DAMA/LIBRA results and perspectives

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Abstract. The DAMA/LIBRA-phase2 experiment (\(\approx 250 \text{ kg} \)) highly radiopure NaI(Tl) equipped with new high quantum efficiency photomultipliers) is in progress in the Gran Sasso National Laboratory of the I.N.F.N.. When considering the data collected by DAMA/LIBRA\textsuperscript{-phase1} and by the former DAMA/NaI experiment (\(\approx 100 \text{ kg} \)) highly radio-pure NaI(Tl)) the data over 14 independent annual cycles, for a total exposure of 1.33 ton \(\times\) yr, have already been released by exploiting the model-independent Dark Matter (DM) annual modulation signature. Cumulatively a DM annual modulation effect has been observed at 9.3 \(C.L.\) supportive the presence of DM particles in the galactic halo. No systematic effect or side reaction able to mimic the observed DM annual modulation has been found. Recent corollary analyses in frameworks of Mirror DM candidates and R\&D efforts for a possible future DAMA/LIBRA-phase3 are mentioned.

1. DAMA/LIBRA results and a few comments

The DAMA project develops and uses low background scintillators and set-ups to investigate rare processes. DAMA/LIBRA is the main experiment [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]; it is 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 \(\approx June 2^{\text{nd}}\) (when the projection of the Earth orbital velocity on the Sun velocity with respect to the Galactic frame is maximum) and minimum around \(\approx December 2^{\text{nd}}\) (when the two velocities are opposite). This 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 $\approx$ June 2nd (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 $\approx 7\%$ for usually adopted halo distributions (6), but it can be larger (even up to $\approx 30\%$) in case of some possible scenarios. This signature is model independent and no systematic effect or side reaction able to mimic the effect (i.e. able to account for the observed modulation amplitude and to simultaneously satisfy all the requirements of the signature) is available [1, 2, 3, 4, 7, 8, 12, 13, 17, 18, 21].

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 data of the 14 independent annual cycles; all the analyses confirm the presence of a peculiar annual modulation satisfying all the features of the investigated DM signature [2, 3, 4, 8]. In Figure 1, as an 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.

![Figure 1](image-url)

**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 sinusoidal 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 2nd) 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 2nd), while the dotted vertical lines correspond to the minimum.

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 2nd) 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 $\sigma$ C.L.. When the period, and the phase are kept free in the fitting procedure the modulation amplitude is $(0.0112 \pm 0.0012)$ cpd/kg/keV (9.3 $\sigma$ 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 2nd and is fully consistent with the value independently determined by Maximum Likelihood analysis [4]. The run test and the $\chi^2$ 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 details in Refs. [7, 13], where it has been demonstrated that they cannot give any significant contribution to the DAMA annual modulation result. Table 1 summarizes the safety upper limits on the contributions to the observed modulation amplitude due to the total neutron flux at LNGS, either from (α, n) reactions, from fissions and from muons and solar-neutrinos interactions in the rocks and in the lead around the experimental set-up; the direct contributions of muons and solar neutrinos are reported there too. 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 9.3 σ 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 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.

Table 1. Summary of the contributions to the total neutron flux at LNGS; the value, $\Phi_{n}^{(n)}$, the relative modulation amplitude, $\eta_{k}$, and the phase, $t_{k}$, of each component is reported. It is also reported the counting rate, $R_{0,k}$, in DAMA/LIBRA for single-hit events, in the (2 – 6) keV energy region induced by neutrons, muons and solar neutrinos, detailed for each component. The modulation amplitudes, $A_{k}$, are reported as well, while the last column shows the relative contribution to the annual modulation amplitude observed by DAMA/LIBRA, $S_{\text{exp}}^{mm} \approx 0.0112$ cpd/kg/keV [4]. For details see Ref. [13] and references therein.

