Spherical Proportional Counter: A review of recent developments

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Abstract. A review of the key developments in the Spherical Proportional Counter is presented. The detector technology and operation principles are described along with results, such as the low-energy calibration, and more recent advances, including the use of resistive materials and a multi-ball readout system. The Spherical Proportional Counter has been utilised by the NEWS-G experiment, performing a direct search for light DM candidates, and a review of the recent results is provided. Prospects for future applications of the technology are also discussed.

1. Introduction

The Spherical Proportional Counter (SPC), was developed in 2006 at CEA Saclay by a group led by I. Giomataris [1, 2]. Originally it aimed at measuring “room” size oscillations of neutrinos from a $^3$H source at its centre [3]. Apart from providing $4\pi$ coverage around the source, a spherical detector has the advantage that it contains the maximum volume for a given surface. Since the majority background in rare event detection experiments originates from the detector surface, such a detector would also maximize the signal to noise ratio.

The first prototypes were realised using decommissioned RF cavities from LEP with a diameter of approximately 1.3 m. The new detector, which has a simple and robust design, demonstrated impressive attributes such as very low energy threshold down to single electron detection, very low electronic noise even for large volumes, read-out through a single channel, and possibility to perform fiducial selections.

The SPC can detect a wide range of radiations including nuclear recoils arising from elastic scattering of an incoming particle on the gas nuclei. This opens an avenue to use the SPC for the direct detection of low mass galactic Dark Matter (DM). A major advantage of the SPC as a light DM detector is the possibility to match the target mass to that of the candidate and, thus, maximise the recoil energy. The NEWS-G experiment [4] employs SPCs to search for DM candidates predicted by a plethora of models in the 100 MeV/$c^2$ to 10 GeV/$c^2$ mass region with an unprecedented sensitivity.
2. The Spherical Proportional Counter

The Spherical Proportional Counter (SPC) is a gaseous detector that is based on the spherical geometry. The detector vessel can be pumped to a high vacuum to remove impurities then be filled with a gas mixture of choice, potentially up to high pressure. The vessel is grounded and acts as the cathode. The anode consists of a small ball, usually made from a metallic or a resistive material, placed in the center of the vessel and supported by a grounded metallic rod, through which the high voltage is applied. A schematic representation of the detector is shown in Figure 1.

The electric field intensity in the detector rapidly varies with the distance from the centre as \(1/r^2\). The difference in the intensity of the electric field, from the outer to the inner radii, divides the detector volume into the drift and the amplification regions. Primary ionization electrons move towards the anode with a drift time that varies from \(\mu s\) to ms depending on the gas mixture and pressure. When these electrons reach a distance of a few millimeters from the anode, the avalanche starts due to the intense electric field. The pulse shape of the signal depends on the spatial distribution of the charge and the distance of the interaction from the anode, because these factors define the spread in arrival time of charges and so the shape of the pulse. A complete description of the SPC, including operation principles, characteristics and capabilities, is given in Ref. [2].

The main advantages of the SPC that make it appropriate for a number of applications are: a) it can be built solely out of radio-pure materials; b) it can sustain high pressure; and c) it allows operation in sealed mode for long periods of time. Below some of these are discussed in more detail.

![Figure 1. A schematic of the Spherical Proportional Counter and the detection principle.](image)

An important advantage offered by a spherical detector is that large volumes can be realised with very low electronic noise. This is a direct result of the small intrinsic capacitance of the detector [5]. In contrast to the parallel plate and cylindrical geometries, where the capacitance scales proportionally to the surface and the length of the detector, respectively, the capacitance in the case of a spherical detector is given by

\[
C = 4\pi\epsilon_0 \frac{r_c r_a}{r_c - r_a}
\]  

(1)
where \( r_c \) is the radius of the outer detector shell and \( r_a \) is the radius of the central anode electrode. For a large volume SPC one has \( r_c \gg r_a \), and the capacitance tends to \( 4\pi\epsilon\epsilon_0 r_a \). As the capacitance is independent of \( r_c \), large volume SPCs can be constructed without a deterioration on the noise characteristics.

