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DIRECT DETECTION OF DARK MATTER PARTICLES

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Abstract

Experimental observations and theoretical arguments have pointed out that a large part of the Universe is composed by Dark Matter particles. This motivates experimental efforts to investigate the direct detection of these particles with detectors placed in underground laboratories. In this paper a short review of some used techniques will be presented. Particular care will be given to the results obtained by the DAMA/LIBRA set-up. In addition, experimental and theoretical uncertainties and their implications in the interpretation and comparison of different kinds of results will be shortly addressed.

1 Direct Dark Matter detection

Many experimental observations and theoretical developments have pointed out that most of our Universe is composed by a Dark Matter component largely in form of relic particles. In theories extending the Standard Model of particle physics, many candidate particles have been proposed having different nature and interaction types [1]. Often the acronym WIMP is adopted as a synonymous of Dark Matter particle, referring usually to a particle with spin-independent elastic scattering on nuclei. On the contrary, also WIMPs are Dark Matter candidates which can have different phenomenologies and interaction types among them. Moreover, even a suitable particle not yet foreseen by theories could be the solution or one of the solutions.

The DM interaction processes can be of well different nature depending on the candidate; the most considered process is the elastic scatterings on target nuclei but other processes have been proposed in literature and, in particular, some in which also electromagnetic radiation is produced in the interaction [2]. Thus, 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 and interaction types, etc.), a widely-sensitive model independent approach is mandatory. Indeed, most of the activities in the field have based the analysis on a particular "a-priori" assumption on the nature of the DM particle and of its interaction to try to overcome the limitation arising from their large measured counting rate.

In the following some recent achievements obtained by experiments exploiting model-dependent and model independent approaches will briefly summarized.

2 Experiments exploiting model-dependent approach

Originally the so-called "traditional" approach was pursued by simply comparing the measured counting rate with an expectation from an assumed scenario (which implies to adopt many assumptions and approximations). To try to reduce the experimental counting rate, large data selections and several subtraction procedures are often applied to derive a set of recoil-like candidates assuming a priori the interaction type and the nature of the DM candidate. This is the approach pursued by experiments like XENON, CDMS, EDELWEISS, CRESST, etc. Several have been discussed at the Conference [3]; here only few are mentioned.

As regard XENON, this project realized so far two set-ups: XENON10 and XENON100 at Gran Sasso Laboratory, using dual phase liquid/gas detectors. Experiments exploiting such technique (like also WARP, ZEPLIN, etc.) 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 recently data for an exposure of 224.6 days, using a fiducial volume of 34 kg of Xenon target mass [4]. The experiment starts from a relevant counting rate and, in order to try to lower it, needs to apply many data selections, subtractions and handling. Each selection step can introduce systematic errors which can also be variable along the data taking period. Efficiencies of the procedures are not explained in details. After these selections procedures, an analysis based on some discrimination between the electromagnetic radiation and recoiling candidates is applied. Concerns are discussed in literature about the real response of such devices, in particular, to low energy recoils [5, 6]. The technical performance of the apparata, confirmed also by similar experiments, has shown that: i) the detectors suffer from non-uniformity; it needs corrections to be evaluated and applied, and systematics 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 proved by source calibrations in the energy interval of interest; the calibrations are done with external sources (due to the use of electric fields) and the lowest energy calibration point is 122 keV of ^{57}Co; no calibration is possible at the quoted energy threshold; montecarlo reconstruction of the spectrum is also required; this limits the sensitivity of the method and the reliability of the results; 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 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 behaviour of the light yield for recoils at low energy is in every case, uncertain.

In the double read-out bolometric technique, the heat signal and the ionization signal are used in order to discriminate between electromagnetic events and recoil-like events. This technique is used by CDMS and EDELWEISS collaborations. CDMS-II detector consists of 19 Ge bolometer of about 230 g each one and 11 Si bolometer of about 100 g each one. The experiment released data for an exposure of about 190 kg $\times$ day [7] 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 employs 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-Nov 08 and April 09-May 10) [8] with a 17% reduction of exposure due to run selection. These two experiments claim to have 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, but their results are, actually, largely based on "a priori" huge data selections and on the application of other preliminary rejection procedures which are generally poorly described and often not completely quantified. An example is the time cut analysis used to remove the so-called surface electrons that are distributed in the electromagnetic band and in the recoiling one, spanning from low to high energy. No detailed discussion about the stability and the robustness of the reconstruction procedure is given; a look-up table to identify such event is used but systematical errors on the stability in time of such table are not discussed. In these experiments few recoil-like events survive the cuts and selection procedures applied in the data analysis. These events are generally interpreted in terms of background. Moreover, most efficiencies and physical quantities entering in the interpretation of the claimed selected events have never been properly accounted. In addition, further uncertainties are present when, as done in some cases, a neutron background modeling is pursued. 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 radiation source introduction for calibration as well as of the limitation arising from the reachable duty cycle. The attempt performed by CDMS-II to search for annual modulation in the data have been done by using only 8 detectors over 30 and using data that are not continuous over the whole annual periods considered in the analysis [9]. The use of non-overlapping time periods collected with detectors having background rate within the signal box that differ orders of magnitude cannot allow one to get any reliable result (see e.g. arguments in [10]).