| Source | $\Phi_{n}^{(n)}$ (neutrons cm$^{-2}$ s$^{-1}$) | $\eta_{k}$ | $t_{k}$ | $R_{0,k}$ (cpd/kg/keV) | $A_{k} = R_{0,k} \eta_{k}$ (cpd/kg/keV) | $A_{k}/S_{\text{exp}}^{mm}$ |
|--------|------------------|-----------|-------|----------------------|-------------------------------|------------------|
| SLOW neutrons | thermal n (10$^{-7}$ – 10$^{-3}$ eV) | $1.68 \times 10^{-6}$ | ≥ 0 | – | < $8 \times 10^{-6}$ | < $8 \times 10^{-6}$ | < $7 \times 10^{-7}$ |
| | epithermal n (eV-keV) | $2 \times 10^{-6}$ | ≥ 0 | – | < $3 \times 10^{-3}$ | < $3 \times 10^{-4}$ | < 0.03 |
| | fission, ($\alpha$, n) → n (1-10 MeV) | < 0.9 | ≥ 0 | – | < $6 \times 10^{-7}$ | < $6 \times 10^{-7}$ | < $5 \times 10^{-7}$ |
| FAST neutrons | $\mu$ → n from rock (> 10 MeV) | $3 \times 10^{-9}$ | 0.0129 | end of June | < $7 \times 10^{-4}$ | < $9 \times 10^{-4}$ | < $8 \times 10^{-4}$ |
| | $\mu$ → n from Pb shield (> 10 MeV) | $6 \times 10^{-9}$ | 0.0129 | end of June | < $1.4 \times 10^{-3}$ | < $2 \times 10^{-4}$ | < $1.6 \times 10^{-3}$ |
| | $\nu$ → n (few MeV) | $3 \times 10^{-10}$ | 0.03442* | Jan. 4th* | < $7 \times 10^{-5}$ | < $2 \times 10^{-6}$ | < $2 \times 10^{-4}$ |
| | direct $\mu$ | $\Phi_{\mu}^{(\mu)} \approx 20 \, \mu$ m$^{-2}$s$^{-1}$ | 0.0129 | end of June | $\approx 10^{-4}$ | $\approx 10^{-4}$ | $\approx 10^{-4}$ |
| | direct $\nu$ | $\Phi_{\nu}^{(\nu)} \approx 6 \times 10^{0} \, \nu$ cm$^{-2}$s$^{-1}$ | 0.03442* | Jan. 4th* | $\approx 10^{-5}$ | $3 \times 10^{-7}$ | $3 \times 10^{-5}$ |

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.
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. Let us also recall for the case of liquid noble gases the comments on fundamental aspects pointed out e.g. in Ref. [37, 38]. Finally it is worth noting that experiments applying statistical multiple rejections of their counting rate and/or use neutron source (and even more high intensity neutron generator as e.g. XENON experiment) cannot reliably investigate the DM annual modulation signature in their target materials.

Finally, for completeness, let us remind the recent investigation on other approaches and second order effects carried out with the DAMA/LIBRA-phase1 data [12, 14] as well as investigation on rare processes other than DM [9, 10, 11]

2. A recent example of corollary analyses

Among the many possible corollary analyses we just mention here the recent one performed on the DAMA/LIBRA-phase1 data in frameworks of mirror dark matter candidates [15, 16], which originate from hidden gauge sectors. Two scenarios have been considered: the asymmetric Mirror DM [15] and the symmetric one [16]. In both cases, the values obtained for the $\sqrt{f\epsilon}$ (where $f$ is the fraction of DM in the Galaxy in form of mirror atoms and $\epsilon$ is the coupling constant) parameter are well compatible with cosmological bounds [15, 16]. In these analyses several uncertainties on the astrophysical, particle physics and nuclear physics models have been taken into account in the calculation. In particular, in the symmetric mirror DM scenario the

$$f \sqrt{\epsilon}$$

![Figure 2](image-url) Figure 2. Example of allowed regions for the $\sqrt{f\epsilon}$ parameter as a function of $v_{\text{halo}}$ (halo temperature $T = 5 \times 10^5$ K). The regions have been obtained by considering a composite dark halo $\text{H}'(20\%), \text{He}'(74\%), \text{C}'(0.9\%), \text{O}'(5\%), \text{Fe}'(0.1\%)$, with $v_0 = 220$ km/s and parameters as given in the set A of ref. [16]. The five contours correspond to different quenching factor modeling (see [16]).

DM particles are expected to form bubbles in the Galaxy with diameter which could be even as large 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, $v_{\text{halo}}$ in the Galactic frame. The velocity distribution of the particles in the bubble 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 $\sqrt{T\epsilon}$ parameter as a function of $v_{\text{halo}}$ in different scenarios are reported; in particular, the regions have been obtained by considering a dark halo made of H$^0$(20%), He$^0$(74%), C$^0$(0.9%), O$^0$(5%), Fe$^0$(0.1%) with a temperature $T = 5 \times 10^5$ K. The depicted contours correspond to different possible quenching factors values (see Ref. [16]). Many other scenarios are discussed in the literature.

3. Perspectives
After DAMA/LIBRA-phase1, an important upgrade has been performed by replacing all the PMTs with new ones having higher Quantum Efficiency (QE). In this new configuration a software energy threshold at 1 keV has been reached [6]. Thus, 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 second order effects; 4) to investigate other signal features; 5) to investigate rare processes other than DM with high sensitivity.

Future improvements to further increase the sensitivity of the set-up (possible DAMA/LIBRA-phase3) can be considered by using new metallic high QE and ultra-low background PMTs to be 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. The developments with Hamamatsu Co. are successful and 4 PMT prototypes are at hand. New protocols, and also alternative ideas, are ongoing that regard the possibility to dismount the light guides of the detectors which also act as optical windows. Finally, the possibility of a pioneer experiment with anisotropic ZnWO$_4$ detectors to further investigate, with the directionality approach, those DM candidates inducing just nuclear recoils is in progress [39]; as e.g. the use of the present detectors untouched but with the new metallic PMTs and new ultra low background crystal scintillators (e.g. ZnWO$_4$) placed among the DAMA/LIBRA detectors in order to reach a high sensitivity and contemporarily to perform directionality measurements is ongoing.

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