From DAMA/NaI to DAMA/LIBRA and beyond

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Abstract. The low background DAMA/NaI experiment (≈ 100 kg highly radiopure NaI(Tl)) at the Gran Sasso National Laboratory of the I.N.F.N. had the unique feature to effectively investigate the presence of Dark Matter particle in the galactic halo by exploiting the model independent annual modulation signature. Data collected over seven annual cycles for a total exposure of ≈ 1.1 × 10⁵ kg × day have pointed out at 6.3 C.L. a positive result; corollary model dependent quests for the candidate particle have also been carried out in several of the many possible scenarios. At present the second generation DAMA/LIBRA set-up (≈ 250 kg highly radiopure NaI(Tl)) is in operation. R&D’s towards a possible ultimate radiopurity 1 ton NaI(Tl) experiment are also in progress.

DAMA/NaI [1, 2, 3, 4, 5, 6, 7, 8] was proposed in 1990 [9], designed and realized with the main aim to investigate the presence of Dark Matter (DM) particles in the galactic halo by exploiting the model independent annual modulation signature [10]. Other approaches for DM particle investigation have also been exploited and several other rare processes studied [2]. The DAMA project consisting of several low background experimental set-ups, such as: i) DAMA/NaI [1, 2, 3, 4, 5, 6, 7, 8]; ii) DAMA/LXe [11]; iii) DAMA/R&D [12]; iv) DAMA/LIBRA [13]; v) DAMA/Ge for sample measurements, which is located in the low background LNGS Ge facility [14].

DAMA/NaI took data over seven annual cycles collecting an exposure of 107731 kg × day. A clear annual modulation of the single-hit events (i.e. events in which just one detector fires) satisfying the many peculiarities expected for a DM particle induced effect has been observed [1]. The presence of an annual modulation with the proper features is favoured at 6.3 σ C.L. with an amplitude equal to (0.0200 ± 0.0032) cpd/kg/keV, a phase t₀ = (140 ± 22) days and a period T = (1.00 ± 0.01) year. Neither systematic effect nor side reaction able to account for the observed modulation amplitude and to satisfy all the requirements of the signature have been found; for details see ref. [1].

A further investigation has been performed on the multiple-hits events (i.e. events in which more than one detector fire). The multiple-hits events class – on the contrary of the single-hit one – does not include events induced by DM particles since the probability that a DM

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particle interacts in more than one detector is negligible. The fitted modulation amplitude is $A = -(3.9 \pm 7.9) \cdot 10^{-4} \text{ cpd/kg/keV}$ for the multiple-hits residual rate [1]. Summarizing, evidence of annual modulation with proper features is present in the single-hit residuals (events class to which the DM particle-induced signals 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. Details can be found in ref. [1].

On the basis of the 6.3 $\sigma$ C.L. model-independent evidence, several corollary model dependent investigations have also been pursued on the nature of the DM candidate [1, 4, 5, 3, 6, 7, 8].

For the class of the WIMP candidates, low and high mass (from GeV to many hundreds of GeV) candidates have been considered, interacting with ordinary matter via: i) mixed SI&SD coupling; ii) dominant SI coupling; iii) dominant SD coupling; iv) preferred SI inelastic scattering, in various scenarios [1]. This analysis has also been extended considering a non-thermalized DM particle component in the dark halo [5]; other non-thermalized substructures or halo models with caustics can be addressed.

It is worth to note that the 6.3 $\sigma$ C.L. model-independent DAMA/NaI evidence is well compatible with theoretical expectations for neutralino in MSSM [15].

It has also been investigated the role of the electromagnetic (e.m.) contribution produced in the interaction of the WIMP with target nuclei [6], named Migdal effect, not yet considered in the field. In fact, a certain quantity of e.m. radiation (made of escaping electron and of X-rays and/or Auger electrons) arises from the rearrangement of the atomic shells induced by the presence of a recoiling atomic nucleus. This radiation is fully contained in a detector of suitable size and because of its e.m. nature, this part of the signal is lost in all those approaches based on discrimination procedures of the e.m. component of the measured counting rate. The inclusion of this effect has a sizeable impact in the DM direct searches when interpreted in terms of low mass WIMP candidates. For a discussion see ref. [6].

Moreover, recently it has also been investigated the possible implications of the channeling effect in NaI(Tl) crystals [7]. This effect can occur in crystalline materials due to correlated collisions of ions with target atoms, resulting in a range for ions much larger than the maximum range they would have if their motion would be either in other directions or in amorphous materials. When a low-energy ion goes into a channel transfers its energy mainly to electrons rather than to the nuclei in the lattice; thus, its quenching factor (namely the ratio between the detected energy in keV electron equivalent and the kinetic energy of the recoiling nucleus in keV) approaches the unity. The inclusion of this effect gives an appreciable impact in corollary analyses in terms of WIMP (or WIMP-like) candidates [7]. In particular, this implies that lower cross sections are obtained for the allowed volumes/regions in given model frameworks by the DAMA/NaI data. For a detailed discussion see ref. [7]. Also this latter result further shows the role of the existing uncertainties and of the correct description and inclusion of all the involved processes.

As regards other scenarios, the investigation on a DM candidate interacting only with electrons [8] has also been considered, while the sterile neutrino is under analysis.

Finally, the 6.3 $\sigma$ C.L. model-independent DAMA/NaI evidence has been investigated in terms of light (≈ keV mass) boson DM candidates [4]. For these candidates, the direct detection process is based on the total conversion in NaI(Tl) crystal of the mass of the absorbed bosonic particle into e.m. radiation, while the target nuclei recoil is negligible and is not involved in the detection process. Also signals from these light bosonic DM candidates are lost in experiments applying rejection procedures of the e.m. contribution to the counting rate. Large part of the
bosonic candidate parameter space allowed by DAMA/NaI are of cosmological interest [4].

In conclusion, the DAMA/NaI experiment pointed out at 6.3 $\sigma$ C.L. the presence of DM particles in the galactic halo by investigating the model independent annual modulation signature over seven annual cycles. Neither systematic effect nor side reaction able to account for the observed effect have been found. In addition, several (of the many possible) corollary quests for the investigation on the nature of the DM candidates have also been pursued. No experiment is available so far – with the exception of DAMA/LIBRA – whose results can be directly compared in a model independent way with that of DAMA/NaI. Thus, claims for contradictions, sometimes reported in the field and in this Conference, have intrinsically no scientific meaning. Some discussion can be found e.g. in ref. [1]. Present positive hints provided by indirect searches are not in conflict with the DAMA/NaI result.

At present the second generation DAMA/LIBRA experiment (a $\sim 250$ kg highly radiopure NaI(Tl) set-up) is in operation [13]; the first release of results will occur not later than the end of 2008.

A third generation R&D towards a possible ultimate radiopure 1 ton NaI(Tl) detector, proposed by DAMA in 1996, is also in progress.

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