Particle Dark Matter in the galactic halo: results from DAMA/LIBRA

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The first results, obtained by the DAMA/LIBRA set-up of the DAMA project, are shortly addressed. It is in operation deep underground at the Gran Sasso National Laboratory of the I.N.F.N.; its sensitive part consists of $\simeq$ 250 kg highly radiopure NaI(Tl) detectors. The DAMA/LIBRA data confirm the evidence for Dark Matter (DM) particles in the galactic halo on the basis of the DM annual modulation signature. Considering the DAMA/LIBRA data together with those collected by the former DAMA/NaI set-up a confidence level of 8.2 σ is achieved for a cumulative exposure of 0.82 ton $\times$ yr. Future perspectives are just mentioned.

1 Introduction

DAMA is an observatory for rare processes and it is in operation deep underground at the Gran Sasso National Laboratory of the I.N.F.N.. This experiment is mainly based on the development and use of low background scintillators with the aim of investigating DM particles in the galactic halo by means of the direct detection. Its main experimental set-ups are: i) DAMA/NaI ($\simeq$ 100 kg of highly radiopure NaI(Tl)) which completed its data taking on July 2002 [1,2,3,4,5,6,7,8,9,10,11,12,13]; ii) DAMA/LXe ($\simeq$ 6.5 kg liquid Kr-free Xenon enriched either in ^{129}Xe or in ^{136}Xe) [14,15]; iii) DAMA/R&D, devoted to tests on prototypes and to small scale experiments [16]; iv) the new second generation DAMA/LIBRA set-up ($\simeq$ 250 kg highly radiopure NaI(Tl)) in operation since March 2003 [17,18,19]. Moreover, in the framework of devoted R&D for radiopure detectors and photomultipliers, sample measurements are carried out by means of the low background DAMA/Ge detector (installed deep underground since more than 10 years);

the detector is also used for small scale experiments [20]. Profiting of the low background features of these set-ups, many rare processes are also investigated obtaining very competitive results.

DAMA/LIBRA is investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature. This signature – originally suggested in the middle of '80 in ref. [21] – exploits the effect of the Earth revolution around the Sun on the number of events induced by DM particles in the detectors. In fact, as a consequence of its annual revolution, the Earth should be crossed by a larger flux of DM particles around ~ 2 June (when its rotational velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around ~ 2 December (when the two velocities are subtracted). This offers an efficient model independent signature and it allows the test of large interval of cross sections and of halo densities. The DM annual modulation signature is very distinctive since the corresponding signal 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 around $\simeq 2^{nd}$ 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 $\lesssim 7\%$ for usually adopted halo distributions (6), but it can be larger in case of some possible scenarios such as e.g. those in refs. [22,23]. Only systematic effects or side reactions able to fulfil these 6 requirements and to account for the whole observed modulation amplitude might mimic this signature [a]; thus, no other effect investigated so far in the field of rare processes offers a so stringent and unambiguous signature.

2 The DAMA/LIBRA results

Detailed description of DAMA/NaI [1,3,4,5] and of DAMA/LIBRA [17] performances has been published. Here we just remind that: i) the detectors' responses range from 5.5 to 7.5 photoelectrons/keV; ii) each detector is equipped with two low background photomultipliers working in coincidence with hardware threshold at single photoelectron level; iii) energy calibrations with X-rays/γ sources are regularly carried out down to few keV; iv) the software energy threshold of the experiment is 2 keV.

The DAMA/NaI experiment collected an exposure of 0.29 ton$\times$yr over 7 annual cycles, while DAMA/LIBRA has released so far an exposure of 0.53 ton$\times$yr collected over 4 annual cycles; thus, the total exposure of the two experiments is 0.82 ton$\times$yr, which is orders of magnitude larger than the exposure typically collected in the field.

The competitiveness of the DAMA/NaI and DAMA/LIBRA target-detectors is based on the reached intrinsic radiopurity of the NaI(Tl) scintillators (obtained after very long and accurate work for the selection of all low radioactive materials, for the definition of suitable protocols, etc.), on the large sensitivity to many DM candidates, interaction types and astrophysical, nuclear and particle Physics scenarios, to the granularity of the set-ups, to the data taking up to the MeV scale (even though the optimization is made for the lowest energy region), to the full control of the running conditions, etc..

