Mem. S.A.It. Vol. 94, 13

Memorie della

Direct Detection of Dark Matter

S. Cebrián[1,2]

[1] Centro de Astropartículas y Física de Altas Eenergías (CAPA), Universidad de Zaragoza, C/ Pedro Cerbuna 12, E-50009 Zaragoza, Spain
[2] Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe s/n, E-22880 Canfranc Estación, Huesca, Spain
e-mail: `scebrian@unizar.es`

Received: 29-11-2022; Accepted: 07-04-2023

Abstract. There are well-motivated dark matter candidates with masses in a wide range from eV/c^2 to TeV/c^2, generically referred as Weakly Interacting Massive Particles (WIMPs), which can be pervading our galactic halo and could be directly detected by measuring their scattering off target nuclei or electrons in a suitable detector. The expected signal from this interaction is rare (demanding ultra-low background conditions and operation in deep underground laboratories to suppress the effect of cosmic rays) and small energy deposits below tens of keV would be produced (requiring low energy detection thresholds). Here, the features of this possible dark matter signal will be summarized, showing the relevance of the possible identification of distinctive signatures (like an annual modulation in the interaction rates or directionality) to assign a dark matter origin to a possible observation. Many different and complementary techniques are being applied or under consideration in experiments attempting the direct detection of dark matter, like solid-state cryogenic detectors, Time Projection Chambers based on noble liquids, scintillating crystals and purely ionization detectors using semiconductors or gaseous targets; these techniques will be briefly described together with the latest results obtained in the field, mainly constraining the properties of the dark matter candidates under different scenarios for the interaction. Exploring regions of cross sections where solar and atmospheric neutrinos become an irreducible background could be at reach for large detectors foreseen for the end of this decade and candidates with increasingly lower masses are being investigated thanks to the development of novel technologies to reduce the energy threshold in smaller detectors.

Key words. Cosmology: dark matter – Galaxy: WIMPs – Galaxy: direct detection

1. Introduction

Dark Matter (DM) is required to explain an important fraction of the energy-mass budget of the Universe following different cosmological and astrophysical observations, although its nature is unknown Bertone & Hooper (2018). A plethora of possible DM candidates have been proposed, being non-zero-mass, stable particles having a very low interaction probability with baryonic matter. Among them, thermal Weakly Interacting Massive Particles (WIMPs) are supposed to have been produced at the early Universe via a freeze-out mechanism when Standard Model (SM) and DM particles were in thermal equilibrium, producing a constant relic density, reproduced for a wide range of masses from a few MeV/c^2 to ~100 TeV/c^2 for standard WIMP conditions Serpico & Raffelt (2004); Bœhm et al. (2013).

Different complementary strategies are being attempted for WIMP detection Cooley et al. (2022). DM candidates could be produced at colliders and indirectly detected by identifying an excess of SM particles like gamma-rays, neutrinos, positrons or antiprotons produced by the annihilation of DM particles. In the direct detection of DM in the galactic halo the goal is to register the elastic scattering of WIMPs off target nuclei or electrons Billard et al. (2022); to compute the expected rate of this interaction ingredients for Particle Physics (mass and interaction cross section of DM particles) are needed together with other ones from Astrophysics, like the local density of DM in the Milky Way (with values in the literature at (0.2-0.6) GeV/cm^3) and the velocity distribution of WIMPs (typically assumed as a Maxwellian distribution for Standard Halo Model (SHM), although there are deviations according to Gaia data). Taking into account the expected signal, the direct detection of DM is really challenging for several reasons: the interaction has an extremely low probability and then large exposures and low background conditions operating deep underground are mandatory; the signal is concentrated at very low energies, which requires the use of low energy threshold detectors; and the signal has a continuum energy spectrum which would appear entangled with background, therefore distinctive signatures would be helpful to identify DM interaction.

