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Status of direct WIMP Dark Matter search

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Summary. — In this paper we give an overview of the experiments in the field of direct Dark Matter search. The physics topic is introduced starting with some historical information and then the experiments, which exploit the most commonly used technologies, are quickly described together with the main features and the expected sensitivity. Not all the experiments are mentioned but attention is put on those that the author judges as the most relevant contributions in the field.

1. – Introduction

In the framework of the Cosmological Standard Model (CSM) the presence in the Universe of a sizable fraction of matter composed by particles not belonging to the Standard Model (SM) of Particle Physics is well assessed. In fact, in 1933 Fritz Zwicky realized, by measuring the velocity of galaxies in the Coma clusters, that it was larger than the escape velocity accounted by visible matter [1]. Thus, he came to the hypothesis of the presence of "Dunkle Materie", today indicated as Dark Matter (DM), which would provide the gravitation force to keep together the matter. Later on, a similar measurement was realized by Vera Rubin [2] on the M31 galaxy, showing that the rotational velocity of stars was higher than what she was able to predict given the visible matter. Also at a galaxy scale the presence of DM is needed to explain the velocity of stars.

2. – Detection principle of DM

A seminal paper where the DM detection was envisaged is [3]. The authors considered several possible candidates and among those also the neutrino's super-partner in a Supersymmetric extension of the SM, that is today the most commonly assumed DM constituent. In this framework DM particles are indicated as Weakly Interacting Massive Particle (WIMP). In [3] the authors discuss the coherent scattering of DM particles, today named as DM direct detection, and the possibility to detect a very small energy release due to the scattering of WIMPs, with mass in the range of 1–10^2 GeV.

The WIMP interaction rates with ordinary matter have been calculated in different theoretical frameworks, all ending up with very low interaction rate and none of them confirmed by any measurement, yet.

The low interaction cross section is also confirmed by the most recent experiments on direct DM search where the negative results impose that the DM rate must be lower than 1 event/kg/yr. The low interaction rate and the very little energy released impose experimental challenges. In fact, suitable detection techniques must have an energy threshold as low as few keV.

The low expected rate imposes also to install the apparatus in a clean and "silent" environment where the flow of cosmic rays is significantly reduced like in an underground laboratory.

A relevant aspect to consider in the design phase of a detector is the capability to measure the radioactive traces in each component of the detector, in order to sort out those with the lowest level of contaminants which might generate fake events. To achieve the desired sensitivity the level of radioactive contaminants required nowadays is less than 1 μBq/kg.

Another important signature of DM interaction is the time variation of the interaction rate which must show a seasonal modulation because of the Earth motion, and so of the experiment, in the galaxy. The Earth speed is almost 10% of the one of the solar system in the galaxy. Thus, the composition of motions generates a variation of the flow and of the interaction rate of DM in a possible experiment.

3. – Overview of the experiments for direct DM detection

In many targets suitable for DM experiments a WIMP scattering provokes the production of phonons (heat), photons and ionization electrons. An optimal experiment should measure the three forms of energy but unfortunately this is never the case. For a complete review of DM experiments one can look at [4] and references therein.

We linger on the topic of the forms of released energy because while the phonon yield is proportional to the energy, the one of photons or ionization electrons strongly depends on $\mathrm{d}E/\mathrm{d}x$. This gives the possibility to distinguish between events originated by gammas or electrons and those originated by alpha or nuclear recoils. Two measurable quantities are sufficient to provide the capability to distinguish among events with different $\mathrm{d}E/\mathrm{d}x$.

The DAMA experiment, held at the Laboratori Nazionali del Gran Sasso (LNGS, INFN laboratory in l'Aquila, Italy), exploits the technology of NaI ultra-pure crystals, at room temperature, read out by high efficiency photodetectors (PMT) on one side. The PMTs measure scintillation photons generated by energy released in NaI crystals. DAMA has reached nowadays 1.33 tonnes$\times$ year of total exposure (DAMA/NaI+DAMA/Libra) with 233 kg of crystals. The DAMA Collaboration claims that DM interactions have been measured in the energy interval of 2–6 keV, and that the rate of events shows a sinusoidal modulation with an amplitude of $\sim 1\%$ above background, with one year period and the maximum on 2 June. All mentioned features are compatible with a signal generated by DM.

Unfortunately, this signal has never been confirmed by any experiment. In fact, XENON100 and CDMS (these detectors will be presented later) were the first experiments to exclude the DAMA signal, as due to nuclear recoil. For a long time the tension between the two results was accommodated either by assuming a negligible cross section of WIMPs on XENON100 and CDMS targets, Xe and Ge respectively, or by assuming the signal as due to WIMP interactions with the atomic electrons. Indeed, the DAMA detector is not capable to distinguish between nuclear and electronic recoil, whereas XENON100 detector has a distinction capability between the two event categories at a level of better than 99%. Recently, the XENON100 has published the most sensitive analysis in which the hypothesis of WIMPs interacting with electrons is excluded [5] and so is the yearly modulation of WIMPs interactions on electrons [6]. Thus the DAMA signal remains unconfirmed.

