ЯДЕРНА ФІЗИКА
NUCLEAR PHYSICS

УДК 539.12:524.88 https://doi.org/10.15407/jnpae2026.02.105

R. Bernabei[1,2,*], P. Belli[1,2], A. Bussolotti[1,2], F. Cappella[3], V. Caracciolo[1,2], R. Cerulli[2], C. J. Dai[4], A. d'Angelo[3,5], A. Incicchitti[3,5], A. Leoncini[1,2], X. H. Ma[4], A. Mattei[3,5], V. Merlo[1,2], F. Montecchia[1,2,6], X. D. Sheng[4], Z. P. Ye[7]

[1] *Department of Physics, University of Rome Tor Vergata, Rome, Italy*
[2] *National Institute for Nuclear Physics, Rome Tor Vergata Section, Rome, Italy*
[3] *National Institute for Nuclear Physics, Rome Section, Rome, Italy*
[4] *State Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, P. R. China*
[5] *Department of Physics, Sapienza University of Rome, Rome, Italy*
[6] *Department of Civil Engineering and Computer Engineering, University of Rome Tor Vergata, Rome, Italy*
[7] *Jinggangshan University, Ji'an, Jiangxi, P.R. China*

*Corresponding author: rita.bernabei@roma2.infn.it

MODEL-INDEPENDENT RESULTS FROM DAMA/LIBRA-PHASE2-EMPOWERED

The DAMA/LIBRA-phase2 experiment was upgraded in 2021 to enhance its sensitivity by lowering the software energy threshold while maintaining a large efficiency. The new configuration, referred to as DAMA/LIBRA-phase2-empowered, collected data for three years. This study extends the investigation of the long-standing, model-independent annual modulation effect pointed out by the DAMA highly radiopure NaI(Tl) experimental setups at the Gran Sasso National Laboratory of the National Institute for Nuclear Physics, using different experimental configurations. The software energy threshold of DAMA/LIBRA-phase2-empowered is below 1 keV, and the exposure is 0.541 t·yr. Adding these new results to the previously released DAMA/LIBRA-phase2, the exposure is 2.07 t·yr over 11 independent annual cycles, yielding evidence for a signal that fulfills all the requirements of the model-independent Dark Matter annual modulation signature at a confidence level of 13.9 σ in the 1–6 keV energy region. In the 2–6 keV interval, where data from DAMA/NaI and DAMA/LIBRA-phase1 are also available, the combined exposure reaches 3.40 t·yr, corresponding to a confidence level of 15.3 σ. No systematic effect or side process capable of simultaneously satisfying all the distinctive features of the exploited Dark Matter annual modulation signature and accounting for the observed modulation amplitude is available.

Keywords: Dark Matter, elementary particle processes, scintillation detectors.

1. Introduction

The DAMA/LIBRA [1–10] experiment and the first-generation DAMA/NaI [1, 11–13] – located in the Gran Sasso National Laboratory of the National Institute for Nuclear Physics – have the main aim to investigate the presence of Dark Matter (DM) particles in the galactic halo, by exploiting the DM annual modulation signature (initially proposed in Refs. [14, 15]). The developed highly radio-pure NaI(Tl) target-detectors ensure sensitivity for a wide range of DM candidates, interaction types, and astrophysical scenarios (see e.g. Ref. [9], and references therein). A comprehensive description of the DAMA/LIBRA apparatus and of the procedures adopted during the data taking and in the analysis has been covered in detail in several detailed publications as [1, 2, 5, 7].

At the end of the DAMA/LIBRA-phase1 data set (end of 2010), all the photomultipliers (PMTs) were replaced by a second-generation effort – with Hamamatsu R6233MOD PMTs, which offer higher quantum efficiency and lower background noise [5] 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 key detector characteristics, including enhanced energy resolution and increased acceptance efficiency near the software energy threshold [5].

To enhance the experimental sensitivity of DAMA/LIBRA to DM model-independent results and to better distinguish in the corollary analyses among the various astrophysical, nuclear, and particle physics scenarios, it was necessary to increase the exposure in the lowest energy bin and further lower the software energy threshold. In fact, we note that the sensitivity of the exploited DM annual modulation signature depends – apart from the counting rate – on the product: $\varepsilon \cdot \Delta E \cdot M \cdot T \cdot \left(\alpha - \beta^2\right)$, thus the increase either of the detection efficiency, ε, and/or of the measurement time, T, and/or enlarging the energy interval, ΔE, practically is equivalent to increasing the exposed mass M; finally, $\left(\alpha-\beta^2\right)$ is the squared cosine averaged over the period where the data taking is active, and it should be ≃ 0.5 for data taking evenly collected over a year, and it is crucial for a reliable investigation of the DM annual modulation signature. Thus, the followed strategy along the DAMA project – apart from DAMA/NaI to DAMA/LIBRA-phase1, when also M was increased – was to pursue an increasing of the experimental sensitivity by improving aspects other than M [1, 9].

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 [10]. A modulation was also observed below 1 keV, and this preliminary result underscored the need for further lowering the software energy threshold through a hardware upgrade and enhanced exposure 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 a suitably large 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. This upgrade was completed in the fall of 2021, and data collection in this new configuration, identified as DAMA/LIBRA-phase2-empowered, began on December 2, 2021.

The data of the former DAMA/NaI setup and, later, those of the DAMA/LIBRA have already given (with high confidence level) positive evidence for the presence of a signal that satisfies all the requirements of the exploited DM annual modulation signature [1, 3, 4, 6–10]. Moreover, no systematic or side processes able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude have been found or suggested by anyone throughout some decades thus far (see e.g. [1, 7, 9]).

In this paper, the model-independent result obtained from three annual cycles of DAMA/LIBRA-phase2-empowered (exposure 0.541 t·yr) is presented. This result is consistent with the long-standing observations reported by DAMA/NaI, DAMA/LIBRA-phase1 and -phase2 (exposure 2.86 t·yr), and extends sensitivity down to a lower software energy threshold. In fall 2024, as planned, the experiment was dismantled upon completion of the DAMA project, which had been in operation for several decades and enabled the realization of numerous low-background setups and measurements of various rare processes [1, 9].

2. From DAMA/LIBRA-phase2 to DAMA/LIBRA-phase2-empowered

The full description of the DAMA/LIBRA setup and other related arguments have been discussed in detail in Refs. [1, 2, 5, 7] and references therein. Here we just remind that the sensitive part of this setup is made of 25 highly radiopure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix) having 9.70 kg mass each one (Fig. 1).

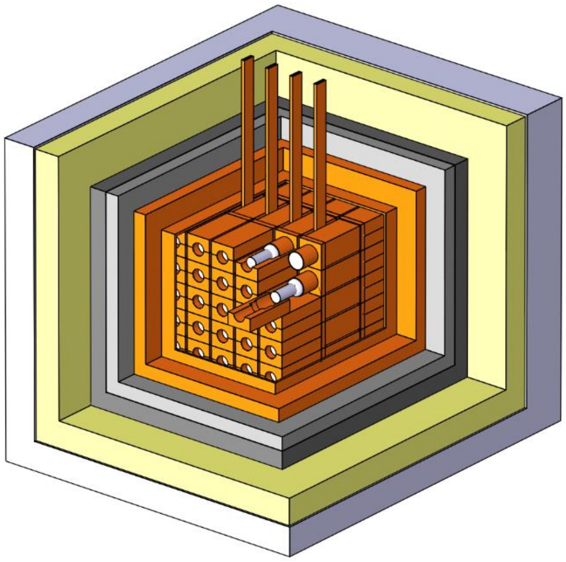

Fig. 1. Schematic view of the DAMA/LIBRA apparatus. The 25 highly radiopure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix), housed in the sealed copper box continuously maintained in High Purity Nitrogen atmosphere, within the multi-ton multi-materials low-radioactive passive shield, are visible. Mostly outside the installation, the DAMA/LIBRA apparatus was also almost fully surrounded by about 1 m of concrete made of the Gran Sasso rock. The copper guides of the calibration system are also shown. For details, see Refs. [1, 2, 5, 7] (See color Figure on the journal website.)