Direct detection experiments can be focused on different physics cases Billard et al. (2022); many of them just look for an excess of events over the known backgrounds, considering Spin-Independent (SI) or Spin-Dependent (SD) interactions, different ranges of candidate masses and Nuclear or Electronic Recoils (NR/ER). Other experiments search specifically for distinctive DM signatures, like the annual modulation in the interaction rate or the directionality.

- There are particular requirements to probe DM candidates with masses at sub-GeV/c^2 scale: lighter targets must be used to keep kinematic matching between WIMPs and nuclei, lower threshold is necessary to detect smaller signals and new search channels (absorption or scattering off by electrons, ER) are being considered as light WIMPs cannot transfer sufficient momentum to generate detectable NR. Following the proposed Migdal effect[1] the DM-nucleus interaction could lead to excitation or ionization of the recoiling atom, being for low mass DM this additional signal above threshold (unlike the NR alone) and then enhancing sensitivity Kouvaris & Pradler (2017); Ibe et al. (2018); Dolan et al. (2018); for this reason, this effect is already being considered by many collaborations to release results exploring sub-GeV masses.
- The movement of the Earth around the Sun makes the relative velocity between detectors and DM particles in the galactic halo oscillate in time, which produces a modulation in the expected DM interaction rate with defined features like a one year period for SHM; this signature would allow to identify a possible DM signal Freese et al. (1988). The DAMA/LIBRA experiment at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy is observing for more than 20 years an annual modulation in the measured rate compatible with DM Bernabei et al. (2021) (see Sec. 2.5).
- The average direction of DM particles through the solar system comes from the constellation of Cygnus, as the Sun is moving around the Galactic center; then, the measured track direction of NR could be used to distinguish a DM signal from background events (expected to be uniformly distributed) and to prove the galactic origin of a possible signal Spergel (1988). The main difficulty is to reconstruct the very short tracks (~1 mm in gas, ~0.1 μm in

[1] Atomic physics effect that leads to the emission of a bound-state electron from atomic or molecular systems when the atomic nucleus is suddenly perturbed. It has been observed for radioactive decays; there is no evidence for NR yet, although attempts are in progress Araújo et al. (2023).

solids) expected for keV scale NRs Battat et al. (2016).

2. Main techniques and latest results

Many different detection technologies are being used in DM direct detection experiments, measuring the heat, light or charge produced or a combination of two of them in hybrid detectors. A discussion of advantages and disadvantages for each of them can be found at Billard et al. (2022); in this section, just a brief summary of the detection mechanisms and latest results obtained is presented for the main applied techniques.

2.1. Liquid Ar and Xe detectors

Dual-phase liquid noble gas detectors are Time Projection Chambers (TPCs) measuring both primary (S1) and secondary scintillation from drifted electrons (S2), as the ratio S1/S2 allows to distinguish ER and NR. Experiments using Xe have set over the last years the strongest constraints for DM candidates with masses from a few GeV/c^2 to TeV/c^2 considering SI interactions; Xe projects with multi-ton detectors have already started the data taking and released first results: new exclusion plots for cross section of DM-nucleon SI scattering have been presented by PANDAX-4T Meng et al. (2021) at Jinping laboratory in China and LUX-ZEPLIN at Sandford in US, having the latter presently the world-leading sensitivity and best limit at 30 Gev/c^2 Aalbers et al. (2023); and the excess of ER observed by XENON1T Aprile et al. (2020) at LNGS does not appear in the first science run of XENONnT Aprile et al. (2022). For the future, the DARWIN detector is being prepared using ~40 tons of liquid Xe.

Liquid Ar produces different scintillation pulse shapes for ER and NR, which gives a very efficient Pulse Shape Discrimination, as demonstrated by the DEAP-3600 experiment operating a single-phase liquid Ar detector measuring only scintillation Ajaj et al. (2019) at the SNOLAB laboratory in Canada. The latest analysis of DarkSide-50, at LNGS, based on a dual-phase liquid Ar detector and using radiopure underground Ar Agnes et al. (2018), has shown leading sensitivity for DM candidates with masses from 1.2 to 3.6 GeV/c^2 Agnes et al. (2023a,b,c). The Global Argon DM Collaboration (GADMC) has been formed to prepare the DarkSide-20k detector, which could start operation in 2026 at LNGS, and in a longer term, the ARGO detector with 360 t mass of liquid Ar.

