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2 DAMA/LIBRA Results and Perspectives

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Abstract. The DAMA/LIBRA experiment is composed by about 250 kg of highly radiopure NaI(Tl). It is in operation at the underground Gran Sasso National Laboratory of the INFN. The main aim of the experiment is to investigate the Dark Matter (DM) particles in the Galactic halo by exploiting the model independent DM annual modulation signature. The DAMA/LIBRA experiment and the former DAMA/NaI (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. In the fall 2010 an important upgrade of the experiment have been performed. All the PMTs of the NaI(Tl) detectors have been replaced with new ones having higher quantum efficiency with the aim to decrease the software energy threshold considered in the data analysis. The perspectives of the running DAMA/LIBRA–phase2 will be shortly summarized.

Povzetek. Experiment, poznan pod imenom DAMA/LIBRA, meri lastnosti galaktičnih delcev, jakost toka katerih niha s periodo kroženja Zemlje okoli Sonca. Postavljen je v podzemeljskem laboratoriju, ki nosi ime Gran Sasso National Laboratory in spada pod INFN. Gradi ga približno 250 kg zelo čistega (brez radioktivnih primesi) NaI(Tl). Prednik tega eksperimenta, DAMA/Na, je imel 100 kg eksponirane mase. Oba skupaj ponujata rezultate, ki ustrezajo celotni ekspoziciji 1.17 ton $\times$ let v trinajstletnih ciklusih. Rezultati so neodvisni od modelov, ki pojasnjujejo iz česa je temna snov. Z zanesljivostjo 8.9 σ potrjujejo obstoj delcev temne snovi v galaksiji. Rezultati naslednjega letnega cikla, ti zaključujejo fazo 1 poskusa DAMA/LIBRA, v to poročilo niso vključeni. V jeseni 2010 je bil eksperiment posodobljen. Fotopomnoževalke v detektorjih z NaI(Tl) so, da bi po večali kvantni izkoristek, zamenjali z novimi in s tem znižali energijski prag, uporabljen v programih za analizo meritev. Predstavimo tudi potekajočo drugo fazo eksperimenta DAMA/LIBRA.

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2.1 The DAMA/LIBRA set-up

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 [1–6]; 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)) [10–18]. Many rare processes have been studied with these set-ups obtaining competitive results.

The main apparatus, DAMA/LIBRA, is investigating the presence of DM particles in the galactic halo by exploiting the model independent DM annual modulation signature. In fact, as a consequence of its annual revolution around the Sun, which is moving in the Galaxy traveling 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 Dark Matter particles around ~2 June (when the Earth orbital velocity is summed to the one of the solar system with respect to the Galaxy) and by a smaller one around ~2 December (when 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: (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 ~ 2nd June; (4) this 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 $\lesssim$7% in case of usually adopted halo distributions, but it may be significantly larger in case of some particular scenarios such as e.g. those in refs. [19,20]. At present status of technology it is the only model independent signature available in direct Dark Matter investigation that can be effectively exploited.

The DAMA/LIBRA data released at time of this Workshop correspond to six annual cycles for an exposure of 0.87 ton$\times$yr [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.

The DAMA/NaI set up and its performances are described in ref. [1,3,5,21], while the DAMA/LIBRA set-up and its performances are described in ref. [10,12]. The sensitive part of the DAMA/LIBRA set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators placed in a 5-rows by 5-columns matrix; each crystal is coupled to two low background photomultipliers working in coincidence at single photoelectron level. The detectors are placed inside a sealed copper box flushed with HP nitrogen and surrounded by a low background and massive shield made of Cu/Pb/Cd-foils/polyethylene/paraffin; 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. The installation has a 3-fold levels sealing system which excludes the detectors from environmental air. The whole installation is air-conditioned and the temperature is continuously monitored and recorded. The detectors' responses range from 5.5 to 7.5 photoelectrons/keV. Energy calibrations with X-rays/γ sources are regularly carried out down to few keV in the same conditions as the production runs. A software energy threshold of 2 keV is considered. The experiment takes data up to the MeV scale and thus it is also sensitive to high energy signals. For all the details see ref. [10].

