Development of a Simulation Framework for Spherical Proportional Counters

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Introduction to Spherical Proportional Counters

The Spherical Proportional Counter (2008 JINST 3 P09007) is a novel gaseous detector with a range of applications:

- Direct low-mass dark matter detection (NEWS-G): Astropart. Phys. 97 (2018) 54
- Neutrinoless double beta-decay (R2D2): 2018 JINST 13 P01009
- Neutron, alpha and gamma ray spectroscopy: Nucl. Instrum. Meth. A 847 (2017) 10
- Low energy neutrino physics: Nucl. Instrum. Meth. A 530 (2004) 330
  Phys. Lett. B 634 (2006) 23
  Phys. Rev. D 79 (2009) 113001

Review of spherical proportional counters: J. Phys. Conf. Ser. 1029 (2018) 012006
Why Spherical Proportional Counters?

Advantages of spherical shape:
- Low capacitance independent of detector size
- High pressure operation
- Maximum volume-to-surface ratio

Additional benefits:
- Simple and robust design
- Flexibility of gas mixtures
- Determination of interaction properties from pulse-shape analysis
Single-Anode Sensor

Single anode at centre of detector, supported by grounded rod

➢ Radial electric field $\propto \frac{1}{r^2}$
➢ Single readout channel

Use a correction electrode to reduce distortion of the electric field by the wire and rod

➢ Sensor optimisation is a focus of development:

2018 JINST 13 P11006
Multi-Anode Sensor: ACHINOS

Operation of large and high pressure detectors are a challenge with the single-anode

➢ Electric field in drift and avalanche regions are linked

ACHINOS - Multiple anodes, placed at equal distances:

2017 JINST 12 P12031

➢ Gain influenced by individual anode sizes
➢ Large-radius electric field determined by collective field of all anodes

Drift and avalanche electric fields are decoupled

Also enables individual anode read-out

➢ Position information of interactions
Simulation Software

Simulations are crucial for detector development

➢ Began development of a purely Garfield++ simulation Summer 2018
➢ Soon after integrated this into a Geant4 application

Use several software toolkits:

➢ Geant4 for the simulation of primary ionisation
➢ Garfield++ for the simulation of electron-ion drift and signal calculation, interfacing:
  ● Heed to aid in simulating primary particle interactions
  ● ANSYS, a finite-element-method software, to model the electric field
  ● Magboltz to model electron transport parameters in gas mixtures

Approach was inspired by recent developments:

Nucl. Instrum. Meth. A 935 (2019) 121
Simulation Framework: Overview

Geant4 application which interfaces Garfield++ in two stages:

A: Primary ionisation, and electron transport and multiplication
   ➢ Implemented a custom model using Geant4 physics parameterisation

B: Signal formation
   ➢ end-of-event-action method enhanced with Garfield++ functionality

Pass information from A to B using Geant4 sensitive detectors
Simulation Framework: Primary Ionisation

Event Flow

Primary Ionisation

- Detector is initialised and initial particle is generated in Geant4
- Geant4 tracks particles and interactions
- Electrons with kinetic energy <2 keV are passed to Garfield++
- Heed calculates further ionisation
- Using the electron transport parameters, ionisation electrons are transported up to the avalanche region
- Electron multiplication is simulated
- Ions and electrons produced in avalanche drift in electric field, and induced electric current is calculated
- Signal is processed through electronics module to form pulse

Electron transport and multiplication

Signal Formation

Ions handled by SRIM - Recently Added

Example: 5.9 keV X-rays from decay of $^{55}$Fe

$\lambda_{\text{fit}} = 7.75 \pm 0.18 \text{ cm}$

$\lambda_{\text{XCOM}} = 7.83 \text{ cm}$
Simulation Framework: Electron Transport and Multiplication

Event Flow

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Drift of ionisation electrons:
- Garfield++ Monte Carlo drift line method
- ANSYS electric field maps
- Magboltz electron transport parameters

Electron multiplication:
- Garfield++ microscopic avalanche or our custom avalanche method
Following multiplication, electron-ion pairs are transported using the Garfield++ drift line RKF method.

