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Highlights of DAMA/LIBRA

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Abstract. The DAMA project develops and uses new/improved low background scintillation detectors to investigate the Dark Matter (DM) particle component(s) in the galactic halo and rare processes deep underground at the Gran Sasso National Laboratory (LNGS) of the I.N.F.N.. Here some highlights of DAMA/LIBRA (Large sodium Iodide Bulk for Rare processes) as a unique apparatus in direct DM investigation for its full sensitive mass, target material, intrinsic radio-purity, methodological approach and all the controls performed on the experimental parameters are outlined. The DAMA/LIBRA–phase1 and the former DAMA/NaI data (cumulative exposure 1.33 ton $\times$ yr, corresponding to 14 annual cycles) have reached a model-independent evidence at 9.3 σ C.L. for the presence of DM particles in the galactic halo exploiting the DM annual modulation signature with highly radio-pure NaI(Tl) target. Some of the perspectives of the presently running DAMA/LIBRA–phase2 are summarised and the powerful tools offered by a model independent strategy of DM investigation are pointed out.

1 Introduction

The DAMA/LIBRA experiment [1–15] as the former DAMA/NaI (see e.g. Refs. [8, 16, 17]), has the main aim to investigate the presence of DM particles in the galactic halo by exploiting the model-independent DM annual modulation signature (originally suggested in Refs. [18, 19]).

As a consequence of the Earth's revolution around the Sun, which is moving in the Galaxy with respect to the Local Standard of Rest towards the star Vega near the constellation of Hercules, the Earth should be crossed by a larger flux of DM particles around ≃2 June and by a smaller one around ≃2 December. In the former case the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy, while in the latter the two velocities are subtracted. Therefore the DM

[a] Deceased.

annual modulation signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons.

This DM annual modulation signature is very distinctive since the effect induced by DM particles must simultaneously satisfy all the following requirements: the rate must contain a component modulated according to a cosine function (1) with one year period (2) and a phase that peaks roughly $\simeq 2$ June (3); this modulation must only be found in a well-defined low energy range, where DM particle induced events 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. Thus this signature is model independent, very effective and, in addition, it allows the test of a large range of DM candidates, interaction types, cross sections and of halo densities. In this case the experimental observable is not – as in other experiments – the constant part of the signal, S_0, but its modulation amplitude, S_m, as a function of energy.

This approach has several advantages; in particular, the only background of interest is the one able to mimic the signature, i.e. able to account for the whole observed modulation amplitude and to simultaneously satisfy all the many specific peculiarities of this signature. No background of this sort has been found or suggested by anyone over more than a decade. Thus, this approach does not require any identification of S_0 from the total counting rate in order to establish the presence of DM particles in the galactic halo. Therefore, the DM annual modulation signature allows one to overcome the large uncertainties associated to: (1) the many data selections/subtractions/statistical-discrimination procedures; (2) the modelling of surviving background in keV region; (3) the a priori assumption on the nature, interaction type, etc. of the DM particle(s), which are necessary in the experiments where the experimental observable is S_0. When the DM annual modulation signature is applied, S_0 can be worked out by corollary model dependent analysis to investigate on the nature of DM candidates, for each considered framework.

The full description of the DAMA/LIBRA set-up and performances during the phase1 and phase2 (presently running) and other related arguments have been discussed in details in Refs. [1–8] and references therein. Here we just point out that the sensitive part of this set-up is made of 25 highly radio-pure NaI(Tl) crystal scintillators (5-rows by 5-columns matrix) having 9.70 kg mass each one. The detectors are housed in a sealed low-radioactive copper box installed in the centre of a low-radioactive Cu/Pb/Cd-foils/polyethylene/paraffin shield. Moreover, about 1 m concrete, made from the Gran Sasso rock material, almost fully surrounds (mostly outside the barrack) this passive shield, acting as a further neutron moderator. A threefold-level sealing system prevents the detectors to be in contact with the environmental air of the underground laboratory. The radio-purity, the protocols, the procedures and the details are discussed in Refs. [1–8] and references therein.

2 DAMA/LIBRA

DAMA/LIBRA is the successor of DAMA/NaI with a higher exposed mass, higher duty cycle and increased sensitivity. Its modularity is an interesting feature to study DM and background identification. The apparatus has also the unique feature (as well as the former DAMA/NaI) that gamma calibrations are regularly performed down to the software energy threshold in the same conditions as in the production runs, without any contact of the detectors with the environment and without switching-off the electronics.

