Annual modulation results from DAMA/LIBRA

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Abstract. The long-standing model-independent annual modulation measured by DAMA at Gran Sasso Laboratory with different experimental configurations is summarized. The full exposure is 2.86 ton $\times$ yr over 22 annual cycles. DAMA/LIBRA–phase2 set-up, $\simeq$ 250 kg highly radio-pure NaI(Tl), confirms the evidence of a signal that meets all the requirements of the model independent Dark Matter annual modulation signature at high confidence level. The new configuration, DAMA/LIBRA–phase2–empowered, has been taking data with lower energy threshold until fall 2024, as stated in the primordial plans of the collaboration; few details are highlighted.

1 Introduction

The DAMA/LIBRA [1–6] experiment, like the first-generation DAMA/NaI [7, 8], has the main aim to investigate the presence of Dark Matter (DM) particles in the galactic halo, exploiting the DM annual modulation signature (initially proposed in Ref. [9, 10]). The developed highly radio-pure NaI(Tl) target-detectors [1, 3, 4] ensure sensitivity for a wide range of DM candidates, interaction types and astrophysical scenarios (see e.g. Ref. [5], and references therein). A comprehensive description of the DAMA/LIBRA apparatus and of the procedures adopted during the phases 1 and 2, together with other related topics, has been covered in detail in several detailed publications, including [1–6]. Additionally, the DM annual modulation signature and its peculiar features are thoroughly discussed in, for example, Refs. [5, 6].

At the end of 2010, all the photomultipliers (PMTs) in the DAMA/LIBRA experiment were replaced with second-generation Hamamatsu R6233MOD PMTs, which offer higher quantum efficiency and lower background noise [3] compared to those used during phase1. The successful commissioning of the DAMA/LIBRA–phase2 experiment took place in 2011, achieving a software energy threshold of 1 keV. This upgrade also led to improvements in

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key detector characteristics, including enhanced energy resolution and increased acceptance efficiency near the software energy threshold [3].

2 The DAMA/LIBRA–phase2 results

The details of the annual cycles of DAMA/LIBRA–phase2 are provided in Ref. [5, 6]. So far, the results of eight annual cycles have been released, corresponding to an exposure of 1.53 ton×yr. Including the data from the previous DAMA/NaI and DAMA/LIBRA–phase1 experiments, the total exposure reaches 2.86 ton×yr. The duty cycle of DAMA/LIBRA–phase2 is consistently high, ranging between 76% and 86%. This high duty cycle is primarily influenced by routine calibrations and, in particular, data collection for the acceptance window efficiency near software energy threshold.

The residual rates of *single-hit* scintillation events in DAMA/LIBRA are reported in Ref. [6]. The energy interval spans from 2 keV (the software energy threshold for DAMA/LIBRA–phase1) to 6 keV. These residuals were fitted using the function: $A\cos\omega(t-t_0)$, where the period $T=\frac{2\pi}{\omega}=1$ yr and the phase $t_0=152.5$ day (June 2) as expected for the DM annual modulation signature. The fit yielded a $\chi^2/d.o.f.=130/155$, and the modulation amplitude was found to be $A=(0.00996\pm0.00074)$ cpd/kg/keV. When both the period and phase were left free in the fit, the achieved confidence level (C.L.) for the full exposure (2.86 ton×yr) is 13.7σ. The modulation amplitude for the *single-hit* scintillation events was (0.01014 ± 0.00074) cpd/kg/keV, with a measured phase of (142.4 ± 4.2) days and a measured period of (0.99834 ± 0.00067) yr. Residuals with software energy threshold of 1 keV (DAMA/LIBRA–phase2 only) are reported in [5, 6]. All these results are in excellent agreement with the values expected for DM particle interactions.

The absence of any significant background modulation in the energy spectrum has been further confirmed by examining energy regions that are not relevant for DM detection. It is worth noting that the obtained results account for whatever kind of background, and no known background process exists that can simultaneously satisfy all the several distinct characteristics of the signature and explain the measured modulation amplitude (see also [1–6]).

