Results from DAMA/LIBRA

R. Bernabei[1], *P. Belli*[1], *F. Cappella*[2], *R. Cerulli*[3], *C.J. Dai*[4], *A. d'Angelo*[2], *H.L. He*[4], *A. Incicchitti*[2], *X.H. Ma*[4], *F. Montecchia*[1,5], *F. Nozzoli*[1], *D. Prosperi*[2,*], *X.D. Sheng*[4], *R.G. Wang*[4], Z.P. Ye[4,6]

[1]Dip. di Fisica, Università di Roma "Tor Vergata" and INFN, sez. Roma "Tor Vergata", I-00133 Rome, Italy
[2] Dip. di Fisica, Università di Roma "La Sapienza" and INFN, sez. Roma, I-00185 Rome, Italy
[3] Laboratori Nazionali del Gran Sasso, I.N.F.N., I-67010 Assergi, Italy
[4] IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China
[5] Lab. Sperim. Policentrico di Ingegneria Medica, Università di Roma "Tor Vergata"
[6] University of Jing Gangshan, Jiangxi, China
[*] deceased

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The 250 kg highly radiopure NaI(Tl) DAMA/LIBRA experiment and the former DAMA/NaI (first generation experiment with $\simeq$ 100 kg exposed mass) have released so far the results obtained cumulatively over 13 annual cycles. Their total exposure of 1.17 ton $\times$ yr gives a model independent evidence of the presence of Dark Matter (DM) particles in the galactic halo at 8.9 σ C.L. on the basis of the DM annual modulation signature.

The DAMA project at the Gran Sasso National Laboratory of the I.N.F.N. is focused on the development and use of low background scintillators for the investigation of many rare processes [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. In particular, DAMA/LIBRA is investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature [17] based on the Earth motion around the Sun, which is moving in the Galaxy. The flux of the DM particles crossing the Earth is expected to be larger around $\sim$ 2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and smaller around $\sim$ 2 December (when the two velocities are subtracted). This signature is very effective and allow the test of a large number of DM candidates, a large interval of cross sections and of halo densities. In particular, the signal 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 around $\simeq$ 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 $\lesssim$7% for usually adopted halo distributions (6), but it can be larger in case of some possible scenarios such as e.g. those in refs. [18, 19]. Only systematic effects or side reactions able to simultaneously fulfil all these requirements and to account for the whole observed modulation amplitude could mimic this signature; thus, no other effect investigated so far in the field of rare processes offers a so stringent and unambiguous signature.

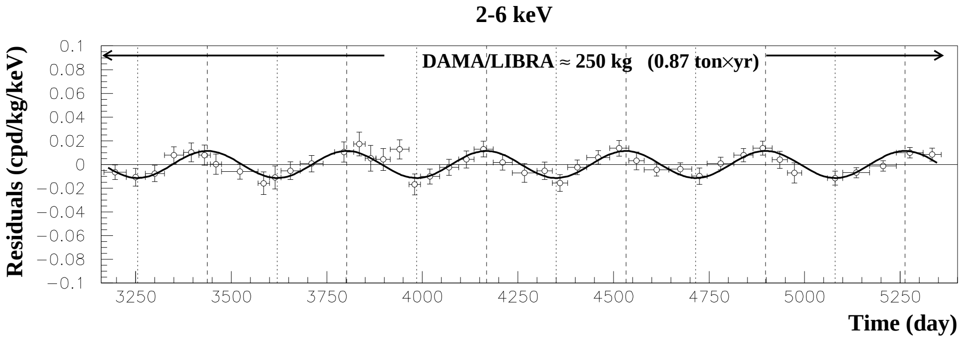

Figure 1: Model-independent result: residual rate of the *single-hit* events, measured by DAMA/LIBRA,1-6 in (2 – 6) keV range as a function of the time. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve is the function $A\cos\omega(t-t_0)$ with $T=\frac{2\pi}{\omega}=1$ yr, $t_0=152.5$ day (June 2^{nd}) and with modulation amplitudes, A, equal to the central values obtained by best fit over the DAMA/LIBRA and DAMA/NaI cumulative exposure (1.17 ton × yr). 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 [20].

