Status and perspectives of DAMA/LIBRA

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The 250 kg highly radiopure NaI(Tl) DAMA/LIBRA experiment is in progress in the Gran Sasso Laboratory in its phase2 after an important upgrade performed in fall 2010. Considering the data collected in the first phase (DAMA/LIBRA–phase1) and with the former DAMA/NaI experiment ($\sim$ 100 kg of highly radio-pure NaI(Tl)) the DAMA Collaboration has released so far data corresponding to 14 independent annual cycles, for a total exposure of 1.33 ton $\times$ yr, exploiting the model-independent Dark Matter (DM) annual modulation signature. Cumulatively 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. Recent analyses considering the Mirror DM candidate will be summarized and the efforts for a possible future third phase of the DAMA/LIBRA experiment mentioned.

The DAMA project is focused on the development and use of low background scintillators for low background measurements. DAMA/LIBRA is the main experiment [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16] being the second generation highly radiopure NaI(Tl) set-up after the pioneering DAMA/NaI [17, 18]. DAMA/LIBRA is further investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature [19, 20].

The DM annual modulation signature is due to the Earth's revolution around the Sun, which is moving in the Galaxy; as a consequence of the velocities composition, the flux of DM particles impinging a terrestrial detector is expected to follow a cosinusoidal behaviour with 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. It is a very effective signature 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

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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 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. This signature is model independent and no systematics or side reactions able to mimic the effect and to to simultaneously satisfy all the requirements is available [1, 2, 3, 4, 7, 8, 12, 13, 17, 18, 21].

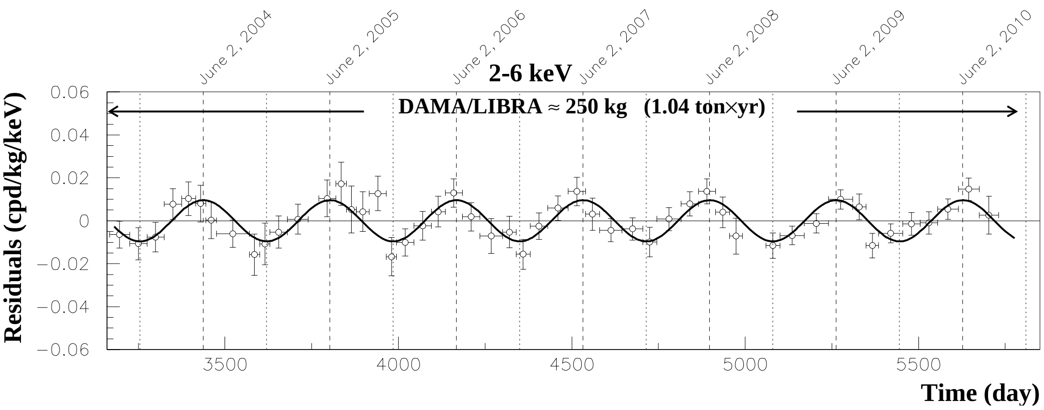

Figure 1: Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. The superimposed curve is the cosinusoidal function behaviour $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2^{nd}) 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 (June 2^{nd}), while the dotted vertical lines correspond to the minimum.

The full description of the DAMA/LIBRA set-up in all its phases is described in details in Refs. [1, 2, 3, 4, 6, 7, 8, 13].

Many independent analyses have been performed on the 14 annual cycles data; all the analyses confirm the presence of an annual modulation satisfying all the features of the signature [2, 3, 4, 8]. In Figure 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 interval 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 (June 2^{nd}) as expected by the DM annual modulation signature, the following modulation amplitude in NaI(Tl) is obtained: $A=(0.0110\pm0.0012)$ 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 $T=(0.998\pm0.002)$ year and the phase $t_0=(144\pm7)$ 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].

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, 3, 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 [17, 18]. In particular, the case of neutrons, muons and solar neutrinos has been discussed in Refs. [7, 13], where it has been demonstrated that they cannot give any significant contribution to the DAMA annual modulation result. Other arguments can be found in Refs. [1, 2, 3, 4, 7, 8, 12, 13, 17, 18, 21]. 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.

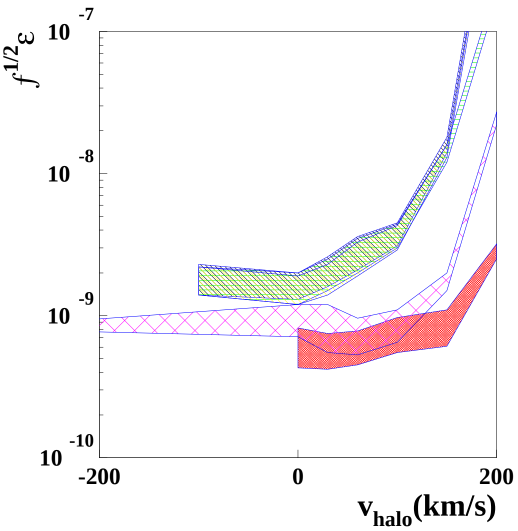

Figure 2: Example of allowed regions for the $\sqrt{f}\epsilon$ parameter as a function of v_{halo} (halo temperature $T = 5 \times 10^5$ K). The regions have been obtained by considering a composite dark halo H′(20%), He′(74%), C′(0.9%), O′(5%), Fe′(0.1%), with $v_0 = 220$ km/s and parameters in the set A. The five contours correspond to different quenching factor modeling (see [16]).

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 scenarios; some given scenarios and parameters are discussed e.g. in Refs. [2, 5, 8, 12, 14, 15, 16, 17, 18, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36] 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 it has been performed an analysis of the DAMA/LIBRA–phase1 data in the framework of a mirror dark matter candidate [15, 16]. In the mirror scenario, the DM particles originate from hidden gauge sectors. Two scenarios have been considered: the asymmetric Mirror DM in Ref. [15] and the symmetric one in Ref. [16]. In both cases, the obtained values of the $\sqrt{f}\epsilon$ (where f is the fraction of DM in the Galaxy in form of mirror atoms and ϵ is the coupling constant) parameter are well compatible with cosmological bounds [15, 16]. In the analysis several uncertainties on the astrophysical, particle physics and nuclear physics models have been taken into account in the calculation.

In the symmetric mirror DM scenario the DM particles are expected to form bubbles in the Galaxy with diameter which could be even as the size of the solar system. The dark halo is composed by different species of mirror DM particles (different mirror atoms) and, at the present epoch, is crossing a region close to the Sun with a constant velocity, v_{halo} in the Galactic frame. The velocity distribution of the particles can be considered maxwellian; it is assumed that the halo has its own local equilibrium temperature, T. In the analysis halo temperature in the range $10^4 - 10^8$ K has been considered. As an example, in Figure 2, the allowed regions for the $\sqrt{f}\epsilon$ parameter as a function of v_{halo} in different scenarios are reported; in particular, the regions have been obtained by considering a composite dark halo composed by H′(20%), He′(74%), C′(0.9%), O′(5%), Fe′(0.1%) with a temperature $T = 5 \times 10^5$ K. The depicted contours correspond to different quenching factor modeling (see [16]).

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 at 1 keV has been reached [6]. DAMA/LIBRA is thus in its phase2, 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 second order effects; 4) to investigate other signal features; 5) to investigate rare processes other than DM with high sensitivity.

Future improvements (possible phase3) 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 are expected.

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