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First Model Independent Results from DAMA/LIBRA–Phase2

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Abstract: The first results obtained by the DAMA/LIBRA–phase2 experiment are presented. The data have been collected over six independent annual cycles corresponding to a total exposure of 1.13 ton $\times$ year, deep underground at the Gran Sasso National Laboratory. The DAMA/LIBRA–phase2 apparatus, about 250 kg highly radio-pure NaI(Tl), profits from a second generation high quantum efficiency photomultipliers and of new electronics with respect to DAMA/LIBRA–phase1. The improved experimental configuration has also allowed to lower the software energy threshold. The DAMA/LIBRA–phase2 data confirm the evidence of a signal that meets all the requirements of the model independent Dark Matter annual modulation signature, at 9.5 σ C.L. in the energy region (1–6) keV. In the energy region between 2 and 6 keV, where data are also available from DAMA/NaI and DAMA/LIBRA–phase1, the achieved C.L. for the full exposure (2.46 ton $\times$ year) is 12.9 σ.

Keywords: dark matter; low background NaI(Tl) scintillators; model-independent annual modulation signature

1. Introduction

The DAMA project aims at the investigation of rare processes by developing and using low background scintillators, such as NaI(Tl) detectors exploited for the investigation of Dark Matter (DM) particles in the galactic halo. The pioneer DAMA/NaI set-up [1–19] and the successor DAMA/LIBRA set-up [1,20–36] have been investigating DM particles through the DM model-independent annual modulation signature [37,38] with increasing sensitivities.

This signature is due to the Earth's revolution around the Sun which is moving in the Galaxy. Thus, a larger flux of DM particles crossing the Earth is expected around $\simeq$2 June, while a smaller one is expected around ≃2 December, depending on the composition of Earth orbital velocity and the Sun velocity with respect to the Galaxy. This signature for DM is a powerful tool because of many requirements that have to be simultaneously satisfied: (i) the rate must contain a component modulated according to a cosine function; (ii) with one year period; and (iii) a phase peaked roughly around ≃2 June (3); (iv) this modulation should be present only in a well-defined low energy range, where DM particle induced events can be present; (v) it applies 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; (vi) in the region of maximal sensitivity the modulation amplitude must be ≃7% for usually adopted halo distributions, but it can be larger (even up to ≃30%) for some cases, such as e.g., those of Ref. [39–43]. Therefore, many DM candidates, interaction types and scenarios can be explored. Only systematic effects or side reactions accounting for the measured modulation amplitude and satisfying all the peculiarities of the signature could mimic it, but none are available [1,3–5,20–23,26,30,31,36].

The DAMA/LIBRA apparatus and all the related features and procedures of *phase1* are fully described e.g., in Ref. [1,20–23]. In particular, the residual internal contaminations have been discussed in Ref. [20]. At the end of 2010, the upgrade of DAMA/LIBRA towards the *phase2* started. All of the photomultipliers (PMTs) were replaced by second generation Hamamatsu PMTs (Hamamatsu City, Japan), model R6233MOD, with higher quantum efficiency (Q.E.) and with lower background with respect to those used in *phase1*; they were produced after a dedicated R&D in the company, tests and selections [25,44]. The new PMTs have Q.E. in the range 33–39% at 420 nm, wavelength of NaI(Tl) emission, and in the range 36–44% at peak. The commissioning of the experiment was successfully performed in 2011, allowing the achievement of the software energy threshold at 1 keV, and the improvement of some detector's features such as energy resolution and acceptance efficiency near software energy threshold. The adopted procedure for noise rejection near the software energy threshold has been discussed in Ref. [25]; in particular, the procedure has been the same along all the data taking, throughout the months and the annual cycles. The overall efficiency for *single-hit* events as a function of the energy is also reported in Ref. [25].

In *phase2*, a range from 6 to 10 photoelectrons/keV is obtained for the light response of the 25 detectors. Calibrations with X-rays/γ sources are periodically performed down to the keV energy region in the same running condition [20,36]. In addition, double coincidences accumulated over long periods (from internal X-rays produced by ^{40}K, present at ppt levels in the crystals) give a 3.2 keV calibration point proximal to the software energy threshold. The data acquisition system (DAQ) acquires 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 DAMA/LIBRA–Phase2 Results

The details of the new DAMA/LIBRA–phase2 data are reported in Table 1. The first annual cycle was dedicated to the commissioning and to the optimizations towards the achievement of the 1 keV software energy threshold [25]. Thus, the considered annual cycles of DAMA/LIBRA–phase2 are six (exposure of 1.13 ton × year). The cumulative exposure, including the former DAMA/NaI and DAMA/LIBRA–phase1, is 2.46 ton × year.

