RESULTS AND DEVELOPMENTS WITH LARGE MASS HIGHLY RADIOPURE NaI(Tl) AT LNGS

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The low background DAMA/NaI experiment ($\simeq$ 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. This experiment has collected data over seven annual cycles for a total exposure of more than 10^5 kg $\times$ day and has pointed out at 6.3 σ C.L. a modulation effect satisfying all the many peculiarities of the signature. Neither systematics nor side reactions able to account for the observed effect were found. Several (but still few with respect to the many possibilities) corollary model dependent quests for the candidate particle have also been carried out. At present the second generation DAMA/LIBRA set-up ($\simeq$ 250 kg highly radiopure NaI(Tl)) is in operation. A R&D towards possible ultimate 1 ton NaI(Tl) experiment is also in progress.

Keywords: Scintillators; NaI(Tl); Dark Matter.

1. The DAMA/NaI experiment

The low background DAMA/NaI experiment was located in the underground laboratory of Gran Sasso; it has been part of the DAMA project, which is also composed by several other low background set-ups, in particular: i) DAMA/LXe [1]; ii) DAMA/R&D [2]; iii) the new second generation radiopure NaI(Tl) DAMA/LIBRA set-up (see later); iv) DAMA/Ge for sample measurements, which is located in the low background LNGS Ge facility [3]. A detailed description of the DAMA/NaI set-up regarding its performances, radiopurity, hardware procedures and the determination of the experimental quantities has been given e.g. in refs. [4,5].

DAMA/NaI was proposed in 1990 [6], designed and realized having the main aim to investigate the presence of Dark Matter (DM) particles in the galactic halo by exploiting the model independent annual modulation signature [7]. In fact, as a consequence of the Earth annual revolution around the Sun, a larger flux of DM particles cross the laboratory around roughly June 2^{nd} (when the Earth velocity is summed to the Sun velocity with the respect to the Galaxy) and by a smaller one around roughly December 2^{nd} (when the two velocities are subtracted). This annual modulation signature offers many peculiarities since a seasonal effect induced by DM particles must simultaneously satisfy all the following requirements: (i) the rate must contain a component modulated according to a cosine function; (ii) with one year period; (iii) a phase roughly around 2^{nd} June; (iv) the modulation must only be found in a well-defined low energy range, where DM particles can induce signals; (v) it must apply just to those events in which only one detector in a multi-detectors set-up actually "fires" (*single-hit* events), since the probability that DM particles would have multiple interactions is negligible; (vi) the modulation amplitude in the region of maximal sensitivity has to be $\leq 7\%$ for usually adopted halo distributions, but it can be significantly larger in case of some possible scenarios such as e.g. those of refs. [8,9]. To mimic such a signature either spurious effects or side reactions should be able not only to account for the observed modulation amplitude but also to contemporaneously satisfy all the requirements; none has been found nor suggested by anyone over about a decade ([4] and refs therein).

Other approaches for DM particle investigation have been exploited by DAMA/NaI as well and, in addition, several other rare processes have also been studied [10].

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2. The DAMA/NaI model-independent result

The DAMA/NaI experiment took data over seven annual cycles collecting an exposure of 107731 kg $\times$ day. A clear annual modulation has been observed in the measured rate of the *single-hit* events in the lowest energy region, satisfying the many peculiarities of a DM particle induced effect. In Fig. 1 the time behaviour of the residual rate of the *single-hit* events in the (2-6) keV energy interval is reported. Fitting the data with a cosine-like