![Figure 2](image)

**Figure 2.** Fluorescence peaks observed from the \(^{241}\text{Am}\) radioactive source through aluminum and polypropylene foils. On the left the Carbon (270 eV) line is shown, followed by the Aluminum peak (1.45 keV), the escape peak (E.P.) of Iron in Argon (3.3 keV), the escape peak of Copper in Argon (5 keV), the Iron line (6.4 keV), the Copper line (8 keV) and the Neptunium line (13.93 keV). From Ref. [6, 7]

The SPC can detect low-energy X-rays with a very good energy resolution, better than 10\% (RMS) at 5.9 keV. An example of low-energy X-ray detection is presented in Figure 2, where the fluorescence lines of a series of elements with energies below approximately 15 keV are measured and resolved by a SPC with a diameter of 165 cm. The capability of an SPC to detect single electrons has been demonstrated, as shown in Figure 3. The detection energy threshold is only limited by the \( W \)-value and the primary ionization statistics of the gas mixture used.

The detection energy range varies from a few tens of eV, thanks to operation with high amplification, to tens of MeV, thanks to the large volume and high pressure operation. This permits the detection of low energy photons, electrons, \( \alpha \) particles, neutrons and heavy ions.

Finally, the SPC can readily be fiducialized [8]. The arrival time dispersion of the primary electrons liberated in the detection volume by ionizing radiation results in pulses with different shape characteristics depending on the nature of the interaction. Events with extended energy depositions can be distinguished from those with point-like energy deposition, by applying pulse-shape analysis. In this case a SPC with a diameter of 30 cm is irradiated with an \(^{241}\text{Am-}^9\text{Be}\) source [9]. The recoils induced by the scattering of fast neutrons from the source have a range substantially shorter than the range of the cosmic muons transversing the entire detector. This difference in their interaction with the detector is depicted in the width, the full width at half maximum of the pulse height distribution, of the recorded pulses. Other differences in the characteristics of the interaction can be reflected in other pulse shape parameter such as the difference in the interaction radius which is reflected in different arrival times and, thus on the rise time of the pulse. Such parameters allow the definition of the fiducial region of the detector volume and provide the possibility to reject the background which usually originates from the
Figure 3. Energy deposition spectrum due to photo-electron extraction from the Copper shell of a SPC by irradiating the detector walls through a window with a UV lamp after attenuating the pulse to ensure single electron detection [6, 7].

outer layers of the detector, based only on the ionisation signal.

3. Applications
In this section some of the applications of the SPC are presented.

3.1. Dark Matter Search
The detection efficiency of SPCs for sub-keV nuclear recoils motivated the construction of an apparatus for the direct measurement of low mass galactic DM. These hypothetical particles are predicted by a series of models, the search for which has become much more interesting after the recent bounds set by the LHC and direct detection search for WIMPs of mass over 10 GeV/c².

Still the direct detection of DM particles below 10 GeV/c² is challenging because of the low energy threshold required and the effect of the quenching factor [9] that limit dramatically the efficiency of detectors using heavy elements (Ar, Xe, Ge, etc). For this reason, large, state-of-the-art experiments have a limited sensitivity to candidate masses below a few GeV/c².

The NEWS-G experiment aspires to extend the search for low-mass DM candidates predicted by a plethora of models in the 100 MeV/c² - 10 GeV/c² with an unprecedented sensitivity, employing spherical gaseous detectors specifically optimised for this search. In this versatile detector different gas mixtures can be used as targets, particularly light elements, such as H, He and Ne. These allow for an optimisation of the momentum transfers for interacting low-mass particles which, together with a more favourable quenching factor, make nuclear recoils induced by sub-GeV DM candidates measurable.

SEDINE is a 60 cm in diameter detector already installed and operating at the Laboratoire Souterrain de Modane (LSM), France. The underground laboratory offers approximately 4800 m equivalent water depth to shield from cosmic radiation. SEDINE is further shielded with layers of copper, lead and polyethylene to further reduce background counting rates. The first results of this detector with a Ne gas target were recently published [10].
Figure 4. The width of the pulse versus energy deposition for data taken using an $^{241}$Am-$^9$Be. Two distinct populations are observed corresponding to events with long ionisation tracks, such as those induced by cosmic muons, and to events with a point-like energy deposition, for instance neutron-induced recoils. These are shown in the solid and the dashed boxes, respectively. This distinction in the pulse width (full width at half maximum) allows discrimination of the interaction type.[9].

Data were collected over a period of 42.7 days filled with a gas mixture of Ne + CH$_4$ (0.7%) at 3.1 bars for a total exposure of 9.6 kg·days. Energy calibrations were performed using both an $^{37}$Ar source that produces 270 eV and 2.82 keV x rays and neutrons from an Am-Be source, providing a large sample of nuclear recoils at sub-keV energies [10]. A calibration was also performed during the physics run, using the 8 keV photon from copper fluorescence.