A further relevant investigation on DAMA/LIBRA–phase2 data was conducted by applying the same hardware and software procedures, used for acquiring and analyzing the *single-hit* residual rate, to the *multiple-hit* residual rate. Since the probability of a DM particle interacting with more than one detector is negligible, a DM signal is expected to appear only in the *single-hit* residual rate. Therefore, comparing the results of the *single-hit* events with those of the *multiple-hit* events is essentially comparing scenarios with DM particles present (*beam-on*) versus absent (*beam-off*). This approach also provides an additional test of the background behavior within the same energy range where the positive modulation effect is observed. While a clear modulation that satisfies all the expected characteristics of the DM annual modulation signature is present in the *single-hit* events, the fitted modulation amplitude for the *multiple-hit* residual rate is consistent with zero [6]. Since the same hardware and software procedures were applied to both event classes, this result offers strong additional evidence supporting the presence of a DM particle component in the galactic halo.

The *single-hit* residuals were also analyzed using Fourier analysis [2]. A distinct peak corresponding to a period of 1 year is clearly observed in the low-energy intervals. However, when the same analysis is applied to the (6–14) keV energy range, only aliasing peaks are detected. No other structures at different frequencies were observed.

The annual modulation observed at low energies is further highlighted by plotting the energy dependence of the modulation amplitude, $S_m(E)$, obtained using the maximum likelihood method with a fixed period and phase (T =1 yr, $t_0=152.5$ day). The modulation amplitudes for the entire data set: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 (with a total exposure of 2.86 ton×yr) are shown in Fig. 1. Data below 2 keV are from DAMA/LIBRA–phase2 only. From this analysis, a clear positive signal is observed in the (1–6) keV energy range (with a new data point added below 1 keV, as discussed later), while S_m values compatible with zero are found above this range. These results confirm the findings of previous analyses. Additionally, testing the hypothesis that the S_m values in the (6–14) keV energy range fluctuate randomly around zero yields a $\chi^2/d.o.f.$ of 20.3/16, with a P-value of 21%, further supporting the absence of significant modulation in this higher energy range.

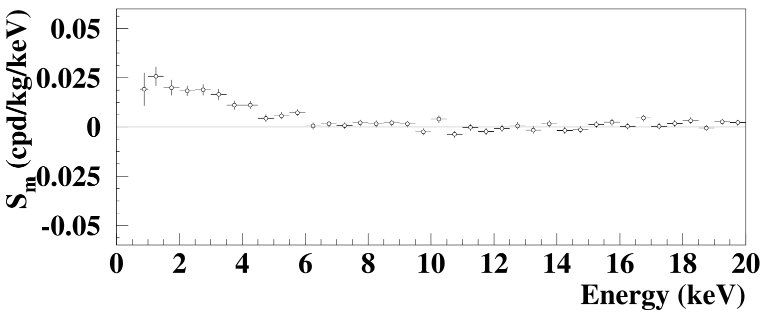

Figure 1. Modulation amplitudes, S_m, as function of the energy in keV(ee) for the whole data sets: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above [6].

The observed annual modulation effect is evenly distributed across all 25 detectors. Specifically, the modulation amplitudes S_m integrated over the (2–6) keV range for each of the 25 detectors during the DAMA/LIBRA periods show random fluctuations around the weighted average value, as verified by the χ^2 analysis. Based on this, the hypothesis that the modulation signal is uniformly distributed across all 25 detectors is accepted.

As an additional test, the hypothesis that the modulation effect is equally shared between the inner and outer detectors was examined. The modulation amplitudes for both groups of detectors were found to be fully consistent, as confirmed by the χ^2 test. Specifically, for the (1–4) keV and (1–20) keV energy intervals, the results yielded $\chi^2/d.o.f.$ = 1.9/6 and 36.1/38, respectively, further supporting the uniform distribution of the modulation effect across the detector array.

To test the hypothesis that the modulation amplitudes calculated for each annual cycle of DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 are compatible and fluctuate normally around their mean values, both the χ^2 test and the *run test* were applied. The results confirm that the data collected across all annual cycles in both DAMA/LIBRA–phase1 and phase2 are statistically consistent and can be considered together for further analysis [6].

Finally, the impact of relaxing the assumption of a fixed phase t_0 = 152.5 days in the procedure used to evaluate the modulation amplitudes has been discussed in [6].

No systematic or side processes capable of mimicking the DM signature, i.e. processes that could simultaneously satisfy all the distinctive features of the signature and explain the full measured modulation amplitude, have been identified or proposed over several decades of study. For further details, see, for example, Refs. [1–6]. Based on this signature, the model-independent DAMA results provide strong evidence at the 13.7σ C.L., accumulated over 22 independent annual cycles and various experimental configurations, for the presence of DM particles in the galactic halo.