The total number of events collected for the energy calibrations during DAMA/LIBRA–phase2 is about 1.3×10^8, while about 3.4×10^6 events/keV have been collected [36] for the evaluation of the acceptance window efficiency for noise rejection near the software energy threshold [20,25]. The duty cycle of the experiment is rather high (see Table 1), ranging between 76% and 85%; it is mainly affected by the routine calibrations and, in particular, by the data collection for the acceptance windows efficiency. The same procedures already adopted for the DAMA/LIBRA–phase1 [1,20–23] have been exploited in the analysis of DAMA/LIBRA–phase2 [36]; the main ones are reported in the following.

Table 1. Details about the annual cycles of DAMA/LIBRA–phase2. 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 live time of the data taking and $t_0 = 152.5$ day, i.e., 2 June); thus, the variance of the cosine, $(\alpha - \beta^2)$, is $\simeq 0.5$ for a detector being operational evenly throughout the year.

DAMA/LIBRA–Phase2 Annual Cycle	Period	Mass (kg)	Exposure (kg × day)	$(\alpha - \beta^2)$
1	23 December 201–9 September 2011		commissioning of *phase2*	
2	2 November 2011–11 September 2012	242.5	62,917	0.519
3	8 October 2012–2 September 2013	242.5	60,586	0.534
4	8 September 2013–1 September 2014	242.5	73,792	0.479
5	1 September 2014–9 September 2015	242.5	71,180	0.486
6	10 September 2015–24 August 2016	242.5	67,527	0.522
7	7 September 2016–25 September 2017	242.5	75,135	0.480
DAMA/LIBRA–phase2	2 November 2011–25 September 2017		411,137 ≃ 1.13 ton × year	0.502
DAMA/NaI + DAMA/LIBRA–phase1 + DAMA/LIBRA–phase2:			2.46 ton × year	

The former DAMA/LIBRA–phase1 and the new DAMA/LIBRA–phase2 residual rates of the *single-hit* scintillation events are reported in Figure 1 from 2 keV, the software energy threshold of DAMA/LIBRA–phase1, up to 6 keV. The residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part, as described in Refs. [1,4,5,21–23]. The null modulation hypothesis is rejected at very high Confidence Level by χ^2 test: $\chi^2/d.o.f.$ = 199.3/102, corresponding to *p*-value = 2.9×10^{-8}.

The residual rates versus time for 1 keV energy threshold are reported in Ref. [36]. The *single-hit* residual rates shown in Figure 1 and those of DAMA/NaI have been fitted with the function: $A\cos\omega(t-t_0)$, considering a period $T = \frac{2\pi}{\omega} = 1$ year and a phase $t_0 = 152.5$ day (2 June) as expected by the DM annual modulation signature. The $\chi^2/d.o.f.$ is equal to 113.8/138 and a modulation amplitude $A = (0.0102 \pm 0.0008)$ cpd/kg/keV is obtained [36].

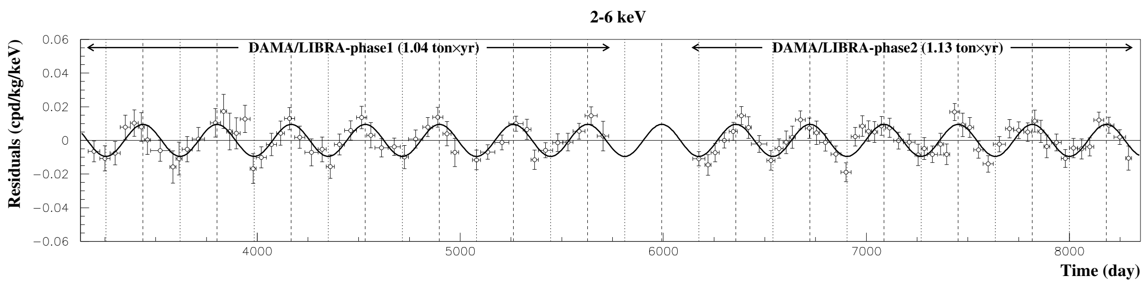

Figure 1. Residual rate for *single-hit* scintillations measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy interval. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ year, a phase $t_0 = 152.5$ day (2 June) and modulation amplitude, A, equal to the central value obtained by best fit on the data points of DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2.