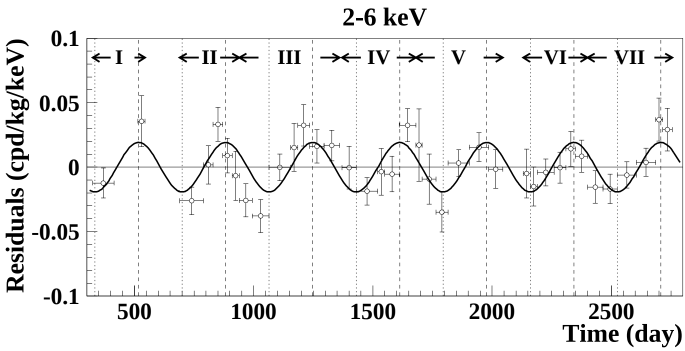

Fig. 1. Experimental residual rate for *single-hit* events in the cumulative (2–6) keV energy interval as a function of the time over 7 annual cycles (total exposure 107731 kg $\times$ day); end of data taking July 2002. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve represents the cosinusoidal function behaviour expected for a DM particle signal with a period equal to 1 year and phase exactly at 2^{nd} June; the modulation amplitude has been obtained by best fit. See ref. [4].

function the presence of annual modulation is favoured at 6.3 σ C.L. with an amplitude equal to (0.0200 ± 0.0032) cpd/kg/keV, a phase $t_0 = (140 \pm 22)$ days and a period $T = (1.00 \pm 0.01)$ year. The period and phase agree with those expected in the case of an effect induced by DM particles in the galactic halo ($T = 1$ year and t_0 roughly at $\simeq 152.5^{th}$ day of the year). The χ^2 test on the (2–6) keV residual rate disfavours the hypothesis of unmodulated behaviour giving a probability of $7 \cdot 10^{-4}$ ($\chi^2/d.o.f. = 71/37$). The same data have also been investigated by a Fourier analysis, where a clear peak corresponding to a period of $\simeq 1$ year is present. For details on other energy intervals see refs. [4] and references therein.

A careful quantitative investigation of all the known possible sources of systematic and side reactions has been regularly carried out and published at time of each data release. No systematic effect or side reaction able to account for the observed modulation amplitude and to satisfy all the requirements of the signature has been found; for details see ref. [4].

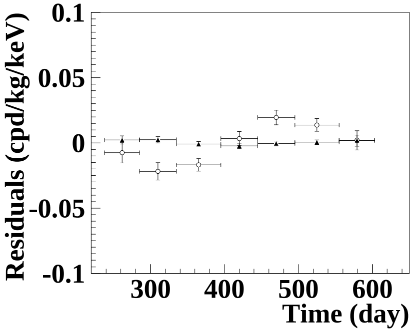

Fig. 2. Experimental residual rates over seven annual cycles for *single-hit* events (open circles) – class of events to which DM particle events belong – and over the last two annual cycles for *multiple-hits* events (filled triangles) – class of events to which DM particle events do not belong – in the (2–6) keV cumulative energy interval. They have been obtained by considering for each class of events the data as collected in a single annual cycle and using in both cases the same identical hardware and the same identical software procedures. The initial time is taken on August 7^{th}.

A further investigation has been performed in the last 2 annual cycles (DAMA/NaI-6 and 7) when each detector was equipped with its own Transient Digitizer and a dedicated renewed electronics has been installed; this has allowed to record the pulse profiles of the *multiple-hits* events (i.e. events in which more than one detector fire in coincidence). This class of events have been studied and analysed by using the same identical hardware and the same identical software procedures as for the case of the *single-hit* events (see Fig. 2). 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 particle interacts in more than one detector is negligible. The fitted modulation amplitudes are: $A = (0.0195 \pm 0.0031)$ cpd/kg/keV and $A = -(3.9 \pm 7.9) \cdot 10^{-4}$ cpd/kg/keV for *single-hit* and *multiple-hits* residual rates, respectively [4]. Thus, 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.

In conclusion, the presence of DM particles in the galactic halo is supported in a model independent way by DAMA/NaI at 6.3 σ C.L.. Except the presently running DAMA/LIBRA, no other experiment whose result can be directly compared with this one is available so far in the field of Dark Matter investigation.

