Recent analyses on the DAMA/LIBRA-phase1 data

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Abstract. The DAMA/LIBRA experiment ($\sim$ 250 kg sensitive mass composed by highly radio-pure NaI(Tl)) is in data taking in the underground Laboratory of Gran Sasso (LNGS). The data collected in its first 7 annual cycles, corresponding to the so called DAMA/LIBRA–phase1, have been released. Considering also of the former DAMA/NaI experiment ($\sim$ 100 kg of highly radio-pure NaI(Tl)) the data of 14 independent annual cycles have been analysed exploiting the model-independent Dark Matter (DM) annual modulation signature (total exposure 1.33 ton $\times$ yr). A DM annual modulation effect has been observed at 9.3 σ C.L., thus the presence of DM particles in the galactic halo has been pointed out. No systematic or side reaction able to mimic the observed DM annual modulation has been found or suggested by anyone. At present DAMA/LIBRA is running after an upgrade of the experiment in its phase2 with increased sensitivity.

The DAMA project is devoted to the development and use of low background scintillators for underground physics. The main experiment is DAMA/LIBRA [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] that, after the pioneering DAMA/NaI [8, 16, 17], is further investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature [18].

Because of the Earth's revolution around the Sun, which is moving in the Galaxy, the flux of DM particles impinging a terrestrial detector is expected to be maximum around $\simeq$ June 2^{nd} when the projection of the Earth orbital velocity on the Sun velocity with respect to the Galactic frame is maximum, and minimum around $\simeq$ December 2^{nd} when the two velocities are opposite. This effect, known as DM annual modulation signature, is very effective because

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the signal induced by DM particles 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 at $\simeq$ June 2^{nd} (3); the modulation must only be present in a well-defined low energy range (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 might be mimicked only by systematic effects or side reactions able to simultaneously satisfy all the requirements given above. No one is available [1, 2, 3, 4, 7, 8, 12, 19, 16, 17, 13].

The data of DAMA/LIBRA–phase1 correspond to 1.04 ton $\times$ yr collected in 7 annual cycles; when including also the data of the DAMA/NaI experiment the exposure becomes 1.33 ton $\times$ yr collected in 14 annual cycles. In order to investigate the presence of an annual modulation in the data many analyses have been carried out. All these analyses point out the presence of an annual modulation satisfying all the requirements of the signature [2, 3, 4, 8]. In Fig. 1, as example, it is plotted 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. The χ^2

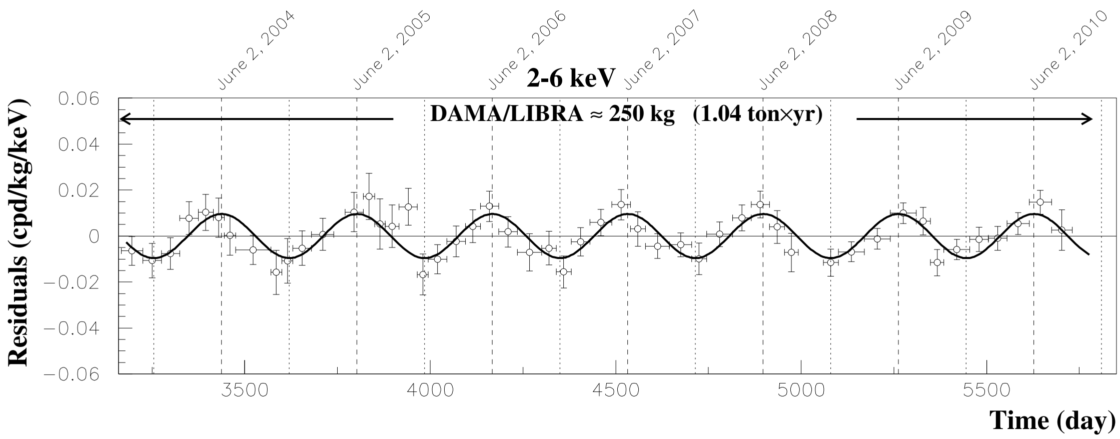

Figure 1. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/NaI and DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time [4].

test excludes the hypothesis of absence of modulation in the data (P-value = 2.2×10^{-3}). When fitting the *single-hit* residual rate of DAMA/LIBRA–phase1 together with the DAMA/NaI ones, 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}) as expected by the DM annual modulation signature, the following modulation amplitude is obtained: $A = (0.0110 \pm 0.0012)$ cpd/kg/keV, corresponding to 9.2 σ C.L.. When the period, and the phase are kept free in the fitting procedure, the modulation amplitude is (0.0112 ± 0.0012) cpd/kg/keV (9.3 σ C.L.), the period $T = (0.998 \pm 0.002)$ year and the phase $t_0 = (144 \pm 7)$ day, values well in agreement with expectations for a DM annual modulation signal. In particular, the phase is consistent with about June 2^{nd} and is fully consistent with the value independently determined by Maximum Likelihood analysis [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, 3, 4].