Keeping the period and the phase free in the fit, the achieved C.L. for the full exposure (2.46 ton × year) is 12.9 σ; the modulation amplitude of the *single-hit* scintillation events is: (0.0103 ± 0.0008) cpd/kg/keV, the measured phase is (145 ± 5) days and the measured period is (0.999 ± 0.001) year, all of these values are well in agreement with those expected for DM particles.

Thus, the DAMA/LIBRA–phase2 data confirm the evidence of a signal that meets all the peculiarities of the model independent DM annual modulation signature. No systematics or side reactions have been found able to mimic the exploited DM signature (i.e., to account for the whole measured modulation amplitude and to simultaneously satisfy all the requirements of the signature).

No background modulation has been observed in the energy regions above 6 keV. For example, the measured rate integrated above 90 keV, R_{90}, as a function of the time has been analysed [1,23,36]; similar results are obtained in other energy regions. This analysis holds for whatever kind of background; moreover, as mentioned, there is no background process able to satisfy all the peculiarities of the annual modulation signature and to account for the measured modulation amplitude (see, e.g., also Ref. [1,20–23,26,30]).

A further notable investigation on DAMA/LIBRA–phase2 data was done—as already performed on the two last annual cycles of DAMA/NaI and on the whole DAMA/LIBRA–phase1 [1,5,21–23]—by applying to the *multiple-hit* residual rate[1] the same hardware and software procedures used to acquire and to analyse the *single-hit* ones. Since the probability that a DM particle interacts in more than one detector is negligible, a DM signal is expected only in the *single-hit* residual rate. Therefore, comparing *single-hit* and *multiple-hit* results is equivalent to comparing the cases of DM particles beam-on and beam-off. In this way, a further test is possible on the background behaviour in the same energy range in which the positive effect is observed.

Figure 2 shows the residual rates of the *single-hit* scintillation events of DAMA/LIBRA–phase2, as collected in a single cycle, and the residual rates of the *multiple-hit* events, in the (1–6) keV energy range. A clear modulation, satisfying all the peculiarities of the DM annual modulation signature, is present in the *single-hit* events, while the fitted modulation amplitude for the *multiple-hit* residual rate is very compatible with zero: (0.0004 ± 0.0004) cpd/kg/keV. Thus, again, evidence of annual modulation with the proper peculiarities of the exploited 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 [5] and for DAMA/LIBRA–phase1 [1,21–23]. The two classes of events were analysed through the same hardware and software procedures; this offers an additional strong support for the presence of a DM particle component in the galactic halo.

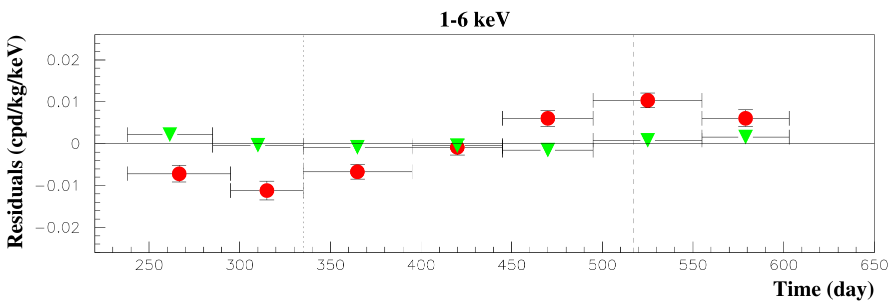

Figure 2. Experimental residual rates of DAMA/LIBRA–phase2 *single-hit* events (circles), class of events to which DM events belong, and for *multiple-hit* events (filled triangles), class of events to which DM events do not belong. For each class of events, the data were considered as collected in a single annual cycle; in both cases, the same hardware and software procedures have been applied. The time scale is the same as the previous DAMA papers for consistency. The experimental points present the errors as vertical bars and the widths of the associated time bins as horizontal bars. Analogous results were obtained for DAMA/NaI (two last annual cycles) and for DAMA/LIBRA–phase1 [1,5,21–23].

