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Towards efficient neutron spectroscopy with a Nitrogen-filled Spherical Proportional Counter

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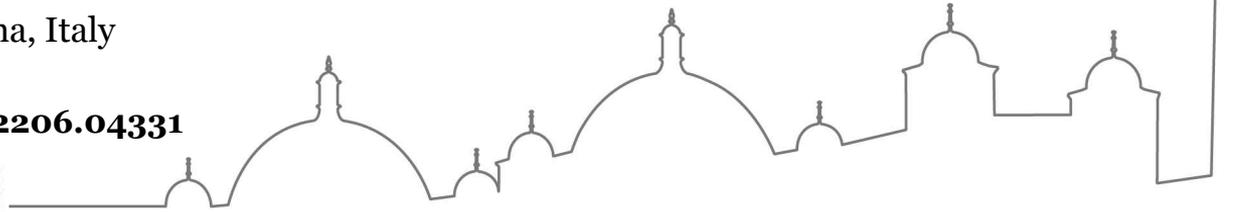
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41th International Conference on High Energy Physics (ICHEP 2022)

7/7/2022, Bologna, Italy

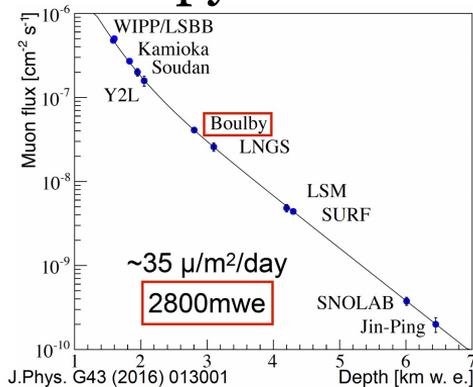
arXiv pre-print: [2206.04331](https://arxiv.org/abs/2206.04331)



This research has been funded by the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Grant Agreements No 845168 (neutronSphere), No 841261 (DarkSphere) and No 101026519 (GaGARin).

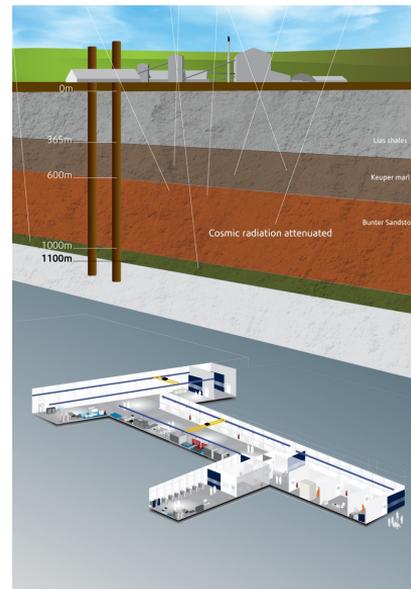


Neutron spectroscopy with the Spherical Proportional Counter



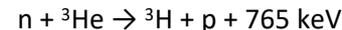
Dark matter underground experiments

- MeV neutrons mimic WIMP signals in the region of interest for Dark Matter detection
 - Sources: Radioactivity of cavern, muon induced hadronic and electromagnetic showers (cosmic rays)
 - Elastic scattering with target nuclei of gas, interaction with detector material
- Neutron rejection: shielding and use of high-purity materials.
- Data analysis require an estimation of the neutron background expected in order to compare with the observed number of events.



Current neutron detector status

^3He proportional counters



- ✓ Efficient for thermal and fast neutrons, low efficiency in γ -rays
- ✗ Wall effect \rightarrow high pressure (impractical)
 ^3He extremely expensive

The Spherical Proportional Counter

Electric field scales as $1/r^2$

- Divided into “drift” and “amplification” regions

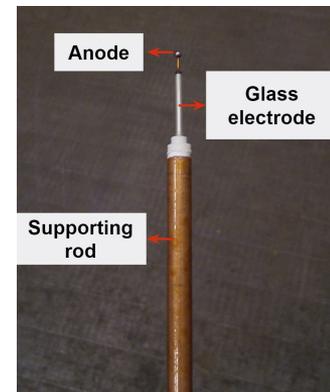
$$\vec{E} = \frac{V_1}{r^2} \frac{r_c r_a}{r_c - r_a} \hat{r} \approx \frac{V_1}{r^2} r_a$$

Capacitance independent of detector size

- Low electronic noise

$$C = 4\pi\epsilon_0 \frac{r_c r_a}{r_c - r_a} \approx 4\pi\epsilon_0 r_a \sim 1\text{pF}$$

- Large gain - Single e^- threshold
- Maximum volume-to-surface ratio
- High pressure operation
- Simple, robust design with a flexibility in target gas
- Applications in n-spectroscopy to DM!



