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

- Neutrinoless double beta-decay (R2D2): 2018 JINST 13 P01009


Principle of operation
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 $\propto 1/r^2$
➢ 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

Ideal

Optimised
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
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:


Development of a simulation framework for spherical proportional counters


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ABSTRACT: The spherical proportional counter is a novel gaseous detector with numerous applications, including direct dark matter searches and neutron spectroscopy. The strengths of the Geant4 and Garfield++ toolkits are combined to create a simulation framework for spherical proportional counters. The interface is implemented by introducing Garfield++ classes within a Geant4 application. Simulated muon, electron, and photon signals are presented, and the effects of gas mixture composition and anode support structure on detector response are discussed.

Simulation framework discussed today:

2020 JINST 15 C06013
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**

- 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

**Primary Ionisation**

- Example: 5.9 keV X-rays from decay of $^{55}$Fe
  - Attenuation length in agreement with XCOM

**Electron transport and multiplication**

- Ions handled by SRIM - Recently Added

![Graph showing cathode, anode, and position of interaction with events vs. position](image)
Simulation Framework: Electron Transport and Multiplication

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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
Simulation Framework: Signal Formation

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

Parameterise gain in custom method:
➢ Numerically integrate effective Townsend coefficient to get \( \bar{G} \)
\[
\bar{G} = \exp \left[ \int \left( \alpha(r) - \eta(r) \right) d\vec{r} \right]
\]
➢ Estimate \( \theta \) using microscopic avalanche - approximately independent with position of avalanche

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

- Microscopic avalanche
- Polya fit
\( \bar{G} = 326 \pm 1 \)
\( \theta = 0.256 \pm 0.006 \)
Application: Effect of Gas Mixture

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
Application: ACHINOS Simulation

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
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
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 $^{210}\text{Po}$

Simulation of Spherical Proportional Counters

R. Ward (University of Birmingham) 25th June 2020
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!