Detecting neutrinos and measuring nuclear quenching factor with spherical proportional counters

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CPAD workshop 2021

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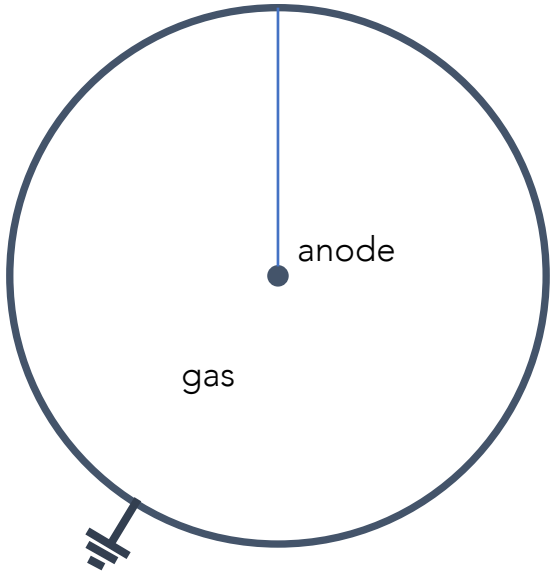
NEWS-G

- Groups scientists from 10 different institutions.

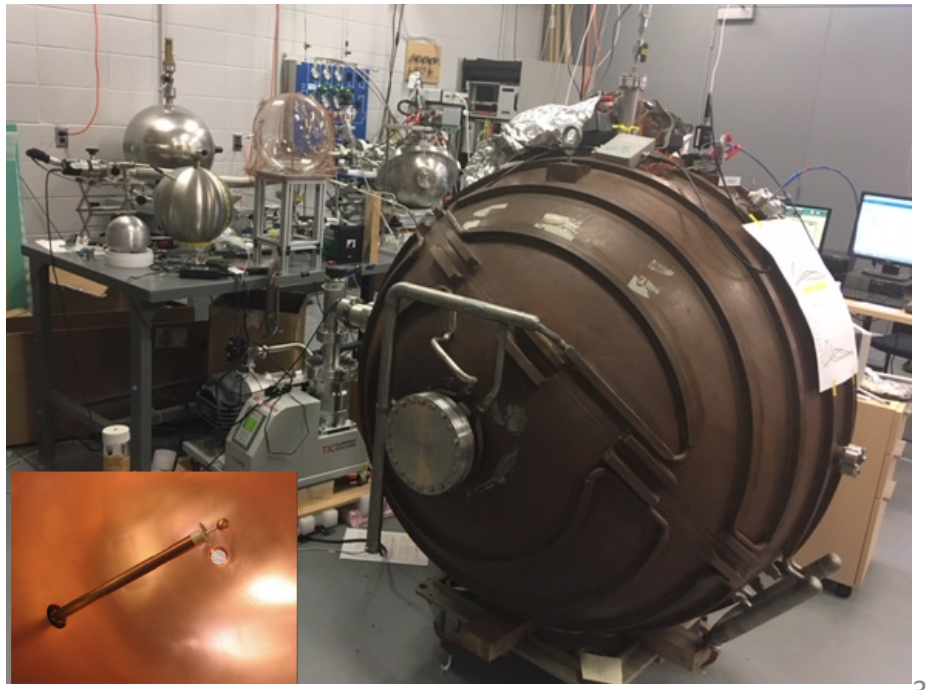
- Main goal: search for low-mass dark matter (WIMPs)
  - direct detection: nuclear recoils

- Other applications:
  - Coherent elastic neutrino-nucleus scattering detection

Spherical proportional counters



- Spherical metallic vessel filled with gas target + HV on central anode.
- SPC diameter: 15, 30, 60, 140 cm
- SPC shell: stainless steel, copper, aluminum
- Gas: Neon, Argon, Helium, CH_4
- Large gain
- Low energy threshold, independent of the SPC size: single electron
- Discrimination surface/volume events



Queen's University lab

SPC: principle

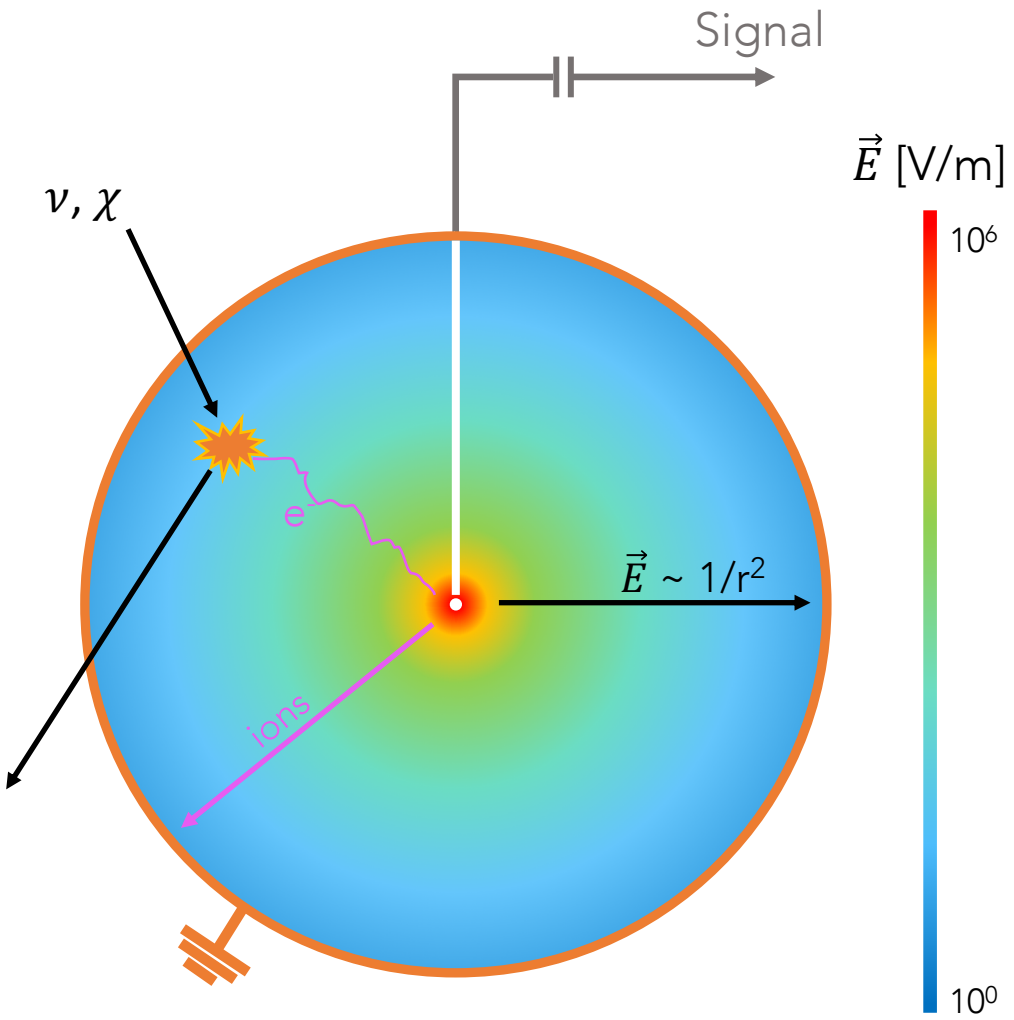
1. Primary ionization
   Mean energy necessary to generate 1 e^-/ion pair

