Above-ground direct searches for WIMPs

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Most direct WIMP searches have located their experimental setup under a large rock overburden in order to drastically reduce the backgrounds caused by cosmic-ray interactions. The absence of signal in current searches had led to revisit of the assumption that the WIMP-nucleon cross section is necessarily low enough to justify neglecting a possible attenuation of the WIMP flux as it passes through the atmosphere and the rock overburden. I will review recent experiments devoted to the direct search for WIMPs having cross-section large enough to escape detection in an underground site, while still being compatible with cosmological and astrophysical constraints.

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1. Introduction

The signal that is the object of direct search of Dark Matter (DM) is the recoiling nuclei produced inside a laboratory target by a collision with a DM particle from our galactic halo. The main focus of these searches has been so far weak-scale interaction rates. For DM-nucleon cross section below 10^{-31} cm^2, the energy loss of the DM particle as it crosses the atmosphere and a few kilometres of rock is neglible. Installing the search experiment in an underground laboratory with a thick rock overburden is thus a very efficient way to suppress the background from nuclear recoils produced by the scattering of fast neutrons induced by cosmic-ray interactions. Therefore, all major direct DM search experiments are located in underground laboratories. Over the years, the sensitivity of detectors to ever lower count rates and thresholds has drastically improved. Nearly all of them are now unable to handle the large background count rates associated to an exposure to the cosmic-ray flux near the Earth surface. However, there has been a renewed interest for DM models where the DM-DM scattering cross section is not weak, but can be as large as strong force interaction (i.e. 1 barn = 10^{-24} cm^2). In these proceedings [1] (see also Ref. [2]), it is argued that the apparent lack of small satellites around the Milky Way and the cusp/core problem of DM halos could be alleviated by assuming that the DM is made by Strongly Interacting Massive Particle (SIMPs), with a SIMP-SIMP elastic scattering cross section as large as 0.57 cm^2 per gram. For example, this corresponds to a SIMP mass of 1 GeV/c^2 and a cross-section of 10^{-24} cm^2. This by no means implies that the SIMP-nucleon elastic scattering cross-section has the same strength. However, it does raises this possibility, and necessitate to look back at direct DM searches data to check what experimental constraints can be set [3]. We must nevertheless be reminded that direct searches can only address those models where the SIMP have strong force interaction with nucleons. We exclude here models where these interactions also involve any charged particles, more often referred to as millicharge interactions[4].

2. SIMPs interactions

Recently there has been many papers that flesh out with increasing details the interaction of a SIMP with the Earth and its atmostphere [5, 6, 7, 8]. As they travel through matter, SIMPs are scattered off their initial direction, thus affecting the directionality of their flux. In particular, the SIMP flux coming in an experiment from below has to go through the Earth globe and is attenuated much more strongly that the flux coming from above. Multiple collisions will reduce the SIMP velocity until it reaches a value that is no longer sufficient to produce a nuclear recoil, and thus escape detection. The energy lost in each collision depends on the ratio of the masses of the SIMP and the atoms it encounters, and on the nature of the matrix element describing the scattering of the SIMPs on nucleons. In these proceedings, the interaction is assumed to be scalar, giving rise to the usual spin-independent coherence effect. Calculations of the attenuation of the SIMP flux before it arrives in a detector are thus complex. Determining the cut-off cross section value above which detection is impossible requires a scan of cross-section values with a fine mesh. Consequently, efforts have been made to develop analytical calculations that give results comparable to lengthier full Monte Carlo calculations [6].

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3. Experimental constraints at high mass

Limits that can be derived from deep underground direct searches for heavy SIMPs were first reported in Ref. [9]. They appear as the black and purple regions shown in the left pannel of figure 1, taken from Ref. [10]. There is a large gap between this region and that excluded by constraints from cosmology [3] (dot-dashed line on that same figure). That gap has been gradually

