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NEWS-G: Search for Light Dark Matter with a Spherical Proportional Counter

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On behalf of the NEWS-G collaboration

The NEWS-G collaboration is searching for light dark matter candidates using a spherical proportional counter. Access to the mass range from 0.1 to 10 GeV is enabled by the combination of low energy threshold, light gaseous targets, and radiopure construction. The current status of the experiment is presented, including the first NEWS-G results obtained with SEDINE, a 60 cm in diameter spherical proportional counter operating at LSM (France). The next generation, 140 cm in diameter, spherical proportional counter that is currently being installed in SNOLAB, Canada, is presented. Its construction at LSM, using C10100 copper and the electroplating of a 500 µm ultra-pure copper layer to the inner detector surface, will be discussed, along with the latest advances in instrumentation, simulation, and gas purification.

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1. Introduction

It is well established from measurements of the Cosmic Microwave Background [1] and astronomical observations [2, 3] that the majority of the Universe's matter content is comprised of cold, non-baryonic Dark Matter (DM). One of the best motivated DM candidates are the Weakly Interacting Massive Particles (WIMPs) [4] - a generic class of neutral particles thermally produced in the early Universe, with a mass in the range of 10-1000 GeV [5]. A wide variety of direct DM search experiments exists [6], using many detector technologies, aiming to measure a signal induced by a DM particle in the galactic halo elastically scattering off a nucleon in the sensitive medium. The current landscape of experimental search constraints are shown in Figure 1. The lack of a DM candidate observation at typical WIMP masses, coupled with theoretical models with candidates with masses below a few GeV [7, 8, 9, 10], have ignited growing interest. Challenges towards low mass DM detection are the sourcing of sufficiently radiopure materials, the need for ever-lower energy thresholds and the reduction in ionisation quenching factor - the fraction of deposited energy visible to an ionisation detector - for decreasing energies. Overcoming these challenges opens a wide region of the mass-cross-section parameter space.

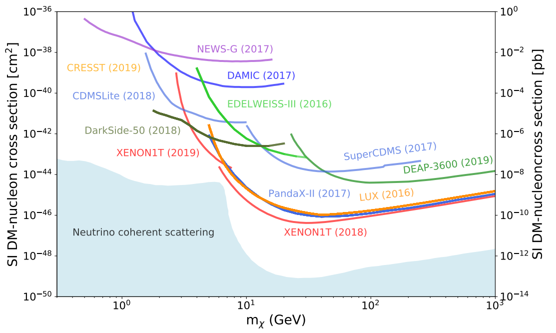


Figure 1: Spin-independent DM-nucleon interaction cross section as a function of DM mass [6].

2. NEWS-G and the Spherical Proportional Counter

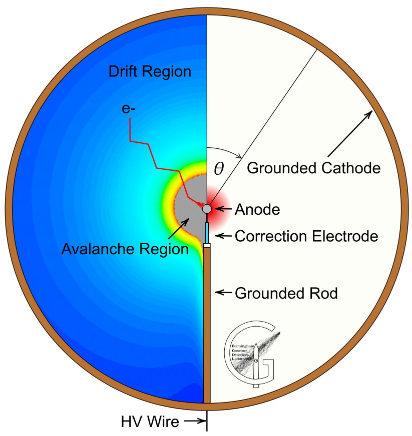
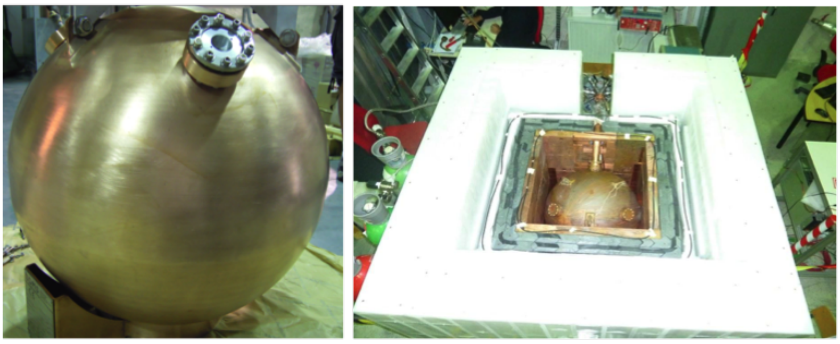


Figure 2: Operational principle of the spherical proportional counter [11].

