DAMA/LIBRA results and perspectives

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Abstract

The DAMA/LIBRA experiment, running at the Gran Sasso National Laboratory of the I.N.F.N. in Italy, has a sensitive mass of about 250 kg highly radiopure NaI(Tl). It is mainly devoted to the investigation of Dark Matter (DM) particles in the Galactic halo by exploiting the model independent DM annual modulation signature. The present DAMA/LIBRA experiment and the former DAMA/NaI one (the first generation experiment having an exposed mass of about 100 kg) have released so far results corresponding to a total exposure of 1.17 ton $\times$ yr over 13 annual cycles. They provide a model independent evidence of the presence of DM particles in the galactic halo at 8.9 $\sigma$ C.L.. A short summary of the obtained results is presented and future perspectives of the experiment mentioned.
1 Introduction

The DAMA project is an observatory for rare processes located deep underground at the Gran Sasso National Laboratory of the I.N.F.N.. It is based on the development and use of low background scintillators. The main experimental set-ups are: i) DAMA/NaI (≃ 100 kg of highly radiopure NaI(Tl)) that took data for 7 annual cycles and completed its data taking on July 2002 [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]; ii) DAMA/LXe, ≃ 6.5 kg liquid Kr-free Xenon enriched either in $^{129}$Xe or in $^{136}$Xe [13]; iii) DAMA/R&D, a facility dedicated to test prototypes and to perform experiments developing and using various kinds of low background crystal scintillators to investigate various rare processes [14]; iv) DAMA/Ge, where sample measurements are carried out and where dedicated measurements on rare events are performed [15]; v) the second generation DAMA/LIBRA set-up, ≃ 250 kg highly radiopure NaI(Tl)) [16, 17, 18, 19, 20] mainly devoted to the investigation of the presence of Dark Matter (DM) particles in the Galactic halo. Profiting of the low background features of these set-ups, many rare processes have been studied.

DAMA/LIBRA is the main apparatus, it is investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature, originally suggested in the mid 80’s [21].

In fact, as a consequence of its annual revolution around the Sun, which is moving in the Galaxy traveling with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules, the Earth should be crossed by a larger flux of Dark Matter particles around $\sim$2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around $\sim$2 December (when the two velocities are subtracted). Thus, this signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons (consider the expected value of the phase as well as the other requirements listed below). 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; (3) with a phase that peaks roughly around $\sim$2nd June; (4) this modulation must be present only in a well-defined low energy range, where DM particles can induce signals; (5) it must be present only in those events where just a single detector, among all the available ones in the used set-up, actually “fires” (single-hit events), since the probability that DM particles experience multiple interactions is negligible; (6) the modulation amplitude in the region of maximal sensitivity has to be $\lesssim$7% in case of usually adopted halo distributions, but it may be significantly larger in case
of some particular scenarios such as e.g. those in refs. [22, 23].

Only systematic effects or side reactions able to simultaneously fulfill all the six requirements given above and to account for the whole observed modulation amplitude might mimic this DM signature; no one has been found or suggested by anyone over more than a decade. Thus, no other effect investigated so far in the field of rare processes offers a so stringent and unambiguous signature.

This offers an efficient model independent signature, able to test a large number of DM candidates, a large interval of cross sections and of halo densities. At present status of technology it is the only model independent signature available in direct Dark Matter investigation that can be effectively exploited.

It is worth noting that the corollary questions related to the exact nature of the DM particle(s) (detected by means of the DM annual modulation signature) and to the astrophysical, nuclear and particle Physics scenarios require subsequent model dependent corollary analyses, as those performed e.g. in refs. [4, 5, 6, 7, 8, 9, 10, 11]. On the other hand, one should stress that it does not exist any approach in direct and indirect DM searches which can offer information on the nature of the candidate in a model independent way, that is without assuming any astrophysical, nuclear and particle Physics scenarios.