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 scintillation light produced. A statistical discrimination of nuclear recoil-like events from electromagnetic radiation is performed. The detector is placed in the Gran Sasso laboratory. The last data released by the experiment have been collected with 8 detectors of 300 g each one, for an exposure of about 730 kg $\times$ day [11]. As regards the cuts and selection procedures applied, most of the above discussion also holds. After selections, 67 recoil-like events have been observed in the Oxygen band. The evaluated background contribution can not account for all the observed events. The unexplained excess of events and their energy distribution can be interpreted in terms of a WIMP candidate with spin-independent interaction and a mass in the range of 10-30 GeV. This is compatible with interpretations of the annual modulation result already reported by DAMA in terms of a WIMP candidate and with the hint reported by CoGeNT (see later). Improvement in the radiopurity of the set-up are planned, in order to reduce known source of background. Future results are foreseen.

Other positive hints of a possible light Dark Matter signal have been reported by the CoGeNT experiment [12]. The set-up is composed by 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 an excess of events with respect to an estimated background in the energy range 0.4-3.2 keVee. The energy spectrum of the excess is compatible with a signal produced by the interaction of a DM particle with a mass around 10 GeV. In addition in an exposure of 146 kg $\times$ days the CoGeNT experiment also reports an evidence at about 2.8σ C.L. of an annual modulation of the counting rate (see later) in (0.5-0.9) keV with phase and period compatible with a Dark Matter signal. The modulation effect observed is similar to that observed with much higher statistical significance by the DAMA collaboration before.

It is worth noting that – in every case – in experiment using discrimination procedures the result will not be the identification of the presence of WIMP elastic scatterings because of the known existing recoil-like indistinguishable background which can hardly be estimated at the needed level of precision. Finally, the electromagnetic component of the counting rate, rejected in this approach, can contain the signal or part of it and will be lost by these approaches.

To search for an elastic scattering WIMP the approach based on the so-called directionality signature can also be considered. It is based on the correlation between the distribution of the recoiling events with the galactic motion of the Earth. 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 yet produced competitive results in the field (see e.g. the DRIFT project or the DM-TPC experiment). It has been been suggested also the use of anisotropic scintillator detectors [13]. Low background $ZnWO_4$ crystal scintillators have been recently proposed; the features and performances of such scintillators are very promising; a paper exploiting this technique has been recently published [14].

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. 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 annual modulation signature [15]. The annual modulation of the signal rate originates from the Earth revolution around the Sun and offers many peculiarities since the 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 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. 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 simultaneously satisfy all the requirements. This signature has been exploited with large exposure – using highly radiopure NaI(Tl) as target material – by the former DAMA/NaI experiment and the present DAMA/LIBRA one. In the following the obtained model-independent result will be briefly recalled.

4 The model independent result obtained by the DAMA project exploiting the annual modulation signature

The DAMA/NaI set up and its performances are described in ref. [16, 17, 18, 19], while the DAMA/LIBRA set-up and its performances are described in ref. [20]; the recent upgrade of DAMA/LIBRA is presented in ref. [21]. The sensitive part of the DAMA/LIBRA set-up is made of 25 highly radiopure NaI(Tl) crystal scintillators placed in a 5-rows by 5-columns matrix; each crystal is coupled to two low background photomultipliers working in coincidence at single photoelectron level. The detectors are placed inside a sealed copper box continuously flushed with HP nitrogen and surrounded by a low background and massive shield. The whole installation is air-conditioned and the temperature is continuously monitored and recorded. The detectors' responses range from 5.5 to 7.5 photoelectrons/keV. Energy calibrations with X-rays/γ sources are regularly carried out down to few keV in the same conditions as the production runs. In the data analysis a software energy threshold of 2 keV is considered.

