Research Article

The Annual Modulation Signature for Dark Matter: DAMA/LIBRA-Phase1 Results and Perspectives

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The results obtained with the total exposure of 1.04 ton × yr collected by DAMA/LIBRA-phase1 deep underground at the Gran Sasso National Laboratory (LNGS) of the I.N.F.N. during 7 annual cycles are summarized. The DAMA/LIBRA-phase1 and the former DAMA/NaI data (cumulative exposure 1.33 ton × yr, corresponding to 14 annual cycles) give evidence at 9.3 σ C.L. for the presence of Dark Matter (DM) particles in the galactic halo, on the basis of the exploited model independent DM annual modulation signature by using highly radiopure NaI(Tl) target. The modulation amplitude of the *single-hit* events in the (2–6) keV energy interval is (0.0112 ± 0.0012) cpd/kg/keV; the measured phase is (144 ± 7) days and the measured period is (0.998 ± 0.002) yr; values are in a good well in agreement with those expected for DM particles. No systematic or side reactions able to mimic the exploited DM signature have been found or suggested by anyone over more than a decade. Some of the perspectives of the presently running DAMA/LIBRA-phase2 are outlined.

1. Introduction

The presently running DAMA/LIBRA [1–11] experiment, as the former DAMA/NaI [12–41], has the main aim to investigate the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature (originally suggested in [42, 43]). Moreover, the developed highly radiopure NaI(Tl) target-detectors [1] assure as well sensitivity to a wide range of DM candidates, interaction types, and astrophysical scenarios.

As a consequence of the Earth's revolution around the Sun, the Earth should be crossed by a larger flux of DM particles around ≃2 June and by a smaller one around ≃2 December. This DM annual modulation signature is very distinctive since the effect induced by DM particles must simultaneously satisfy all the following requirements: (1) the rate must contain a component modulated according to a cosine function (2) with one year period and (3) a phase that peaks roughly ≃2 June; (4) this modulation must only be found in a well-defined low energy range, where DM particle

induced events can be present; (5) 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; (6) the modulation amplitude in the region of maximal sensitivity must be ≃7% for usually adopted halo distributions (see, e.g., [8, 23, 24]), but it can be larger in case of some possible scenarios such as, for example, those in [44–48] (even up to ≃30%). Thus, this signature is model-independent, is very effective, and, in addition, it allows the test of a large range of cross sections and of halo densities.

This DM signature might be mimicked only by systematic effects or side reactions able to account for the whole observed modulation amplitude and to simultaneously satisfy all the requirements given above. No one is available [1–3, 7, 8, 22–24].

The full description of the DAMA/LIBRA setup during phase1 and other related arguments have been discussed in detail in [1–4, 8] and references therein. Here, we just remind the reader that the sensitive part of this setup is made of 25 highly radiopure NaI(Tl) crystal scintillators (5 rows by 5-column matrix) having 9.70 kg mass each one. 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 with two low background photomultipliers (PMTs) working in coincidence at single photoelectron level. The low background 9265-B53/FL and 9302-A/FL PMTs, developed by EMI-Electron Tubes with dedicated R&Ds, were used in the phase1; for details, see [1, 21, 23] and references therein. 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. A threefold-level sealing system prevents the detectors from being in contact with the environmental air of the underground laboratory [1]. The light response of the detectors during phase1 typically ranges from 5.5 to 7.5 photoelectrons/keV, depending on the detector. The hardware threshold of each PMT is at single photoelectron, while a software energy threshold of 2 keV electron equivalent (hereafter keV) is used [1, 21]. Energy calibration with X-rays/γ sources are regularly carried out in the same running condition down to few keV [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 (for details, see [1]). The radiopurity, the procedures, and details are discussed in [1–4, 8] and references therein.

2. The Results of DAMA/LIBRA-Phase1 and DAMA/NaI

The total exposure of DAMA/LIBRA-phase1 is 1.04 ton × yr in seven annual cycles; when including also that of the first generation DAMA/NaI experiment, it is 1.33 ton × yr,
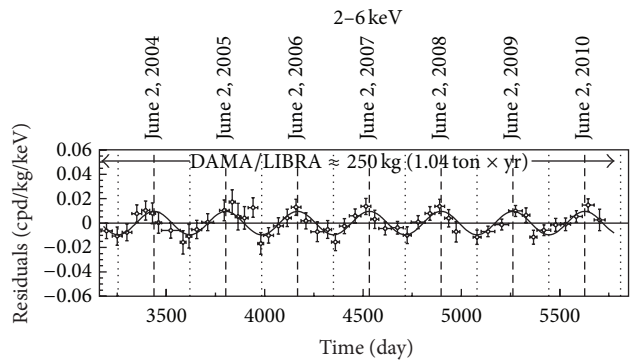

FIGURE 1: Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA-phase1 in the (2–6) keV energy interval as a function of the time. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the cosinusoidal functions behaviour A cos $\omega(t - t_0)$ with a period $T = 2\pi/\omega = 1$ yr, a phase $t_0 = 152.5$ day (June 2nd) and modulation amplitudes, A, equal to the central values obtained by best fit on the data points of the entire DAMA/LIBRA-phase1. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted vertical lines correspond to the minimum.

corresponding to 14 annual cycles. The variance of the cosine $(\alpha - \beta^2) = (\langle\cos^2\rangle - \langle\cos\rangle^2)$, where the averages $\langle\cdots\rangle$ are taken over the periods in which the data taking was on, is 0.518 during the DAMA/LIBRA-phase1, showing that the setup has been operational evenly throughout the years (the expectation value for full-year data taking is $(\alpha - \beta^2) = 0.5$). For details, see [2–4, 8].

