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DAMA/LIBRA results and perspectives

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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). Its first phase (DAMA/LIBRA–phase1) and the former DAMA/NaI experiment ($\sim$ 100 kg of highly radio-pure NaI(Tl)) collected data for 14 independent annual cycles, 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., supporting the presence of DM particles in the galactic halo. No systematic or side reaction able to mimic the observed DM annual modulation has been found or suggested by anyone. Recent analyses on possible diurnal effects, on the Earth shadowing effect and on possible interpretation in terms of Asymmetric Mirror DM will be mentioned. At present DAMA/LIBRA is running in its phase2 with increased sensitivity.

1 Introduction

The DAMA project is dedicated to the development and use of low background scintillators for underground physics. The main experiment is DAMA/LIBRA [1–15] that, after the pioneering DAMA/NaI [16, 17], is further investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature [18, 19].

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 $\simeq 2^{nd}$ June 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 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 $\simeq 2^{nd}$ June (3); the modulation must only be present in a well-defined low energy range (4); it must

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apply only to those events in which just one detector among 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 (see for example Ref. [20–24]). 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 [1–4, 7, 8, 12, 13, 16, 17, 25].

The full description of the DAMA/LIBRA set-up and performance during the phase1 and phase2 (presently running) and other related arguments have been discussed in details in Refs. [1–4, 6–8, 13] and references therein.

2 DM annual modulation results

The data of DAMA/LIBRA–phase1 and of DAMA/NaI experiment correspond to an exposure of 1.33 ton $\times$ yr collected in 14 annual cycles. In order to investigate the presence of annual modulation with proper features, many analyses have been carried out. All these analyses point out the presence of annual modulation satisfying all the requirements of the signature [2–4, 8]. In Fig. 1, as example, the time behaviour of the experimental residual rate of the *single-hit* scintillation events for DAMA/LIBRA–phase1 in the (2–6) keV energy interva is plotted. 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 (2^{nd} June) as expected by the DM annual modulation signature, the following modulation amplitude in NaI(Tl) 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 2^{nd} June 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 [2–4].

No modulation was found in any possible source of systematics or side reactions; thus, cautious upper limits on possible contributions to the DAMA/LIBRA–phase1 measured modulation amplitude were obtained (see Refs. [2–4]). It is worth noting that they do not quantitatively account for the measured modulation amplitudes, and are even not able to simultaneously satisfy all the many requirements of the signature. Similar analyses were also performed for the DAMA/NaI data [16, 17].

In particular, in Ref. [7, 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. [1–4, 7, 8, 12, 13, 16, 17, 25]. In conclusion, DAMA gives 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, 5, 8, 12, 14–17, 26–40] and references therein. Further large literature is available on the topics (see for example Ref. [41]). In conclusion, both negative results and possible positive hints