A full campaign of new experiments based on a DAMA-like technology has started, exploiting a new generation of ultra-pure NaI crystals. At LNGS the SABRE experimental project is in the phase of proof of principle and it is based on high quantum efficiency PMTs reading out NaI crystals on both sides to increase the light collection efficiency. Similar projects are also ongoing in other laboratories.

It is worth pointing out that to improve WIMP search for large masses ($M_{\rm WIMP} > 10\,{\rm GeV}$) large mass detectors are required whereas to improve the sensitivity for low WIMP masses (*i.e.*, $M_{\rm WIMP} < 10\,{\rm GeV}$) the energy threshold must be reduced.

A different category of detectors, so called cryogenic calorimeters, leads the field of DM search in the sensitivity region below 10 GeV of WIMPs masses. This type of apparatus detects photons by measuring tiny temperature jumps. For this reason it is kept at temperatures as low as $\sim 10\,{\rm mK}$. The SuperCDMS detector is the last of a family called CDMS(I-II) installed in the Soudan mine in Minnesota, USA, that exploited Si and Ge crystals. SuperCDMS will be installed at the SNOWLAB in Canada. It exploits the technology of cryogenic calorimeter made of Ge crystals of 600 g equipped with devices capable to measure phonons and electrons.

With these types of detector it is hard to obtain target masses of tonnes, thus the main feature is the low energy threshold that gives good sensitivity at low WIMPs masses.

The EDELWEISS experiment (at the Laboratoire Souterrain de Modane in France) exploits the same technology as the one of SuperCMDS, with 800 g Ge crystals cooled at 18 mK, read out by temperature sensors based on a different technology with respect to those of SuperCDMS. The ionization electrons are measured as well and so particle identification is possible. Both SuperCDMS and EDELWEISS aim at achieving a threshold on released energy lower than 100 eV.

The last experiment we want to mention, in this field, is CRESST, held at LNGS in Italy. It exploits scintillation of $CaWO_4$ crystals, cooled down at 8 mK. The comparison between phonons measurements and the scintillation light provides particle identification and also space resolution. Crystals of 250 g are presently used and the energy threshold is 300 eV. A factor ten reduction in mass of crystals is envisaged to reduce the threshold by a factor three. The first prototypes have overcame the design goal showing a 50 eV threshold. In the future the CRESST experiment aims at achieving the best sensitivity in the low WIMP mass region. So far no evidence of DM observation came from these experiments.

The challenge of DM direct search in the field of large WIMP masses is lead by detectors using liquefied noble gases such as liquid Ar (LAr) and liquid Xe (LXe). DEAP-3600 is a single phase LAr detector exploiting 3600 kg of LAr in a spherical cryostat surrounded by an instrumented water detector (veto detector). The scintillation light of LAr is detected by means of 255 high quantum efficiency PMTs once the Ar scintillation light (at 128 nm) has been shifted in the visible region to match the efficiency curve of PMTs. The scintillation of Ar comes from singlets and triplets molecular states which decay with very much different decay times. The amount of light decaying with fast (ns) and slow (μs) decay time depends strongly on ${\rm d}E/{\rm d}x$ allowing a high efficiency particle identifications. The use of Ar has the drawback that it comes with an isotope,

^{39}Ar, which gives roughly one hertz of beta decay per kg of natural Ar. This reduces significantly the DM discovery potential of the Ar based detectors. In fact, all apparatuses exploiting an Ar target plan to use the so called depleted Ar, where the unstable isotope has been removed by means of distillation processes or by an underground gas production plant, where Ar comes without its unstable isotope.

The X-MASS detector exploits 830 kg of LXe, in a spherical copper cryostat, instrumented by 642 PMTs for a 62% photocathode coverage. The large photocathode coverage provides position sensitivity allowing to select those events taking place in the center of the active volume. This is a crucial feature to exploit the fact that the Xe is very clean, has no long-lived unstable isotope, and has a perfect self-screening capability.

An evolution of such a type of detector concept is the double phase liquefied noble gas detectors using either Ar or Xe. Both LAr and LXe, when energy is released in the active volume, create scintillation and ionization. A drift E-field prevents the full electrons recombination with the parent nuclei and drifts the electrons to the liquid-gas interface. A higher amplitude E-field extracts the electrons to the gaseous phase, accelerate them and generate a second light pulse. The two light pulses are detected by means of PMTs and the time difference between the two pulses allows to measure the depth or the coordinate across the drift field. The most suited geometry is a cylindrical one where the active volume is closed by a cathode and an anode. Field shapers are used to make the drift field as uniform as possible. The light pattern of the second pulse allows to reconstruct the transverse coordinates, orthogonal to the drift field direction. Thus a complete space reconstruction of events is possible. This type of detector takes the name of double phase Time Projection Chamber (TPC).

