DAMA/LIBRA results and perspectives

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Abstract.

The DAMA/LIBRA experiment is running at LNGS; it has a sensitive mass of about 250 kg highly radiopure NaI(Tl) and 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 × yr, collected over 13 annual cycles. They provide a model independent evidence of the presence of DM particles in the galactic halo at 8.9 σ C.L.. Some obtained results are shortly summarized and future perspectives mentioned.

1. Introduction

The DAMA project 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 ¹²⁹Xe or in ¹³⁶Xe [13]; iii) DAMA/R&D, a facility dedicated to tests on prototypes and to perform experiments developing and using various kinds of low background crystal scintillators in order 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] 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 and competitive results have been obtained.

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[20]. As a consequence of the annual revolution of the Earth around
the Sun, moving in the Galaxy with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules, our planet should be crossed by a larger flux of Dark Matter particles around ~2 June (when the Earth orbital velocity has the same versus of the solar system with respect to the Galaxy) and by a smaller one around ~2 December (when the two velocities are opposite). Thus, this signature depends on the composition of the Earth and Sun velocities and it is not correlated with seasons. 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 ~ 2nd June; (4) 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 less about 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. [21, 22]. Only systematic effects or side reactions able to simultaneously fulfil all the mentioned requirements and able to account for the whole observed modulation amplitude might mimic this DM signature; no one has been found or suggested. At present status of technology it is the only model independent signature which can effectively be exploited by direct Dark Matter investigation.

The DAMA/LIBRA data released so far correspond to six annual cycles for an exposure of 0.87 ton·yr [17, 18]. Considering these data together with those previously collected by DAMA/NaI over 7 annual cycles (0.29 ton·yr), the total exposure collected over 13 annual cycles is 1.17 ton·yr; this is orders of magnitude larger than the exposures typically collected in the field.

2. DAMA/LIBRA results

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 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 and the whole installation is air-conditioned. 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. The software energy threshold is 2 keV. The DAMA/NaI set up and its performances are described in ref.[1, 3, 4, 5], while for the DAMA/LIBRA set-up and its performances see refs. [16, 18].

Several analyses on the model-independent DM annual modulation signature have been performed [17, 18]. 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]. In particular, in the cumulative (2–6) keV energy interval one gets: $A = (0.0116 \pm 0.0013)$ cpd/kg/keV, $T = (0.999 \pm 0.002)$ yr and $t_0 = (146 \pm 7)$ day. Thus, the analysis of the single-hit
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. 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 same data of Fig. 1 have also been investigated by a Fourier analysis, obtaining a clear peak corresponding to a period of 1 year [18]; this analysis in other energy regions shows only aliasing peaks instead. Moreover, 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 in energy regions not of interest for DM detection has also been investigated. This has allowed the exclusion 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 [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. 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 (2–6) keV 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 [18]. Similar results were previously obtained also for the DAMA/NaI case [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
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 [17, 18]. See text.

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. 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 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]. Other interesting results have been obtained by analysing the data introducing a sine-like modulation in the maximum likelihood procedure. In this case alternatively the signal can be 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 $S_{0,k}$, $S_{m,k}$ and $Z_{m,k}$ are the constant part, the cosine-like and sine-like modulation amplitudes 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 [7] and the caustics [23]. 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 Fig. 4 [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; $t^* = (150.5 \pm 7.0)$
Figure 3. Energy distribution of the modulation amplitudes $S_m$ for the total cumulative exposure 1.17 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 $\chi^2$ equal to 27.5 for 28 degrees of freedom. See Refs. [17, 18].

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 1.17 ton × yr. See text.
Both the data of DAMA/LIBRA and of DAMA/NaI fulfil all the requirements of the DM annual modulation signature.

Careful investigations on absence of any significant systematics or side reaction have been quantitatively carried out (see e.g. ref. [4, 5, 16, 17, 18, 24], and 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.