3. Corollary model-dependent quests

On the basis of the obtained 6.3 σ C.L. model-independent result, corollary investigations can also be pursued on the nature of the DM candidate particle. This latter investigation is instead model-dependent and – considering the large uncertainties which exist on the astrophysical, nuclear and particle physics assumptions and on the parameters needed in the calculations – has no general meaning (as it is also the case of exclusion plots and of the DM particle parameters evaluated in indirect detection experiments). Thus, it should be handled in the most general way, as pointed out with time passing [4,9,11,12].

For simplicity, the results of the corollary analyses are presented in terms of allowed volumes/regions obtained as superposition of the configurations at given C.L. for the considered model frameworks. Details on the followed procedure can be found e.g. in ref. [4,9,11,12]. It is worth to note that although we have taken into account some of the existing uncertainties of the models and parameters needed in the calculations, the inclusion of other existing uncertainties would further extend the allowed volumes/regions and increase the sets of obtained best fit values. In addition we remind that the results briefly summarized here and the several other ones available in literature are not exhaustive of the many scenarios possible at present level of knowledge.

3.1. *Some corollary quests for WIMP class candidates*

For the case of WIMP class candidates, it has been considered so far low (of order of few GeV) and high mass (up to many hundreds of GeV) candidates interacting with ordinary matter via: i) mixed spin-independent (SI) & spin-dependent (SD) coupling; ii) dominant SI coupling; iii) dominant SD coupling; iv) preferred SI inelastic scattering. A detailed discussion on the volumes/regions allowed by the DAMA/NaI data for these candidates in some given model frameworks can be found in ref. [4]. This analysis has been extended in ref. [11] by including the possible contribution arising from a non thermalized DM particle component in the dark halo; in particular, the Sagittarius Dwarf Elliptical Galaxy (SagDEG) has been considered. In Fig. 3, examples of slices of the allowed region for purely SI candidate

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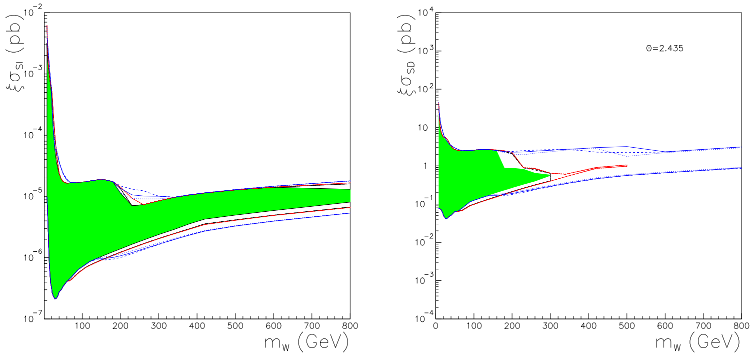

Fig. 3. Left: Region allowed in the $(\xi\sigma_{SI}, m_W)$ plane in the considered scenarios for pure SI coupling. Right: a slice of the 3-dimensional allowed volume in the $(\xi\sigma_{SD}, m_W)$ plane for $\theta = 2.435$ in the considered scenarios and for pure SD coupling. The filled region has been determined for no SagDEG contribution as in the previous subsection [4], while the areas enclosed by lines are obtained by introducing in the analysis the SagDEG stream. Different lines refer to the considered possibilities for the SagDEG stream velocity and velocity dispersion [11]; see ref. [11] for more results on the various couplings and for details.

and of the 3-dimensional allowed volume for a candidate with purely SD coupling are shown for the considered scenarios [11]. The filled region has been determined for no SagDEG contribution while the areas enclosed by lines are obtained by introducing in the analysis the SagDEG stream with DM density not larger than 0.1 GeV cm^{-3}. Different line types refer to the various considered possibilities for the SagDEG stream velocity and velocity dispersion. For details refer to [11]. Other non-thermalized substructures, such as the Canis Major satellite galaxy or the streams in the halo models with caustics, can be considered in near future.