The total number of events collected for the routine calibrations during the entire DAMA/LIBRA-phase1 is about 9.6×10^7, while about 3.5×10^6 events/keV have been collected for the evaluation of the acceptance window efficiency for noise rejection near energy threshold [1]. The duty cycle of the experiment is high [4]; the routine calibrations and, in particular, those related to the acceptance windows efficiency mainly affect it.

Figure 1 shows the time behaviour of the experimental residual rates of the *single-hit* scintillation events in the (2–6) keV energy interval for DAMA/LIBRA-phase1. The residuals of the DAMA/NaI data (0.29 ton × yr) are given in [2, 8, 23, 24]. We remind the reader that these residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part: $\langle r_{ijk} - \text{flat}_{jk}\rangle_{jk}$. Here, r_{ijk} is the rate in the considered ith time interval for the jth detector in the kth energy bin, while flat_{jk} is the rate of the jth detector in the kth energy bin averaged over the cycles; it is of order of ≲1 cpd/kg/keV [1, 2, 49]. The average is made on all the detectors (j index) and on all the energy bins (k index) which constitute the considered energy interval. The weighted mean of the residuals must obviously be zero over one cycle.

The χ^2 test excludes the hypothesis of absence of modulation in the data: $\chi^2/\text{d.o.f.} = 83.1/50$ and the P value is $P = 2.2 \times 10^{-3}$ for the (2–6) keV energy interval. When fitting

the *single-hit* residual rate of DAMA/LIBRA-phase1 (Figure 1) together with the DAMA/NaI ones, with the function, A cos $\omega(t - t_0)$, considering a period $T = 2\pi/\omega = 1$ yr and a phase $t_0 = 152.5$ day (June 2nd) as expected by the DM annual modulation signature, the following modulation amplitude is obtained: $A = (0.0110 \pm 0.0012)$ cpd/kg/keV corresponding to 9.2σ C.L. (χ^2 of the fit is 70.4 over 86 d.o.f.).

When the period and the phase are kept free in the fitting procedure, the modulation amplitude is (0.0112 ± 0.0012) cpd/kg/keV (9.3σ C.L.), the period $T = (0.998 \pm 0.002)$ year, and the phase $t_0 = (144 \pm 7)$ day. The period and the phase are well compatible with expectations for a 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 in case of possible contributions of nonthermalized DM components to the galactic halo, such as, for example, the SagDEG stream [26, 50–54] and the caustics [55]. For more details, see [4].

The modulation amplitudes singularly calculated for each annual cycle of DAMA/NaI and DAMA/LIBRA-phase1 are compatible among them and are normally fluctuating around their best fit values [2–4]. In particular, for the (2–6) keV energy interval, the χ^2 is 10.8 over 13 d.o.f. corresponding to an upper tail probability of 63%, while the *run test* yields a lower tail probability of 23%. This analysis confirms that the data collected in all the annual cycles with DAMA/NaI and DAMA/LIBRA-phase1 are statistically compatible and can be considered together, on the contrary of the statements in [56].

The DAMA/LIBRA-phase1 *single-hit* residuals of Figure 1 and those of DAMA/NaI have also been investigated by a Fourier analysis. The data analysis procedure has been described in detail in [8]. A clear peak corresponding to a period of 1 year (see Figure 2) is evident for the (2–6) keV energy interval; the same analysis in the (6–14) keV energy region shows instead only aliasing peaks. No other structure at different frequencies has been observed (see also [8]).

Absence of any other significant background modulation in the energy spectrum has been verified in energy regions not of interest for DM. (In fact, 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. Thus, if a modulation detected in the lowest energy region was 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.) For example, the measured rate integrated above 90 keV, R_{90}, as a function of the time has been analysed [4]. Similar result is obtained when comparing the *single-hit* residuals in the (2–6) keV with those in other energy intervals; for example, Figure 3 shows the *single-hit* residuals in the (2–6) keV and in the (6–14) keV energy regions for the entire DAMA/LIBRA-phase1 data as if they were collected in a single annual cycle (i.e., binning in the variable time from the Jan 1st of each annual cycle). It is worth noting that the obtained results account for whatever kind of background and, in
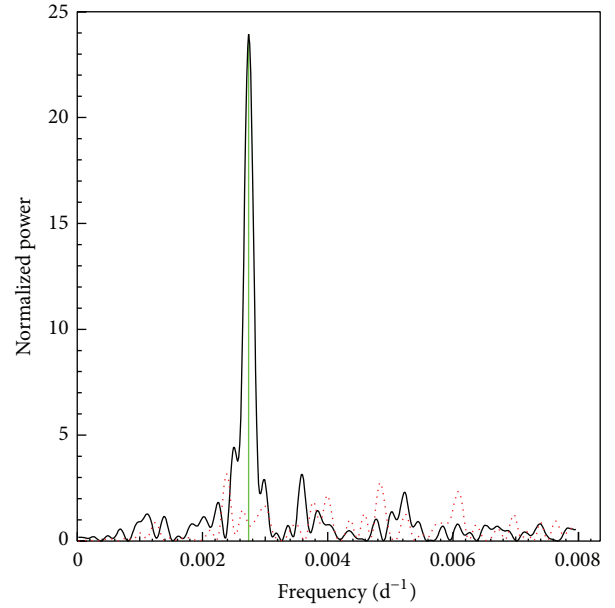

