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DAMA/LIBRA-phase1 results and perspectives of the phase2

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Abstract. 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 radio-pure NaI(Tl) target. No systematic or side reaction able to mimic the exploited DM signature has been found or suggested by anyone over more than a decade. The same data of DAMA/LIBRA–phase1 have also been analyzed searching for possible DM second-order diurnal effect; at present, the DM diurnal modulation amplitude – expected because of the Earth diurnal motion – evaluated on the basis of the DAMA Dark Matter annual modulation results is below the reached experimental sensitivity. Some of the perspectives of the presently running DAMA/LIBRA–phase2 are outlined.

1 Introduction

The DAMA/LIBRA experiment [1–13] is presently running in its phase2; as the former DAMA/NaI (see for example Ref. [8, 14, 15] and references therein), it has the main aim to investigate the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature.

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: the rate must contain a component modulated according to a cosine function (1) with one year period (2) and a phase that peaks roughly ≃ 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 $\simeq 7\%$ for usually adopted halo distributions (6), but it can be larger (even up to $\simeq 30\%$) in case of some possible scenarios such as e.g. those in Ref. [16, 17]. Thus this signature is model independent, very effective and, in addition, it allows the test of a large range of DM candidates, interaction types, 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 [1–4, 7, 8, 12–15, 18].

The full description of the DAMA/LIBRA set-up during the phase1 and other related arguments have been discussed in details in Ref. [1–4, 8] and references therein. Here we just remind that the sensitive part of this set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix) having 9.70 kg mass each one. 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 to be in contact with the environmental air of the underground laboratory. 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. The radiopurity, the procedures and details are discussed in Ref. [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, corresponding to 14 annual cycles [2–4, 8].

Fig. 1 shows the time behaviour of the experimental residual rates of the *single-hit* scintillation events for DAMA/LIBRA–phase1 in the (2–6) keV energy interval. Those of the DAMA/NaI (0.29 ton × yr) are given in Ref. [2, 8, 14, 15].

The χ^2 test excludes the hypothesis of absence of modulation in the data: χ^2/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 together with the DAMA/NaI ones, with the function: $A \cos \omega(t - t_0)$, considering a period $T = \frac{2\pi}{\omega} = 1$ yr and a phase $t_0 = 152.5$ day (June 2^{nd}) 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 9.2 σ C.L..

When the period, and the phase are kept free in the fitting procedure, the modulation amplitude is (0.0112 ± 0.0012) cpd/kg/keV (9.3 σ C.L.), the period $T = (0.998 \pm 0.002)$ year and the phase $t_0 = (144 \pm 7)$ day, values well compatible with expectations for a DM annual modulation signal. In particular, the phase is consistent with about June 2^{nd} 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 non-thermalized DM components to the galactic halo, such as e.g. the SagDEG stream [19–21] and the caustics [22].

The modulation amplitudes singularly calculated for each annual cycle of DAMA/NaI and DAMA/LIBRA–phase1 are normally fluctuating around their best fit values [2–4].

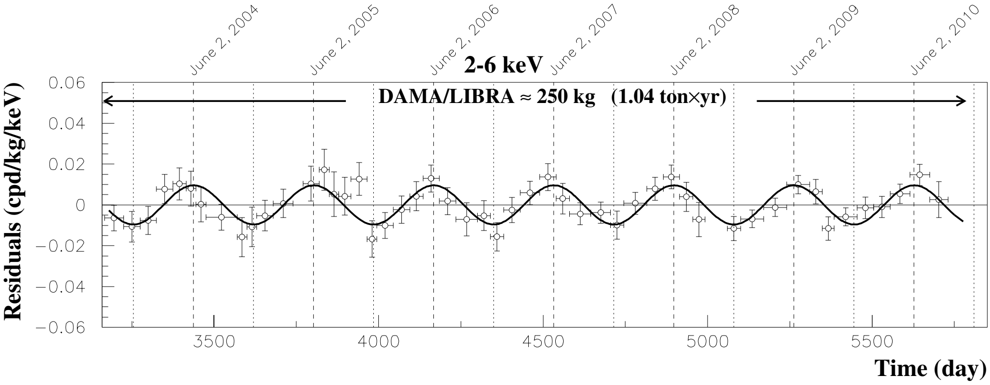

Figure 1. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the cosinusoidal functions behaviours $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, a phase $t_0 = 152.5$ day (June 2^{nd}) 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 2^{nd}), while the dotted vertical lines correspond to the minimum.