2 DAMA/LIBRA results

The DAMA/NaI set up and its performances are described in ref. [1, 3, 4, 5], while the DAMA/LIBRA set-up and its performances are described in ref. [16]. The sensitive part of the DAMA/LIBRA set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators placed in a 5-rows by 5-columns matrix; each crystal is coupled to two low background photomultipliers working in coincidence at single photoelectron level. The detectors are placed inside a sealed copper box continuously flushed with HP nitrogen and surrounded by a low background and massive shield made of Cu/Pb/Cd-foils/polyethylene/paraffin; moreover, about 1 m concrete (made from the Gran Sasso rock material) almost fully surrounds (mostly outside the barrack) this passive shield, acting as a further neutron moderator. The installation has a 3-levels sealing system which excludes the detectors from environmental air. The whole installation is air-conditioned and the temperature is continuously monitored and recorded. The detectors’ responses range from 5.5 to 7.5 photoelectrons/keV. Energy calibrations with X-rays/γ sources are regularly carried out down to few keV in the same conditions as the production runs. In the data analysis a software
energy threshold of 2 keV is considered.

Figure 1: Experimental model-independent residual rate of the single-hit scintillation events, measured by DAMA/NaI over seven and by DAMA/LIBRA over six annual cycles in the (2 – 6) keV energy interval as a function of the time [4, 5, 17, 18]. The zero of the time scale is January 1st of the first year of data taking. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve is $A \cos \omega (t - t_0)$ with period $T = \frac{2 \pi}{\omega} = 1$ yr, phase $t_0 = 152.5$ day (June 2nd) and modulation amplitude, $A$, equal to the central value obtained by best fit over the whole data: cumulative exposure is 1.17 ton $\times$ yr. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted vertical lines correspond to the minimum. See Refs. [17, 18] and text.

The DAMA/LIBRA data released so far correspond to six annual cycles for an exposure of 0.87 ton$\times$yr [17, 18]. Considering these data together with those previously collected by DAMA/NaI over 7 annual cycles (0.29 ton$\times$yr), the total exposure collected over 13 annual cycles is 1.17 ton$\times$yr; this is orders of magnitude larger than the exposures typically collected in the field. Several analyses on the model-independent DM annual modulation signature have been performed (see Refs. [17, 18] and references therein); here just few arguments are mentioned. In particular, Fig. 1 shows the time behaviour of the experimental residual rates of the single-hit events collected by DAMA/NaI and by DAMA/LIBRA in the (2–6) keV energy interval [17, 18]. The superimposed curve is the cosinusoidal function: $A \cos \omega (t - t_0)$ with a period $T = \frac{2 \pi}{\omega} = 1$ yr, with a phase $t_0 = 152.5$ day (June 2nd), and modulation amplitude, $A$, obtained by best fit over the 13 annual cycles. The hypothesis of absence of modulation in the data can be discarded [17, 18] and, when the period and the phase are released in the fit, values well compatible with those expected for a DM particle induced effect are obtained [18]; for example, in the cumulative (2–6) keV energy interval: $A = (0.0116 \pm 0.0013)$ cpd/kg/keV, $T = (0.999 \pm 0.002)$ yr.
and $t_0 = (146 \pm 7) \text{ day}$. Summarizing, the analysis of the single-hit residual rate favours the presence of a modulated cosine-like behaviour with proper features at $8.9 \sigma$ C.L.\cite{18}.

