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SIGNALS FROM THE DARK UNIVERSE

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Abstract

About a century of experimental observations and theoretical arguments allows one to conclude that a large fraction of the Universe is composed by Dark Matter (DM) particles. Many possibilities are open on their nature(s) and interaction types. Moreover, the poor knowledge of many fundamental astrophysical, nuclear and particle Physics aspects as well as of some experimental and theoretical parameters, the different used approaches and/or target materials, etc. leave open space in serious comparisons. A model independent approach based on the investigation of the DM annual modulation signature with widely sensitive target materials and full control of all the detectors and running features at the needed level has allowed to unambiguously test their presence at galactic scale. Some arguments are shortly addressed here.

1 Introduction

In theories extending the Standard Model of particle physics, many candidates having different nature and interaction types have been proposed as DM particles, as e.g.: SUSY particles (as e.g. neutralino or sneutrino in various scenarios), inelastic DM in various scenarios, electron interacting DM, a heavy neutrino of the 4-th family, sterile neutrino, Kaluza-Klein particles, self-interacting DM, axion-like (light pseudoscalar and scalar candidate), mirror DM in various scenarios, Resonant DM, DM from exotic 4th generation quarks, Elementary Black holes, Planckian objects, Daemons, Composite DM, Light scalar WIMP through Higgs portal, Complex Scalar DM, specific two Higgs doublet models, exothermic DM, Secluded WIMPs, Asymmetric DM, Isospin-Violating DM, Singlet DM, Specific GU, SuperWIMPs, WIMPzilla, Dark Atoms (as *O-Helium*), etc.; a wide literature is available. Moreover, even a suitable particle not yet foreseen by theories could be the solution or one of the solutions.

In fact, considering the richness in particles of the visible matter which is less than 1% of the Universe density, one could also expect that the DM particles in the Universe can also be multicomponent. It is worth noting that often the definition "WIMP" is used as synonymous of DM particle; on the contrary it refers not to a specific particle, but to a class of different particles which can also have well different phenomenologies; moreover, many other DM candidates with well different nature and interaction types are available.

Often, the elastic scattering on target nuclei is the considered interaction process, but other processes are possible and considered in literature, as e.g. those 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 as well as full control of the running conditions. 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 — by various kind of events subtraction/rejection — the limitation arising from their originally measured counting rate. On the other hand, it is worth noting that experiments at accelerators may prove — when they can state a solid model independent result — the existence of some possible DM candidate particles, but they cannot credit 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.

The expected energy distribution for the interactions of DM particles in a terrestrial detector depends — among others — on their density and velocity distribution at Earth's position. However, the experimental observations regarding the dark halo of our Galaxy do not allow one to get information on this crucial aspect without introducing a model for the Galaxy matter density. Because of its simplicity, the isothermal sphere model (which consists in a spherical infinite system with a flat rotational curve) is a widely used assumption for the DM density distribution, and thus in the evaluation of DM expected rates. However, many of its underlying assumptions (sphericity of the halo, absence of rotation, isotropy of the dispersion tensor, flatness of the rotational curve) are not strongly constrained by astrophysical observations. Moreover, the isothermal sphere is strictly unphysical and may only represent the behavior of the inner part of physical systems, since it has a total infinite mass and needs some cutoff at large radii. Thus, the use of more realistic halo models is mandatory in the interpretation and comparison procedures of different experiments, since the model dependent results can significantly vary [1, 2].

In conclusion, the uncertainties still present on the shape of the DM halo and on the density and velocity distribution prevent the definition of a "standard" halo and illustrate how the comparisons among the experiments of direct detection of DM particles can be consistent even just considering this particular aspect (also see Ref. [3]). Moreover, many other experimental and theoretical uncertainties exist and must be considered in whatever suitable model dependent analysis and comparison among the experiments of direct detection of DM particles.

2 The Dark Matter particles direct detection

Considering the many available DM candidate particles and scenarios, and the existing uncertainties on the astrophysical, nuclear and particle physics, a model independent approach, a ultra-low-background suitable target material, a large exposure and a full control of running conditions are mandatory to pursue a widely sensitive direct detection of DM particles in the galactic halo.

Actually, most activities in the field release marginal exposures even after many years underground, and often 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 on all the involved aspects of the overall scenario and related parameters. They assume the elastic scattering on target nuclei as the DM particles interaction with matter and pursue through data selection and several/many subtraction procedures the selection of a recoil-like sample in the data. It is worth noting that both the specific nature of the candidate and the kind of interaction are not identified since several candidates can give rise to nuclear recoils and with different kind of interaction types, and known undistinguishable recoil-like events from background exist. Moreover, e.g. the applied subtraction procedures are — by the fact — statistical and cannot offer an unambiguous identification of a similar signal because of 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" by several procedures in this approach, can contain either the signal or part of it, and it will be lost.

