Dark Matter: DAMA/LIBRA and its perspectives

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Abstract

The long-standing model-independent annual modulation effect measured by DAMA deep underground at Gran Sasso Laboratory with different experimental configurations is summarized and perspectives will be highlighted. DAMA/LIBRA–phase2 set-up, $\simeq$ 250 kg highly radio-pure NaI(Tl) confirms the evidence of a signal that meets all the requirements of the model independent Dark Matter annual modulation signature at high C.L.; the full exposure is 2.86 ton $\times$ yr over 22 annual cycles. The experiment is currently collecting data in the DAMA/LIBRA–phase2 empowered configuration with an even lower software energy threshold. Other recent claims are shortly commented.

1 Introduction

The DAMA/LIBRA [1–20] experiment, as the pioneer DAMA/NaI [21, 22], has the main aim to investigate the presence of Dark Matter (DM) particles in the galactic halo by exploiting the DM annual modulation signature (originally suggested in Ref. [23, 24]). In addition, the developed highly radio-pure NaI(Tl) target-detectors [1, 6, 9, 25] ensure sensitivity to a wide range of DM candidates, interaction types and astrophysical scenarios (see e.g. Ref. [19], and references therein). The DM annual modulation signature and its peculiar features are described elsewhere (for example in [19, 20]). The full description of the DAMA/LIBRA set-up and the adopted procedures during the phase1 and phase2 and other related arguments have been discussed in details e.g. in Refs. [1–6, 15–20].

At the end of 2010 all the photomultipliers (PMTs) were replaced by a second generation PMTs Hamamatsu R6233MOD, with higher quantum efficiency (Q.E.) and with lower background [6,25] with respect to those used in phase1. The commissioning of the DAMA/LIBRA–phase2 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 [6].

2 The DAMA/LIBRA–phase2 results

The details of the annual cycles of DAMA/LIBRA–phase2 are reported in Ref. [19, 20]. The first annual cycle was dedicated to the commissioning and to the optimizations towards the achievement of the 1 keV software energy threshold [6]. Thus, the considered annual cycles of DAMA/LIBRA–phase2 released so far are eight (exposure of 1.53 ton×yr); when considering also the former DAMA/NaI and DAMA/LIBRA–phase1, the exposure is 2.86 ton×yr. The duty cycle of the DAMA/LIBRA–phase2 experiment is high, ranging between 76% and 86%. The routine calibrations and, in particular, the data collection for the acceptance windows efficiency mainly affect it.

Residual rates versus time for 1 keV energy threshold are reported in Ref. [20]. The former DAMA/LIBRA–phase1 and the new DAMA/LIBRA–phase2 residual rates of the *single-hit* scintillation events are reported in Fig. 1. The energy interval is from 2 keV, the software energy threshold of DAMA/LIBRA–phase1, up to 6 keV. The data of Fig. 1 and those of DAMA/NaI have been fitted with the function: $A\cos\omega(t-t_0)$, considering a period $T=\frac{2\pi}{\omega}=1$ yr and a phase $t_0=152.5$ day (June 2^{nd}) as expected by the DM annual modulation signature. The obtained $\chi^2/d.o.f.$ is 130/155 and the modulation amplitude $A=(0.00996\pm0.00074)$ cpd/kg/keV is obtained. When the period and the phase are kept free in the fitting procedure, the achieved

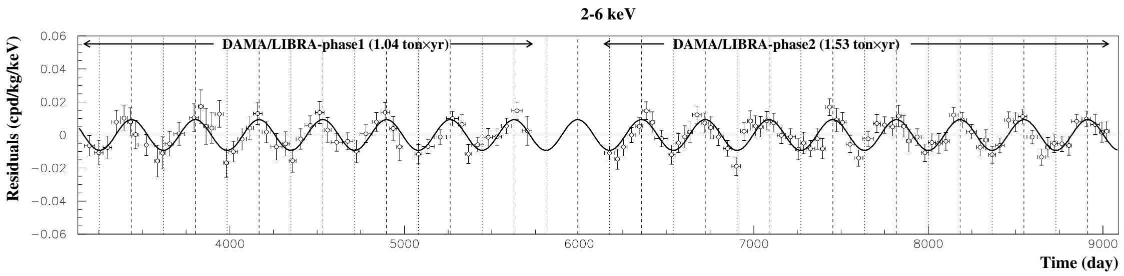

Figure 1: Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2^{nd}) and modulation amplitude, A, equal to the central value obtained by best fit. This figure is being reused from [20].