2. Drift of primary e^- (pe) towards sensor
   Typical drift times: ~ 100 μs for 30cm Ø

3. Avalanche in the vicinity of the anode
   Generation of thousands of secondary e^-/ion pairs

4. Signal formation
   Current induced by ions → sphere surface

5. Signal readout
   Induced current integrated by a preamplifier



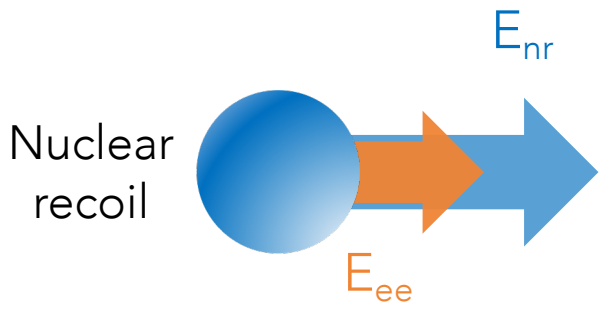
Cartoon: arbitrary scale

Nuclear quenching factor measurements

(QF)

Motivation for QF measurements

- energy calibration: γ or X rays interact with electrons → electronic recoils (ER)
- (ν, χ) interact with nuclei → nuclear recoils (NR)
- ER and NR don't ionize the same amount of gas.



$E_{ee} < E_{nr}$

- The quenching factor is :
  - the ratio of the observed ionization recoil energy (E_{ee}) to the total nuclear recoil energy (E_{nr}).

$$QF(E_{nr}) = \frac{E_{ee}}{E_{nr}}$$

  - scale to go from E_{ee} to E_{nr}.

Motivation for QF measurements

- First NEWS-G results [1] relied on SRIM [2] quenching factor estimates.
  - SRIM (The stopping and range of ions in matter): Monte Carlo software

- Effort invested to obtain QF measurements at low energies
  - No existing measurements of quenching factor in neon gas.
  - 1st QF measurement in neon gas

→ Need a source of known nuclear recoil energies (E_{nr})

[1] Q. Arnaud et al. (NEWS-G), Astropart. Phys. 97, 54 (2018)
[2] J.F. Ziegler, M.D. Ziegler, J.P. Biersack, Nucl. Instrum. Methods Phys. Res. B 268 (2010) 1818 – 1823. doi:10.1016/j.nimb.2010.02.091, 19th International Conference on Ion Beam Analysis

Quenching factor measurements

- Source of known nuclear recoil energies (E_{nr}):
  - Neutrons scatter off nuclei → nuclear recoils
  - Easier to do QF measurements with a monoenergetic neutron beam

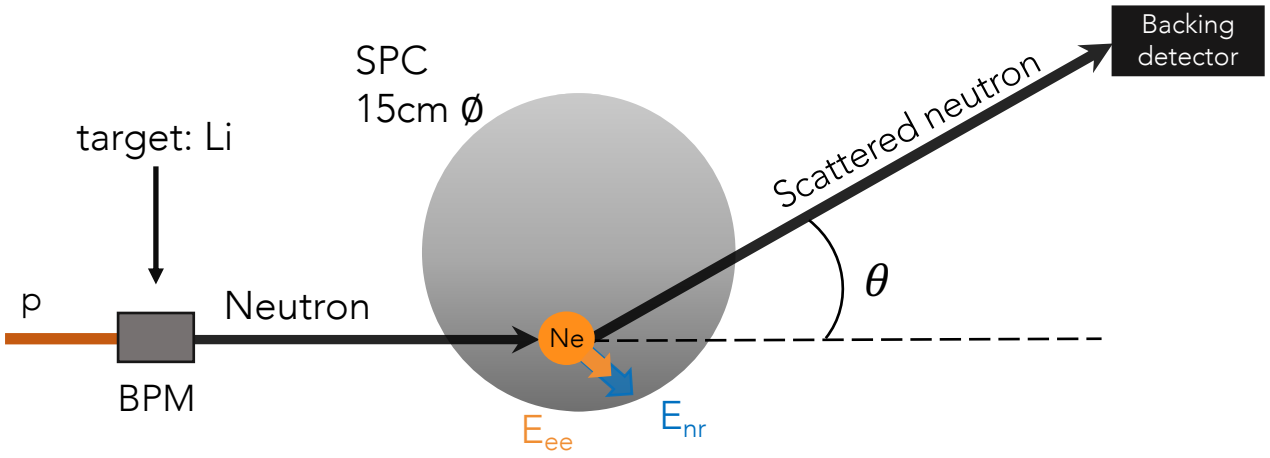
- The TUNL (Triangle University National Laboratory) facility has a tandem 10MV accelerator [3].