2.2. Solid-state cryogenic detectors

In cryogenic detectors made of crystals, heat released by particle interactions is measured through the tiny temperature increase induced by using appropriate sensors. The simultaneous measurement of ionization or scintillation (with yields dependent on the type of particle producing the interaction) allows an efficient ER/NR discrimination. As these detectors can reach low energy thresholds of just tens of eV, they have leading sensitivity in the sub-GeV region of candidate masses. The CRESST experiment at LNGS uses now mainly small $CaWO_4$ scintillating bolometers Abdelhameed et al. (2019) but other targets can be operated too having sensitivity to both SI and SD interactions Angloher et al. (2022b,a).

Germanium or Silicon bolometers measuring heat and charge are being used in the EDELWEISS experiment Arnaud et al. (2020); Armengaud et al. (2022) in the Modane laboratory in France and in the SuperCDMS project Agnese et al. (2019), installed at SNOLAB after first operation at Soudan laboratory in US; the recent use of small crystals with masses of tens of grams o even less has allowed to explore low mass candidates at MeV/c^2 scale when considering the Migdal effect or electron scattering Amaral et al. (2020); Alkhatib et al. (2021).

2.3. Semiconductor and gaseous detectors

Purely ionization detectors with low energy threshold at or below 100 eV are being used for low mass DM detection too. Silicon charge-coupled devices (CCDs) offer an effective particle identification and then background rejection, as demonstrated by the DAMIC experiment Aguilar-Arevalo et al. (2020) operated at SNOLAB and beging enlarged now as DAMIC-M at Modane. The innovative Skipper readout to reduce noise and achieve single electron counting has already been used in small CCDs by SENSEI Barak et al. (2020), releasing the leading constraints on cross sections for electron scattering, even if operating at shallow depth at Fermilab in US. Point-Contact Germanium detectors are being used by the CDEX project Liu et al. (2019), which has now in operation a 10 kg detector array at Jinping Dai et al. (2022).

Gaseous detectors filled with mixtures of light targets like Ne are in development; the use of Spherical Proportional Counters has been demonstrated with the SEDINE sphere Arnaud et al. (2018) at Modane and is underway in the NEWS-G experiment at SNOLAB, while a TPC holding a pressurized gas equipped with micromesh gas structures (Micromegas) readouts is being considered in the TREX-DM project Castel et al. (2019) to be operated at the Canfranc Underground Laboratory in Spain.

2.4. Bubble chambers

In bubble chambers, target liquids are kept in metastable superheated state and the formed bubbles by energy depositions are read by cameras. They are almost immune to ER background sources and, as most of the used targets contain ^{19}F, they have excellent sensitivity to SD DM-proton couplings. Limits on cross section for this interaction from the PICO-60 experiment at SNOLAB are still the most stringent ones for masses above 3 GeV/c^2 Amole et al. (2019).

