DAMA/LIBRA-phase1 results and perspectives of the phase2

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The DAMA/LIBRA experiment — consisting of ∼ 250 kg of highly radio-pure NaI(Tl) — is in data taking in the underground Laboratory of Gran Sasso. The data collected in its first configuration (DAMA/LIBRA—phase1) together with the data of the former DAMA/NaI experiment (∼ 100 kg first generation highly radio-pure NaI(Tl)) correspond to 14 independent annual cycles, for a total exposure of 1.33 ton × yr and point out the presence of DM particle in the Galactic halo at 9.3 σ C.L. on the basis of the model-independent Dark Matter (DM) annual modulation signature. No systematic or side reaction able to mimic the exploited DM signature has been found or suggested by anyone. After an upgrade of the experiment DAMA/LIBRA is now running in its phase2 with increased sensitivity. Here, after briefly reporting the DAMA model independent results, the recent analysis in terms of Mirror Dark Matter candidate will be mentioned.

Keywords: Dark matter; low background scintillators; annual modulation.

1. The annual modulation results

The DAMA project is an observatory of rare processes consisting of various set-ups placed in the underground laboratory of Gran Sasso. Low background scintillators have been developed and used. The main apparatus DAMA/LIBRA, as the former DAMA/NaI (see for example Refs. 8, 16, 17 and references therein), is further investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature.[1–15] This signature is due to the Earth's motion around the Sun; in particular around June 2^{nd} — when the projection of the Earth orbital velocity on the Sun velocity with respect to

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the Galaxy is maximum — the Earth should be crossed by a larger flux of DM particles while around December 2^{nd} — when the two velocities are opposite — the Earth should be crossed by a smaller one.[18] This DM annual modulation signature is very effective since the expected signal rate induced by the DM flux variation must simultaneously satisfy many requirements: the rate must contain a component modulated according to a cosine function (1) with one year period (2) and a phase peaked roughly $\simeq$ 2 June (3); this modulation must only be found in a well-defined low energy range, where events induced by DM particle 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 $\simeq$ 7% for usually adopted halo distributions (6), but it can be larger (even up to $\simeq$ 30%) in case of some possible scenarios. This signature is model independent and it allows to test a large range of cross sections and halo densities. In addition it might be mimicked only by systematic effects or side reactions able to account for the whole observed modulation amplitude and to simultaneously satisfy all the requirements given above. No one is available.[1–4,7,8,12,13,16,17,19]

The exposure collected by DAMA/LIBRA in its first 7 annual cycles (DAMA/LIBRA-phase1) is 1.04 ton × yr; when including also the data collected by the first generation DAMA/NaI experiment, the total exposure is 1.33 ton × yr, corresponding to 14 annual cycles.[2–4,8]

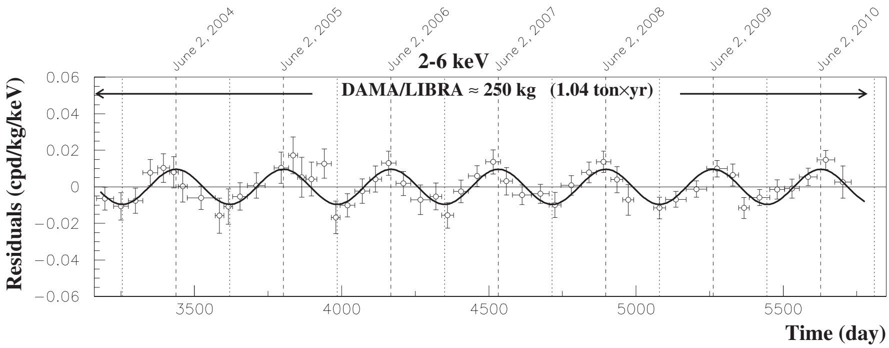

Fig. 1. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/NaI and DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time.[4]