The high light yield and other response features have allowed working in a safe and reliable way down to 2 keV (DAMA/LIBRA–phase1). The light response of the detectors during phase1 typically ranged from 5.5 to 7.5 photoelectrons/keV, depending on the detector. The hardware threshold of each photomultiplier (PMT) was at single photoelectron, while a software energy threshold of 2 keV electron equivalent (hereafter keV) was used.

At the end of DAMA/LIBRA–phase1 new PMTs with higher quantum efficiency were installed, other optimisations were performed during 2011 and then data taking started as DAMA/LIBRA–phase2, allowing a decrease in the energy threshold. In addition the developments of other new electronic modules have been progressed and new-concept preamplifiers were installed. Studies on other DM features, second order effects, and several other rare processes are in progress as well as the data taking. Preliminary studies on the possibility to realise new concepts PMTs towards a possible phase3 have been started.

Among further scientific goals of this apparatus we point out here: i) investigation with high sensitivity of the DM particle component in the galactic halo by the model independent approach known as DM annual modulation signature, with highly precise determination of the modulation parameters (which carry crucial information); ii) corollary investigations on the nature of the candidate and on the many possible astrophysical, nuclear and particle physics scenarios; iii) investigations on other possible model dependent and/or model independent approaches to further investigate DM particles' features and second order effects; study of exotic scenarios (as SIMPs, neutral nuclearites, Q-balls, etc.); iv) improved search for processes of Pauli exclusion principle violation in ^{23}Na and ^{127}I; v) search for possible electric charge non-conservation (CNC) processes (electron decay into invisible channels, $e^- \rightarrow \nu_e + \gamma$, excitations of nuclear levels of ^{23}Na and ^{127}I after CNC electronic capture); vi) search for possible nucleon, di-nucleon and tri-nucleon decay into invisible channels in ^{23}Na and in ^{127}I; vii) search for solar axions by Primakoff effect in NaI(Tl); viii) search for nuclear rare decays in ^{23}Na, ^{127}I and Tl isotopes (super-dense states, cluster decay, etc.); ix) search for possible neutral particles (QED new phase) in ^{241}Am decays, etc. Most of these investigations will require further dedicated data taking and high exposure to reach competitive sensitivities. As regards the DM features, which can be suitably further exploited collecting very large exposure, see e.g. Sect. 6 of Ref. [17], Appendix of Ref. [2], Ref. [13]. In particular, that Appendix shows how the decreasing of the software energy threshold as in the present DAMA/LIBRA–phase2 also offers the unique possibility to investigate the modulation amplitude at lower energy, disentangling among many DM scenarios when a suitable exposure is collected.

3 DM annual modulation results

The total exposure of DAMA/LIBRA–phase1 is 1.04 ton × yr in seven annual cycles; when including also that of the first generation DAMA/NaI experiment it is 1.33 ton × yr, corresponding to 14 annual cycles [2–4, 8].

Figure 1 shows the time behaviour of the experimental residual rates of the *single-hit* scintillation events in the (2–6) keV energy interval for the complete DAMA/LIBRA–phase1. The residuals of the DAMA/NaI data (0.29 ton × yr) are given in Refs. [2, 16, 17]. These residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part: $< r_{ijk} - flat_{jk} >_{jk}$. Here r_{ijk} is the rate in the considered *i*-th time interval for the *j*-th detector in the *k*-th energy bin, while $flat_{jk}$ is the rate of the *j*-th detector in the *k*-th energy bin averaged over the cycles. The average is made on all the detectors (*j* index) and on all the energy bins (*k* index) which constitute the considered energy interval. The weighted mean of the residuals must obviously be zero over one cycle.

A clear modulation is present in the (2–6) keV single-hit events and fulfils all the requirements of the DM annual modulation signature; in particular, no modulation is observed either above 6 keV or in the (2–6) keV multiple-hits events [2–4]. Many other analysis have been performed (Fourier analysis,