Recently, it has also been investigated the role of the electromagnetic contribution produced in the interaction of the WIMP with target nuclei [12]. Since the 40's, in fact, it has been shown that a recoiling atomic nucleus can induce ionization and excitation of bound atomic electrons. As a consequence, a certain quantity of electromagnetic radiation (made of escaping electron and of X-rays and/or Auger electrons) arises from the rearrangement of the atomic shells. This radiation is fully contained in a detector of suitable size. This effect, named hereafter Migdal effect [13], was not yet considered in any investigations on WIMP-nucleus elastic scattering. Note that, because of its electromagnetic (e.m.) nature, this part of the signal is lost in all those approaches based on discrimination procedures of the electromagnetic component of the measured counting rate. Although the Migdal effect appears quite small, the e.m. unquenched nature of this contribution – with respect to the behaviour of the energy distribution of the nuclear recoils – can have appreciable impact in the DM direct searches when interpreted in terms of WIMP candidates, with particular regard for the low mass WIMP. Note that in order to point out just the impact of the Migdal effect, the same scenarios as in ref. [4] have been considered without any inclusion of the possible SagDEG contribution. Some examples of the results obtained by including the Migdal effect analyses for the WIMP quest are reported in Fig. 4 . As it can be seen, the accounting for the electromagnetic aspects of the interactions provides in the considered scenarios

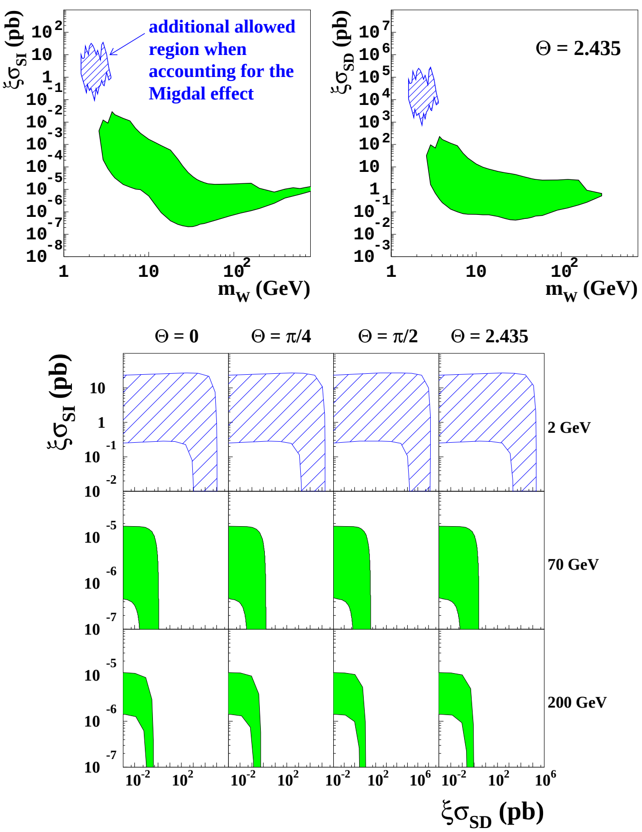

Fig. 4. Examples of region/slices allowed in the considered model frameworks for: i) pure SI coupling (upper-left); ii) pure SD coupling for the value $\theta = 2.435$ (note that θ can range from 0 to π) (upper-right); iii) mixed SI&SD coupling for some mass and θ values (bottom). The hatched region appears when accounting for the Migdal effect. Note that the inclusion of other contributions and/or of other uncertainties on parameters and models, e.g. the SagDEG contribution or more favourable form factors, would further extend the region and increases the sets of the best fit values. See ref. [12] for details.

additional volumes/regions at GeV mass scale, not topologically connected with the remaining allowed parts. This depends on the behaviour of the expected energy distributions at low masses (where the Migdal contribution is appreciable) with respect to that at higher masses, where recoils dominate.

