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

[1] *Dipartimento di Fisica, Università di Roma "Tor Vergata", Rome, Italy*
[2] *INFN, Sezione Roma "Tor Vergata", Rome, Italy*
[3] *Dipartimento di Fisica, Università di Roma "La Sapienza", Rome, Italy*
[4] *INFN, Sezione Roma, Rome, Italy*
[5] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, P.R. China*
[6] *Dipartimento Ingegneria Civile e Ingegneria Informatica, Università di Roma "Tor Vergata", Rome, Italy*
[7] *University of Jinggangshan, Ji'an, Jiangxi, P.R. China*

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

FURTHER RESULTS FROM DAMA/LIBRA-phase2 AND PERSPECTIVES

The data collected by the DAMA/LIBRA-phase2 set-up during two additional annual cycles have been analyzed, further investigating the long-standing model-independent annual modulation effect pointed out by DAMA deep underground at the Gran Sasso National Laboratory of the I.N.F.N. by using various different experimental configurations. Including the new results, the total exposure of DAMA/LIBRA-phase2 over 8 annual cycles is 1.53 t·yr and the evidence for a signal that meets all the requirements of the model-independent Dark Matter annual modulation signature is 11.8 σ C.L. in the energy region (1 – 6) keV. In the (2 – 6) keV energy interval, where data are also available from DAMA/NaI and DAMA/LIBRA-phase1, the achieved C.L. for the full exposure of 2.86 t·yr is 13.7 σ. No systematics or side reaction able to mimic this signature (i.e., to account for the whole measured modulation amplitude and to simultaneously satisfy all the requirements of the signature) has been found or suggested by anyone throughout some decades thus far. A preliminary result on the further lowering of the software energy threshold and perspectives are also mentioned.

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

1. Introduction

The DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 experiments [1 - 24] as the former DAMA/NaI [25 - 51] have been based on the developments of highly radio-pure NaI(Tl) target-detectors with selected radio-pure, multiple purified powders available at time of creation, and peculiar protocols for growing with Kyropoulous methods in Pt crucible and for handling the crystals' and the detectors' selected materials as well as a low background multi-ton multi-components shield, etc. as described e.g., in Refs. [1, 6, 9, 52]. They ensure sensitivity to a wide range of Dark Matter (DM) candidates, interaction types, and astrophysical scenarios (see e.g., Refs. [2, 14, 16 - 18, 25 - 32, 35 - 42], and in literature).

The main aim is to investigate the presence of DM particles in the galactic halo by exploiting the DM annual modulation signature, originally suggested in Refs. [53, 54]. This largely model-independent DM annual modulation signature and related properties are a consequence of the Earth's revolution around the Sun, which is moving in the Galaxy with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules. Because of those velocities composition during the year, the Earth should be crossed by a larger flux of DM particles around ≃ 2 June (when the Earth orbital velocity is summed to that of the solar system with respect to the Galaxy) and by a smaller one around ≃ 2 December (when the Earth orbital velocity is subtracted to that of the solar system with respect to the Galaxy). Thus, one can also describe this DM signature as due to the Earth's motion with respect to the DM particles constituting the Galactic Dark Halo. As known, the distinctive effect of the DM annual modulation signature requires that simultaneously: the rate must contain a component modulated according to a cosine function (1) with 1-year period (2) and a phase that peaks roughly on ≃ 2 June (3); this modulation must only be found in a well-defined low energy range, where DM particle-induced events can be present (4);

it must apply only to those events in which just one detector of many actually “fires” (*single-hit* events) since the DM particle multi-interaction probability is negligible (5); the modulation amplitude in the region of maximal sensitivity must be $\lesssim 7\,\%$ of the constant part of the signal for usually adopted halo distributions (6), but it can be larger (even up to $\simeq 30\,\%$) in case of some scenarios such as e.g., those in Refs. [55 - 59]. When exploiting the DM annual modulation signature, the experimental observable to point out a signal presence is the modulated part of the signal, $S_m(E)$, and does not require the – always hypothetical – extraction of the constant part of the signal, $S_0(E)$, from the measured counting rate via many statistical subtractions and uncertain Monte-Carlo hypotheses as discussed elsewhere. We also note that the comparison of results from experiments measuring $S_m(E)$ from those extracting $S_0(E)$ requires model-dependent analyses even if the targets are nominally similar.

This signature not only has many useful peculiarities but also allows for testing a wide range of parameters in many of the possible astrophysical, nuclear, and particle physics scenarios. Only systematic effects or side reactions able to account for the whole observed modulation amplitude and simultaneously satisfy all the requirements given above might mimic this DM signature.

The description of the DAMA/LIBRA set-up and the adopted procedures during phase1 and phase2 and other related arguments have been discussed in detail e.g., in Refs. [1 - 6, 19 - 21, 23]. The radio purity and details are discussed e.g., in Refs. [1 - 5, 52] and references therein. The adopted procedures provide sensitivity to large and low mass DM candidates inducing nuclear recoils and/or electromagnetic signals. The data of the former DAMA/NaI setup and, later, those of the DAMA/LIBRA-phase1 have already given (with a high confidence level) positive evidence for the presence of a signal that satisfies all the requirements of the exploited DM annual modulation signature [2 - 5, 35, 36]. In particular, at the end of 2010, all the photomultipliers (PMTs) were replaced by a second-generation PMTs Hamamatsu R6233MOD, with higher quantum efficiency and with lower background with respect to those used in the phase1, allowing the achievement of the software energy threshold at 1 keV as well as the improvement of some detector’s features such as energy resolution and acceptance efficiency near the software energy threshold [6]. The adopted procedure for noise rejection near the software energy threshold and the acceptance windows are the same unchanged along with all the DAMA/LIBRA-phase2 data taken, throughout the months and the annual cycles. The typical behavior of the overall efficiency for *single-hit* events as a function of the energy is also shown in Ref. [6]; the percentage variations of the efficiency follow a gaussian distribution with $\sigma = 0.3\,\%$ and do not show any modulation with period and phase as expected for the DM signal (for a partial data release see Ref. [21]). At the end of 2012 new preamplifiers and specially developed trigger modules were installed and the apparatus was equipped with more compact electronic modules [60]. In particular, the sensitive part of DAMA/LIBRA-phase2 set-up is made of 25 highly radio-pure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix) having 9.70 kg mass each one realized with peculiar R&D’s, materials, purifications, growth technique, and protocols. Quantitative analyses of residual contaminants are given in Ref. [1]. In each detector, two 10 cm long UV light guides (made of Suprasil B quartz) also act 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 level. The detectors are housed in a sealed low-radioactive copper box installed in the center of a low-radioactive Cu/Pb/Cd-foils/polyethylene/paraffin shield; moreover, about 1 m concrete (made from the Gran Sasso rock material) almost fully surrounds (mostly outside the barrack) this passive shield, acting as a further neutron moderator. The shield is decoupled from the ground by a metallic structure mounted above a concrete basement; a neoprene layer separates the concrete basement and the floor of the laboratory. The space between this basement and the metallic structure is filled with paraffin for several tens of cm in height. A threefold-level sealing system prevents the detectors from contact with the environmental air of the underground laboratory and continuously holds them in high-purity Nitrogen atmosphere. The whole installation is under air conditioning to ensure a suitable and stable working temperature. The huge heat capacity of the multi-tons’ passive shield ($\approx 10^6$ cal/^{o}C) guarantees further relevant stability of the detectors’ operating temperature. Two independent systems of air conditioning are available for redundancy: one cooled by water refrigerated by a dedicated chiller and the other operating with cooling gas. A hardware/software monitoring system provides data on the operating conditions. Several probes are read out and the results are stored with the production data. Moreover, self-controlled computer-based processes automatically monitor several parameters, including those from data acquisition (DAQ), and manage the alarms system. All these procedures, already experienced during DAMA/LIBRA-phase1 [1 - 5], allow us to control and maintain the running conditions stable at a level better than 1 % also in DAMA/LIBRA-phase2 (see e.g., Refs. [21, 23]).

During phase2 the light response of the detectors typically ranges from 6 to 10 photoelectrons/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 keV (for details see e.g., Ref. [1]); 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; in the following – if not otherwise stated – keV means keV electron equivalent. 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 MeV region despite the optimization being performed for the lowest energy.

