Highlights of DAMA

R Bernabei$^1$, P Belli$^1$, F Montecchia$^1$, F Nozzoli$^1$, F Cappella$^2$, A d’Angelo$^{2,5}$, A Incicchitti$^{2,*}$, D Prosperi$^2$, R Cerulli$^3$, C J Dai$^1$, H L He$^1$, H H Kuang$^4$, J M Ma$^4$ and Z P Ye$^{4,6}$

$^1$Dip. di Fisica, Università di Roma “Tor Vergata” and INFN, sez. Roma 2, I-00133 Rome, Italy
$^2$Dip. di Fisica, Università di Roma “La Sapienza” and INFN, sez. Roma, I-00185 Rome, Italy
$^3$INFN, Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy
$^4$IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China
$^5$Paper presented at the conference by A Incicchitti
$^*$E-mail: bernabei@roma2.infn.it

Abstract. DAMA is an observatory for rare processes and it is operative deep underground at the Gran Sasso National Laboratory of the I.N.F.N.. In particular, the DAMA/NaI set-up ($\approx 100$ kg highly radiopure NaI(Tl)) has effectively investigated the model-independent annual modulation signature. The data of seven annual cycles (total exposure of 107731 kg x day) have offered 6.3 $\sigma$ C.L. model-independent evidence for the presence of a Dark Matter particle component in the galactic halo. Some corollary model-dependent quests for the candidate particle have been investigated. In particular, in addition to WIMPs, also light bosonic candidates can account for the model independent DAMA/NaI result. At present, the second generation DAMA/LIBRA set-up ($\approx 250$ kg highly radiopure NaI(Tl)) is in data taking.

1. Introduction

DAMA is an observatory for rare processes based on the development and use of various kinds of radiopure scintillators. Several low background set-ups have been realised, in particular: i) DAMA/NaI ($\approx 100$ kg of highly radiopure NaI(Tl)) [1]; ii) DAMA/LXe ($\approx 6.5$ kg liquid Xenon) [1]; iii) DAMA/R&D, devoted to tests on prototypes and small scale experiments [1]; iv) the new second generation DAMA/LIBRA set-up ($\approx 250$ kg highly radiopure NaI(Tl)) in operation since March 2003 [1]. Moreover, in the framework of devoted R&D for radiopure detectors and photomultipliers, sample measurements are carried out by means of the low background DAMA/Ge detector, installed deep underground since more than 10 years and, in some cases, by means of Ispra facilities.

In the following, we will focus our attention only on the results obtained by DAMA/NaI regarding the annual modulation signature for the investigation of a particle Dark Matter (DM) component in the galactic halo [1, 2, 3, 4, 5], originally suggested in [6].

At present, apart from DAMA/LIBRA, no other experiment is sensitive, for mass, radiopurity and stability, to such a model independent signature. It requires the simultaneous satisfaction of all the following requirements: 1) the rate must contain a component modulated according to

\[ \frac{dN}{dt} = \left( \frac{m_\chi}{m_\nu} \right)^2 \frac{\sigma_{\chi\nu}}{m_\chi^2} \frac{4 \pi r_\chi^2}{m_\nu} \frac{\rho_\chi}{m_\nu} \frac{1}{2\pi} \cos \left( \frac{2\pi t}{\tau} \right) \]

where $m_\chi$, $m_\nu$, $\sigma_{\chi\nu}$, $\rho_\chi$, and $r_\chi$ are the mass of the particle, the mass of the neutrino, the spin-independent cross section, the density of the dark matter component in the galactic halo, and the mean distance of closest approach of the Earth to the Sun, respectively.


$^5$also: Scuola di Specializzazione in Fisica Sanitaria, Università di Roma “Tor Vergata”, I-00133 Rome, Italy
$^6$also: University of Jing Gangshan, Jiangxi, China

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to a cosine function, 2) with one year period, $T$, 3) phase, $t_0$, that peaks around $\approx 2^{nd}$ June, 4) this modulation must only be found in a well-defined low energy range, where DM particle can induce signals, 5) it must apply to those events in which only one detector "fires" (single-hit events), since the DM particle multi-scattering probability is negligible, 6) the modulation amplitude in the region of maximal sensitivity is expected to be $\leq 7\%$ for usually adopted dark halo distributions, but it can be larger in case of different scenarios (see e.g. refs. [7, 8]). To mimic such a signature spurious effects or side reactions should be able to account for the observed modulation amplitude and also to satisfy all its requirements [2].