The power spectrum of the *single-hit* residuals of DAMA/LIBRA–phase1 and DAMA/NaI is reported in Fig. 2 for (2–6) keV energy interval [8]; the same analysis has been also done in the energy interval, just above the region where the signal is present, (6–14) keV. As can be seen, the principal mode present in the (2–6) keV energy interval is at 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.

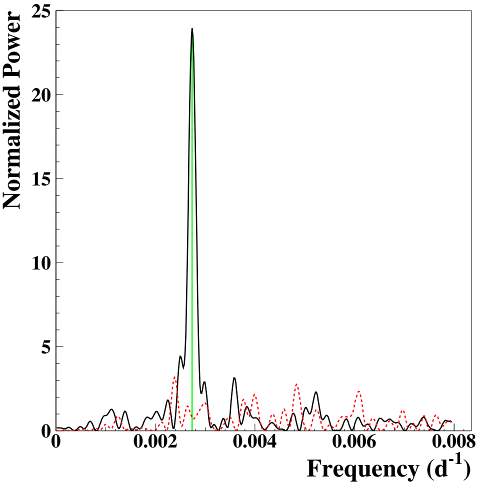

Figure 2. Power spectrum of the measured *single-hit* residuals in the (2–6) keV (solid lines) and (6–14) keV (dotted lines) energy intervals calculated according to Ref. [8], including also the treatment of the experimental errors and of the time binning. The data refer to DAMA/NaI and DAMA/LIBRA–phase1. 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.

Absence of any other significant background modulation in the whole energy spectrum has been verified in other energy regions not of interest for DM; e.g. the measured rate integrated above 90 keV, R_{90}, as a function of the time has been analysed [4]. Similar result is obtained in other energy intervals. It is worth noting that the obtained results account of whatever kind of background and, in 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 whole measured modulation amplitude) is available (see also discussions e.g. in Ref. [1–4, 7, 8, 12, 13]).

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. 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, the residual rates of the *single-hit* events measured over the DAMA/LIBRA–phase1 annual cycles are reported in Ref. [4], as collected in a single cycle, together with the residual rates of the *multiple-hit* events, in the (2–6) keV energy interval. As already observed, 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 well compatible with zero: $-(0.0005 \pm 0.0004)$ cpd/kg/keV in the same energy region (2–6) keV. Thus, again evidence of annual modulation with the features 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 [15], when the electronics allowed it. 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 considering T =1 yr and $t_0 = 152.5$ day. For such purpose 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, ϵ_{jk} is the overall efficiency. 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 $y_k = -2ln(\mathbf{L_k}) - const$ for each energy bin; the free parameters of the fit are $(b_{jk} + S_{0,k})$ and $S_{m,k}$. Hereafter, the index k is omitted for simplicity.

In Fig. 3 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 degrees of freedom (upper tail probability of 15%). All this confirms the previous analyses.

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

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:

$$\begin{aligned} S_i &= S_0 + S_m \cos\omega(t_i - t_0) + Z_m \sin\omega(t_i - t_0) \qquad (1) \\ &= S_0 + Y_m \cos\omega(t_i - t^*). \end{aligned}$$

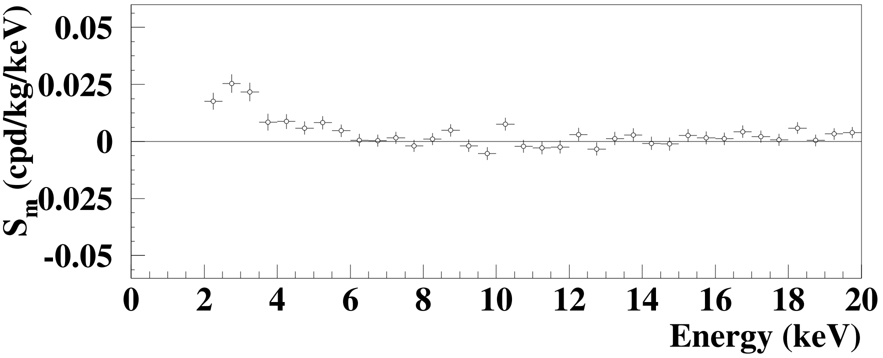

Figure 3. Energy distribution of the S_m variable for the total cumulative exposure 1.33 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability of 15%).

For signals induced by DM particles one should expect: i) $Z_m \sim 0$ (because of the orthogonality between the cosine and the sine functions); ii) $S_m \simeq Y_m$; 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 could be expected in case of possible contributions from non-thermalized DM components, such as e.g. the SagDEG stream [19–21] and the caustics [22].