Calculate induced signal with Garfield++ sensor objects
- Shockley-Ramo theorem

Calculate readout pulse in custom electronics module
- Applies transfer function to induced current via a fast Fourier transform

Example: simple charge sensitive amplifier with 140μs time constant
Simulation Framework: Custom Electron Multiplication

Microscopic tracking models multiplication down to individual electron-atom collisions

➢ Most precise method, but costly to compute

Electron multiplication follows a Polya distribution:

\[
P\left(\frac{G}{\bar{G}}\right) = \left(1 + \theta\right)\frac{G}{\bar{G}}\right)^\theta \exp\left[-\left(1 + \theta\right)\frac{G}{\bar{G}}\right]
\]

Parameterise gain in custom method:

➢ Numerically integrate effective townsend co-efficient to get \(\bar{G}\)

\[
\bar{G} = \exp\left[\int_{\vec{r}} \left(\alpha(\vec{r}) - \eta(\vec{r})\right) d\vec{r}\right]
\]

➢ Estimate \(\theta\) using microscopic avalanche - approximately independent with position of avalanche

![Graph](https://example.com/graph.png)

- Cathode: 15 cm radius
- Anode: 1 mm radius; 1430 V
- Ar:CH\(_4\) (98%:2%); 300 mbar

- Microscopic avalanche
- Polya fit

\[\bar{G} = 326 \pm 1\]
\[\theta = 0.256 \pm 0.006\]
Physics of simulation demonstrated by comparing gas mixtures:

- Gain in He:Ne:CH$_4$ larger than that in Ne:CH$_4$, determined by Townsend and attachment coefficients

- Gain fluctuations shown by variation in pulse amplitude

- Differences in electron drift velocity determine start time of pulses
Use simulation to measure effect of anode support structure on detector response:

- Detect 5.9 keV line of $^{55}$Fe and a 2.9 keV argon escape peak
- Response is homogenous with $\theta$ for ideal electric field
- Response depends on $\theta$ for single anode configuration
Simulation can be used for particle identification:

- Cosmic muons may mask interaction of $^{55}$Fe X-rays
- Ionisation profiles are different - pulse-shape analysis informs selections to suppress backgrounds
Developing ACHINOS simulation to have multiple read-outs

➢ Separate anodes into two hemispheres
  ● 5 Anodes near the rod; 6 anodes far from rod

➢ Calculate two separate signals
  ● One signal per hemisphere

➢ Calculate weighting fields with ANSYS

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Application: ACHINOS Simulation

➢ Majority of pulse for events in hemisphere away from rod is formed on far anodes
  - Negative pulse on near anodes

➢ See opposite effect for events in hemisphere near bar

➢ Electrons produced from the side drift to far hemisphere

➢ Use asymmetry to discern which hemisphere the interaction occurred

Pulse asymmetry:
\[ A = \frac{F - N}{F + N} \]

➢ F = amplitude of pulse on far anodes
➢ N = amplitude of pulse on near anodes
Ionisation electrons produced in events at edge of detector drift longer than electrons near the centre:

- Using ACHINOS in single read-out mode, simulate 2.82 keV electrons from the decay of $^{37}$Ar

- Events at large radii have increased rise-times (time for a pulse to go 10% to 90% of its amplitude)

- Use rise-time relationship to reconstruct interaction radius

- Majority of background for rare events searches originate at detector surface
Application: Fast Neutron Spectroscopy

Neutron spectroscopy with Spherical Proportional Counter

- Use Nitrogen as gas
- \(^{14}\text{N} + n \rightarrow ^{14}\text{C} + p + 625\text{ keV}\)
- \(^{14}\text{N} + n \rightarrow ^{11}\text{B} + \alpha - 159\text{ keV}\)

Simulation Parameters:
- Ø vessel 30 cm
- Nitrogen at 300 mbar
- Anode Ø 2 mm

Neutron Beam

4 MeV
Application: R2D2 Collaboration

R2D2 (Rare Decays with Radial Detectors) collaboration (website):

➢ R&D for $0\nu\beta\beta$ experiment with $^{136}\text{Xe}$

➢ Validate detector using 5.3 MeV $\alpha$-decays of $^{210}\text{Po}$
Conclusions

Developed a flexible and predictive framework for simulating spherical proportional counters
➢ Combines the strengths of Geant4 and Garfield++ toolkits
➢ Accelerates detector R&D, experimental design, and physics analysis
➢ Details in the recent publication: 2020 *JINST* **15** C06013

Next steps:
➢ Study in more detail the space charge effects
  ● Preliminary studies already performed
➢ Apply simulation method to micropattern gaseous detectors
➢ Improve user interface to facilitate its wider use by the community

Thank you for the invitation to speak today - we look forward to giving updates in the future!