It is worth to note that we remind that GeV mass DM particles have been widely proposed in literature in order to offer a mechanism able to account for the Baryon Asymmetry in the Universe and to explain other cosmological topics [14–16]. Among the GeV mass WIMP candidates we remind: i) the H dibaryon, already predicted within the Standard Model of particle Physics [16]; ii) the *Darkon*, a real scalar field in an extended Standard Model [17]; iii) the light photino early proposed in models of low-energy supersymmetry [18]; iv) the very light neutralino in Next-to-MSSM model [19]; v) the scalar GeV mass DM candidates of ref. [20]; vi) the mirror Deuterium in frameworks where mirror matter interactions [21] with ordinary matter are dominated by very heavy particles.

3.2. *Possible implications of the channeling effect in NaI(Tl) crystals*

Recently, we have also investigated the implication of the channeling effect in NaI(Tl) crystals [22]. Some experimental results, in fact, have shown that ions and recoiling nuclei move in a crystal in a different way than in amorphous materials. In particular, in the case of motion along crystallographic axes and planes, ions manifest an anomalous deep penetration into the lattice of the crystal and their range become much larger than the maximum they would have in case of motion in other directions or in amorphous materials. This is due to the fact that a low-energy ion, entering in the lattice into a channel, transfers its energy mainly to electrons rather than to the nuclei and, thus, its quenching factor (namely the ratio between the detected energy in keV electron equivalent [keVee] and the kinetic energy of the recoiling nucleus in keV) approaches the unity.

It is worth to note that the results about quenching factor obtained for NaI(Tl) crystals (and in general also for other crystal detector) using neutron source and published in literature can contain channeled events, but considering the low-statistics of these measurements, the small effect looked for and the energy resolution of the detectors they cannot easily be identified. Moreover, the channeling effect becomes less important at increasing energy and its contribution results more suppressed. Therefore, there is no hope to single out the channeling effect in the already-collected neutron data [22].

