Development of Spherical Proportional Counter for light WIMP search within NEWS-G collaboration

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Abstract
The Spherical gaseous detector (or Spherical Proportional Counter, SPC) has a broad range of applications. In this work, we will focus on the light WIMP Dark Matter particle search, that is, below a few GeV. The NEWS-G collaboration operates a 60 cm diameter detector at Modane underground laboratory (LSM). Running the detector at 3 bars of Neon gas, some competitive limits have been set down to 0.5 GeV WIMP mass thanks to an energy threshold of around 100 eV. To reach better performances, the next generation of SPC (140cm), NEWS-G_SNO, is under construction. We will focus here on the fabrication method, the different low energy calibration methods using 37Ar, neutron and UV laser, on the cleaning methods to remove the surface contamination and mitigation of 210Pb bulk contamination.

Keywords: Dark Matter search, Light WIMP search, Spherical Proportional Counter, Spherical detector

1. Introduction
Dark Matter (DM) is currently seen as an unavoidable piece of the Universe puzzle and is central to a lot of new theories and models of particle physics [1].

The WIMP (Weakly Interacting Massive Particles) Dark Matter is one of the most probable candidate and "WANTED" particle by the DM community. So, the search for WIMP’s is under intense development and relies on the detection of low energy recoils (keV scale) produced by the elastic interaction of WIMPS with the nuclei of the detector. Although the whole possible DM mass range covers 90 order of magnitude, the main focus has been put on the WIMP mass range between few tens and few hundreds of GeV. To cover a large range of masses, many experiments address the search of WIMPs from a few GeV down to few 100 MeV. The presently studied detector, a Spherical Proportional Counter (SPC) -gaseous detector- , initially proposed by I.Giomataris [2], will allow to explore such new parameter space for Dark Matter.

NEWS-G (New Experiments With Spheres - Gas) [3] is a direct DM detection experiment using SPCs to find a signature of DM at the GeV scale. Since low-background, low-energy threshold are keys for their detection, the NEWS-G detectors are fabricated with very radiopure material - mainly copper - and operated at energy threshold below down to single electron detection.

NEWS-G_LSM, a 60 cm diameter SPC installed at Laboratoire Souterrain de Modane (LSM) [4] is under operation since 2012. Thanks to a very low background and an energy threshold of around 100 eV, a 41 days phys run with gas mixture based on Ne and 0.7 % of CH4 at 3 bars allowed to produce a competitive limit on light WIMP searches [5].

A larger and lower activity detector, a 140 cm SPC, NEWS-G_SNO , is being built together with improved compact shielding and will be installed in SNOLAB. Since the fabrication of sphere and lead shield took place in France and to insure that all manufacturing construction parameters have been taken into account, the preliminary test and calibration will be completed at LSM in next months of 2019, and the setup will be operated in late 2019.

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at SNOLAB [6].

Other applications of SPC’s range from radon emanation gas monitoring, neutron flux, gamma counting and spectroscopy, to neutrino physics, double beta decay [7] and coherent neutrino scattering. Expertise in these various applications is shared within the NEWS-G collaboration.

2. Detector description

The SPC consists of a grounded spherical metallic vessel (15 cm to 140 cm in diameter), the cathode, and a small ball (1 mm to 16 mm in diameter), the anode, placed at the centre of the vessel at the end of a grounded metallic rod. A wire connects the anode to the high voltage and the signal is read-out through a capacitor. The electric field varies as $1/r^2$ inside the spherical vessel, where "r" is radius. To compensate the inhomogeneous electric field close to the rod, a second electrode is designed upstream to the ball. More details of recent development and application are given in Ref. [8].

The electrons created in the gas volume drift to the central anode. A few millimetres from the ball, in region of high field, an avalanche occurs and induces the signal (figure 1).

![Figure 1: Principle of operation of spherical gas detector](image1)

**Sensor:** The sensor, main part of the detector, consists of a ball connected to the HV and a second electrode (umbrella) which aims at keeping an homogeneous $1/r^2$ electric field. In figure 2 the evolution of the various sensors fabricated and used in SPC’s. Recently, a multi-ball sensor is under test for new generation of SPC [9].