A regards experimental activities with liquid noble gases - more recently considered in the field - both single and dual phase liquid/gas detectors (as XENON, LUX, DARKSIDE) (see e.g. Ref. [4, 5] and refs therein), the released results suffer e.g. because of their largely disuniform and non-linear response, of physical energy thresholds not suitably proved, of absence of routine calibration in the same running conditions, of the fact that - despite of the small light response (2.28 photoelectron/keVee) - an energy threshold at 1 keVee is claimed, the energy resolution is poor and its naive convolution give rise to illusory sensitivity to low mass candidates in the single — largely arbitrary — fixed scenario they adopt, the behaviour of the light yield for recoils at low energy is uncertain, in the scale-up of the detectors the performances deteriorate, etc. For detailed discussion the reader can refer to the dedicated paper [5] and in other literature.

A positive hint for a signal of light DM candidates has been reported by the CoGeNT experiment [6, 7].

In the double read-out bolometric technique, the heat signal and the ionization signal are used to try to discriminate between electromagnetic and recoil-like events (as CDMS and EDELWEISS). Generally the published exposures are absolutely marginal and hugely selected. Some comments can be found e.g. in [8]. In these very small exposure 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. In particular, the results of CDMS-II with the Si detectors were published in two close-in-time data releases [9, 10]; while no events in six detectors (corresponding exposure of only 55.9 kg×day before analysis cuts) were reported in the former [9], 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 [10].

Finally I remind the case of the CRESST-II experiment, which exploits the double read-out bolometric technique, using the heat signal due to an interacting particle in the $CaWO_4$ crystals and the heating of another device by scintillation light produced in the crystal at same time. The light signal is very poor and the possibility to efficiently collect all is — in my opinion — questionable. However, a statistical discrimination of nuclear recoil-like events from electromagnetic radiation is performed, and many cuts and selection procedures are applied. A previous run (8 detectors of 300 g each one, for an exposure of about 730 kg × day) showed that, after selections, 67 nuclear recoil-like events were observed in the Oxygen band [11] and a 4σ effect for possible signal was claimed. However, this result has been not confirmed in last run [12], where however a more marginal exposure has been used (52 kg × day and energy threshold of 0.6 keV). This discrepancy confirms the difficulties in managing the systematics in such kind of experiment.

In conclusion, suitable experiments offering a model independent signature for the presence of DM particles in the galactic halo are mandatory, as those realized by DAMA (see next section).

3 The DM model independent results of DAMA

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 [13]. 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 Ref. [14, 15].

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 [16, 17, 2, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39].

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 σ 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 [36]. 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 as a function of the sidereal time expected – because of the Earth diurnal motion – on the basis of the DAMA DM annual modulation results is below the present sensitivity [36]. 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" [38].

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 [30]. Since then, after tests and optimization periods, 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 [33, 34, 35, 36, 37, 38, 39].

The DM model-independent DAMA result 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 Ref. [2, 18, 19, 20, 21, 22, 23, 24, 26, 32, 39]. Further large literature is available on the topics [40]; other possibilities are open. Let us remark that no other experiment exists, whose result can be directly compared – at least in principle – in a model-independent way with those by DAMA/NaI and DAMA/LIBRA.

It should also be stressed that the so-called "Snowmass plot" (and the analogous reported in the Ref. [41]), where in the plane cross section on nucleon vs particle mass there are depicted all together some kinds of exclusion plots, allowed regions and sensitivity curves, has not universal validity for the reasons given above and other ones (see for example discussions in Ref. [2, 26, 18, 4, 5, 42]).

4 Future perspectives 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 particular, 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.

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, DMTPC, DAMIC, NEWS). 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 [43, 44, 45]; their use was proposed for the first time in Ref. [43] and revisited in Ref. [44].

In particular, low background $ZnWO_4$ crystal scintillators have been recently proposed since their features and performances are very promising [46]. 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 events (that does not give rise to any anisotropic effects).

Other advantages offered by $ZnWO_4$ detectors are very good radio-purity starting 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). Discussions can be found in Ref. [46].

5 Conclusions

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..

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.

At present DAMA/LIBRA-phase2 is running with a lower software energy threshold.

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