The same data of Fig.\cite{1} have also been investigated by a Fourier analysis, obtaining a clear peak corresponding to a period of 1 year \cite{18}; this analysis in other energy regions shows instead only aliasing peaks. Moreover, while in the (2–6) keV single-hit residuals a clear modulation is present, it is absent at energies just above \cite{18}. In particular, in order to verify absence of annual modulation in other energy regions and, thus, to also verify the absence of any significant background modulation, the energy distribution measured during the data taking periods in energy regions not of interest for DM detection has also been investigated. 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 part of the spectrum; thus, if a modulation detected in the lowest energy region would be 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. The data analyses have allowed to exclude the presence of a background modulation in the whole energy spectrum at a level much lower than the effect found in the lowest energy region for the single-hit events \cite{18}. A further relevant investigation has been done by applying the same hardware and software procedures, used to acquire and to analyse the single-hit residual rate, to the multiple-hits events in which more than one detector “fires”. 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, this allows the study of the background behaviour in the same energy interval of the observed positive effect. The result of the analysis is reported in Fig.\cite{2} where it is shown the residual rate of the single-hit events measured over the six DAMA/LIBRA annual cycles, as collected in a single annual cycle, together with the residual rates of the multiple-hits events, in the same considered energy interval. A clear modulation is present in the single-hit events, while the fitted modulation amplitudes for the multiple-hits residual rate are well compatible with zero \cite{18}. Similar results were previously obtained also for the DAMA/NaI case \cite{5}. 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-hits residual rate (event class to which only background events belong). 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 further excluding any side effect either from hardware or from software procedures or from background.

Figure 2: Experimental residual rates over the six DAMA/LIBRA annual cycles for 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. See text and Refs. [17, 18].

The annual modulation present at low energy has also been analyzed by depicting the differential modulation amplitudes, $S_m$, as a function of the energy; the $S_m$ is the modulation amplitude of the modulated part of the signal obtained by maximum likelihood method over the data, considering $T = 1$ yr and $t_0 = 152.5$ day. The $S_m$ values are reported as function of the energy in Fig. 3. It can be inferred that a positive signal is present in the (2–6) keV energy interval, while $S_m$ values compatible with zero are present just above; in particular, the $S_m$ values in the (6–20) keV energy interval have random fluctuations around zero with $\chi^2$ equal to 27.5 for 28 degrees of freedom. It has been also verified that the measured modulation amplitudes are statistically well distributed in all the crystals, in all the annual cycles and energy bins; these and other discussions can be found in ref. [18].

It is also interesting the results of the analysis performed by releasing the assumption of a phase $t_0 = 152.5$ day in the procedure of maximum likelihood to evaluate the modulation amplitudes from the data of the seven annual cycles of DAMA/NaI and the six annual cycles of DAMA/LIBRA. In this case alternatively the signal has been written as: $S_{0,k} + S_{m,k} \cos \omega (t - t_0) + Z_{m,k} \sin \omega (t - t_0) = S_{0,k} + Y_{m,k} \cos \omega (t - t^*)$, where $S_{0,k}$ and $S_{m,k}$ are the constant part and the modulation amplitude of the signal in $k$-th energy
interval. Obviously, for signals induced by DM particles one would 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; however, it is worth noting that slight differences in the phase could be expected in case of possible contributions from non-thermalized DM components, such as e.g. the SagDEG stream and the caustics. The $2\sigma$ contours in the plane $(S_m, Z_m)$ for the (2–6) keV and (6–14) keV energy intervals and those in the plane $(Y_m, t^*)$ are reported in [18]. The best fit values for the (2–6) keV energy interval are (1$\sigma$ errors): $S_m = (0.0111 \pm 0.0013)$ cpd/kg/keV; $Z_m = -(0.0004 \pm 0.0014)$ cpd/kg/keV; $Y_m = (0.0111 \pm 0.0013)$ cpd/kg/keV; $t^* = (150.5 \pm 7.0)$ day; while for the (6–14) keV energy interval are: $S_m = -(1.0001 \pm 0.0008)$ cpd/kg/keV; $Z_m = (0.0002 \pm 0.0005)$ cpd/kg/keV; $Y_m = -(0.0001 \pm 0.0008)$ cpd/kg/keV and $t^*$ obviously not determined. These results confirm those achieved by other kinds of analyses. In particular, a modulation amplitude is present in the lower energy intervals and the period and the phase agree with those expected for DM induced signals. For more detailed discussions see ref. [18].