The main features of the SPC include a very low capacitance, a low energy threshold independent of the volume (down to single ionization electron), a good energy resolution, robustness and a single detection readout channel.

3. Material selection

Copper is the main component of the spherical vessel in the SPCs; it represents more than 90% of the weight and 95% of the detector surface. This is the reason why all of our efforts go to choose ultra radiopure copper, to store it in the underground laboratory between steps of fabrication, to take care of fabrication method and to perform chemical cleaning to reduce all background sources coming from copper surfaces.

**Fabrication:** The NEW-G LSM has been fabricated with NOSV copper, all measurements are referenced in [10]. Concerning the 140 cm diameter, used copper is the commercial Aurubis Oxygen Free Copper C10100. For both detectors, the hemispheres were welded with electron beam not to add extra material. The NEWS-G_SNO will use a compact shield as shown in figure 3.

The ICPMS measurement at PNNL [11] allowed to determine the activity of Uranium and Thorium in copper:

$^{238}\text{U} = 1 - 5 \mu\text{Bq/kg}$

$^{232}\text{Th} = 7 - 25 \mu\text{Bq/kg}$

**Cleaning:** Although the copper was chosen with a very pure quality, it still had a non negligible $^{210}\text{Pb}$ bulk contamination. The activity of $^{210}\text{Pb}$ has been measured to be around 40 mBq/kg, thanks
to an agreement with the XMASS group [12] who developed an alpha spectrometry method using an XIA detector. Through simulations, the measured bulk contaminations has been anticipated to be responsible for 80% of the background in the region of interest for light DM search, below a few keV.

For NEWS-G_LSM, chemical cleaning using nitric acid solution based (resp. 17% and 30%) allowed to reduce the surface contamination by two order of magnitudes [13].

For the NEWS-G_SNO detector vessel, to mitigate impact of contaminations of $^{210}$Pb, $^{210}$Bi betas and X-rays, a 500 $\mu$m pure copper was deposited by electroplating on the inner surface of the two hemispheres before welding. Electropolishing was also performed at beginning to remove the surface layer.

4. Calibrations and results

For the SPC energy calibrations, three calibrations methods were developed.

The volume energy calibration is performed with low energy X rays from $^{37}$Ar gas, made from fast neutron irradiation of $^{40}$Ca in the slowpoke reactor of RMCC [14]. The detector filled with the appropriate target gas then $^{37}$Ar gas, which fills all volume and allows to measure the homogeneity of response of the detector. $^{37}$Ar decays through electron capture with $t_{1/2} = 35$ day, giving $^{37}$Cl, emitting single X rays $X_{\alpha,1}$ of 2.6 keV and $X_{L,3\beta}$ of 260 eV (see figure 4).

A neutron source has been used to calibrate the risetime distribution of low energy events, reflecting the radius distribution of point like energy deposition inside the sphere. Figure 5 shows the rise time spectrum at the lowest [150, 250] eVee energy bin used to set limits on sub-GeV/c$^2$ WIMPs together with the quite good agreement with our modeling of detector response.

Also, thanks to the use of a pulsed 213nm Laser, we developed an original characterization methodology allowing to measure simultaneously the single electron response, the first ionization potential “$w$”, the gain of the detector, the $\theta$ parameter of Polya distribution “$\theta_{Polya}$” and to monitor gain stability within 1%. [15]

Dark Matter search: The result of a Dark Matter search run taken with NEWS-G_LSM (60 cm sphere) and the analysis strategy is presented in this reference [5].

Figure 6 summarizes the already obtained result in the cross section-WIMP mass parameter space together with the projection of the expected results with NEWS-G_SNO, assuming an exposure of 20 kg.d with Ne + 10% CH4 gas mixture, a single electron energy threshold and the anticipated background budget based on simulations.

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Figure 6: Result of NEWS-G, LSM and projection of NEWS-G, SNO sensitivity for WIMP search using Ne + (10%) CH4 gas mixture

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