Figure 2: Power spectrum of the measured *single-hit* residuals in the (2–6) keV (solid lines) and (6–14) keV (dotted lines) energy intervals calculated according to [8], including also—as usual in DAMA analyses—the treatment of the experimental errors and of the time binning. The data refer to DAMA/NaI and DAMA/LIBRA-phase1. As it can be seen, the principal mode present in the (2–6) keV energy interval corresponds to a frequency of 2.737×10^{-3} d^{-1} (vertical lines), corresponding to a period of ≃1 year. A similar peak is not present in the (6–14) keV energy interval.

addition, 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) is available (see also discussions, for example, in [1–4, 7, 8, 49, 57–62]).

A further relevant investigation in the DAMA/LIBRA-phase1 data has been performed by applying the same hardware and software procedures, used to acquire and to analyse the *single-hit* residual rate, to the *multiple-hit* one. (A *multiple-hit* event is defined when more scintillating pulses arrive within a time window of about 600 ns.) In fact, since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just in the *single-hit* residual rate. Thus, the comparison of the results of the *single-hit* events with those of the *multiple-hit* ones corresponds practically to compare between them 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 Figure 4, the residual rates of the *single-hit* events measured over the DAMA/LIBRA-phase1 annual cycles are reported, as collected in a single cycle, together with the residual rates of the *multiple-hit* events, in the (2–6) keV energy interval. 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: $-(0.0005 \pm 0.0004)$ cpd/kg/keV
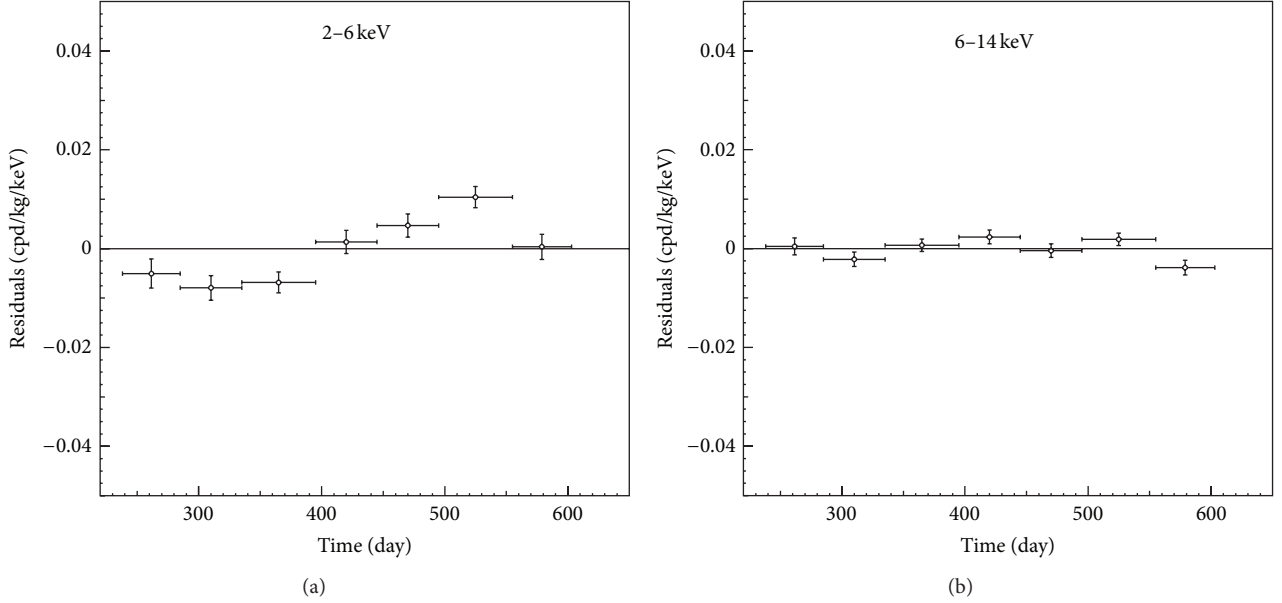
(a)

(b)