To reject pulses originating from background events at the surface of the sphere, a trigger cut was applied to the rise time of a pulse. Figure 5(b) and Figure 5(a) shows the simulated distribution of surface and volume events in the sphere, respectively, which may be clearly distinguished down to the analysis energy threshold of 150 eV electron equivalent ($eV_{ee}$).

The analysis of the data collected was performed using a Boosted Decision Tree (BDT) [11] to optimise the signal to background discrimination for eight candidate DM masses between 0.5 GeV/$c^2$ and 16 GeV/$c^2$. Considering all events that are remaining after the cuts to be DM candidates, a 90% confidence level upper limit on the spin-independent WIMP-nucleon scattering cross section was derived from Poisson statistics and is presented in Figure 6 [12], along with other state-of-the-art searches. A new limit in the DM candidate mass-cross-section parameter space at 0.6 GeV/$c^2$ was obtained, with a cross-section of $4.4 \times 10^{-37}$ cm$^2$ for a WIMP mass of 0.5 GeV/$c^2$ excluded at the 90% confidence level.

This result is the first in the low-mass Dark Matter candidate search to be produced using a gaseous detector. The detector is currently operating using a helium target. The results obtained with SEDINE are very promising for the main detector of the NEWS-G experiment. It will consist of a 140 cm diameter SPC made of C10100 copper, enclosed in compact shielding and is expected to be installed in SNOLAB, Canada, by the end of 2018. This is expected to
Figure 5. Rise time against energy distribution of $10^6$ simulated events distributed (a) throughout the detector volume and (b) at the detector surface. Events of each type are distinguishable down to the energy threshold. [10]

have lower background rate and larger target mass, which will increase the sensitivity of the experiment by about three orders of magnitude.

3.2. Neutron Spectroscopy
The SPC technology may also be applied to direct spectroscopy of fast neutrons. Such measurements have broad interest, ranging from neutron background estimation to applications in industry. Commercially available gaseous neutron counters are generally filled with either the expensive $^3$He or the toxic BF$_3$ gases [13]. Such detectors are limited by the positive $Q$-values of the neutron interactions which makes them sensitive to both thermal and fast neutrons. As a result, direct fast neutron spectroscopy is challenging without the use of a moderator.

The SPC provides a low cost and robust alternative to these technologies and neutron interactions have been successfully observed using $^3$He [14]. However, the SPC may also be operated using N$_2$, potentially with a small amount of a quenching gas, which is cheaper than the mentioned alternatives and non-toxic. Nitrogen is sensitive to neutrons through two interactions, $^{14}N(n,p)^{14}C$ and $^{14}N(n,a)^{11}B$ which have $Q$-values of 625.9 keV and $-158$ keV, respectively. The negative $Q$-value of the second process allows N$_2$ to be used for direct fast neutron spectroscopy.
Figure 6. Experimental constraints in the WIMP-nucleon cross section vs. WIMP mass plane. The result of the NEWS-G experiment is shown as a dashed purple line, compared to the constraints and signals reported by other experiments. [10]

Measurements of the neutron spectrum of several sources were conducted using a 1.3 m copper sphere filled with N$_2$ with a silicon central electrode [8]. The measured rise time versus energy distribution of neutrons from a $^{252}$Cf source filled with 400 mbar of N$_2$ is shown in Figure 7(a). A clear group of events is seen at 625.8 keV arising due to thermal neutrons interacting via the $^{14}$N\textit{(n,p)}$^{14}$C process, with fast neutrons appearing at higher amplitudes. The fast neutrons are detected through both interactions. Energy depositions below the peak are due to recoils induced by the elastic scattering of fast neutrons.

In Figure 7(b) the rise time versus energy distribution of atmospheric neutrons is shown following a 16-hour data-taking using 500 mbar of N$_2$ The 625.6 keV thermal neutron peak is clearly visible.