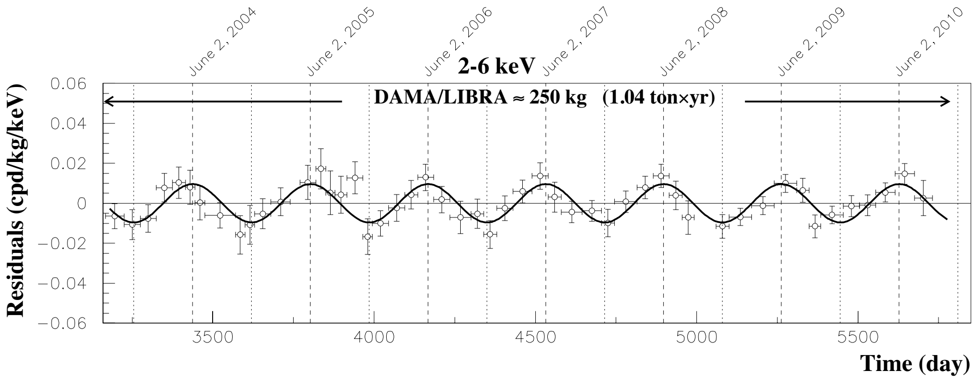

Figure 1. Experimental residual rate of the *single-hit* scintillation events measured by DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. The time scale is maintained the same of the previous DAMA papers for coherence. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. 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.

maximum likelihood analysis, etc.) that further confirm the same evidence [2–4]. In general it is worth noting that this model independent signature, based on the correlation of the measured experimental rate with the Earth galactic motion, itself acts as an effective background rejection, while rejection strategies cannot safely be applied. In fact, the effect searched for (which is in most scenarios at level of few %) would be largely affected by the uncertainties associated to the rejection procedure.

The DAMA/LIBRA–phase1 data give evidence for the presence of DM particles in the galactic halo, on the basis of the exploited model independent DM annual modulation signature by using highly radio-pure NaI(Tl) target, at 7.5 σ C.L.. Including also the first generation DAMA/NaI experiment (cumulative exposure 1.33 ton × yr, corresponding to 14 annual cycles), the C.L. is 9.3 σ. In particular, with the cumulative exposure the modulation amplitude of the single-hit events in the (2–6) keV energy interval, measured in NaI(Tl) target, is (0.0112 ± 0.0012) cpd/kg/keV; the measured phase is (144 ± 7) days (corresponding to May 24 ± 7 days) and the measured period is (0.998 ± 0.002) year, values well in agreement with those expected for the DM particles.

At present status of technology DM annual modulation is the only model independent signature available in direct DM investigation that can be effectively exploited. All the many specific requirements of the signature are fulfilled by the DAMA data and no systematic or side reaction able to mimic it is available (see e.g. Refs.[2–4, 6, 7, 16, 17, 20]).

Sometimes naive statements were put forward as the fact that in nature several phenomena may show some kind of periodicity. It is worth noting that the point is whether they might mimic the annual modulation signature in DAMA/NaI and in DAMA/LIBRA, i.e. whether they might be not only quantitatively able to account for the observed modulation amplitude but also able to contemporaneously satisfy all the requirements of the DM annual modulation signature. The same is for side reactions too. This has already been deeply investigated and discussed in DAMA literature.

In particular, in Refs. [6, 7] a quantitative evaluation why the neutrons, the muons and the solar neutrinos cannot give any significant contribution to the DAMA annual modulation results and cannot mimic this signature is outlined. Table 1 summarises 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.

Table 1. Summary of the contributions to the total neutron flux at LNGS; the value, $\Phi^{(n)}_{0,k}$, the relative modulation amplitude, η_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, $S_m^{exp} \simeq 0.0112$ cpd/kg/keV [4]. For details see Ref. [7] and references therein.

Source		$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)	$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2} - 10^{-1}$ eV)	1.08×10^{-6}	$\simeq 0$ however $\ll 0.1$	–	$< 8 \times 10^{-6}$	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6}	$\simeq 0$ however $\ll 0.1$	–	$< 3 \times 10^{-3}$	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$	$\simeq 0$ however $\ll 0.1$	–	$< 6 \times 10^{-4}$	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$	0.0129	end of June	$\ll 7 \times 10^{-4}$	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$	0.0129	end of June	$\ll 1.4 \times 10^{-3}$	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$	0.03342*	Jan. 4th*	$\ll 7 \times 10^{-5}$	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
direct μ		$\Phi^{(\mu)}_0 \simeq 20\ \mu$ m^{-2}d^{-1}	0.0129	end of June	$\simeq 10^{-7}$	$\simeq 10^{-9}$	$\simeq 10^{-7}$
direct ν		$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\ \nu$ cm^{-2}s^{-1}	0.03342*	Jan. 4th*	$\simeq 10^{-5}$	3×10^{-7}	3×10^{-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 any case no systematic effects or side reactions able to account for the whole observed modulation amplitude and to simultaneously satisfy all the requirements of the exploited DM signature have been found. A detailed discussion about all the related arguments can be find in Refs. [1–4, 6–8, 13, 16, 17, 20].

