Results and strategies in dark matter detection

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The dark matter (DM) parallel session DM2 of the 14th Marcel Grossmann Meeting was enriched by several contributions about the results and the strategies in the study and in the detection of DM particles in the Galactic halo. In the following, an overview of the latest results in this field will be summarized. A particular care will be given to the results obtained by exploiting the model independent DM annual modulation signature for the presence of DM particles in the galactic halo. Results from the other experiments using different procedures, different techniques and different target materials will be shortly addressed as well as implications and experimental perspectives.

Keywords: Dark matter; direct detection.

1. Introduction

Experimental observations and theoretical arguments have pointed out that most of the matter in the universe has a nonbaryonic nature and is in form of dark matter (DM) particles. Many candidates — different in nature and with different and various interaction types — as DM particles of the universe have been proposed within theories beyond the Standard Model of particle physics; some of them have been addressed in the parallel session DM2 of the 14th Marcel Grossmann Meeting[1–3].

Depending on the DM candidate, the interaction processes can be various, as e.g.: (1) elastic scatterings on target nuclei with either spin-independent or spin-dependent or mixed coupling; moreover, an additional electromagnetic contribution can arise, in case of few GeV candidates, from the excitation of bound electrons by the recoiling nuclei[4]; (2) inelastic scatterings on target nuclei with either spin-independent or spin-dependent or mixed coupling in various scenarios[5–10]; (3) interaction of light DM either on electrons or on nuclei with production of a lighter particle[11]; (4) preferred interaction with electrons[12]; (5) conversion of DM particles into electromagnetic radiation[13]; (6) etc. Often, the elastic scattering on target nuclei is the considered interaction process, but other processes are possible and considered in literature, as those aforementioned where also electromagnetic radiation is produced. Hence, considering the richness of particle possibilities and the existing uncertainties on related astrophysical (e.g. halo model and related parameters, etc.), nuclear (e.g. form factors, spin factors, scaling laws, etc.) and particle physics (e.g. particle nature, interaction types, etc.), a widely-sensitive model independent approach is mandatory. Most activities in the field are instead based on a particular *a priori* assumption on the nature of the DM particle and of its interaction, in order to try to overcome the limitation arising from their generally large originally measured counting rate.

Moreover, many other experimental and theoretical uncertainties exist and must be properly considered in a suitable interpretation and comparison among experiments of direct detection of DM particles.

Before summarizing the efforts of the most important direct detection experiments, let us briefly comment few items. Firstly, the DM indirect search — that is the study of possible products either of decay or of annihilation of DM particles in the galactic halo or in celestial body — is performed as by-product of experiments located underground, under-water, under-ice, or in space, as also addressed[14–16]. The interpretation of such a study is strongly dependent on the chosen assumptions for the modeling of the background and is restricted to some DM candidates with peculiar features. Therefore, all that shows the intrinsic uncertainties of the DM indirect searches to unambiguously assess presence of DM in the galactic halo. On the other hand, experiments at accelerators may prove — when they can state a solid model independent result — the existence of some possible DM candidate particles, but they could never credit by themselves that a certain particle is a/the only solution for DM particle(s). Moreover, DM candidate particles and scenarios (even, e.g. in the case of the neutralino candidate) exist which cannot be investigated at accelerators.

2. The Dark Matter Particles Detection

In order to pursue a widely sensitive direct detection of DM particles in the galactic halo, a model independent approach, a ultra-low-background suitable target material, a very large exposure and the full control of running conditions are strictly necessary.

Indeed, most activities in the field release marginal exposures even after many years underground; they do not offer suitable information, e.g. about operational stability and procedures during the running periods, and generally base their analysis on a particular *a priori* assumption on the nature of the DM particle and its interaction, and of all the used parameters.

In particular, the applied rejection and subtraction procedures to reduce the experimental counting rate, in order to derive a set of recoil-like candidates, is pursued by experiments as CDMS, EDELWEISS, CRESST, XENON, LUX, etc. It is worth noting that the applied subtraction procedures are statistical and cannot offer an unambiguous identification of the presence of DM particle elastic scatterings because of the known existing recoil-like indistinguishable background; tails of the subtracted populations can play a role as well. Finally, the electromagnetic component of the counting rate, statistically "rejected" in this approach, can contain either the signal or part of it, and it will be lost. In the following, few main experimental activities are mentioned as examples. Some arguments can be also found in Refs. 17 and 18.