The NEWS-G collaboration endeavors to probe the $0.1 - 10$ GeV DM mass range, by exploiting the Spherical Proportional Counter [12, 13, 14, 15]. Shown in Figure 2, the spherical proportional counter is a gaseous detector comprising a grounded spherical shell with an $\mathcal{O}(1\text{ mm})$ spherical sensor anode at its centre. The electric field in the ideal detector varies as $1/r^2$, which naturally divides the detector into a drift region, where electrons produced by interactions in the gas drift towards the anode in the low electric field, and an amplification region, where the electric field becomes sufficiently large for the electrons to create an avalanche, providing charge amplification.

Compared to traditional gaseous detector geometries, the spherical shape lends several advantages for large-volume, and so large active mass, detectors: (1) small number of read-out channels, with future potential for directional sensitivity [16] (2) capacitance independent of detector size (3) smallest surface-area to volume ratio (4) ability to operate at high gain, while maintaining its stability, for long periods of time (5) background rejection through pulse-shape analysis (6) simple design with ability to use highly-radiopure materials (7) ability to vary gas target, especially the use of light nuclei targets to kinematically match sub-GeV DM particles (8) ability to vary operational pressure, gas mixture and voltage in order to investigate possible unknown background sources



(a) (b)

Figure 3: (a) ⌀60 cm spherical proportional counter, SEDINE, and (b) shielding of 8 cm copper, 15 cm lead and 30 cm polyethylene.

The first results were obtained with the ⌀60 cm spherical proportional counter, SEDINE, at LSM, France. The detector was operated in sealed mode with the Ne:CH_4 (99.3% : 0.7%) gas mixture at 3.1 bar pressure for 42.7 days, with a total exposure of 9.7 kgdays. The Region Of Interest (ROI) was optimised for 8 candidate DM masses from 0.5 GeV to 16 GeV using a Boosted Decision Tree. Using standard DM halo assumptions, and considering all events in the ROI of each candidate mass as signal, the results shown in Figure 1 were obtained with Poisson statistics. A spin-independent DM-nucleon scattering cross-section of 4.4×10^{-37} cm^2 is excluded at 90% confidence level (CL) for DM mass of 0.5 GeV.

3. NEWS-G at SNOLAB

The next stage of the direct DM search with NEWS-G is a ⌀130 cm spherical proportional counter with a compact shield, shown in Figure 4, following commissioning in LSM, will be installed in SNOLAB, Canada. SNOLAB offers a 6000 m water equivalent overburden, and a cosmic muon flux of approximately $0.25/\text{m}^2/\text{day}$, as well as being a Class2000 clean room. One of the major sources of background in the detector is natural contamination of uranium and thorium, and their daughter isotopes, in the construction materials. The detector shell is made from C10100 (99.99% pure) Aurubis copper. However, it was recently shown [17] that there is more ^{210}Pb, a daughter of ^{232}U, than would be inferred from the measurements of uranium contamination. More information on this can be found in Refs. [17, 18]. An

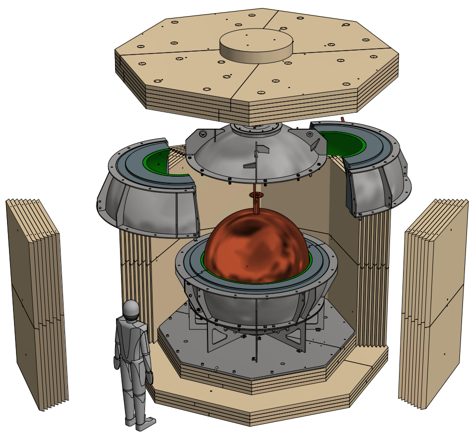


Figure 4: Schematic of the ⌀130 cm NEWS-G detector and shielding comprising 3 cm archaeological Pb, 22 cm low radioactivity Pb and 40 cm high-density polyethylene (HDPE).

XIA UltraLo-1800 alpha counter was used to measure the ^{210}Po activity, and from that a ^{210}Pb activity of 29^{+8+9}_{-8-3} mBq kg^{-1} was inferred. This would correspond to approximately 82% of the total background below 1 keV, as estimated by a Geant4 simulation [19]. Similarly, it was found that a 500 µm layer of ultra-pure layer of copper would suppress this background by a factor of 2.6.