2.5. NaI(Tl) scintillators

NaI(Tl) detectors, being quite cheap and robust detectors, are ideal for annual modulation searches demanding large exposures, although developments have been required to achieve low background and low threshold. The overall results of the DAMA/LIBRA experiment corresponding to 22 annual cycles (2.86 ton×y) favor the presence of a modulation with proper features at 13.7σ C.L. Bernabei et al. (2021); but there is a strong tension with other null results using different targets (see for instance Billard et al. (2022) if this is interpreted as due to DM, not only in the standard paradigm but even assuming different halo/interaction models. For this reason, there are several projects underway to get a model-independent proof or disproof of the DAMA/LIBRA result using the same target. Two of them are taking data and results for 3 years have been published: in ANAIS-112 at the Canfranc laboratory the null hypothesis is well supported with best fits for the modulation amplitude incompatible with DAMA/LIBRA at 3.3 (2.7)σ for the regions of 1-6 (2-6) keV (electron equivalent energy) Amaré et al. (2021) while for COSINE-100, operated at the Yangyang laboratory in South Korea, the deduced amplitude is still consistent with both that reported by DAMA and the no-modulation case Adhikari et al. (2022). Figure 1 compares the values of the modulation amplitudes deduced by the three experiments in the two analysis energy regions. Application of machine-learning techniques to improve the rejection of noise events will help to increase the sensitivity to the DAMA/LIBRA annual modulation of ANAIS-112 Coarasa et al. (2022). SABRE Antonello et al. (2019) at LNGS and PICOLON Fushimi et al. (2021) at Kamioka in Japan are preparing experiments with purified NaI(Tl) detectors too; COSINUS Angloher et al. (2016) plans to use at LNGS scintillating bolometers made of NaI having the capability of discriminating NRs from background events Angloher et al. (2023).

2.6. Directional detectors

In directional detectors, the goal is to register the direction of NR (axis, sense) or at least a head-tail asymmetry (by measuring the relative energy loss along the track). Low pressure gaseous targets, mostly based on CF_4 mixtures with ^{19}F, inside TPCs with different electron amplification devices and track readouts (Multi-wire proportional chambers (MWPC),

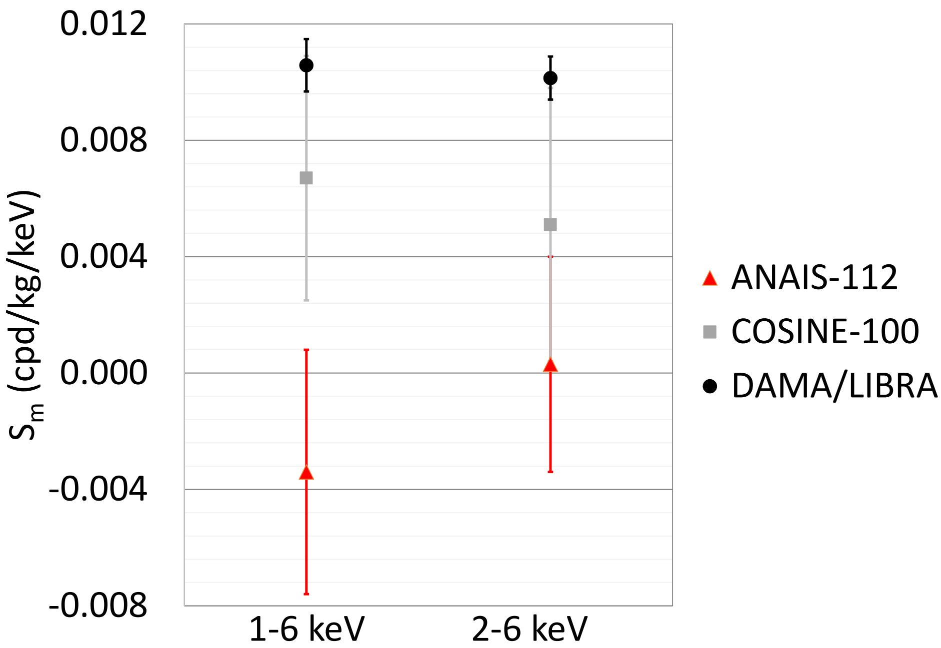

Fig. 1. Comparison of the modulation amplitudes obtained by DAMA/LIBRA Bernabei et al. (2021), ANAIS-112 Amaré et al. (2021) and COSINE-100 Adhikari et al. (2022) experiments in the energy regions of 1-6 keV and 2-6 keV (electronic equivalent energy).

Micro pattern gaseous detectors (MPGDs) or optical readouts) are being considered Battat et al. (2016); O'Hare et al. (2022) together with nuclear emulsions Agafonova et al. (2018). The CYGNUS collaboration has been conceived as a a multi-site, multi-target observatory at the ton-scale to probe DM below the neutrino floor Vahsen et al. (2020); prototypes at the 1 m^3 scale, based on smaller detectors, are being developed in several laboratories like Boulby in UK, LNGS Mazzitelli et al. (2023) or Kamioka Ikeda et al. (2021).