2. The presently analyzed DAMA/LIBRA-phase2 annual cycles

In this paper, the results obtained by analyzing the data of two new annual cycles, collected by the DAMA/LIBRA-phase2 set-up, are presented, and included in the whole collected exposure. The details of the data takings are summarized in Table 1.

Table 1.

DAMA/LIBRA-phase2 annual cycle	Period	Mass, kg	Exposure, kg·d	$(\alpha - \beta^2)$
1	Dec. 23, 2010 – Sept. 9, 2011	Commissioning of phase2		
2	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
3	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
4	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
5	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
6	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
7	Sept. 7, 2016 – Sept. 25, 2017	242.5	75135	0.480
8	Sept. 25, 2017 – Aug. 20, 2018	242.5	68759	0.557
9	Aug. 24, 2018 – Oct. 3, 2019	242.5	77213	0.446
DAMA/LIBRA-phase2	Nov. 2, 2011 – Oct. 3, 2019	557109 kg·d ≃ 1.53 t·yr		0.501
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2:		2.86 t·yr		

N o t e. The DAMA/LIBRA-phase2 annual cycles. 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 d, i.e. June 2nd); thus, the variance of the cosine, $(\alpha - \beta^2)$, is ≃ 0.5 for a detector operational evenly throughout the year. The duty cycle of the experiment is high, ranging between 76 and 86 %; the routine calibrations and the data collection for the acceptance windows efficiency near the software energy threshold mainly affect it.

As shown, the first cycle was dedicated to commissioning and optimizations towards the achievement of the 1 keV software energy threshold [6]; moreover, it cannot be used for DM annual modulation studies because: i) no data were available before/near December 2, 2010 (the expected minimum for DM signal); ii) the data sets were taken with some set-up modifications; iii) $(\alpha - \beta^2) = 0.355$ well different from 0.5 (i.e., the detectors were not being operational evenly throughout the year); however, data have been used for other purposes [6, 13]. Therefore, the considered annual cycles of DAMA/LIBRA-phase2 are eight for an exposure of 1.53 t·yr, as shown in Table 1.

The total number of events collected for the energy calibrations during these eight DAMA/LIBRA-phase2 annual cycles is about $1.6 \cdot 10^8$, while about $1.7 \cdot 10^5$ events/keV have been collected to evaluate the acceptance window efficiency for noise rejection near the software energy threshold [1, 6].

When also considering the former DAMA/NaI and DAMA/LIBRA-phase1 data, the total exposure is 2.86 t·yr.

3. The annual modulation of the residual rate

The *single-hit* residual rates, calculated as described in Refs. [2 - 5, 35, 36], have been investigated also for the two new annual cycles. We remind that the residuals of the DAMA/NaI data (0.29 t·yr) are given in Refs. [2, 5, 35, 36], while those of DAMA/LIBRA-phase1 (1.04 t·yr) in Refs. [2 - 5].

Fig. 1 shows the time behaviors of the experimental residual rates of the *single-hit* scintillation events in the (1 – 3) and (1 – 6) keV energy intervals for all the eight cycles of DAMA/LIBRA-phase2; the new results of the last two cycles are in very good agreement with the previous ones. The null modulation hypothesis is rejected at very high C.L. by χ^2 test: χ^2 = 176 and 202, respectively, over 69 *d.o.f.* ($P = 2.6 \cdot 10^{-11}$ and $P = 5.6 \cdot 10^{-15}$, respectively).

In Fig. 2 the residual rates of the *single-hit* scintillation events of the former DAMA/LIBRA-phase1 set-up and the present eight annual cycles of DAMA/LIBRA-phase2 are shown; there the energy interval is from 2 keV, the software energy threshold of DAMA/LIBRA-phase1, up to 6 keV. The null modulation hypothesis is here again rejected at very high C.L. by χ^2 test: χ^2/*d.o.f.* = 240/119, corresponding to P-value = $3.5 \cdot 10^{-10}$.

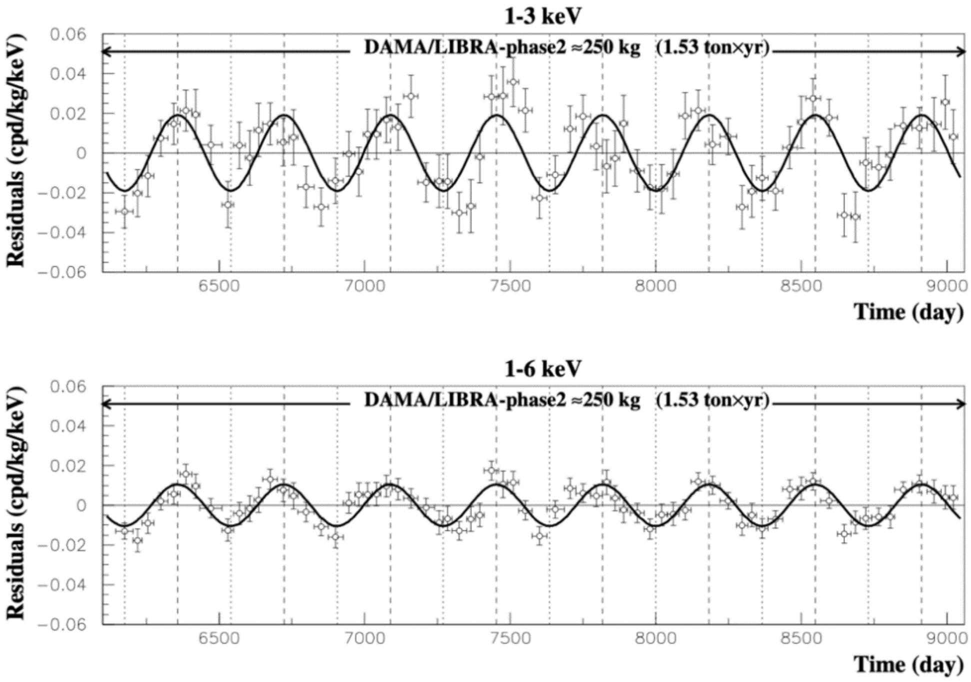

Fig. 1. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA-phase2 over eight annual cycles in the (1 – 3), and (1 – 6) keV energy intervals as a function of the time. The time scale is maintained the same as the previous DAMA papers for consistency. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the co-sinusoidal functional forms $A \cos \omega(t - t_0)$ with a period $T = 2\pi/\omega = 1$ yr, a phase $t_0 = 152.5$ d (June 2nd) and amplitudes, A, equal to the central values obtained by the best fit on the data points of the entire DAMA/LIBRA-phase2. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted vertical lines correspond to the expected minimum. The new results of the last two cycles are in very good agreement with the previous ones.

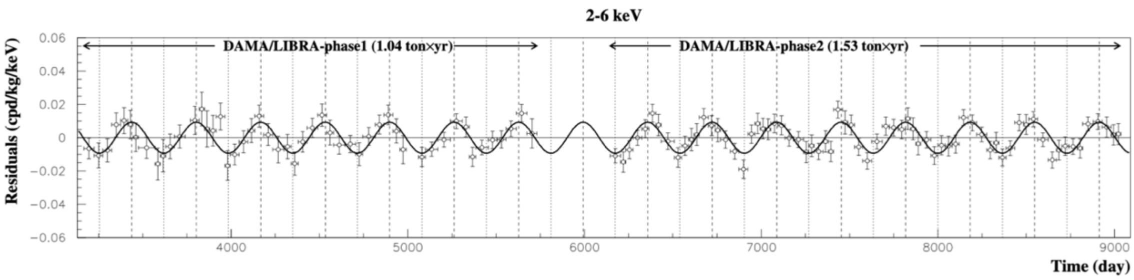

Fig. 2. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 in the (2 – 6) keV energy intervals as a function of the time. The superimposed curve is the co-sinusoidal functional form $A \cos \omega\,(t - t_0)$ with a period $T = 2\pi/\omega$, a phase $t_0 = 152.5$ d (June 2nd), and a modulation amplitude, A, equal to the central value obtained by the best fit on the data points of DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2. For details see the caption of Fig. 1.