The XENON Collaboration leads the field of LXe double phase TPC, building and running several detectors of increasing sensitivity at the LNGS; two of them are named XENON10 and XENON100. The last one, still in the phase of analyzing the data, has been the detector with the best sensitivity until 2013. The third detector of the family,

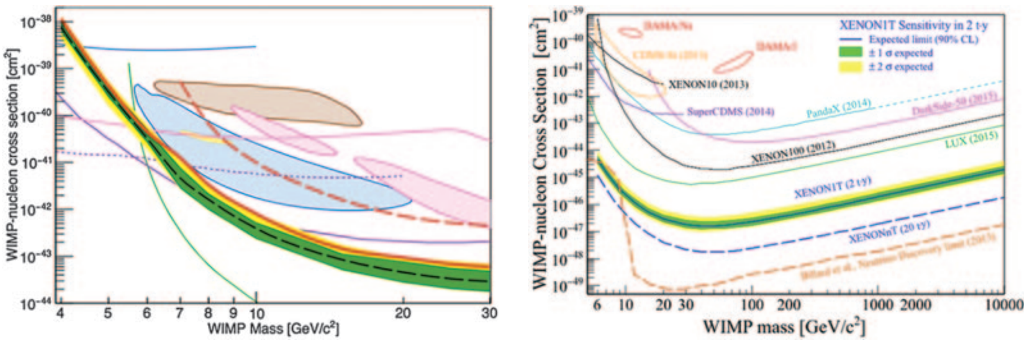

Fig. 1. – The most updated results either in terms of discovery claim or exclusion limits are shown. For low WIMP masses (< 30 GeV) [7], left figure, the legenda is: red curve, green and yellow bands represent the exclusion limit at 90% C.L. and the sensitivity regions at 1 and 2 σ in absence of signal of EDELWEISS-III, whereas yellow, blue, pink and brown contours are the claims of discovery by CoGeNT, CDMS-Si, CRESST-II and DAMA, respectively. The limits by EDELWEISS-II (dashed red), LUX (green), DAMIC (blue), CRESST (pink), CDMSLite (dashed violet) and SuperCDMS are also shown. For large WIMP masses (> 6 GeV to 10 TeV) [8], right figure, the plot is self-explaining. The aimed-at exclusion limits of the experiments with the best projected sensitivity are also shown.

XENON1T, is expected to lead the field for the next years. It uses 3.5 tonnes of LXe as instrumented mass and more than 1 tonne of fiducial mass and is presently taking physics data. The expected sensitivity is such that the minimum cross section 2×10^{-47} cm^2 for a WIMP mass of 50 GeV will be reached in two years of DM data-taking.

The LUX experiment, exploiting the same XENON technology, located at the Sanford Laboratory in South Dakota, USA, is the direct competitor of XENON100 with 250 kg of fiducial mass that in 2013 has published the best results. In the most recent update [9] an exclusion limit (at 90% C.L.) with a minimum cross section of 0.6×10^{-45} cm^2 has been shown at 33 GeV WIMP masses after 1.41×10^4 kg $\times$ day exposure.

The PandaX-II built and run a LXeTPC at the Jin-Ping laboratory in China, with 500 kg instrumented mass and has published [10] an exclusion limit (at 90% C.L.) with a minimum of 0.25×10^{-45} cm^2 at 40 GeV WIMP mass after 98.7 days of data-taking.

Experiments using double phase LArTPC are also very active in the field of direct DM search. The leading one is the DarkSide-50 experiment, running at LNGS, which has proved the principle and has shown the very high particle identification capability that can be achieved by exploiting the short and slow decay time constant. Recently the first results obtained with depleted Ar have been published.

The plots in fig. 1 summarize the situation of the most important exclusion curves from experiments that exclude the DAMA observation, which is presently the only one claiming DM signal observation.

4. – Conclusion

The claim of DM observation from the DAMA Collaboration requires desperately a confirmation or a clear disclaim. The DM is the physics topic where the largest number of experiments are involved in the challenge in any corner of the space of parameters. We think that there are good chances to come to a result in the next 10 years.

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REFERENCES

[1] Zwicky F., *Helv. Phys. Acta*, **6** (1933) 110.
[2] Rubin V. C. and Ford W. K. jr., *Astrophys. J.*, **159** (1970) 379.
[3] Goodman M. W. and Witten E., *Phys. Rev. D*, **31** (1985) 359.
[4] Marrodán Undagoitia T. and Rauch L., *J. Phys. G*, **43** (2016) 013001.
[5] XENON Collaboration (Aprile E. *et al.*), *Science*, **349** (2015) 851.
[6] XENON Collaboration (Aprile E. *et al.*), *Phys. Rev. Lett.*, **115** (2015) 091302.
[7] EDELWEISS-III Collaboration (Armengaud E. *et al.*), *JCAP*, **05** (2016) 19.
[8] XENON Collaboration (Aprile E. *et al.*), *JCAP*, **04** (2016) 27.
[9] LUX Collaboration (Akerib D. S. *et al.*), *Phys. Rev. Lett.*, **116** (2016) 161102.
[10] Panda-X II Collaboration (Tan A. *et al.*), *Phys. Rev. Lett.*, **117** (2016) 121303.