C.L. for the full exposure (2.86 ton×yr) is 13.7σ; the modulation amplitude of the *single-hit* scintillation events is: (0.01014 ± 0.00074) cpd/kg/keV, the measured phase is (142.4 ± 4.2) days and the measured period is (0.99834 ± 0.00067) yr, all these values are well in agreement with those expected for DM particles.

Absence of any significant background modulation in the energy spectrum has also been verified in the present data taking for energy regions not of interest for DM [2–5, 9, 15–17, 19, 20]. 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 measured modulation amplitude) is available (see also discussions e.g. in Ref. [1–5, 7, 8, 15–17, 19, 20]).

A further relevant investigation on DAMA/LIBRA–phase2 data has been performed by applying the same hardware and software procedures, used to acquire and to analyze the *single-hit* residual rate, to the *multiple-hit* one. Since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just 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 to compare 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. While 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 [20]. Since the same identical hardware and the same identical software procedures have been used to analyze the two classes of events, the obtained result offers an additional strong support for the presence of a DM particle component in the galactic halo.

The *single-hit* residuals have also been investigated by a Fourier analysis [5]. A clear peak corresponding to a period of 1 year is evident in the low energy intervals; the same analysis in the (6–14) keV energy region shows only aliasing peaks instead. Neither other structure at different frequencies has been observed.

The annual modulation present at low energy can also be pointed out by depicting the energy dependence of the modulation amplitude, $S_m(E)$, obtained by maximum likelihood method considering fixed period and phase: T =1 yr and t_0 = 152.5 day. The modulation amplitudes for the whole data sets: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 (total exposure 2.86 ton×yr) are plotted in Fig. 2; the data below 2 keV refer only to the DAMA/LIBRA-phase2 exposure (1.53 ton×yr). It can be inferred that positive signal is present in the (1–6) keV energy interval (a new data point below 1 keV has been added, see later), 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 interval have random fluctuations around zero yields $\chi^2/d.o.f.$ equal to 20.3/16 (P-value = 21%).

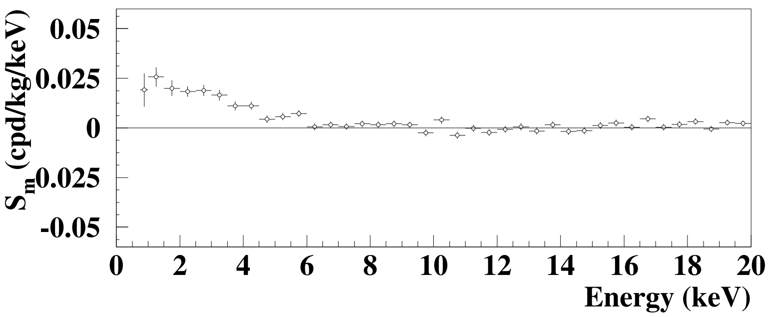

Figure 2: Modulation amplitudes, S_m, as function of the energy in keV(ee) for the whole data sets: DAMA/NaI, DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 (total exposure 2.86 ton×yr) above 2 keV; below 2 keV only the DAMA/LIBRA-phase2 exposure (1.53 ton × yr) is available and used. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. This figure is being reused from [20].

It has been verified that the observed annual modulation effect is 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 have random fluctuations around the weighted averaged value confirmed by the χ^2 analysis.

Thus, the hypothesis that the signal is well distributed over all the 25 detectors is accepted.

Among further additional tests, the analysis of the modulation amplitudes separately for the nine inner detectors and the external ones has been carried out for DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2, as already done for the other data sets [2–5, 15–17, 19, 20]. The obtained values are fully in agreement; in fact, the hypothesis that the two sets of modulation amplitudes belong to same distribution has been verified by χ^2 test, obtaining e.g.: $\chi^2/d.o.f.$ = 1.9/6 and 36.1/38 for the energy intervals (1–4) and (1–20) keV, respectively ($\Delta E = 0.5$ keV). This shows that the effect is also well shared between inner and outer detectors.