FIGURE 3: Experimental *single-hit* residuals in the (2–6) keV and in the (6–14) keV energy regions for the entire DAMA/LIBRA-phase1 data as if they were collected in a single annual cycle (i.e., binning in the variable time from the Jan 1st of each 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 at August 7th. A clear modulation satisfying all the peculiarities of the DM annual modulation signature is present in the lowest energy interval with $A = (0.0088 \pm 0.0013)$ cpd/kg/keV, while it is absent just above $A = (0.00032 \pm 0.00076)$ cpd/kg/keV.
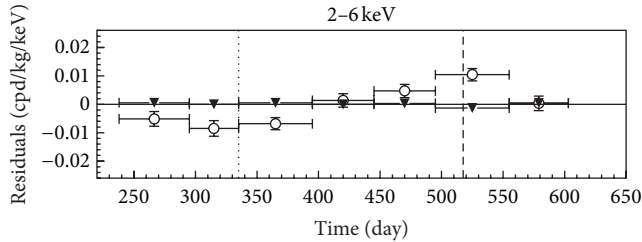

FIGURE 4: Experimental residual rates of DAMA/LIBRA-phase1 *single-hit* events (open circles), class of events to which DM events belong, and, for *multiple-hit* events (filled triangles), class of events to which DM events do not belong. They have been obtained by considering for each class of events 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 the DAMA/NaI data [24].

in the energy region (2–6) keV. 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 last two annual cycles of the DAMA/NaI experiment [24]. Since the same identical hardware and the same identical software procedures have been used to analyse the two classes of events, the obtained

result offers an additional strong support for the presence of a DM particle component in the galactic halo.

The annual modulation present at low energy can also be pointed out by depicting—as a function of the energy—the modulation amplitude, $S_{m,k}$, obtained by maximum likelihood method over the data considering $T = 1$ yr and $t_0 = 152.5$ day. For such purpose, the likelihood function of the *single-hit* experimental data in the kth energy bin is defined as $\mathbf{L_k} = \mathbf{\Pi}_{ij} e^{-\mu_{ijk}} (\mu_{ijk}^{N_{ijk}} / N_{ijk}!)$, where N_{ijk} is the number of events collected in the ith time interval (hereafter 1 day), by the jth detector and in the kth energy bin. N_{ijk} follows a Poisson's distribution with expectation value $\mu_{ijk} = [b_{jk} + S_{ik}] M_j \Delta t_i \Delta E \epsilon_{jk}$. The b_{jk} are the background contributions, M_j is the mass of the jth detector, Δt_i is the detector running time during the ith time interval, ΔE is the chosen energy bin, ϵ_{jk} is the overall efficiency (for details, see, e.g., [1]). Moreover, the signal can be written as $S_{ik} = S_{0,k} + S_{m,k} \cdot \cos \omega(t_i - t_0)$, 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 $y_k = -2 \ln(\mathbf{L_k})$ − 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.

In Figure 5, the obtained S_m are shown in each considered energy bin (there $\Delta E = 0.5$ keV) when the data of DAMA/NaI and DAMA/LIBRA-phase1 are considered. It can be inferred that positive signal is present in the (2–6) keV energy interval, 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 χ^2 equal to 35.8 for 28

TABLE 1: Best fit values for the (2–6) and (6–14) keV energy intervals (1σ errors) for S_m versus Z_m and Y_m versus t^*, considering the cumulative exposure of DAMA/NaI and DAMA/LIBRA-phase1. See also Figure 6.

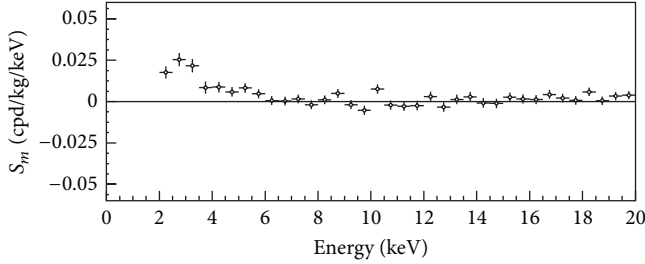| E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t^* (day)
2–6	(0.0106 ± 0.0012)	$-(0.0006 \pm 0.0012)$	(0.0107 ± 0.0012)	(149.5 ± 7.0)
6–14	(0.0001 ± 0.0007)	(0.0000 ± 0.0005)	(0.0001 ± 0.0008)	Undefined

FIGURE 5: S_m variable as a function of the energy for the total cumulative exposure 1.33 ton × yr. The energy bin 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 χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability of 15%).

degrees of freedom (upper tail probability of 15%). All this confirms the previous analyses.

As described in [2–4, 8], the observed annual modulation effect is well distributed in all the 25 detectors at 95% C.L.

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 the entire DAMA/LIBRA-phase1. The obtained values are fully in agreement; in fact, the hypothesis that the two sets of modulation amplitudes as a function of the energy belong to the same distribution has been verified by χ^2 test, obtaining χ^2/d.o.f. = 3.9/4 and 8.9/8 for the energy intervals (2–4) and (2–6) keV, respectively ($\Delta E = 0.5$ keV). This shows that the effect is also well shared between inner and outer detectors.