The *single-hit* residual rates of the DAMA/LIBRA-phase2 (see Fig. 1) have been fitted with the function: $A \cos \omega(t - t_0)$, considering a period $T = 2\pi/\omega = 1$ yr and a phase $t_0 = 152.5$ d (June 2nd) as expected by the DM annual modulation. When also including the former DAMA/NaI and DAMA/LIBRA-phase1 data, this can be repeated for the (2 – 6) keV energy interval. The goodness of the fits is well supported by the χ^2 tests; for example, $\chi^2/d.o.f.$ = 81.6/68, 66.2/68, 130/155 are obtained for the (1 – 3) keV and (1 – 6) keV cases of DAMA/LIBRA-phase2, and for the (2 – 6) keV case of DAMA/NaI, DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2, respectively. The results of the best fits in the different cases are summarized in Table 2, where also the cases when the period and the phase are kept free in the fitting procedure are shown. The latter ones are well compatible with expectations for the DM annual modulation signal. In particular, the phase is consistent with about June 2nd and is fully consistent with the value independently determined by Maximum Likelihood analysis (see later). For completeness, we recall that a slight energy dependence of the phase could be expected (see e.g., Refs. [38, 58, 59, 61 - 63]), providing intriguing information on the nature of DM candidate and related aspects; this demonstrates for example the relevance to increase at most the precision in the t_0 determination.

Table 2.

E, keV	A, cpd/kg/keV	$T = 2\pi/\omega$, yr	t_0, d	C.L.
DAMA/LIBRA-phase2:				
1 – 3	(0.0191 ± 0.0020)	1.0	152.5	9.7 σ
1 – 6	(0.01048 ± 0.00090)	1.0	152.5	11.6 σ
2 – 6	(0.00933 ± 0.00094)	1.0	152.5	9.9 σ
1 – 3	(0.0191 ± 0.0020)	(0.99952 ± 0.00080)	149.6 ± 5.9	9.6 σ
1 – 6	(0.01058 ± 0.00090)	(0.99882 ± 0.00065)	144.5 ± 5.1	11.8 σ
2 – 6	(0.00954 ± 0.00076)	(0.99836 ± 0.00075)	141.1 ± 5.9	12.6 σ
DAMA/LIBRA-phase1 + phase2:				
2 – 6	(0.00941 ± 0.00076)	1.0	152.5	12.4 σ
2 – 6	(0.00959 ± 0.00076)	(0.99835 ± 0.00069)	142.0 ± 4.5	12.6 σ
DAMA/NaI + DAMA/LIBRA-phase1 + phase2:				
2 – 6	(0.00996 ± 0.00074)	1.0	152.5	13.4 σ
2 – 6	(0.01014 ± 0.00074)	(0.99834 ± 0.00067)	142.4 ± 4.2	13.7 σ

N o t e. Modulation amplitudes, A, obtained by fitting the *single-hit* residual rate of DAMA/LIBRA-phase2 as reported in Fig. 1, as well as also including the residual rates of the former DAMA/NaI and DAMA/LIBRA-phase1. It was obtained by fitting the data with the formula: $A \cos \omega(t - t_0)$; the period $T = 2\pi/\omega$ and the phase t_0 are kept fixed at 1 yr and at 152.5 d (June 2nd), respectively, 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.

4. 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 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 the time has been analyzed, and Fig. 3 depicts the distribution of the percentage variations of R_{90} with respect to the mean values for all the detectors in DAMA/LIBRA-phase2. The cumulative behavior is gaussian with $\sigma \simeq 1$ %, which is well accounted for by the statistical spread provided by the used sampling time. 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.

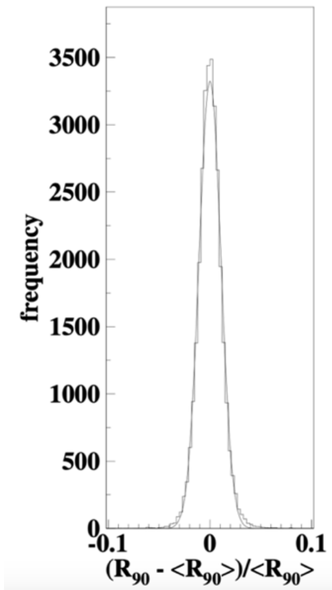

Fig. 3. Distribution of the percentage variations of R_{90} with respect to the mean values for all the detectors in the DAMA/LIBRA-phase2 (histogram) over the eight annual cycles; the superimposed curve is a gaussian fit.

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 results are obtained when comparing the *single-hit* residuals in the (1 – 6) keV with those in other energy intervals; for example, Fig. 4 shows the *single-hit* residuals in the (1 – 6) keV and the (10 – 20) keV energy regions, for the eight annual cycles of DAMA/LIBRA-phase2 as if they were collected in a single annual cycle. Moreover, Table 3 also shows the modulation amplitudes obtained by fitting the time behavior of the residual rates of the *single-hit* scintillation events in the (6 – 14) keV energy interval for the DAMA/LIBRA-phase2 annual cycles. In the fit, the phase and the period are at the values expected for a DM signal. The obtained amplitudes are compatible with zero.

Table 3.

DAMA/LIBRA-phase2 annual cycle	$A_{R_{90}}$, cpd/kg	$A_{(6-14)}$, cpd/kg/keV
2	(0.12 ± 0.14)	(0.0032 ± 0.0017)
3	–(0.08 ± 0.14)	(0.0016 ± 0.0017)
4	(0.07 ± 0.15)	(0.0024 ± 0.0015)
5	–(0.05 ± 0.14)	–(0.0004 ± 0.0015)
6	(0.03 ± 0.13)	(0.0001 ± 0.0015)
7	–(0.09 ± 0.14)	(0.0015 ± 0.0014)
8	–(0.18 ± 0.13)	–(0.0005 ± 0.0013)
9	(0.08 ± 0.14)	–(0.0003 ± 0.0014)

N o t e. Second column: modulation amplitudes, A_{R90}, obtained by fitting the time behavior of R_{90} in DAMA/LIBRA-phase2 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 σ) with modulation amplitudes of tens cpd/kg (see text). Third column: modulation amplitudes, $A_{(6-14)}$, obtained by fitting the time behavior of the residual rates of the *single-hit* scintillation events in the (6 – 14) keV energy interval; in the fit, the phase and the period are at the values expected for a DM signal, the obtained amplitudes are compatible with zero.

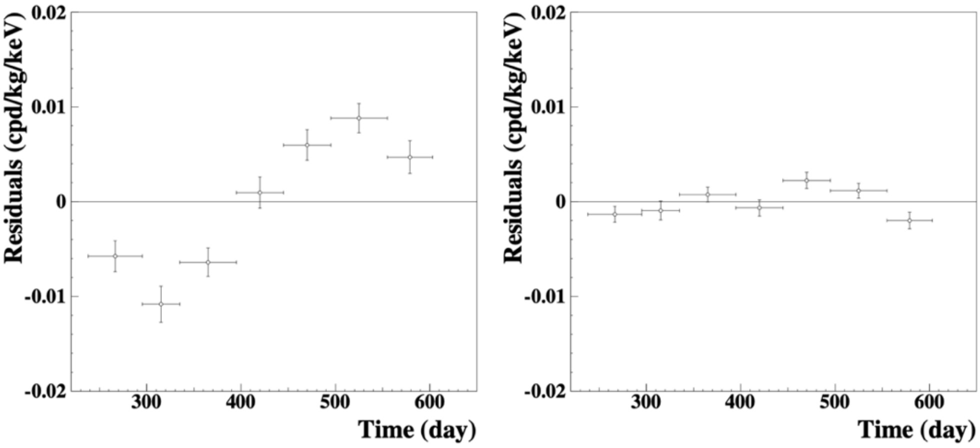

Fig. 4. Experimental *single-hit* residuals in the (1 – 6) keV and the (10 – 20) keV energy regions for DAMA/LIBRA-phase2 as if they were collected in a single annual cycle. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The initial time of the figures is taken on August 7th. A clear modulation satisfying all the peculiarities of the DM annual modulation signature is present in the lowest energy interval with A = (0.00956 ± 0.00090) cpd/kg/keV, while it is absent just above: A = (0.0007 ± 0.0005) cpd/kg/keV.