The DAMA model-independent evidence is compatible with a broad range of astrophysical, nuclear, and particle physics scenarios, including both high- and low-mass DM candidates that induce nuclear recoil and/or electromagnetic radiation. Furthermore, both the negative results and the possible positive hints observed in the field thus far can be compatible with the DAMA model-independent annual modulation results in many scenarios, taking into account existing experimental and theoretical uncertainties. This is also true for indirect detection methods. For a more detailed discussion, see, for example, Refs. [2, 5] and the references therein.

2.1 Few arguments about the analysis procedure

As previously reported in the DAMA papers, data collection for each annual cycle begins before the expected minimum of the DM signal (about December 2) and continues beyond its expected maximum (about June 2). In this approach, a constant background, evaluated within each annual cycle, is used in the data analysis. This ensures that any potential decay of long–lived isotopes cannot mimic the distinctive features of a DM signal. Instead, it would only lead to a possible underestimation of the DM annual modulation amplitude, depending on the radio-purity of the setup.

In this context, the analysis of the last three published years of DAMA/LIBRA–phase2, where there was continuity between consecutive years, was performed using the same background (with and without accounting for any slope). The resulting modulation amplitudes, S_m, are fully consistent with those shown in Fig. 1. This confirms that any effects from a long-term, time-varying background, or an anomalous increase in the low-energy rate over time, are negligible in DAMA/LIBRA. This is due to the high radio-purity of the setup and the long-term underground location of the ULB DAMA/LIBRA NaI(Tl) detectors. Therefore, the original DAMA analyses can be safely relied upon.

3 DAMA/LIBRA–phase2–empowered

To enhance the experimental sensitivity of DAMA/LIBRA and better distinguish among the various astrophysical, nuclear, and particle physics scenarios involved in the investigation of DM candidate particles, it was necessary to increase the exposure in the lowest energy bin and further lower the software energy threshold.

Efforts to lower the software energy threshold were initially focused on the already-acquired data from DAMA/LIBRA–phase2. The same technique used previously was applied, along with dedicated studies on efficiency, leading to the addition of a new data point in the modulation amplitude as a function of energy, extending down to 0.75 keV (see Fig. 1). A modulation was observed even below 1 keV, and this preliminary result underscored the need for further lowering the software energy threshold through a hardware upgrade and enhanced statistics in the lowest energy bin.

To address this, a dedicated hardware upgrade for DAMA/LIBRA–phase2 was implemented to improve experimental sensitivity by lowering the energy threshold with suitable large acceptance efficiency. All PMTs were equipped with miniaturized low-background preamplifiers of a new design, along with miniaturized high-voltage dividers mounted on the same socket. The electronics chain was further upgraded by incorporating 14-bit digitizers with higher vertical resolution. The DAMA/LIBRA–phase2 upgrade was completed in the fall of 2021, and data collection in this new configuration, identified as DAMA/LIBRA–phase2–empowered, began on December 1, 2021. The operational features of the upgraded system have proven to be very stable, as demonstrated in the examples of Fig. 2. Data collection with the lower energy threshold continued through the fall of 2024, in line with the collaboration's original plans. New results are foreseen in the near future.

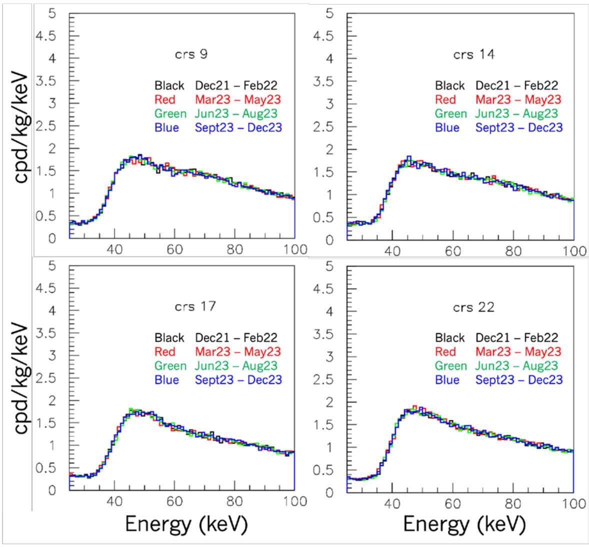

Figure 2. Examples of the stability of the counting rate and energy scale of four detectors in the energy region where the ^{210}Pb and ^{129}I contaminations contribute and are dominant. The data collected in almost one year are grouped in four time-intervals.

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