Let us, finally, release the assumption of a phase $t_0 = 152.5$ day in the procedure to evaluate the modulation amplitudes. In this case, the signal can be written as

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

For signals induced by DM particles, one should expect the following: (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; however, as mentioned above, slight differences can be expected in case of possible contributions from nonthermalized DM components, such as, for example, the SagDEG stream [26, 50–54] and the caustics [55].

Considering cumulatively the data of DAMA/NaI and DAMA/LIBRA-phase1 (exposure 1.33 ton × yr) 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 Figure 6(a), while in Figure 6(b) the obtained 2σ contours in the plane (Y_m, t^*) are depicted. The best fit values for the (2–6) and (6–14) keV energy intervals (1σ errors) for S_m versus Z_m and Y_m versus t^* are reported in Table 1.

Finally, setting S_m in (1) to zero, the Z_m values as function of the energy have also been determined by using the same procedure. The values of Z_m as a function of the energy is reported in Figure 7; they 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, for example, in the (2–14) keV and (2–20) keV energy region the χ^2/d.o.f. are equal to 23.0/24 and 46.5/36 (probability of 52% and 11%), respectively.

The behaviour of the phase t^* variable as function of energy is shown in Figure 8 for the cumulative exposure of DAMA/NaI and DAMA/LIBRA-phase1 (1.33 ton × yr). No modulation is present above 6 keV and the phase is undetermined.

Sometimes naive statements were put forward as the fact that, in nature, several phenomena may show some kind of periodicity. It is worth noting that the point is whether they might mimic the annual modulation signature in DAMA/LIBRA (and former DAMA/NaI), that is, whether they might be not only quantitatively able to account for the observed modulation amplitude but also able to contemporaneously satisfy all the requirements of the DM annual modulation signature. The same is also for side reactions. This has already been deeply investigated in [1–4] and references therein; the arguments and the quantitative conclusions, presented there, also apply to the entire DAMA/LIBRA-phase1 data. Additional arguments can be found in [7, 8, 49, 57–62].

Firstly, in order to continuously monitor the running conditions, several pieces of information are acquired with the production data and quantitatively analysed. In particular, all the time behaviour of the running parameters, acquired with the production data, have been investigated. Table 2 shows the modulation amplitudes obtained for each annual cycle when fitting the time behaviour of the values of the main parameters including a cosine modulation with the same phase and period as for DM particles. As can be seen, all the measured amplitudes are well compatible with zero.

No modulation has been found in any possible source of systematics or side reactions; thus, cautious upper limits (90% C.L.) on possible contributions to the DAMA/LIBRA measured modulation amplitude are summarized in Table 3 (also see [2–4]). It is worth noting that they do not quantitatively account for the measured modulation amplitudes and also are
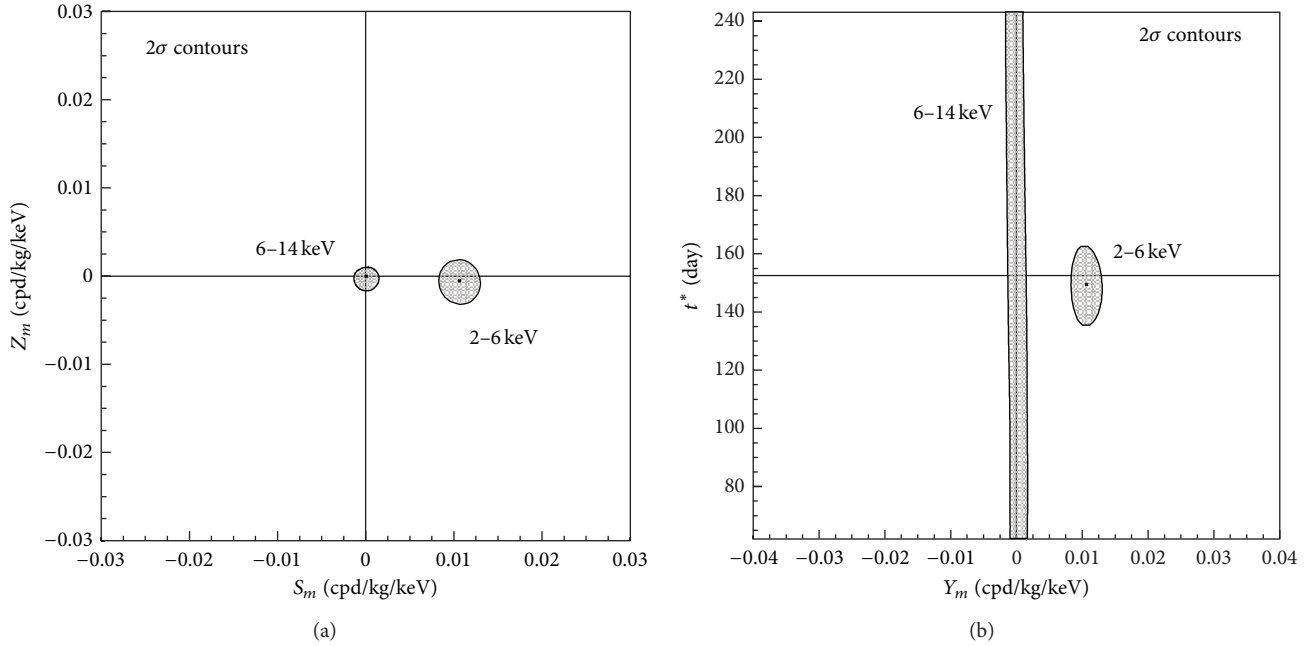
(a)

(b)

FIGURE 6: 2σ contours in the plane (S_m, Z_m) (a) and in the plane (Y_m, t^*) (b) for the (2–6) keV and (6–14) keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of DAMA/NaI and DAMA/LIBRA-phase1. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See text.