2.2 Short summary of the results

Several analyses on the model-independent DM annual modulation signature have been performed (see Refs. [11–13] and references therein). Here Fig. 2.1 shows the time behaviour of the experimental residual rates of the *single-hit* 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

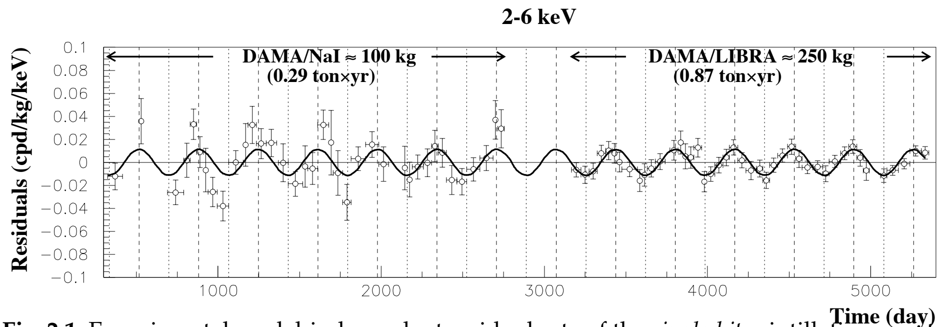

Fig. 2.1. Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/NaI over seven and by DAMA/LIBRA over six annual cycles in the (2 – 6) keV energy interval as a function of the time [5,21,11,12]. The zero of the time scale is January 1st of the first year of data taking. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. See refs. [11,12] and text.

a period $T = \frac{2\pi}{\omega} = 1$ yr, with a phase $t_0 = 152.5$ day (June 2nd), 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; for example, in the cumulative (2–6) keV energy interval: $A = (0.0116 \pm 0.0013)$ cpd/kg/keV, $T = (0.999 \pm 0.002)$ yr and $t_0 = (146 \pm 7)$ day. Summarizing, the analysis of the *single-hit* residual rate favours the presence of a modulated cosine-like behaviour with proper features at 8.9σ C.L.[12].

The same data of Fig. 2.1 have also been investigated by a Fourier analysis obtaining a clear peak corresponding to a period of 1 year [12]; this analysis in other energy regions shows instead only aliasing peaks. It is worth noting that for this analysis the original formulas in Ref. [23] have been slightly modified in order to take into account for the different time binning and the residuals errors (see e.g. Ref. [13]).

Moreover, 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 time distribution in energy regions not of interest for DM detection has also been investigated: this allowed the exclusion of 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 [12]. A further relevant investigation has been done by applying the same hardware and software procedures, used to acquire and to analyse the *single-hit* residual rate, to the *multiple-hits* events in which more than one detector "fires". 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. The result of the analysis is reported in Fig. 2.2 where it is shown the residual rate of the *single-hit* events measured over the six DAMA/LIBRA annual cycles, as collected in a single annual cycle, together with the residual rates of the *multiple-hits* events, in the same considered energy interval. A clear modulation is present in the *single-hit*

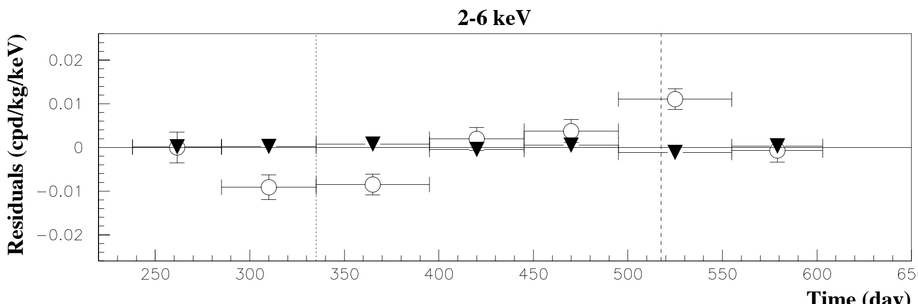

Fig. 2.2. Experimental residual rates over the six DAMA/LIBRA annual cycles for *single-hit* events (open circles) (class of events to which DM events belong) and for *multiple-hit* events (filled triangles) (class of events to which DM events do not belong). The initial time of the figure is taken on August 7^{th}. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. See text and refs. [11,12].

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 [21]. 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 analyze 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.

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; the S_m is the modulation amplitude of the modulated part of the signal obtained by maximum likelihood method over the data, considering $T = 1$ yr and $t_0 = 152.5$ day. The S_m values are reported as function of the energy in Fig. 2.3. It can be

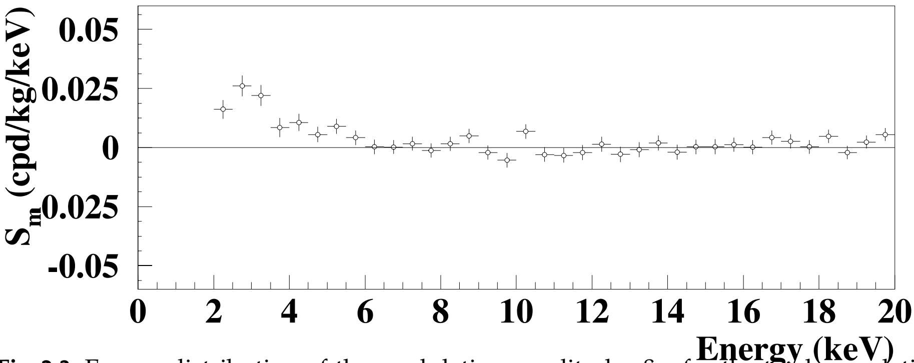

Fig. 2.3. Energy distribution of the modulation amplitudes S_m for the total cumulative exposure 1.17 ton×yr obtained by maximum likelihood analysis. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. See refs. [11,12] and text.

