NEWS-G, a Spherical Proportional Counter with low-Z target to search for sub-GeV Weakly Interacting Particles.

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Abstract. Despite several large-scale direct detection experiments operating worldwide, dark matter remains elusive. Not favoured by supersymmetric theories, the low Weakly Interacting Massive Particle (WIMP) mass regime (less than few GeV) has been largely ignored. The NEWS-G project builds on the experience gathered with the operation of the SEDINE detector at the Laboratoire Souterrain de Modane (France). The goal is to construct a 140 cm diameter low-background Spherical Proportional Counter (SPC) capable of holding up to 10 bar of gas and to be operated at the SNOLAB underground facility (Canada). The use of low-Z target materials such as Ne, He and H, together with a strict selection of low activity materials will provide sensitivity to WIMP masses down to 0.1 GeV/c^2. The detector is expected to be deployed in 2018.

1. introduction
Dark matter is now well established as an essential ingredient of our understanding of the Universe. Its nature is still unknown but a theoretically motivated class of candidate particles, called Weakly Interacting Massive Particles (WIMPs), has been traditionally favoured. There is, however, no consensus on a theoretical framework of particle physics which would account for additional particles fitting the dark matter cosmological requirements. The most well-known theory is Supersymmetry (SUSY): the simplest models support the lightest supersymmetric particle, the neutralino, as a candidate for dark matter with a mass between tens of GeV and TeV. However, the search for evidence of SUSY particles at the Large Hadron Collider (LHC) has so far been unsuccessful and dark matter hunters are left with a wide-open parameter space to explore. New ideas are now expanding the region of interest. Several new approaches (dark sector, asymmetric dark matter, generalized effective theory, etc.) open the way to less paradigmatic candidates, with lower mass and/or more complex couplings than the traditional spin-dependent or spin-independent ones.

The current generation of experiments focuses on large mass ranges, and is often not sensitive to masses below 10 GeV/c^2 due to the lower recoil energies. The NEWS-G project proposes a novel gaseous spherical detector capable of reaching unprecedented low energy thresholds [1] and providing sensitivity to masses down to a tenth of a GeV/c^2.

Due to kinematic considerations, low-Z target materials are best suited to detect WIMPs with a mass comparable of the mass of a proton. Coupled with the requirements for radiopurity,
noble gases such as Helium and Neon are materials of choice for gas detectors. Hydrogen is a suitable candidate as well, but safety considerations will limit its concentration.

2. Spherical Proportional Counter at SNOLAB

The principle of the detector is summarized in figure 1. A high voltage is applied to the central electrode, typically a few kV, while the sphere is grounded. It creates a radial electric field, with a potential decreasing as $1/r^2$. The nucleus recoil generated by a dark matter particle scattering off a target nuclei ionizes the gas (1). Due to the field, the electrons drift towards the electrode (2). Close to the centre, the field becomes strong enough to induce an avalanche process, creating thousands of secondary electron-ion pairs (3). While the electrons are captured by the sensor, the secondary ions drift towards the sphere (4). The collected charge is measured through a charge-sensitive pre-amplifier and digitized. Beside its simplicity, which is an asset for low background detector, this geometry presents the advantage of a low capacitance, largely independent to the diameter of the sphere. It means that it is possible to build a relatively large detector while keeping a low energy threshold. After deconvolution of the pre-amplifier response, it is possible to extract two observables from the measured pulses: the amplitude and the rise time. The former is directly dependent on the energy of the nuclear recoil and the latter depends on the primary ionization track length as well as the drifting distance. The two observables allow for some level of background discrimination. In particular, the events happening near the surface of the sphere, or the events whose primary ionization is not point-like (expected for a nuclear recoil) can be rejected.

The principle has been demonstrated first at the CEA research centre in Saclay (France) and later with the SEDINE detector, a 60 cm low activity copper sphere deployed at the Laboratoire Souterrain de Modane (LSM, France), which has been operated for several years. In 2015, a dark matter run of 42.7 days was taken, with Neon as main target material [2]. After data quality cut, a total exposure of 9.6 kg·day was kept. A Boosted Decision Tree (BDT) was used to optimize the signal/background discrimination, and a 90% C.L. upper-limit was set on the WIMP-nucleon cross section (cf. solid red line figure 2).

After this encouraging result, the SEDINE detector is now used as a prototype for the next generation of the project which aims at the deployment of a 140 cm copper sphere at SNOLAB (Sudbury, Canada). The thicker overburden of this underground facility will reduce the cosmic ray flux by approximatively a factor 4 compared to LSM. By running the detector with Neon up to 10 bar and imposing stricter background requirements on the materials used, the goal is to improve the sensitivity at 2 GeV/c² by 3 orders of magnitude. Additional phases with Helium and Hydrogen as main target material are planned to extend the search down to one tenth of the GeV/c² but with weaker sensitivity.

Figure 3 shows an exploded view of the detector. The material selected for the sphere is
Figure 2. Constraints in the Spin-Independent WIMP-nucleon cross section vs WIMP mass plane as defined by the dark matter search with SEDINE for a total exposure after cut of 9.6 kg·day [2].

