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DAMA RESULTS: DARK MATTER IN THE GALACTIC HALO

R. Bernabei[a,b,*], P. Belli[b], F. Cappella[c,d], V. Caracciolo[e], R. Cerulli[e], C.J. Dai[f], A. d'Angelo[c,d], A. Di Marco[a,b], H.L. He[f], A. Incicchitti[d], X.H. Ma[f], F. Montecchia[b,g], X.D. Sheng[f], R.G. Wang[f], Z.P. Ye[f,h]

[a] *Dip. di Fisica, Università di Roma "Tor Vergata", I-00133 Rome, Italy*
[b] *INFN, sez. Roma "Tor Vergata", I-00133 Rome, Italy*
[c] *Dip. di Fisica, Università di Roma "La Sapienza", I-00185 Rome, Italy*
[d] *INFN, sez. Roma, I-00185 Rome, Italy*
[e] *Laboratori Nazionali del Gran Sasso, I.N.F.N., Assergi, Italy*
[f] *IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China*
[g] *Laboratorio Sperimentale Policentrico di Ingegneria Medica, Università degli Studi di Roma "Tor Vergata"*
[h] *University of Jing Gangshan, Jiangxi, China*
[*] corresponding author: rita.bernabei@roma2.infn.it

Abstract. Experimental efforts and theoretical developmens support that most of the Universe is Dark and a large fraction of it should be made of relic particles; many possibilities are open on their nature and interaction types. In particular, the DAMA/LIBRA experiment at Gran Sasso Laboratory (sensitive mass: ~ 250 kg) is mainly devoted to the investigation of Dark Matter (DM) particles in the Galactic halo by exploiting the model independent DM annual modulation signature with higly radiopure Na I(Tl) targets. DAMA/LIBRA is the succesor of the first generation DAMA/Na I (sensitive mass: ~ 100 kg); cumulatively the two experiments have released so far the results obtained by analyzing an exposure of 1.17 t yr, collected over 13 annual cycles. The data show a model independent evidence of the presence of DM particles in the galactic halo at 8.9σ confidence level (C.L.). Some of the already achieved results are shortly reminded, the last upgrade occurred at fall 2010 is mentioned and future perspectives are sumarized.

Keywords: dark matter, dark matter annual modulation signature, highly radiopure Na I(Tl) crystals.

1. Introduction

About one century of experimental efforts and of theoretical developments has pointed out that most of our Universe is Dark and that a large fraction of it should be in form of relic particles. Many possibilities are open about the nature and the interaction types of such particles. Often WIMP is adopted as a synonymous of DM particle, referring usually to a particle with spin-independent elastic scattering on nuclei. On the contrary, WIMP identifies a class of DM candidates which can have different phenomenologies and interaction types. There are many open aspects, having large impact on model dependent investigations and comparisons, as e.g. which is the right description of the dark halo and related parameters, which is the right related atomic/nuclear and particle physics, etc. as well as the fundamental question on how many kinds of DM particles exist in the Universe.

The experiments at accelerators could prove the existence of some possible DM candidate particles, but they could never credit by themselves that a certain particle is in the halo as a solution or the only solution for DM particle(s). Moreover, DM candidate particles and scenarios (even for neutralino candidate) exist which cannot be investigated at accelerators. Thus, to pursue direct detection of DM particles with a model independent approach, with suitably large exposure, with full control of the running conditions and ultra-low-background (ULB) widely sensitive target material is mandatory.

The direct detection of DM particles is based on different approaches. The DM interaction processes can be of well different nature depending on the candidate, as e.g.:

(1.) elastic scatterings on target nuclei with either spin-indepedent or spin-dependent or mixed coupling; moreover, additional electromagnetic contribution in case of few GeV candidates can arise from excitation of bound electrons by the recoiling nuclei [1];

(2.) inelastic scatterings on target nuclei with either spin-indepedent or spin-dependent or mixed coupling in various scenrios [2, 3];

(3.) interaction of light DM (LDM) either on electrons or on nuclei with production of a lighter particle [4];

(4.) preferred interaction with electrons [5];

(5.) conversion of DM particles into electromagnetic radiation [6];

(6.) etc.

Thus, considering the richness of particle possibilities and the existing uncertainties on related astrophysical (e.g. halo model and related parameters, etc.), nuclear (e.g. form factors, spin factors, scaling laws, etc.) and particle physics (e.g. particle nature and interaction types, etc.), a widely-sensitive model independent approach is mandatory as well as a suitable exposure, and full control of the running condition over the whole data taking.

