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NEW RESULTS FROM DAMA/LIBRA: FINAL MODEL-INDEPENDENT RESULTS OF DAMA/LIBRA-PHASE1 AND PERSPECTIVES OF PHASE2

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Abstract

The DAMA/LIBRA–phase1 and the former DAMA/NaI data (cumulative exposure 1.33 ton × yr, corresponding to 14 annual cycles) give evidence at 9.3 σ C.L. for the presence of Dark Matter (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. Few arguments on results and comparisons will be summarized.

1 Introduction

About 80 years of experimental observations and theoretical arguments have pointed out – both at Galaxy and larger scales – that a large fraction of the Universe is composed by Dark Matter particles [1].

[1]For completeness, we recall that some efforts to find alternative explanations to Dark Matter have been proposed such as *MOdified Gravity Theory*

The presently running DAMA/LIBRA ($\simeq$ 250 kg of full sensitive target-mass) [1, 2, 3, 4, 5, 6, 7, 8] experiment, as well as the former DAMA/NaI ($\simeq$ 100 kg of full sensitive target-mass) [9, 10, 11, 12, 13], 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 Ref. [14]). Moreover, the developed highly radio-pure NaI(Tl) target-detectors [1] and the adopted procedures assure as well sensitivity to a wide range of DM candidates (both inducing nuclear recoils and/or electromagnetic radiation), interaction types and astrophysical scenarios.

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 $\simeq$ 2 June and by a smaller one around $\simeq$ 2 December[2]. 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. 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 (9 in DAMA/NaI and 25 in DAMA/LIBRA) actually "fires" (*single-hit* events),

(MOG) and *MOdified Newtonian Dynamics* (MOND); they hypothesize that the theory of gravity is incomplete and that a new gravitational theory might explain the experimental observations. MOND modifies the law of motion for very small accelerations, while MOG modifies the Einstein's theory of gravitation to account for an hypothetical fifth fundamental force in addition to the gravitational, electromagnetic, strong and weak ones. But: i) there is no general underlying principle; ii) they are generally unable to account for all small and large scale observations; iii) they fail to reproduce accurately the Bullet Cluster; iv) generally they require some amount of DM particles as seeds for the structure formation.

[2]Thus, the DM annual modulation signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons (consider the expected value of the phase as well as the other requirements listed below).

since the DM particle multi-interaction probability is negligible (5) and this offers in DAMA experiments an unique further way of signal identification and background rejection; 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 such as e.g. those in Ref. [15, 16]. Thus, this signature is model independent, very effective and, in addition, it allows the test of a large range of DM candidates, of cross sections and of halo densities.

In particular, the experimental observable in DAMA experiments is the modulated component of the signal in NaI(Tl) target and not the constant part of it as in other approaches as those by CDMS, Xenon, etc., where in addition e.g. detectors and/or many (by the fact largely uncertain) data selections/subtractions, etc. are applied.

The DM annual modulation signature might be mimicked only by systematic effects or side reactions able to account for the whole observed modulation amplitude and to simultaneously satisfy all the requirements given above. No one is available or suggested by anyone over more than a decade [1, 2, 5, 6, 8, 11].

The signature itself acts as a strong background reduction as pointed out since the early paper by Freese et al., and especially when all the above peculiarities can be experimentally verified in suitable dedicated set-ups as it is the case of the DAMA experiments.

2 The results of DAMA/LIBRA–phase1 and DAMA/NaI

The total exposure of DAMA/LIBRA–phase1 is: 1.04 ton $\times$ yr in seven annual cycles; when including also that of the first generation DAMA/NaI experiment it is 1.33 ton $\times$ yr, corresponding to 14 annual cycles. The variance of the cosine during the DAMA/LIBRA–phase1 data taking is 0.518, showing that the set-up has been operational evenly throughout the years [2, 6].

Many independent data analyses have been carried out [2, 6] and all of them confirm the presence of a peculiar annual modulation in the *single-hit* scintillation events in the 2-6 keV energy interval, which – in agreement with the requirements of the signature – is absent in other part of the energy spectrum and in the *multiple-hit* scintillation events in the same 2-6 keV energy interval (this latter correspond to have "switched off the beam" of DM particles). All the analyses and details can be found in the literature given above.

Here due to the pages restriction, we just show in Fig. 1 the time behaviour of the experimental residual rates of the *single-hit* scintillation events for DAMA/NaI [11] and DAMA/LIBRA–phase1 [2, 6] cumulatively in the (2–6) keV energy interval; 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 amplitudes, A, equal to the central values obtained by best fit on the data points. 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 major upgrades are also pointed out.