In conclusion, no background that can mimic the exploited DM signature, simultaneously accounting for the measured modulation amplitude and satisfying all the peculiarities of the signature, has been found or suggested by anyone throughout some decades thus far (see, e.g., in Ref. [1,20–23,26,31,36]).

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1 An event is considered multiple if a deposition of energy occurs in coincidence in more than one detector of the set-up. In DAMA/LIBRA the multiplicity can, in principle, range from 2 to 25. A multiple event in a given energy interval, say (1–6) keV, is given by an energy deposition between 1 and 6 keV in one detector and other deposition(s) in other detector(s).

The *single-hit* residuals were also investigated by Fourier analysis. Figure 3 shows the power spectra of DAMA/LIBRA–phase1 and phase2 in the (2–6) keV energy interval (*left* panel) and only of DAMA/LIBRA–phase2 in the (1–6) keV energy interval (*right* panel). The analysis procedure is detailed in Ref. [36]. An evident peak corresponding to a period of one year is present in the low energy region; only aliasing peaks are instead present in the (6–14) keV energy region. No structures were observed at different frequencies (see also Ref. [36]).

The annual modulation measured at low energy can also be highlighted by studying as a function of energy the modulation amplitude, S_m, obtained by maximum likelihood method fixing $T = 1$ year and $t_0 = 152.5$ day. In particular, the likelihood function of the *single-hit* experimental data in the k-th energy bin is defined as: $\mathbf{L_k} = \mathbf{\Pi}_{ij} e^{-\mu_{ijk}} \frac{\mu_{ijk}^{N_{ijk}}}{N_{ijk}!}$, 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, and ϵ_{jk} is the overall efficiency. The signal can be written as $S_{i,k} = S_{0,k} + S_{m,k} \cdot \cos \omega (t_i - t_0)$, where $S_{0,k}$ is the constant part of the signal and $S_{m,k}$ is the modulation amplitude. The usual procedure is to minimize the function $y_k = -2ln(\mathbf{L_k}) - const$ for each energy bin; the free parameters of the fit are the $(b_{jk} + S_{0,k})$ contributions and the $S_{m,k}$ parameter. Hereafter, the index k is omitted for simplicity.

The modulation amplitudes for the whole data sets: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 (total exposure 2.46 ton $\times$ year) are plotted in Figure 4; the data below 2 keV refer only to the DAMA/LIBRA–phase2 exposure (1.13 ton $\times$ year). It can be deduced that the positive signal is present in the (1–6) keV energy range, while S_m values compatible with zero are present just above. All this confirms the previous analyses. The test of the hypothesis that the S_m values in the (6–14) keV energy range have random fluctuations around zero yields χ^2 equal to 19.0 for 16 $d.o.f.$ (upper tail probability of 27%).