Considering cumulatively the data of DAMA/NaI and DAMA/LIBRA–phase1 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. 4–*left* while in Fig. 4–*right* the obtained 2σ contours in the plane (Y_m, t^*) are depicted.

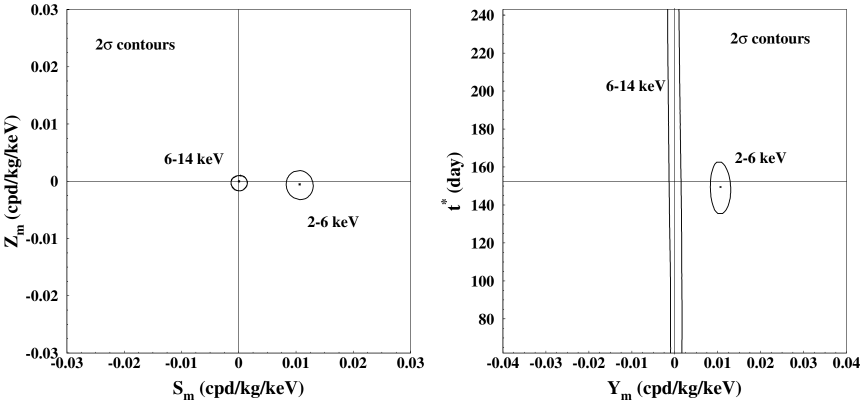

Figure 4. 2σ contours in the plane (S_m, Z_m) (*left*) and in the plane (Y_m, t^*) (*right*) for the (2–6) keV and (6–14) keV energy intervals. The contours have been obtained by the maximum likelihood method, considering the cumulative exposure of DAMA/NaI and DAMA/LIBRA–phase1. A modulation amplitude is present in the lower energy intervals and the phase agrees with that expected for DM induced signals. See text.

Sometimes naive statements were put forwards as the fact that in nature several phenomena may show some kind of periodicity. The point is whether they might mimic the annual modulation signature in DAMA/LIBRA (and former DAMA/NaI), i.e. 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 Ref. [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 Ref. [7, 8, 12, 13].

No modulation has been found in any possible source of systematics or side reactions; thus, cautious upper limits on possible contributions to the DAMA/LIBRA measured modulation amplitude are summarized in Ref. [2–4]. It is worth noting that they do not quantitatively account for the measured modulation amplitudes, and also are not able to simultaneously satisfy all the many requirements of the signature. Similar analyses have also been performed for the seven annual cycles of DAMA/NaI [14, 15].

Table 1. Summary of the contributions to the total neutron flux at LNGS; the value, $\Phi^{(n)}_{0,k}$, the relative modulation amplitude, η_k, and the phase, t_k, of each component is reported. It is also reported the counting rate, $R_{0,k}$, in DAMA/LIBRA for *single-hit* events, in the $(2-6)$ 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, $S_m^{exp} \simeq 0.0112$ cpd/kg/keV [4]. As can be seen, they are all negligible and they cannot give any significant contribution to the observed modulation amplitude. In addition, neutrons, muons and solar neutrinos are not a competing background when the DM annual modulation signature is investigated since in no case they can mimic this signature. For details see Ref. [13] 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, $(\alpha, n) \rightarrow$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$	$\simeq 0$ however $\ll 0.1$	–	$< 6 \times 10^{-4}$	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \rightarrow$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$	0.0129	end of June	$\ll 7 \times 10^{-4}$	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \rightarrow$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$	0.0129	end of June	$\ll 1.4 \times 10^{-3}$	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \rightarrow$ n (few MeV)	$\simeq 3 \times 10^{-10}$	0.03342*	Jan. 4th*	$\ll 7 \times 10^{-5}$	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi^{(\mu)}_0 \simeq 20\, \mu$ m^{-2}d^{-1}	0.0129	end of June	$\simeq 10^{-7}$	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\, \nu$ cm^{-2}s^{-1}	0.03342*	Jan. 4th*	$\simeq 10^{-5}$	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.

In particular, in Ref. [13] a simple and intuitive way why the neutrons, the muons and the solar neutrinos cannot give any significant contribution to the DAMA annual modulation results is outlined. Table 1 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 also reported there. As seen in Table 1, they are all negligible and they cannot give any significant contribution to the observed modulation amplitude. In addition, neutrons, muons and solar neutrinos are not a competing background when the DM annual modulation signature is investigated since in no case they can mimic this signature. For details see Ref. [13] and references therein.

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.

