Direct searches for Dark Matter particles (above LN\textsubscript{2} temperature)

P. Belli
INFN, Sezione di Roma Tor Vergata, I-00133 Rome, Italy
E-mail: pierluigi.belli@roma2.infn.it

Abstract. Experimental observations and theoretical considerations have shown that a large part of the Universe is made of Dark Matter particles; this has currently motivated a large experimental effort to investigate them by direct detection approaches. In particular, several techniques are developed. A short review of those that use target at temperature above 77 K is summarized, with particular care to the approaches able to offer a suitable model-independent signature. Some perspectives will also be mentioned.

1. Introduction
The problem of the existence of Dark Matter in our Universe dates back to the astrophysical observations at the beginning of the past century. Many observations from the galactic to the cosmological scale support that most of the Universe is dark and large space for Dark Matter (DM) particles in the Universe exists. Most of the DM particles, relics from the Big Bang, were either produced at rest or non relativistic at decoupling time. The DM candidates have to be neutral, stable or quasi-stable (e.g. with a decay time of order of or larger than the age of the Universe) and have to be elusive in the interaction with ordinary matter. These features are respected, for example, by the axions, by axion-like candidates with mass in the keV range, by possible sterile neutrino, by a class of candidates named WIMPs (Weakly Interacting Massive Particles) and by some other candidates which cannot properly be classified as WIMP, but which offer similar phenomenology.

The study of DM candidates implies that a window beyond the Standard Model is investigated. At present, a widely considered candidate for DM is the lightest supersymmetric particle (LSP) that is stable in supersymmetric theories where the R-parity is conserved. The neutralino can be a suitable LSP candidate and is widely considered as DM particle [1]. However, other DM candidates can also be considered, such as e.g. a heavy neutrino of the 4th family or a sneutrino (the spin-0 supersymmetric partner of the neutrino) in a multi-component Dark Matter scenario. Moreover, a dominant contribution due to a sneutrino candidate remains still possible in supersymmetric models with violation of lepton number, where two mass states and a small energy splitting is present [2]. Other possible candidates are the particles from multi-dimensional Kaluza-Klein-like theories, the mirror Dark Matter particles [3], the self-interacting dark matter particles [4], etc. Recently, also a DM candidate interacting only with electrons has been proposed [5]. The case of a light (~ keV mass) DM candidate, a bosonic particle either with pseudoscalar or with scalar coupling, has also been considered [6]. The sterile neutrino can also be a good DM candidate.

Several observations have pointed out that our Galaxy should also be embedded in a dark halo with mass at least 10 times larger than that of the luminous matter. The presence of DM
particles in this dark halo can be investigated by direct approaches in underground laboratory. In case of WIMP or WIMP-like candidates, their interactions induce recoiling nuclei and/or, in case of inelastic scattering, also the successive de-excitation gamma’s. Moreover, it has been pointed out that a recoiling nucleus can also induce ionization and excitation of bound atomic electrons; as a consequence, a certain quantity of electromagnetic radiation can contribute to the signal [7]. Recently, also a DM candidate interacting only with electrons has been proposed [5]. In case the light (∼ keV mass) bosonic particles are considered [6], the direct detection process is based on the total conversion in the detector of their mass into electromagnetic radiation. In these last processes the target nuclei recoil is negligible and is not involved in the detection process; therefore, because of their electromagnetic nature, these signals are lost in all those experiments using approaches based on discrimination procedures of the electromagnetic component of the measured counting rate.

In the world there are several experiments aiming to perform a direct DM investigation, using different kind of detectors and exploiting different approaches. Some of those that use target at temperature above 77 K will be summarized here, with particular care to the different experimental approaches.

2. Experiments using liquid noble gases

In this section we briefly summarize the experiments using scintillating liquid noble gases as target materials. The DAMA/LXe, started in 1990 [8], was the first experiment that developed liquid Xenon as target material for DM searches. Afterwards, exploiting the pulse shape discrimination techniques, results with a single phase detector have been realized by DAMA/LXe itself [9] and by ZEPLIN-I [10].

In the last years dual phase detectors have been proposed. These experiments exploit some discrimination between nuclear recoils candidates and the electromagnetic component of the measured counting rate through the ratio of the prompt scintillation signal ($S_1$) and the delayed signal ($S_2$) due to drifted electrons in the gaseous phase.