The long-standing annual-modulation evidence measured in DAMA experiments is model-independent, i.e. in particular independent on theoretical interpretations of the identity of DM and specifics of its interactions. It can be related to a variety of interaction mechanisms of DM particles with the detector materials and is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle Physics. For example, some of the scenarios available in literature and the different parameters are discussed in Refs.[2, 8, 16] and references therein, and recently e.g. in Refs. [15, 21] . A further large literature is available on the topics; many possibilities are open.

Moreover, both negative results and positive hints are largely compatible with the DAMA model-independent DM annual modulation results in many scenarios considering the existing experimental and theoretical uncertainties (see e.g. Refs. [8, 9, 22–24]); the same holds for indirect approaches which are strongly model dependent.

4 Other signatures?

In the framework of direct DM investigations crystal scintillators represent a reliable technology to investigate model independent signatures. An apparatus made by an array of such detectors, in addition to the already mentioned advantages, allows a long term stability and effective routine calibrations down to keV energy region in the same conditions as production runs. Moreover due to the wide choice of nuclei and isotopes, they are sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios. In particular in order to disentangle in the corollary investigation on the candidate particle(s) at least some of the many possible astrophysical, nuclear and particle Physics scenarios and related experimental and theoretical uncertainties, the decreasing of the software energy threshold and higher exposures are necessary.

Finally the ultimate challenge and the only effective method for such studies is the investigation of a model independent signature and of second order effects.

Many topics could be investigated:

- the peculiarities of the annual modulation phase;
- the peculiarities of the DM interaction mechanisms;
- the velocity and spatial distribution of the DM particles in the galactic halo;
- the effects induced on the DM particles distribution in the galactic halo by contributions from satellite galaxies tidal streams;
- the effects induced on the DM particles distribution in the galactic halo by the possible existence of caustics;
- the detection of possible solar wakes or gravitational focusing effect of the Sun on the DM particle;
- the investigation of possible diurnal effects and so on.

Some of these studies already started with DAMA/LIBRA–phase1([8, 13, 23] and references therein), but a further important step towards such investigations will be represented by the larger exposure collected by DAMA/LIBRA–phase2, with lower energy threshold.

4.1 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 (1.04 ton × year exposure) have been analysed in terms of a DM second order model-independent effect due to the Earth diurnal rotation around its axis [13]. In particular, the data were analysed using the sidereal time referred to Greenwich, often called GMST.

This daily modulation of the rate on the sidereal time, expected when taking into account the contribution of the Earth rotation velocity, has several requirements as the DM annual modulation effect does. The interest in this signature is that the ratio R_{dy} of this diurnal modulation amplitude over the annual modulation amplitude is a model independent constant at given latitude; considering the LNGS latitude one has:

$$R_{dy} = \frac{S_d}{S_m} \simeq 0.016 \qquad (1)$$

Taking into account R_{dy} and the DM annual modulation effect pointed out by DAMA/LIBRA–phase1 for *single-hit* events in the low energy region, it is possible to derive the diurnal modulation amplitude expected for the same data. In particular, when considering the (2–6) keV energy interval, the observed annual modulation amplitude in DAMA/LIBRA–phase1 is: (0.0097 ± 0.0013) cpd/kg/keV [4] and the expected value of the diurnal modulation amplitude is $\simeq 1.5\times 10^{-4}$ cpd/kg/keV.

For completeness figure 2 shows the time and energy 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 and (6–14) keV intervals. The used time bin is 1 (either solar or sidereal) hour.