The obtained DAMA model independent evidence is compatible with a wide set of scenarios regarding the nature of the DM candidate, the interaction type and many astrophysical, nuclear and particle Physics. For examples some given scenarios and parameters are discussed e.g. in Ref. [2, 8, 14] and references therein. Further large literature is available on the topics (see e.g. Ref. [8]).

We note that no direct model independent comparison is possible in the field when different target materials and/or approaches are used; the same is for the indirect searches. Thus, 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 holds for indirect approaches; see e.g. arguments in Ref. [8] and references therein.

3 Investigation of possible diurnal effects in DAMA/LIBRA–phase1

The results obtained in the search for possible diurnal effects in the *single-hit* low energy scintillation data collected by DAMA/LIBRA–phase1 have been presented in Ref. [12]. A diurnal effect with the sidereal time is expected for DM because of Earth rotation; this DM second-order effect is model-independent and has several peculiar requirements as the DM annual modulation effect does. Moreover, since potential environmental backgrounds may be in principle correlated with the solar time, the analysis has been also performed in terms of solar time referred to the LNGS site.

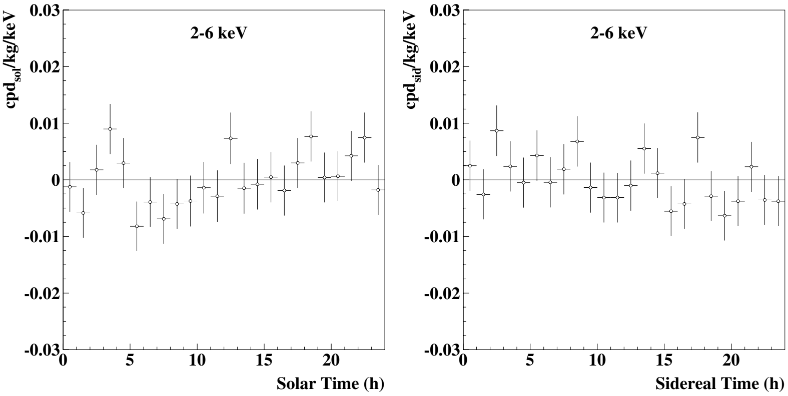

Figure 5. Experimental model-independent diurnal residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the hour of the solar (*left*) and sidereal (*right*) day. The experimental points present the errors as vertical bars and the associated time bin width (1 hour) as horizontal bars. The cumulative exposure is 1.04 ton × yr. For details see Ref. [12].

As demonstrated in Ref. [12], the ratio R_{dy} of the diurnal modulation amplitude to the annual modulation amplitude is a model independent constant; considering the LNGS latitude $R_{dy} \simeq 0.016$. Taking into account R_{dy} and the annual modulation effect pointed out by DAMA/LIBRA–phase1 for *single-hit* scintillation events in the low energy region, it is possible to derive the diurnal modulation amplitude expected for the same data. In particular, when considering the (2–6) keV energy interval, the observed annual modulation amplitude in DAMA/LIBRA–phase1 is: (0.0097 ± 0.0013) cpd/kg/keV [4] and the expected value of the diurnal modulation amplitude is $\simeq 1.5\times 10^{-4}$ cpd/kg/keV [12].

Fig. 5 shows the time and energy behavior of the experimental residual rates of *single-hit* events both as a function of solar (*left*) and of sidereal (*right*) time, in the (2–6) keV energy interval. The used time bin is 1 (either solar or sidereal, respectively) hour. For more energy intervals and more details see Ref. [12].

The null hypothesis (absence of residual rate diurnal variation) has been tested by a χ^2 test, obtaining χ^2/d.o.f. = 25.8/24 and 21.2/24 for solar and sidereal time, respectively; the upper tail probabilities (P-values), calculated by the standard χ^2 distribution, are P = 36% and 63%, respectively. Thus, no diurnal variation with a significance of 95% C.L. is found [12].

In addition, another independent statistical test has been applied: the run test; it verifies the hypothesis that the positive and negative data points are randomly distributed. The lower tail probabilities are equal to 7% and 78% in the (2–6) keV energy region for the solar case and for the sidereal case, respectively. Thus, in conclusion the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity.