In the double read-out bolometric technique[19], the heat signal and the ionization signal are used in order to discriminate between electromagnetic and recoil-like events. This technique is used by CDMS and EDELWEISS collaborations. In particular, the CDMS-II detector consisted of 19 Ge bolometers of about 230 g each one and of 11 Si bolometers of about 100 g each one. The experiment released data for an exposure of about 194 kg $\times$ day[20] using only 10 Ge detectors in the analysis (discarding all the data collected with the other ones) and considering selected time periods for each detector. EDELWEISS employed a target fiducial mass of about 2 kg of Ge and has released data for an exposure of 384 kg $\times$ day collected in two different periods (July–November 08 and April 09–May 10)[21] with a 17% reduction of exposure due to run selection. These two experiments claim an "event by event" discrimination between noise + electromagnetic background and recoil + recoil-like (neutrons, end-range alphas, fission fragments, . . .) events by comparing the bolometer and the ionizing signals for each event. Thus, their results are, actually, largely based on huge data selections, as for example, the time cut analysis used to remove the so-called surface electrons that are distributed in both the electromagnetic and recoil bands. The stability, the nonlinear response and the robustness of the reconstruction procedure are key points, as well as the associated systematical errors. In these experiments, few recoil-like events survive the many selections/subtractions cuts applied in the data analysis; these events are generally interpreted in terms of background. As regards, in particular, their application to the search for time dependence of the data (such as the annual modulation signature), it would require — among other — to face the objective difficulty to control all the operating conditions — at the needed level ($< 1\%$) — despite of the required periodical procedures, e.g. for cooling and for calibration and owing to the limitation arising from the low duty cycle. For example, the attempt by CDMS-II to search for annual modulation in Ge target has been performed with a marginal exposure by using only eight detectors over 30 and using — among others — data that are not continuous over the whole annual periods considered in the analysis[22]; the use of nonoverlapping time periods, collected with detectors having different background rates within the signal box does not allow one to get any reliable result in the investigation of an effect at few percent level (see, e.g. arguments in Ref. 23).

Other data taking was dedicated to measurements using a calorimetric technique, named CDMSlite, which relies on voltage-assisted Luke–Neganov amplification of the ionization energy deposited by particle interactions[24]. The data were collected with a single 0.6 kg germanium detector running for 10 live days at the Soudan underground laboratory. A low energy threshold of 170 eV_{ee} (electron equivalent) was claimed[24], while recent data taking achieved even lower energy threshold[25]. In the meanwhile SuperCDMS at SNOlab[26] reported preliminary results corresponding to an exposure of 577 kg $\times$ days[27], with an increased mass of 9.0 kg (15 detectors of 600 g each) and with increased detectors' performances. Eleven events were observed not fully compatible with background expectation, even assuming the correctness of all the adopted procedures[27].

The results of CDMS-II with the Si detectors were published in two close-in-time data releases[28,29]; while no events in six detectors (corresponding exposure of only 55.9 kg × day before analysis cuts) were reported in the former[28], three events in eight detectors (corresponding raw exposure of 140.2 kg × day) were reported over the residual background, estimated after subtraction: $\simeq 0.4$ in the second one[29]. The latter result could be interpreted — under certain assumptions — in terms of a DM candidate with spin-independent interaction and a mass around 10 GeV, which is compatible with some interpretations of the model independent DM annual modulation result already reported by DAMA in terms of this kind of DM candidate and with some other hints reported by CoGeNT (see later).

In the meanwhile EDELWEISS was in data taking in the period July 2014–April 2015 and restarted in June 2015 with 36 detectors installed corresponding to a target fiducial mass of more than 14 kg of Ge[30]; new results collected with eight full inter digitized (FID) detectors (582 kg × day) have been recently presented[31].

The CRESST experiment exploits the double read-out bolometric technique, using the heat signal due to an interacting particle in the $CaWO_4$ crystals and the produced scintillation light. A statistical discrimination of nuclear recoil-like events from electromagnetic radiation is performed. As regards the applied cuts and selection procedures, most of the above discussion still holds. A previous run (eight detectors of 300 g each one, for an exposure of about 730 kg × day[32]) showed that, after selections, 67 nuclear recoil-like events were observed in the oxygen band. The background contribution estimated by authors ranges from 37 to 43 events, and does not account for all the observed events. The remaining number of events and their energy distribution could be interpreted — under certain assumptions — in terms of a DM candidate with spin-independent interaction and a mass in the range of 10–30 GeV. This result has been not confirmed in the last run[33], where a more marginal exposure has been used (52 kg × day and energy threshold of 307 eV), confirming the difficulties to manage the systematics in such experiments.