In each detector, two 10 cm long UV light guides (made of Suprasil B quartz) act also as optical windows on the two end faces of the crystal and are coupled to two low background PMTs working in coincidence at a single photoelectron (ph.el.) level. The detectors are housed in a sealed low-radioactive copper box installed in the centre of a low-radioactive Cu/Pb/Cd-foils/polyethylene/paraffin shield; moreover, about 1 m of concrete (made from the Gran Sasso rock material) almost fully surrounds (mostly outside the barrack) this passive shield, acting as a further neutron moderator. A threefold levels sealing system prevents the detectors from being in contact with the environmental air of the underground laboratory.

The light responses of the detectors during DAMA/LIBRA-phase2 and DAMA/LIBRA-phase2-empowered phases typically range from 6 to 10 ph.el./keV, depending on the detector. Energy calibration with X-rays/γ sources are regularly carried out in the same running condition down to a few kiloelectronvolt, without switching the high voltages off; in particular, double coincidences due to internal X-rays from ^{40}K (which is at ppt levels in the crystals) provide (when summing the data over long periods) a calibration point at 3.2 keV close to the software energy threshold. The DAQ system records both *single-hit* events (where just one of the detectors fires) and *multiple-hit* events (where more than one detector fires) up to the mega-electronvolt region, despite the optimization being performed for the lowest energy.

To further enhance the experimental sensitivity and reduce the software energy threshold, several R&D approaches were investigated. Ultimately, a safer and more cost-effective solution was adopted, aimed at improving the signal-to-noise ratio in the lowest energy bins and, consequently, lowering the software energy threshold and enhancing the associated performance quantities. In particular, new low-background preamplifiers were developed, integrating the voltage divider and the preamplifier – implemented with miniaturized, carefully selected components – into a single device mounted on a dedicated low-background board (Fig. 2).

The main features of this new voltage divider plus preamplifier system are: i) signal/noise: ≃ 3.0–9.0; ii) discrimination of single photoelectron from electronic noise: 3–8; iii) peak to valley ratio: 4.7–11.6; iv) residual radioactivity lower than that of a single PMT. Further relevant improvements arise from improvements in the electronic chain; in particular,

Fig. 2. Photo of the low-background voltage divider and pre-amplifier system mounted on the same board in DAMA/LIBRA-phase2-empowered. (See color Figure on the journal website.)

all the Transient Digitizers were substituted with new ones having higher vertical resolution (14 bits). The operational features of this new configuration result in being very stable; in particular, the baseline fluctuations are more than a factor of two lower than those of the previous configuration, and the RMS of the baseline distributions is around 150 μV, ranging between 110 and 190 μV.

3. DAMA/LIBRA-phase2-empowered

The DAMA/LIBRA-phase2-empowered consists of the approximately 3 annual cycles, the details of which are summarized in Table 1. Their total exposure is 0.541 t·yr and the variance of the cosine, $(\alpha - \beta^2)$, is ≃ 0.5, pointing out that the detectors were being operational evenly throughout the year. The duty cycle of the experiment is high, 85–90 %; the routine calibrations and the data collection for the acceptance windows efficiency near the software energy threshold mainly affect it. The data-taking behavior is shown in Fig. 3. As can be seen, the data taking was continuous without long interruptions, apart from the periods dedicated to the routine calibrations, which were performed exactly under the same conditions as the production runs.

Table 1. **The DAMA/LIBRA-phase2-empowered annual cycles**

DL2-empowered annual cycles	Period	Exposure, kg·day	$(\alpha - \beta^2)$
1	Dec. 2, 2021 – Oct. 5, 2022	63294	0.410
2	Oct. 6, 2022 – Sept. 5, 2023	68139	0.500
3	Sept. 6, 2023 – July 9, 2024	66064	0.531
DL2-empowered	Dec. 2, 2021 – July 9, 2024	197497 = 0.541 t·yr	0.482
DL2 + DL2-empowered:		2.07 t·yr	
DAMA/NaI + DL1 + DL2 + DL2-empowered:		3.40 t·yr	

Note. The mean value of the squared cosine is $\alpha = \langle cos^2\omega(t - t_0)\rangle$ and the mean value of the cosine is $\beta = \langle cos\omega(t - t_0)\rangle$ (the averages are taken over the lifetime of the data taking, and t_0 = 152.5 day, i.e. June 2); thus, the variance of the cosine, $(\alpha - \beta^2)$, is ≃ 0.5 for a detector operating evenly throughout the year. For simplicity, DL1, and DL2 indicate DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2, respectively.

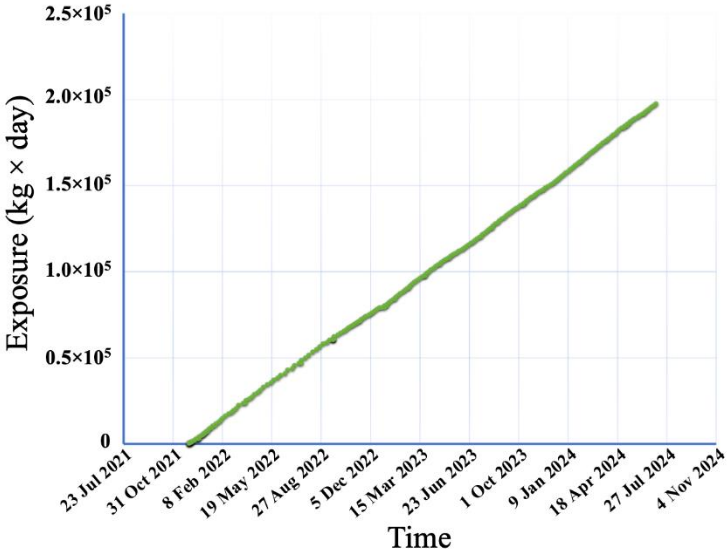

Fig. 3. Exposure collected by DAMA/LIBRA-phase2-empowered as a function of time. As can be seen, the data taking was continuous without long interruptions, apart from the periods dedicated to the routine calibrations, which were performed exactly under the same conditions as the production runs. (See color Figure on the journal website.)

The total number of events collected for the energy calibrations during DAMA/LIBRA-phase2-empowered is about $7.8 \cdot 10^7$; in addition, about $6.9 \cdot 10^4$ events/keV were collected for each crystal to evaluate the acceptance window efficiency for noise rejection near the software energy threshold.

The operational features of the upgraded system have proven to be very stable, as demonstrated in Fig. 4, which shows examples of stability of the counting rate and energy scale of four detectors in the energy region where the ^{210}Pb and the ^{129}I contaminations are dominant. The data collected in the last annual cycle are grouped into four-time intervals.