TABLE 2: Modulation amplitudes (1σ error) obtained by fitting the time behaviours of the main running parameters including a possible annual modulation with phase and period as for DM particles. These running parameters, acquired with the production data are (i) the operating temperature of the detectors; (ii) the HP Nitrogen flux in the inner Cu box housing the detectors; (iii) the pressure of the HP Nitrogen atmosphere of the inner Cu box housing the detectors; (iv) the environmental Radon in the inner part of the barrack from which the detectors are, however, excluded; (v) the hardware rate above single photoelectron threshold. All the measured amplitudes are compatible with zero.

	DAMA/LIBRA-1	DAMA/LIBRA-2	DAMA/LIBRA-3	DAMA/LIBRA-4
Temperature (°C)	$-(0.0001 \pm 0.0061)$	(0.0026 ± 0.0086)	(0.001 ± 0.015)	(0.0004 ± 0.0047)
Flux (L/h)	(0.13 ± 0.22)	(0.10 ± 0.25)	$-(0.07 \pm 0.18)$	$-(0.05 \pm 0.24)$
Pressure (10^{-3} mbar)	(15 ± 30)	$-(13 \pm 25)$	(22 ± 27)	(1.8 ± 7.4)
Radon (Bq/m^3)	$-(0.029 \pm 0.029)$	$-(0.030 \pm 0.027)$	(0.015 ± 0.029)	$-(0.052 \pm 0.039)$
Hardware rate (10^{-2} Hz)	$-(0.20 \pm 0.18)$	(0.09 ± 0.17)	$-(0.03 \pm 0.20)$	(0.15 ± 0.15)
	DAMA/LIBRA-5	DAMA/LIBRA-6	DAMA/LIBRA-7	
Temperature (°C)	(0.0001 ± 0.0036)	(0.0007 ± 0.0059)	(0.0000 ± 0.0054)	
Flux (L/h)	$-(0.01 \pm 0.21)$	$-(0.01 \pm 0.15)$	$-(0.00 \pm 0.14)$	
Pressure (10^{-3} mbar)	$-(0.8 \pm 1.2)$	(0.7 ± 1.3)	$-(2.6 \pm 5.5)$	
Radon (Bq/m^3)	(0.021 ± 0.037)	$-(0.028 \pm 0.036)$	(0.012 ± 0.047)	
Hardware rate (10^{-2} Hz)	(0.03 ± 0.14)	(0.08 ± 0.11)	(0.06 ± 0.10)	

not able to simultaneously satisfy all the many requirements of the signature. Similar analyses have also been done for the seven annual cycles of DAMA/NaI [23, 24].

In conclusion, the model-independent DAMA results give evidence (at 9.3σ C.L. over 14 independent annual cycles) for the presence of DM particles in the galactic halo.

In order to perform corollary investigation on the nature of the DM particles, model-dependent analyses are necessary; thus, many theoretical and experimental parameters and models are possible and many hypotheses must also be exploited.

In particular, the obtained DAMA model independent evidence is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear, and particle Physics. For example, some given scenarios and parameters are discussed in [2, 8, 13–20, 22, 23, 26]. Further large literature is available on the topics (see e.g., in [8]). Moreover, both the negative results and all the possible positive hints, achieved so far in the field, are largely compatible with the DAMA model-independent DM annual modulation results in many scenarios considering also the existing experimental and theoretical uncertainties; the same

TABLE 3: Summary of the results obtained by investigating possible sources of systematics or side processes [1–4, 7, 8, 49, 57–62]. None able to give a modulation amplitude different from zero has been found; thus, cautious upper limits (90% C.L.) on the possible contributions to the measured modulation amplitude have been calculated and are shown here for DAMA/LIBRA-phase1 as done before for the seven annual cycles of DAMA/NaI [23, 24].