Absence of any other significant modulation in the energy spectrum has been verified [4]; it is worth noting that the obtained results account for whatever kind of background and, in addition,

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no background process able to mimic the DM annual modulation signature (that is able to simultaneously satisfy all the peculiarities of the signature and to account for the whole measured modulation amplitude) 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 to acquire and to analyse 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. 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: $-(0.0005 \pm 0.0004)$ cpd/kg/keV. Thus, 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). 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.

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. Other arguments can be found in Refs. [7, 8, 12, 13].

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.

As regards comparisons, we recall that no direct model independent comparison is possible in the field when different target materials and/or approaches are used; the same is for the strongly model dependent indirect searches. In particular, the 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, 8, 16] and references therein. Further large literature is available on the topics. In conclusion, both negative results and possible positive hints reported in literature can be compatible with the DAMA model-independent DM annual modulation results in various scenarios considering also the existing experimental and theoretical uncertainties. Moreover, scenarios also exist for which the DAMA approach is favoured.

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 performed also 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].

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

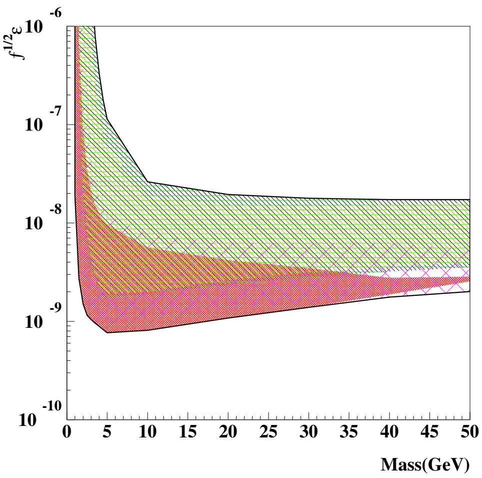

Figure 2. Allowed regions for the $\sqrt{f}\epsilon$ parameter as function of $M_{A'}$, mirror hydrogen mass, obtained by marginalizing all the models for each considered scenario. The $M_{A'}$ interval from few GeV up to 50 GeV is explored. These allowed intervals identify the $\sqrt{f}\epsilon$ values 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; see the details in ref. [15].

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, it is assumed that the mirror parity is spontaneously broken and the electroweak symmetry breaking scale v' in the mirror sector is much larger than that in the Standard Model, $v = 174$ GeV. In this case, the mirror world becomes a heavier and deformed copy of our world, with mirror particle masses scaled in different ways with respect to the masses of the ordinary particles. Taking the mirror weak scale e.g. of the order of 10 TeV, the mirror electron would become two orders of magnitude heavier than the ordinary electron while the mirror nucleons p' and n' only about 5 times heavier than the ordinary nucleons. Then 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. Asymmetric mirror model can be considered as a natural benchmark for more generic types of atomic dark matter with *ad hoc* chosen parameters. 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.

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 order: (1) to increase the experimental sensitivity thanks to the lower software energy threshold of the experiment; (2) to improve the corollary investigation on the nature of the DM particle and related astrophysical, nuclear and particle physics arguments; (3) to investigate other signal features; (4) to investigate rare processes other than DM with high sensitivity. Another upgrade at the end of 2012 was concluded: new-concept pre-amplifiers were installed. Further improvements are planned.

Finally, other possibility to further increase the sensitivity of the set-up are in new R&D studies.

References

[1] Bernabei R *et al* 2008 *Nucl. Instr. and Meth. A* **592** 297
[2] Bernabei R *et al* 2008 *Eur. Phys. J. C* **56** 333
[3] Bernabei R *et al* 2010 *Eur. Phys. J. C* **67** 39
[4] Bernabei R *et al* 2013 *Eur. Phys. J. C* **73** 2648
[5] Belli P *et al* 2011 *Phys. Rev. D* **84** 055014
[6] Bernabei R *et al* 2012 *J. of Instr.* **7** P03009
[7] Bernabei R *et al* 2012 *Eur. Phys. J. C* **72** 2064
[8] Bernabei R *et al* 2013 *Int. J. of Mod. Phys. A* **28** 1330022
[9] Bernabei R *et al* 2009 *Eur. Phys. J. C* **62** 327
[10] Bernabei R *et al* 2012 *Eur. Phys. J. C* **72** 1920
[11] Bernabei R *et al* 2013 *Eur. Phys. J. A* **49** 64
[12] Bernabei R *et al* 2014 *Eur. Phys. J. C* **74** 2827
[13] Bernabei R *et al* 2014 *Eur. Phys. J. C* **74** 3196
[14] Bernabei R *et al* 2015 *Eur. Phys. J. C* **75** 239
[15] Addazi A R *et al* 2015 *Eur. Phys. J. C* **75** 400
[16] Bernabei R *el al* 2003 *La Rivista del Nuovo Cimento* **26** 1
[17] Bernabei R *et al* 2004 *Int. J. Mod. Phys. D* **13** 2127
[18] Drukier K *et al* 1986 *Phys. Rev. D* **33** 3495 ; Freese K *et al* 1988 *Phys. Rev. D* **37** 3388
[19] Bernabei R *et al* 2000 *Eur. Phys. J. C* **18** 283