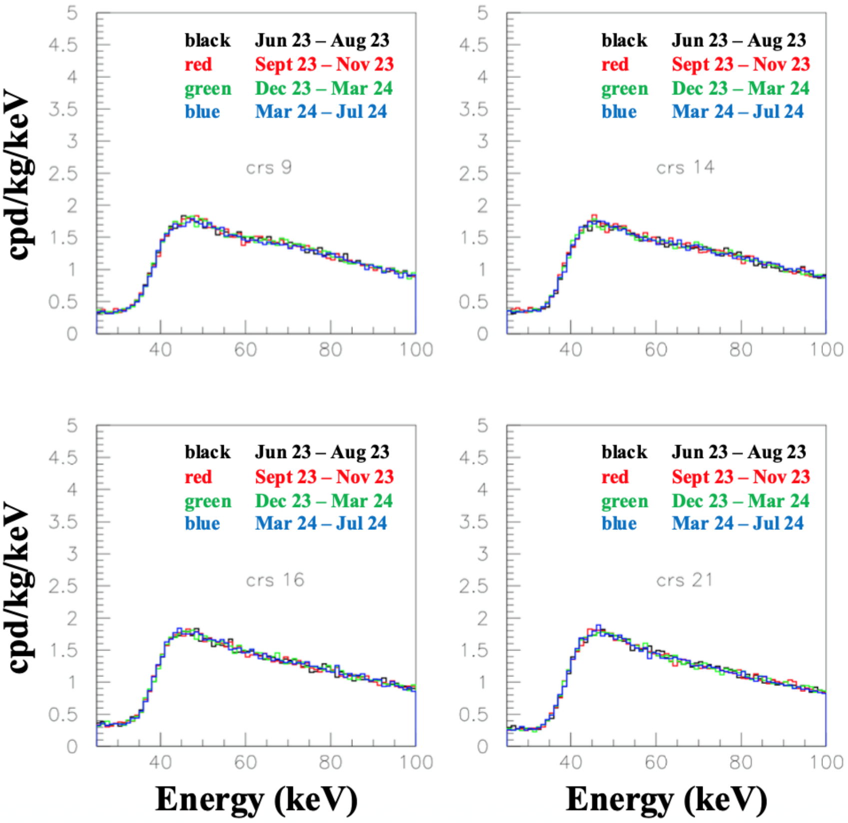

Fig. 4. Examples of stability of the counting rate and energy scale of four detectors in the energy region where the ^{210}Pb and the ^{129}I contaminations are dominant. Data collected in the last annual cycle are grouped in four-time intervals. (See color Figure on the journal website.)

The total exposure of all the available data sets, the former DAMA/NaI, DAMA/LIBRA-phase1, DAMA/LIBRA-phase2, and DAMA/LIBRA-phase2-empowered, is 3.40 t·yr.

The adopted procedure for noise rejection near the software energy threshold is discussed in several papers by the DAMA collaboration over the years and data releases; in particular, a dedicated discussion on the data collected in DAMA/LIBRA-phase2 is presented in Ref. [5]. The procedure and the acceptance windows are the same, unchanged along all the DAMA/LIBRA-phase2 and DAMA/LIBRA-phase2-empowered data takings, throughout the months and the annual cycles. The typical behavior of the efficiency, ε_{AW}, for *single-hit* events as a function of the energy is shown in Ref. [5].

The percentage variations of the efficiency ε_{AW}, considering all the DAMA/LIBRA-phase2-empowered annual cycles presented here, follow a Gaussian distribution with $\sigma = 0.25$ % and do not show any modulation with period and phase as expected for DM signal.

Below 1 keV, to take into account the overall detection efficiency, it was necessary to evaluate an additional efficiency for the hardware trigger and for the new offline procedure described below.

In DAMA/LIBRA, the hardware trigger of a detector is produced by the electronic chain when a signal above the single photoelectron level, which is the hardware energy threshold, is detected in both the PMTs within a coincidence window of 100 ns. In addition, in the offline data analysis at low energy, only events with at least two ph.el. (#ph.el > 1) in each of the two PMTs (A,B) of a detector are accepted. This condition of offline trigger (#ph.el$_A$ > 1.AND.#ph.el$_B$ > 1) allows the removal of a large part of the noise events near energy threshold, and it is obtained by applying a suitable acceptance window on the variables *tm600*, the mean-time over 600 ns evaluated for each PMT pulse ($tm600_A$ and $tm600_B$): $tm600_{A,B} > tm600_{lim}$ for either PMT signal. The value of $tm600_{lim}$ is approximately 25 ns for nearly all detectors. It can be easily evaluated by Monte Carlo simulation that the probability to evade this constraint is negligible: $1.2 \cdot 10^{-4}$.

The efficiency, ε_{MC}, of the hardware trigger and this preliminary offline procedure are evaluated by a Monte Carlo simulation.

Fig. 5 shows the calculated efficiency ε_{MC} band as functions of the energy for a detector with light yield (LY) of 9 ph.el./keV. The band considers light yields ranging within a ± 10 % interval. The spread of the band is used to evaluate the uncertainty of the ε_{MC} efficiency in the given energy bin.

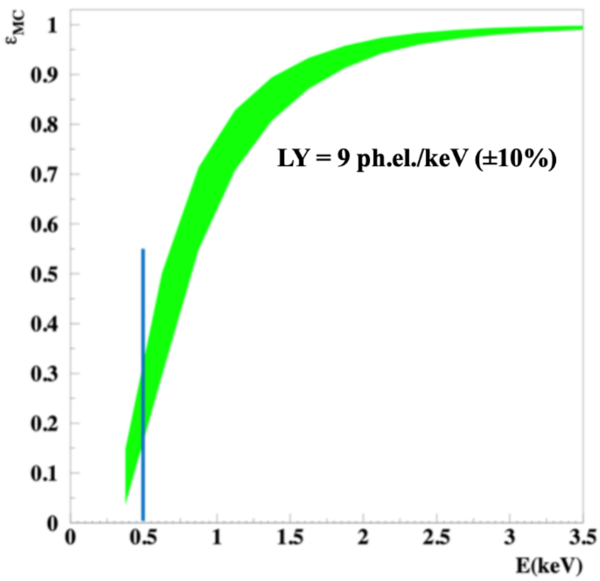

Fig. 5. Efficiency, ε_{MC}, for the statistical distributions of the photoelectrons in the two PMTs of a detector with LY equal to 9 ph.el./keV (± 10 %). The *blue vertical line* represents the considered software energy threshold, while the *shaded green area* accounts for the 10 % spread on the LY assumed in the Monte Carlo calculation. (See color Figure on the journal website.)

It can be noted that this efficiency mainly affects the energy region below approximately 1 keV. The behaviors of ε_{MC} and its band were properly calculated for every detector of DAMA/LIBRA-phase2-empowered data set.

In conclusion, as shown in Fig. 5, the ε_{MC} efficiency for the hardware-trigger and the preliminary offline coincidences allows the study of the counting rate below 1 keV, which was the main purpose of the DAMA/LIBRA-phase2-empowered data set.

4. The annual modulation of the residual rate

The *single-hit* residual rates, calculated as described, e.g., in Refs. [1, 9, 10], have been produced for the DAMA/LIBRA-phase2-empowered annual cycles. For the previous data releases of the residuals of DAMA/NaI (0.29 t·yr), DAMA/LIBRA-phase1 (1.04 t·yr), and DAMA/LIBRA-phase2 (1.53 t·yr), the reader can refer to the given references.

Fig. 6 shows the time behaviors of the experimental residual rates of the *single-hit* scintillation events in the 0.5–3 and 0.5–6 keV energy intervals of DAMA/LIBRA-phase2-empowered. The null modulation hypothesis is rejected at very high C.L. by χ^2 test: $\chi^2 = 50.5$ and 73.9, respectively, over 24 d.o.f. (p-value = $1.2 \cdot 10^{-3}$ and $5.5 \cdot 10^{-7}$, respectively).