To investigate the presence of an annual modulation in the data many analyses have been carried out. All the analyses point out the presence of an annual modulation in the data that satisfies all the requirements of the signature. Here, as example, the time behaviour of the experimental residual rate of the *single-hit* scintillation events for DAMA/NaI and DAMA/LIBRA—phase1 in the (2–6) keV energy interval is plotted in Fig. 1. The χ^2 test excludes the hypothesis of absence of modulation in the data (P-value = 2.2×10^{-3}). When fitting the reported *single-hit* residual rate 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}), a modulation amplitude $A=(0.0110\pm0.0012)$ cpd/kg/keV is obtained, corresponding to 9.2 σ C.L. When the period, and the phase are kept free in the fit, a modulation amplitude (0.0112 ± 0.0012) cpd/kg/keV (9.3 σ C.L.), the period $T=(0.998\pm0.002)$ year and the phase $t_0=(144\pm7)$ day, are obtained; these values are well in agreement with expectations for the DM annual modulation signal.[4] The run test and the χ^2 test on the data have shown that the modulation amplitudes singularly calculated for each annual cycle of DAMA/NaI and DAMA/LIBRA—phase1 are normally fluctuating around their best fit values.[2–4]

We have also performed a power spectrum analysis of the *single-hit* residuals of DAMA/LIBRA—phase1 and DAMA/NaI, obtaining a clear principal mode in the (2–6) keV energy interval at a frequency of 2.737×10^{-3} d^{-1}, corresponding to a period of $\simeq 1$ year, while only aliasing peaks are present in energy intervals above 6 keV.[8]

Absence of any significant background modulation in the energy spectrum has been verified in energy regions not of interest for DM; it is worth noting that the obtained results account for whatever kind of background and, in addition, no background process able to mimic the DM annual modulation signature is available (see also discussions e.g. in Refs. 1, 2, 3, 4, 7, 8, 12, 13).

A further relevant investigation in the DAMA/LIBRA—phase1 data has been performed by applying the same hardware and software procedures used for the *single-hit* residual rate, to the *multiple-hit* one. 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, the comparison of the results of the *single-hit* events with those of the *multiple-hit* ones corresponds practically to compare between them 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. In particular, the residual rates of the *single-hit* events measured over the DAMA/LIBRA—phase1 annual cycles are reported in Ref. 4 together with the residual rates of the *multiple-hit* events, in the (2–6) keV energy interval. A clear modulation is present in the *single-hit* events, while the fitted modulation amplitude of the *multiple-hit* residual rate in the same energy region (2–6) keV is well compatible with zero: $-(0.0005\pm0.0004)$ cpd/kg/keV. Thus, again evidence of annual modulation with the features 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-hit* residual rate (event class to which only background events belong). This result offers an additional strong support for the presence of a DM particle component in the galactic halo.

Sometimes naive statements were put forward as the fact that in nature several phenomena may show some kind of periodicity. 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 satisfy simultaneously all the requirements of the DM annual modulation signature. The same is also for side reactions. A deep investigation is reported in Refs. 1, 2, 3, 4 and references therein; additional arguments can be found e.g. in Refs. 7, 8, 12, 13. No modulation has been found in any possible source of systematics or side reactions; thus, cautious upper limits on possible contributions to the DAMA/LIBRA measured modulation amplitude have been obtained (see Refs. 2, 3, 4). It is worth noting that they do not quantitatively account for the measured modulation amplitudes, and also are not able to simultaneously satisfy all the many requirements of the signature. Similar analyses have also been performed for the DAMA/NaI data.[16,17] In particular, in Ref. 13 a simple and intuitive way why the neutrons, the muons and the solar neutrinos cannot give any significant contribution to the DAMA annual modulation results is outlined.

In conclusion, DAMA give model-independent evidence (at 9.3σ C.L. over 14 independent annual cycles) for the presence of DM particles in the galactic halo.

Recently an investigation of possible diurnal effects in the *single-hit* low energy scintillation events collected by DAMA/LIBRA—phase1 has been carried out.[12] In particular, a model-independent diurnal effect with the sidereal time is expected for DM because of Earth rotation. The presence of diurnal variation and of diurnal time structures in the data are not pointed out at the present level of sensitivity for both the cases of solar and sidereal time; in particular, the DM diurnal modulation amplitude expected, because of the Earth diurnal motion, on the basis of the DAMA DM annual modulation results is below the present sensitivity.[12] It will be possible to investigate such a diurnal effect with adequate sensitivity only when a much larger exposure will be available; moreover better sensitivities can also be achieved by lowering the software energy threshold as in the presently running DAMA/LIBRA—phase2.

For completeness we recall that recently we have also performed an analysis considering the so called “Earth Shadow Effect”.[14] Other rare processes have also been searched for by DAMA/LIBRA-phase1; see for details Refs. 9, 10, 11.