Several model-independent analyses have been performed in order to investigate the DM annual modulation signature. Here just few arguments are reminded. In Fig. 1 it is shown the time behaviour of the experimental residual rates (i.e. the rate after subtracting its constant

[a] It is worth noting that the DM annual modulation is not – as often naively said – a "seasonal" variation and it is not a "winter-summer" effect. In fact, the DM annual modulation is not related to the relative Sun position, but it is related to the Earth velocity in the galactic frame. Moreover, the phase of the DM annual modulation (roughly 2^{nd} June) is well different than those of physical quantities (such as temperature of atmosphere, pressure, other meteorological parameters, cosmic rays flux, ...) instead correlated with seasons.

part) for *single-hit* events collected by DAMA/NaI and by DAMA/LIBRA in the (2–4), (2–5) and (2–6) keV energy intervals. The superimposed curves represent the cosinusoidal functions: $A\cos\omega(t-t_0)$ with $T=\frac{2\pi}{\omega}=1$ yr and phase $t_0=152.5$ day (June 2^{nd}), while the modulation amplitudes, A, have been obtained by best fit over the DAMA/NaI and DAMA/LIBRA data. When the period and the phase parameters are released in the fit, values well compatible with those expected for a DM particle induced effect are obtained [18]. Summarizing, the cumulative analysis of the *single-hit* residual rate favours the presence of a modulated cosine-like behaviour with proper features at 8.2 σ C.L. [18].

The same data of Fig.1 have also been investigated by a Fourier analysis [18]. 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 spectrum above 6 keV 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