Recently, some results from prototypes have been published by: i) XENON10 [11], using a fiducial volume of 5.4 kg of liquid natural Xenon and an exposure of 136 kg × days; ii) WARP [12], using a fiducial volume of 2.3 liters of liquid natural Argon and an exposure of 96.5 kg × days; iii) ZEPLIN-II [13], using a fiducial volume of 7.2 kg of liquid natural Xenon and an exposure of 225 kg × days.

These experiments start from sizable counting rate and, in order to try to lower it, need to apply many data selections and handling. Each selection step can introduce systematic errors which can also be variable along the data taking period. After these selections procedures, an analysis based on some discrimination between the electromagnetic radiation and recoiling candidates is applied. In Fig. 1 examples of the published plots – obtained after applying the above mentioned cuts – have been reported for the three experiments, respectively.

The selected events are shown in scatter plots obtained by considering some discrimination variables. The acceptance windows (50% efficiency for XENON10 and ZEPLIN-II) for recoils candidates are also shown there; as it can be seen, several recoils and/or recoil-like candidates survive all the rejection procedures. Generally all of them are interpreted as residual background of various (even “unknown”) nature. This appears at the moment a great limitation of this technique.

It is worth to point out some warnings about the present stage of the dual phase detectors, such as: i) the physical energy threshold is not properly evaluated by source calibrations in the energy interval of interest; ii) the detectors suffer from disuniformity (this seems to be an intrinsic limitation of the technique; it needs corrections to be applied and systematics to be accounted for, see in ref. [11, 14, 10, 13]); iii) the used gas is natural Xenon or Argon, with an unavoidable content of Krypton and $^{39}$Ar, respectively; iv) the small and not linear light
responses (e.g. $\simeq 2.2$ and roughly $0.5 \div 1$ photoelectrons/keVee claimed for XENON10 and for WARP, respectively); v) the poor energy resolutions (e.g. $\sigma/E \simeq 13\%$ and $16\%$ at $122$ keV $\gamma$ rays for WARP and ZEPLIN-II, respectively); vi) despite of the small light response, an energy threshold of $2$ keVee is claimed by XENON10; vii) the large number of materials involved in the core of the experiments (for example, in XENON10 there are $89$ PMTs, all the materials for the electric field, the stainless steel containers, ...) prevents low level counting rate; etc.

To be short, all similar items can affect the robustness of whatever presented conclusion.

Furthermore, it is my opinion that electromagnetic rejection techniques, e.g. double phase read-out in liquid noble gases experiments, heat/ionizing and heat/light signals in bolometers, would require a much deeper and quantitative investigation than those made available up to now. It is worth to note that a “discrimination on an event-by-event base” might be possible only in the ideal case of zero systematics. Moreover, even in an ideal case, the result will not be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well known existing recoil-like indistinguishable background. Finally, the electromagnetic component of the counting rate can contain itself the signal or part of it, as mentioned above, and will be lost by these approaches.

3. Model independent signatures

To obtain a reliable signature for the presence of DM particles in the galactic halo, it is necessary to follow a suitable model independent approach. In principle, two main possibilities exist; they are based on the correlation between the distribution of the events detected in a suitable underground set-up with the galactic motion of the Earth.

The first one – applying only for the WIMPs class of DM candidates – correlates the recoil direction with that of the Earth velocity, but it is practically disfavoured mainly by the technical difficulties in detecting the short recoil track. Few R&D attempts have been carried out so far, while suggestions, based on the use of anisotropic scintillators, were proposed in [15]. Recently, the project DRIFT (see Fig. 2) has collected an exposure of $10.2$ kg $\times$ days with a $1$ m$^3$ active volume filled by $40$ Torr of CS$_2$ gas (that is $167$ g of target material). A population of nuclear recoil candidates (interpreted as due to the decay of unexpected $^{222}$Rn daughter nuclei, present in the chamber) has been observed [16]. Efforts are planned towards the future.

The second possibility, feasible and able to test a large range of cross sections and of DM particle halo densities, is the so-called annual modulation signature [17]. This is the main signature already exploited by the DAMA/NaI set-up ($\simeq 100$ kg highly radiopure NaI(Tl) detectors) [18, 19]. The annual modulation of the signal rate originates from the Earth revolution around the Sun and 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) with a phase roughly around 2nd 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. [2, 6]. 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.

The signature approach is a unique tool for a model-independent investigation of DM particles in the galactic halo. In particular, the annual modulation has been exploited – using highly radiopure NaI(Tl) as target material – by the DAMA/NaI experiment, whose model-independent result will be briefly recalled in the following; the corollary model-dependent quests for the DM candidates will be summarized too, since they also allow to offer – at some extent – a view on the complexity of the astrophysical, nuclear and particle physics aspects related to the field.