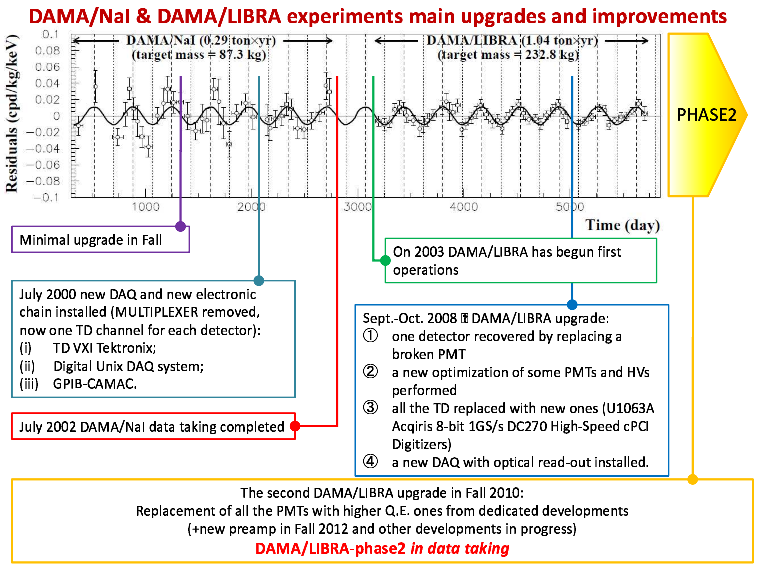

Figure 1: *Experimental residual rate of the single-hit scintillation events measured by DAMA/NaI and DAMA/LIBRA–phase1 in the (2–6) keV energy interval as a function of the time. See text. The major upgrades are also pointed out.*

In order to continuously monitor the running conditions, several pieces of information are acquired with the production data and quantitatively analysed. In particular, all the time behaviours of the running parameters, acquired with the production data, have been investigated: the modulation amplitudes obtained for each annual cycle when fitting the time behaviours of the parameters including a cosine modulation with the same phase and period as for DM particles are well compatible with zero. In particular, no modulation has been found in any possible source of systematics or side reactions; thus, cautious upper limits (90% C.L.) on possible contributions to the DAMA/LIBRA measured modulation amplitude have been derived (see e.g. [2]). 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 done for the DAMA/NaI data [11].

For completeness we mention that sometimes naive statements are put forwards as the fact that in nature several phenomena may show some kind of periodicity. The point is whether they might mimic the annual modulation signature in DAMA/LIBRA (and former DAMA/NaI), i.e. whether they might be not only quantitatively able to account for the whole observed modulation amplitude but also able to simultaneously satisfy all the requirements of the DM annual modulation signature. The same is also for side reactions. This has already been quantitatively investigated in our literature [1, 2, 5, 6, 8, 17, 18]. In particular, any relevant contribution to the DAMA modulation effect from the μ and from neutrons induced by μ can be excluded for the many scientific arguments discussed in details in Ref. [5] and recalled in Ref. [6]. Moreover, we also recall that the neutrons of whatever origin, surviving the shield against them, can be and have been quantitatively studied in various ways in DAMA experiments (see literature quoted above). For example, even when cautiously assuming a 10% modulation (of whatever origin) of the fast neutrons flux, and even assuming the same phase and period as for the DM case, the corresponding modulation amplitude is 2-3 orders of magnitude lower than the DAMA observed modulation amplitude. Finally, in no case neutrons (of whatever origin) can mimic the DM annual modulation signature since some of the peculiar requirements of the signature would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events, etc. which were not observed.

In conclusion, the model-independent DAMA results give evidence – at

9.3σ C.L. in 14 annual cycles independent measurements - for the presence of DM particles in the galactic halo satisfying all the many requirements of the exploited signature.

2.1 On comparisons

No direct model independent comparison is possible in the field when different target materials and/or approaches are used; the same is for the indirect searches.

In order to perform corollary investigations on the nature of the DM particles, model-dependent analyses are necessary[3]; thus, many theoretical and experimental parameters and models are possible and many hypotheses must also be exploited.

Many candidates, interactions, halo models, etc. are possible, while specific experimental and theoretical assumptions are generally adopted in a single arbitrary scenario without accounting neither for existing uncertainties nor for alternative possible scenarios, interaction types, etc.

The obtained 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 Ref. [9, 11, 2, 6]. Further large literature is available on the topics (see for example in the bibliography of Ref. [6]). Moreover, both the negative results and all the possible positive hints are largely compatible with the DAMA model-independent DM annual modulation results in various scenarios considering also the existing experimental and theoretical uncertainties; the same holds for indirect approaches; see e.g. arguments in Ref. [6] and references therein.