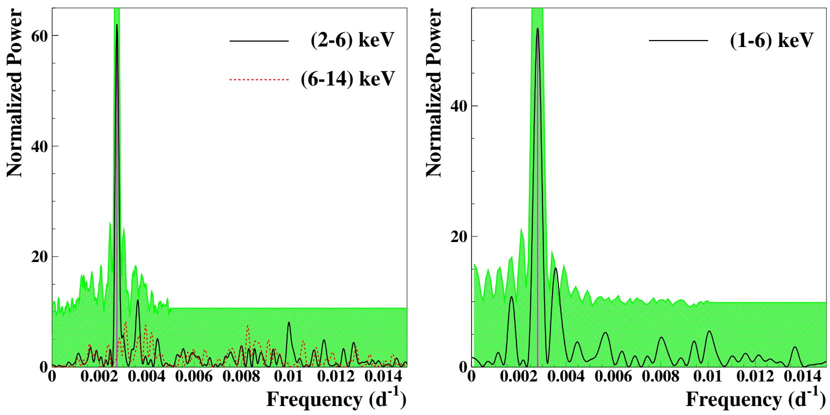

Figure 3. Power spectra of the time sequence of the measured *single-hit* events for DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 grouped in one day bins around the 1 y^{-1} peak, for (2–6) keV (solid line) and (6–14) keV (dotted line) energy intervals (left panel) and for only DAMA/LIBRA–phase2 in the (1–6) keV energy interval (right panel). The main mode present at the lowest energy interval corresponds to a frequency of 2.74×10^{-3} day^{-1} (left panel) and 2.79×10^{-3} day^{-1} (right panel), vertical line, purple online. It corresponds to a period of $\simeq$ 1 year. A similar peak is not present in the (6–14) keV energy interval. The shaded (green online) area in the bottom 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 and (1–6) keV energy intervals. In the frequency range far from the signal for the (2–6) keV and (1–6) keV energy regions and for the whole (6–14) keV spectrum, the upper limit of the shaded region (90% C.L.) can be calculated to be 10.6 (continuous lines, green online).

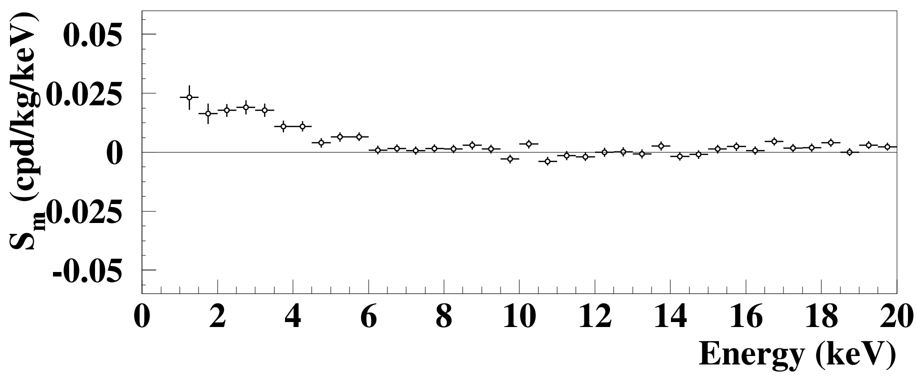

Figure 4. Modulation amplitudes, S_m, for the whole data sets: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 (total exposure 2.46 ton × year) above 2 keV; below 2 keV only the DAMA/LIBRA-phase2 exposure (1.13 ton × year) is available and used. The energy bin ΔE is 0.5 keV. A modulation is evident in the lowest energy interval, and only S_m's compatible with zero are present just above. In particular, the S_m have random fluctuations around zero in (6–20) keV energy region with χ^2 equal to 42.6 for 28 $d.o.f.$ (upper tail probability of 4%); see text for comments.

For the case of (6–20) keV, energy interval $\chi^2/d.o.f. = 42.6/28$ (upper tail probability of 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 11% and 25%.

As already done for the other data releases [1,21–23,34], the observed annual modulation effect has been verified to be well distributed in all the 25 detectors. In particular, the modulation amplitudes S_m integrated in the range (2–6) keV for each of the 25 detectors for the DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 periods are reported in Figure 5. They have random fluctuations around the weighted averaged value (shaded band) confirmed by the $\chi^2/d.o.f.$ equal to 23.9/24. Other approaches are described in Ref. [36]. Thus, the hypothesis that the signal is well distributed over all the 25 detectors is accepted.

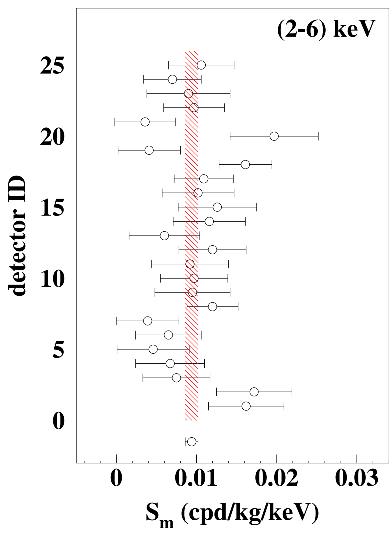

Figure 5. Modulation amplitudes S_m integrated in the range (2–6) keV for each of the 25 detectors for the DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 periods. The errors are at 1σ confidence level. The weighted averaged point and 1σ band (shaded area) are also reported. The χ^2 is 23.9 over 24 $d.o.f.$, supporting the hypothesis that the signal is well distributed over all the 25 detectors.