![Figure 7](image)

Figure 7. Measured pulse rise time versus amplitude distribution of neutrons interactions using an N$_2$ filled SPC, with (a) neutrons from a $^{252}$Cf source and (b) using atmospheric neutrons [8].
An exciting capability of this detector is the direct detection of fast neutrons, which has been demonstrated using both a $^{252}$Cf and an Am-Be source. Fast neutrons from these sources have energies of several MeV. The spectrum of fast neutrons recorded from the $^{252}$Cf source is shown in Figure 8(a) while the recoil energy spectrum from a Geant4 simulation [15] is shown in Figure 8(b). The features in the measured spectrum that are not observed in the emission energy spectrum are due to the energy dependence of the cross-section for the $^{14}$N(n,a)$^{11}$B interaction [16].

![Figure 8](image)

**Figure 8.** (a) The measured energy spectrum of fast neutrons from a $^{252}$Cf source. (b) The neutron energy spectrum of a $^{252}$Cf source [17]. The characteristics in the measured spectrum are due to the cross-section dependence on energy. [8]

### 3.3. Further Applications

The use of an SPC to study neutrinoless double beta decay, $\beta\beta_{0\nu}$, has been considered through the use of $^{136}$Xe gas. Simulation studies have been performed for a copper sphere with a radius of 37 cm filled with pure $^{136}$Xe at 40 bars, which is equivalent to 50 kg of gas [18]. A liquid scintillator layer surrounding this sphere is used to veto events generated in the copper or surrounding materials. For this detector mass, a background rate of 2 events per year is possible, allowing the detector to be competitive with the current generation of detectors.

The SPC technology also lends itself to neutrino detection through neutrino-nucleus coherent scattering. High pressure SPC operation, together with the cross-section enhancement due to the coherent interaction with all nucleons in the target atom, would allow detection of neutrinos from supernova [19]. For a 6 m diameter sphere filled with Xe at 10 atm with a threshold of 100 eV, one would expect between 300 and 500 events for a supernova.

It has been proposed that a global network of such relatively cheap and stable detectors could be employed to detect neutrinos from supernova explosions [19]. With many interactions in coincidence, a shielding of 100 meters of water equivalent would be sufficient to reduce the background from cosmic muons. Due to the simplicity of the detector, they could be operated by university or secondary school groups, and managed by an international scientific consortium.

### 4. Developments

In this section, recent developments in the geometry and materials used in the design of the central anode and support structures are discussed.
4.1. Resistive Materials

Operation at higher pressures requires a higher bias voltage on the anode to maintain both the detector gain and drift times. However, with the standard sensor design the maximum operating pressure is limited by the voltage which can be achieved without electric discharge occurring between the ball and the support rod. A solution to this problem is the use of resistive materials for a field corrector. The field corrector is mounted between the anode ball and the support rod to reduce the risk of electric discharge. This structure also provides a second electrode, whose voltage \( HV_2 \) may be used to adjust the uniformity electric field. The use of materials with a resistivity in the range \( 10^9 \, \Omega \cdot \text{cm} \) to \( 10^{12} \, \Omega \cdot \text{cm} \) allows for the application of a bias at the surface of the material, which further reduces the risk of electrical discharge, and enables the use of larger bias voltages \( HV_1 \).

![Image of sensor](image1)

**Figure 9.** A sensor, showing the support rod, bakelite field corrector and anode ball.

It has been found that bakelite is ideally suited to this purpose, having a measured resistivity of the order \( 10^{12} \, \Omega \cdot \text{cm} \). Figure 9 shows the design of the sensor, including the bakelite field corrector. In the standard sensor arrangement, the electric field in the hemisphere containing the support rod is distorted from the ideal \( 1/r^2 \) dependence. Such a distortion causes the same signals generated by events in the different hemispheres to have different characteristics. Through the application of a voltage \( HV_2 \) on the surface of the bakelite, the shape of the electric field may be recovered to some extent, as shown in Figure 10.

![Image of electric field contours](image2)

**Figure 10.** Calculated electric field contours surrounding the anode ball of a sensor with a bakelite field corrector in the case where (a) no voltage is applied on the surface of the field corrector and (b) a voltage is applied to the surface of the field corrector.
### 4.2. The multiball structure: ACHINOS

In the case where the radius of the central anode $r_a$ is very much less than the radius of the detector $r_c$, the radial electric field $E(r)$ in the volume may be approximated as

$$E(r) \approx \frac{V_0}{r^2} r_a,$$

(2)

where $V_0$ is the bias of the central anode. This proves challenging for larger detectors or operation at pressures greater than a few bar. The drift time of primary ionization particles depends on the electric field and gas pressure, however, for large radial distances the magnitude of the electric field can become very low. To compensate for this the radius of the anode ball could be increased. If a larger central anode is used, then a significantly higher bias voltage is required to maintain the same gain at the surface of the anode, which greatly increases the probability of electronic discharge to the supporting structures. Similarly, for higher pressures a smaller anode ball is required to maintain the same gain, however, this reduces the electric field at large radii.