The *single-hit* residual rates in Fig. 6 were fitted with the function: $A \cos\omega(t - t_0)$, assuming a period $T = 2\pi/\omega$, = 1 yr and a phase $t_0 = 152.5$ days (June 2), as expected for the annual modulation induced by

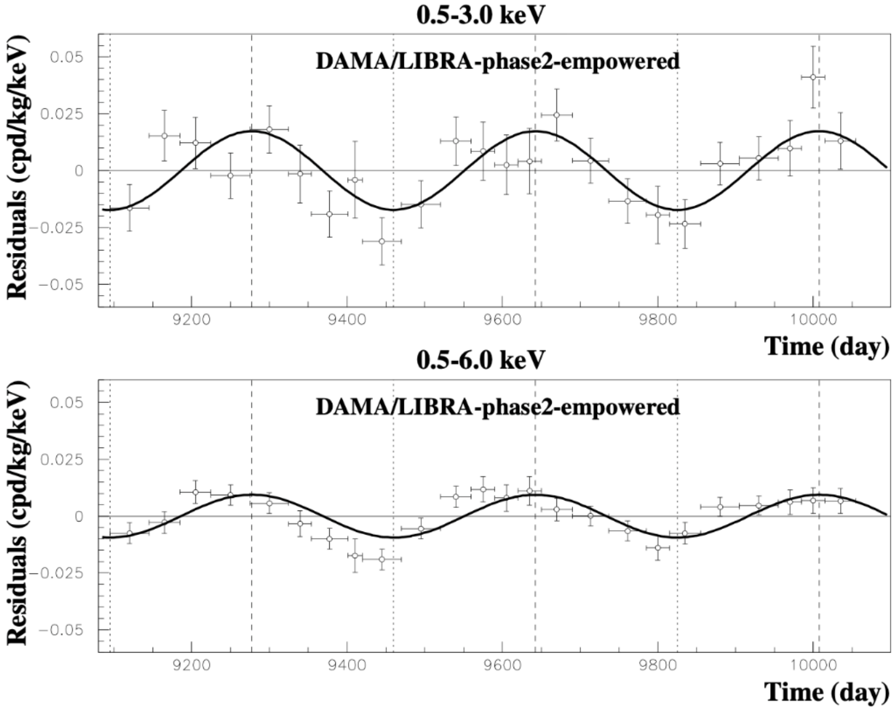

Fig. 6. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA-phase2-empowered in the 0.5–3 and 0.5–6 keV energy intervals as a function of time. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the cosinusoidal functional forms $A \cos \omega(t - t_0)$ with a period $T = 2\pi/\omega = 1$ yr, a phase $t_0 = 152.5$ days (June 2), and amplitudes, A, reported in Table 2. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2), while the dotted vertical lines correspond to the expected minimum.

Table 2. **Modulation amplitudes obtained from fits of the *single-hit* residual rate**

Energy intervals, keV	A, cpd/kg/keV	$T = \frac{2\pi}{\omega}$, yr	t_0, days	C.L.	χ^2 / d.o.f
DL2-empowered:					
0.5–3	0.0173 ± 0.0033	1	152.5	5.2 σ	23.2/23
0.5–6	0.0094 ± 0.0015	1	152.5	6.3 σ	31.9/23
0.5–3	0.0187 ± 0.0033	0.998 ± 0.003	148 ± 30	5.7 σ	19.3/21
0.5–6	0.0116 ± 0.0015	0.996 ± 0.003	155 ± 20	7.7 σ	12.4/21
DL2 + DL2-empowered:					
1–6	0.01018 ± 0.00076	1	152.5	13.4 σ	98.4/92
1–6	0.01069 ± 0.00077	0.998 ± 0.001	154.1 ± 4.1	13.9 σ	81.0/90
DAMA/NaI + DL1 + DL2 + DL2-empowered:					
2–6	0.00976 ± 0.00066	1	152.5	14.8 σ	162.9/179
2–6	0.01028 ± 0.00067	0.99748 ± 0.00053	153.5 ± 3.8	15.3 σ	141.1/177

Note. Modulation amplitudes, A, obtained by fitting the *single-hit* residual rate of Fig. 6, and also including the former DAMA/NaI, DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2. The labels in this table have the same meaning as in Table 1. The formula: $A \cos \omega(t - t_0)$ was used, where the period $T = 2\pi/\omega$ and the phase t_0 are kept fixed at 1 yr and at 152.5 days (June 2), as expected from the DM annual modulation signature, and alternatively kept free. The results are well compatible with expectations for a signal in the DM annual modulation signature.

DM particles. The results of the best fits for the various cases are summarized in Table 2, which also reports the fits where the period and phase are left free, as well as those including the earlier data sets DAMA/NaI, DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2. The goodness of the fits is well supported by the χ^2 tests. The results are well compatible with expectations for the DM annual modulation signal.

Fig. 7 shows the residual rates of the *single-hit* scintillation events of DAMA/LIBRA-phase2 and the present DAMA/LIBRA-phase2-empowered; the energy interval is from 1 keV, the software energy threshold of DAMA/LIBRA-phase2, up to 6 keV. The null modulation hypothesis is again rejected at very high C.L. by χ^2 test: χ^2/d.o.f. = 276/93, corresponding to p-value = $5 \cdot 10^{-20}$.

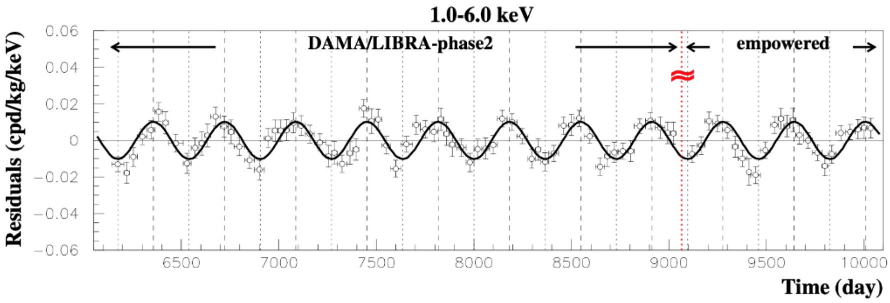

Fig. 7. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA-phase2 and DAMA/LIBRA-phase2-empowered in the 1–6 keV energy intervals as a function of time. The superimposed curve is the cosinusoidal functional form $A \cos \omega (t - t_0)$ with a period $T = 2\pi/\omega$, a phase t_0 = 152.5 days (June 2) and modulation amplitude, A, reported in Table 2. The interruption between the two experimental configurations (see Ref. [10] and Table 1) is highlighted by the vertical dotted red line with the proper symbol. (See color Figure on the journal website.)

5. No modulation in the background

Since the background in the lowest energy region is essentially due to "Compton" electrons, X-rays and/or Auger electrons, muon induced events, etc., which are strictly correlated with the events in the higher energy region of the spectrum, if a modulation detected in the lowest energy region were due to a modulation of the background (rather than to a signal), an equal or larger modulation in the higher energy regions should be present. Thus, as done in previous data releases, the absence of any significant background modulation in the energy spectrum for energy regions not of interest for DM has also been verified in the present one. In particular, the measured rate integrated above 90 keV, R_{90}, as a function of time has been analyzed, and Fig. 8 depicts the distribution of the percentage variations of R_{90} with respect to the mean values for all the detectors in DAMA/LIBRA-phase2-empowered.

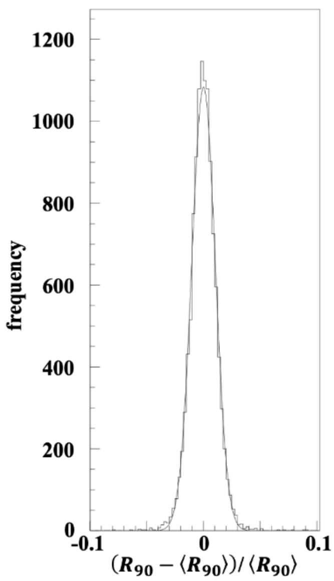

Fig. 8. Distribution of the percentage variations of R_{90} with respect to the mean values for all the detectors in the DAMA/LIBRA-phase2-empowered (*histogram*); the superimposed curve is a Gaussian fit.

The cumulative behavior is Gaussian with $\sigma \simeq 1$ %, which is well accounted for by the statistical spread provided by the sampling time used. When fitting the time behavior of R_{90}, including a term with phase and period as for DM particles, a modulation amplitude A_{R90} compatible with zero has been found for all the annual cycles, as shown in Table 3.