Both the data of DAMA/LIBRA and of DAMA/NaI fulfil all the requirements of the DM annual modulation signature.

Sometimes naive statements were put forwards 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), 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.

Careful investigations on absence of any significant systematics or side reaction able to account for the measured modulation amplitude and to simultaneously satisfy all the requirements of the signature have been quantitatively carried out (see e.g. ref. [4, 5, 17, 25, 26, 27, 28, 29], refs therein). No systematics or side reactions able to mimic the signature (that is, able to account for the measured modulation amplitude and simultaneously satisfy all the requirements of the signature) has been found or suggested by anyone over more than a decade.

Figure 4: Regions in the nucleon cross section vs DM particle mass plane allowed by DAMA in three different instances for the Na and I quenching factors: 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 using the energy-dependent Na and I quenching factors [30] [(red) cross-hatched region]. The velocity distributions and the same uncertainties as in Refs. [4, 5] are considered here. The allowed region obtained for the CoGeNT experiment, including the same astrophysical models as in Refs. [4, 5] and assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters, is also reported and denoted by a (black) thick solid line. For details see Ref. [30].

The obtained 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 examples some given scenarios and parameters are discussed e.g. in Refs. [2, 4, 5, 6, 7, 8, 9, 10, 11] and in Appendix A of Ref. [17]. Further large literature is available on the topics; other possibilities are open. Here we just recall the recent papers [30, 31] where the DAMA/NaI and DAMA/LIBRA results, which fulfill all
the many peculiarities of the model-independent DM annual modulation signature, are examined under the particular hypothesis of a light-mass DM candidate particle interacting with the detector nuclei by coherent elastic process. In particular, in Ref. [30] allowed regions are given for DM candidates interacting by elastic scattering on nuclei including some of the existing uncertainties; comparison with theoretical expectations for neutralino candidate and with the recent possible positive hint by CoGeNT [32] is also discussed there (see Fig. 5), while comparison with possible positive hint by Cresst [33] is discussed in Ref. [31].

It is worth noting that no experiment exists, whose result can be directly compared in a model-independent way with those by DAMA/NaI and DAMA/LIBRA.

Some activities (e.g. [34, 35, 36]) claim model-dependent exclusion under many largely arbitrary assumptions (see for example discussions in [4, 17, 5, 37, 38]); often some critical points also exist in their experimental aspects (e.g. use of marginal exposures, determination of the energy threshold, of the energy resolution and of the energy scale in the few keV energy region of interest, multiple selection procedures, non-uniformity of the detectors response, absence of suitable periodical calibrations in the same running conditions and in the claimed low energy region, stabilities, tails/overlapping of the populations of the subtracted events and of the considered recoil-like ones, well known side processes mimicking recoil-like events, etc.); moreover, the existing experimental and theoretical uncertainties are generally not considered in their presented model dependent result. Moreover, implications of the DAMA results are generally presented in incorrect/partial/unupdated way.

3 Upgrades and perspectives

A first upgrade of the DAMA/LIBRA set-up 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, having better performances and a new DAQ with optical read-out was installed.

A further and more important upgrade has been performed in the end of 2010 when all the PMTs have been replaced with new ones having higher quantum efficiency; details on the reached performances are reported in Ref. [39]. The purpose of the last upgrade of the running second generation DAMA/LIBRA set-up is: 1) to increase the experimental sensitivity lowering the software energy threshold of the experiment; 2) to improve the investigation on the nature of the Dark Matter particle and related as-
trophysical, nuclear and particle physics arguments; 3) to investigate other signal features; 4) to improve the sensitivity in the investigation of rare processes other than Dark Matter as done by the former DAMA/NaI apparatus in the past [12] and by itself so far [19, 20]. This requires long and heavy full time dedicated work for reliable collection and analysis of very large exposures, as DAMA collaboration has always done.

Since January 2011 the DAMA/LIBRA experiment is again in data taking in the new configuration, named DAMA/LIBRA-phase 2.

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