A further relevant investigation of DAMA/LIBRA-phase2 data has been performed by applying the same hardware and software procedures, used to acquire and analyze the *single-hit* residual rate, to the *multiple-hit* one. Since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just at the *single-hit* residual rate.

Thus, the comparison of the results of the *single-hit* events with those of the *multiple-hit* ones corresponds to comparing the cases of DM particles beam-on and beam-off. This procedure also allows an additional test of the background behaviour in the same energy interval where the positive effect is observed. In particular, in Fig. 5 the residual rates of the *single-hit* scintillation events collected during eight annual cycles of DAMA/LIBRA-phase2 are reported, as collected in a single cycle, together with the residual rates of the *multiple-hit* events, in the considered energy intervals.

While, as already observed, a clear modulation, satisfying all the peculiarities of the DM annual modulation signature, is present in the *single-hit* events, the fitted modulation amplitude for the *multiple-hit* residual rate is well compatible with zero: (0.00030 ± 0.00032) cpd/kg/keV in the (1 – 6) keV energy region. Thus, again evidence of annual modulation with proper features as required by the DM annual modulation signature is present in the *single-hit* residuals (events class to which the DM particle-induced events belong), while it is absent in the *multiple-hit* residual rate (event class to which only background events belong). Similar results were also obtained for the two last annual cycles of DAMA/NaI [36], for DAMA/LIBRA-phase1 [2 - 5], and for the first data release of DAMA/LIBRA-phase2 [20, 23]. Since the same identical hardware and the same identical software procedures have been used to analyze the two classes of events, the obtained result offers additional strong support for the presence of a DM particle component in the galactic halo.

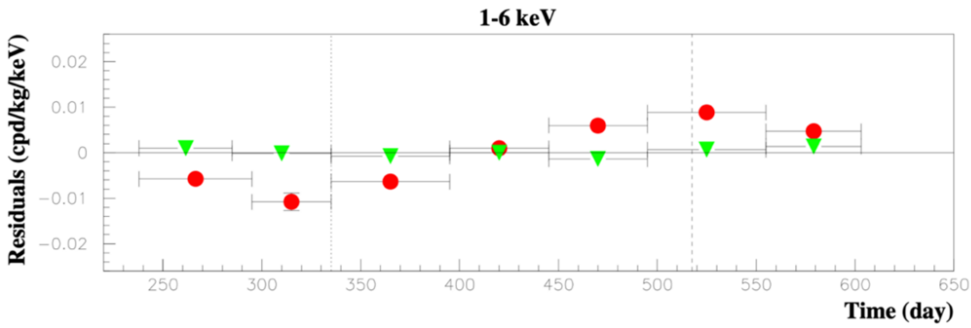

Fig. 5. Experimental residual rates of DAMA/LIBRA-phase2 *single-hit* events (filled red online circles), class of events to which DM events belong, and for *multiple-hit* events (filled green online triangles), class of events to which DM events do not belong. They have been obtained by considering for each class of events the data as collected in a single annual cycle and by using in both cases the same identical hardware and the same identical software procedures. The initial time of the figure is taken on August 7th. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. Analogous results were obtained for DAMA/NaI (two last annual cycles) and DAMA/LIBRA-phase1 [2 - 5, 36]. (See color Figure on the journal website.)

In conclusion, no background process able to mimic the DM annual modulation signature (that is, able to simultaneously satisfy all the peculiarities of the signature and account for the measured modulation amplitude) has been found or suggested by anyone throughout some decades thus far (see e.g., the discussions in Refs. [1 - 5, 7, 8, 19 - 21, 23, 34 - 36]).

5. The analysis of the frequency

In order to perform the Fourier analysis of the data of DAMA/LIBRA-phase1 and of the present eight annual cycles of DAMA/LIBRA-phase2 in a wider region of considered frequency, the *single-hit* events have been grouped in 1-day bins. Due to the low statistics in each time bin, the procedure detailed in Ref. [64] has been applied. On the left of Fig. 6 the whole power spectra up to the Nyquist frequency is shown and, on the right, the zoomed ones: a clear peak corresponding to a period of 1 yr is evident for the lowest energy interval, while the same analysis in the (6 – 14) keV energy region shows only aliasing peaks, instead. Neither other structure at different frequencies has been observed. To derive the significance of the peaks in the periodogram, one can remind that the periodogram ordinate, z, at each frequency follows a simple exponential distribution e^{-z} in case of null hypothesis or white noise [65]. Thus, if M independent frequencies are scanned, the probability to obtain values larger than z is: $P(>z) = 1 - (1 - e^{-z})^M$; in general, M depends on the number of sampled frequencies, on the number of data points N, and on their detailed spacing. It turns out that $M \simeq N$ when the data points are approximately equally spaced and when the sampled frequencies cover the frequency range from 0 to the Nyquist one [66, 67]. In the present case, the number of data points used to obtain the spectra in Fig. 6 is N = 5047 (days measured over the 5479 days of the 15 DAMA/LIBRA-phase1 and phase2 annual cycles) and the full frequencies region up to Nyquist one has been scanned. Thus, assuming $M = N$, the significance levels P = 0.10, 0.05 and 0.01, corresponding to peaks with heights larger than z = 10.8, 11.5, and 13.1, respectively, in the spectra of Fig 6. Below 6 keV a signal is present; thus, the signal must be included to properly evaluate the C.L. This has been done by a dedicated Monte-Carlo procedure where many similar experiments have been simulated. The 90 % C.L. region (shaded, green online), where all the peaks are expected to fall for the (2 – 6) keV energy interval, is also reported there; several peaks, the satellite of the one-year period frequency, are present.

In addition, for each annual cycle of DAMA/LIBRA-phase1 and phase2, the annual baseline counting rates have been calculated for the (2 – 6) keV energy interval; their power spectrum in the frequency range (0.00013 - 0.0019) d^{-1} (corresponding to a period range 1.4 - 21.1 yr) has been calculated according to Ref. [5]. No statistically significant peak is present at frequencies lower than 1 yr^{-1}; this implies that no evidence for a long-term modulation in the counting rate is present.

Finally, the case of the (1 – 6) keV energy interval of the present DAMA/LIBRA-phase2 data is reported in Fig. 6 bottom. As previously, the only significant peak is the one corresponding to a one-year period; no other peak is statistically significant being below the shaded (green online) area obtained by the Monte-Carlo procedure.

In conclusion, apart from the peak corresponding to a 1-year period, no other peak is statistically significant either in the low and high energy regions.