A detailed discussion on the main topics related to DAMA/NaI result as well as a description of the set-up and its performances is given e.g. in refs. [2, 3].

2. The model-independent result of DAMA/NaI

In Fig. 1 the time behaviour of the single-hit residual rate in the (2–6) keV energy interval is shown. The experimental points show the errors as vertical bars and the time bin width as horizontal bars. The superimposed curve represents the cosinusoidal function behaviour expected for a Dark Matter 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. The data offer $6.3 \sigma$ C.L. evidence for the presence of an annual modulation of the measured rate of the single-hit events in the lowest energy region. In fact, fitting the experimental points with modulated cosine-like function ($A \cdot \cos(\omega(t - t_0))$), a modulation amplitude equal to $(0.0200 \pm 0.0032)$ cpd/kg/keV, $t_0 = (140 \pm 22)$ days and $T = \frac{2\pi}{\omega} = (1.00 \pm 0.01)$ year are obtained. The period and phase agree with those expected in case of an effect induced by Dark Matter particles in the galactic halo ($T = 1$ year and $t_0$ roughly at $\simeq 152.5^{th}$ day of the year). The hypothesis of unmodulated behaviour can be excluded being the $\chi^2/d.o.f. = 71/37$ on the (2–6) keV residual rate, which corresponds to a probability of $7 \cdot 10^{-4}$. Other model-independent analyses on the data have also been pursued[1, 2]; they give similar results and support the annual modulation effect observed at the same statistical significance.

The multiple-hit events collected during the DAMA/NaI-6 and 7 running periods have been analysed by using identical hardware and software procedures as for the case of the single-hit events, thanks to an improvement in the electronics performed before those cycles. The multiple-hit event class – on the contrary of the single-hit one – does not include events induced by Dark Matter particles since the probability that a Dark Matter 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-hit residual rates, respectively [2]. Thus, the absence of modulation in the multiple-hit event class in the 2–6 keV energy region offers an additional strong support for the presence of Dark Matter
particles in the galactic halo, further excluding any side effect either from hardware or from software procedures or from background.

Moreover, a careful investigation of all the known possible sources of systematics and side reactions has been regularly carried out and published at time of each data release (see refs. [2, 4] and references therein for quantitative discussions). No systematic effect or side reaction able to account for the observed modulation amplitude and all the requirements of the signature has been found (see e.g. ref. [2]).

In conclusion, the data of the seven annual cycles support at 6.3 \( \sigma \) C.L. the presence of an annual modulation in the residual rate of the single-hit events in the lowest energy interval (2 – 6) keV, satisfying all the features expected for a Dark Matter particle component in the galactic halo. No systematic effect or side reaction able to account for the observed effect has been found. This is the experimental result of DAMA/NaI; it is model-independent. No other experiment, whose result can be directly compared with this one in a model independent way, is available so far in the field of Dark Matter investigation.

### 3. Some corollary model-dependent quests: WIMP-like candidates

Corollary investigations have been pursued on the nature of the Dark Matter particle candidate. This latter investigation is instead model-dependent and due to the large uncertainties on the astrophysical, nuclear and particle physics assumptions and on related parameters, it has no general meaning (as well as exclusion plots in direct and indirect detection experiments). Thus, it should be handled in the most general way [2, 4, 5]. DAMA/NaI, having both a light (the \(^{23}\text{Na}\)) and a heavy (the \(^{127}\text{I}\)) target-nucleus, is intrinsically sensitive to Dark Matter particle both of low and high mass.

The results briefly summarized here are not exhaustive of the many scenarios possible at present level of knowledge [1, 2], including those depicted in some more recent works such as e.g. refs. [8, 9]. The general case is a four dimensional allowed volume (\(\xi \sigma_{SI}, \xi \sigma_{SD}, m_W\) and \(\theta\) values); in Figs. 2, 3, 4 only some of the allowed slices/regions are given as example. See e.g. ref.[2] where a detailed discussion is given and a WIMP with a preferred inelastic interaction [7] is also considered. The comparison of the case for purely SI candidate with neutralino can be found e.g. in ref. [10]. Some positive hints from indirect detection are not in contradiction with