Table 3. **Modulation amplitudes A_{R90}**

DAMA/LIBRA-phase2-empowered annual cycle	A_{R90}, cpd/kg
1	(0.15 ± 0.14)
2	– (0.15 ± 0.12)
3	(0.01 ± 0.12)
1 – 3	– (0.011 ± 0.073)

Note. The modulation amplitudes, A_{R90}, obtained by fitting the time behavior of R_{90} in DAMA/LIBRA-phase2-empowered by including a term with a cosine function having phase and period as expected for a DM signal. They are compatible with zero, and incompatible ($\simeq 100\ \sigma$) with modulation amplitudes of tens cpd/kg (see text).

This also excludes the presence of any background modulation in the whole energy spectrum at a level much lower than the effect measured in the lowest energy region for the *single-hit* scintillation events. In fact, otherwise, considering the R_{90} mean values, a modulation amplitude of the order of tens cpd/kg would be present for each annual cycle, that is $\simeq 100\ \sigma$ far away from the measured values.

Similar analyses can be performed in other energy regions. For example, Fig. 9 shows the *single-hit* residuals in the 6–10 keV energy regions for the DAMA/LIBRA-phase2-empowered as if they were collected in a single annual cycle. The fitted amplitude – under the assumption that the period and the phase are as for DM particles – is compatible with the absence of modulation even at energies just above those where the signal is observed.

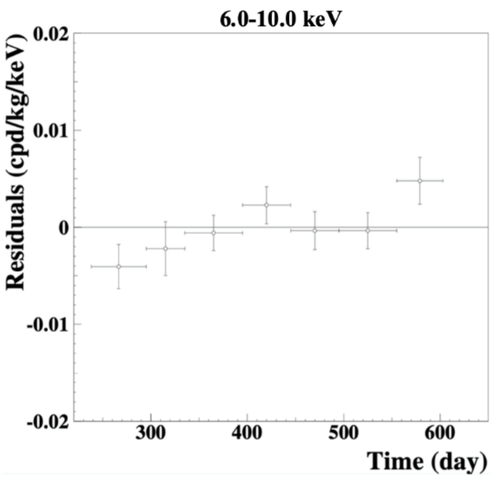

Fig. 9. Experimental *single-hit* residuals in the 6–10 keV energy regions for DAMA/LIBRA-phase2-empowered as if they were collected in a single annual cycle. The fitted modulation amplitude is A = (0.0011 ± 0.0011) cpd/kg/keV, compatible with a null modulation.

Finally, no background process able to mimic the DM annual modulation signature (that is, able to simultaneously satisfy all the peculiarities of the signature and to account for the measured modulation amplitude) has been found or suggested by anyone throughout some decades thus far (see e.g. [1, 7, 9]).

As in previous data releases, we verified that the *multiple-hit* sample does not show any annual modulation in the low-energy intervals.

6. The maximum likelihood modulation amplitudes

The annual modulation present at low energy can also be pointed out by depicting the energy dependence of the modulation amplitude, $S_m(E)$, obtained by the maximum likelihood method, considering a fixed period and phase: T = 1 yr and t_0 = 152.5 days, respectively. For this purpose, the likelihood function of the *single-hit* experimental data can be constructed considering that the number of events collected in the i-th time interval (hereafter 1 day), by the j-th detector and in the k-th energy bin follows a Poisson's distribution with expectation value:

$$\mu_{ijk} = \left[b_{jk} + S_{ik} \right] M_j \Delta t_i \Delta E \varepsilon_{AW,jk} \varepsilon_{MC,jk}.$$

The b_{jk} are the background contributions, M_j is the mass of the j-th detector, Δt_i is the detector running time during the i-th time interval, ΔE is the chosen energy bin, $\varepsilon_{AW,jk}$ is the acceptance window efficiency and $\varepsilon_{MC,jk}$ is the efficiency for the hardware-trigger and the preliminary offline coincidences (see above). The signal, S_{ik}, can be written as:

$$S_{ik} = S_{0k} + S_{mk} \cos\omega\left(t_i - t_0\right),$$

where S_{0k} is the constant part of the signal and S_{mk} is the modulation amplitude, in the k-th energy bin. The free parameters of the fit are the $\left(b_{jk} + S_{0k}\right)$ contributions and the S_{mk} parameter[1]. In the following, the k-index will be omitted for simplicity.

In the used procedure, the data taking of each annual cycle starts before the expected minimum of the DM signal (about December 2) and ends after its expected maximum (about June 2). Thus, adopting in the data analysis a constant background, b_{jk}, evaluated within each annual cycle, any possible decay of long-term-living isotopes cannot mimic a DM positive signal with all its peculiarities. On the contrary, it may only lead to underestimating the DM annual modulation amplitude, depending on the radio-purity of the setup.

The obtained results are presented in Fig. 10 where the modulation amplitudes, S_m, of the DAMA/LIBRA-phase2-empowered data set (0.541 t·yr) with an energy threshold of 0.5 keV (*black filled squares*) are reported in comparison with the S_m from the already-published data sets: DAMA/NaI, DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 (total exposure: 2.86 t·yr, white open circles). As can be seen, they are compatible: in detail, the $\chi^2\left(1 - 20\,\text{keV}\right) = 39.3$, $\text{d.o.f.} = 38$ (p-value = 41 %), and thus they can be combined together. The combined modulation amplitudes for the whole data sets: DAMA/NaI, DAMA/LIBRA-phase1, DAMA/LIBRA-phase2, and DAMA/LIBRA-phase2-empowered (total exposure 3.40 t·yr) are plotted in Fig. 11. It can be inferred that a positive signal is present in the 0.5–6 keV energy interval, while $S_m(E)$ values compatible with zero are present just above. All this confirms the previous analyses. The test of the hypothesis that the $S_m(E)$ values in the 6–14 keV energy range have random fluctuations around zero yields χ^2/d.o.f. = 17.0/16 (p-value = 39 %).

We note that the low-energy scale and its stability are monitored as discussed above and, e.g., in Refs. [2, 3, 9]; the related uncertainties have negligible impact on S_m compared to statistical errors in the modulation fit [2, 3, 9].

[1] This procedure allows the extraction of the S_m values underlying the model-independent signature, but it does not allow for a separate determination of the S_0 and b components. It is therefore worth noting that, in subsequent model-dependent interpretations, upper limits on S_0 should be included as priors. These limits can be derived from the measured counting rate, $b + S_0$, as described, e.g., in Ref. [9].

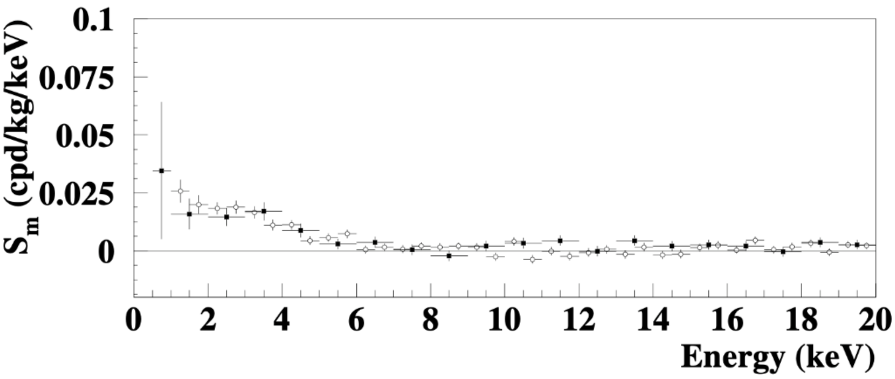

Fig. 10. Modulation amplitudes, S_m, of the DAMA/LIBRA-phase2-empowered data set (0.541 t·yr) with an energy threshold of 0.5 keV (*black filled squares*). For comparison, the S_m of the already-published data sets: DAMA/NaI, DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2 (total exposure: 2.86 t·yr) are also reported (*white open circles*). The two data sets are compatible, and they can be combined together.