To test the hypothesis that the modulation amplitudes calculated for each DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 annual cycle are compatible and normally fluctuating around their mean values, the χ^2 test and the *run test* have been used. This analysis confirms that the data collected in all the annual cycles with DAMA/LIBRA–phase1 and phase2 are statistically compatible and can be considered together [20].

Finally, the release of the assumption of the phase $t_0 = 152.5$ day in the procedure to evaluate the modulation amplitudes has been discussed in [20].

No systematic or side processes able to mimic the signature, i.e. able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude, has been found or suggested by anyone throughout some decades thus far (for details see e.g. Ref. [1–5, 7, 8, 15–22]).

In particular, arguments related to any possible role of some natural periodical phenomena have been discussed and quantitatively demonstrated to be unable to mimic the signature (see references; e.g. Refs. [7, 8]). Thus, on the basis of the exploited signature, the model independent DAMA results give evidence at 13.7σ C.L. (over 22 independent annual cycles and in various experimental configurations) for the presence of DM particles in the galactic halo.

The DAMA model independent evidence is compatible with a wide set of astrophysical, nuclear and particle physics scenarios for high and low mass candidates inducing nuclear recoil and/or electromagnetic radiation, as also shown in various literature. Moreover, both the negative results and all the possible positive hints, achieved so-far in the field, can be compatible with the DAMA model independent DM annual modulation results in many scenarios considering also the existing experimental and theoretical uncertainties; the same holds for indirect approaches. For a discussion see e.g. Ref. [5, 19] and references therein.

3 Few arguments about the analysis procedure

As reported several times along the years [2–5, 15–17, 19, 20], the data taking of each annual cycle in DAMA/LIBRA starts before the expected minimum of the DM signal (about 2 December) and ends after its expected maximum (about 2 June). Thus, adopting in the data analysis a constant background evaluated within each annual cycle, any possible decay of long–term–living isotopes cannot mimic a DM positive signal with all its peculiarities. On the contrary, it may only lead to underestimate the DM annual modulation amplitude, depending on the radio-purity of the set-up.

Despite this obvious fact, Refs. [26, 27] claim that the DAMA annual modulation result might be mimicked by the adopted analysis procedure. Detailed analyses on this argument have already been reported in Ref. [19], confuting these claims quantitatively, even considering the case of a rate at low energy in DAMA/LIBRA with odd behavior, increasing with time.

More recently, Ref. [27] claims that an annual modulation in the COSINE–100 data can appear if they use an analysis method somehow similar to DAMA/LIBRA. However, as expected from the rate of COSINE–100 very–decreasing with time and from what mentioned above, the authors obtain a modulation with reverse phase [27]; this corresponds, when fixing the phase to $t_0 = 152.5$ day, to *NEGATIVE* modulation amplitudes, as expected by the elementary considerations reported before. This artificial effect has no way to mimic the observed DM signature with its peculiarity.

Thus, while the appearance of modulation with *NEGATIVE* amplitudes is due to the peculiar behavior of the COSINE–100 rate very–decreasing with time, this is not the case of DAMA/LIBRA. In particular, the DAMA/LIBRA NaI(Tl) detectors are not the "same" as those of COSINE–100, since e.g. they were grown starting from different powders, using different purification, growing procedures and protocols; they have been stored underground since decades, they have different quenching factors for alpha's and nuclear recoils, etc. Thus, they have well different residual contaminations and features[1] as well as different electronics and all other details of the experimental set-up.

Moreover, the stability with time of the running parameters of each DAMA/LIBRA annual cycle is reported e.g. in Refs. [2–5,15–17,19,20]. As regards the odd idea that the low-energy rate in DAMA/LIBRA might increase with time due to spill out of noise [27] , we just recall two facts that rule out this possibility: 1) the stability with time of noise, reported in several papers [2–5,15–17,19,20]; 2) the estimate of the remaining noise tail after the noise rejection procedure $\ll 1\%$ [6].

Finally, the arguments of Ref. [19] already showed that any possible effect in DAMA/LIBRA due to either long–term time–varying background or odd behavior of the rate, increasing with time, is negligible. Here we just recall:

- The (2–6) keV *single-hit* residual rates have been recalculated considering a possible time–varying background. They provide modulation amplitude, fitted period and phase well compatible with those obtained in the *original* analysis, showing that the effect of long–term time–varying background – if any – is marginal [19].