![Figure 2. Case of a Dark Matter particle with mixed Spin-Independent & Spin-Dependent interaction for the model frameworks given in ref. [2]. Coloured areas: example of slices (of the 4-dimensional allowed volume) in the plane \(\xi \sigma_{SI}\) vs \(\xi \sigma_{SD}\) for some of the possible \(m_W\) and \(\theta\) values. Here, \(\xi\) is the fractional amount of local density of Dark Matter particles, \(\sigma_{SI}\) and \(\sigma_{SD}\) are the Spin-Independent and Spin-Dependent DM particle-nucleon cross sections and \(\theta\), defined in the \([0,\pi]\) interval, is an angle whose tangent is the ratio between the effective DM particle-nucleon coupling strengths for Spin-Dependent interaction.](image-url)
the DAMA/NaI result. It has also been suggested [12] that these positive hints and the effect observed by DAMA/NaI can be described in a scenario with multi-component Dark Matter in the galactic halo, made of a subdominant component of heavy neutrinos of the 4th family and of a sterile dominant component. Other scenarios have been and are under consideration.

4. Another class of candidates: axion-like particles

As mentioned, in the framework of DAMA investigation some corollary quests for a candidate particle have been carried out on the class of DM candidate particles named WIMPs [2, 4, 5]; in literature several candidates for WIMPs have been considered, all foreseen in theories beyond the Standard Model of particle Physics. Moreover, other possibilities exist with a phenomenology similar as for the WIMP cases: the mirror Dark Matter particles [13], the self-interacting dark matter particles [14], etc. and in principle even whatever particle with suitable characteristics, not yet foreseen by theories, can be a good candidate as DM in the galactic halo.

Recently the DAMA collaboration has also considered another class of candidates in some of the possible scenarios: axion-like particles, of \( \sim \) keV mass\(^7\), either with the pseudoscalar or scalar coupling [15], which are non-relativistic since they should be trapped in the galactic halo.

The full analysis of the 107731 kg \cdot day exposure from DAMA/NaI in this framework has been given in a devoted publication [15]. Here it will be briefly summarised only the result on pseudoscalar case, while the scalar case can be found in Nozzoli’s contribution to these proceedings [16].

\(^7\) In fact, considering the phenomenology of this candidate a keV-scale bosonic candidate naturally arises as an additional solution to the observed model-independent DAMA/NaI annual modulation signal.
Axion-like particles can be considered particles having similar phenomenology with ordinary matter like the axion, but with coupling constants and mass significantly different than those foreseen in the DFSZ and KSVZ models: for example, the axion itself in the Kaluza-Klein theories [17], where it would have similar couplings as in the DFSZ and KSVZ models, but much higher mass states or the "exotic" axion models proposed by [18]. Other candidates are pseudo-Nambu-Goldstone bosons related to spontaneous global symmetry breaking different from the $U(1)^{PQ}$ hypothesized by Peccei-Quinn, such as the pseudoscalar familon in the case of the family symmetry or the Majoron for the lepton number symmetry [19].

It is worth to note that some indirect astrophysical observations: i) the Solar corona problem; ii) the X-rays flux detected by ROSAT in the direction of the dark side of the Moon; iii) the X-rays background radiation in the 2-8 keV region measured by CHANDRA (XRB); iv) the excess of X-rays from clusters of galaxies; have recently been analysed in a model of axion-like particles with mass in the keV range and coupling to photons $g_{a\gamma\gamma}$ of the order of $10^{-13} GeV^{-1}$ [20], that is requiring a model with expectations for the coupling constants and masses well different compared to those expected in the DFSZ and KSVZ models. It has also been argued that the existence of axion-like particles may account for the high energy cosmic rays [21]. Finally, a keV Majoron has been suggested as DM particle [22] and a $\sim$ keV DM pseudoscalar candidate has also been taken into account in ref. [18, 23].

Several mechanisms can be advocated for the production of these particles in the early Universe (see e.g. ref. [18, 22, 23]) demonstrating that they can be of cosmological interest.

It is worth to note that the direct detection process for light bosonic DM candidates 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, signals from these light bosonic DM candidates are lost in all the experiments based on rejection procedures of the electromagnetic contribution to the counting rate.

The main processes involved in the detection of a DM light bosonic particle (here generically named $a$ for the pseudoscalar case) both in the pseudoscalar and in the scalar interaction types are "Compton - like" effect, "Axioelectric" or photoelectric-like effect and Primakoff effect.