At present the only model independent signature, which can be effectively exploited is the DM annual modulation signature, originally suggested in [7] and investigated by the DAMA experiments at the Gran Sasso National Laboratory with highly radiopure Na I(Tl) as target-detectors; in the following the already-achieved results (see [8–14] and references therein) are briefly summarized.

2. The DAMA project

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. Profiting of the low background features of the realized set-ups, many rare processes are studied [1, 4–6, 8–13, 15–25].

The main apparatus, DAMA/LIBRA, is investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature.

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 DM particles around June 2 (when the Earth orbital velocity is summed to the one of the Sun with respect to the Galaxy) and by a smaller one around December 2 (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 June 2;

(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 $\simeq 7\,\%$ 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 [3, 26].

The DAMA/LIBRA data released so far correspond to six annual cycles for an exposure of 0.87 t yr [9, 10]. Considering these data together with those previously collected by DAMA/Na I over 7 annual cycles (0.29 t yr), the total exposure collected over 13 annual cycles is 1.17 t yr; this is orders of magnitude larger than the exposures typically released in the field.

The DAMA/Na I set up and its performances are described in [15, 17–19], while the DAMA/LIBRA set-up and its performances are described in [8, 10]. The sensitive part of the DAMA/LIBRA set-up is made of 25 highly radiopure Na I(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-fold 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. A software energy threshold of 2 keV is considered. The experiment takes data up to the MeV scale and thus it is also sensitive to high energy signals. For all the details see [8].

Several analyses on the model-independent DM annual modulation signature have been performed (see [9, 10] and references therein). Figure 1 shows the time behaviour of the experimental residual rates of the *single-hit* events collected by DAMA/Na I and by DAMA/LIBRA in the $(2 \div 6)$ keV energy interval [9, 10]. 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 2), 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 [9, 10] 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 [10]; for example, in the cumulative $(2 \div 6)$ keV energy interval: $A = (0.0116 \pm 0.0013)$ cpd/kg/keV, $T = (0.999 \pm 0.002)$ yr and $t_0 = (146 \pm 7)$ day. Summarizing, the analysis of

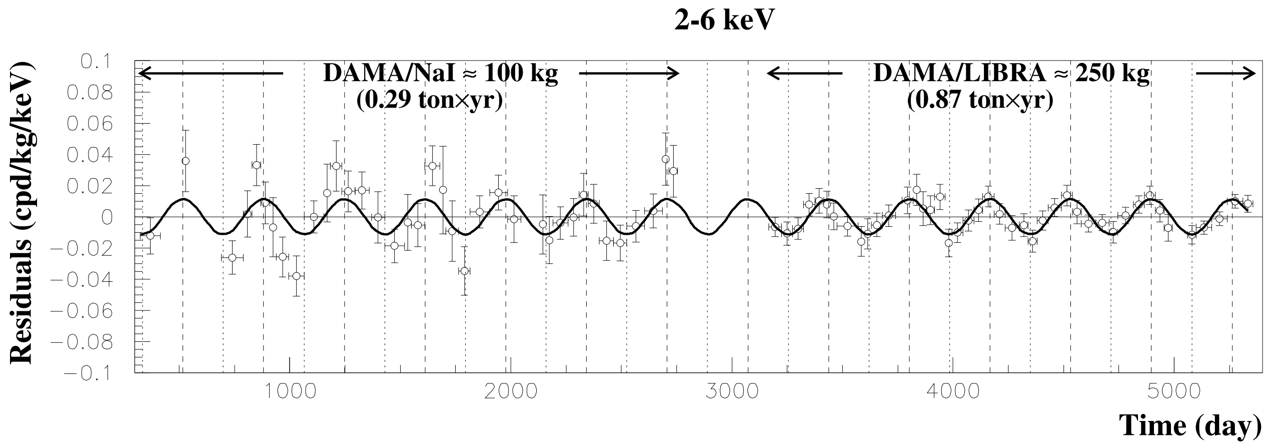

Figure 1. Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/Na I over seven and by DAMA/LIBRA over six annual cycles in the $(2 \div 6)$ keV energy interval as a function of the time [9, 10, 18]. The zero of the time scale is January 1 of the first 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 $T = \frac{2\pi}{\omega} = 1\,\mathrm{yr}$, phase $t_0 = 152.5$ day (June 2) 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 2), while the dotted vertical lines correspond to the minimum ([9, 10] and references therein).

the *single-hit* residual rate favours the presence of a modulated cosine-like behaviour with proper features at 8.9σ confidence level (C.L.) [10].