Potentiostatic electroforming [17, 20], also employed by other experiments [21], was used to grow a 500 µm layer of ultra-pure copper on the inner surface of the detector. The procedure was performed at LSM, with the set-up shown in Figure 5, as described in Ref. [18].

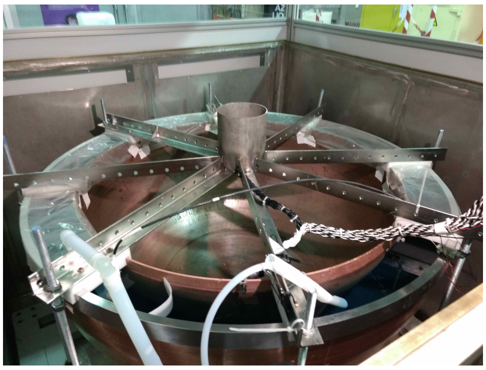


Figure 5: Electroplating set-up at LSM, showing detector hemisphere, anode, support structures and fixtures [18].

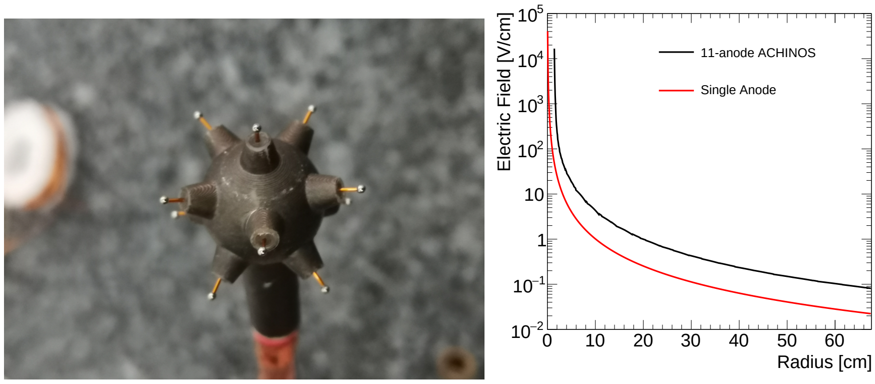
The detector hemispheres were initally sanded and cleaned before being chemically etched with an acidified hydrogen peroxide solution [22]. They were then electropolished, the opposite of electroplating, to remove (21.2 ± 0.1) µm and (28.2 ± 0.1) µm from each detector hemisphere, respectively, to expose the underlying crystalline structure of the copper and increase the concentration of copper ions in the electrolyte. Following this, the electroplating continued for approximately 21 days for each hemisphere using a pulse reverse current technique. The potential difference used between the anode and the cathode for electroplating was 0.3 V, the established value for electroplating pure copper. From the recorded current, and by assuming uniform deposition of copper, it was estimated that (502.1 ± 0.2) µm and (539.2 ± 0.2) µm of copper were plated onto the surface of the two hemispheres, respectively. The achieved plating rate corresponds to approximately 1.3 cm/year, which is promising for a future underground fully-electrofromed sphere.

4. Instrumentation Developments

4.1 ACHINOS

One of the main challenges in the development of a large volume spherical proportional counter is the $1/r^2$ dependence of the electric field, resulting in poor electron collection efficiency. While increasing the anode voltage would improve the electron collection efficiency, it also increases the avalanche fields which can lead to breakdown and so unstable detector operation. This interdependence of the drift and avalanche fields presents a limitation to detector operation with a single anode sensor. For this reason a multi-anode sensor - ACHINOS - has been developed [23, 16]. Shown in Figure 6a, ACHINOS comprises multiple anodes, placed equidistantly from each other and the same radius from the centre of the detector. This decouples the avalanche field, which is determined by the individual anode size and voltage, and the drift field, which is the collective field of all the anodes. This allows the detector to operate stably in high gain which increasing the high-radius electric field, enabling the operation of larger volume detectors.