r_c = cathode radius
 r_a = anode radius

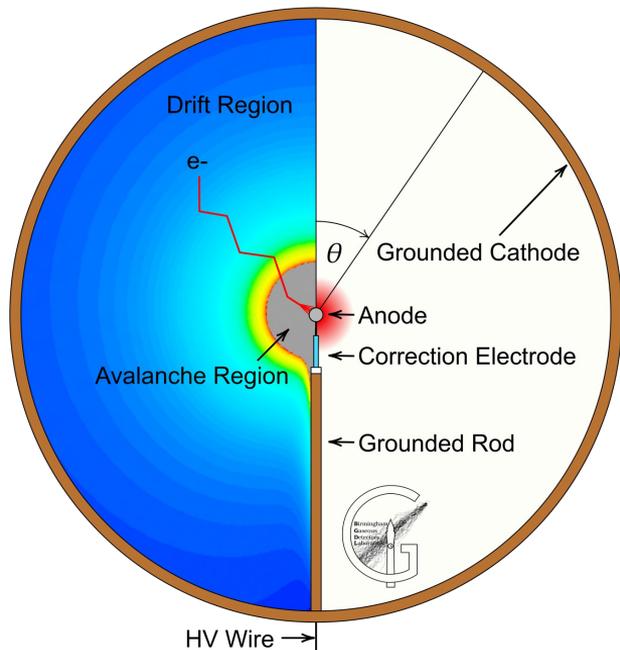


[10.1016/j.astropartphys.2017.10.009](https://doi.org/10.1016/j.astropartphys.2017.10.009)

More about SPC in ICHEP

K. Nikolopoulos → Dark matter session (9/7 @10:20)

R. Ward → Neutrino Physics session (9/7 @16:15)



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[I.Giomataris et al, JINST, 2008, P09007](#)

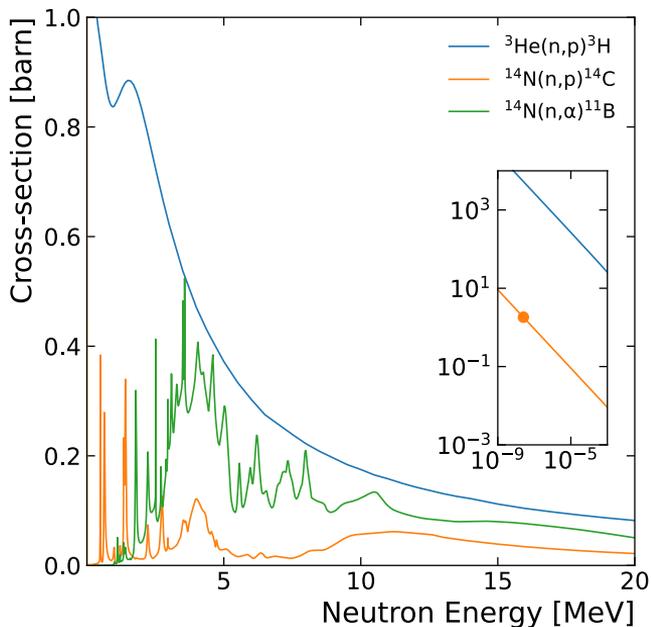
[I.Katsioulas et al, JINST, 13, 2018, no.11, P11006](#)

Neutron detection with the Spherical Proportional Counter



- ✓ Non-toxic
- ✓ Non-flammable
- ✓ Simple and robust setup
- ✓ Easy deployment and operation
- ✓ Cost efficient

- ✓ Wall effect suppressed due to higher atomic number of N₂ relative to ³He → lower pressure
- ✓ Good efficiency in detecting thermal neutrons in large volumes
- ✓ Low γ-ray efficiency
- ✓ Spectroscopic measurement of neutrons



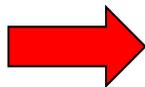
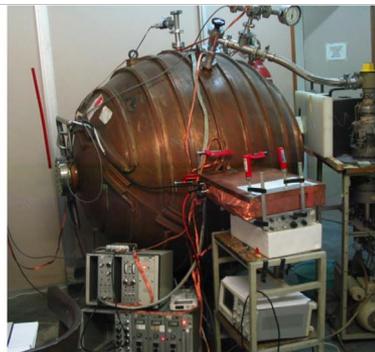
Nitrogen as target

$^{14}\text{N} + n \rightarrow ^{14}\text{C} + p + 625 \text{ keV}, \sigma_{\text{th}} = 1.83 \text{ b}$

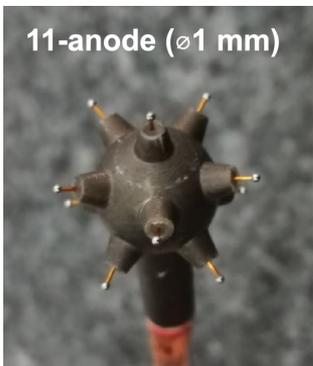
$^{14}\text{N} + n \rightarrow ^{11}\text{B} + \alpha - 159 \text{ keV}, \text{thres} = 1.7 \text{ MeV}$

Neutron detection with the Spherical Proportional Counter

Proof of principle



Instrumentation advancements



Limiting Factors:

- Wall effect (i.e. recoiling particle escape the active volume)
- Sparking/Stability
- Low pressure operation (up to 0.5 bar)
- Impurities
- Charge collection efficiency

Bougamont, E et al (2017). NIM A, 847, 10–14

i.manthos@bham.ac.uk - ICHEP 2022

Multi anode **ACHINOS** sensor

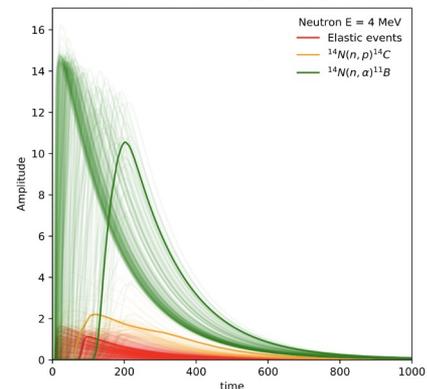
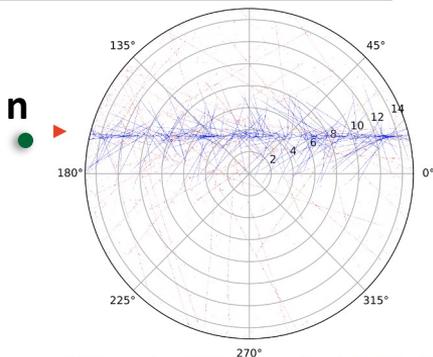
- Decouples drift and amplification fields
 - Small anode size → high gain
 - More anodes → Efficient charge collection
- Allows for increased target mass
 - Larger volume
 - Higher pressure
- Improves detector fiducialisation

