12], and to evaluate the experiment sensitivity [13].

Background models were developed for each one of the nine ANAIS-112 detectors based on the quantified radioactivity of the different components, which were independently estimated following several approaches [12,14]. The spectra measured in different energy regions and conditions are well reproduced in the models. The measured, efficiency-corrected background level is 3.58 ± 0.02 c/keV/kg/day from 1 to 6 keV and the bulk contamination of NaI(Tl) crystals is identified as the main background source; contributions of ^{210}Pb and ^{40}K and of cosmogenic ^{22}Na and ^{3}H are the most relevant ones [15,16].

Results on annual modulation from ANAIS-112 data were firstly presented after unblinding 1.5 years of data. This corresponds to an exposure of 157.55 kg·y. The designed analysis protocol was applied [5]. Using the same procedure, a new modulation analysis was performed for the first 2 years of data collection until the beginning of September 2019, corresponding to 220.69 kg·y [17]. This model-independent analysis carried out was intended to search for modulation in the energy regions, [1–6] keV and [2,6] keV, analyzed by DAMA/LIBRA. A least-squared fit was made considering the measured rate R over the time t, summing all modules as:

$$R(t) = R_0 + R_1\, exp(-t/\tau) + S_m\, cos(\omega(t - t_0)), \quad (1)$$

where R_0 and R_1 are free. The τ parameter was fixed from the time evolution given by the background model for the considered energy region. The period and phase, related to ω and t_0, were fixed as 1 y and maximum at 2 June, following the predictions for a standard galactic halo. The modulation amplitude, S_m, was set to zero when considering the null hypothesis. Figure 2 presents the fit of the counting rate to Equation (1) for the two considered energy regions. Results were consistent with the null hypothesis; the best fits for the amplitude under the modulation hypothesis were $S_m = -0.0029 \pm 0.0050$ c/keV/kg/day and $S_m = -0.0036 \pm 0.0054$ c/keV/kg/day for the [2–6] and [1–6] keV energy regions, respectively. These values were compatible at 1σ with the absence of modulation and were incompatible with DAMA/LIBRA result at ~2.6σ. Now, the analysis of the first 3 years of data accumulated (corresponding to 313.6 kg·y) is underway.

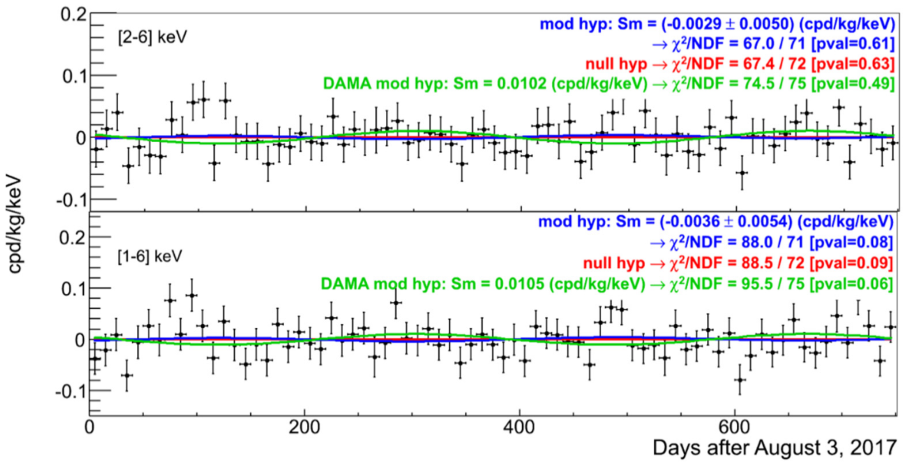


Figure 2. Results of the fit of ANAIS-112 data for first 2 years to Equation (1) in the two energy regions of [1–6] and [2–6] keV in the modulation (blue) and null hypothesis (red). The non-modulated components were subtracted after fitting. DAMA/LIBRA results are shown too (in green) for comparison.

4. Discussion

Figure 3 compares these results obtained from ANAIS-112 data for the modulation amplitude S_m to those obtained by DAMA/LIBRA [3]. In addition, the estimated sensitivity of ANAIS-112 at different confidence levels is depicted.