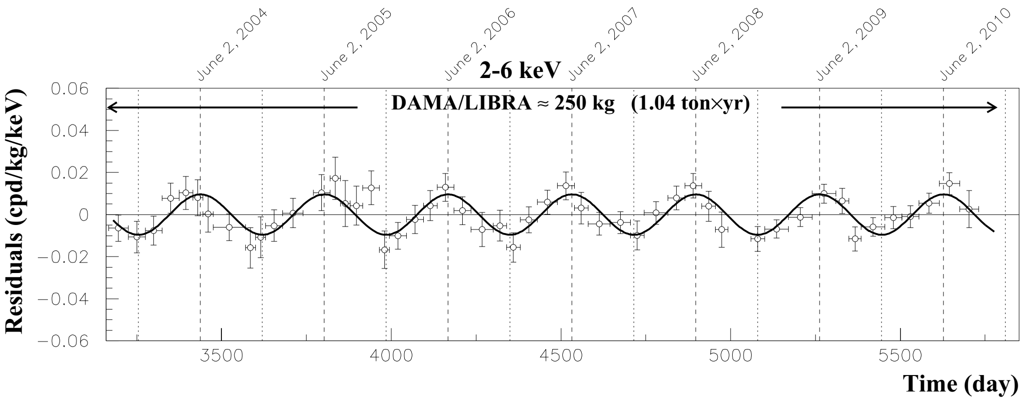

Figure 1. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. The superimposed curve is the cosinusoidal function behaviour $A \cos \omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, a phase $t_0 = 152.5$ day (2^{nd} June) and modulation amplitude, A, equal to the central values obtained by best fit on the data points of the entire DAMA/LIBRA–phase1. The dashed vertical lines correspond to the maximum expected for the DM signal (2^{nd} June), while the dotted vertical lines correspond to the minimum.

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.

Three analyses on the DAMA/LIBRA–phase1 data are summarized in the following. In the first one the presence of possible diurnal effects has been investigated [12], while in the second one the so called "Earth Shadow Effect" has been considered [14]. Finally, the annual modulation result has been interpreted in terms of Asymmetric Mirror DM [15]. These items were extensively studied in the quoted references, here the results are shortly addressed.

3 Diurnal modulation

The results obtained by investigating the presence of possible diurnal variation in the low-energy *single-hit* scintillation events collected by DAMA/LIBRA–phase1 have been analysed in terms of a DM second order model-independent effect due to the Earth diurnal rotation around its axis [12].

Also this daily modulation of the rate on the sidereal time – expected when taking into account the contribution of the Earth rotation – presents some specific peculiarities. In particular the interest in this signature is also that the ratio R_{dy} of this DM diurnal modulation amplitude over the DM annual modulation amplitude is a model independent constant at given latitude; considering the LNGS latitude, $R_{dy} = \frac{S_d}{S_m} \simeq 0.016$. Thus, taking into account the DM annual modulation effect pointed out by DAMA/LIBRA–phase1 for *single-hit* events in the low energy region, the expected value of the diurnal modulation amplitude for the (2–6) keV energy interval is $\simeq 1.5\times 10^{-4}$ cpd/kg/keV. Fig. 2 shows the time behaviour of the experimental residual rates of *single-hit* events both as a function of solar (*left*) and of sidereal (*right*) time, in the (2–6) keV interval [12].

No diurnal variation with a significance of 95% C.L. is found at the reached level of sensitivity [12]. In conclusion the presence of any significant diurnal variation and of time structures can be

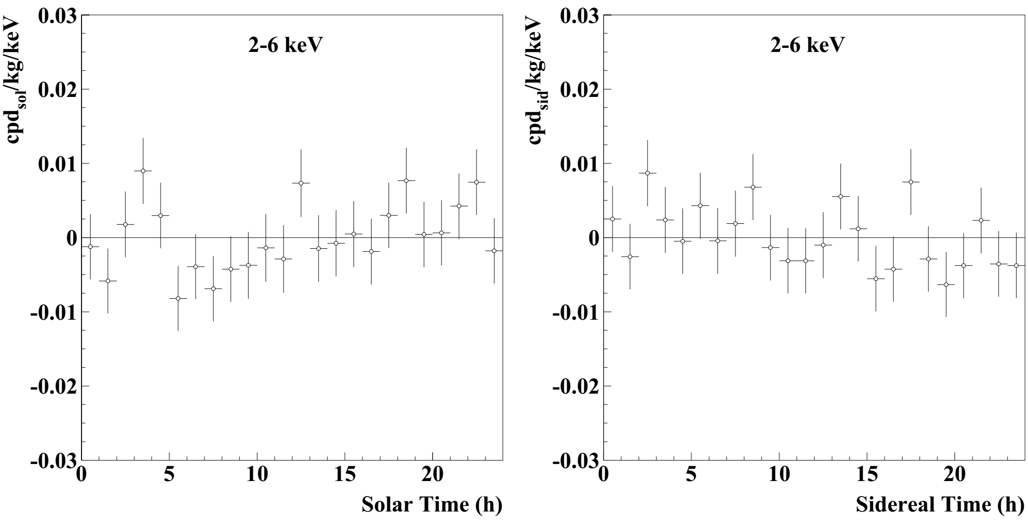

Figure 2. Experimental model-independent diurnal residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA–phase1 in the (2–6) keV energy intervals as a function of the hour of the solar (*left*) and sidereal (*right*) day. See Ref. [12] for details.