The new version of CRESST (CRESST-III) will use new detector modules of 24 g each trying to attain low energy thresholds. Projects of large mass bolometers are also planned in Europe (EURECA) and at SNOlab.

The XENON project uses instead dual phase liquid/gas detectors. Experiments exploiting such technique (as also LUX, DARKSIDE, see also Ref. 34) perform statistical discrimination between nuclear recoil-like candidates and electromagnetic component of the measured counting rate through the ratio of the prompt scintillation signal ($S1$) and the delayed signal ($S2$) due to drifted electrons in the gaseous phase. The XENON100 experiment has released data taken in the years 2011–2012 for an exposure of 224.6 days, using a fiducial volume of just 34 kg of Xenon target mass[35]. See related discussions in literature about the detector response of such devices, in particular, to low energy recoils[17,18,36]. The technical performance of the apparata, confirmed also by similar experiments, has shown, e.g. that: (i) the detectors are affected by large nonuniformity; some kind of corrections may be estimated and applied, but significant systematics has to be accounted for; (ii) the response of these detectors is not linear, i.e. the number of photoelectrons/keV depends on the energy scale and depends also on the applied electric field; (iii) the physical energy threshold is not suitably proved (iv) the use of energy calibration lines from Xe activated by neutrons cannot be applied as routine and the studies on a possible calibration with internal sources in the same running conditions have not been realized so far; (v) despite of the small light response (2.28 photoelectron/keVee), an energy threshold at 1.3 keVee is claimed; (vi) the energy resolution is poor; (vii) in the scale-up of the detectors the performances deteriorate; (viii) the behavior of the light yield for recoils at low energy is uncertain in every case. LUX — a dual phase TPC filled with Xenon — reports the first results corresponding to an exposure of 85.3 days, using a fiducial volume of 118 kg [37]; the last data release refers to about 1.4×10^4 kg × day [38]. On the other hand, the first result of DARKSIDE has been obtained with the TPC filled with atmospheric Argon for an exposure of 1422 kg × day [39]. Similar considerations, as above, hold about the robustness of these results. Moreover, such considerations become still more restrictive when considering the future plans of larger set-ups [17,18].

A positive hint for a signal of light DM candidates inducing just nuclear elastic scatterings has been also reported by the CoGeNT experiment [40,41]. The set-up is composed by a 440 g, *p*-type point contact (PPC) Ge diode, with a very low energy threshold at 0.4 keVee. It is located in the Soudan underground laboratory. In the data analysis, no discrimination between electromagnetic radiation and nuclear recoils is applied; only noise events are rejected. The experiment observes more events than they expect from estimate of the background in the energy range 0.4–3.2 keVee. The energy spectrum of these events is compatible — under certain assumptions — with a signal produced by the interaction of a DM particle with a mass around 10 GeV. In addition, considering an exposure of 146 kg × days CoGeNT experiment also reports an evidence at about $2.2\,\sigma$ C.L. of an annual modulation of the counting rate in (0.5–2) keVee with phase and period compatible — although the small confidence level — with a DM signal [41]. This result is compatible with interpretations of the DM model independent annual modulation result already reported by DAMA in terms of this kind of DM candidate and with the possible hint reported above. A new data release is planned in the incoming months, and CoGeNT is upgrading towards C-4 with the aim to improve by a factor four the total mass, to decrease the total background and to reduce substantially the energy threshold; Soudan is still the laboratory. Other activities exploiting Ge detectors are Texono and CDEX at CJPL, the Chinese underground laboratory.

In conclusion, suitable experiments offering a model independent signature for the presence of DM particles in the galactic halo are mandatory.

2.1. *DM model independent signature and DAMA results*

To obtain a reliable signature for the presence of DM particles in the galactic halo, it is necessary to exploit a suitable model independent signature. With the present technology, one feasible and able to test a large range of cross-sections and of DM particle halo densities, is the so-called DM annual modulation signature[42]. The annual modulation of the signal rate originates from the Earth revolution around the Sun. 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 DM 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). Thus, this signature has a different origin and peculiarities than the seasons on the Earth and than effects correlated with seasons (consider the expected value of the phase as well as the other requirements listed below). 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. 9 and 43. At present status of technology, it is the only DM model independent signature available in direct DM investigation that can be effectively exploited.

This signature has been exploited with large exposure — using highly radiopure NaI(Tl) as target material — by the former DAMA/NaI ($\simeq 100$ kg sensitive mass) experiment and by the currently running DAMA/LIBRA ($\simeq 250$ kg sensitive mass), within the DAMA project[4,11–13,44–65].