I. Katsioulas et al. 2018 JINST 13 P11005

I. Giomataris et al 2020 JINST 15 P11023

UoB simulation framework

Fast n



I. Katsioulas et al 2020 JINST 15 C06013

The Graphite stack @ University of Birmingham



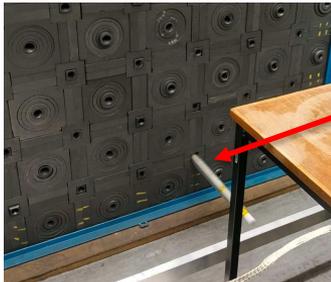
Investigate the capability of the SPC to detect fast neutrons and neutrons thermalized by the graphite.

Spherical Proportional Counter

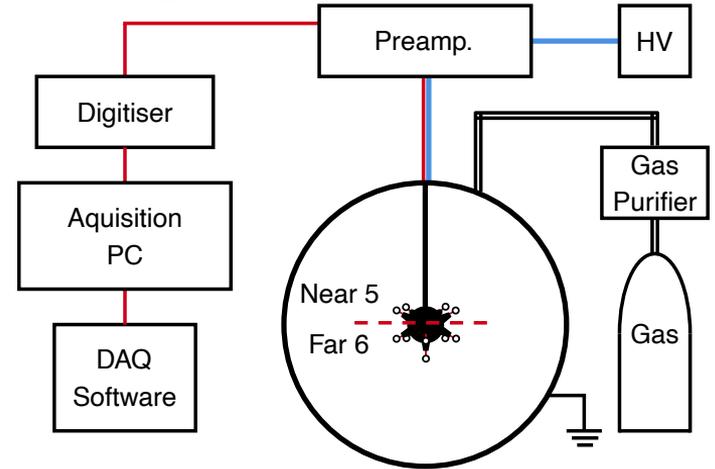
- 30 cm \emptyset
- N₂ gas filling

Multi-anode sensor

- 11 anodes
- 1mm \emptyset
- Reading in 2 channels (near – far)



²⁴¹Am⁹Be neutron source
A = 2.6 x 10⁶ Bq

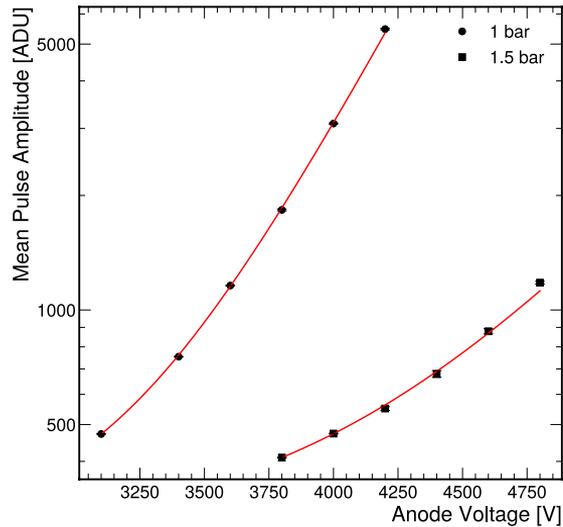


- Calibration measurements
- Thermal and fast neutrons at 1 bar and [3.6, 4.2] kV bias
- Thermal and fast neutrons at 1.5 bar and 4.5 kV bias
- Thermal neutrons at 1.8 bar and 6 kV bias

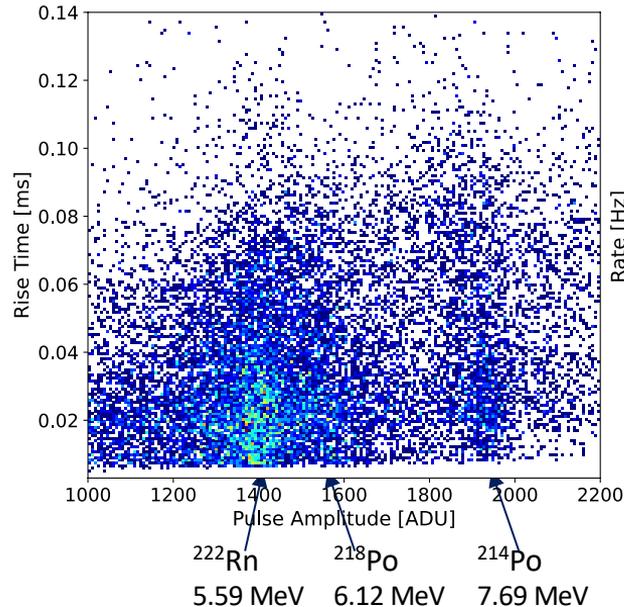
Neutron measurements with the Spherical Proportional Counter