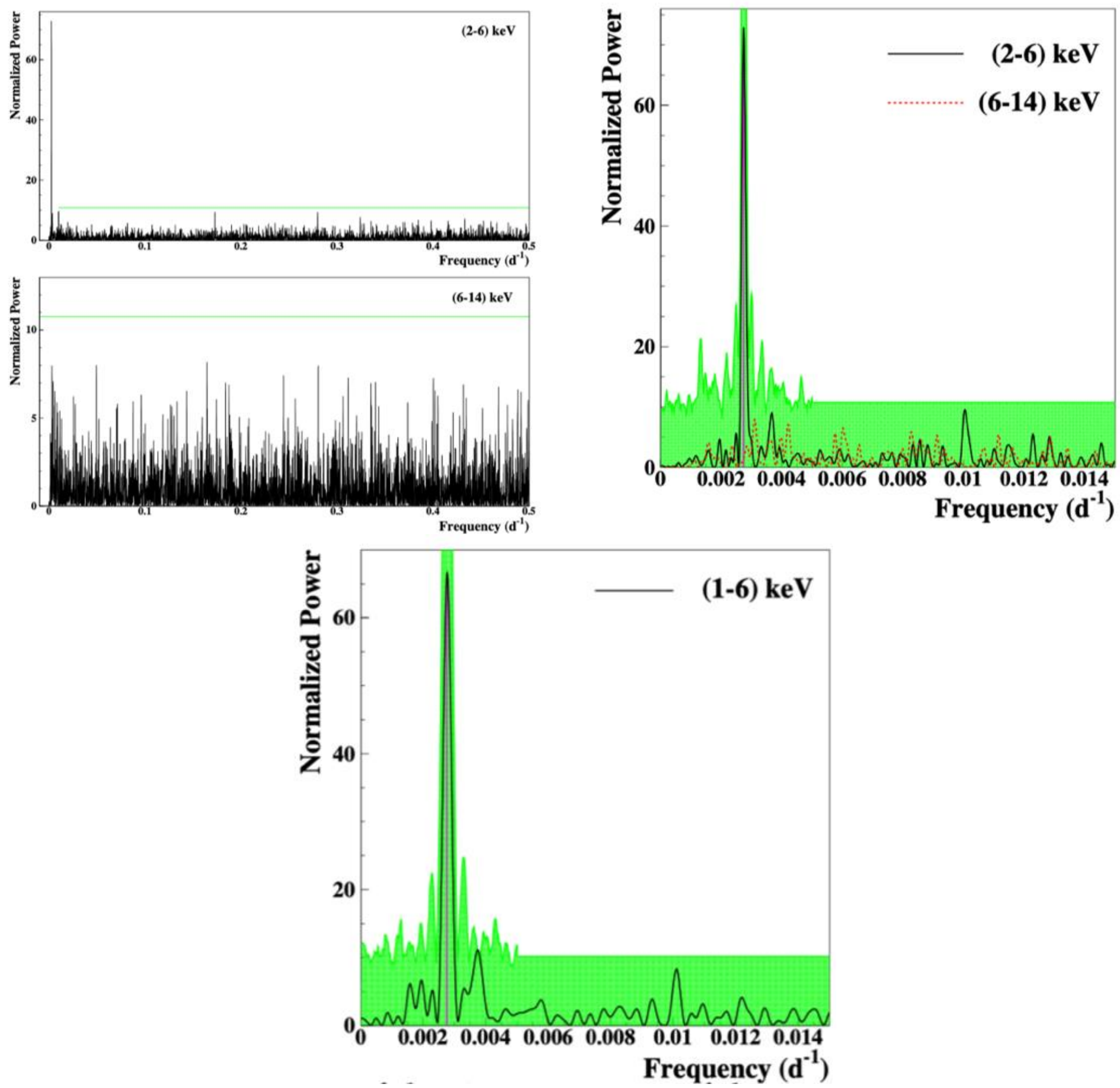

Fig. 6. *Top left:* Power spectra of the time sequence of the measured *single-hit* events for DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 grouped in 1-day bins up to the Nyquist frequency for (2 – 6) keV and (6 – 14) keV energy intervals. *Top right*: their zoom around the 1 yr^{-1} peak, for (2 – 6) keV (solid line) and (6 – 14) keV (dotted line) energy intervals. The main mode present at the lowest energy interval corresponds to a frequency of $2.74 \cdot 10^{-3}$ d^{-1} (vertical line, purple online). It corresponds to a period of $\simeq$ 1 yr. A similar peak is not present in the (6 – 14) keV energy interval. The shaded (green online) area in the *top-right* figure – calculated by Monte-Carlo procedure – represents the 90 % C.L. region where all the peaks are expected to fall for the (2 – 6) keV energy interval. In the frequency range far from the signal for the (2 – 6) keV energy region and for the whole (6 – 14) keV spectrum, the upper limit of the shaded region (90 % C.L.) can be calculated to be 10.8 (continuous lines, green online). *Bottom:* Power spectrum of the time sequence of the measured *single-hit* events in the (1 – 6) keV energy interval for DAMA/LIBRA-phase2 grouped in 1-day bin. The main mode present at the lowest energy interval corresponds to a frequency of $2.77 \cdot 10^{-3}$ d^{-1} (vertical line, purple online). It corresponds to a period of $\simeq$ 1 yr. The shaded (green online) area – calculated by the Monte-Carlo procedure – represents the 90 % C.L. region where all the peaks are expected to fall for the (1 – 6) keV energy interval. (See color Figure on the journal website.)

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 fixed period and phase: T = 1 yr and t_0 = 152.5 d. For this purpose, the likelihood function of the *single-hit* experimental data in the k–th energy bin is defined as:

$$L_k = \prod_{ij} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!},$$

where: N_{ijk} is 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. N_{ijk} follows a Poisson's distribution with expectation value:

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

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, ϵ_{jk} is the overall efficiency. The signal, S_{ik}, can be written as: $S_{0,k} + S_{m,k} \cos \omega(t_i - t_0)$, where $S_{0,k}$ is the constant part of the signal and $S_{m,k}$ is the modulation amplitude, averaged in the *k-th* energy bin. The usual procedure is to minimize the function $y_k = -2\ln(L_k) - const$ for each energy bin; the free parameters of the fit are the $(b_{jk} + S_{0,k})$ contributions and the $S_{m,k}$ parameter. In the following, the *k*-index will be omitted for simplicity.

In Fig. 7 the modulation amplitudes for the whole data sets: DAMA/NaI, DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2 (total exposure 2.86 t·yr) are plotted; the data below 2 keV refer only to the DAMA/LIBRA-phase2 exposure (1.53 t·yr). It can be inferred that a positive signal is present in the (1 – 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 $\chi^2/d.o.f.$ = 20.3/16 (P-value = 21 %).

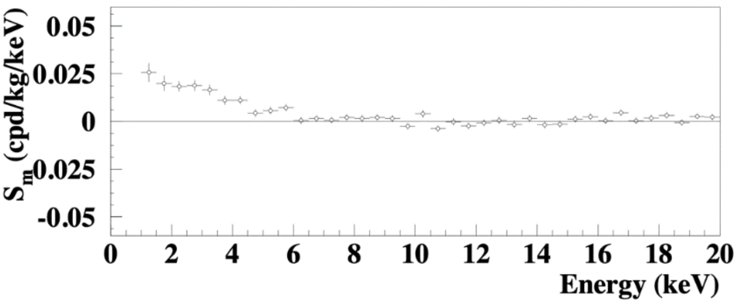

Fig. 7. Modulation amplitudes, S_m, for the whole data sets: DAMA/NaI, DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 (total exposure: 2.86 t·yr) above 2 keV; below 2 keV only the DAMA/LIBRA-phase2 exposure (1.53 t·yr) is available and used. The energy bin ΔE is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6 – 20) keV energy interval have random fluctuations around zero with $\chi^2/d.o.f.$ equal to 42.2/28 (P-value is 4 %).

For the case of (6 – 20) keV energy interval, one gets: $\chi^2/d.o.f.$ = 42.2/28 (P-value = 4 %); 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 14 and 23 %.

This method also allows the determination of $S_m(E)$ for each detector. In particular, the modulation amplitudes $S_m(E)$ integrated in the range (2 – 6) keV for each of the 25 detectors for the DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 periods can be produced. They have random fluctuations around the weighted average confirmed by the χ^2 analysis. Thus, the hypothesis that the signal is well distributed over all the 25 detectors is accepted. As previously done for the other data releases [2 - 5, 19 - 21, 23], $S_m(E)$ for each detector for each annual cycle and for each energy bin has been obtained. The S_m values are expected to follow a normal distribution in absence of any systematic effects. Thus, the variable $x = (S_m - \langle S_m \rangle)/\sigma$ has been considered to verify that the S_m values are statistically well distributed in the 16 energy bins (ΔE = 0.25 keV) in the (2 – 6) keV energy interval of the seven DAMA/LIBRA-phase1 annual cycles and in the 20 energy bins in the (1 – 6) keV energy interval of the eight DAMA/LIBRA-phase2 annual cycles, and in each detector. Here, σ are the errors associated with S_m, and $\langle S_m \rangle$ are the mean values of the S_m averaged over the detectors and the annual cycles for each considered energy bin. Defining $\chi^2 = \Sigma x^2$, where the sum is extended over all the 272 (192 for the 16th detector [4]) x values, $\chi^2/d.o.f.$ values ranging from 0.8 to 2.0 are obtained, depending on the detector. The mean value of the 25 $\chi^2/d.o.f.$ is 1.092, slightly larger than 1. Although this can be still ascribed to statistical fluctuations, let us ascribe it to possible systematics. In this case, one would derive an additional error to the modulation amplitude measured below 6 keV: $\leq 2.4 \cdot 10^{-4}$ cpd/kg/keV, if combining quadratically the errors, or $\leq 3.6 \cdot 10^{-5}$ cpd/kg/keV, if linearly combining them. This possible additional error: ≤ 2.4 % or ≤ 0.4 %, respectively, on the DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 modulation amplitudes, is an upper limit of possible systematic effects.