- 2018 preliminary experiment using:
  - $D+D \rightarrow n+{}^{3}He+\gamma$,
  - E_n = 3.68 MeV,
  - 4 energy points: 4.95-28 keV_{nr}
  - → proof of concept

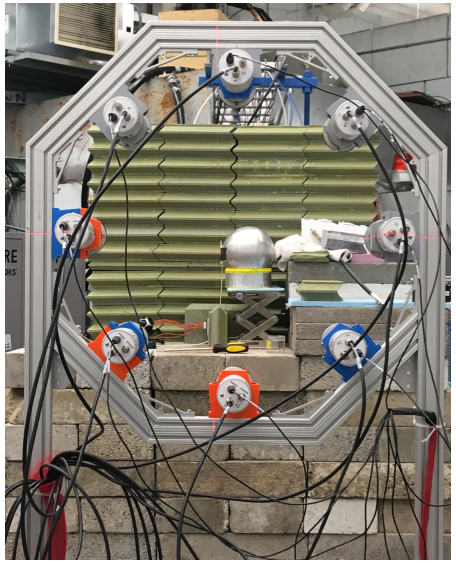
- **2019 campaign** using:
  - $p + {}^{7}Li \rightarrow n + {}^{7}Be + \gamma$,
  - E_n = 545 keV,
  - 8 energy points: 0.34-6.8 keV_{nr}

[3] https://tunl.duke.edu/

QF experiment



Run	E_{nr} [keV_{nr}]	θ [°]
8	6.8	29.02
7	2.93	18.84
14	2.02	15.63
9	1.7	14.33
10	1.3	12.48
14	1.03	11.13
11	0.74	9.4
14	0.34	6.33



Method

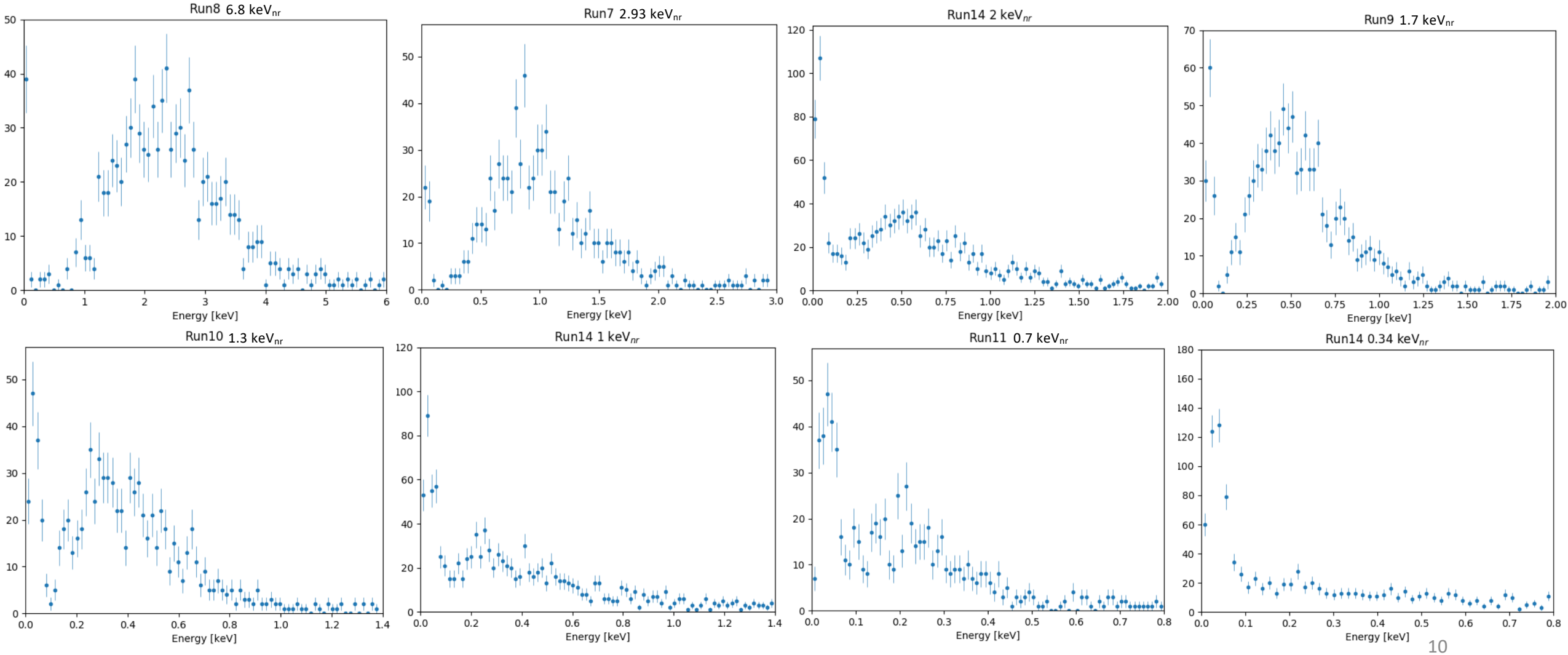
- From kinematics: can calculate E_{nr} as a function of the scattering angle (θ_s) and the neutron energy (E_n).
- θ_s provided by backing detectors (BDs) configuration
- Calculate: $QF(E_{nr}) = E_{ee}/E_{nr}$