Calibration of the detector

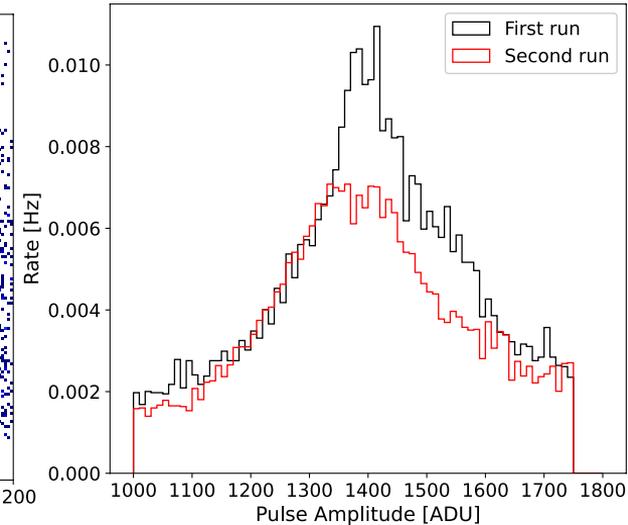
- Amplitude curve
 ^{210}Po source (alpha 5.30 MeV)
 1 and 1.5 bar N_2



- Getter filter emits ^{222}Rn ,
 Radon decay chain used
 for calibration

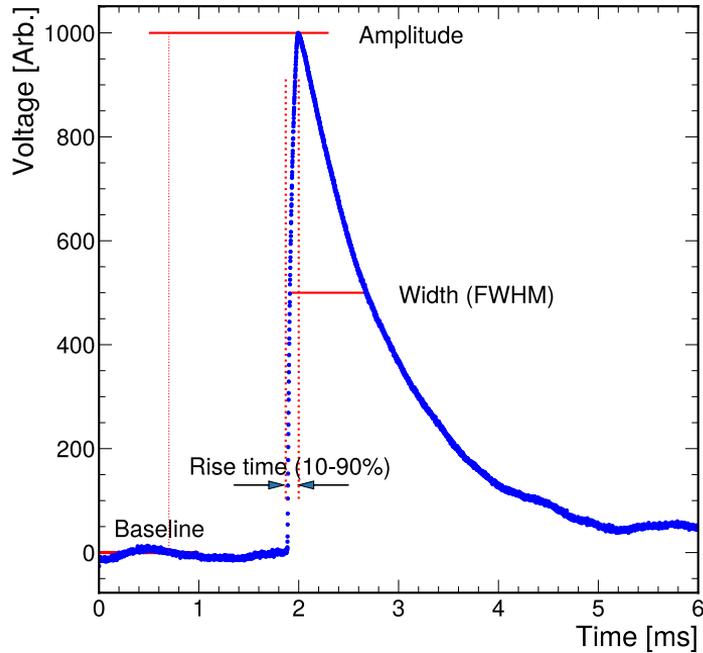


- Confirm Radon decay
 rate with 3% accuracy
 (half-life ~ 3.8 days)



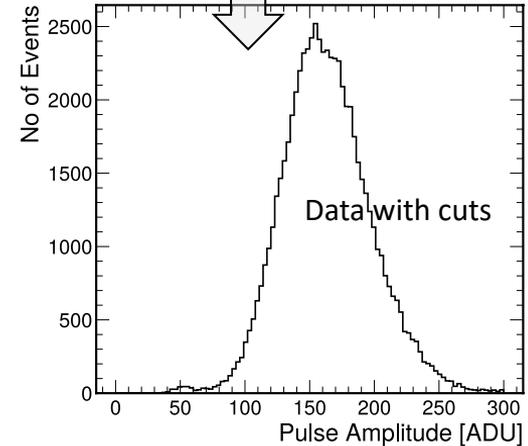
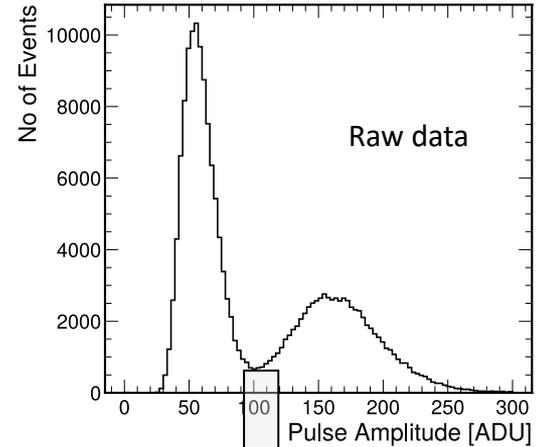
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Neutron measurements with the Spherical Proportional Counter



Pulse shape analysis parameters:

- Rise time (10-90%)
- Width (FWHM)
- Fall time (exponential fit)
- FWHM/Amplitude
- Integral
- Baseline