Among further additional tests, the analysis of the modulation amplitudes as a function of the energy separately for the nine inner detectors and the remaining external ones has been carried out for

DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2, as already done for the other data sets [2 - 5, 19 - 21, 23]. The obtained values are fully in agreement; in fact, the hypothesis that the two sets of modulation amplitudes belong to the same distribution has been verified by χ^2 test, obtaining e.g.: $\chi^2/d.o.f.$ = 1.9/6 and 36.1/38 for the energy intervals (1 – 4) keV and (1 – 20) keV, respectively (ΔE = 0.5 keV). This shows that the effect is also well shared between inner and outer detectors.

Moreover, to test the hypothesis that the amplitudes, singularly calculated for each annual cycle of DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2, are compatible and normally fluctuating around their mean values, the χ^2 test has been performed together with another independent statistical test: the *run test* (see e.g., Ref. [68]), which verifies the hypothesis that the positive (above the mean value) and negative (under the mean value) data points are randomly distributed. Both tests accept at 95 % C.L. the hypothesis that the modulation amplitudes are normally fluctuating around the best fit values.

7. Investigation of the annual modulation phase

Finally, let us release the assumption of the phase value at t_0 = 152.5 d in the procedure to evaluate the modulation amplitudes, writing the signal as:

$$S_i(E) = S_0(E) + S_m(E)\cos\omega(t_i - t_0) + Z_m(E)\sin\omega(t_i - t_0)$$

$$= S_0(E) + Y_m(E)\cos\omega(t_i - t^*). \qquad (1)$$

For signals induced by DM particles one should expect: i) $Z_m(E) \sim 0$ (because of the orthogonality between the cosine and the sine functions); ii) $S_m(E) \simeq Y_m(E)$; iii) $t^* \simeq t_0$ = 152.5 d. In fact, these conditions hold for most of the dark halo models; however, as mentioned above, slight differences can be expected in the case of possible contributions from non-thermalized DM components (see e.g., Refs. [38, 58, 59, 61 - 63]).

Considering cumulatively the data of DAMA/NaI, DAMA/LIBRA-phase1, and present DAMA/LIBRA-phase2, the obtained 2σ contours in the plane (S_m, Z_m) for the (2 – 6) keV and (6 – 14) keV energy intervals are shown in Fig. 8, *left*, while the obtained 2σ contours in the plane (Y_m, t^*) are depicted in Fig. 8, *right*. Moreover, Fig. 8 also shows the 2σ contours in the (1 – 6) keV energy interval only for DAMA/LIBRA-phase2. The best fit values in the considered cases (1σ errors) for S_m versus Z_m and Y_m versus t^* are reported in Table 4.

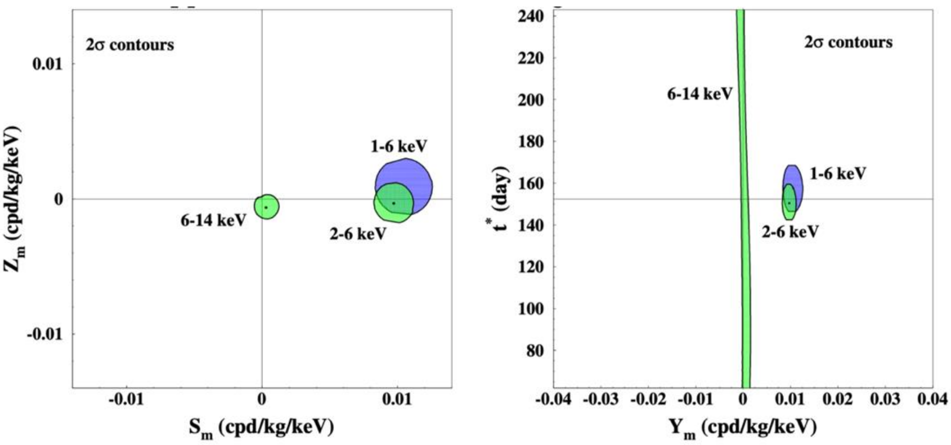

Fig. 8. 2σ contours in the plane (S_m, Z_m) (*left*) and in the plane (Y_m, t^*) (*right*) for: i) DAMA/NaI, DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2 in the (2 – 6) keV and (6 – 14) keV energy intervals (light areas, green online); ii) only DAMA/LIBRA-phase2 in the (1 – 6) keV energy interval (dark areas, blue online). The contours have been obtained by the maximum likelihood method. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM-induced signals. (See color Figure on the journal website.)

Table 4.

E, keV	S_m, cpd/kg/keV	Z_m, cpd/kg/keV	Y_m, cpd/kg/keV	t^*, d
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2:				
2 – 6	(0.0097 ± 0.0007)	–(0.0003 ± 0.0007)	(0.0097 ± 0.0007)	(150.5 ± 4.0)
6 – 14	(0.0003 ± 0.0005)	–(0.0006 ± 0.0005)	(0.0007 ± 0.0010)	undefined
DAMA/LIBRA-phase2:				
1 – 6	(0.0104 ± 0.0007)	(0.0002 ± 0.0007)	(0.0104 ± 0.0007)	(153.5 ± 4.0)

N o t e. Best fit values (1σ errors) for S_m versus Z_m and Y_m versus t^*, considering: i) DAMA/NaI, DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2 in the (2 – 6) keV and (6 – 14) keV energy intervals; ii) only DAMA/LIBRA-phase2 in the (1 – 6) keV energy interval. See also Fig. 8.

Finally, $Z_m(E)$ as a function of the energy has also been determined by using the same procedure and setting $S_m(E)$ in Eq. (1) to zero. The $Z_m(E)$ as a function of the energy for DAMA/NaI, DAMA/LIBRA- phase1, and DAMA/LIBRA-phase2 data sets are expected to be zero. The χ^2 test applied to the data supports the hypothesis that the Z_m values are simply fluctuating around zero; in fact, in the (1 – 20) keV energy region the $\chi^2/d.o.f.$ is equal to 40.6/38 corresponding to a P-value = 36 %.

The energy behaviors of $Y_m(E)$ and of phase t^* are also produced for the cumulative exposure of DAMA/NaI, DAMA/LIBRA-phase1, and DAMA/LIBRA-phase2; as in the previous analyses, an annual modulation effect is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. No modulation is present above 6 keV and the phase is undetermined.

8. Perspectives

To further increase the experimental sensitivity of DAMA/LIBRA and to disentangle some of the many possible astrophysical, nuclear, and particle physics scenarios in the investigation on the DM candidate particle(s), an increase of the exposure ($M{\cdot}t_{running}$, i.e., $t_{running}$ in our case at fixed M) in the lowest energy bin and a further decreasing of the software energy threshold are needed. This is pursued by running DAMA/LIBRA-phase2 and upgrading the experimental set-up to lower the software energy threshold below 1 keV with high acceptance efficiency.

Firstly, particular efforts for lowering the software energy threshold have preliminarily been done in the already-acquired data of DAMA/LIBRA-phase2 by using the same technique as before with dedicated studies on the efficiency. Consequently, a new data point has been added in the modulation amplitude as a function of energy down to 0.75 keV (Fig. 9), but with larger uncertainty; nevertheless, a modulation is also present below 1 keV, from 0.75 keV. This preliminary result confirms the relevance to lower the software energy threshold by a hardware upgrade, assuring high acceptance efficiency and improved statistics.

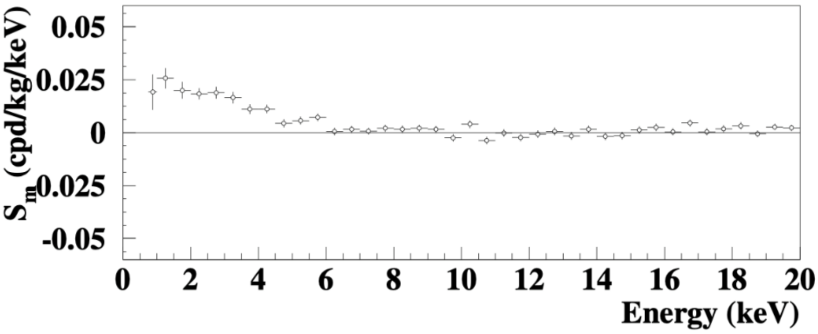

Fig. 9. The new data point below 1 keV, with a software energy threshold at 0.75 keV, shows that an annual modulation is also present below 1 keV but with larger uncertainty. This preliminary result confirms the relevance to lower the software energy threshold by a hardware upgrade, ensuring high acceptance efficiency and improved exposure.