In all these processes the total (including the secondary processes: X-rays and Auger electrons) energy release, $E_{rel}$, in the detector (providing that its detection efficiency is $\approx 1$ for low-energy electrons and low-energy photons) matches the total energy of the $a$ particle, $E_a \approx m_a$ since the $a$ velocity is of the order of $10^{-3}c$. In terms of annual modulation investigation all the interactions considered above for the pseudoscalar candidate contribute to the constant part of the signal, while the Compton-like interaction does not contribute to the modulation part of the signal. Moreover, as it can be easily demonstrated, for the pseudoscalar case the axioelectric contribution to the total expected counting rate is largely dominant with the respect to the contributions of Primakoff and Compton-like on nuclei at least in all the "natural" cases, where $g_{ae}/m_a$ is not lower than a factor $\sim 10^{-3}$ the coupling constant to mass ratios of the other charged fermions; in addition, it still remains at least one order of magnitude larger than the one due to the Compton-like effect on electrons, for a particle mass below $\approx 6$ keV.

Obviously, these results are not exhaustive of the many scenarios (still possible at present level of knowledge) for these [15] and for other classes of candidates (such as the WIMPs we have already deeply investigated [2, 4, 5]).

First of all, as already mentioned, the axioelectric contribution is dominant with the respect to the Compton-like and Primakoff effects in all the "natural" cases; thus, the results can be presented in terms of only two variables $g_{ae}$ and $m_a$. The allowed region in the plane defined by these two variables has been calculated considering the DAMA/NaI results on the model independent annual modulation signature (see Fig. 5). This allowed region is almost independent on the adopted $g_{a\alpha\alpha}$ and $g_{a\alpha\alpha}$ coupling constants.
The allowed region reported in Fig. 5 can only marginally be affected by the results already presented at low energy by low-background ionization detectors; in fact, due e.g. to their energy resolution and to their quoted counting rate at low energy, in particular their results do not rule out a particles with \( m_a \lesssim 3 \) keV and, for \( m_a \gtrsim 3 \) keV, a particles with \( g_{a\bar{e}e} \lesssim 2 \times 10^{-10} \).

Some strongly model dependent astrophysical limits on the \( g_{a\bar{e}e} \) can be found in literature (see e.g. [24]) by studying the globular cluster stars; however, these constraints only apply to particles with masses much below few keV, which is the typical core temperature of the stars.

**Figure 5.** DAMA/NaI allowed region at 3σ C.L. in the plane \( g_{a\bar{e}e} \) vs \( m_a \); see ref.[15].

The pseudoscalar boson particle can decay into two photons but its lifetime can be also of cosmological interest as shown in Fig. 6, where the allowed region in the plane \( g_{a\gamma\gamma} \) vs \( m_a \) is reported.

The upper bound on \( g_{a\gamma\gamma} \) is given when the Primakoff effect is largely dominant (that is, if \( g_{a\bar{e}e} = g_{a\bar{u}u} = g_{a\bar{d}d} = 0 \) and only contributions from other charged fermions are present). All the other values of \( g_{a\gamma\gamma} \) below this upper bound are allowed depending on the values of all the \( g_{a\bar{f}f} \).

In conclusion, a pseudoscalar DM candidate as well as a scalar one [15, 16] can also account for the DAMA/NaI model independent result as well as the WIMP solution we extensively discussed elsewhere [2, 4, 5].

**Figure 6.** DAMA/NaI allowed region at 3σ C.L. 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 \( g_{a\bar{f}f} \); see ref.[15].

5. Towards the future: from DAMA/NaI to DAMA/LIBRA and beyond

In 1996 DAMA proposed to realize a ton set-up [25] 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 experiment, successor of DAMA/NaI, with an exposed mass of about 250 kg.

As a consequence of the results of this second generation R&D, the new experimental setup 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 at end 1999 and realised. The experimental site as well as many components of the installation...
itself have been implemented (environment, shield of the photomultipliers, wiring, High-Purity Nitrogen system, cooling water of air conditioner, electronics and data acquisition system, etc.). In particular, all the Copper parts have been chemically etched before their installation following a new devoted protocol and all the procedures performed during the dismounting of DAMA/NaI and the installation of DAMA/LIBRA detectors have been carried out in High-Purity Nitrogen atmosphere [26].

DAMA/LIBRA is taking data since March 2003 and the first data release will, most probably, occur when an exposure larger than that of DAMA/NaI will have been collected and analysed in all the aspects. The highly radiopure DAMA/LIBRA set-up is a powerful tool that will further investigate the model independent evidence pointed out by DAMA/NaI with increased sensitivity and some interesting physical and astrophysical aspects (see ref. [16]).

At present a third generation R&D effort towards a possible NaI(Tl) ton set-up has been funded by I.N.F.N. and related works have already been started.

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