In particular, the experimental observable in DAMA experiments is the modulated component of the signal in NaI(Tl) target and not the constant part of it, as done in the other approaches aforementioned.

The sensitive part of the DAMA/LIBRA set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators placed in a five-rows by five-columns matrix; each crystal is coupled to two low background photomultipliers working in coincidence at single photoelectron level. The software energy threshold in DAMA/LIBRA-phase1 is 2 keVee. For details, see Ref. 51. The whole DAMA/LIBRA-phase1 results correspond to seven annual cycles for an exposure of $1.04\,\mathrm{ton} \times \mathrm{yr}$[52–54]. Considering these data together with those previously collected by DAMA/NaI over seven annual cycles, the total exposure collected over 14 annual cycles is 1.33 ton $\times$ yr, orders of magnitude larger than the exposures typically reported in the field.

The DAMA/NaI and DAMA/LIBRA-phase1 results give evidence for the presence of DM particles in the galactic halo, on the basis of the exploited model independent DM annual modulation signature, at $9.3\,\sigma$ C.L. The modulation amplitude of the *single-hit* events in the (2–6) keV energy interval in NaI(Tl) target is: (0.0112 ± 0.0012) cpd/kg/keV; the measured phase is (144 ± 7) days and the measured period is (0.998 ± 0.002) yr, values well in agreement with those expected for DM particles. No systematic or side reaction able to mimic the exploited DM signature has been found or suggested by anyone over more than a decade.

Recently, an investigation of possible diurnal effects in the *single-hit* low energy scintillation events collected by DAMA/LIBRA-phase1 has been carried out[62]. A model independent diurnal effect with the sidereal time is expected for DM because of Earth rotation. At the present level of sensitivity, the presence of any significant diurnal variation and of diurnal time structures in the data can be excluded for both the cases of solar and sidereal time; in particular, the DM diurnal modulation amplitude expected, because of the Earth diurnal motion, on the basis of the DAMA DM annual modulation results is below the present sensitivity[62]. It will be possible to investigate such a diurnal effect with adequate sensitivity only when a much larger exposure will be available and exploiting the lower energy threshold as in the presently running DAMA/LIBRA-phase2. For completeness, we recall that a recent analysis has been performed considering the so-called "Earth Shadow Effect."[64]

After a first upgrade in 2008, a further upgrade of DAMA/LIBRA has been performed at the end of 2010 when all the PMTs have been replaced with new ones having higher quantum efficiency[56]. Since then, after a test and optimization period, 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 and second-order effects. DAMA/LIBRA also continue its study on several other rare processes[59–65].

Finally, other activities using inorganic scintillators are in progress and at the R&D stage; in particular here we remind the efforts of the long-standing ANAIS project whose goal is to run about 100 kg of NaI(Tl) at Canfranc laboratory in Spain[66].

3. Implications and Comparisons

The DM model independent evidence obtained by DAMA is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle Physics. For example, some given scenarios and parameters are discussed, e.g. in Refs. 4, 11–13, 47–50, 52 and 58; some of them were also discussed in the parallel session DM2 of the 14th Marcel Grossmann Meeting[1–3]. Further, large literature is available on the topics; other possibilities are open.

It is worth noting that no other experiment exists, whose result can be directly compared in a model independent way with those by DAMA/NaI and DAMA/LIBRA. Some activities claim model dependent exclusion under many largely arbitrary assumptions (see for example discussions in Refs. 17, 18, 36, 47, 48 and 52). Moreover, often some critical points exist in their experimental aspects, as mentioned above, and the existing experimental and theoretical uncertainties are generally not considered in their presented single model dependent result; moreover, implications of the DAMA results are often presented in incorrect/partial/unupdated way. Both the accounting of the existing uncertainties and the existence of alternative scenarios (see literature) allow one to note that model dependent results by indirect and direct experiments actually are not in conflict with the DAMA model independent result.

4. Prospects for the DM Directionality Approach

The directionality approach — based on the study of the correlation between the recoil direction of the target nuclei and the Earth motion in the galactic rest frame — can offer a good approach to study those DM candidate particles able to induce just nuclear recoils. In fact, the dynamics of the rotation of the Milky Way galactic disc through the halo of DM causes the Earth to experience a wind of DM particles apparently flowing along a direction opposite to that of the solar motion relative to the DM halo. Hence, in the case of DM candidate particles interacting with nuclei the induced nuclear recoils are expected to be strongly correlated with the impinging direction of DM, while the background events are not; therefore, the study of the nuclear recoils direction can offer a way for pointing out the presence of these DM candidate particles.