Experiment

- 15 cm SPC
- Gas: Neon + CH_4 (97:3) @ 2 bar
- Pulsed beam: $E_n = 545 \pm 20$ keV
- 8 energy points: 0.34 to 6.8 keV_{nr} (see table)

- DAQ triggered on BDs
- Beam Pick-off Monitor (BPM): TOF neutrons
- Energy calibration: ^{55}Fe source

Energy spectra



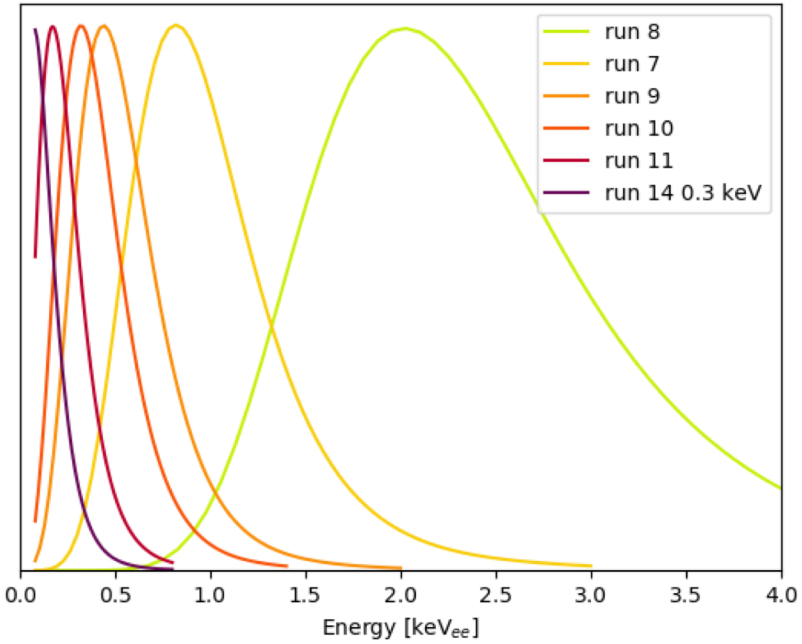
Analysis

- Classic method:
  - Recoil Energy spectrum symmetric
  - Use the mean of the recoil energy spectrum
  - Calculate: $QF(E_{nr}) = E_{ee}/ E_{nr}$

- We want to do an unbinned likelihood fit to the data that will return the most probable value of the QF.
- Joint fit to the data due to energy overlaps.

- Our energy spectra are asymmetric
  - Not clear what we should use: the mean? The mode?
  - We can't use $QF(E_{nr}) = E_{ee}/ E_{nr}$