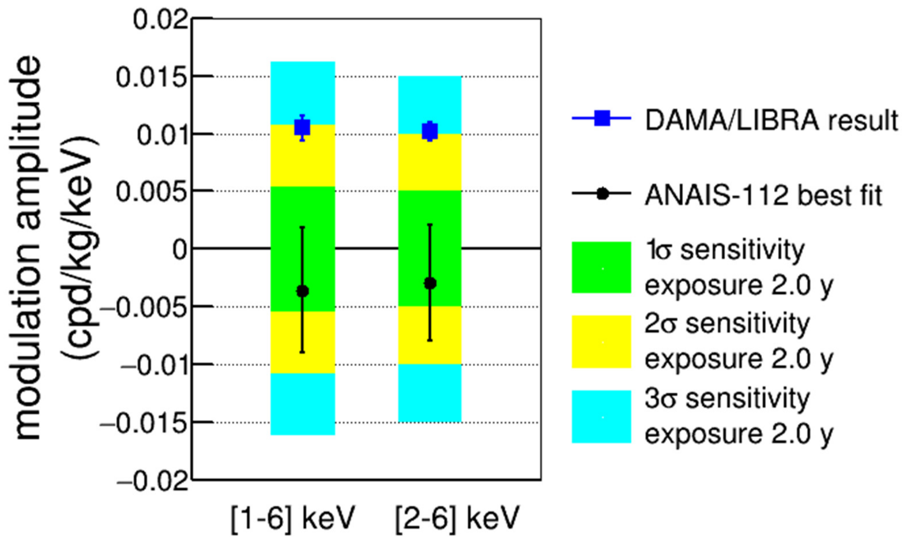


Figure 3. Comparison between ANAIS-112 best fit for the annual modulation amplitude S_m from the first 2 years of data and DAMA/LIBRA result [3], for the two considered energy regions. The estimated sensitivity is presented too at several confidence levels as coloured bands: 1σ (green), 2σ (yellow) and 3σ (cyan).

The obtained results from the analysis of ANAIS-112 and its two-year data collection fully confirm the sensitivity prospects previously evaluated [13], being at 2σ level for 2 years. This supports the achievement of 3σ for 5 years of data, as shown in Figure 4, which presents the ANAIS-112 projected sensitivity to DAMA/LIBRA (in units of σ C.L) as a function of time. This sensitivity is quoted as the ratio between the measured DAMA/LIBRA modulation and the standard deviation on S_m from ANAIS-112.

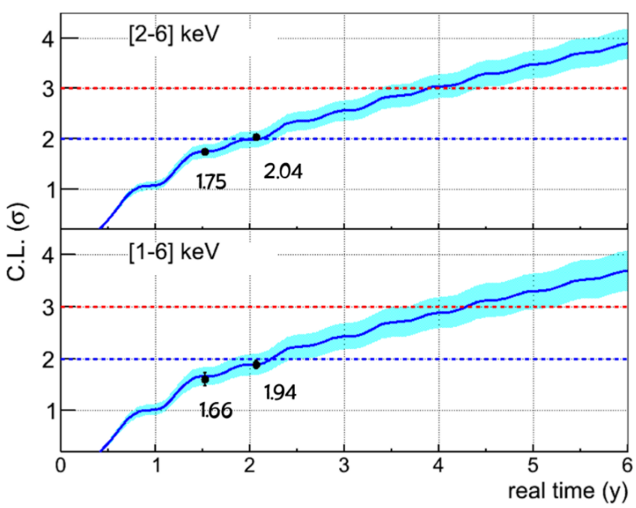


Figure 4. ANAIS-112 sensitivity to DAMA/LIBRA signal in units of σ C.L. as a function of time. Cyan bands show the 68% C.L. DAMA/LIBRA uncertainty in the modulation amplitude. Black dots and numbers gave the experimental sensitivities obtained in the two ANAIS-112 annual modulation analysis carried out for 1.5 and 2 years.