4. The DAMA/NaI experiment

The low background DAMA/NaI experiment [18, 19, 20] 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 (see Cerulli’s paper in these Proceedings, ref. [21] and the references therein).

4.1. The model-independent result

The DAMA/NaI experiment took data over seven annual cycles collecting an exposure of $\approx 1.1 \times 10^5$ 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 [18, 19]. In Fig. 3 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 function the presence of annual modulation is favoured at 6.3 $\sigma$ C.L. with an amplitude equal to $(0.0200 \pm 0.0032)$ 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 $\approx 152.5^{th}$ day of the year). For details see refs. [18, 19] and references therein. Note that, while an evidence for a modulated part of the signal with proper features is present in the single-hit residuals (events class to which the DM particle-induced signals belong), it is absent in the multiple-hits residual rate (event class to which only background events belong) [19]. 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.
Figure 3. 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 × day); end of data taking July 2002. 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 2nd June. See ref. [18, 19].

A careful quantitative investigation of all the known possible sources of systematic and side reactions has been carried out; 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 quantitative discussion see ref. [18, 19].

In conclusion, the presence of DM particles in the galactic halo is supported in a model independent way by DAMA/NaI at 6.3 $\sigma$ 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.

4.2. The corollary model-dependent quests
On the basis of the obtained 6.3 $\sigma$ C.L. model-independent result, corollary investigations can also be pursued on the nature of the DM particle candidate. This latter investigation is model-dependent and – considering the large uncertainties 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 [18, 19, 5, 6, 7, 22, 23].

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. 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 mentioned here and the several other ones available in literature are not exhaustive of the many scenarios possible at present level of knowledge.

For the case of WIMP class 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 [18, 19]. This analysis has also been extended considering a non thermalized DM particle component in the dark halo [22]; other non-thermalized substructures or halo models with caustics can be addressed.

It is worth to note that the model-independent DAMA/NaI evidence is well compatible with theoretical expectations for neutralino in MSSM [1].

It has also been investigated the role of the electromagnetic radiation produced in the interaction of the WIMP with target nuclei [7] (hereafter Migdal effect). 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. [7].

Recently, the implication of the “channeling” effect in NaI(Tl) crystals has been investigated [23]. 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 approaches the unity. Moreover, it has been demonstrated that such an effect cannot be singled out in the already-collected neutron calibration data [23]. The inclusion of this existing effect gives an appreciable impact in corollary analyses in terms of WIMP (or WIMP-like) candidates [23]. 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. [23]. 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 \( q \approx 1 \) – 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 \( q_{\text{ion}} < 1 \), since some events (those with \( q_{\text{ion}} \approx 1 \)) are lost.

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

The DAMA/NaI model-independent evidence has also been investigated by considering as a DM candidate a light (\( \sim \) keV mass) bosonic particle, either with pseudoscalar or with scalar coupling [6]. For these candidates, the direct detection process is based on the total conversion in the detector’s material 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. Large part of the bosonic candidate parameter space allowed by DAMA/NaI are of cosmological interest [6].

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. [1, 2, 3, 4, 24, 25, 26]. Recently, the DAMA Collaboration have also investigated a DM candidate interacting only with electrons [5]. An investigation on the sterile neutrino as DM candidate is also under consideration.

5. Some perspectives

At present the annual modulation is exploited by the second generation DAMA/LIBRA experiment (a \( \sim 250 \) kg highly radiopure NaI(Tl) set-up), in operation [27] at Gran Sasso (see Fig. 4). The first release of results will occur not later than end of 2008.

Two other experiments plan to exploit such a signature: ANAIS [28] at Canfranc tunnel, which is trying to improve the features of old NaI(Tl) detectors by home-made efforts, and KIMS [29] at Yangyang, using CsI(Tl) detectors. The latter experiment has recently presented a preliminary study by means of pulse shape discrimination [29]; considerations similar than those already discussed before about discrimination procedures hold.

Finally, note that some alternative techniques are under investigation, such as those using the
Figure 4. Installing the highly radiopure NaI(Tl) crystals inside the low background shield of the DAMA/LIBRA set-up in HP Nitrogen atmosphere [27].

Moreover, efforts and developments are in progress towards larger mass set-ups by all the experimental activities.

6. Conclusions

Large experimental efforts have been done in the investigation of the DM particles in the galactic halo. In particular, several techniques have been used. Some of them have been summarized here with the particular care to the techniques able to offer model-independent signatures.

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