This dedicated hardware upgrade of DAMA/LIBRA-phase2 is underway. It consists in equipping all the PMTs with miniaturized low background new concept preamplifiers and high voltage (HV) dividers mounted on the same socket, and related improvements of the electronic chain, mainly the use of higher vertical resolution 14-bit digitizers.

9. Conclusions

DAMA/LIBRA-phase2 confirms a peculiar annual modulation of the *single-hit* scintillation events in the (1 – 6) keV energy region satisfying all the many requirements of the DM annual modulation signature; the cumulative exposure by the former DAMA/NaI, DAMA/LIBRA-phase1 and the present DAMA/LIBRA-phase2 is 2.86 t·yr. As required by the exploited DM annual modulation signature: 1) the *single-hit* events show a clear cosine-like modulation as expected for the DM signal; 2) the measured period is well compatible with the 1 yr period as expected for the DM signal; 3) the measured phase is compatible with the roughly ≃ 152.5 d expected for the DM signal; 4) the modulation is present only in the low energy (1 – 6) keV interval and not in other higher energy regions, consistently with expectation for the DM signal; 5) the modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal; 6) the measured modulation amplitude in NaI(Tl) target of the *single-hit* scintillation events in the (2 - 6) keV energy interval, for which data are also available by DAMA/NaI and DAMA/LIBRA-phase1, is: (0.01014 ± 0.00074) cpd/kg/keV (13.7 σ C.L.). No systematic or side processes able to mimic the signature, i.e., able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude, has been found or suggested by anyone throughout some decades thus far (for details see e.g., Refs. [1 - 5, 7, 8, 19 - 23, 35, 36]). In particular, arguments related to any possible role of some natural periodical phenomena have been discussed and quantitatively demonstrated to be unable to mimic the signature (see e.g., Refs. [7, 8]). Thus, based on the exploited signature, the model-independent DAMA results give evidence at 13.7 σ C.L. (over 22 independent annual cycles and in various experimental configurations) for the presence of DM particles in the galactic halo based on the exploited DM signature.

The DAMA model-independent evidence is compatible with a wide set of astrophysical, nuclear, and particle physics scenarios for high and low mass candidates inducing nuclear recoil and/or electromagnetic radiation, as also shown in various literature. Moreover, both the negative results and all the possible positive hints, achieved so far in the field, can be compatible with the DAMA model-independent DM annual modulation results in many scenarios considering also the existing experimental and theoretical uncertainties; the same holds for indirect approaches. For a discussion see e.g., Ref. [5] and references therein.

The present newly released data determine the modulation parameters with increasing precision and will allow us to disentangle with larger C.L. among different DM candidates, DM models, and astrophysical, nuclear, and particle physics scenarios.

Finally, we stress that to efficiently disentangle among at least some of the many possible candidates and scenarios an increase of exposure in the new lowest energy bin and the decrease of the software energy threshold below the present 1 keV with high overall efficiency is important. The empowering of DAMA/LIBRA-phase2 is completed and DAQ and tests in the lower energy bins are in progress; a preliminary result below 1 keV is anyhow already given here based on dedicated software analyses of previous data.

REFERENCES

1. R. Bernabei et al. The DAMA/LIBRA apparatus. Nucl. Instrum. Methods A 592(3) (2008) 297.
2. R. Bernabei et al. First results from DAMA/LIBRA and the combined results with DAMA/NaI. Eur. Phys. J. C 56 (2008) 333.
3. R. Bernabei et al. New results from DAMA/LIBRA. Eur. Phys. J. C 67 (2010) 39.
4. R. Bernabei et al. Final model independent result of DAMA/LIBRA-phase1. Eur. Phys. J. C 73 (2013) 2648.
5. R. Bernabei et al. Dark Matter investigation by DAMA at Gran Sasso. Int. J. of Mod. Phys. A 28 (2013) 1330022.
6. R. Bernabei et al. Improved model-dependent corollary analyses after the first six annual cycles of DAMA/LIBRA-phase2. J. of Instr. 7 (2012) P03009.
7. R. Bernabei et al. No role for muons in the DAMA annual modulation results. Eur. Phys. J. C 72 (2012) 2064.
8. R. Bernabei et al. No role for neutrons, muons and solar neutrinos in the DAMA annual modulation results. Eur. Phys. J. C 74 (2014) 3196.
9. DAMA coll., issue dedicated to DAMA. Int. J. of Mod. Phys. A 31 (2016) and Refs. therein.
10. Model independent result on possible diurnal effect in DAMA/LIBRA-phase1. Eur. Phys. J. C 74 (2014) 2827.
11. R. Bernabei et al. New search for processes violating the Pauli exclusion principle in sodium and in iodine. Eur. Phys. J. C 62 (2009) 327.
12. R. Bernabei et al. Search for charge non-conserving processes in ^{127}I by coincidence technique. Eur. Phys. J. C 72 (2012) 1920.
13. R. Bernabei et al. New search for correlated e^+e^- pairs in the α decay of ^{241}Am. Eur. Phys. J. A 49 (2013) 64.
14. R. Bernabei et al. Investigating Earth shadowing effect with DAMA/LIBRA-phase1. Eur. Phys. J. C 75 (2015) 239.
15. P. Belli et al. Observations of annual modulation in direct detection of relic particles and light neutralinos. Phys. Rev. D 84 (2011) 055014.
16. A. Addazi et al. DAMA annual modulation effect and asymmetric mirror matter. Eur. Phys. J. C 75 (2015) 400.
17. R. Bernabei et al. The DAMA project. Int. J. of Mod. Phys. A 31 (2016) 1642009.
18. R. Cerulli et al. DAMA annual modulation and mirror Dark Matter. Eur. Phys. J. C 77 (2017) 83.
19. R. Bernabei et al. First Model Independent Results from DAMA/LIBRA-Phase2. Universe 4 (2018) 116.
20. R. Bernabei et al. First model independent results from DAMA/LIBRA-phase2. Nucl. Phys. At. Energy 19 (2018) 307.
21. R. Bernabei. New Model Independent Results from the First Six Full Annual Cycles of DAMA/LIBRA-phase2. Bled Workshops in Physics 19(2) (2018) 27.
22. R. Bernabei et al. Improved model-dependent corollary analyses after the first six annual cycles of DAMA/LIBRA-phase2. Nucl. Phys. At. Energy 20(4) (2019) 317.
23. R. Bernabei et al. The DAMA project: Achievements, implications and perspectives. Prog. Part. Nucl. Phys. 114 (2020) 103810.
24. R. Bernabei et al. The dark matter: DAMA/LIBRA and its perspectives. arXiv:2110.04734 [hep-ph].
25. R. Bernabei et al. New limits on WIMP search with large-mass low-radioactivity NaI(Tl) set-up at Gran Sasso. Phys. Lett. B 389 (1996) 757.
26. R. Bernabei et al. Searching for WIMPs by the annual modulation signature. Phys. Lett. B 424 (1998) 195.
27. R. Bernabei et al. On a further search for a yearly modulation of the rate in particle Dark Matter direct search. Phys. Lett. B 450 (1999) 448.
28. P. Belli et al. Extending the DAMA annual modulation region by inclusion of the uncertainties in astrophysical velocities. Phys. Rev. D 61 (2000) 023512.