The DAMA/LIBRA set-up [14] is composed by a sensitive part made of 25 highly radiopure NaI(Tl) crystal scintillators placed in a 5-rows by 5-columns matrix; the detectors' responses range from 5.5 to 7.5 photoelectrons/keV, allowing the experiment to set the software energy threshold at 2 keV (here and hereafter keV means keV electron equivalent), while the hardware threshold of each photomultiplier (PMT) is at single photoelectron (each detector is equipped with two low background PMTs working in coincidence); energy calibration with X-rays/γ sources are regularly carried out down to few keV in the same conditions as the production runs.

The DAMA/LIBRA data released so far corresponds to six annual cycles for an exposure of 0.87 ton×yr [15, 20]. Considering these data together with those previously collected by DAMA/NaI over 7 annual cycles (0.29 ton×yr), the total exposure collected over 13 annual cycles is 1.17 ton×yr; this is orders of magnitude larger than the exposures typically collected in the field.

Several analyses to investigate the model-independent DM annual modulation signature have been performed (see ref. [15, 20] and references therein); here just few arguments are mentioned. In particular, Fig. 1 shows the time behaviour of the experimental residual rates of the *single-hit* events collected by DAMA/LIBRA in the (2–6) keV energy interval. The superimposed curve is the cosinusoidal function: $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr and with a phase $t_0=152.5$ day (June 2^{nd}), and modulation amplitude, A, obtained by best fit over the seven cycles of DAMA/NaI [4, 5] and the six of DAMA/LIBRA [15, 20]. When the period and the phase parameters are also released in the fit, values well compatible with those expected for a DM particle induced effect are obtained; in the (2–6) keV energy interval it results: $A=(0.0116\pm0.0013)$ cpd/kg/keV, $T=(0.999\pm0.002)$ yr and $t_0=(146\pm7)$ day. 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..

A Fourier analysis on the the (2–6) keV *single-hit* residuals has been performed in order to extract the modes of the modulation. The principal mode of the obtained power spectrum is consistent with a frequency corresponding to a period of 1 year; the same analysis in other energy region shows instead only aliasing peaks. Thus, a clear modulation is present at low energy while it is absent at energies just above, as expected for the anual modulation signature.

The measured energy distribution has been investigated in energy regions not of interest for DM. The data analyses have allowed to exclude the presence 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* events [15, 20].

A further analysis show that while a clear modulation is present in the (2–6) keV *single-hit* events, amplitudes well compatible with zero are obtained for the *multiple-hits* events in the same energy range. Similar results were previously obtained also for the DAMA/NaI case [5]. Thus, again evidence of annual modulation with proper features, as required by the DM annual modulation signature, is present in the *single-hit* residuals (events class to which the DM particle induced events belong), while it is absent in the *multiple-hits* residual rate (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 DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background [15, 20].

It has been also verified that the measured modulation amplitudes are statistically well distributed over all the crystals, over all the annual cycles and energy bins [15, 20].

It is also worth to mention the results of the analysis performed by releasing the assumption of a phase $t_0 = 152.5$ day in the procedure of maximum likelihood to evaluate the modulation amplitudes from the data of the seven annual cycles of DAMA/NaI and the six annual cycles of DAMA/LIBRA. The obtained results confirm that a modulation amplitude is present in the lower energy intervals for single hit events and that the period and the phase agree with those expected for DM induced signals [15, 20].

As previously done for DAMA/NaI [4, 5], Careful investigations on absence of any significant systematics or side reaction effect in DAMA/NaI and in DAMA/LIBRA have been quantitatively carried out and reported in details in ref. [4, 5, 15, 22, 23, 24] 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, DAMA/LIBRA has confirmed the presence of an annual modulation satisfying all the requirements of the DM annual modulation signature, as previously pointed out by DAMA/NaI; in particular, the evidence for the presence of DM particles in the galactic halo is cumulatively supported at 8.9 σ C.L.. As regards the corollary investigation on the nature of the DM candidate particle(s) and related astrophysical, nuclear and particle physics scenarios, it has been shown that the obtained model independent evidence can be compatible with a wide set of possibilities; see for example [2, 4, 5, 6, 7, 8, 9, 10, 11, 15]. Many other interpretations of the annual modulation results are available in literature (as e.g. [18, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34], etc.); others are open. For discussions about the comparison between this result and the results obtained by other experiments see ref. [4, 5, 15, 36, 37]

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