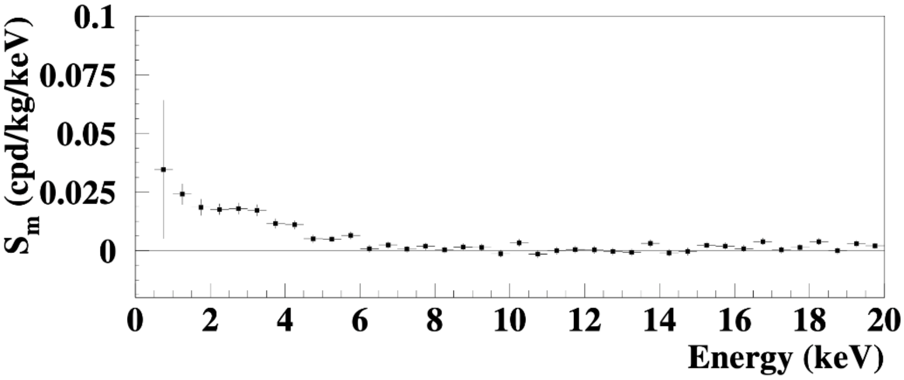

Fig. 11. Modulation amplitudes, S_m, for the whole data sets: DAMA/NaI, DAMA/LIBRA-phase1, DAMA/LIBRA-phase2, and DAMA/LIBRA-phase2-empowered (total exposure: 3.40 t·yr). A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the 6–14 keV energy interval have random fluctuations around zero with χ^2/d.o.f. equal to 17.0/16 (p-value is 39 %).

For the case of 6–20 keV energy interval, one gets: χ^2/d.o.f. = 44.4/28 (p-value = 2.5 %); the obtained χ^2 value is rather large due mainly to two data points, whose centroids are at 16.75 and 18.25 keV, far away from the 1–6 keV energy interval. The p-values obtained by excluding only the first and either the points are 9 % (χ^2/d.o.f. = 37.2/27) and 28 % (χ^2/d.o.f. = 29.7/26).

7. Data analysis considering the same background over the three annual cycles

The analysis procedure described above assumes a constant background evaluated within each annual cycle. This procedure ensures that any possible decay of long–lived isotopes cannot mimic a positive DM signal with all its characteristic features. On the contrary, such decays could only lead to an underestimation of the DM annual modulation amplitude, depending on the radiopurity of the setup.

Therefore, given this procedure, the observed DAMA annual modulation result cannot be mimicked by an artifact of the analysis method. Detailed studies on this topic have already been discussed, e.g., in Refs. [1, 9, 16, 17], quantitatively confuting this hypothesis – even under the arbitrary assumption of a low-energy rate in DAMA/LIBRA with an unconventional, not observed, behavior increasing over time.

To further address this point, the collaboration has presented an analysis in which the data of the last three published years of DAMA/LIBRA-phase2 (where continuity between successive years was also present) were analyzed assuming a common background over the annual cycles; see e.g. [16, 17]. This confirmed that the standard analyses, where a constant background within each annual cycle was assumed, can be safely adopted.

In this Section – taking advantage of the fact that the approximately 3 annual cycles of DAMA/LIBRA-phase2-empowered are continuous without any long interruption or upgrade during the three years – the entire DAMA/LIBRA-phase2-empowered data set is also analyzed under the assumption of a common background across all cycles.

Just as an example, Fig. 12 reports the counting rates of all the 25 detectors during the DAMA/LIBRA-phase2-empowered data set in the 3–4 keV energy bin. The time bin is 5 days, and the *red solid curve* (online) is the result of the maximum likelihood analysis considering the same background over approximately 3 yr of data taking. The χ^2/d.o.f. ranges from 0.94 to 1.13.

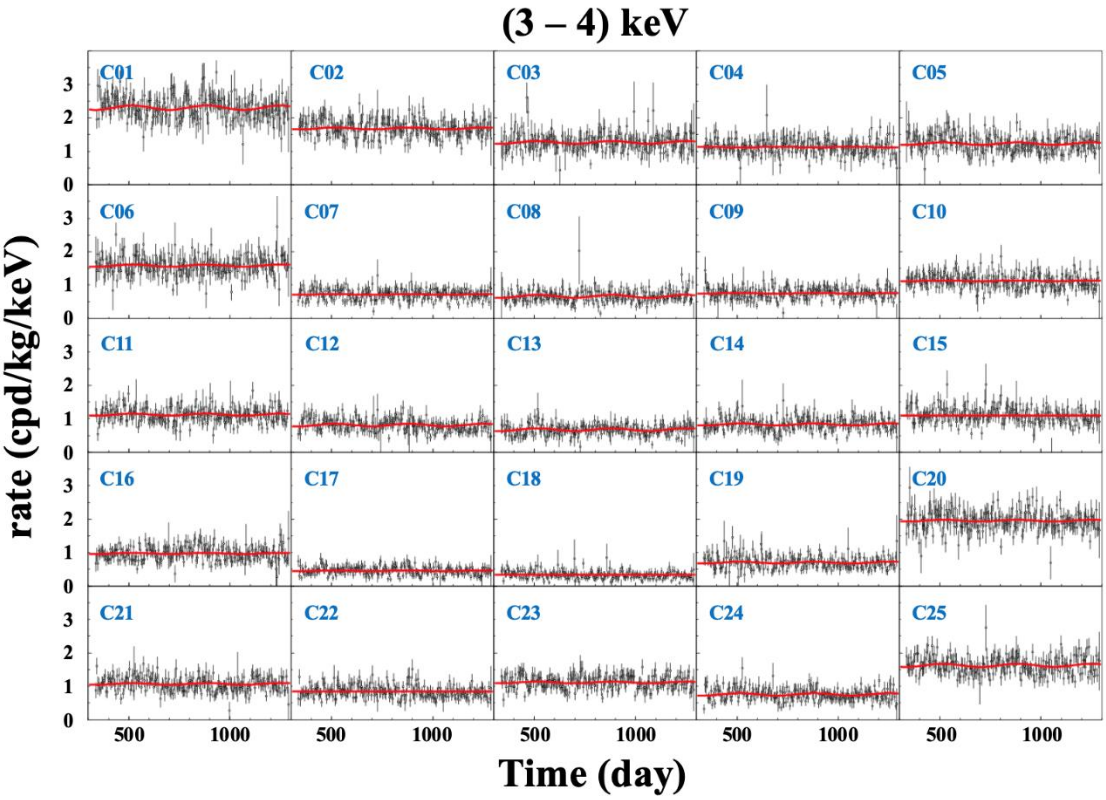

Fig. 12. Counting rates of each detector during the DAMA/LIBRA-phase2-empowered data set in the 3–4 keV energy bin. The time bin is 5 days. The red superimposed curves are the results of the maximum likelihood analysis considering the same background during the approximately 3 yr of this data taking. The values of the modulation amplitudes are reported in Fig. 13-*right*. The χ^2/d.o.f. ranges from 0.94 to 1.13. (See color Figure on the journal website.)

