Results from DAMA/LIBRA and perspectives

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2013-04/cerulli_riccardo

The DAMA/LIBRA experiment (about 250 kg of highly radiopure NaI(Tl)) is in operation at the Gran Sasso National Laboratory of the INFN. The main aim of the experiment is to further investigate the Dark Matter (DM) particles in the Galactic halo by exploiting the model independent DM annual modulation signature. At the time of this Workshop, the DAMA/LIBRA experiment and the former DAMA/NaI one (the first generation experiment having an exposed mass of about 100 kg) have released results corresponding to a total exposure of 1.17 ton $\times$ yr over 13 annual cycles; they have provided a model independent evidence of the presence of DM particles in the galactic halo at 8.9 σ C.L.. The results of a further annual cycle, concluding the DAMA/LIBRA–phase1, have been released after this Workshop and are not included here. After the upgrade at fall 2010 when all the PMTs have been replaced with new ones having higher quantum efficiency, the feasibility to decrease the software energy threshold has been demonstrated and the set-up is running in this new configuration, named DAMA/LIBRA–phase2.

1 The DAMA/LIBRA results

The DAMA project develops and uses low background scintillators. It consists of the following experimental set-ups: i) DAMA/NaI ($\simeq$ 100 kg of highly radiopure NaI(Tl)) that took data for 7 annual cycles and completed its data taking on July 2002 [1, 2, 3, 4, 5, 6]; ii) DAMA/LXe, $\simeq$ 6.5 kg liquid Kr-free Xenon enriched either in ^{129}Xe or in ^{136}Xe [7]; iii) DAMA/R&D, a facility dedicated to tests on prototypes and to perform experiments developing and using various kinds of low background crystal scintillators in order to investigate various rare processes [8]; iv) DAMA/Ge, where sample measurements and measurements dedicated to the investigation of several rare processes are carried out as well as in the LNGS STELLA facility [9]; v) DAMA/CRYS, a new small set-up to test prototype detectors; vi) the second generation DAMA/LIBRA set-up, $\simeq$ 250 kg highly radiopure NaI(Tl)) [10, 11, 12, 13, 14, 15, 16, 17, 18]. Many rare processes have also been studied with these set-ups obtaining competitive results.

In particular, the DAMA/LIBRA set-up is mainly investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature, originally suggested in [19]. As a consequence of the annual revolution of the Earth around the Sun, moving in the Galaxy, our planet should be crossed by a larger flux of DM particles around $\sim$ June 2^{nd} (when the Earth orbital velocity has the same versus of the Sun velocity with respect to the Galaxy) and by a smaller one around $\sim$ December 2^{nd} (when the two velocities are opposite). Thus, this signature depends on the composition of the Earth and Sun velocitites and it is not 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: (1) the rate must contain a component modulated according to a cosine function; (2) with one year period; (3) with a phase that peaks roughly around $\sim$ June 2^{nd}; (4) modulation must be present only in a well-defined low energy range, where DM particles can induce signals; (5) it must be present only in those events where just a single detector, among all the available ones in the used set-up, actually "fires" (*single-hit* events), since the probability that DM particles experience multiple interactions is negligible; (6) the modulation amplitude in the region of maximal sensitivity has to be less about 7% in case of usually adopted halo distributions, but it may be significantly larger in case of some particular scenarios. No systematic effects or side reactions able to simultaneously fulfil all the mentioned requirements have been found or suggested by anyone over more than a decade. At present status of technology it is the only model independent signature which can effectively be exploited by direct Dark Matter investigation. The ULB NaI(Tl) are suitable detectors to investigate this signature thanks to its very good sensitivity to many DM candidates and interaction types.

The description and the performances of the DAMA/LIBRA set-up are given in Ref. [10], where the procedures followed in the data taking are also described.

The DAMA/LIBRA data released at time of this Workshop correspond to six annual cycles for an exposure of 0.87 ton$\times$yr [10, 11, 12]. Considering these data together with those previously collected by DAMA/NaI over 7 annual cycles (0.29 ton$\times$yr), the total exposure collected over 13 annual cycles is 1.17 ton$\times$yr; this is orders of magnitude larger than the exposures typically collected in the field.