A solution to this problem is the use of a multiball structure, called ACHINOS, to replace the single anode ball [20]. Such a structure comprises a central resistive sphere with smaller anode balls projected from this in a regular pattern and is presented in Figure 11(a). The anode balls are placed at a constant distance from the central sphere so that they lie on the surface of a virtual sphere with larger radius than central sphere. A high voltage $HV_1$ is applied to the individual anode balls through kapton insulated wires joining them to the central sphere. A high voltage $HV_2$ may also be applied on the surface of the central sphere, such that it optimises the electric field configuration. Signals may be either read out from each high voltage wire individually or by connecting all wires together. The former creates a spherical Time Projection Chamber (TPC), allowing 3D capability.

In Figure 11(b) the calculated electric field of a 2 mm anode ball sensor placed inside a shell of diameter 300 mm is compared to that of ACHINOS structures with 5, 11 and 33 anode balls, as calculated from a COMSOL simulation. The anode balls of the ACHINOS structure are distributed over a virtual sphere of 41 mm in diameter. The magnitude of the electric field at the surface of the shell is approximately 9 times higher for the 11-ball ACHINOS structure than the single ball structure.

![Design of 11-ball ACHINOS structure with anode balls located at the faces of a regular polyhedron (in this case a pentagonal dodecahedron).](a)

![The calculated Electric field as a function of radius for a standard 2 mm ball anode at HV$_1$ 2015 V, and 5, 11 and 33 ball ACHINOS sensors, with the anode balls at HV$_1$ 2015 V.](b)

**Figure 11.** (a) Design of 11-ball ACHINOS structure with anode balls located at the faces of a regular polyhedron (in this case a pentagonal dodecahedron). (b) The calculated Electric field as a function of radius for a standard 2 mm ball anode at HV$_1$ 2015 V, and 5, 11 and 33 ball ACHINOS sensors, with the anode balls at HV$_1$ 2015 V. [20]
Several prototypes of the ACHINOS structure have been constructed and tested. Figure 12 shows a comparison of the rise time versus amplitude distribution of a single 2 mm ball anode and an 11-ball ACHINOS structure with 2 mm anode balls, with the anode balls in each case being set at HV$_1$ = 2015 V. Thanks to the strong electric field at larger radii, the width of the rise time distribution of the ACHINOS sensor is 1.1 $\mu$s, much narrower than the distribution of 9.6 $\mu$s for the single ball anode.

![Figure 12](image)

**Figure 12.** The rise time as a function of amplitude (a) for a standard 2 mm single ball anode at HV$_1$ 2015 V and (b) for an 11-ball ACHINOS structure with each 2 mm ball at HV$_1$ 2015 V. [20]

5. **Summary**

The design and operation principles of the SPC are presented, along with demonstrations of the response to low energy X-rays and single electrons. Recent developments in the design of the support structure of the central anode improve the uniformity of the electric field around the anode and reduce the occurrence of electrical discharges. This is achieved through the use of a bakelite structure below the anode, which permits operation of the SPC at higher gas pressures. A second design of sensor using multiple anode balls situated symmetrically about a central structure goes further by allowing a larger central structure, and so increasing the magnitude of the electric field at large radii, while also maintaining the size of each individual anode spheres, ensuring that the same gain as a single anode structure may be achieved for the same applied voltage. The capability to individual read out of the anode balls would allow TPC-like operation with 3D track reconstruction.

Applications of the SPC are discussed, particularly the ability of the detector to directly detect fast neutrons and its use in direct DM searches. The first results of a direct DM search using an SPC based in LSM established a new upper limit on the spin-independent WIMP-nucleon scattering cross-section at the 90% confidence level of $4.4 \times 10^{-37}$ cm$^2$ for a WIMP mass of 0.5 GeV/$c^2$. A forthcoming DM search using a helium based target gas will be a better kinematic match for low mass DM candidates, and should increase the sensitivity of the detector in the sub-GeV range. The detector with a diameter of 140 cm, to be installed at SNOLAB near the end of 2018 at SNOLAB, is expected to improve the sensitivity by three orders of magnitude.
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