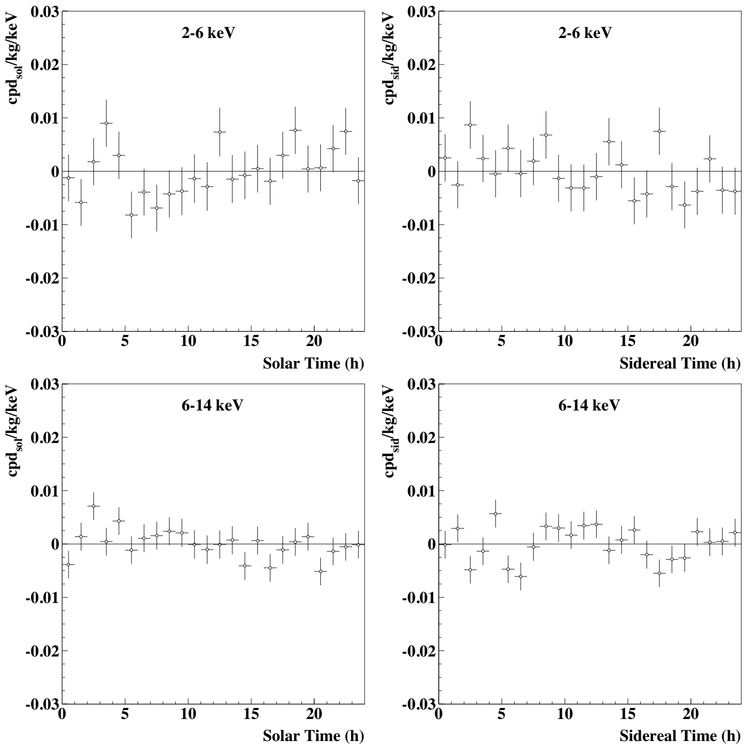

Figure 2. Experimental model-independent diurnal residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA–phase1 in the (2–6) and (6–14) keV energy intervals as a function of the hour of the solar (*left*) and sidereal (*right*) day. The experimental points present the errors as vertical bars and the associated time bin width (1 hour) as horizontal bars. The cumulative exposure is 1.04 ton × yr. See Ref. [13] for details.

The null hypothesis (absence of residual rate diurnal variation) has been tested by a χ^2 test, obtaining the results given in table 2; there the upper tail probabilities (P-values), calculated by the standard χ^2 distribution, are also reported. Thus, no diurnal variation with a significance of 95% C.L. is found at the reached level of sensitivity.

In addition to the χ^2 test, another independent statistical test has been applied: the run test [13] ; it verifies the hypothesis that the positive and negative data points are randomly distributed. The lower tail probabilities are equal to: 7% and 26% in the (2–6) and (6-14) keV energy region, respectively, for the solar case and 78% and 16% in the (2–6) and (6-14) keV energy region, respectively, for the sidereal case. Thus, in conclusion the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity (see e.g. the error bars in figure 2).

Table 2. Test of absence of diurnal effect in the DAMA/LIBRA–phase1 data. The P-values, calculated by the standard χ^2 distribution, are also shown. As can be seen, the χ^2 test supports the hypothesis that the diurnal residual rates in DAMA/LIBRA–phase1 are simply fluctuating around zero.

Energy	Solar Time	Sidereal Time
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24 → P = 6%

In order to compare the experimental data with the DM diurnal effect due to the Earth rotation around its axis, the sidereal diurnal modulation amplitude of the (2–6) keV energy interval is taken into account: $A_d^{exp} = -(1.0 \pm 1.3) \times 10^{-3}$ cpd/kg/keV. Following the Feldman-Cousins procedure an upper limit can be obtained for the measured diurnal modulation amplitude: $A_d^{exp} < 1.2 \times 10^{-3}$ cpd/kg/keV (90% C.L.); thus, the DAMA/LIBRA–phase1 experimental sensitivity is not sufficient to point out this second order diurnal effect (expected amplitude $\simeq 1.5\times 10^{-4}$ cpd/kg/keV).

In conclusion, at that level of sensitivity of DAMA/LIBRA–phase1 the presence of a significant diurnal variation and of diurnal time structures in the data can be excluded for both the cases of solar and sidereal time. In particular, the sidereal diurnal modulation amplitude expected – because of the Earth diurnal motion – on the basis of the DAMA DM annual modulation results cannot be investigated at the present sensitivity; DAMA/LIBRA–phase2, presently running, with a lower software energy threshold [5] can also offer an alternative possibility to increase sensitivity to such an effect.

4.2 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 (1.04 ton × year exposure) have been analysed in terms of Earth Shadow Effect, a model-dependent effect that could be expected in case of DM candidates inducing just nuclear recoils and having high cross-section with ordinary matter, which implies low DM local density in order to fulfil the DAMA/LIBRA DM annual modulation results [14].

In fact a diurnal variation of the low energy rate could be expected [25, 26] for these specific candidates, because during the sidereal day the Earth shields a given detector with a variable thickness, eclipsing the wind of DM particles. The induced effect should be a daily variation of their velocity distribution, therefore of their flux and, of course, 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 that could constitute a little fraction (ξ) in the Galactic dark halo.