Several independent analyses on the model-independent DM annual modulation signature have been performed [11, 12]. In particular, Fig. 1 shows the time behaviour of the experimental residual rates of the *single-hit* scintillation events collected by DAMA/NaI and by DAMA/LIBRA in the (2–6) keV energy interval [11, 12]. The superimposed curve is the cosinusoidal function: $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, with a phase $t_0=152.5$ day (June 2^{nd}), and modulation amplitude, A, obtained by best fit over the 13 annual cycles. The hypothesis of absence of modulation in the data can be discarded [11, 12] and, when the period and the phase are released in the fit, values well compatible with those expected for a DM particle induced effect are obtained [12]. In particular, in the cumulative (2–6) keV energy interval one gets: $A=(0.0116\pm0.0013)$ cpd/kg/keV, $T=(0.999\pm0.002)$ yr and $t_0=(146\pm7)$ day. Thus, the analysis of the *single-hit* residual rate favours the presence of a modulated cosine-like behaviour with proper features at 8.9 σ C.L.[12].

The same data of Fig. 1 have also been investigated by a Fourier analysis, obtaining a clear peak corresponding to a period of 1 year [12, 13]; this analysis in other energy regions shows only aliasing peaks instead. It is worth noting that for this analysis the original formulas in Ref. [20] have been slightly modified in order to take into account for the different time binning and the residuals errors (see e.g. Ref. [13]). In particular, DAMA has always shown the power spectrum up to the Nyquist frequency of the given residuals, which is $\simeq 3$ y^{-1}. Only recently [13] the power spectrum above 3 y^{-1} (up to 22 y^{-1}) has been shown in order to demonstrate that – as expected – no significant peak is present above the Nyquist frequency.

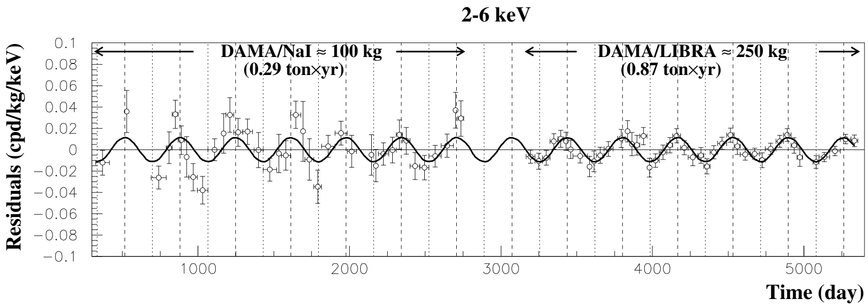

Figure 1: Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/NaI over seven and by DAMA/LIBRA over six annual cycles in the (2 – 6) keV energy interval as a function of the time [5, 11, 12, 13]. The zero of the time scale is January 1^{st} of the first year of data taking. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve is $A\cos\omega(t-t_0)$ with period $T=\frac{2\pi}{\omega}=1$ yr, phase $t_0=152.5$ day (June 2^{nd}) and modulation amplitude, A, equal to the central value obtained by best fit over the whole data. 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. See Ref. [11, 12, 13], references therein and text.

For completeness, we recall that long term modulation, with period higher than one year, has also been excluded by a different dedicated analysis reported e.g. in Refs. [13, 17].

In order to verify absence of annual modulation in other energy regions and, thus, to also verify the absence of any significant background modulation, the energy distribution in energy regions not of interest for DM detection has also been investigated. This has allowed the exclusion of a background modulation in the whole energy spectrum at a level much lower than the effect found in the lowest energy region for the *single-hit* scintillation events [12, 13].