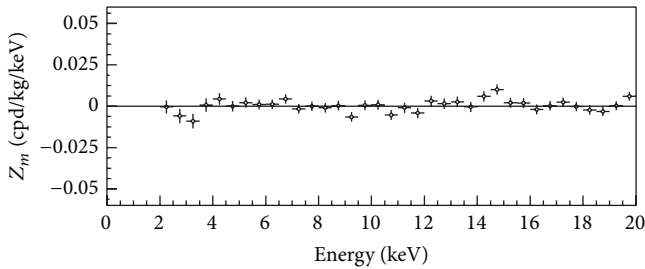| Source	Main comment	Cautious upper limit (90% C.L.)
Radon	Sealed Cu Box in HP Nitrogen atmosphere, 3 levels of sealing	$<2.5 \times 10^{-6}$ cpd/kg/keV
Temperature	Air conditioning + huge heat capacity	$<10^{-4}$ cpd/kg/keV
Noise	Efficient rejection	$<10^{-4}$ cpd/kg/keV
Energy scale	Routine + intrinsic calibrations	$<1 - 2 \times 10^{-4}$ cpd/kg/keV
Efficiencies	Regularly measured	$<10^{-4}$ cpd/kg/keV
Background	No modulation above 6 keV; no modulation in the (2–6) keV *multiple-hit* events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
Side reactions	From muon flux variation measured by MACRO	$<3 \times 10^{-5}$ cpd/kg/keV
In addition: no effect can mimic the signature		

FIGURE 7: Z_m variable as a function of the energy for the cumulative exposure of DAMA/NaI and DAMA/LIBRA-phase1, once setting S_m in (1) to zero. The energy bin is 0.5 keV. The Z_m values 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. See text.
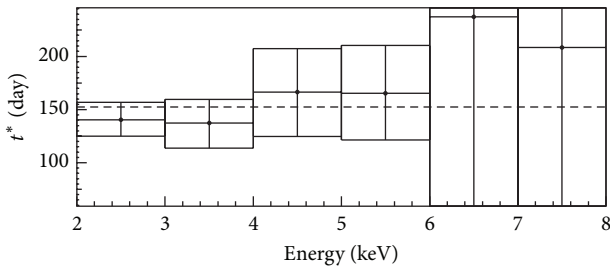

FIGURE 8: Phase t^* as a function of the energy for the total exposure; here, the errors are at 2σ. The vertical scale spans over ± a quarter of period around 2 June; other intervals are replica of it. An annual modulation effect is present in the lower energy intervals up to 6 keV and the phase agrees with that expected for DM induced signals. No modulation is present above 6 keV and thus the phase is undetermined. See text.

holds for indirect approaches; see, for example, arguments in [8] and references therein. As an example in Figure 9, there are allowed regions shown for DM candidates interacting by elastic scattering on target-nuclei with spin-independent coupling, including also some of the existing uncertainties [5].

3. DAMA/LIBRA-Phase2 and Perspectives

A first upgrade of the DAMA/LIBRA setup was performed in September 2008. One detector was recovered by replacing a broken PMT and a new optimization of some PMTs and HVs was done; the transient digitizers were replaced with new ones (the U1063A Acqiris 8-bit 1GS/s DC270 High-Speed cPCI Digitizers) having better performances and a new DAQ with optical readout was installed. The DAMA/LIBRA-phase1 concluded its data taking in this configuration on 2010.

A further and more important upgrade has been performed at the end of 2010 when all the PMTs have been replaced with new ones having higher quantum efficiency (Q.E.), realized with a special dedicated development by HAMAMATSU Co. Details on the developments and on the reached performances in the operative conditions are reported in [6]. Just as example, Figure 10 shows the values of the Q.E. of the new 50 HAMAMATSU PMTs installed in DAMA/LIBRA both at peak and at the λ of the NaI(Tl) scintillation light. We remind the reader that up to October 2010 low background PMTs, developed by EMI-Electron Tubes with dedicated R&D, were used (Q.E. ≃ 30% at $\lambda =$ 380 nm [1, 6, 21]); the light yield and other response features already allowed a software energy threshold of 2 keV in the data analysis. The feasibility to decrease the software energy threshold below 2 keV in the new configuration has been demonstrated [6].

Since the fulfillment of this upgrade, the DAMA/LIBRA-phase2 is continuously running in order (1) to increase the experimental sensitivity lowering the software energy threshold of the experiment, (2) to improve the corollary investigation on the nature of the DM particle and related astrophysical, nuclear, and particle physics arguments, and (3) to investigate other signal features. This requires long and heavy full time dedicated work for reliable collection and analysis of very large exposures.