- Any possible long–term time–varying background would also induce a fake modulation amplitudes (Σ) on the tail of the $\mathcal{S}_m$ distribution above the energy region where the signal has been observed. The analysis in Ref. [19] shows that $|\Sigma| < 1.5 \times 10^{-3}$ cpd/kg/keV. Thus, taking into account that the observed *single-hit* annual modulation amplitude at low energy is order of 10^{-2} cpd/kg/keV, any possible effect of long–term time–varying background – if any – is marginal [19].

- The maximum likelihood analysis has been repeated including a linear term decreasing with time. The obtained $\mathcal{S}_m$ averaged over the low energy interval are compared with those obtained in the *original* analysis, showing that their differences are well below the statistical errors [19].

- The behaviour of the *multiple-hit* events, where no modulation has been found [19,20] in the same energy region where the annual modulation is present in the *single-hit* events, strongly disfavours the hypothesis that the counting rate has significant long–term time–varying contributions.

Summarizing, the arguments of Ref. [19] already showed that any possible effect in DAMA/LIBRA due either to long–term time–varying background or to any odd behavior of the rate, increasing with time, is negligible and the *original* analyses, that assume a constant background within each annual cycle, can be safely adopted. Similar conclusions were also reported in Ref. [28].

[1] The DAMA/LIBRA set-up had some upgrades – one of them is that from phase1 to phase2 to lower the software energy threshold – also acting to improve the signal/background ratio.

4 Perspectives, comparisons and conclusions

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

Firstly, particular efforts for lowering the software energy threshold have been done in the already-acquired data of DAMA/LIBRA–phase2 by using the same technique as before with dedicated studies on the efficiencies. Consequently, a new data point has been added in the modulation amplitude as a function of energy down to 0.75 keV, see Fig. 2. A modulation is also present below 1 keV. This preliminary result confirms the necessity to lower the software energy threshold by a hardware upgrade and an improved statistics in the first energy bin.

A dedicated hardware upgrade of DAMA/LIBRA–phase2 was done. All the PMTs were equipped with miniaturized low background new concept preamplifiers and miniaturized HV dividers mounted on the same socket. The electronic chain was improved mainly by using higher vertical resolution 14–bit digitizers. This upgrade aims to improve the experimental sensitivity through a lower software energy threshold and a large acceptance efficiency. The experiment is currently running in this new configuration, DAMA/LIBRA–phase2 empowered, and new results are foreseen in the near future.

References

[1] R. Bernabei et al., *The DAMA/LIBRA apparatus*, Nucl. Instr. and Meth. A **592**, 297 (2008), doi:10.1016/j.nima.2008.04.082.

[2] R. Bernabei et al., *First results from DAMA/LIBRA and the combined results with DAMA/NaI*, Eur. Phys. J. C **56**, 333 (2008), doi:10.1140/epjc/s10052-008-0662-y.

[3] R. Bernabei et al., *New results from DAMA/LIBRA*, Eur. Phys. J. C **67**, 39 (2010), doi:10.1140/epjc/s10052-010-1303-9.

[4] R. Bernabei et al., *Final model independent result of DAMA/LIBRA–phase1*, Eur. Phys. J. C **73**, 2648 (2013), doi:10.1140/epjc/s10052-013-2648-7.

[5] R. Bernabei et al., *Dark Matter Investigation by DAMA at Gran Sasso*, Int. J. of Mod. Phys. A **28**, 1330022 (2013), doi:10.1142/S0217751X13300226.

[6] R. Bernabei et al., *Performances of the new high quantum efficiency PMTs in DAMA/LIBRA*, JINST **7**, P03009 (2012), doi:10.1088/1748-0221/7/03/P03009.

[7] R. Bernabei et al., *No role for muons in the DAMA annual modulation results*, Eur. Phys. J. C **72**, 2064 (2012), doi:10.1140/epjc/s10052-012-2064-4.

[8] R. Bernabei et al., *No role for neutrons, muons and solar neutrinos in the DAMA annual modulation results*, Eur. Phys. J. C **74**, 3196 (2014), doi:10.1140/epjc/s10052-014-3196-5.