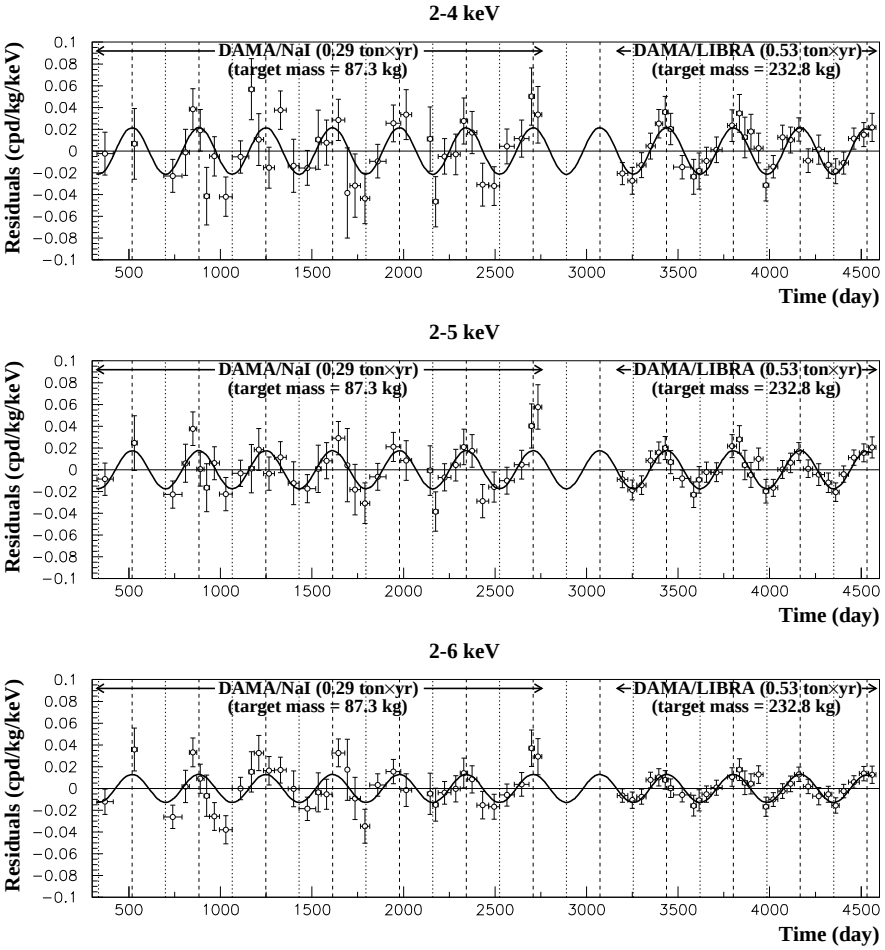

Figure 1: Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/NaI and DAMA/LIBRA in the (2 – 4), (2 – 5) and (2 – 6) keV energy intervals as a function of the time. The zero of the time scale is January 1^{st} of the first year of data taking of DAMA/NaI. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the cosinusoidal functions behaviors $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, with a phase $t_0=152.5$ day (June 2^{nd}) and with modulation amplitudes, A, equal to the central values obtained by best fit over the whole data, that is: (0.0215 ± 0.0026) cpd/kg/keV, (0.0176 ± 0.0020) cpd/kg/keV and (0.0129 ± 0.0016) cpd/kg/keV for the (2 – 4) keV, for the (2 – 5) keV and for the (2 – 6) keV energy intervals, respectively. The dashed vertical lines correspond to the maximum of the signal (June 2^{nd}), while the dotted vertical lines correspond to the minimum. The total exposure is 0.82 ton × yr. For details see [18].

equal or larger modulation should be present in the higher energy regions. The data analyses 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 [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* events, to the *multiple-hits* ones. 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 verification of the background behaviour in the same energy interval where the positive effect is observed. In particular, Fig. 2 shows the residual rates of the *single-hit* events measured over the four DAMA/LIBRA annual cycles, presented as if they would have been collected in a single annual

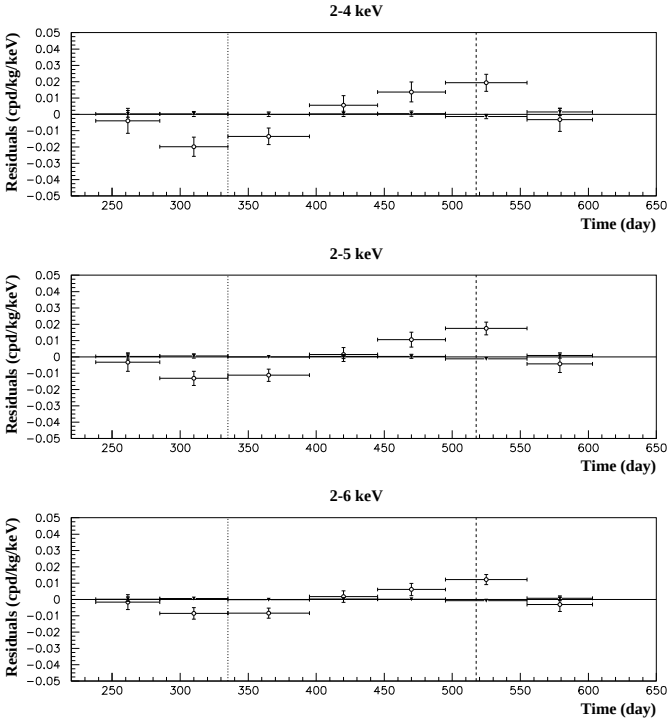

Figure 2: Experimental residual rates over the four DAMA/LIBRA annual cycles for *single-hit* events (open circles) (class of events to which DM events belong) and for *multiple-hits* events (filled triangles) (class of events to which DM events do not belong), in the energy intervals (2 – 4), (2 – 5) and (2 – 6) keV, respectively. 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 scale is taken on August 7^{th}. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. See ref. [18]. Analogous results were obtained for the DAMA/NaI data in ref. [5].

cycle, together with the residual rates of the *multiple-hits* events. 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: $-(0.0004\pm0.0008)$ cpd/kg/keV, $-(0.0005\pm0.0007)$ cpd/kg/keV, and $-(0.0004\pm0.0006)$ cpd/kg/keV in the energy regions (2 – 4), (2 – 5) and (2 – 6) keV, respectively. 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* residual rate (events class to which the DM particle induced events belong), while it is absent in the *multiple-hits* one (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.