A further relevant investigation has been performed by applying to the *multiple-hits* scintillation events (in which more than one detector "fires") the same hardware and software procedures used to acquire and to analyse the *single-hit* residual rate. In fact, since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just in the *single-hit* residual rate. Thus, this allows the study of the background behaviour in the same energy interval of the observed positive effect. A clear modulation is present in the *single-hit* scintillation events, while the fitted modulation amplitudes for the *multiple-hits* residual rate are well compatible with zero [12]. Similar results were previously obtained also for the DAMA/NaI case [5].

The annual modulation present at low energy has also been analyzed by depicting the differential modulation amplitudes, S_m, as a function of the energy [12]; in this case a maximum likelihood of the *single-hit* scintillation events is carried out considering $T=1$ yr and $t_0=152.5$ day. The measured S_m values as function of the energy are given in Fig. 2.

It can be inferred that a positive signal is present in the (2–6) keV energy interval, while S_m values compatible with zero are present just above. It has also been verified that the measured modulation amplitudes are statistically well distributed in all the crystals, in all the annual cycles and energy bins; these and other discussions can be found in Ref. [12, 13].

Many other analyses and discussions can be found in Refs. [11, 12, 13] and references therein. Both the data of DAMA/LIBRA and of DAMA/NaI fulfil all the requirements of the

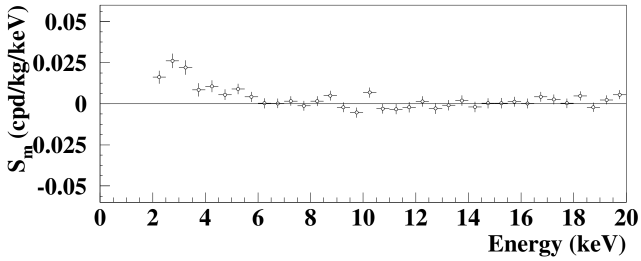

Figure 2: Energy distribution of the modulation amplitudes S_m for the total cumulative exposure 1.17 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom. See Ref. [11, 12, 13].

DM annual modulation signature.

Careful investigations on absence of any significant systematics or side reaction have been quantitatively carried out (see e.g. Ref. [5, 3, 10, 11, 12, 17, 13, 21, 22, 23, 24, 25, 26, 27], and references therein). No systematics or side reactions able to mimic the signature (that is, able to account for the measured modulation amplitude and simultaneously satisfy all the requirements of the signature) has been found or suggested by anyone over more than a decade.

In conclusion, the model-independent DAMA results have given evidence at 8.9 σ C.L. over 13 independent annual cycles for the presence of DM particles in the galactic halo.

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. [2, 3, 4, 5, 11, 13]. Further large literature is available on the topics (see for example in Ref [13]). Moreover, both the negative results and all the possible positive hints, achieved so-far in the field, are largely compatible with the DAMA model-independent DM annual modulation results in many scenarios considering also the existing experimental and theoretical uncertainties; the same holds for indirect approaches; see e.g. arguments in Ref. [13] and references therein.

We recall that a first upgrade of the DAMA/LIBRA set-up was performed in September 2008 when a broken PMT was replaced and a new DAQ with optical read-out and new Digitizers were also installed. The DAMA/LIBRA–phase1 concluded its data taking in this configuration on 2010; the results of the last (seventh) annual cycle of this phase1 have been released after this Workshop [28]. A further and more important upgrade has been performed at the end of 2010 when all the PMTs have been replaced with new ones having higher quantum efficiency; details on the developments and on the reached performances in the operative conditions are reported in Ref. [18]. Since then, the DAMA/LIBRA–phase2 is continuously running in order: (1) to increase the experimental sensitivity lowering the software energy threshold of the experiment; (2) to improve the corollary investigations on the nature of the DM particle and related astrophysical, nuclear and particle physics arguments; (3) to investigate other signal features. This requires long and heavy full time dedicated work for reliable collection and analysis of very large exposures, as DAMA collaboration has always done. Another upgrade at the end of 2012 was successfully concluded, while further improvements are planned. In the future DAMA/LIBRA will also continue its study on several other rare processes [14, 15, 16] as also the former DAMA/NaI apparatus also did [6].

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