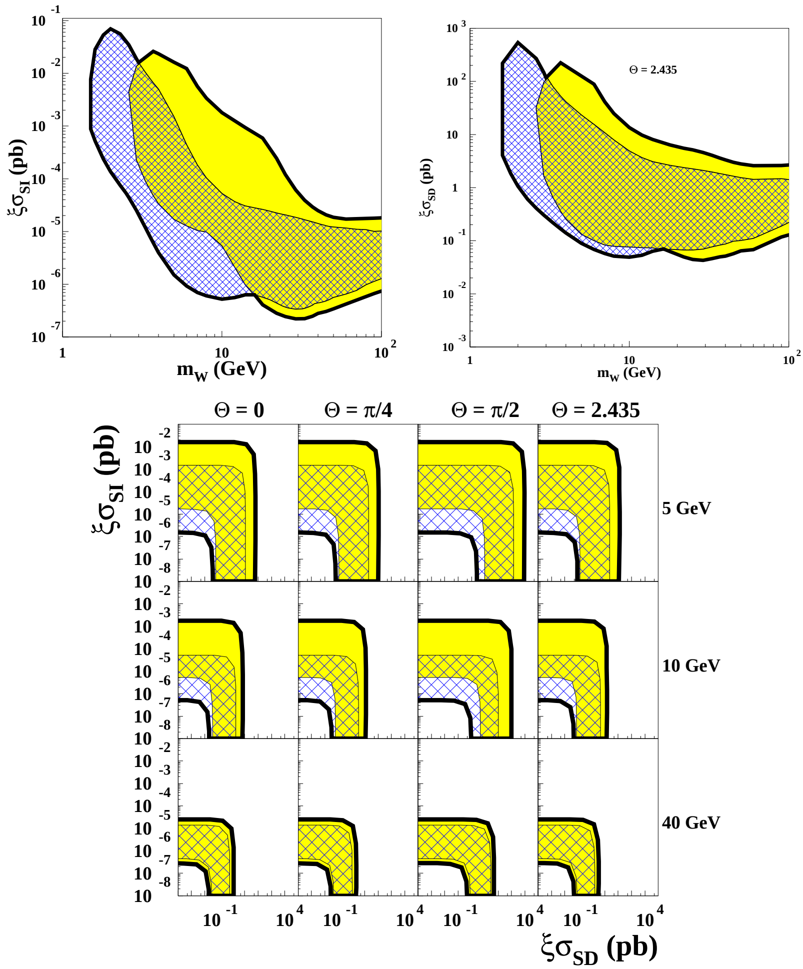

Fig. 5. Examples of region/slices allowed in the considered model frameworks for: i) pure SI coupling (upper-left); ii) pure SD coupling for the value $\theta = 2.435$ (note that θ can range from 0 to π) (upper-right); iii) mixed SI&SD coupling for some mass and θ values (bottom). The dotted region is obtained in absence of channeling effect, while the dashed one is obtained when accounting for it. The dark line marks the overal external contour. It is worth to note that the inclusion of other contributions and/or of other uncertainties on parameters and models, such as e.g. the possible SagDEG contribution and the Migdal effect or more favourable form factors, different scaling laws, etc., would further extend the region and increases the sets of the best fit values. See ref. [22] for details.

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The inclusion of this existing effect gives an appreciable impact in corollary analyses in terms of WIMP (or WIMP-like) candidates since, as mentioned, the quenching factor is a key quantity to derive the energy of the recoiling nucleus after an elastic scattering [22]. In particular lower cross sections are explorable in given models for WIMP and WIMP-like candidates by crystal scintillators, such as NaI(Tl). Similar situation holds for purely ionization detectors, as Ge (HD-Moscow - like experiments), while a loss of sensitivity is expected when pulse shape discrimination is used in crystal scintillators (such e.g. in KIMS) since the channeled events – having $q \simeq 1$ – are probably lost. Moreover, no enhancement can be present either in liquid noble gas experiments (DAMA/LXe, WARP, XENON, ...) or in bolometer experiments; on the contrary some loss of sensitivity can be expected when applying discrimination procedures, based on $q_{ion} << 1$, since some events (those with $q_{ion} \simeq 1$) are lost.

In Fig. 5 are reported some examples of regions/volumes allowed by the DAMA/NaI data when the channeling effect has been taken into account. It has been considered cases of a DM particle with pure SI, pure SD and SI&SD coupling in some given model frameworks. Also for this analysis, in order to point out just the impact of the channeling effect, the same scenarios as in ref. [4] have been considered without any inclusion of the possible SagDEG contribution and the existing Migdal effect already discussed.

The results further show the role of the existing uncertainties and of correct/complete description and inclusion of all the involved processes.

3.3. *Results for light bosonic candidates*

The DAMA/NaI model-independent evidence has also been investigated by considering as a DM candidate a light ($\simeq$ keV mass) bosonic particle, either with pseudoscalar or with scalar coupling [9]. 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 electromagnetic radiation. Thus, in these processes the target nuclei recoil is negligible and is not involved in the detection process; therefore, also signals from these light bosonic DM candidates are lost in experiments applying rejection procedures of the electromagnetic contribution to the counting rate.

In all the main processes involved in the detection of a DM light bosonic particle – both in the pseudoscalar and in the scalar interactions – the total (including the secondary processes: X-rays and Auger electrons) energy release, E_{rel}, in the detector matches the total energy of the a particle, $E_a \simeq m_a$, since the a velocity is of the order of 10^{-3}c. For details refer to [9].