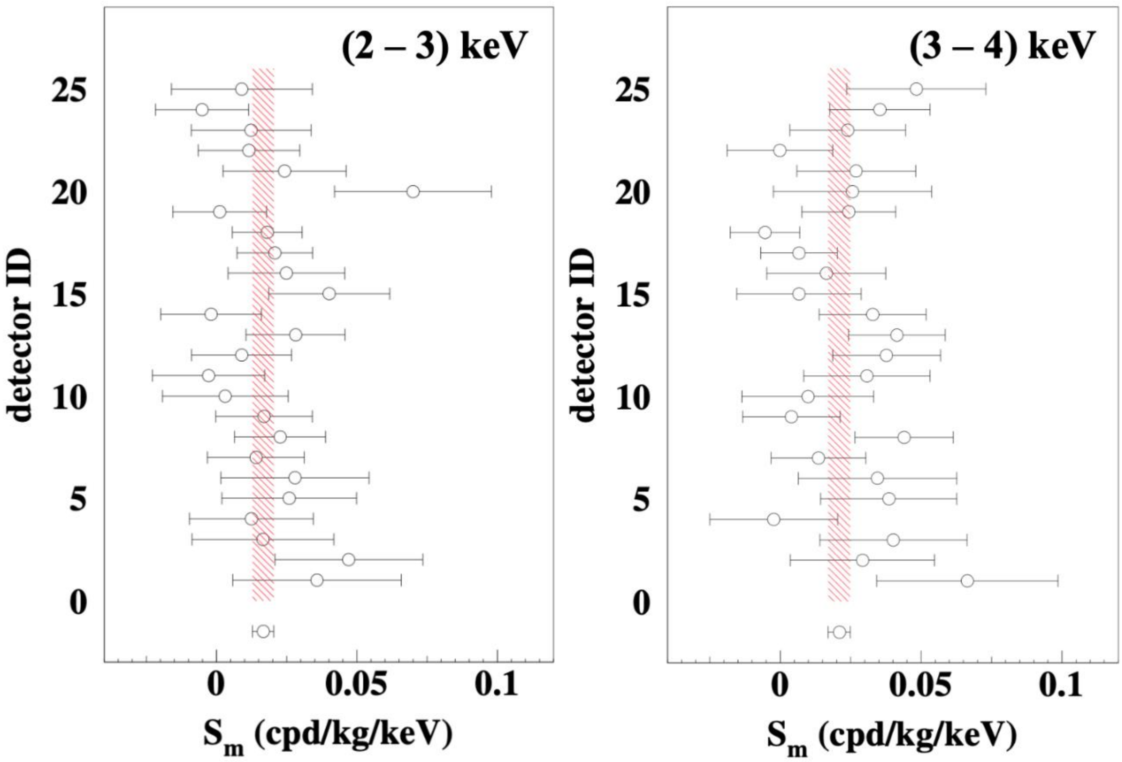

Fig. 13. Modulation amplitudes S_m in the 2–3 keV (*left panel*) and 3–4 keV (*right panel*) energy intervals for each of the 25 detectors of the DAMA/LIBRA-phase2-empowered data set. The errors are at 1 σ confidence level. The weighted average point and 1 σ band (*shaded area*) are also reported. Here, the analysis was done considering the same background in the three years. The χ^2 are 13.3 and 19.8 over 24 d.o.f. (p-values = 96 % and 71 %), respectively, supporting the hypothesis that the signal is well distributed over all 25 detectors. (See color Figure on the journal website.)

The modulation amplitudes S_m for each of the 25 detectors of the DAMA/LIBRA-phase2-empowered data set, obtained by assuming the same background during the approximately 3 yr of data taking, are depicted in Fig. 13 for the particular cases of the 2–3 keV (*left panel*) and 3–4 keV (*right panel*) energy intervals. They have random fluctuations around the weighted average value (shaded band) confirmed by the χ^2 equal to 13.3 and 19.8 over 24 d.o.f. (p-values = 96 % and 71 %), respectively. Thus, the hypothesis that the signal is well distributed over all 25 detectors is accepted.

Finally, Fig. 14 shows the comparison between the modulation amplitudes, S_m, obtained with the standard analysis (white open circles) and with the analysis considering the same background over the approximately 3 annual cycles (*black filled squares*); in both cases, the used data set is the entire DAMA/LIBRA-phase2-empowered.

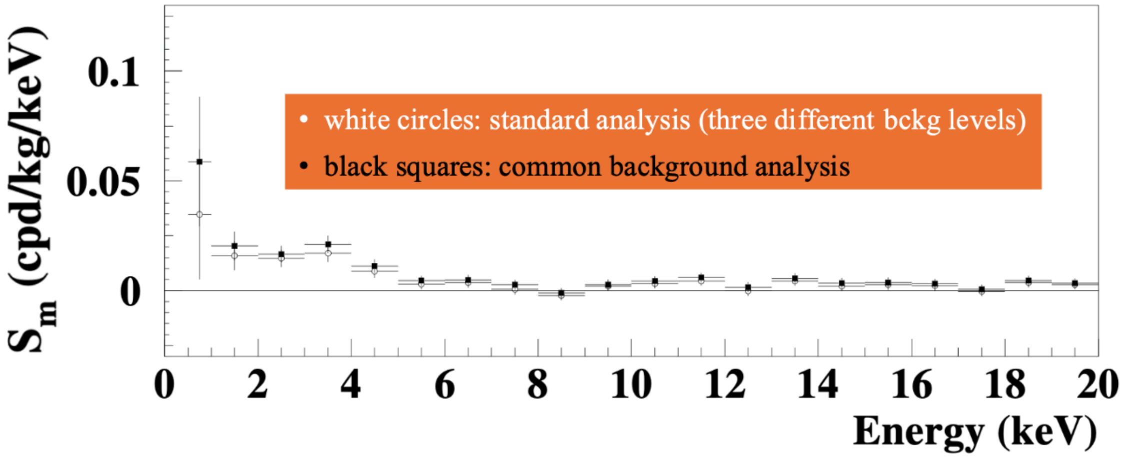

Fig. 14. Comparison of the modulation amplitudes, S_m, obtained with the standard analysis (*white open circles*) and with the analysis considering the same background over the approximately 3 annual cycles (*black filled squares*); in both cases, the used data set is the entire DAMA/LIBRA-phase2-empowered. (See color Figure on the journal website.)

As can be seen, the modulation amplitudes obtained by the two methods of analysis are consistent with each other (χ^2/d.o.f. equal to 8.4/20), further confirming that any effects from long-term, time-varying backgrounds – even from any hypothetical slowly increasing low-energy rate – are negligible in DAMA/LIBRA, thanks to the detectors' performances and long-term underground operation. Therefore, the standard DAMA analysis can be reliably used.

Let us note that the S_m values obtained using the same background across the three annual cycles are systematically slightly higher than those derived from the standard analysis. The average shift in the modulation amplitudes remains well below the uncertainty of each individual data point. Therefore, the standard analysis can be regarded as a more conservative and safer approach.

Summarizing the arguments, e.g., of Refs. [9, 16, 17] and the analysis reported in this Section further show that any possible effect in DAMA/LIBRA due either to any long-term, time-varying backgrounds or to any odd behavior of the rate, increasing with time, is negligible and the standard analyses, that assume a constant background within each annual cycle, can be safely adopted. Moreover, the hypothesis that the signal is well distributed over all 25 detectors is accepted.

8. Conclusions

The DAMA project has been in operation for several decades, during which numerous low-background experimental setups were developed and employed to measure a variety of rare processes [18]. Its primary original goal was the investigation of the presence of a DM particle component in the galactic halo using different detector configurations, based on the development and deployment of highly radiopure NaI(Tl) target-detectors. DM has also been investigated using complementary approaches and within several corollary model-dependent interpretations (see e.g. Ref. [1]). In particular, the highly radiopure NaI(Tl) setups – DAMA/NaI, DAMA/LIBRA-phase1, DAMA/LIBRA-phase2, and DAMA/LIBRA-phase2-empowered (total cumulative exposure: 3.40 t·yr) – have provided evidence for an effect that simultaneously satisfies all the specific requirements of the exploited DM annual modulation signature, with very high confidence level.

In this paper, the new results obtained with the latest DAMA/LIBRA-phase2-empowered configuration (exposure: 0.541 t·yr) are presented. The reduction of the software energy threshold down to 0.5 keV has further improved the experimental sensitivity. The effect, already observed in previous configurations, is also present in this new configuration. Moreover, the continuous data-taking procedure has allowed us to further demonstrate the robustness of the DAMA standard model-independent analysis and to further exclude any hypothetical effect from a long-term, time-varying background.