C10100 copper, that the preliminary assay deemed sufficiently clean. The copper plates will be spun into two hemispheres and welded together using electron beam welding. The inner surface will be cleaned by acid etching to remove the surface contamination. It will be followed by electrolyzing of a millimetre thick layer of pure copper to suppress the background coming from the bulk material. In order to suppress the background coming from the surrounding rock, the copper sphere will be encased in a compact lead shield, consisting of a minimum of 25 cm of lead. The inner 3 cm will be made of archeological lead, while the outer layer will be cast with low activity lead. The whole system will be surrounded by a 40 cm thick high-density polyethylene shield to moderate the neutrons coming from the rock.

In parallel to the construction of the sphere and the shield, a significant R&D program aims to improve the characteristics of the detector. The sensor is a critical element of the detector. Its size and the value of the high voltage need to be optimized in order to reach a compromise between the amplification, the drift field and the risk of electric breakdown. The collaboration is studying the behaviour of multi-branched electrodes, or “achinos”, as shown on figure 4. This kind of geometry has the same effect as a large ball at long distance, providing a high enough drift field, and at the same time exhibits the behaviour of small balls at short distance, ensuring a sufficient amplification. A successful implementation of this geometry could pave the way to a multi-electrode system. The resulting segmentation of the detector volume could lead to some level of directional sensitivity. In the vicinity of the support rod, the electric field is distorted, as visible on figure 1. This feature creates shorter drift trajectories for electrons created in this part of the detector, which is detrimental to the resolution. As it is challenging to create a rod with a gradient of potential that would correct the field while fulfilling the cleanliness requirements, an alternative is to add a secondary electrode called “umbrella” (cf. figure 4) next to the sensor to improve the behaviour in the affected region.

The NEWS-G detector will be calibrated using three different methods. Two standard
Figure 3. Exploded view of the detector to be installed at SNOLAB. The sphere is made of copper and surrounded by two shields. The inner part of the Compact Lead shield is cast from archeological lead, and the outer part is made from low activity lead. Each piece of the lead shield has a stainless steel skin used as a support. The whole system is sitting in a high-density polyethylene (HDPE) shield to thermalize and capture the neutrons. One section of the HPDE wall and the support structure has been removed for clarity.

Figure 4. (Left) “Achinos” prototype sensor. All the small balls are connected to the same central wire. (Right) Schematic view of a simple umbrella. The small negative potential under the ball improves the behaviour in the affected region.
radioactive sources, \(^{22}\text{Na}\) for high energy gammas and AmBe for neutrons, will be deployed through the shielding using a specially placed copper tube. A 230 nm pulsed laser will be used to extract electrons from the inner surface of the sphere. Depending on the laser power, it will be possible to create a wide range of event energies, from single electrons all the way to alpha-like events. The last calibration method is the use of a radioactive gas to generate low energy events in the volume of the detector. \(^{37}\text{Ar}\) has a life time of 35 days and emits quasi mono-energetic X-rays (270 eV and 2.82 keV) through electron capture. It is produced by the irradiation of \(^{40}\text{Ca}\) powder with fast neutrons at the Royal Military College of Canada, into a clean container suitable for the injection into the low background experiment gas system. The first calibration using this method was performed in May 2017 at Queen’s University on a \(\varnothing 30\) cm sphere. The two energy lines are particularly suitable for studying the effect of the umbrella voltage.

The initial plan of NEWS-G at SNOLAB was to use a pressure of 10 bar in the detector, in order to bring the active mass to 40 kg in the case of Neon. In order to take advantage of this mass, the cleanliness requirements for the construction material have to be stringent, as visible in Table 1. Unfortunately, the assay of C10100 copper by the XMASS collaboration [3] tends to show that the \(^{210}\text{Pb}\) activity in the bulk of the copper is significantly higher than expected and this generation of detector will be background limited. Alternative copper supply is being investigated for the next generation (N6 grade, electroforming, ...).

| Source Location | Quantity | Source | Contamination | Units | Evt/kg/day <1 keV |
|-----------------|----------|--------|----------------|-------|------------------|
| Copper          | 627.83 kg | 60Co   | 30             | mBq/kg | 0.054            |
| Copper          | 627.83 kg | 238U   | 3              | mBq/kg | 0.111            |
| Copper          | 627.83 kg | 232Th  | 12.9           | mBq/kg | 0.063            |
| Inner surface   | 57255 cm² | 210Pb  | 1              | nBq/cm² | 0.012           |
| Archeological Lead | 2108.95 kg | 238U | 61.8           | mBq/kg | 0.062            |
| Archeological Lead | 2108.95 kg | 232Th | 9.13           | mBq/kg | 0.010            |
| Rod             | 0.0932 kg | 60Co   | 30             | mBq/kg | 0.000            |
| Rod             | 0.0932 kg | 238U   | 3              | mBq/kg | 0.000            |
| Rod             | 0.0932 kg | 232Th  | 12.9           | mBq/kg | 0.000            |
| Wire            | 2.66x10-5 kg | 60Co | 31000          | mBq/kg | 0.000            |
| Wire            | 2.66x10-5 kg | 238U | 3x105          | mBq/kg | 0.001            |
| Wire            | 2.66x10-5 kg | 232U | 5x104          | mBq/kg | 0.000            |
| Wire            | 2.66x10-5 kg | 40K   | 166x104        | mBq/kg | 0.001            |
| Laboratory      | 208Tl/40K |        |                |       | 0.076            |

The design of the detector is soon to be complete and the construction about to start. The deployment of the detector at SNOLAB is scheduled for the mid-2018.

References
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