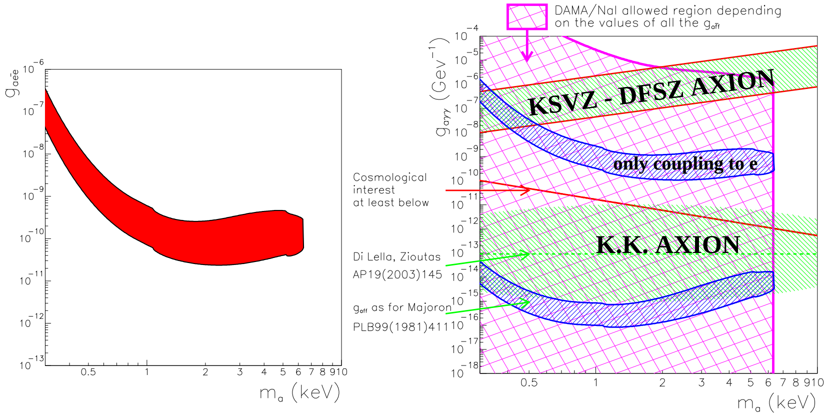

Fig. 6. Case of a pseudoscalar boson candidate (here named a). Left: region allowed at 3σ C.L. in the plane $g_{a\bar{e}e}$ vs m_a by the DAMA/NaI annual modulation data in the considered model framework. Right: allowed region in the plane $g_{a\gamma\gamma}$ vs m_a (crossed hatched region). All the configurations in this region can be allowed depending on the values of all the $g_{a\bar{f}f}$ (couplings to fermions). In the plot examples of the expectations for some models are also shown. The solid line corresponds to a particle with lifetime equal to the age of the Universe; at least all the $g_{a\gamma\gamma}$'s below this line are of cosmological interest. See ref. [9].

In Fig. 6 just the results obtained for the case of a pseudoscalar boson (here named a) are shown. In particular, in Fig. 6-left the allowed region in the plane $g_{a\bar{e}e}$ (coupling constant of the particle to the electrons,) and m_a (the particle mass) is reported. The allowed configuration can be also of cosmological interest as shown in Fig. 6-right.

Furthermore, in the case of a scalar boson (here named h), only a coupling to hadronic matter can be considered in order to account for the DAMA observations [9] and the result is an allowed multi-dimensional volume in the space defined by m_h and by all the $g_{h\bar{q}q}$, coupling constants to quarks.

For related results and discussion see ref. [9].

3.4. *... and more*

Various possibilities for some of the many possible astrophysical, nuclear and particle Physics scenarios can be considered and are also available in literature, such as e.g. refs. [8,23–32]. Recently, the DAMA Collaboration have also investigated a DM candidate interacting only with electrons [33]. An investigation of the DAMA/NaI effect in terms of sterile neutrino as DM candidate is also under consideration.

4. Some comparisons in the field

No experiment is available so far – with the exception of the presently running DAMA/LIBRA – whose results can be directly compared in a model independent way with that of DAMA/NaI. Thus, claims for contradictions have intrinsically no scientific meaning. Some discussions can be found e.g. in ref. [4,11].

In particular, as regards some claimed model-dependent comparisons presented so far we just mention – among the many existing arguments – that the other experiments available so far: i) are insensitive to the annual modulation signature; ii) use different exposed materials; iii) release just a marginal exposure (orders of magnitude lower than the one by DAMA/NaI) after several/many years underground; iv) exploit strong data selection and strong and often unsafe multiple rejection techniques of their huge counting rate, becoming at the same time insensitive to several DM candidates; v) consider a single model fixing all the astrophysical, nuclear and particle Physics assumptions as well as all the theoretical and experimental parameters at a single questionable choice; vi) generally quote in an incorrect/partial/not updated way the implications of the DAMA/NaI result.