As regards the recent plot from Snowmass and that in Ref. [19], widely used in this conference about the "status of the Dark Matter search", it should be noted that it does not point out at all the real status of Dark Matter searches since: i) Dark Matter has wider possibilities than WIMPs inducing just nuclear recoil with spin-independent interaction under single (largely arbitrary) set of

[3]For completeness, we recall that it does not exist any approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer that information independently on assumed astrophysical, nuclear and particle Physics scenarios

assumptions; ii) neither the uncertainties for existing experimental and theoretical aspects nor alternative assumptions (which at present stage of knowledge are possible as well) are accounted for; iii) they do not include possible systematic errors affecting the data from which the exclusion plots are derived (such as e.g. "extrapolations" of energy threshold, of energy resolution and of efficiencies, quenching factors values, convolution with poor energy resolution, correction for non-uniformity of the detector, multiple subtractions/selection of detectors and/or data, assumptions on quantities related to halo model, form factors, scaling laws, etc.); iv) the DAMA implications – even adopting the many arbitrary assumptions considered there – appear incorrect[4]. On the other hand, for a similar picture one should quote in details the adopted "cooking" for each case otherwise it is even more meaningless. It also should be noted – in addition – that in those plots the allowed regions from the DAMA 9.3 σ C.L. model-independent evidence (1.33 ton $\times$ yr total exposure; confirmed over 14 independent experiment of 1 year each one) and from some recent possible published hints (only some kg $\times$ day exposure) are presented at level of 90% C.L. from the minimum found for each one by the author(s) of those plots under their own (often arbitrary) adopted "assumptions". Considering the well different C.L. of the experimentally observed effects, a more correct procedure would be to refer the allowed regions to the absence of signal (which is a common reference level).

It is also worth to remind that DAMA experiments are not only sensitive to DM particles with Spin-independent coupling inducing just nuclear recoils, but also to other couplings and to other DM candidates as those giving rise to

[4]We take this occasion to recall that in the DAMA/LIBRA experiment the measured counting rate in the cumulative energy spectrum is about 1 cpd/kg/keV in the lowest energy bins; this latter is the sum of the constant background contribution and of the constant part of the signal S_0. As discussed e.g. in TAUP2011 [18], the constant background in the cumulative spectrum in the 2-4 keV energy region is estimated to be not lower than about 0.75 cpd/kg/keV; this gives an upper limit on S_0 of about 0.25 cpd/kg/keV. Thus, the S_m/S_0 ratio is equal or larger than about 0.01/0.25. To not account for this experimental fact is one of the reasons (together with other erroneous assumptions also on some other experimental quantities) of the incorrect allowed regions put forward as "DAMA" by most authors and in the plots mentioned above for the very particular (arbitrary) scenario they adopt.

part or all the signal in electromagnetic form. Finally, scenarios exist in which other kind of targets/approaches are disfavoured or even blind.

3 DAMA/LIBRA–phase2 and perspectives

An important upgrade has started at end of 2010 replacing all the PMTs with new ones having higher Quantum Efficiency; details on the developments and on the reached performances in the operative conditions are reported in Ref. [4]. They have allowed to lower the software energy threshold of the experiment to 1 keV and improve also other features as e.g. the energy resolution [4].

Since the fulfillment of this upgrade, DAMA/LIBRA–phase2 – after optimization periods – is continuously running in order: (1) to increase the experimental sensitivity thanks to the lower software energy threshold; (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 and second order effects. This requires long and dedicated work for reliable collection and analysis of very large exposures.

In the future DAMA/LIBRA will also continue its study on several other rare processes as also the former DAMA/NaI apparatus did.

Finally, further future improvements of the DAMA/LIBRA set-up to increase the sensitivity (possible DAMA/LIBRA-phase3) and the developments towards the possible DAMA/1ton, we proposed in 1996, are considered.

4 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 by the former DAMA/NaI and DAMA/LIBRA–phase1 is 1.33 ton $\times$ yr.

As required by the DM annual modulation signature: 1) the *single-hit* events show a clear cosine-like modulation as expected for the DM signal; 2) the measured period is equal to (0.998 ± 0.002) yr well compatible with the 1 yr period as expected for the DM signal; 3) the measured phase (144 ± 7) days is compatible with $\simeq 152.5$ days as expected for the DM signal; 4) the modulation is present only in the low energy (2–6) keV interval and not in other higher energy regions, consistently with expectation for the DM signal; 5) the modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal; 6) the measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2–6) keV energy interval is: (0.0112 ± 0.0012) cpd/kg/keV (9.3 σ C.L.). No systematic or side processes able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available.

DAMA/LIBRA–phase2 is continuously running in its new configuration with a lower software energy threshold aiming to improve the knowledge on corollary aspects regarding the signal and on second order effects as discussed e.g. in Ref. [6, 8].

Few comments on model–dependent comparisons have also been addressed here.

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