Recent advancements in the instrumentation of ACHINOS [16] include the use of Diamond-Like Carbon (DLC) coatings applied to 3D printed substrates in order to construct the central



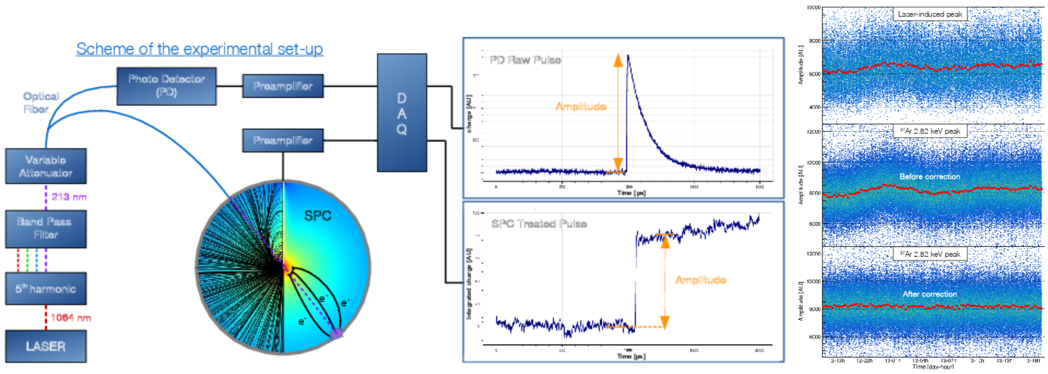
(a) (b)

Figure 6: (a) Example of an 11-anode ACHINOS with DLC-coated 3D printed central electrode [16]. (b) Comparison of electric field magnitude of an ACHINOS with eleven 1 mm anodes compared, as calculated using Finite Element Method (FEM) software, to a single 1 mm anode sensor.

electrode, which serves to hold the anodes in place but also to shape the electric field. This advancement has greatly improved the operation stability of the detector and robustness to sparking.

4.2 Detector Calibration and Characterisation

Detector performance monitoring and detailed detector response studies at the single electron level are enabled by a laser-based calibration system [24], shown in Figure 7. The system, that can be used in parallel to physics data-taking, employs a monochromatic UV laser beam with variable intensity and a trigger provided by a photo-detector, allowing precision measurements of electron transport parameters, avalanche gain, and trigger efficiency. Calibrations with ^{37}Ar gaseous source are complementary and allow W-value and Fano factor extraction.



(a) (b)

Figure 7: (a) Laser calibration system schematic. (b) Gas gain monitoring: (Top panel) pulse amplitude distribution for laser-induced events (Middle/Bottom panel) pulse amplitude distribution for ^{37}Ar events before/after correction derived using laser-induced events [24].

4.3 Gas Purity

Despite using 6N (99.9999% pure) gases, it has been found that the amount of electronegative

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impurities present significantly affects detector performance. This effect is only accentuated for larger detectors or higher pressure operation. For this reason, gas filtering if of paramount importance. While commercial filters, such as getters, have been demonstrated to adequately remove electronegative contaminants, they have also been shown to emit a non-negligible amount of ^{222}Rn. Extensive effort has been undertaken to mitigate this contamination by developing radon removal techniques for the next stage of the experiment in SNOLAB.

5. Simulation Framework

A simulation framework developed in Birmingham [11] can provide further insights. Combining the strengths of Geant4 [26] and Garfield++ [27], and using realistic electric field configurations calculated with Finite Element Method (FEM) software, e.g. ANSYS [28], it enables detailed detector response studies, under different conditions, and accelerates R&D efforts.

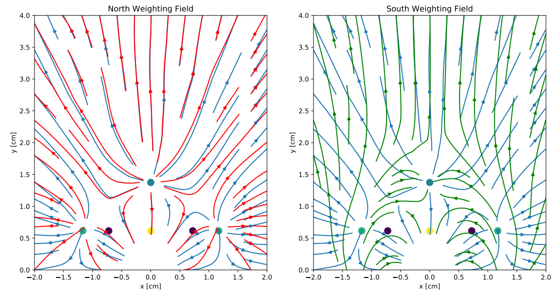

Figure 8: ACHINOS weighting and operating electric fields from simulation [25].

6. Summary and Future Prospects

The spherical proportional counter is a versatile detector offering significant advantages in the search for light DM candidates. Several improvements in the instrumentation, including read-out sensors, gas purification, and laser-based detector calibration systems pave the way for larger active volumes. Currently, a ⌀140 cm detector is being installed in SNOLAB, Canada, by the NEWS-G collaboration. In parallel, the construction of a fully-electroformed underground detector is planned in the context of the Electroformed CUprum Manufacturing Experiment (ECUME).

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