Particle dark matter in the galactic halo: results from DAMA/LIBRA

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The DAMA/LIBRA experiment at the Gran Sasso National Laboratory of the I.N.F.N. has confirmed with higher sensitivity the model independent evidence for Dark Matter (DM) particles in the galactic halo obtained by the former DAMA/NaI experiment by investigating the DM annual modulation signature. Considering the data collected by DAMA/NaI and by DAMA/LIBRA (cumulative exposure of 0.82 ton $\times$ yr), a confidence level of 8.2 σ has been achieved. No systematics or side reactions able to account for the measured modulation amplitudes and to simultaneously satisfy all the many peculiarities of the signature have been found or suggested by anyone over more than a decade.

DAMA is an observatory for rare processes operating deep underground in the Gran Sasso National Laboratory of the I.N.F.N.. The experiment is mainly devoted to the development and use of low background scintillators. The main experimental set-ups are: i) the first generation DAMA/NaI set-up[1, 2]; ii) DAMA/LXe[3, 4]; iii) DAMA/R&D[5]; iv) DAMA/Ge[6]; v) the new second generation DAMA/LIBRA set-up ($\simeq$ 250 kg highly radiopure NaI(Tl))[7, 8, 9]. Many rare processes have been investigated obtaining often competitive results. In particular, DAMA/LIBRA is further investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature. This signature – originally suggested in the middle of '80 in ref. [10] – exploits the effect of the Earth revolution around the Sun on the flux of DM particles in the detectors. In fact, as a consequence of its annual revolution, the Earth should be crossed by a larger flux of DM particles around $\sim$ 2 June (when its rotational velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around $\sim$ 2 December (when the two velocities are subtracted). This offers an efficient model independent signature and allows to test large intervals of cross sections and halo densities.

In particular, the DM annual modulation signature is very distinctive since the corresponding signal must simultaneously satisfy all the following requirements: i) the rate must contain a component modulated according to a cosine function; ii) the period is one year; iii) the phase is roughly $\simeq$ 2nd June; iv) this modulation must only be found in a well-defined low energy range, where DM particle induced events can be present ; v) 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; vi) the modulation amplitude in the region of maximal sensitivity must be $\lesssim$7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios as e.g. those in refs. [11, 12]. Only systematic effects or side reactions able to account for the whole observed modulation amplitude and to contemporaneously fulfil all the requirements given above might mimic this signature; thus, no other effect investigated so far in the field of rare processes offers a so stringent and unambiguous signature. It is worth noting that the DM annual modulation is not – as often naively said – a "seasonal" variation and it is not a "winter-summer" effect. In fact, the DM annual modulation is not related to the relative Sun position, but it is related to the Earth velocity in the galactic frame. Moreover, the phase of the DM annual modulation (roughly 2nd June) is well different than those of physical quantities (such as temperature of atmosphere, pressure, other meteorological parameters, cosmic rays flux, ...) instead correlated with seasons.

Detailed descriptions of DAMA/NaI[13, 14, 15, 16] and of DAMA/LIBRA[7] performances have been published. The DAMA/NaI experiment collected an exposure of 0.29 ton$\times$yr running over 7 annual cycles, while DAMA/LIBRA has released so far the data of its first 4 annual cycles for an exposure of 0.53 ton$\times$yr. The total exposure of the two experiments is 0.82 ton$\times$yr, which is orders of magnitude larger than the exposure typically collected in the field.

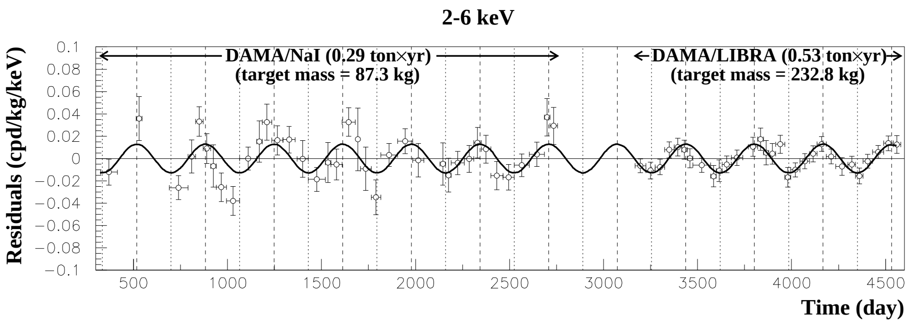

Figure 1: Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/NaI and DAMA/LIBRA in the (2 – 6) keV energy intervals as a function of the time. The zero of the time scale is January 1^{st} of the first year of data taking of the former DAMA/NaI experiment. The superimposed curve is the cosinusoidal functions with 1 year period, June 2^{nd} phase and fitted amplitude (0.0129 ± 0.0016) cpd/kg/keV. The dashed vertical lines correspond to the maximum of the signal (June 2^{nd}), while the dotted vertical lines correspond to the minimum. For details see[8].