29. R. Bernabei et al. Search for WIMP annual modulation signature: results from DAMA/NaI-3 and DAMA/NaI-4 and the global combined analysis. Phys. Lett. B 480 (2000) 23.
30. R. Bernabei et al. Investigating the DAMA annual modulation data in a mixed coupling framework. Phys. Lett. B 509 (2001) 197.
31. R. Bernabei et al. Investigating the DAMA annual modulation data in the framework of inelastic dark matter. Eur. Phys. J. C 23 (2002) 61.
32. P. Belli et al. Effect of the galactic halo modeling on the DAMA-NaI annual modulation result: An extended analysis of the data for weakly interacting massive particles with a purely spin-independent coupling. Phys. Rev. D 66 (2002) 043503.
33. R. Bernabei et al. Performances of the $\simeq$ 100 kg NaI(Tl) set-up of the DAMA experiment at Gran Sasso. Il Nuovo Cim. A 112 (1999) 545.
34. R. Bernabei et al. On the investigation of possible systematics in WIMP annual modulation search. Eur. Phys. J. C 18 (2000) 283.
35. R. Bernabei et al. Dark matter search. La Rivista del Nuovo Cimento 26(1) (2003) 1 and Refs. therein.
36. 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 and Refs. therein.
37. R. Bernabei et al. Investigating pseudoscalar and scalar dark matter. Int. J. Mod. Phys. A 21 (2006) 1445.
38. R. Bernabei et al. Investigating halo substructures with annual modulation signature. Eur. Phys. J. C 47 (2006) 263.
39. R. Bernabei et al. On electromagnetic contributions in WIMP quests. Int. J. Mod. Phys. A 22 (2007) 3155.
40. R. Bernabei et al. Possible implications of the channeling effect in NaI(Tl) crystals. Eur. Phys. J. C 53 (2008) 205.
41. R. Bernabei et al. Investigating electron interacting dark matter. Phys. Rev. D 77 (2008) 023506.
42. R. Bernabei et al. Investigation on light dark matter. Mod. Phys. Lett. A 23 (2008) 2125.
43. R. Bernabei et al. Search for non-paulian transitions in ^{23}Na and ^{127}I. Phys. Lett. B 408 (1997) 439.
44. P. Belli et al. New experimental limit on the electron stability and non-paulian transitions in Iodine atoms. Phys. Lett. B 460 (1999) 236.
45. R. Bernabei et al. Extended limits on neutral strongly interacting massive particles and nuclearites from NaI(Tl) scintillators. Phys. Rev. Lett. 83 (1999) 4918.
46. P. Belli et al. New limits on the nuclear levels excitation of ^{127}I and ^{23}Na during charge nonconservation. Phys. Rev. C 60 (1999) 065501.
47. R. Bernabei et al. Investigation on possible diurnal effects induced by dark matter particles. Il Nuovo Cimento A 112 (1999) 1541.
48. R. Bernabei et al. Search for solar axions by Primakoff effect in NaI crystals. Phys. Lett. B 515 (2001) 6.
49. F. Cappella et al. A preliminary search for Q-balls by delayed coincidences in NaI(Tl). Eur. Phys. J.-direct C 14 (2002) 1.
50. R. Bernabei et al. Search for spontaneous transition of nuclei to a superdense state. Eur. Phys. J. A 23 (2005) 7.
51. R. Bernabei et al. A search for spontaneous emission of heavy clusters in the ^{127}I nuclide. Eur. Phys. J. A 24 (2005) 51.
52. R. Bernabei, A. Incicchitti. Low background techniques in NaI(Tl) setups. Int. J. Mod. Phys. A 32 (2017) 1743007.
53. K.A. Drukier et al. Detecting cold dark-matter candidates. Phys. Rev. D 33 (1986) 3495.
54. K. Freese et al. Signal modulation in cold-dark-matter detection. Phys. Rev. D 37 (1988) 3388.
55. D. Smith, N. Weiner. Inelastic dark matter. Phys. Rev. D 64 (2001) 043502.
56. D. Tucker-Smith, N. Weiner. Status of inelastic dark matter. Phys. Rev. D 72 (2005) 063509.
57. D.P. Finkbeiner et al. Inelastic dark matter and DAMA/LIBRA: An experimentum crucis. Phys. Rev. D 80 (2009) 115008.
58. K. Freese et al. Detectability of weakly interacting massive particles in the Sagittarius dwarf tidal stream. Phys. Rev. D 71 (2005) 043516.
59. K. Freese et al. Effects of the Sagittarius dwarf tidal stream on dark matter detectors. Phys. Rev. Lett. 92 (2004) 111301.
60. P. Belli et al. The electronics and DAQ system in DAMA/LIBRA. Int. J. of Mod. Phys. A 31 (2016) 1642005.
61. P. Gondolo et al. DarkSUSY 4.00 neutralino dark matter made easy. New Astron. Rev. 49 (2005) 193.
62. G. Gelmini, P. Gondolo. Weakly interacting massive particle annual modulation with opposite phase in late-infall halo models. Phys. Rev. D 64 (2001) 023504.
63. F.S. Ling, P. Sikivie, S. Wick. Diurnal and annual modulation of cold dark matter signals. Phys. Rev. D 70 (2004) 123503.
64. G. Ranucci, M. Rovere. Periodogram and likelihood periodicity search in the SNO solar neutrino data. Phys. Rev. D 75 (2007) 013010.
65. J.D. Scargle. Studies in astronomical time series analysis. II - Statistical aspects of spectral analysis of unevenly spaced data. Astrophys. J. 263 (1982) 835.
66. W.H. Press et al. *Numerical recipes in Fortran 77: The Art of Scientific Computing* (Cambridge, England, Cambridge University Press, 1992) Section 13.8.
67. J.H. Horne, S.L. Baliunas. A Prescription for Period Analysis of Unevenly Sampled Time Series. Astrophys. J. 302 (1986) 757.
68. W.T. Eadie et al. *Statistical Methods in Experimental Physics* (American Elsevier Pub., 1971).

Р. Бернабей[1,2,*], П. Беллі[1,2], А. Буссолотті[1,2], В. Караччіоло[1,2], Ф. Капелла[3,4], Р. Черуллі[1,2], Ц. Ж. Дай[5], А. д'Анджело[3,4], Н. Феррарі[1,2], А. Інчікітті[3,4], А. Леончіні[1,2], І. Х. Ма[5], А. Маттей[3,4], В. Мерло[1,2], Ф. Монтеккі[1,2,6], І. Д. Шенг[5], З. П. Йе[5,7]

[1] *Фізичний факультет, Римський університет «Тор Вергата», Рим, Італія*
[2] *Національний інститут ядерної фізики, відділення у Римі «Тор Вергата», Рим, Італія*
[3] *Фізичний факультет, Римський університет «Ла Сапієнца», Рим, Італія*
[4] *Національний інститут ядерної фізики, відділення у Римі, Рим, Італія*
[5] *Ключова лабораторія астрофізики частинок, Інститут фізики високих енергій, Китайська академія наук, Пекін, КНР*
[6] *Факультет цивільної інженерії та інформатики, Римський університет «Тор Вергата», Рим, Італія*
[7] *Університет Цзінганшань, Цзянь, Цзянси, КНР*

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

НОВІ РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТУ DAMA/LIBRA-phase2 ТА ПЕРСПЕКТИВИ

Дані, зібрані установкою DAMA/LIBRA-phase2 протягом двох додаткових річних циклів, були проаналізовані з метою подальшого дослідження модельно-незалежного ефекту річних модуляцій, що давно спостерігаються в експерименті DAMA глибоко під землею в Національній лабораторії Гран-Сассо I.N.F.N. за допомогою різних експериментальних конфігурацій. Враховуючи нові результати, загальна статистика DAMA/LIBRA-phase2 протягом 8 річних циклів становить 1,53 т·рік, і сигнал, який відповідає всім вимогам модельно-незалежної річної сигнатури темної матерії, спостерігається на рівні 11,8 σ в області енергій (1 – 6) кеВ. В інтервалі енергій (2 – 6) кеВ, де також доступні дані з DAMA/NaI і DAMA/LIBRA-phase1, досягнута повна експозиція 2,86 т·рік, і рівень спостереження сигналу становить 13,7 σ. Жодна систематика чи побічна реакція, здатна імітувати виміряний сигнал (тобто врахувати виміряну амплітуду модуляції та одночасно задовольнити всі вимоги сигнатури темної матерії) не була знайдена протягом 30 років історії експерименту DAMA. Наведено також попередній результат по подальшому зниженню енергетичного порога (за допомогою програмного забезпечення) та перспективи.

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

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