In addition, the modulation amplitudes were calculated for DAMA/LIBRA–phase2 separately for the nine inner detectors and the sixteen external ones, as already done for the other data sets [1,21–23]. The obtained values are fully in agreement; in particular, it has been verified by χ^2 test that the two sets of modulation amplitudes, as a function of the energy, belong to same distribution, obtaining e.g., $\chi^2/d.o.f.$ = 2.5/6 and 40.8/38 for the energy intervals (1–4) and (1–20) keV, respectively (ΔE = 0.5 keV). Thus, the annual modulation effect is well shared between inner and outer detectors.

The hypothesis that the modulation amplitudes singularly calculated for each annual cycle of DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 are compatible and normally fluctuating around their mean values has been tested by χ^2 and *run test* [36]. It confirms the hypothesis that the data collected in all the annual cycles with DAMA/LIBRA–phase1 and phase2 are statistically compatible and can be analyzed together [36].

Finally, if the assumption of the phase $t_0 = 152.5$ day is released in the procedure to evaluate the modulation amplitudes, the signal can be written as:

$$\begin{aligned} S_{ik} &= S_{0,k} + S_{m,k} \cos\omega(t_i - t_0) + Z_{m,k} \sin\omega(t_i - t_0) \\ &= S_{0,k} + Y_{m,k} \cos\omega(t_i - t^*). \end{aligned} \quad (1)$$

For DM, one should expect: (i) $Z_{m,k} \sim 0$ (because of the orthogonality between the cosine and the sine functions); (ii) $S_{m,k} \simeq Y_{m,k}$; (iii) $t^* \simeq t_0 = 152.5$ day. In fact, these conditions hold for most of the dark halo models, even if slight differences are expected for possible contributions from non-thermalized DM components (see, e.g., Ref. [15,42,43,45–47]).

The allowed 2σ contours in the plane (S_m, Z_m) for the (2–6) keV and (6–14) keV energy ranges are shown in Figure 6—left, while the allowed 2σ contours in the plane (Y_m, t^*) are depicted in Figure 6—right; here, DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 are considered all together. Moreover, Figure 6 also shows only for DAMA/LIBRA–phase2 the 2σ contours in the (1–6) keV energy interval.

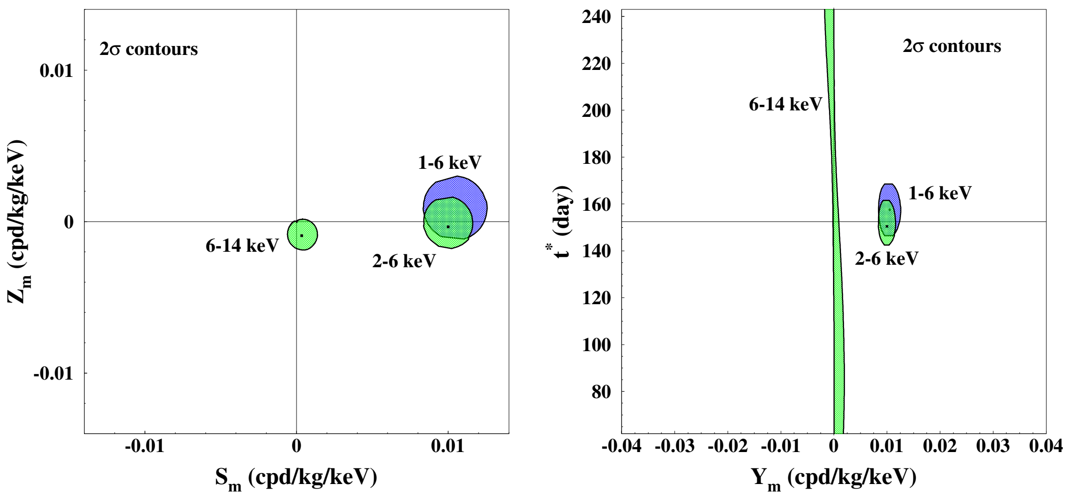

Figure 6. 2σ contours in the plane (S_m, Z_m) (left) and in the plane (Y_m, t^*) (right) for: (i) DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV and (6–14) keV energy ranges (light areas, green online); (ii) only DAMA/LIBRA–phase2 in the (1–6) keV energy interval (dark areas, blue online). The contours are obtained by maximum likelihood method. A modulation amplitude is found in the lower energy ranges and the phase agrees with the expectation for DM induced signals.