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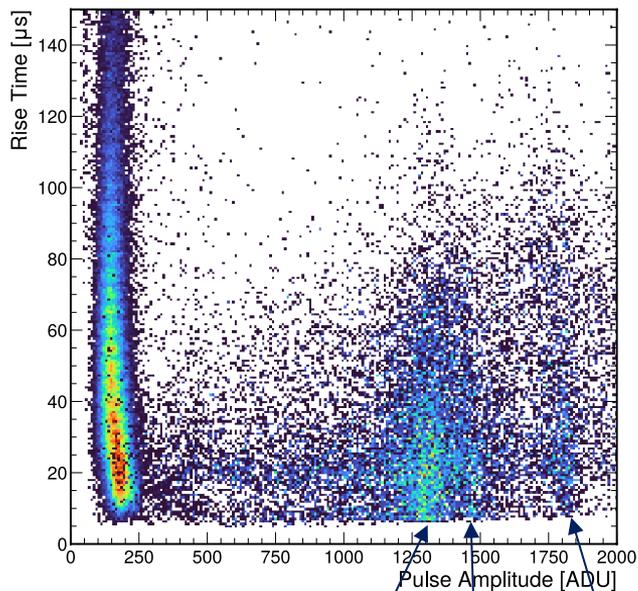
Neutron measurements with the Spherical Proportional Counter

$^{241}\text{Am}^9\text{Be}$ neutron source

1 bar N_2 , 3.6 kV

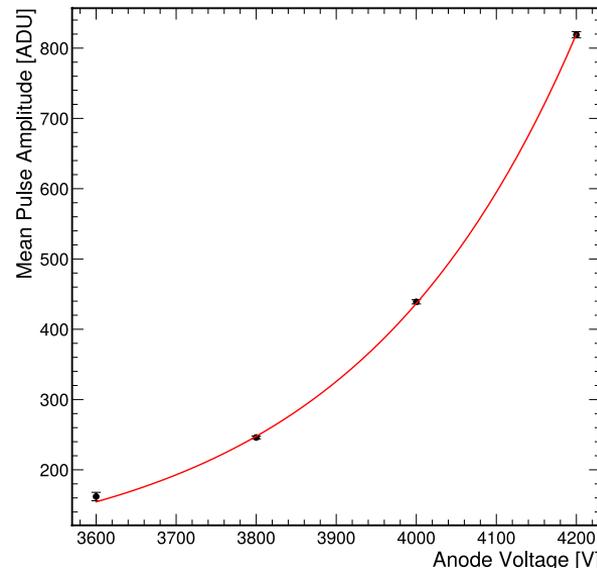
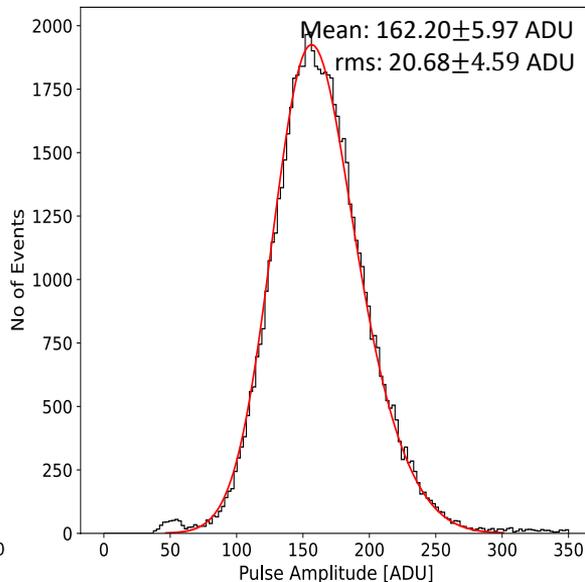
Response to thermal neutrons

- Thermal neutrons peak follows exponential form for various anode voltages at 1 bar N_2



Rn decay chain peaks
confirm thermal peak

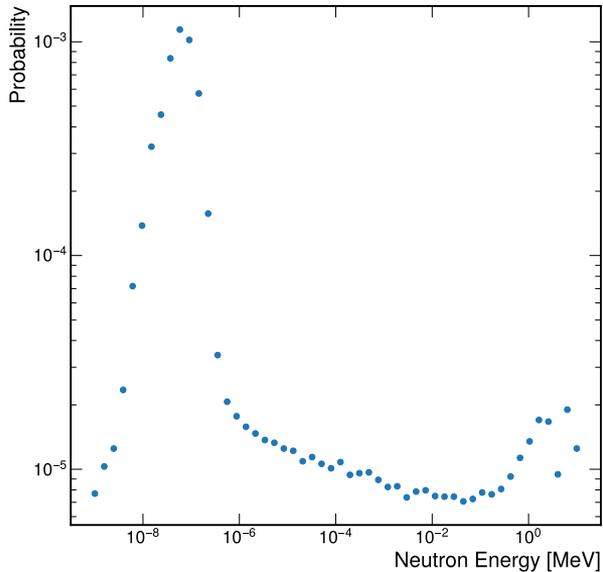
^{222}Rn	^{218}Po	^{214}Po
5.59 MeV	6.12 MeV	7.69 MeV



Thermal peak correspond to 625 keV recoil energy ($^{14}\text{N} + n \rightarrow ^{14}\text{C} + p + 625 \text{ keV}$)

Simulation of the detector response

- **Simulation study (MCNP 6.1):** Probability of each neutron to reach detector volume after thermalized in graphite stack ($\sim 5 \times 10^{-3}$)