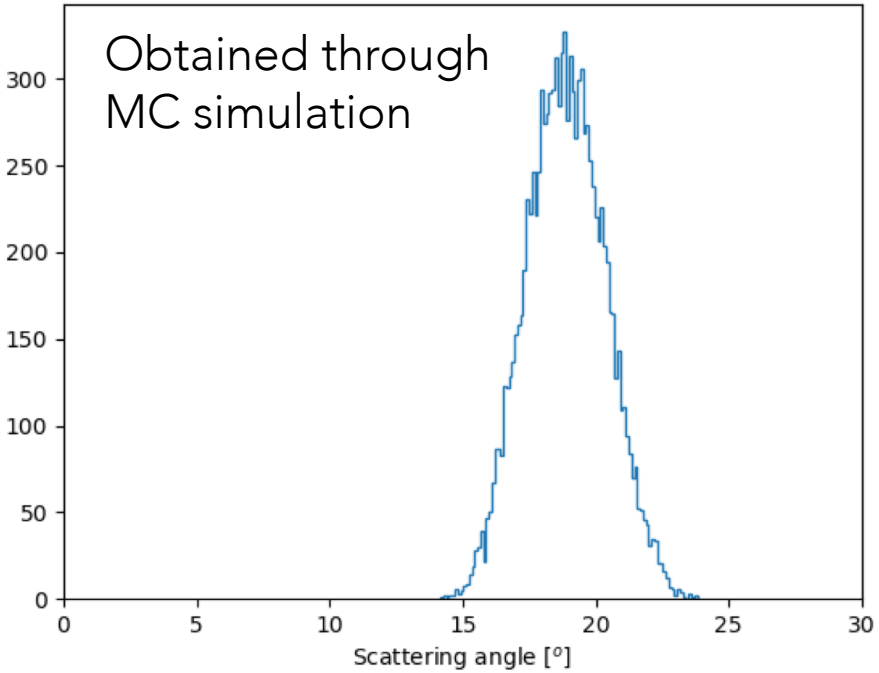
Recoil distributions

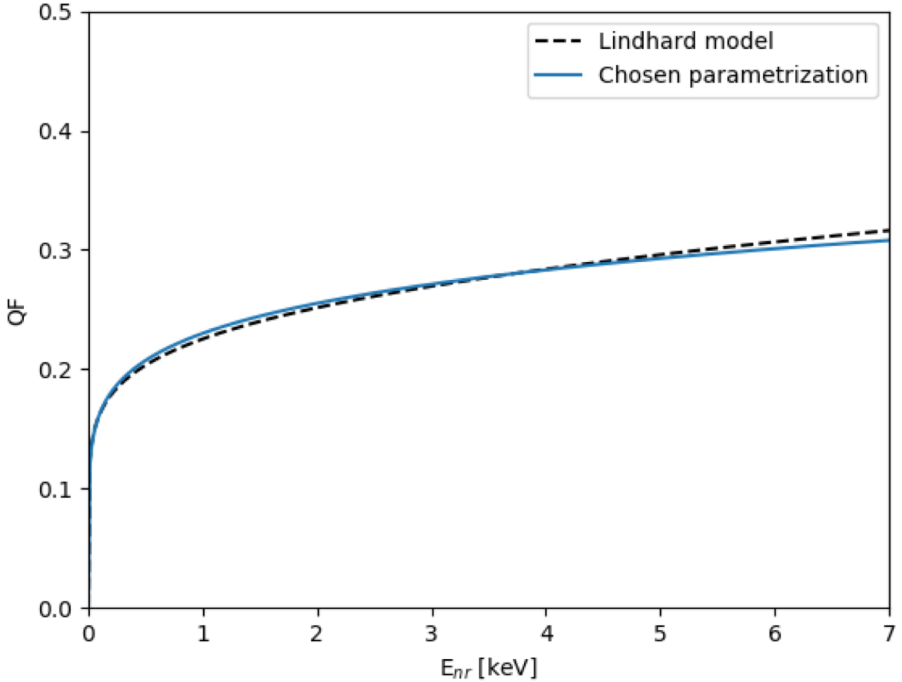


Model

- Geometry of the experiment:
  - scattering angle distribution
  - impact E_{nr} spectrum
- Neutron energy distribution
- Response of the detector:
  - Primary ionization: Poisson
  - Secondary ionization (avalanche): Polya
- Include quenching factor:
  - Depends on the energy
  - $QF(Enr) = \alpha E_{nr}^{\beta}$
  - α and β are free parameters of the fit
  - matches Lindhard theory [4].

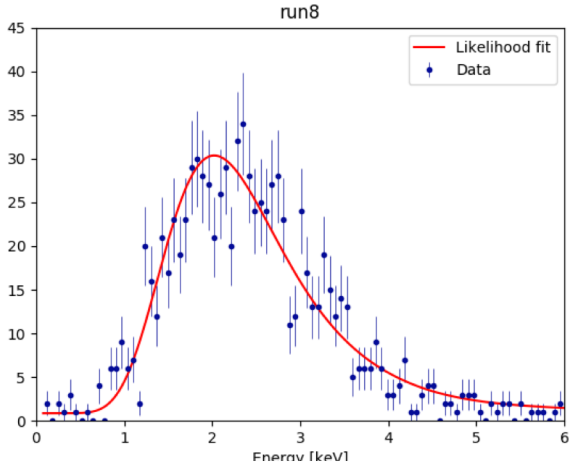
- Background: uniform distribution in energy

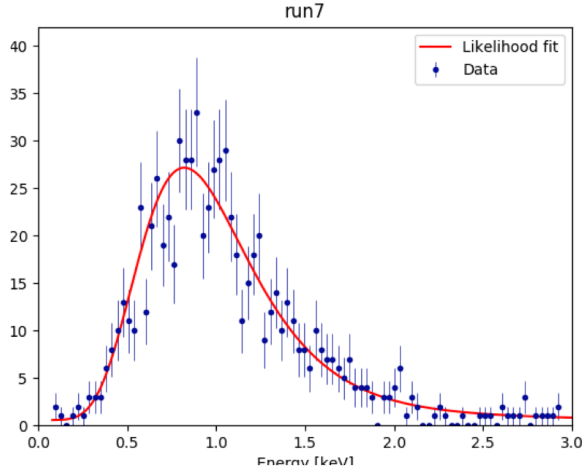


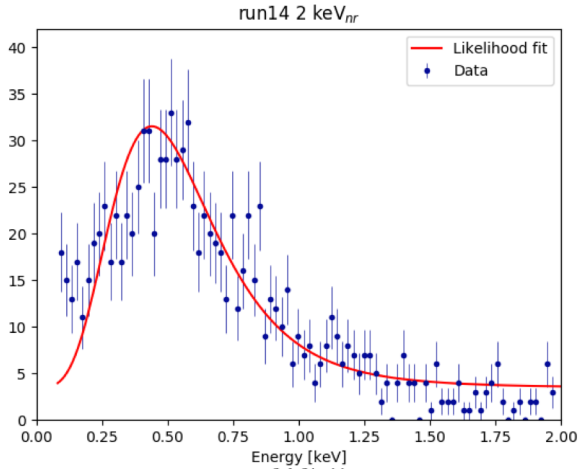


[4] J. Lindhard, V. Nielsen, M. Scharff and P.V. Thomsen, Mat. Fys. Medd. Dan. Vid. Selsk. 33 10 (1963)