The best fit values are reported in Ref. [36]; for example, in the (2–6) keV energy range, they are: $S_m = (0.0100 \pm 0.0008)$ cpd/kg/keV, $Z_m = -(0.0003 \pm 0.0008)$ cpd/kg/keV and $Y_m = (0.0100 \pm 0.0008)$ cpd/kg/keV, $t^* = (150.5 \pm 5.0)$ day, respectively [36]. Thus, a modulation amplitude is present in the lower energy range and the phase agrees with the expectation for DM induced signals.

Finally, the Z_m can also be worked out by the same procedure under the hypothesis that S_m is zero in Equation (1). The Z_m's are reported as a function of the energy for DAMA/NaI, DAMA/LIBRA–phase1, and DAMA/LIBRA–phase2 data sets in Ref. [36]; they are expected to be zero. The χ^2 test applied to the data supports such hypothesis; in fact, in the (1–20) keV energy region, the $\chi^2/d.o.f.$ is equal to 44.5/38 corresponding to a p-value = 22%.

No modulation has been found in any possible source of systematics or side reactions; therefore, cautious upper limits on possible contributions to the DAMA/LIBRA measured modulation amplitude have been obtained (see Ref. [3–5,21–23,26,31]). They do not account for the measured modulation amplitudes, and also are not able to simultaneously satisfy all the many requirements of the signature; similar analyses were also performed for the DAMA/NaI data [4,5].

As an example, we report the results obtained in Ref. [26,31], where a quantitative study is reported on why neutrons, muons and solar neutrinos are not able to give any significant contribution to the DAMA annual modulation results and cannot mimic this signature. Table 2 summarizes the safety upper limits on the contributions to the observed modulation amplitude due to the total neutron flux at LNGS, either from (α, n) reactions, from fissions and from muons' and solar-neutrinos' interactions in the rocks and in the lead around the experimental set-up; the direct contributions of muons and solar neutrinos are reported there too.

Table 2. Contributions to the total neutron flux at Laboratori Nazionali del Gran Sasso (LNGS); the value, $\Phi^{(n)}_{0,k}$, the relative modulation amplitude, η_k, and the phase, t_k, of each component are reported. It is also reported the counting rate, $R_{0,k}$, in DAMA/LIBRA–phase2 for *single-hit* events, in the $(1-6)$ keV energy region induced by neutrons, muons and solar neutrinos, detailed for each component. The modulation amplitudes, A_k, are reported as well, while the last column shows the relative contribution to the annual modulation amplitude observed by DAMA/LIBRA–phase2, $S_m^{exp} \simeq 0.011$ cpd/kg/keV. For details, see Ref. [31] and references therein.

	Source	$\Phi^{(n)}_{0,k}$ (Neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)	$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2}-10^{-1}$ eV)	1.08×10^{-6}	$\simeq 0$ however $\ll 0.1$	–	$<8 \times 10^{-6}$	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV–keV)	2×10^{-6}	$\simeq 0$ however $\ll 0.1$	–	$<3 \times 10^{-3}$	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1–10 MeV)	$\simeq 0.9 \times 10^{-7}$	$\simeq 0$ however $\ll 0.1$	–	$<6 \times 10^{-4}$	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock (>10 MeV)	$\simeq 3 \times 10^{-9}$	0.0129	end of June	$\ll 5 \times 10^{-4}$	$\ll 7 \times 10^{-6}$	$\ll 6 \times 10^{-4}$
	$\mu \to$ n from Pb shield (>10 MeV)	$\simeq 6 \times 10^{-9}$	0.0129	end of June	$\ll 1.1 \times 10^{-3}$	$\ll 1.4 \times 10^{-5}$	$\ll 1.3 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$	0.03342 *	4 January *	$\ll 5 \times 10^{-5}$	$\ll 1.8 \times 10^{-6}$	$\ll 1.6 \times 10^{-4}$
	direct μ	$\Phi^{(\mu)}_0 \simeq 20$ μm^{-2}d^{-1}	0.0129	end of June	$\simeq 10^{-7}$	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}$ ν cm^{-2}s^{-1}	0.03342 *	4 January *	$\simeq 10^{-5}$	3×10^{-7}	3×10^{-5}