At present, the DAMA cumulative model-independent DM annual modulation effect, corresponding to a total exposure of 3.40 t·yr, is observed at a confidence level of 15.3 σ.

It should be emphasized that the DAMA observed effect remains compatible with a wide class of theoretical models, particularly in light of the substantial uncertainties that persist in astrophysical, nuclear, and particle-physics aspects (see e.g. Ref. [1]).

For the sake of completeness, we recall that several efforts employing different target detectors are currently ongoing (see e.g. Refs. [19, 20]). Concerning more recent activities focused on measurements performed with the same target nuclei as those used by ANAIS-112 and COSINE-100 (for initial remarks that remain relevant, we refer the reader to Ref. [9], where, among other topics, the different quenching factors are discussed) we briefly note that some of their conclusions – including the intrinsically uncertain joint combinations [21] – should be interpreted in light of the differences in detector performance, shielding and environmental conditions, electronics, data-taking procedures, and analysis methods. Nevertheless, these activities represent potentially interesting experimental efforts.

Finally, we note that the DAMA project was concluded as planned, and the DAMA experimental setups were dismantled in fall 2024 [18].

Both model-independent and model-dependent analyses on several rare processes and related aspects are ongoing.

REFERENCES

1. DAMA Collaboration. Publication list, http://dama.web.roma2.infn.it
2. R. Bernabei et al. The DAMA/LIBRA apparatus. Nucl. Instrum. Methods A 592 (2008) 297.
3. R. Bernabei et al. First results from DAMA/LIBRA and the combined results with DAMA/NaI. Eur. Phys. J. C 56 (2008) 333.
4. R. Bernabei et al. New results from DAMA/LIBRA. Eur. Phys. J. C 67 (2010) 39.
5. R. Bernabei et al. Performances of the new high quantum efficiency PMTs in DAMA/LIBRA. JINST 7 (2012) P03009.
6. R. Bernabei et al. Final model independent result of DAMA/LIBRA-phase1. Eur. Phys. J. C 73 (2013) 2648.
7. DAMA Collaboration. Special issue dedicated to DAMA Collaboration. Int. J. of Mod. Phys. A 31(31) (2016).
8. R. Bernabei et al. First model independent results from DAMA/LIBRA-phase2. Nucl. Phys. At. Energy 19 (2018) 307.
9. R. Bernabei et al. The DAMA project: Achievements, implications and perspectives. Prog. Part. Nucl. Phys. 114 (2020) 103810.
10. R. Bernabei et al. Further results from DAMA/LIBRA-phase2 and perspectives. Nucl. Phys. At. Energy 22 (2021) 329.
11. R. Bernabei et al. Performances of the ≃ 100 kg NaI(Tl) set-up of the DAMA experiment at Gran Sasso. Il Nuovo Cim. A 112 (1999) 545.
12. R. Bernabei et al. Dark Matter search. Riv. Nuovo Cim. 26(1) (2003) 1.
13. R. Bernabei et al. Dark matter particles in the galactic halo: Results and implications from DAMA/NaI. Int. J. Mod. Phys. D 13 (2004) 2127.
14. A.K. Drukier, K. Freese, D.N. Spergel. Detecting cold dark-matter candidates. Phys. Rev. D 33 (1986) 3495.
15. K. Freese, J. Frieman, A. Gould. Signal modulation in cold-dark-matter detection. Phys. Rev. D 37 (1988) 3388.
16. R. Bernabei et al. Status of DAMA/LIBRA-phase2 and its empowered stage. Bled Workshops in Physics 25 (2024) 1.
17. P. Belli. Annual modulation results from DAMA/LIBRA. Talk at the RICAP-2024 (The 9th edition of the Roma International Conference on AstroParticle Physics), Frascati, Sept 23-27, 2024. EPJ Web of Confer. 319 (2025) 10001.
18. R. Bernabei for DAMA activities. The DAMA project legacy. Bled Workshops in Physics 26 (2025) 44.
19. E. Aprile et al. (The XENON Collaboration). WIMP Dark Matter search using a 3.1 tonne-year exposure of the XENONnT experiment. Phys. Rev. Lett. 135 (2025) 221003.
20. M.F. Albakry et al. (The SuperCDMS Collaboration). Search for low-mass electron-recoil dark matter using a single-charge sensitive SuperCDMS-HVeV Detector. Phys. Rev. D 113 (2026) 032001.
21. N. Carlin et al. (The COSINE-100 Collaboration, ANAIS-112 Collaboration). Combined annual modulation Dark Matter search with COSINE–100 and ANAIS–112. Phys. Rev. Lett. 135 (2025) 121002.

Р. Бернабей[1,2,*], П. Беллі[1,2], А. Буссолотті[1,2], Ф. Каппелла[3], В. Карaччоло[1,2], Р. Черуллі[2], Ц. Дж. Дай[4], А. д'Анджело[3,5], А. Інчіккітті[3,5], А. Леончіні[1,2], С. Х. Ма[4], А. Маттей[3,5], В. Мерло[1,2], Ф. Монтеккі[1,2,6], С. Д. Шен[4], Ц. П. Йе[7]

[1] *Фізичний факультет, Римський університет «Тор Вергата», Рим, Італія*
[2] *Національний інститут ядерної фізики, секція «Рим – Тор Вергата», Рим, Італія*
[3] *Національний інститут ядерної фізики, Римська секція, Рим, Італія*
[4] *Державна ключова лабораторія фізики елементарних частинок і астрофізики, Інститут фізики високих енергій, Китайська академія наук, Пекін, КНР*
[5] *Фізичний факультет, Римський університет «Сапієнца», Рим, Італія*
[6] *Факультет цивільної інженерії та комп'ютерної інженерії, Римський університет «Тор Вергата», Рим, Італія*
[7] *Джінганшаньський університет, Цзіань, провінція Цзянсі, КНР*

*Відповідальний автор: rita.bernabei@roma2.infn.it

МОДЕЛЬНО-НЕЗАЛЕЖНІ РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ DAMA/LIBRA-PHASE2-EMPOWERED

Експеримент DAMA/LIBRA-phase2 був модернізований у 2021 р. для підвищення його чутливості через зниження програмного енергетичного порогу при збереженні високої ефективності. Нова конфігурація, що називається DAMA/LIBRA-phase2-empowered, накопичувала дані протягом трьох років. Нові дані розширюють дослідження давно відомого, модельно-незалежного ефекту річної модуляції, виявленого експериментальними установками DAMA з використанням сцинтиляційних детекторів NaI(Tl) з високою радіаційною чистотою у Національній лабораторії Гран-Сассо Національного інституту ядерної фізики в різних експериментальних конфігураціях. Програмний енергетичний поріг DAMA/LIBRA-phase2-empowered є нижчим 1 кеВ, а експозиція становить 0,541 т·рік. Додаючи ці нові результати до раніше опублікованих даних DAMA/LIBRA-phase2, експозиція становить 2,07 т·рік протягом 11 незалежних річних циклів, демонструючи наявність сигналу, який відповідає всім вимогам модельно-незалежної річної модуляційної сигнатури темної матерії з рівнем достовірності 13,9 σ в області енергій 1–6 кеВ. В інтервалі 2–6 кеВ, де також доступні дані DAMA/NaI та DAMA/LIBRA-phase1, комбінована експозиція досягає 3,40 т·рік, що відповідає рівню достовірності 15,3 σ. Немає жодного систематичного ефекту чи побічного процесу, здатного одночасно задовольнити всі характерні риси спостереженої річної модуляційної сигнатури темної матерії та врахувати спостережувану амплітуду модуляції.

Ключові слова: темна матерія, елементарні частинки, сцинтиляційні детектори.

Надійшла / Received 19.02.2026