In the practice, this approach has some technical difficulties because it is arduous to detect the short recoil track. Different techniques are under consideration but, up to now, they are at R&D stage and have not produced yet competitive results in the field (see, e.g. DRIFT[67], DMTPC[68], DAMIC[69], or NEWS[70]). In fact, they are generally limited by the difficulty of detecting very short tracks and of achieving high stability, large sensitive volume and very good spatial resolution.

To overcome such a difficulty, it has been suggested the use of anisotropic scintillator detectors[71–73]; their use was proposed for the first time in Ref. 71 and revisited in Ref. 72. In particular, low background $ZnWO_4$ crystal scintillators have been recently proposed since their features and performances are very promising[74]. In fact, both the light output and the scintillation pulse shape depend on the impinging direction of heavy particles (p, alpha, nuclear recoils, etc.) with respect to the crystal axes and can supply two independent ways to study the directionality and to discriminate the electromagnetic background (that does not give rise to any anisotropic effects).

Other advantages offered by $ZnWO_4$ detectors are very good radio-purity levels (about 0.1 cpd/kg/keV at low energy) and the potentiality to reach energy thresholds at keV level. Both these features can also be improved (e.g. the light yield shows a significant enhancement when working at low temperatures — about 100 K — and better radiopurity levels can be reached with dedicated R&D). A detailed discussion can be found in Ref. 74.

Finally, let us remind a new class of detectors presented in Ref. 75 based on room temperature bolometers: small amounts of energy deposited into nano-scale grains trigger a release of chemical energy, leading to a "nano-explosion."[75] These detectors can allow the study of directionality too.

5. Axion and Axionlike Particles

For completeness, it is also worth to mention the efforts to investigate axion and axionlike candidates. Axionlike DM particles can be detected using the conversion of DM particles into electromagnetic radiation[13]. An overview of this subject has been given in the parallel session DM2 of the 14th Marcel Grossmann Meeting[76].

As regards the research exploiting resonant tuned cavity for relic axion detection, the axion dark matter eXperiment (ADMX) has a leading role in the field; present efforts and the current and future sensitivity have been summarized in this session as well[77].

ADMX experiment uses a 8T solenoid, 1.1 m long and 60 cm in diameter, and it has developed and deployed microstrip-coupled SQUID Amplifiers (MSA) which have demonstrated near quantum-limited performance in the laboratory.

The ADMX experiment ran with a MSA from 2008–2010 at pumped LHe temperatures ($\simeq$ 1.2 K). The experiment was then moved in the summer of 2010 from LLNL to the University of Washington (UW) with new dilution refrigerators. This allows for operations at a physical temperature of $\simeq$ 50 mK, a regime in which the MSA is expected to be quantum limited. Moreover, additional improvements have also been included.

ADMX has published an exclusion region over roughly an octave in mass (460–860 MHz, or 1.9–3.6 μeV) for KSVZ axions saturating the galactic halo.

A second smaller platform, called ADMX-HF (High Frequency) designed for the 4–40 GHz range, has been built to focus on specific challenges of the axion search at high masses. The superconducting magnet is a solenoid of only 15 cm by 40 cm; it has a 9T central field. The entire experiment is cooled by a dilution refrigerator to 25 mK. It is in data taking since summer 2015[77].

6. Conclusions and Perspectives

Large efforts are in progress with different approaches and target materials to investigate various kinds of DM candidates and scenarios (as also described at some extent in the parallel session DM2 of the 14th Marcel Grossmann Meeting[78]). Due to the difficulty of measuring at very low energy, several techniques still would require further work for results' qualifications before enlarging their target mass.

As regards, the possibility to exploit the directionality for some DM candidates, new efforts have to be encouraged towards a first realistic exploitation.

The DM model independent annual modulation signature with widely sensitive target materials still remains a major approach, offering an unique possibility for detection; it requires well known techniques, full proved detector stability, well known and proved detector response in all the aspects, etc. At present, the DAMA positive model independent evidence for the presence of DM particles in the galactic halo is supported at very high confidence level. It has been shown in literature that this is compatible with many DM scenarios.

I have been also recalled the recent possible positive hints exploiting different approaches and different target materials, and the existing uncertainties in the model dependent results and comparisons.

Finally, very useful complementary results can arise from experiment exploiting other target detectors and approaches adopting adequately safe experimental procedures.

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