The annual modulation present at low energy has also been shown by depicting the differential modulation amplitudes, $S_{m,k}$, as a function of the energy; the $S_{m,k}$ 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. In Fig. 3 the measured $S_{m,k}$ for the total exposure (0.82 ton×yr, DAMA/NaI and DAMA/LIBRA) are reported as function of the energy. A positive signal is present in the (2–6) keV energy interval, while $S_{m,k}$ values compatible with

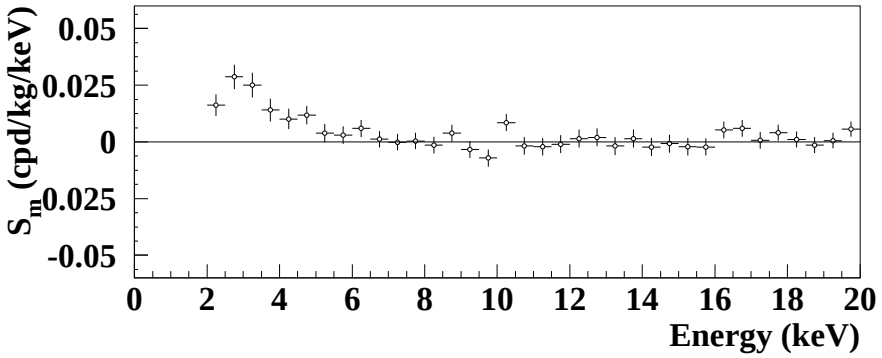

Figure 3: Energy distribution of the $S_{m,k}$ variable for the total exposure of DAMA/NaI and DAMA/LIBRA: 0.82 ton×yr. A clear modulation is present in the lowest energy region, while $S_{m,k}$ values compatible with zero are present just above. In fact, the $S_{m,k}$ values in the (6–20) keV energy interval have random fluctuations around zero with $\chi^2/d.o.f.$ equal to 24.4/28. See ref. [18].

zero are present just above. In fact, the $S_{m,k}$ values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 24.4 for 28 degrees of freedom.

It has also been verified that the measured modulation amplitudes are statistically well distributed in all the crystals, in all the annual cycles and in the energy bins; these and other discussions can be found in ref. [18]. Other analyses have also been carried out [18].

All the analyses confirm that a modulation amplitude is present in the lower energy intervals with the period and the phase in agreement with those expected for DM induced signals. In addition, the observed annual modulation signal fulfils all the requirements of the DM signature.

As previously done for the case of DAMA/NaI [3,4,5], careful investigations on absence of any significant effect from systematics or side reaction have been quantitatively carried out also for DAMA/LIBRA; it is reported in details in ref. [18]. In Table 1 the results obtained by investigating all possible sources of systematics and side reactions are reported. No systematics or side reactions able to account for the measured modulation amplitude and to contemporaneously satisfy all the requirements of the signature have been found or suggested by anyone over more than a decade.

Summarizing, DAMA/LIBRA has confirmed the presence of an annual modulation satisfying all the requirements of the DM annual modulation signature; in particular, the evidence for the presence of DM particles in the galactic halo is cumulatively supported by DAMA/NaI and DAMA/LIBRA at 8.2 σ C.L..

3 On corollary quests and on comparisons

As regards the corollary investigation on the nature of the DM candidate particle(s) and related astrophysical, nuclear and particle Physics scenarios, it has been shown – on the basis of the DAMA/NaI result – that the obtained model independent evidence can be compatible with a wide set of possibilities (see e.g. ref. [4,5,6,8,9,10,11] and in literature, for example see [24]); many others are also open. This is also the case when the DAMA/NaI and DAMA/LIBRA data are

Table 1: Summary of the results obtained by investigating all possible sources of systematics and side reactions in the data of the DAMA/LIBRA four annual cycles. None able to give a modulation amplitude different from zero has been found; thus cautious upper limits (90% C.L.) on the possible contributions to the measured modulation amplitude have been calculated and are shown here. It is worth noting that none of them is able to mimic the DM annual modulation signature, that is none is able to account for the observed modulation amplitude and to contemporaneously satisfy all the requirements of the signature. For details see ref. [18]. Analogous results were obtained for DAMA/NaI[4,5].