5. Conclusions

The ANAIS-112 experiment aims to confirm or refute the annual modulation signal observed over two decades by the DAMA/LIBRA experiment at the Gran Sasso Underground Laboratory. It operates at the Canfranc Underground Laboratory with 112.5 kg of NaI(Tl) crystals and the data collection for dark matter searches has been progressing smoothly since 2017. For the first 2 years of data collection (220.69 kg·y), the modulation amplitudes derived for the [2–6] and [1–6] keV energy regions ($S_m = -0.0029 \pm 0.0050$ c/keV/kg/day and $S_m = -0.0036 \pm 0.0054$ c/keV/kg/day, respectively) are compatible with modulation absence and are incompatible with DAMA/LIBRA observation at 2.6σ, being the experimental sensitivity at 2σ. The preliminary analysis of the first 3 years of data (313.6 kg·y) seem to corroborate these conclusions; the publication of these results is in preparation. As the ANAIS-112 sensitivity prospects are fully confirmed, the ability of testing DAMA/LIBRA at 3σ over 5 years of data collection (expected for August 2022) is guaranteed, which will shed light to the long-standing DAMA/LIBRA conundrum.

Author Contributions: A.O.d.S. and M.L.S. designed the experiment; J.A., M.Á.O., A.O.d.S., A.S., M.L.S. and P.V. commissioned the experiment; J.A., D.C., M.M., M.Á.O., Y.O., A.O.d.S. and M.L.S. performed calibration and maintenance of the experiment; M.Á.O., M.M. and M.L.S. developed analysis tools; I.C., M.M, J.P. and M.L.S. analyzed the data; S.C. and P.V. developed background simulation codes; E.G., A.O.d.S. and J.P. performed radiopurity measurements; I.C., E.G., M.M., and J.P. contributed to sensitivity estimates; S.C. prepared the manuscript. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

ANAIS	Annual modulation with NAIs Scintillators
COSINUS	Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches
DAMA/LIBRA	DArk MAtter/Large sodium Iodide Bulk for RAre processes
LSC	"Laboratorio Subterráneo de Canfranc" (Canfranc Underground Laboratory)
phe	photoelectron
PICOLON	Pure Inorganic Crystal Observatory for LOw-energy Neutr(al)ino
PMT	Photomultiplier Tube
SABRE	Sodium-iodide with Active Background REjection
WIMP	Weakly Interacting Massive Particle

References

1. Schumann, M. Direct detection of WIMP Dark Matter: Concepts and Status. *J. Phys. G Nucl. Part. Phys.* **2019**, *46*, 103003. [CrossRef]
2. Freese, K.; Frieman, J.; Gould, A. Signal modulation in cold-dark-matter detection. *Phys. Rev. D* **1988**, *37*, 3388. [CrossRef] [PubMed]
3. Bernabei, R.; Belli, P.; Bussolotti, A.; Cappella, F.; Caracciolo, V.; Cerulli, R.; Dai, C.; d'Angelo, A.; Marco, A.D.; He, H.; et al. First model independent results from DAMA/LIBRA–phase2. *Nucl. Phys. At. Energy* **2018**, *19*, 307. [CrossRef]