3. Summary

The direct detection of DM particles which could be present in the galactic halo is really challenging due to the small and rare signal expected and is being attempted by complementary experiments, based on different detection technologies and targets, exploring different interactions, mass ranges of candidates and possible signatures.

For high mass DM, experiments using liquid noble detectors (Xe and Ar) provide now leading constraints for SI DM-nucleus interaction and will explore cross sections down to the irreducible neutrino background with projects starting at the end of the decade Akerib et al. (2022) while for SD DM-proton interaction, bubble chambers provide best limits.

For low mass DM, the best sensitivity comes from a combination of experiments based on different detection techniques: solid-state cryogenic detectors (using scintillating bolometers or small mass Ge and Si semiconductor crystals), purely ionization detectors (Ge diodes, CCDs or gaseous detectors) and liquid noble detectors operated in S2-only mode (charge collection); new developments to further lower the energy threshold are underway Essig et al. (2022).

The SI and SD DM-nucleon scattering cross section space considering current limits and future prospects is shown in Figs. 7 and 8, respectively, of the "Report of the Topical Group on Particle Dark Matter for Snowmass 2021" Cooley et al. (2022)[2].

It is also worth noting that important results from NaI(Tl) experiments to solve the long-standing conundrum of the DAMA/LIBRA annual modulation result have been presented and that studies for a DM detector with directional sensitivity are underway to prove the galactic origin of a possible signal.

Acknowledgements. I am grateful to all the researchers of GIFNA (Group in Nuclear and Astroparticle Physics) and LSC (Canfranc Underground Laboratory) staff for their kind support. I would like to acknowledge too financial support from Gobierno de Aragón under grant E27_20R (Group in Nuclear and Astroparticle Physics).

References

Aalbers, J., Akerib, D. S., Akerlof, C. W., et al. 2023, Phys. Rev. Lett., 131, 041002
Abdelhameed, A. H., Angloher, G., Bauer, P., et al. 2019, Phys. Rev. D, 100, 102002
Adhikari, G., Barbosa de Souza, E., Carlin, N., et al. 2022, Phys. Rev. D, 106, 052005
Agafonova, N. et al. 2018, Eur. Phys. J. C, 78, 578
Agnes, P., Albuquerque, I. F. M., Alexander, T., et al. 2018, Phys. Rev. D, 98, 102006
Agnes, P., Albuquerque, I. F. M., Alexander, T., et al. 2023a, Phys. Rev. Lett., 130, 101001
Agnes, P., Albuquerque, I. F. M., Alexander, T., et al. 2023b, Phys. Rev. Lett., 130, 101002
Agnes, P., Albuquerque, I. F. M., Alexander, T., et al. 2023c, Phys. Rev. D, 107, 063001
Agnese, R., Aralis, T., Aramaki, T., et al. 2019, Phys. Rev. D, 99, 062001
Aguilar-Arevalo, A., Amidei, D., Baxter, D., et al. 2020, Phys. Rev. Lett., 125, 241803
Ajaj, R., Amaudruz, P.-A., Araujo, G. R., et al. 2019, Phys. Rev. D, 100, 022004