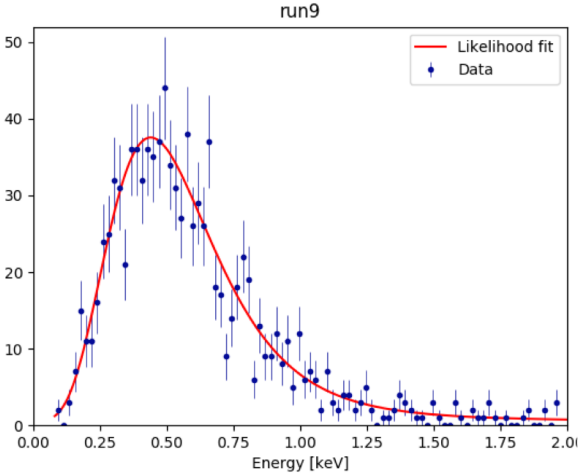
Result of the joint Likelihood fit

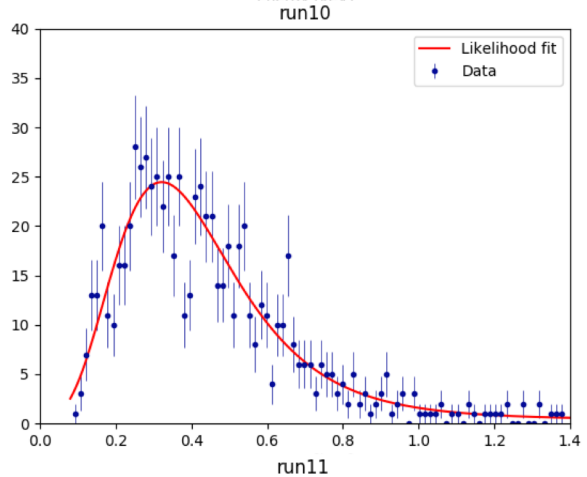


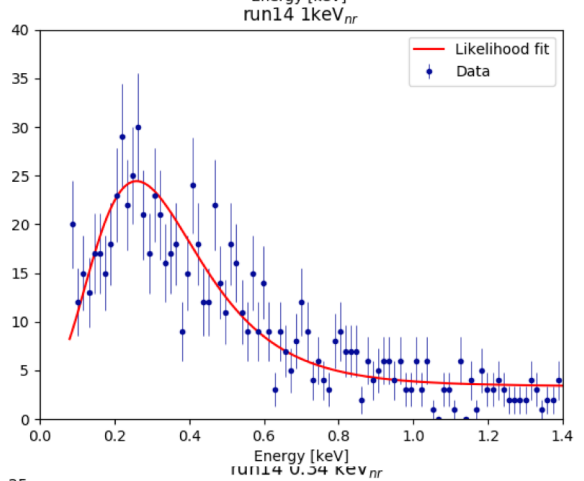


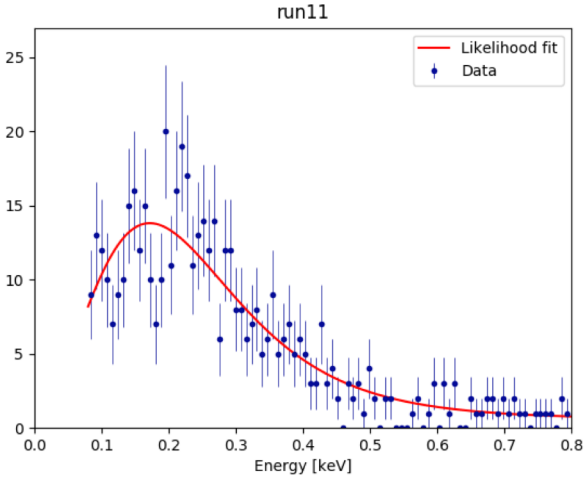


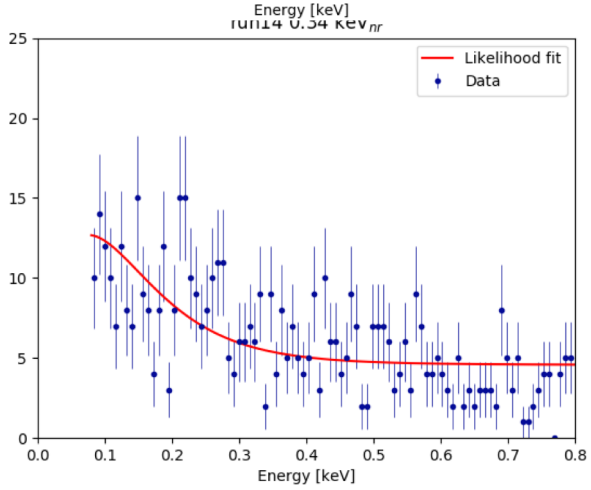
Runs	χ^2	ndf	χ^2/ndf	p-values
run8	95.45	81	1.18	0.13
run7	53.2	80	0.66	0.99
run9	78.94	78	1.01	0.45
run10	74.9	81	0.92	0.67
run11	48.96	79	0.62	0.99
run14, 0.34 keV	97.55	89	1.09	0.25
run14, 1 keV	94.7	88	1.07	0.29
run14, 2 keV	165.04	85	1.94	4.7×10^{-7}









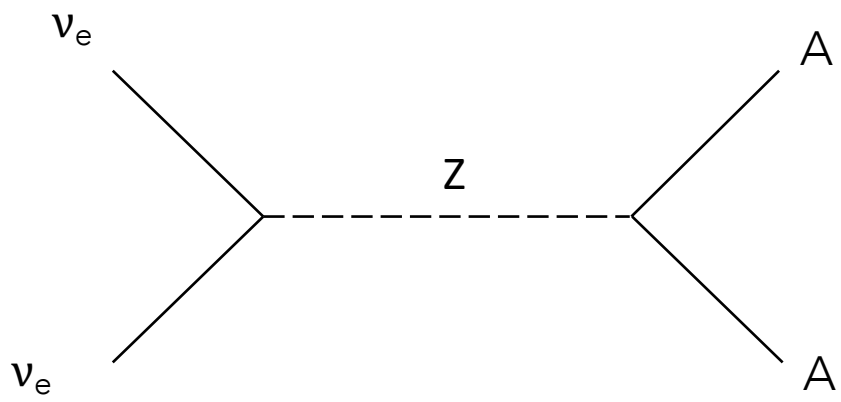


- Model fits the data well.
- Estimation of the quenching factor in neon gas between 0.35 and 11 keV$_{nr}$.
- Paper is in preparation (internally reviewed)