Source	Main comment (also see ref.[17])	Cautious upper limit (90%C.L.)
Radon	Sealed Cu Box in HP Nitrogen atmosphere, 3-level of sealing	$< 2.5 \times 10^{-6}$ cpd/kg/keV
Temperature	Air conditioning + huge heat capacity	$< 10^{-4}$ cpd/kg/keV
Noise	Efficient rejection	$< 10^{-4}$ cpd/kg/keV
Energy scale	Routine + intrinsic calibrations	$< 1 - 2 \times 10^{-4}$ cpd/kg/keV
Efficiencies	Regularly measured	$< 10^{-4}$ cpd/kg/keV
Background	No modulation above 6 keV; no modulation in the (2 – 6) keV *multiple-hit* events; this limit includes all possible sources of background	$< 10^{-4}$ cpd/kg/keV
Side reactions	From muon flux variation measured by MACRO	$< 3 \times 10^{-5}$ cpd/kg/keV
In addition: no effect can mimic the signature		

considered all together; an updating of allowed volumes/regions in some given frameworks is foreseen.

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. In particular, let us also point out that results obtained with different target materials and/or different approaches cannot intrinsically be directly compared among them even when considering the same kind of candidate and of coupling, although apparently all the presentations generally refer to cross section on nucleon.

In particular, claims for contradictions made by experiments insensitive to the DM annual modulation signature, using different target materials and approaches, exploiting marginal exposures, having well different sensitivities to various DM candidate and interactions, etc. have by the fact no impact even in the single arbitrary scenario they usually consider (without accounting for experimental and theoretical uncertainties, often using crude approximation in the calculation, etc). Moreover, as pointed out (see for example [25]), some critical points exist on relevant experimental aspects. Finally, a relevant argument is also the methodological robustness [26].

Finally, as regards the indirect detection searches, let us note that also no direct model-independent comparison can be performed between the results obtained in direct and indirect activities, since it does not exist a biunivocal correspondence between the observables in the two kinds of experiments. Anyhow, if possible excesses in the positron to electron flux ratio and in the γ rays flux with respect to some simulations of the hypothesized contribution, which is expected from standard sources, might be interpreted in terms of Dark Matter (but e.g. more complete handling of some aspects of the simulations are available [27] and the pulsars contribution

[28] should also be included), this would not be in conflict with the experimental observations by DAMA experiments.

4 Already performed and planned upgradings

During September 2008 the first upgrading of the DAMA/LIBRA set-up has been realized and the shield has been opened in HP Nitrogen atmosphere. This has allowed the increase of the exposed mass, since one detector has been recovered by replacing a broken PMT. Moreover, a new optimization of some PMTs and HVs has been done. Finally, a total replacement of the used transient digitizers with new ones, having better performances, has been realized and a new DAQ with optical fibers has been installed and put in operation. The data taking has been restarted on October 2008.

In particular, the model independent results achieved by the DAMA/LIBRA set-up has pointed out the relevance to lower the software energy threshold used by the experiment. Thus, the replacement of all the PMTs with other ones with higher quantum efficiency has been planned; this will also improve – as evident – other significant experimental aspects.

A larger exposure collected by DAMA/LIBRA (or possibly by DAMA/1ton; see later) and the lowering of the 2 keV energy threshold will improve the corollary information on the nature of the DM candidate particle(s) and on the various related astrophysical, nuclear and particle Physics scenarios.

In addition, it is worth noting that ultra low background NaI(Tl) scintillators can also offer the possibility to achieve significant results on several other rare processes as already done e.g. by the former DAMA/NaI apparatus [12,13].

Finally, we mention that a third generation R&D effort towards a possible NaI(Tl) ton set-up was funded.

5 Conclusions

The highly radiopure NaI(Tl) DAMA set-ups have investigated the presence of DM particles in the galactic halo by exploiting the DM annual modulation signature; they have cumulatively achieved a model independent evidence at 8.2 σ C.L..

The collection of larger exposures (with the upgraded DAMA/LIBRA or possibly with DAMA/1ton) can allow a significant investigation of several open aspects on the nature of the candidate particle(s) and on the various related astrophysical, nuclear and particle Physics as well as other DM features and second order effects.

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