[9] DAMA coll., *issue dedicated to DAMA*, Int. J. of Mod. Phys. A **31** (2016) and refs therein, doi:10.1142/S0217751X1642001X.

[10] R. Bernabei et al., *Investigating Earth shadowing effect with DAMA/LIBRA–phase1*, Eur. Phys. J. C **75**, 239 (2015), doi:10.1140/epjc/s10052-015-3473-y.

[11] P. Belli et al., *Observations of annual modulation in direct detection of relic particles and light neutralinos*, Phys. Rev. D **84**, 055014 (2011), doi:10.1103/PhysRevD.84.055014.

[12] A. Addazi et al., *DAMA annual modulation effect and asymmetric mirror matter*, Eur. Phys. J. C **75**, 400 (2015), doi:10.1140/epjc/s10052-015-3634-z.

[13] R. Bernabei et al., *On corollary model-dependent analyses and comparisons*, Int. J. of Mod. Phys. A **31**, 1642009 (2016), doi:10.1142/S0217751X16420094.

[14] R. Cerulli et al., *DAMA annual modulation and mirror Dark Matter*, Eur. Phys. J. C **77**, 83 (2017), doi:10.1140/epjc/s10052-017-4658-3.

[15] R. Bernabei et al., *First Model Independent Results from DAMA/LIBRA–phase2*, Universe **4**, 116 (2018), doi:10.3390/universe4110116.

[16] R. Bernabei et al., *First Model Independent Results from DAMA/LIBRA–phase2*, Nucl. Phys. At. Energy **19**, 307 (2018), doi:10.15407/jnpae2018.04.307.

[17] R. Bernabei, *New model independent results from the first six full annual cycles of DAMA/LIBRA–phase2*, Bled Workshops in Physics **19** n. 2, 27 (2018), http://bsm.fmf.uni-lj.si/bled2018bsm/talks/BledVol19No2proc.pdf.

[18] R. Bernabei et al., *Improved Model-Dependent Corollary Analyses after the First Six Annual Cycles of DAMA/LIBRA–phase2*, Nucl. Phys. At. Energy **20(4)**, 317 (2019), doi:10.15407/jnpae2019.04.317.

[19] R. Bernabei et al., *The DAMA project: Achievements, implications and perspectives*, Prog. Part. Nucl. Phys. **114**, 103810 (2020), doi:10.1016/j.ppnp.2020.103810.

[20] R. Bernabei et al., *Further results from DAMA/LIBRA–phase2 and perspectives*, Nucl. Phys. At. Energy **22**, 329 (2021), doi:10.15407/jnpae2021.04.329.

[21] R. Bernabei el al., *Dark Matter search*, La Rivista del Nuovo Cimento **26** n.1, 1-73 (2003).

[22] R. Bernabei et al., *Dark Matter particles in the Galactic halo: results and implications from DAMA/NaI*, Int. J. Mod. Phys. D **13**, 2127 (2004), doi:10.1142/S0218271804006619 and refs. therein.

[23] K.A. Drukier et al., *Detecting cold dark-matter candidates*, Phys. Rev. D **33**, 3495 (1986), doi:10.1103/PhysRevD.33.3495.

[24] K. Freese et al., *Signal modulation in cold-dark-matter detection*, Phys. Rev. D **37**, 3388 (1988), doi:10.1103/PhysRevD.37.3388.

[25] R. Bernabei and A. Incicchitti, *Low background techniques in NaI(Tl) setups*, Int. J. of Mod. Phys. A **32**, 1743007 (2017), doi:10.1142/S0217751X17430072.

[26] D. Buttazzo et al., *Annual modulations from secular variations: relaxing DAMA?*, JHEP **2020**, 137 (2020), doi:10.1007/JHEP04(2020)137.

[27] G. Adhikari et al., *An induced annual modulation signature in COSINE–100 data by DAMA/LIBRA's analysis method*, http://arxiv.org/abs/2208.05158.

[28] A. Messina et al., *Annual modulations from secular variations: not relaxing DAMA?*, JCAP **04**, 037 (2020), doi:10.1088/1475-7516/2020/04/037.