3. About interpretation
A rich variety of theoretical patterns are present in literature. The scenarios are stimulating and intriguing to interpret in model dependent way the results coming from different experiments on dark matter investigation.

Anyhow, it is worth noting that DAMA has firstly a model independent result due to the exploitation of a DM signature with specific peculiarities.

About the interpretation of this model independent result in terms of a particular astrophysical, nuclear and particle physics scenario and in order to consider a comparative overview with measurements by other experiments, it is important to refresh that there is neither an unique reference theoretical model of interpretation, nor a single set of assumptions for parameters in astrophysical, nuclear and particle Physics. In addition often comparisons are not performed in a fully consistent way. Thus every model dependent analysis chooses a model framework by fixing many parameters and assumptions, but many uncertainties are present. Uncertainties are present on the models about the nature of the candidate particle, on the interaction coupling, on the form factors for each target material, on spin factors, on the energy threshold, on extrapolated energy scale, on extrapolated energy resolution, definition of a fiducial volume, on possible non-uniformity of some detector response, not regular and/or suitable calibration procedures, on quenching factors, on stability of the operating conditions, etc.. In addition, in some cases, there are significant uncertainties on subtraction/rejection procedures when applied and on the stability of all the selection windows and related quantities. All these aspects can affect results and comparisons at various extent, precluding the comparisons from an universal value.

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 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 [25, 26]; other possibilities are open and we just recall the recent paper [26] on the case of a light-mass Dark Matter candidate particle interacting with the detector nuclei by coherent elastic process; comparison with recent possible positive hint [27] is also given.

It is worth noting that no other experiment exists, whose result can be directly compared in a model-independent way with those by DAMA/NaI and DAMA/LIBRA. Moreover, concerning those activities claiming model dependent exclusion under some largely arbitrary assumptions (see for example discussions in [4, 5, 17, 28, 29]) and generally using marginal exposures, it is worth noting that often important critical points exist in some of their experimental aspects (as discussed before and in many papers); in addition existing experimental and theoretical uncertainties are not considered.

Similar considerations hold for the indirect detection searches, in fact also in this case no direct
model-independent comparison can be performed between the results obtained in direct and indirect activities, since it does not exist a bimivocal correspondence between the observables in the two kinds of experiments. Moreover, these searches are restricted to some DM candidates and scenarios and their results are strongly model dependent. Anyhow, measurements published up to now are not in conflict with the effect observed by DAMA experiments.

4. Upgrades and perspectives
A first upgrade of the DAMA/LIBRA set-up was performed in September 2008. A further and more important upgrade has been performed in the end of 2010 when all the PMTs have been replaced with new ones with higher quantum efficiency; this will allow the lowering of the software energy threshold and, hence, the improvement of the performance and of the sensitivity of the experiment. A deeper corollary information on the nature of the DM candidate particle(s) and on the various related astrophysical, nuclear and particle Physics scenarios will be possible.

Since January 2011 the DAMA/LIBRA experiment is again in data taking in the new configuration. Further improvements are foreseen with new preamplifiers and trigger modules realised to further implement the low energy studies. In the future DAMA/LIBRA will also continue its study on several other rare processes [19] as also the former DAMA/NaI apparatus did [12]. Further developments are in progress.

5. Conclusion
The positive model independent evidence for the presence of DM particles in the galactic halo is now supported by DAMA/NaI and DAMA/LIBRA at 8.9σ C.L.; the cumulative exposure is 1.17 ton×yr, collected over 13 annual cycles. Further corollary analyses in some of the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc., are in progress as well as analyses/data taking to investigate other rare processes. The last upgrade in fall 2010 was successfully concluded and further improvements are planned. The strictly quality control allows DAMA/LIBRA to be still the highest radiopure set-up in the field with the largest exposed sensitive mass, the full control of running conditions, the largest duty-cycle and on the various related astrophysical, nuclear and particle Physics scenarios will be possible.

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