* The annual modulation of solar neutrino is due to the different Sun–Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

Finally, let us comment about the possibility that the radioactive ^{37}Ar could play any role as described in Ref. [48]. ^{37}Ar decays by electron capture with half-life of 35 days emitting characteristic X-rays or Auger electrons with total energy below 2.8 keV. Firstly, let us remind that: (i) each NaI(Tl) bare crystal was tightly enveloped in Tetratec-teflon foils and encapsulated in low radioactivity freshly electrolyzed copper housing (1 mm thick) in controlled atmosphere; therefore, any significant presence of Ar inside the Cu housing is excluded; (ii) the HPN$_2$, fluxed in the sealed Cu box housing the detectors, is a N5.5 gas (<5 ppm impurities) stored underground for a long time before using; (iii) any contribution to the DAMA signal from ^{37}Ar possibly present in the HPN_2 gas among the detectors is excluded: the probability for a 2.8 keV photon to survive 1 mm Cu housing is $\approx 10^{-342}$. In addition, even if we assume that: (i) HPN_2 gas may leak in the sealed 1.5 mm gap (actually filled by Tetratec-teflon) between the copper housing and the bare crystal (but this hypothesis is absurd considering that whatever micro-crack destroys the detector features); (ii) <5 ppm contamination of ^{nat}Ar (as in the atmosphere) is present in the HPN_2 gas; (iii) the detection efficiency of the 2.8 keV photons from ^{37}Ar "among" Teflon (MFP = 0.016 mm) is 0.3%; (iv) a hypothetical annual variation of the ^{37}Ar activity is 25% and with proper features as for DM, arbitrarily without any reason; one would expect modulation amplitude <4 $\times 10^{-9}$ cpd/kg/keV in the low energy region from ^{37}Ar, that is <4 $\times$ 10^{-7} fraction of the observed signal. In conclusion, any possible role of ^{37}Ar in the DAMA results is excluded.

No systematic effects or side reactions able to simultaneously satisfy all the requirements of the exploited DM signature and to account for the whole observed modulation amplitude have been found; related arguments are discussed in Ref. [1,3–5,20–23,26,30,31,34,36].

3. Implications and Comparisons

The long-standing annual-modulation evidence observed by the DAMA experiments is model-independent, i.e., without any a priori assumption of theoretical interpretations about the identity of the DM particle and its interactions. It can be related to a variety of interaction mechanisms of DM particles with the detector materials and is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle physics (see e.g., Ref. [1,4,5,14–19,21,34] and references therein, and recently e.g., Ref. [33,35,49]). Additional literature is available on the topics (see e.g., in Ref. [1]) and many possibilities are open.

No other experiment exists, whose result can be—at least in principle— directly compared in a model-independent way with those by DAMA experiments. On the other hand, 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. [1] and references therein.

4. Conclusions

The data of the new DAMA/LIBRA–phase2 further confirm a peculiar annual modulation of the *single-hit* scintillation events in the (1–6) keV energy region which satisfies all the many requirements of the DM exploited signature; the cumulative exposure by the former DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 is 2.46 ton $\times$ year.

As required by the investigated 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 equal to (0.999 ± 0.001) year well compatible with the 1-year period as expected for the DM signal; (3) the measured phase (145 ± 5) days is compatible with the roughly $\simeq$ 152.5 days expected for the DM signal; (4) the modulation is present only in the (1–6) keV low energy range 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 of the *single-hit* scintillation events in the (2–6) keV energy range (where data are available also by DAMA/NaI and DAMA/LIBRA—phase1) is in NaI(Tl) target: (0.0103 ± 0.0008) cpd/kg/keV (12.9 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 over some decades thus far. Thus, on the basis of the exploited signature, the model independent DAMA results give evidence at 12.9σ C.L. (over 20 independent annual cycles and in various experimental configurations) for the presence of DM particles in the galactic halo.

Finally, we stress that, to efficiently disentangle at least some of the many possible candidates and scenarios, an increase of exposure in the new lowest energy bin is important. The experiment is collecting data and related R&D is under way.

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