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; in particular, 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. It has been also 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].

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

Careful investigations on absence of any significant systematics or side reaction have been quantitatively carried out (see e.g. Ref. [5,3,10–12,17,13,24–30], 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.

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. [2–5,11,13]. 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. As an example in Fig. 2.4 there are shown allowed regions for DM candidates interacting by elastic scattering on target-nuclei with spin-independent coupling, including also some of the existing uncertainties [31].

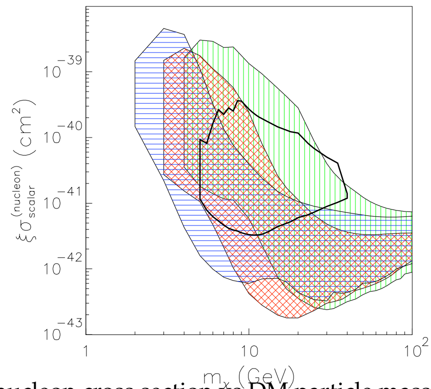

Fig. 2.4. Regions in the nucleon cross section vs DM particle mass plane allowed by DAMA for a DM candidate interacting via spin-independent elastic scattering on target-nucleus; three different instances for the Na and I quenching factors have been considered: i) without including the channeling effect [(green) vertically-hatched region], ii) by including the channeling effect [(blue) horizontally-hatched region)], and iii) without the channeling effect considering energy-dependence of Na and I quenching factors [31] [(red) crosshatched region]. The velocity distributions and the same uncertainties as in refs. [5,21] are considered here. These regions represent the domain where the likelihood-function values differ more than 7.5 σ from the null hypothesis (absence of modulation). The allowed region obtained for the CoGeNT experiment, including the same astrophysical models as in refs. [5,21] and assuming for simplicity a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters, is also reported by a (black) thick solid line. This region includes configurations whose likelihood-function values differ more than 1.64 σ from the null hypothesis (absence of modulation). For details see ref. [31].

2.3 DAMA/LIBRA–phase2 and perspectives

A first upgrade of the DAMA/LIBRA set-up was performed in September 2008. One detector was recovered by replacing a broken PMT and a new optimization of some PMTs and HVs was done; the transient digitizers were replaced with new ones (the U1063A Acqiris 8-bit 1GS/s DC270 High-Speed cPCI Digitizers) having better performances and a new DAQ with optical read-out was installed. The DAMA/LIBRA–phase1 concluded its data taking in this configuration on 2010; the data of the last (seventh) annual cycle of this phase1 have been released after this Workshop [35].

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 (Q.E.), realized with a special dedicated development by HAMAMATSU co.. Details on the developments and on the reached performances in the operative conditions are reported in Ref. [18]. We remind that up to October 2010 low background PMTs, developed by EMI-Electron Tubes with dedicated R&D, were used; the light yield and other response features already allowed a software energy threshold of 2 keV in the data analysis. The feasibility to decrease the software energy threshold below 2 keV in the new configuration has been demonstrated[18].

Since the fulfillment of this upgrade, 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 investigation 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: new-concept preamplifiers were installed, with suitable operative and electronic features; in particular, they allow the direct connection of the signal to the relative channel of the Transient Digitizer (TD).

Moreover, further improvements are planned. In particular, new trigger modules have been prepared and ready to be installed. A further simplification of the electronic chain has been proposed and funded; for such purpose a new electronic module, New Linear FiFo (NLF), has been designed. It will allow – among the others – a significant reduction of the number of used NIM slots with definitive advantage.

In the future DAMA/LIBRA will also continue its study on several other rare processes [14–16] as also the former DAMA/NaI apparatus did [6].

Finally, further improvements to increase the sensitivity of the set-up are under evaluation; in particular, the use of high Q.E. and ultra-low background PMTs directly coupled to the NaI(Tl) crystals is considered[1]. This possible configuration will allow a further large improvement in the light collection and a further lowering of the software energy threshold. Moreover, efforts towards a possible highly radiopure NaI(Tl) "general purpose" experiment (DAMA/1ton) having full sensitive mass of 1 ton (we already proposed in 1996 as general purpose set-up) are continuing in various aspects.

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