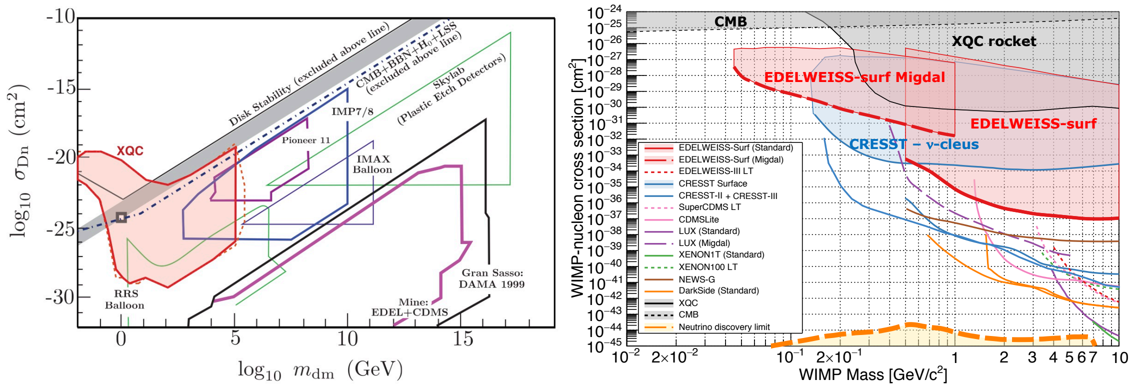

Figure 1: Left panel: constraints on large-mass SIMPs particles, taken from Ref. [10]. Right pannel: experimental constraints for SIMP masses below 10 GeV/c^2, adapted from Ref. [14]. See references therein for the list of the different experiments appearing in the two panels.

filled by additional constraints from space- and ballon-borne experiments. The sensitivity of these experiments is improved by avoiding the effect of the atmosphere. More recent constraints at high mass were provided by IceCube [11]. A recent review of these constraints can be found in Ref. [7]. The gap is now closed for all cross section values for SIMP masses above a fraction of a GeV/c^2. Below this value, sensitivities are limited by the experimental thresholds on the detectable recoil energy. The contours for deep underground experiments (black and purple regions shown in the left pannel of figure 1) show that these cannot provide constraints for SIMPs with scattering cross-section above 10^{-31}cm^2 and masses below 1000 GeV/c^2. This is also the case for the deep-underground experiment results depicted as full and dashed lines on the right panel of figure 1.

4. Recent experimental results for low-mass SIMPs

New detectors have been proposed to cover the sub-GeV/c^2 mass range for SIMPs. The interpretation of recent results obtained liquid detector scintillators [12] depends on an aggressive subtraction of the single-electron noise of the photo multiplier tubes used for the signal readout. More robust results have been obtained with small cryogenic detectors developed in the context of searches of Dark Matter particles with sub-GeV/c^2 masses and also the studies of the coherent elastic scattering of reactor neutrinos on nuclei. The CRESST/ν-CLEUS [13] and EDELWEISS-Surf [14] experiments involve small cryogenic detectors (0.5 g Al_2O_3 and 33 g Ge, respectively), operated at depths of less than 1 m, so that the majority of the shielding effect come from the atmosphere. Cryogenic detectors are true calorimeters that measure the elevation of temperature arising from the thermalisation of the kinetic energy of the nuclear recoil produced in the collision. The interpretation of the low-energy data of these detectors signal does not suffer from the quenching effects that are encountered when using ionisation or scintillation signals. The two experiments are complementary in terms of experimental thresholds and backgrounds. The threshold in recoil energy used in the analysis of the CRESST and EDELWEISS data were 20 and 60 eV, respectively, favouring the CRESST detector. However, the observed backgrounds were favouring the EDELWEISS detector, with rates of approximately 10^5 and 200 events per keV, per gram and per day, respectively. Low background levels are important since reliable models for them have not yet been established in these newly-developed detectors. For this reason, both analyses set limits with the conservative assumption that all observed events are potential SIMP-induced nuclear recoil candidates. Both results have been interpreted [15, 14] in terms of constraints on SIMPs by taking into account all material crossed by the flux before it reaches the detectors. The corresponding excluded regions are shown respectively on Figure 1 as the blue and red surfaces with a lower bound delimited by a full line. The upper bounds of the excluded regions of both experiments are similar because the dominant effect of the Earth's atmosphere on the attenuation of the SIMP flux and velocity distribution. The lower bound of the regions reflects the difference in backgrounds. However, despite the larger backgrounds, the CRESST contour extends mass values that are a factor 3 lower than EDELWEISS, mostly because of the equivalent factor in their relative thresholds and also because of the use of lighter target atoms in CRESST.