4. Bernabei, R.; Belli, P.; Bussolotti, A.; Cappella, F.; Caracciolo, V.; Cerulli, R.; Dai, C.; d'Angelo, A.; Marco, A.D.; Ferrari, N.; et al. The DAMA project: Achievements, implications and perspectives. *Prog. Part. Nucl. Phys.* **2020**, *114*, 103810. [CrossRef]
5. Amaré, J.; Cebrián, S.; Coarasa, I.; Cuesta, C.; García, E.; Martínez, M.; Oliván, M.A.; Ortigoza, Y.; Ortiz de Solórzano, A.; Puimedón, J.; et al. First Results on Dark Matter Annual Modulation from the ANAIS-112 Experiment. *Phys. Rev. Lett.* **2019**, *123*, 031301. [CrossRef] [PubMed]
6. Adhikari, G.; Adhikari, P.; de Souza, E.B.; Carlin, N.; Choi, S.; Djamal, M.; Ezeribe, A.; Ha, C.; Hahn, I.; Jeon, E.; et al. Search for a Dark Matter-Induced Annual Modulation Signal in NaI(Tl) with the COSINE-100 Experiment. *Phys. Rev. Lett.* **2019**, *123*, 03130. [CrossRef] [PubMed]
7. Antonello, M.; Barberio, E.; Baroncelli, T.; Benziger, J.; Bignell, L.J.; Bolognino, I.; Calaprice, F.; Copello, S.; D'Angelo, D.; D'Imperio, G.; et al. The SABRE project and the SABRE Proof-of-Principle. *Eur. Phys. J. C* **2019**, *79*, 36. [CrossRef]
8. Fushimi, K.I. Low Background Measurement by Means of NaI(Tl) Scintillator -Improvement of Sensitivity for Cosmic Dark Matter-. *Radioisotopes* **2018**, *67*, 101. [CrossRef]
9. Angloher, G.; Hauff, D.; Gironi, L.; Gotti, C.; Pessina, G.; Gütlein, A.; Maino, M.; Nagorny, S.; Pagnanini, L.; Petricca, F.; et al. The COSINUS project—Perspectives of a NaI scintillating calorimeter for dark matter search. *Eur. Phys. J. C* **2016**, *76*, 441. [CrossRef]
10. Amaré, J.; Cebrián, S.; Coarasa, I.; Cuesta, C.; García, E.; Martínez, M.; Oliván, M.A.; Ortigoza, Y.; Ortiz de Solórzano, A.; Puimedón, J.; et al. Performance of ANAIS-112 experiment after the first year of data taking. *Eur. Phys. J. C* **2019**, *79*, 228. [CrossRef]
11. Oliván, M.A.; Amaré, J.; Cebrián, S.; Cuesta, C.; García, E.; Martínez, M.; Ortigoza, Y.; Ortiz de Solórzano, A.; Pobes, C.; Puimedón, J.; et al. Light yield determination in large sodium iodide detectors applied in the search for dark matter. *Astropart. Phys.* **2017**, *93*, 86. [CrossRef]
12. Amaré, J.; Cebrián, S.; Coarasa, I.; Cuesta, C.; García, E.; Martínez, M.; Oliván, M.A.; Ortigoza, Y.; Ortiz de Solórzano, A.; Puimedón, J.; et al. Analysis of backgrounds for the ANAIS-112 dark matter experiment. *Eur. Phys. J. C* **2019**, *79*, 412. [CrossRef]
13. Coarasa, I.; Amaré, J.; Cebrián, S.; Cuesta, C.; García, E.; Martínez, M.; Oliván, M.A.; Ortigoza, Y.; Ortiz de Solórzano, A.; Puimedón, J.; et al. ANAIS-112 sensitivity in the search for dark matter annual modulation. *Eur. Phys. J. C* **2019**, *79*, 233. [CrossRef]
14. Amaré, J.; Cebrián, S.; Cuesta, C.; García, E.; Martínez, M.; Oliván, M.A.; Ortigoza, Y.; Ortiz de Solórzano, A.; Puimedón, J.; Sarsa, M.L.; et al. Assessment of backgrounds of the ANAIS experiment for dark matter direct detection. *Eur. Phys. J. C* **2016**, *76*, 429. [CrossRef]
15. Amaré, J.; Cebrián, S.; Cuesta, C.; García, E.; Ginestra, C.; Martínez, M.; Oliván, M.A.; Ortigoza, Y.; Ortiz de Solórzano, A.; Pobes, C.; et al. Cosmogenic radionuclide production in NaI(Tl) crystals. *J. Cosmol. Astropart. Phys.* **2015**. [CrossRef]
16. Amaré, J.; Castel, J.; Cebrián, S.; Coarasa, I.; Cuesta, C.; Dafni, T.; Galán, J.; García, E.; Garza, J.G.; Iguaz, F.J.; et al. Cosmogenic production of tritium in dark matter detectors. *Astropart. Phys.* **2018**, *97*, 96. [CrossRef]
17. Amaré, J.; Cebrián, S.; Cintas, D.; Coarasa, I.; García, E.; Martínez, M.; Oliván, M.A.; Ortigoza, Y.; Ortiz de Solórzano, A.; Puimedón, J.; et al. ANAIS-112 status: Two years results on annual modulation. *J. Phys. Conf. Ser.* **2020**, *1468*, 012014. [CrossRef]