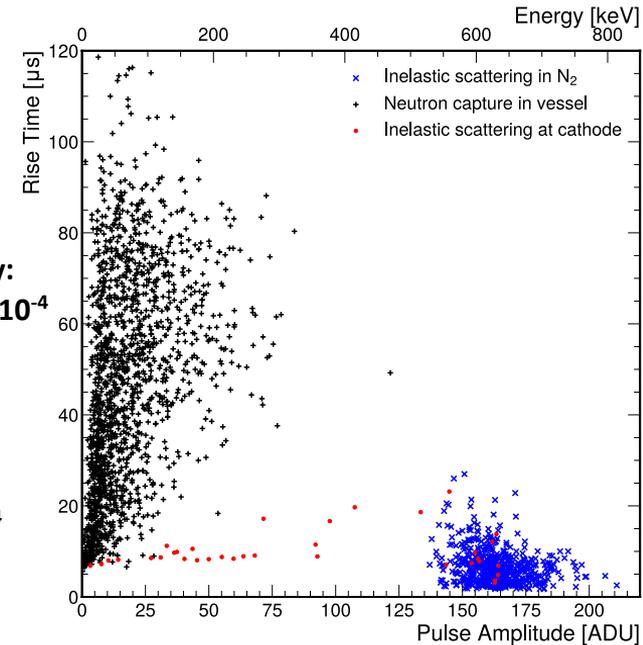
- Source activity: 2.6 MBq
- Probability to reach detector volume $\sim 5 \times 10^{-3}$
- Detection rate: ~ 5 Hz

Efficiency:
 $\sim 3.7 \times 10^{-4}$

Simulation results

Efficiency:
 2.2×10^{-4}

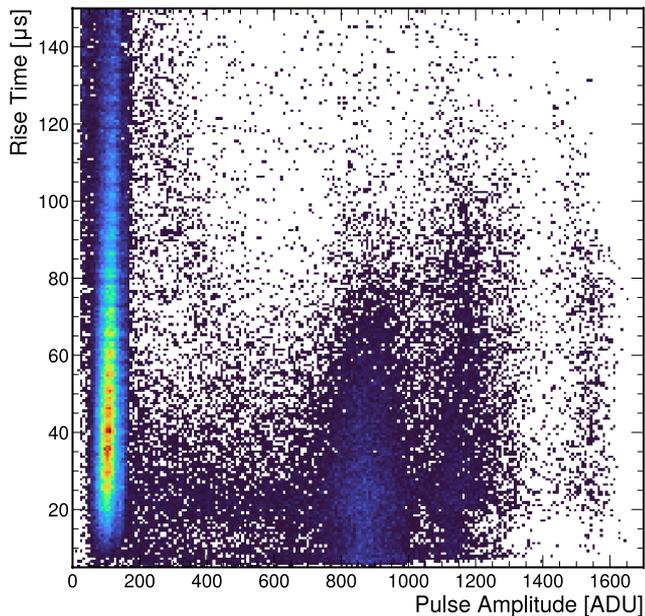
- Detector response to thermal neutrons with 1 bar N_2 and 3.6 kV bias voltage



Neutron measurements with the Spherical Proportional Counter

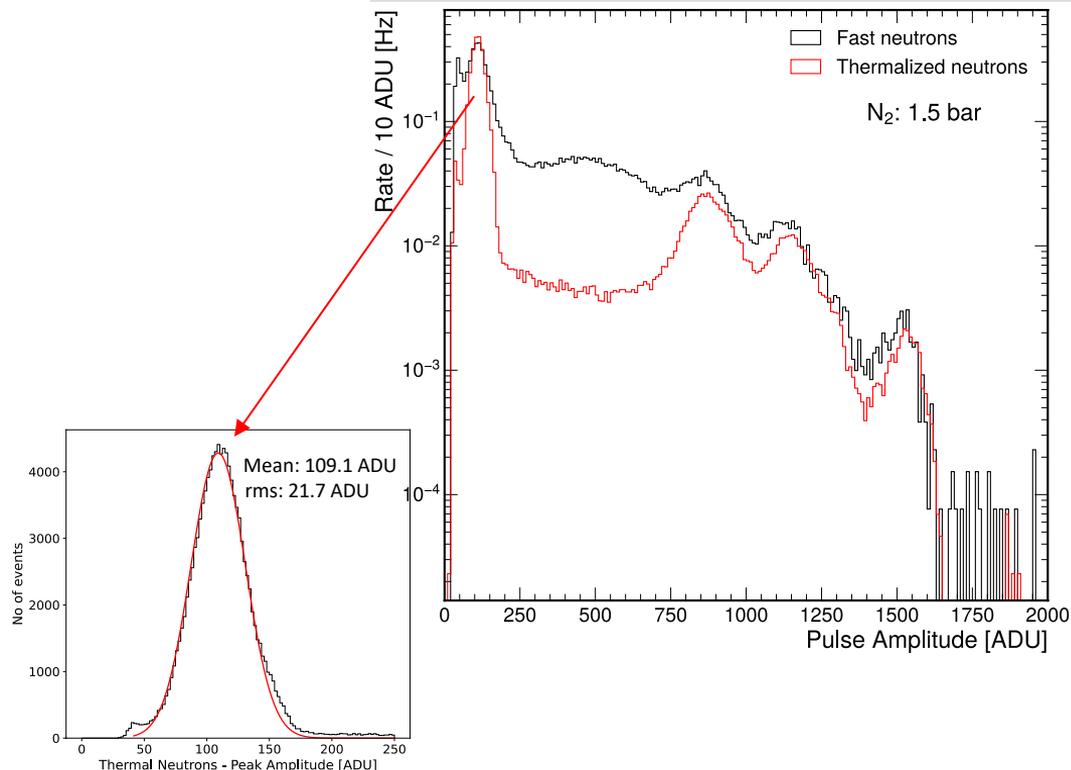
$^{241}\text{Am}^9\text{Be}$ neutron source