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 [10]; 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 [10]. 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. 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 [10]. Similar results were previously obtained also for the DAMA/Na I case [19].

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

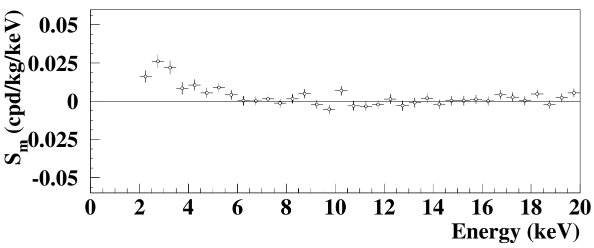

Figure 2. Energy distribution of the modulation amplitudes S_m for the total cumulative exposure 1.17 t yr obtained by maximum likelihood analysis. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the $(6 \div 20)$ keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom [9, 10].

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. 2. It can be inferred that a positive signal is present in the $(2 \div 6)$ keV energy interval, while S_m values compatible with zero are present just above; in particular, the S_m values in the $(6 \div 20)$ keV energy interval have random fluctuations around zero with χ^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 [10].

These results confirm those achieved by other kinds of analyses. In particular, a modulation is present in the rate of the *single-hit* events of the lower energy intervals; the period and the phase agree with those expected for DM signals [10]. 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. [8–10, 13, 18, 27], and references 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.

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 [1, 4–6, 16, 18–21] and in Appendix A of [9]. Further large literature is available on the topics [28]; other possibilities are open. Here we just recall the recent papers [29, 30] where the DAMA/NaI and DAMA/LIBRA results, which fulfil 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; comparison with some recent possible positive hints [31, 32] are also given.

No other experiment exists, whose result can be directly compared in a model-independent way with those by DAMA/NaI and DAMA/LIBRA. Some activities claim model-dependent exclusion under many largely arbitrary assumptions (see for example discussions in [9, 18, 19, 33, 34]); often some critical points 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.), and the existing experimental and theoretical uncertainties are usually not considered in their presented model dependent result. Moreover, implications of the DAMA results are generally presented in incorrect/partial/not-updated way, as appeared in many papers in literature and in conferences.

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 biunivocal 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.

In conclusion, for completeness we remind: i) the recent possible positive hints presented by CoGeNT and Cresst exploiting different approaches/different target materials; ii) the uncertainties in the model dependent results and comparisons; iii) the relevant argument of the methodological robustness [35]. In particular, the general considerations on comparisons reported in Appendix A of [9] still hold; on the other hand, whatever possible "positive" result has to be interpreted and a large room of compatibility with the DAMA annual modulation evidence is present.

3. Last DAMA/LIBRA upgrade and perspectives

The positive model independent evidence for the presence of DM particles in the galactic halo is now supported at 8.9σ C.L. (cumulative exposure: 1.17 t yr, i.e. 13 annual cycles of DAMA/NaI and DAMA/LIBRA). It is worth noting e.g. that: i) the exploited Dark matter annual modulation signature acts itself as a strong background reduction procedure as pointed out since the papers in the 80's, mentioned above; ii) this signature is unambiguous since it requires the simultaneous fulfilment of many peculiarities; iii) the DAMA positive evidence has already been verified over 13 independent experiments of 1 year each one and in different experimental situations (different detectors, different assembling, slight different shield, different electronics, etc.); iv) no systematic or side reaction able to mimic this signature (that is, able to account for the observed modulation amplitude and to simultaneously satisfy all the many peculiarities of the signature) has been found or suggested by anyone over more than a decade.

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.

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; all the details related to the developments and to the features of these high Q.E. PMTs in DAMA/LIBRA are reported in [14].

The purpose of this upgrade is: i) to increase the experimental sensitivity lowering the software energy threshold of the experiment; 2) to improve the corollary investigations on the nature of the Dark Matter particle and related astrophysical, 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. 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, which is identified as DAMA/LIBRA stage 2. Further improvements are foreseen with new preamplifiers and trigger modules realised to further implement the lowest energy studies. Moreover, in the future DAMA/LIBRA will also continue its studies on several other rare processes [11, 12] as also the former DAMA/NaI apparatus did [22]. Further developments are in progress.

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Discussion

Francesco Ronga — When the data with the new set-up will be released?

Rita Bernabei — The first data release will occur when we will have collected and analized adequately large exposure to start to present significant results on the topics which have motivated this effort. For completeness I mention that we plan to release the results of the last annual cycle of DAMA/LIBRA stage 1 in incoming year or before.