The DAMA/LIBRA data released so far correspond to six annual cycles for an exposure of 0.87 ton$\times$yr [24]. Considering these data together with those previously collected by DAMA/NaI over 7 annual cycles (0.29 ton$\times$yr), the total exposure collected over 13 annual cycles is 1.17 ton$\times$yr; this is orders of magnitude larger than the exposures typically collected in the field. Several analyses on the model-independent DM annual modulation signature have been performed (see Refs. [22, 23] and references therein); here just few arguments are mentioned. In particular, Fig. 1 shows the time behaviour of the experimental residual rates of the *single-hit* events collected by DAMA/NaI and by DAMA/LIBRA in the (2–6) keV energy interval [22, 23]. The superimposed curve is the cosinusoidal function: $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, with a phase $t_0=152.5$ day (June 2^{nd}), and modulation amplitude, A, obtained by best fit over the 13 annual cycles. The hypothesis of absence of modulation in the data can be discarded [22, 23] and, when the period and the phase are

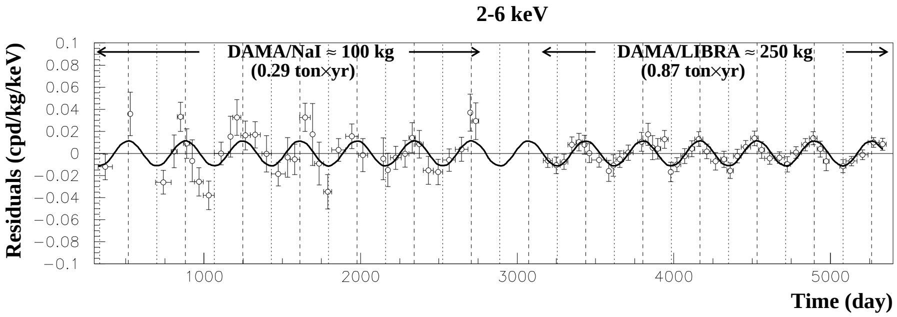

Figure 1: Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/NaI over seven and by DAMA/LIBRA over six annual cycles in the (2 – 6) keV energy interval as a function of the time [18, 19, 22, 23]. The zero of the time scale is January 1^{st} of the first year of data taking. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curve is $A \cos \omega(t - t_0)$ with period $T = \frac{2\pi}{\omega} = 1$ yr, phase $t_0 = 152.5$ day (June 2^{nd}) and modulation amplitude, A, equal to the central value obtained by best fit over the whole data: cumulative exposure is 1.17 ton × yr. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2^{nd}), while the dotted vertical lines correspond to the minimum. See Refs. [22, 23] and text.

released in the fit, values well compatible with those expected for a DM particle induced effect are obtained [23]; for example, in the cumulative (2–6) keV energy interval: $A = (0.0116 \pm 0.0013)$ cpd/kg/keV, $T = (0.999 \pm 0.002)$ yr and $t_0 = (146 \pm 7)$ day. Summarizing, the analysis of the *single-hit* residual rate favours the presence of a modulated cosine-like behaviour with proper features at 8.9 σ C.L. [23].

The same data of Fig.1 have also been investigated by a Fourier analysis including the treatment of the experimental errors and of the time binning; a clear peak corresponding to a period of 1 year [23] has been obtained; this analysis in other energy regions has shown instead only aliasing peaks. Moreover, while in the (2–6) keV *single-hit* residuals a clear modulation is present, it is absent at energies just above [23]. In particular, in order to verify absence of annual modulation in other energy regions and, thus, to also verify the absence of any significant background modulation, the energy distribution measured during the data taking periods in energy regions not of interest for DM detection has also been investigated. The data analyses have allowed to exclude the presence of a background modulation in the whole energy spectrum at a level much lower than the effect found in the lowest energy region for the *single-hit* events [23]. A further relevant investigation has been done by applying the same hardware and software procedures, used to acquire and to analyse the *single-hit* residual rate, to the *multiple-hits* events in which more than one detector "fires". In fact, since the probability that a DM particle interacts in more than one detector is negligible, a DM signal can be present just in the *single-hit* residual rate. Thus, this allows the study of the background behaviour in the same energy interval of the observed positive effect. A clear modulation is present in the *single-hit* events, while the fitted modulation amplitudes for the *multiple-hits* residual rate are well compatible with zero [23]. Similar results were previously obtained also for the DAMA/NaI case [19]. Thus, again evidence of annual modulation with proper features, as required by the DM annual modulation signature, is present in the *single-hit* residuals (events class to which the DM particle induced events belong), while it is absent in the *multiple-hits* residual rate (event class to which only background events belong). The obtained result offers an additional strong support for the presence of a DM particle component in the galactic halo further excluding any side effect either from hardware or from software procedures or from background.