Several model-independent analyses have been performed[8]. Figure 1 shows the time behaviour of the experimental (2–6) keV residual rates for *single-hit* events collected by DAMA/NaI and by DAMA/LIBRA. The superimposed curve represents the cosinusoidal functions: $A \cos \omega(t - t_0)$ with $T = \frac{2\pi}{\omega} = 1$ yr and phase $t_0 = 152.5$ day (June 2^{nd}), while the modulation amplitudes, A, is the best fit value obtained over the DAMA/NaI and DAMA/LIBRA data. When the period and the phase parameters are released in the fit, values well compatible with those expected for a DM particle induced effect are obtained[8]: $T = (0.998 \pm 0.003)$ yr and $t_0 = (144 \pm 8)$ day in the (2–6) keV energy interval. The same data of Figure 1 have also been investigated by a Fourier analysis[8]. For all the performed analyses and for details see ref. [8]. In particular, a relevant investigation has been performed by applying the same hardware and software procedures, used to acquire and to analyse the *single-hit* events, to the *multiple-hits* ones. 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 where the positive effect is observed. In particular, while a clear modulation with proper features is present in the $2-6$ keV *single-hit* events, the modulation amplitude of the *multiple-hits* ones in the same energy interval is well compatible with zero[8] (see Figure 2). Similar results were previously obtained also for the

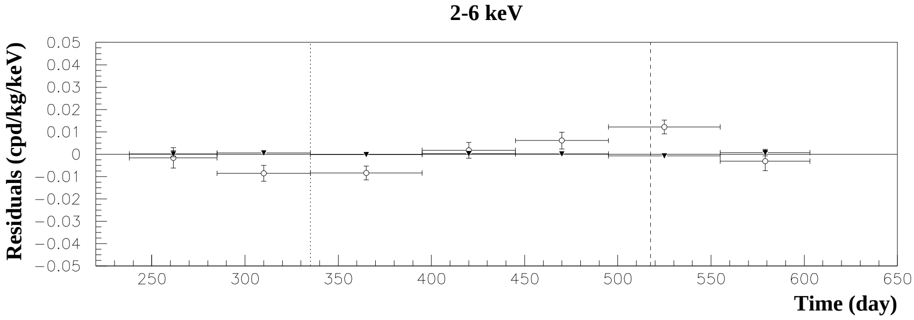

Figure 2: Experimental model-independent residual rates of the $(2-6)$ keV *single-hit* events (open circles) (class of events to which DM events belong) and of the $(2-6)$ keV *multiple-hits* events (filled triangles) (class of events to which DM events do not belong), measured in the four DAMA/LIBRA annual cycles (as collected in a single cycle; the initial time of the scale is taken on August 7^{th}.). The same identical hardware and the same identical software procedures have been applied in both cases. In the plots the experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. For details see[8].

DAMA/NaI data[16]. Thus, again evidence of annual modulation with proper features, as required by the DM annual modulation signature, is present in the *single-hit* residual rate (events class to which the DM particle induced events belong), while it is absent in the *multiple-hits* one (event class to which only background events belong). Since the same identical hardware and the same identical software procedures have been used to analyse the two classes of events, the obtained result offers an additional strong support for the presence of a DM particle component in the galactic halo further excluding any side effect either from hardware or from software procedures or from background.

All the performed analyses[8] confirm that a modulation amplitude is present in the lower energy intervals with the period and the phase in agreement with those expected for DM induced signals; in addition, the observed annual modulation fulfills the requirements of the DM signature.

As previously done for the case of DAMA/NaI[14, 15, 16], careful investigations on absence of any significant effect from systematics or side reactions have been quantitatively carried out also for DAMA/LIBRA; it is reported in details in ref. [8]. No systematics or side reactions able to account for the measured modulation amplitude and to simultaneously satisfy all the requirements of the signature have been found or suggested by anyone over more than a decade.

In September 2008 a first upgrading of the DAMA/LIBRA set-up has been realized by substituting some PMTs and replacing the transient digitizers with new ones. A new DAQ system with optical readout has also been installed.

Moreover, mainly in order to lower the energy threshold of the experiment, the replacement of all the PMTs with new ones having higher quantum efficiency is planned for the next year; this will also improve other significant experimental aspects. The increasing of the exposure and the hardware improvements will allow the further investigation of some open aspects in the DM field and of second order effects.

Finally, other processes are also investigated by DAMA/LIBRA; in particular, recently new results on the search for possible processes violating the Pauli-Exclusion-Principle in Sodium and in Iodine have been presented in ref. [9].

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