[2] `https://arxiv.org/abs/2209.07426`

Akerib, D. S., Cushman, P. B., Dahl, C. E., et al. 2022, arXiv e-prints, arXiv:2203.08084
Alkhatib, I., Amaral, D. W. P., Aralis, T., et al. 2021, Phys. Rev. Lett., 127, 061801
Amaral, D. W., Aralis, T., Aramaki, T., et al. 2020, Phys. Rev. D, 102, 091101
Amaré, J., Cebrián, S., Cintas, D., et al. 2021, Phys. Rev. D, 103, 102005
Amole, C., Ardid, M., Arnquist, I. J., et al. 2019, Phys. Rev. D, 100, 022001
Angloher, G., Banik, S., Benato, G., et al. 2022a, Phys. Rev. D, 106, 092008
Angloher, G., Benato, G., Bento, A., et al. 2022b, European Physical Journal C, 82, 207
Angloher, G., Bharadwaj, M., Dafinei, I., et al. 2023, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1045, 167532
Angloher, G. et al. 2016, Eur. Phys. J. C, 76, 441
Antonello, M. et al. 2019, Eur. Phys. J. C, 79, 363
Aprile, E., Aalbers, J., Agostini, F., et al. 2020, Phys. Rev. D, 102, 072004
Aprile, E., Abe, K., Agostini, F., et al. 2022, Phys. Rev. Lett., 129, 161805
Araújo, H. M., Balashov, S. N., Borg, J. E., et al. 2023, Astroparticle Physics, 151, 102853
Armengaud, E., Arnaud, Q., Augier, C., et al. 2022, Phys. Rev. D, 106, 062004
Arnaud, Q., Armengaud, E., Augier, C., et al. 2020, Phys. Rev. Lett., 125, 141301
Arnaud, Q., Asner, D., Bard, J.-P., et al. 2018, Astroparticle Physics, 97, 54
Barak, L., Bloch, I. M., Cababie, M., et al. 2020, Phys. Rev. Lett., 125, 171802
Battat, J. B. R. et al. 2016, Phys. Rept., 662, 1
Bernabei, R. et al. 2021, Nucl. Phys. At. Energy., 22, 329
Bertone, G. & Hooper, D. 2018, Rev. Mod. Phys., 90, 045002
Billard, J., Boulay, M., Cebrián, S., et al. 2022, Reports on Progress in Physics, 85, 056201
Bœhm, C., Dolan, M. J., & McCabe, C. 2013, Journal of Cosmology and Astroparticle Physics, 2013, 041

Castel, J. et al. 2019, Eur. Phys. J. C, 79, 782
Coarasa, I., Apilluelo, J., Amaré, J., et al. 2022, Journal of Cosmology and Astroparticle Physics, 2022, 048
Cooley, J., Lin, T., Lippincott, W. H., et al. 2022, arXiv e-prints, arXiv:2209.07426
Dai, W. H., Jia, L. P., Ma, H., et al. 2022, Phys. Rev. Lett., 129, 221802
Dolan, M. J., Kahlhoefer, F., & McCabe, C. 2018, Phys. Rev. Lett., 121, 101801
Essig, R., Giovanetti, G. K., Kurinsky, N., et al. 2022, arXiv e-prints, arXiv:2203.08297
Freese, K., Frieman, J., & Gould, A. 1988, Phys. Rev. D, 37, 3388
Fushimi, K. et al. 2021, Progress of Theoretical and Experimental Physics, 2021, 043F01
Ibe, M., Nakano, W., Shoji, Y., et al. 2018, J. High Energ. Phys., 194, 2018
Ikeda, T., Nakamura, K., Shimada, T., et al. 2021, Progress of Theoretical and Experimental Physics, 2021, 063F01
Kouvaris, C. & Pradler, J. 2017, Phys. Rev. Lett., 118, 031803
Liu, Z. Z., Yue, Q., Yang, L. T., et al. 2019, Phys. Rev. Lett., 123, 161301
Mazzitelli, G., Domingues, F. A., Baracchini, E., et al. 2023, Nucl. Instrum. & Meth. A, 1045, 167584
Meng, Y., Wang, Z., Tao, Y., et al. 2021, Phys. Rev. Lett., 127, 261802
O'Hare, C. A. J., Loomba, D., Altenmüller, K., et al. 2022, arXiv e-prints, arXiv:2203.05914
Serpico, P. D. & Raffelt, G. G. 2004, Phys. Rev. D, 70, 043526
Spergel, D. N. 1988, Phys. Rev. D, 37, 1353
Vahsen, S. E., O'Hare, C. A. J., Lynch, W. A., et al. 2020, arXiv e-prints, arXiv:2008.12587