The annual modulation present at low energy has also been analyzed by depicting the differential modulation amplitudes, S_m, as a function of the energy. A positive signal is present in the (2–6) keV energy interval, while S_m values compatible with zero are present just above. It has been also verified that the measured modulation amplitudes are statistically well distributed in all the crystals, in all the annual cycles and energy bins; these and other discussions can be found in ref. [23] and ref. therein.

Concluding the data of DAMA/LIBRA and of DAMA/NaI fulfil all the requirements of the DM annual modulation signature.

Sometimes naive statements were put forwards as the fact that in nature several phenomena may show some kind of periodicity. It is worth noting that the point is whether they might mimic the annual modulation signature in DAMA/LIBRA (and former DAMA/NaI), i.e. whether they might be not only quantitatively able to account for the observed modulation amplitude but also able to simultaneously satisfy all the requirements of the DM annual modulation signature; the same is also for side reactions.

Careful investigations on absence of any significant systematics or side reaction able to account for the measured modulation amplitude and to simultaneously satisfy all the requirements of the signature have been quantitatively carried out (see e.g. ref. [18, 19, 22, 25, 26, 27, 28, 29], refs therein). No systematics or side reactions able to mimic the signature (that is, able to account for the measured modulation amplitude and simultaneously satisfy all the requirements of the signature) have been found or suggested by anyone over more than a decade.

5 Comparison

The DAMA obtained model independent evidence is compatible with a wide set of scenarios regarding the nature of the DM candidate and related astrophysical, nuclear and particle Physics. For examples some given scenarios and parameters are discussed e.g. in Refs. [18, 19, 30, 31, 32, 33, 34, 35, 36] and in Appendix A of Ref. [22]. Further large literature is available on the topics; other possibilities are open. Here we just recall the recent papers [37, 38] where the DAMA/NaI and DAMA/LIBRA results, which fulfill all the many peculiarities of the model independent DM annual modulation signature, are examined under the particular hypothesis of a light-mass DM candidate particle interacting with the detector nuclei by coherent elastic process. In particular, in Ref. [37] allowed regions are given for DM candidates interacting by elastic scattering on nuclei including some of the existing uncertainties; comparison with theoretical expectations for neutralino candidate and with the recent possible positive hint by CoGeNT [12] is also discussed there (see Fig. 5), while comparison with possible positive hint by Cresst [11] is discussed in Ref. [38].

It is worth noting that no experiment exists, whose result can be directly compared in a model-independent way with those by DAMA/NaI and DAMA/LIBRA.

Other mentioned activities (e.g. [4, 7, 8]) claim model-dependent exclusion under many largely arbitrary assumptions (see for example discussions in [5, 6, 18, 22, 19]); often some critical points also exist in their experimental aspects. Although often the limits achieved by this approach have been presented as robust reference points, it can be easily understood that similar results are quite uncertain not only because of possible underestimated or unknown systematics in the large data selections and in some experimental aspects, but also because the results refer only to a certain (generally largely arbitrary) set of assumptions. The accounting of the many existing experimental and theoretical uncertainties can significantly vary the given model dependent results. In addition implications of the DAMA results are generally presented in incorrect/partial/no-updated way.

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 shortly summarized here. DAMA project reported a model independent evidence for the presence of DM particles in the galactic halo at 8.9σ C.L. (on a cumulative exposure of 1.17 ton$\times$yr i.e. 13 annual cycles of DAMA/NaI and DAMA/LIBRA). Positive hints, compatible in some scenarios with the DAMA results, have been recently reported by CoGeNT and CRESST experiments. Claimed exclusion mentioned have been obtained by neglecting some critical points regarding experimental and theoretical aspects. All the activities mentioned foreseen upgrade of their experimental set-up. Further interesting results are expected.

In particular DAMA/LIBRA will release soon the results of the last annual cycle collected in its phase 1. At present - after the relevant upgrade occurred in 2010 [21] - it is continuously taking data in the new phase 2.

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