2. The case of asymmetric mirror matter

The model independent annual modulation effect observed by the DAMA experiments has recently also been investigated — among the many possibilities — in terms of a mirror-type dark matter candidates in some scenarios (see Ref. 15 and references therein). Here we just recall some arguments.

In the framework of asymmetric mirror matter, the DM originates from hidden (or shadow) gauge sectors which have particles and interaction content similar to that of ordinary particles.[15] In the asymmetric mirror matter considered scheme, the mirror world becomes a heavier and deformed copy of our world, with mirror

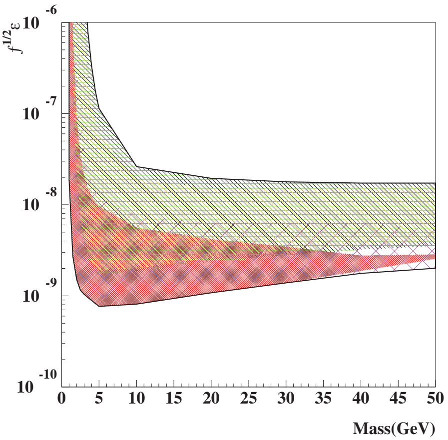

Fig. 2. Allowed regions for the $\sqrt{f}\epsilon$ parameter as function of $M_{A'}$, mirror hydrogen mass, obtained by marginalizing all the models for each considered scenario. The $M_{A'}$ interval from few GeV up to 50 GeV is explored. These allowed intervals identify the $\sqrt{f}\epsilon$ values corresponding to C.L. larger than 5σ from the *null hypothesis*, that is $\sqrt{f}\epsilon = 0$. The allowed regions corresponding to five different scenarios are depicted in different hatching; the black line is the overall boundary.[15].

particle masses scaled in different ways with respect to the masses of the ordinary particles. In particular, one possibility is that dark matter would exist in the form of mirror hydrogen composed of mirror proton and electron, with mass of about 5 GeV which is a rather interesting mass range for dark matter particles. Owing to the large mass of mirror electron, mirror atoms should be more compact and tightly bound with respect to ordinary atoms. The annual modulation observed by DAMA in the framework of asymmetric mirror matter has been analysed in the light of the very interesting interaction portal which is kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$ of two massless states, ordinary photon and mirror photon. This mixing mediates the mirror atom (that are very compact objects) scattering off the ordinary target nuclei in the NaI(Tl) detectors of the DAMA/LIBRA set-up with the Rutherford-like cross sections.

The data analysis in the Mirror DM model framework allows the determination of the $\sqrt{f}\epsilon$ parameter (where f is the fraction of DM in the Galaxy in form of mirror atoms and ϵ is the coupling constant). In the analysis several uncertainties on the astrophysical, particle physics and nuclear physics models have been taken into account in the calculation. For detailed discussion see.[15] To estimate the free parameter of the analysis (e.g. $\sqrt{f}\epsilon$ in the DM model) a comparison of the expectations of the mirror DM with the experimental results has been performed considering a χ^2 analysis.[15] The obtained values of the $\sqrt{f}\epsilon$ parameter in the case of mirror hydrogen atom, $Z' = 1$, ranges between 7.7×10^{-10} to 1.1×10^{-7}; they are well compatible with cosmological bounds. In addition, releasing the assumption $M_{A'} \simeq 5m_p$, the allowed regions for the $\sqrt{f}\epsilon$ parameter as function of $M_{A'}$, mirror hydrogen mass, obtained by marginalizing all the models for each considered scenario, are shown in Fig. 2 where the $M_{A'}$ interval from few GeV up to 50 GeV is explored. The five scenarios are reported with different hatching of the allowed regions; the black line is the overall boundary.

3. DAMA/LIBRA—phase2 and perspectives

After a first upgrade of the DAMA/LIBRA set-up in 2008, a more important upgrade has been performed at the end of 2010 when all the PMTs have been replaced with new ones having higher Quantum Efficiency (Q.E.), realized with a special dedicated development by HAMAMATSU co.. Details on the developments and on the reached performances are reported in Ref. 6 where the feasibility to decrease the software energy threshold below 2 keV has also been demonstrated.

DAMA/LIBRA—phase2 is continuously running in this configuration in order to increase the experimental sensitivity lowering the software energy threshold of the experiment. Another upgrade at the end of 2012 was concluded: new-concept pre-amplifiers were installed. Further improvements and other possibility to further increase the sensitivity of the set-up are under study.

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