In the case of EDELWEISS, a complementary search was performed using the same data, but considering also the Migdal effect, in order to expand the detector sensitvity to lower masses [14]. Indeed, in most cases, the collision of a SIMP with a nucleus will make it recoil with some kinetic energy. The Midgal effect considers instead the combined response of the nucleus and its electron cloud. The sudden boost of the nucleus relative to the electrons creates an electric dipole that must be considered. Full calculations [16] show that the collision has a small but non-negligible probability to result in the ejection of one of the bound electron with a net kinetic energy that can exceed the maximal energy value expected from the simple two-body kinematics of the SIMP and the nucleus. In germanium, electrons from the $n = 3$ shell can be ejected with energies of the order of 100 eV. Electrons from deeper shells have considerably smaller probabilities to aquire such large kinetic energies, and the signal from valence electrons in the $n = 4$ shell is conservatively ignored, as the calculations so far do not take into account the perturbation from atomic bonds [16]. The red region with the dashed lower bound on figure 1 shows the range in mass and cross section that is excluded by taking into account the added contribution of the Midgal electrons to the thermal signal of the EDELWEISS-Surf cryogenic germanium detector [14]. This added contribution does not improve the constraints for SIMP masses above 600 MeV/c^2 due to its $< 0.1\%$ probability. However it makes it possible for the first time to exclude coherent scattering cross-section values of the order of 10^{-27} cm^2 for SIMPs with masses as low as 45 MeV/c^2. Further improvements to fill the gap between these constraints and those imposed by cosmological observables would require to further reduce the background in the detector without using an additional shielding that would affect the SIMP flux.

5. Results for spin-dependent interactions for low-mass SIMPs

As already stated, so far only coherent spin-independent interaction have been considered.

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The data can also be interpreted as constraints on other type of interactions, and in particular of spin-dependent interactions. The calculation of the effect of the Earth, atmosphere and detector shielding on the velocity field must take into account the spin content and form factors of all elements entering their composition (see e.g Ref. [8]). The nucleus ^{14}N has both unpaired proton and neutron spins, and therefore the atmosphere attenuates indiscriminately spin-dependent interactions with both type of nucleons. Figure 2 shows the existing constraints for spin-dependent interactions of SIMPs on neutrons and protons. Compared to the spin-independent results, for which coherence effects play a large role, the detectors probe larger values of SIMP-nucleus cross-sections, and therefore the role of shielding effects are more dramatic, especially at low mass. The constraints therefore apply to a more limited mass range.

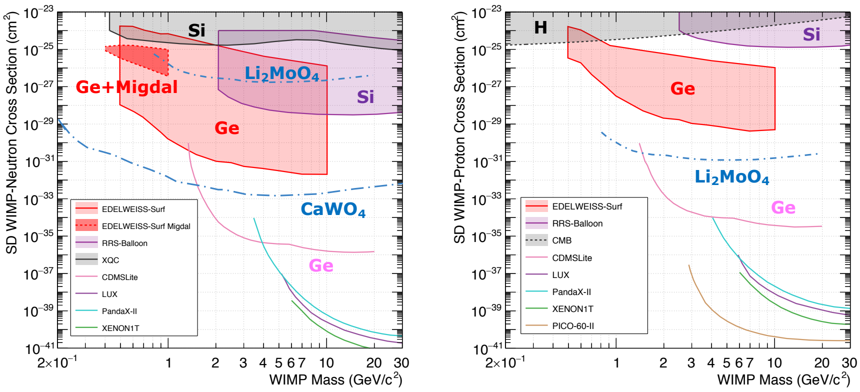

Figure 2: Constraints for spin-dependent interaction of SIMPs on neutrons (left panel) and protons (right panel), adapted from Ref. [14]. See references therein for the list of the different experiments, while the $CaWO_4$ and Li_2MoO_4 result are from Refs. [17] and [18], respectively. As in the previous figure, full contours correspond to calculations that include the full attenuation effects of Earth, atmosphere and experimental shielding. All lines correspond to limits that do not take these effect into account.

6. Conclusion

There is a renewed interest for SIMP models where the interaction cross section between Dark Matter particles is strong-sized. By extension, the direct search for Dark Matter particle having strong-sized interaction cross sections with nucleon is still relevant, especially for SIMP masses below 1 GeV/c^2, where previous experiments failed to provide constraints. Recent above-ground searches with relatively small cryogenic detectors are starting to provide additional constraints, down to SIMP masses as low as 45 MeV/c^2. Further progress will depend on reductions of experimental energy thresholds and reductions in backgrounds. The latter may prove to be more challenging, since they must occur without increasing the external shielding around the experiment, since this would only further attenuate the SIMP flux impinging on the detector. The use of the Midgal effect enables the searches to be extended to significantly lower SIMP masses and emphasises the importance to confirm the prediction of its existence.

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