1.5 bar N_2 , 4.5 kV



Confirmation of thermal neutrons peak from ^{222}Rn decay peaks

- Detection of thermal and fast neutrons

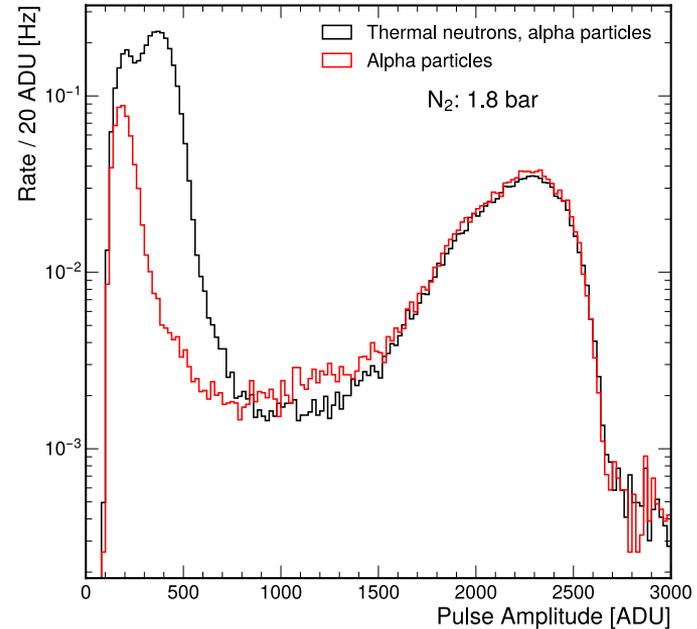
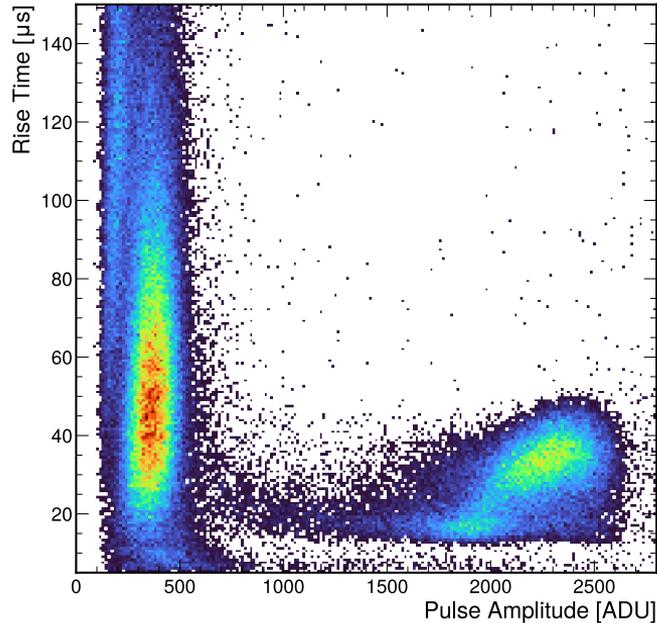


Neutron measurements with the Spherical Proportional Counter

$^{241}\text{Am}^9\text{Be}$ neutron source

1.8 bar N_2 , 6 kV

Thermal neutrons detection



^{210}Po alpha (5.30 MeV) sample, inside the detector → energy reference

Neutron measurements at MC40 cyclotron

Spectroscopic measurement of fast neutrons

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^9Be target on deuterium beamline