When considering the DM diurnal effect due to the Earth rotation around its axis [12], only an upper limit can be derived. In particular, the residual rates of the *single-hit* events in the (2–6) keV energy interval as a function of the sidereal time (see Fig. 5 *right*) have been fitted with the formula $A_d^{exp} \cos[\omega_{rot}(t - t_d)]$. The amplitude A_d^{exp} is a free parameter, while the period is fixed at 24 h and the phase at 14 h, as expected for the DM diurnal effect at LNGS site [12]. The obtained amplitude is $A_d^{exp} = -(1.0 \pm 1.3) \times 10^{-3}$ cpd/kg/keV (χ^2/d.o.f. = 20.6/23 and P = 61%). Following the Feldman-Cousins [23] procedure an upper limit can be obtained for the measured diurnal modulation amplitude: $A_d^{exp} < 1.2 \times 10^{-3}$ cpd/kg/keV (90% C.L.). Considering also other energy intervals, all the diurnal modulation amplitudes are compatible with zero.

Fig. 6 shows the diurnal modulation amplitudes, A_d, as function of energy (the energy bin is 1 keV) obtained by fitting the *single-hit* residual rate of the entire DAMA/LIBRA–phase1 as function of the sidereal time, with the formula $A_d \cos[\omega_{rot}(t - t_d)]$. The period is fixed at 24 h and the phase at 14 h, as expected for the DM diurnal effect (see above). The A_d values are compatible with zero, having random fluctuations around zero with χ^2 equal to 19.5 for 18 degrees of freedom.

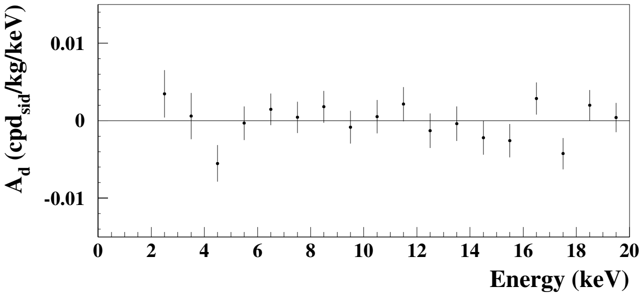

Figure 6. Diurnal modulation amplitudes, A_d, as function of energy obtained by fitting the *single-hit* residual rate of the entire DAMA/LIBRA–phase1 as function of the sidereal time. The amplitude A_d is a free parameter, while the period is fixed at 24 h and the phase at 14 h, as expected for the DM diurnal effect at LNGS site. The A_d values are compatible with zero. See Ref. [12].

In order to compare the experimental data with the DM diurnal effect due to the Earth rotation around its axis, the measured upper limit of A_d^{exp} (see above) for the (2−6) keV energy interval is taken into account. Thus, the present experimental sensitivity is larger than the expected diurnal modulation amplitude ($\simeq 1.5\times 10^{-4}$ cpd/kg/keV) derived above from the DAMA/LIBRA–phase1 observed effect.

In conclusion, at the present level of sensitivity the presence of any significant diurnal variation and of diurnal time structures in the data can be excluded for both the cases of solar and sidereal time. In particular, the DM diurnal modulation amplitude expected, because of the Earth diurnal motion, on the basis of the DAMA Dark Matter annual modulation results is below the present sensitivity. It will be possible to investigate such a diurnal effect with adequate sensitivity only when a much larger exposure will be available. On the other hand, better sensitivities can also be achieved by lowering the software energy threshold; in fact an almost exponential rising of the signal rate is expected at lower energy for some DM candidates. This is one of the goals of the presently running DAMA/LIBRA–phase2.

4 DAMA/LIBRA–phase2 and perspectives

After a first upgrade of the DAMA/LIBRA set-up in September 2008, a 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 Ref. [6]. 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, DAMA/LIBRA–phase2 – after optimization periods – is continuously running in order: (1) to increase the experimental sensitivity lowering the software energy threshold of the experiment; (2) to determine with ever better precision the DM parameters, which contain crucial information; (3) to improve the corollary investigation on the nature of the DM particle and related astrophysical, nuclear and particle physics arguments; (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. 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 [24].

Finally, further improvements to increase the sensitivity of the set-up 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. 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) have been continued in various aspects.

5 Conclusions

The data of DAMA/LIBRA–phase1 have further confirmed the presence of 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 (9.3 σ 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 is available.

The same data of DAMA/LIBRA–phase1 have also been investigated in terms of possible diurnal effects. At the present level of sensitivity the presence of any significant diurnal variation and of diurnal time structures in the data can be excluded for both the cases of solar and sidereal time. In particular, the second-order diurnal modulation amplitude expected, because of the Earth diurnal motion, on the basis of the DAMA Dark Matter annual modulation results is below the present sensitivity.

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 e.g. in Ref. [8, 12]. Further efforts are also in progress.

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