Hereafter few considerations will be summarized. For the WIMP case they do not account for the existing uncertainties on the real coupling with ordinary matter, on the spin-dependent and spin-independent form factors and related parameters for each nucleus, on the spin factor used for each nucleus, on the real scaling laws for nuclear cross sections among different target materials; on the experimental and theoretical parameters, on the effect of different halo models and related parameters on the different target materials, etc. Moreover, large differences are expected in the counting rate among nuclei fully sensitive to the SD interaction (as ^{23}Na and ^{127}I) with the respect to nuclei largely insensitive to such a coupling (as e.g ^{nat}Ge, ^{nat}Si, ^{nat}Ar, ^{nat}Ca, ^{nat}W, ^{nat}O) and also when nuclei in principle all sensitive to this coupling but having different unpaired nucleon (e.g. neutron in case of the odd spin nuclei, such as ^{129}Xe, ^{131}Xe, ^{125}Te, ^{73}Ge, ^{29}Si, ^{183}W and proton in the ^{23}Na and ^{127}I). Obviously, when the detection of the DM particles involves electromagnetic signals (see, for example, the case of the light bosons discussed above, but also electromagnetic contribution in WIMP detection arising e.g. from known effect induced by recoiling nuclei, etc.), all the other experiments do lose the signal in their data selection and multiple "rejection" procedures of the electromagnetic contribution to the counting rate.

In addition, the other experiments present many critical points e.g. re-

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garding their energy threshold, their energy scale determination in the energy range of interest for the investigation of DM candidate particles and their multiple selection procedures, on which their claimed "sensitivities" for a "single" set of assumptions and parameters' values (ignoring both experimental and theoretical uncertainties) are based. In addition, critical items in the used "rejection" procedures are the related stabilities and efficiencies, the systematics in the evaluations of the rejection factors (ranging from 10^{-4} to 10^{-8}), stabilities and monitoring of the spill-out factors, ...

For completeness, it is also worth to further note that no results obtained with different target material can intrinsically be directly compared even for the same kind of coupling, although apparently all the presentations generally refer to cross section on the nucleon. The situation is much worse than the one in the field of double beta decay experiments when different isotopes are used.

As regards the indirect searches, a comparison would always require the calculation and the consideration of all the possible DM particle configurations in the given particle model, since it does not exist a biunivocal correspondence between the observables in the two kinds of experiments. However, the present positive hints provided by indirect searches are not in conflict with the DAMA/NaI result.

Finally, it is worth to note that – among the many corollary aspects still open – there is f.i. the possibility that the particle dark halo can have more than one component; some example have already been considered in literature.

5. The new DAMA/LIBRA and beyond

In 1996 DAMA proposed to realize a ton set-up and a new R&D project for highly radiopure NaI(Tl) detectors was funded at that time and carried out for several years in order to realize – as an intermediate step – the second generation DAMA/LIBRA experiment (successor of DAMA/NaI) with an exposed mass of about 250 kg. Thus, as a consequence of the results of this second generation R&D, the new experimental set-up DAMA/LIBRA (Large sodium Iodide Bulk for RAre processes), $\simeq$ 250 kg highly radiopure NaI(Tl) crystal scintillators (matrix of twenty-five $\simeq$ 9.70 kg NaI(Tl) crystals), was funded and realized. In fact, after the completion of the DAMA/NaI data taking on July 2002, the dismounting of DAMA/NaI occurred and the installation of DAMA/LIBRA started. The experimental site as well as many components of the installation itself have also been implemented [34]. DAMA/LIBRA started to take data in March 2003 and

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the first data release will, most probably, occur at end 2008. At present it is also in progress a new R&D for a possible ultimate radiopure 1 ton NaI(Tl) set-up.

6. Conclusion

DAMA/NaI experiment pointed out at 6.3 σ C.L. the presence of DM particles in the galactic halo by investigating the model independent annual modulation signature over seven annual cycles. No systematic effect or side reaction able to account for the observed effect has been found. Several corollary quests for the investigation on the nature of the DM candidates have also been pursued and shortly reminded here, others are available in literature considering various DM candidates and scenarios. At present the second generation DAMA/LIBRA (a $\sim$ 250 kg highly radiopure NaI(Tl) set-up) is in operation [34]. The first data release will, most probably, occur at end 2008. Finally, a third generation R&D for a possible ultimate radiopure 1 ton NaI(Tl) detector, proposed in 1996, is also in progress.

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