The Earth's velocity in the galactic frame, $\vec{v}_e(t)$[1], defines an angle, θ, with the vector joining the centre of the Earth to the position of the laboratory. Because of the Earth's rotational motion, the θ angle varies with the diurnal sidereal time and ranges between a minimum and a maximum which depend on the laboratory position on the Earth. In particular the larger is the allowed range of θ the larger is the effect resulting. The time dependence of θ can be expressed as a function of the laboratory latitude, λ, according to $\cos\theta(t) = \cos\psi\cos\lambda\cos(\omega t + \phi_0) + \sin\psi\sin\lambda$, where $\omega = (2\pi/24^h)$ is the Earth's angular rotational velocity and t the sidereal time in hours. The angles $\psi = (48.1)^0$ and $\phi_0 = (42.4)^0$ depend on the orientation of the Earth axis in the galactic frame [27].

By the fact, the diurnal variation of the velocity distribution and of the counting rate proves undetectable for cross-sections on proton $\leq 10^{-3}$ pb, since the Earth is practically transparent to similar

[1] The Earth's orbital speed around the Sun, which is the most relevant component for the annual modulation signature among the terms contributing to $\vec{v}_e(t)$, can be neglected in the present case because the data, taken in different periods during the year, contribute approximately to the same diurnal time intervals.

particles, while high cross-section values give velocity distributions (and counting rates) significantly dependent on the considered time interval, producing a well detectable diurnal effect.

A study on diurnal variation in the rate with suitable exposure and stability could allow to investigate in some model scenarios high cross sections (σ_p) DM particle component (with small ξ) in the dark halo and decouple ξ from σ_p.

In particular, for each set of parameters [14], one can evaluate the $\xi\sigma_n$ allowed values as:

$$\xi\sigma_n = \frac{S_m^{exp}}{S'_{m,(2-4)keV}(m_{DM}, \sigma_n)}. \tag{2}$$

This corresponds, once including the experimental uncertainties on S_m^{exp}, to a band in the ξ vs σ_n plane.

Finally, for each considered set of parameters the three-dimensional allowed region in the parameter's space: ξ, σ_n, m_{DM} can be studied. In Ref. [14] results in a considered scenario and details are given.

4.3 Directionality with anisotropic scintillators

For completeness, we also mention a different approach for the direct detection of DM candidates inducing just nuclear recoils; it is based on the study of the correlation of the nuclear recoil direction with the Earth velocity [28]. This approach has relevant technical difficulties, when the detection of the short nuclear recoil track is pursued; similar activities are up to now at R&D stage.

An interesting possibility is offered by anisotropic scintillators [29, 30]. They have different light responses depending on the nucleus recoil direction with respect to the scintillator's axes. Since the response to γ/β radiation is isotropic instead, these detectors can offer the possibility to efficiently study possible anisotropy of nuclear recoils [29–32].

So directionality can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day. In fact the diurnal Earth rotation changes the impinging direction of the DM particle flux and therefore the mean direction of the recoil nuclei induced by DM particle with respect to the crystal axes.

Low background $ZnWO_4$ crystal scintillators have recently been proposed because their light output and pulse shape depend on the direction of the impinging particles with respect to the crystal axes. Both these anisotropic features can provide two independent ways to exploit the directionality approach; the features and performances of such scintillators are very promising [33] and will be explored in future.

5 Conclusions

The data of DAMA/LIBRA–phase1 have further confirmed the presence of a peculiar annual modulation of the *single-hit* events in the (2–6) keV energy region satisfying all the many requirements of the DM annual modulation signature. The cumulative exposure with NaI(Tl) target by the former DAMA/NaI and DAMA/LIBRA–phase1 is 1.33 ton × yr giving a model-independent positive evidence at 9.3 σ C.L. and a full sensitivity to many kinds of astrophysical, nuclear and particle Physics scenarios.

DAMA/LIBRA is continuously running in its new configuration (named DAMA/LIBRA–phase2) with a lower software energy threshold aiming to improve the knowledge on corollary aspects regarding the signal and on second order effects. It can play a unique role in the future, both in the investigation of DM peculiarities and in the search for rare processes. Further efforts are also in progress, in particular preliminary studies on the possibility to realise new concepts PMTs towards a possible phase3.

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