Another upgrade at the end of 2012 was successfully concluded: new-concept preamplifiers were installed, with suitable operative and electronic features; in particular, they allow the direct connection of the signal to the relative channel of the Transient Digitizer (TD).
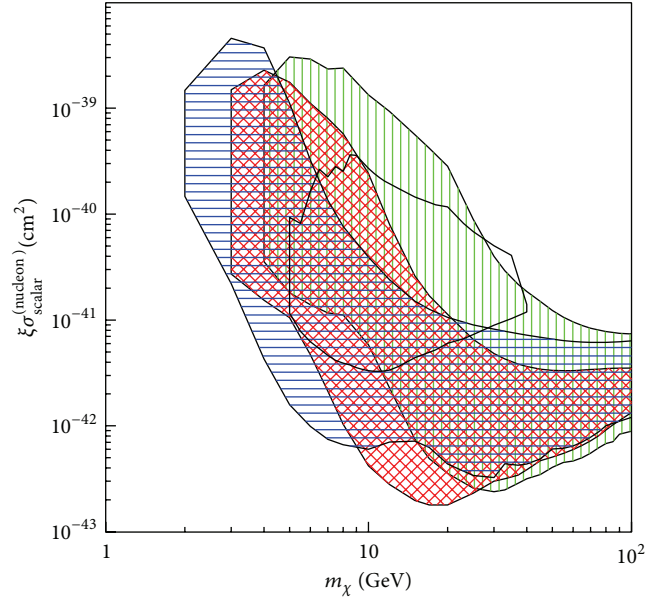
FIGURE 9: Regions in the nucleon cross section versus DM particle mass plane allowed by DAMA for a DM candidate interacting via spin-independent elastic scattering on target-nucleus; three different instances for the Na and I quenching factors have been considered: (i) without including the channeling effect [(green) vertically hatched region], (ii) by including the channeling effect [(blue) horizontally hatched region)], and (iii) without the channeling effect considering energy dependence of Na and I quenching factors [5] [(red) crosshatched region]. The velocity distributions and the same uncertainties as in [23, 24] are considered here. These regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation). The allowed region obtained for the CoGeNT experiment, including the same astrophysical models as in [23, 24] and assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters, is also reported by a (black) thick solid line. This region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). For details, see [5].
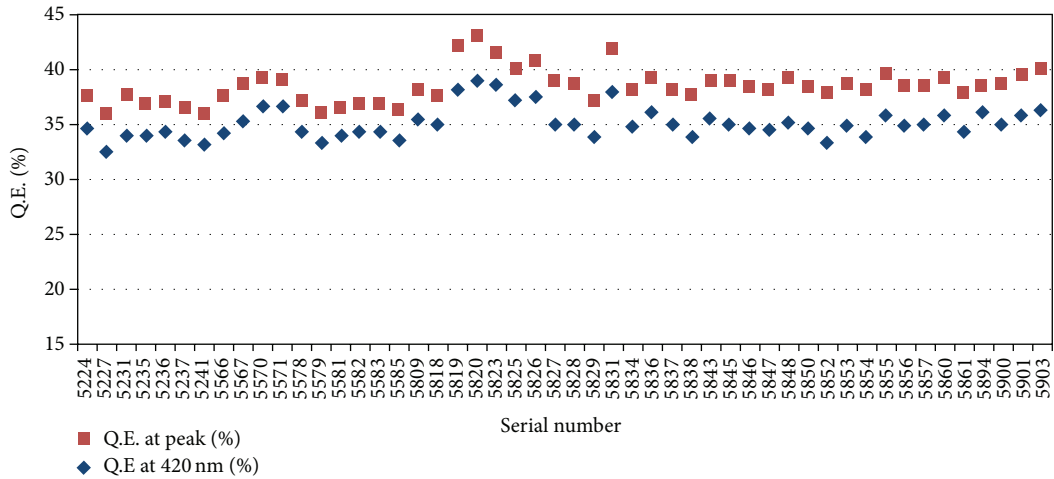

FIGURE 10: Q.E. at peak and at 420 nm of each one of the 50 high Q.E. PMTs, installed in DAMA/LIBRA-phase2. The averages (RMS) are 38.5% (1.6%) and 35.1% (1.4%), respectively; the RMS show that the Q.E. spread in the PMTs production is well limited.

Moreover, further improvements are planned. In particular, new trigger modules have been prepared and ready to be installed.

In the future, DAMA/LIBRA will also continue its study on several other rare processes [9–11] as also the former DAMA/NaI apparatus did [31–40].

Finally, further improvements to increase the sensitivity of the setup can be considered; in particular, the use of high

Q.E. and ultra-low background PMTs directly coupled to the NaI(Tl) crystals is an interesting possibility. (However, this would require the disassembling of the detectors since the light guides act at present also as optical windows.) This possible configuration can allow a further large improvement in the light collection and a further lowering of the software energy threshold. Moreover, efforts towards a possible highly radiopure NaI(Tl) "general purpose" experiment

(DAMA/1ton) having full sensitive mass of 1 ton (we already proposed in 1996 as a general purpose setup) have been continued in various aspects.

4. Conclusions

The data of DAMA/LIBRA-phase1 have further confirmed a peculiar annual modulation of the *single-hit* events in the (2–6) keV energy region satisfying all the many requirements of the DM annual modulation signature; the cumulative exposure by the former DAMA/NaI and DAMA/LIBRA-phase1 is 1.33 ton × yr.

In fact, as required by the 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 (0.998 ± 0.002) yr well compatible with the 1 yr period as expected for the DM signal; (3) the measured phase, (144 ± 7) days, is compatible with $\simeq 152.5$ days as expected for the DM signal; (4) the modulation is present only in the low energy (2–6) 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) of the *single-hit* events in the (2–6) keV energy interval is (0.0112 ± 0.0012) cpd/kg/keV (9.3σ C.L.). 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 are available.

DAMA/LIBRA is continuously running in its new configuration (named DAMA/LIBRA-phase2) with a lower software energy threshold aiming to improve the knowledge on corollary aspects regarding the signal and on second order effects as discussed, for example, in [8].

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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