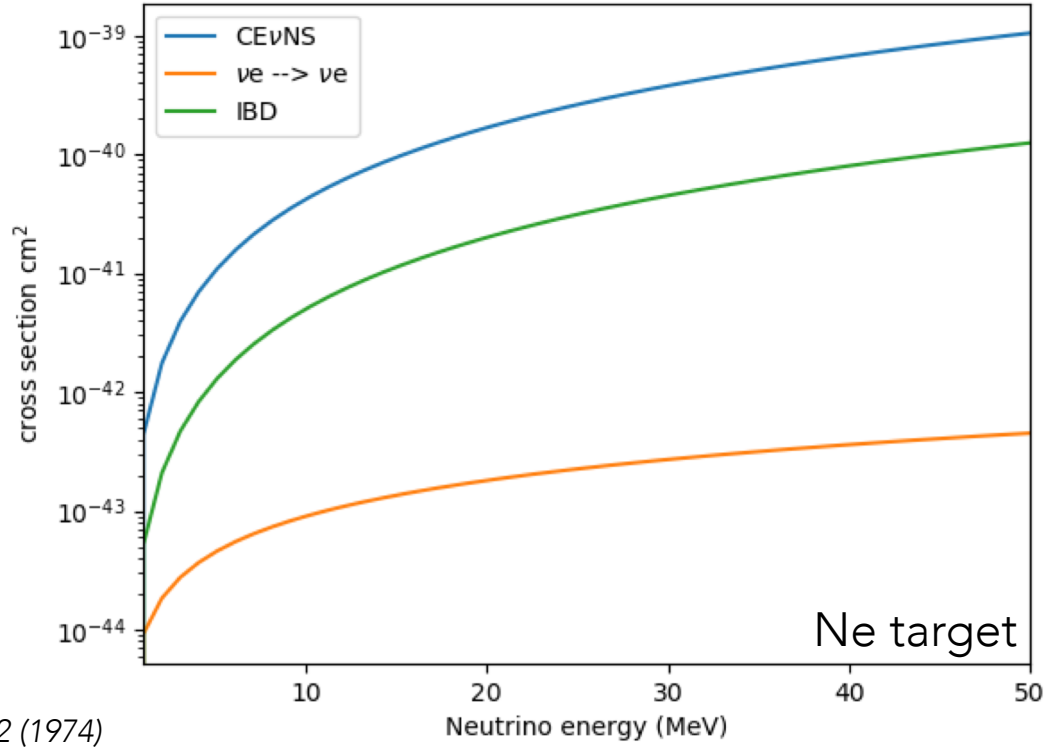
Coherent elastic neutrino-nucleus scattering

CEνNS

What is CEνNS?



- Coherent elastic neutrino-nucleus scattering: neutral current
- Coherence if qR^* ≤ ~ 1 (q depends on target mass)
  - E_ν ≤ ~ 50 MeV for medium A nuclei (i.e. ^{55}Cs)
- Large cross-section [5]: ∝ N^2
- First predicted by Freedman in 1974 [6]
- Low E_{nr} (few keV)→ challenging to detect
- First detection by COHERENT in 2017 [7]



q: momentum transfer, R: nuclear radius

[5] D. Z. Freedman, Coherent effects of a weak neutral current. Phys. Rev. D 9, 1389– 1392 (1974)
[6] D. Akimov et al. (COHERENT), Science 357, 1123 (2017), arXiv:1708.01294 [nucl-ex]
[7] A. Drukier, L. Stodolsky, Principles and applications of a neutral-current detector for neutrino physics and astronomy. Phys. Rev. D 30, 2295–2309 (1984)

Applications of CEνNS (some)

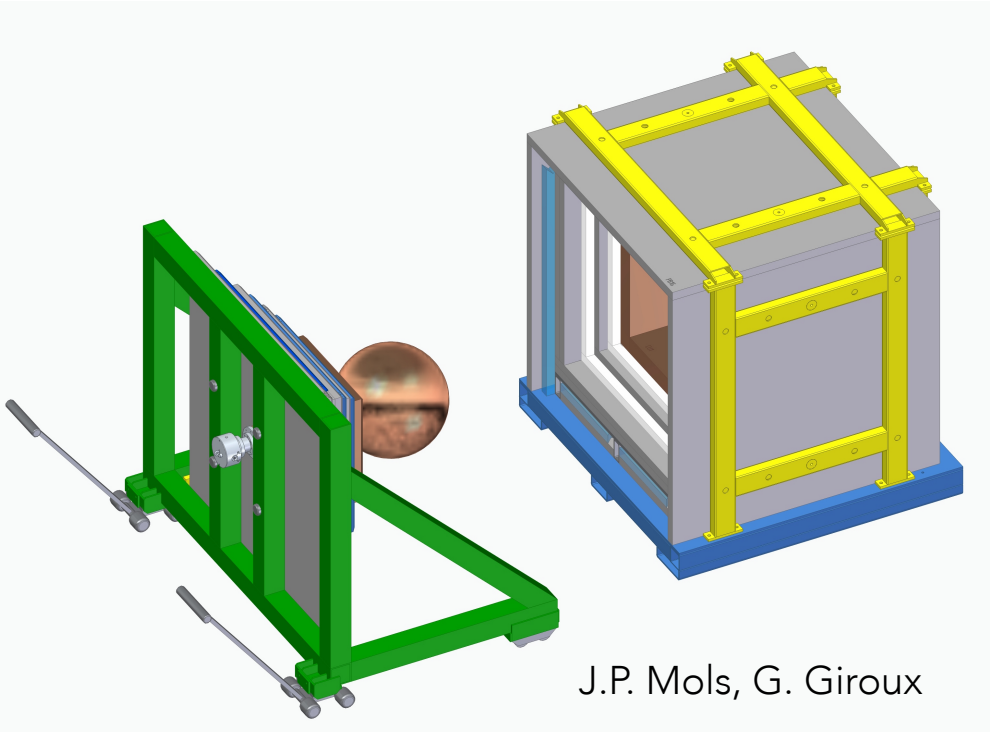
- Study of the neutrino flux from nuclear reactor
  - Oscillation studies
  - Application in monitoring reactor neutrino flux for non-proliferation
- Neutrino magnetic moment searches
- Nuclear form factor measurements
- Supernovae neutrinos search
- Weak mixing angle precision measurements
- Sterile neutrino search
- NSI
- …

CEνNS & NEWS-G

- Interested in detecting CEνNS at nuclear reactor
  - single flavor: ν_e
  - continuous source: understand cycle for BG rejection
  - ν flux: ~ 10^{20} $GW^{-1}cm^{-2}$ s^{-1}
  - $E_\nu \in [0, 12]$ MeV
  - $E_{nr} < \sim 1$ keV_{nr}

- Need low energy threshold: ok
- Can try different targets

- Need to understand surface background: 1st step NEWS-G3 shield @Queen's
  - Compact shielding: Cu, Pb, PE
  - commissioning planned for 2021



NEWS-G3 shield

Feasibility

- We want to assess the feasibility of detecting CEνNS using a SPC at a nuclear reactor.