excluded at the reached level of sensitivity. In addition, considering the (2–6) keV energy interval the obtained upper limit on the DM diurnal modulation amplitude is 1.2×10^{-3} cpd/kg/keV (90% C.L.) [12]; thus, the effect of DM diurnal modulation, expected because of the Earth diurnal motion on the basis of the DAMA DM annual modulation results, is out the present sensitivity [12]. DAMA/LIBRA–phase2, presently running, with a lower software energy threshold [6] can also offer the possibility to increase sensitivity to such an effect.

4 Daily effect on the sidereal time due to the shadow of the Earth

The results obtained in the investigation of possible diurnal effects for low-energy *single-hit* scintillation events of DAMA/LIBRA–phase1 have been analysed in terms of Earth Shadow Effect, a model-dependent effect that is expected for DM candidates inducing only nuclear recoils and having high cross-section (σ_n) with ordinary matter [14].

In fact a diurnal variation of the low energy rate could be expected for these specific candidates, because of the different thickness of the shield due to the Earth during the sidereal day, eclipsing the wind of DM particles. The induced effect should be a daily variation of their velocity distribution, and therefore of the signal rate measured deep underground. However, this effect is very small and would be appreciable only in case of high cross-section spin independent coupled candidates. Such candidates must constitute a little fraction (ξ) of the Galactic dark halo in order to fulfil the positive DAMA result on annual modulation. By the fact, this analysis decouples ξ from σ_n. Considering the measured DM annual modulation effect and the absence – at the present level of sensitivity – of diurnal effects, the analysis selects allowed regions in the three-dimensional space: ξ, σ_n and DM particle mass in some model scenarios; for details see Ref. [14].

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5 Asymmetric Mirror DM

The model independent annual modulation effect observed by the DAMA experiments has also been investigated in terms of a mirror-type dark matter candidates in some scenarios [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. 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. Then, in this scenario 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.

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. The obtained values of the $\sqrt{f}\epsilon$ parameter in the case of mirror hydrogen atom ranges between 7.7×10^{-10} to 1.1×10^{-7}; they are well compatible with cosmological bounds [15].

In addition, releasing the assumption $M_{A'} \simeq 5m_p$, 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, have been obtained [15].

6 Conclusions and Perspectives

The cumulative exposure with ultra low background NaI(Tl) target by the former DAMA/NaI and DAMA/LIBRA–phase1 is 1.33 ton × yr (orders of magnitude larger than those available in the field) giving a model-independent positive evidence at 9.3 σ C.L. for the presence of DM candidates in the galactic halo with full sensitivity to many kinds of astrophysical, nuclear and particle Physics scenarios. Other rare processes have also been searched for by DAMA/LIBRA-phase1; see for details Refs. [9–11].

After the phase1, an important upgrade has been performed when all the PMTs have been replaced with new ones having higher Quantum Efficiency (QE). In this new configuration a software energy threshold below 2 keV has been reached [6]. DAMA/LIBRA is thus in its phase2, and after optimization periods it is continuously running with higher sensitivity.

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.

Future improvements to increase the sensitivity of the set-up can be considered by using high QE and ultra-low background PMTs directly coupled to the NaI(Tl) crystals. In this way a further large improvement in the light collection and a further lowering of the software energy threshold would be obtained.

Finally, for completeness, we also mention that low background $ZnWO_4$ crystal scintillators have recently been proposed within the DAMA collaboration for the study of the directionality of DM candidates inducing just nuclear recoils. The features and performances of such anisotropic scintillators are very promising [42] and are under exploration.

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