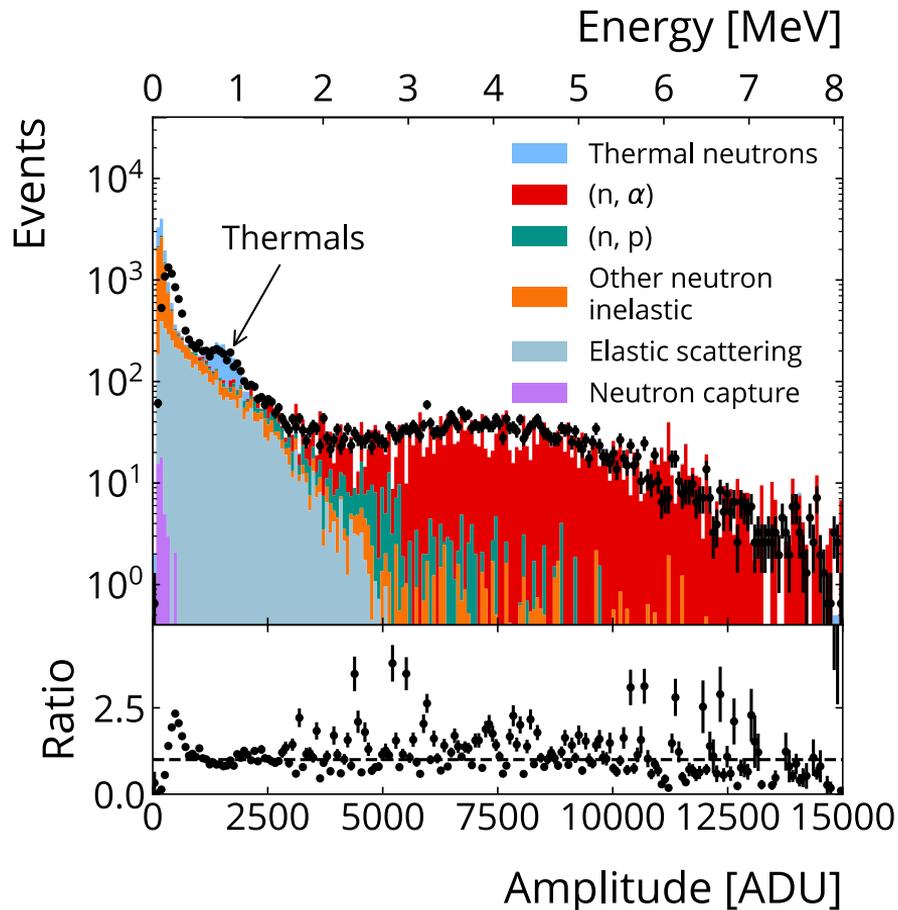
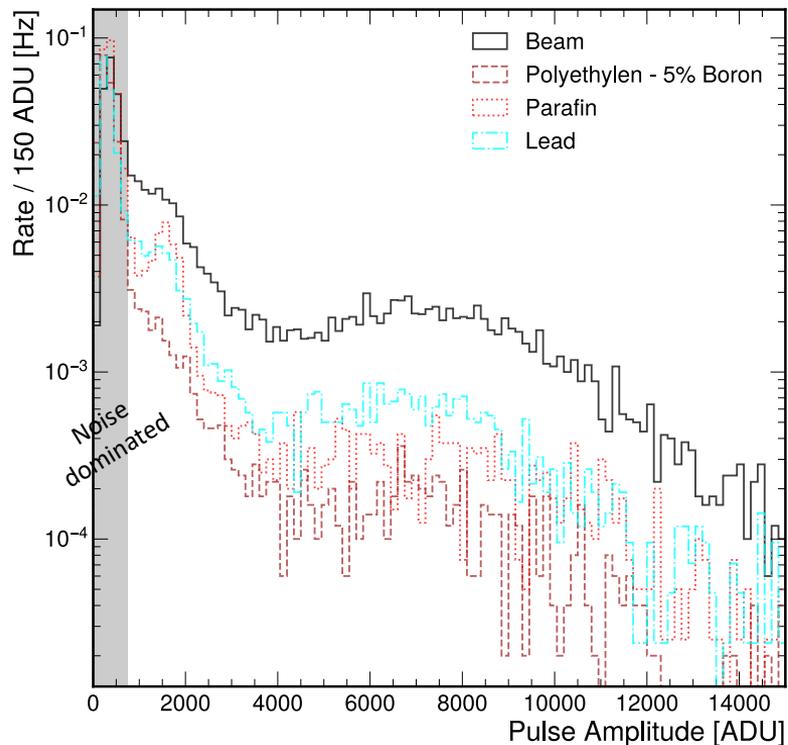
- 5.90 ± 0.08 MeV deuterons
- $^9\text{Be}(d,n)$ reaction
- Same detector setup
- Moderators used to study neutron detection (paraffin, Polyethylene +5% Boron, lead)



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Neutron measurements at MC40 cyclotron

Spectroscopic measurement of fast neutrons



Neutron measurements at the Boulby Underground Laboratory

- Underground facility 1100 m under surface, North Yorkshire (UK)
- Instrumentation R&D and neutron measurements at controlled environment
- 30cm Ø Spherical Proportional Counter installed and operating
- ^{252}Cf neutron source available
- Measurements and analysis ongoing

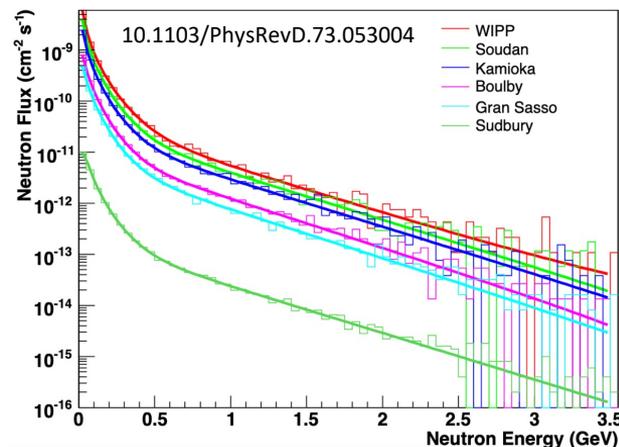


Boulby Underground Laboratory



Expected thermalized neutron background flux with 2 bar N_2 filling with...

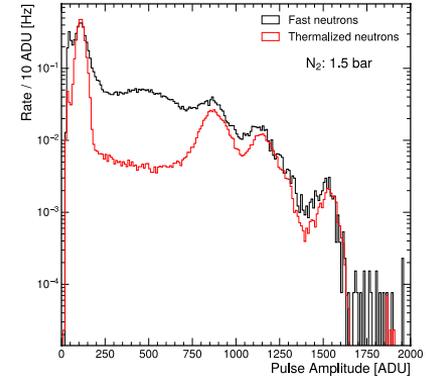
	60 cm SPC	140 cm SPC
neutrons/day	2.2	11.4
neutrons/month	67.1	351.9
neutrons/year	791.9	4142.8



Neutron detection with the Spherical Proportional Counter

Summary

- Neutron measurements set up accomplished
- Neutron detection performed in the Graphite stack and at the MC40 cyclotron facilities in Birmingham
- Corresponding measurements in Boulby
- Mono-energetic neutron measurement (e.g. @ Demokritos, Greece)



arXiv pre-print: 2206.04331



Boulby Underground Laboratory