- Need to know the expected signal in our detector
  - Calculate the differential event rate

- Need to know the background contributions
  - from the detector + shielding
  - from the nuclear reactor
  - cosmic muons

  → Geant4 simulation

Differential event rate

- Huber-Mueller-Baldoncini's flux [8],[9],[10]
- 10 m from source
- 1 GW thermal power

- Including response of the detector
  - Primary ionization
  - Secondary ionization

- QF: Lindhard theory

- Investigate the signal in 4 different targets to estimate best candidate

- 1kg of target material in a 60 cm SPC, corresponds to:

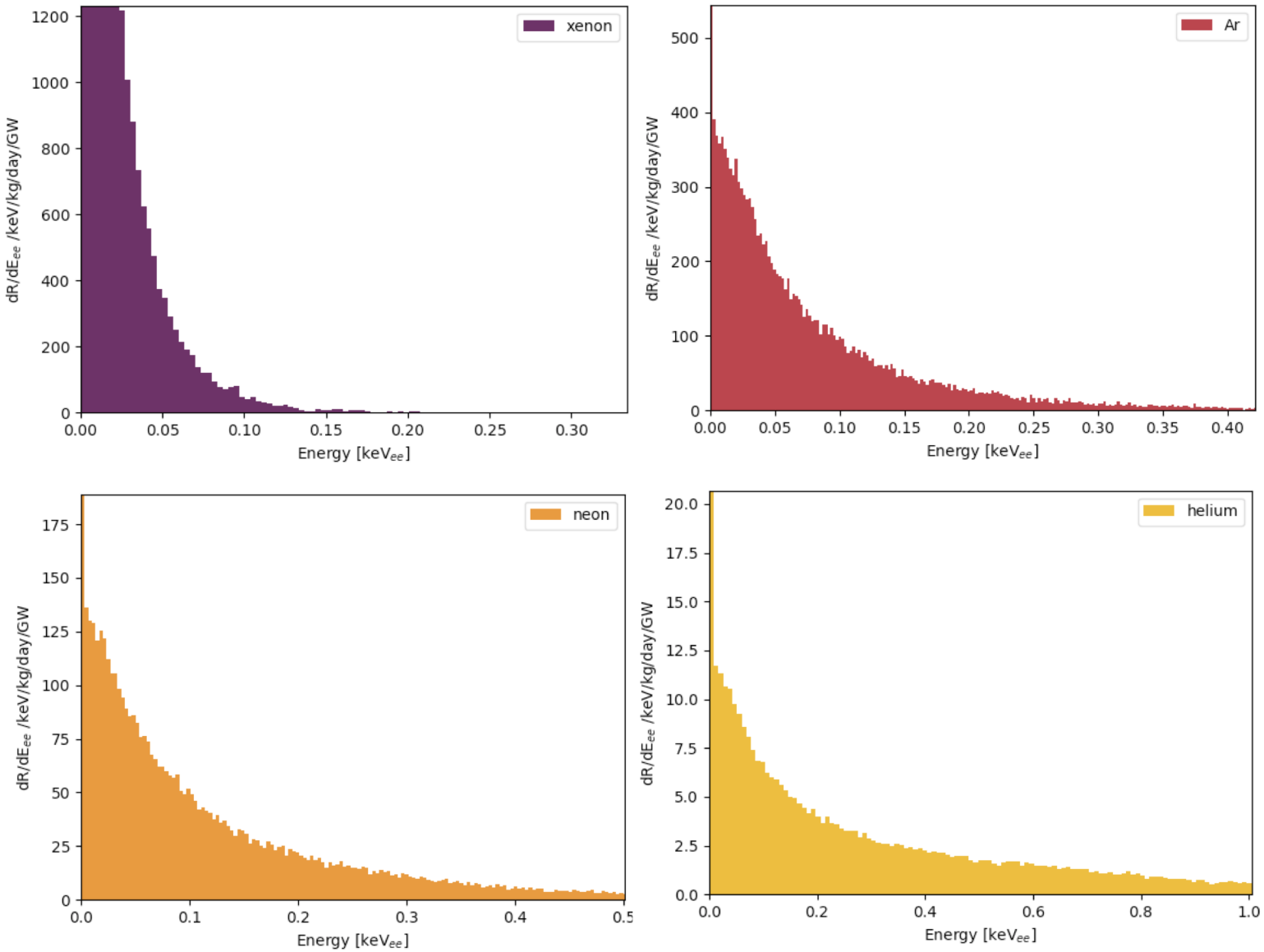
	Pressure (bar)			
Temperature	Xenon	Argon	Neon	Helium
273 K	1.5	5	9.9	50
293 K	1.6	5.3	10.6	53

[8] M. Baldoncini et al., Phys. Rev. D 91, 065002 (2015)
[9] T. A. Mueller et al., Phys. Rev. C 83, 054615 (May 2011)
[10] P. Huber and T. Schwetz, Phys. Rev. D70, 053011 (2004)

dR/dEee

- Considering E_{th} = 50 eV_{ee}
  - Xe: ~ 9 CEνNS events/kg/day/GW
  - Ar: ~ 15 CEνNS events/kg/day/GW
  - Ne: ~ 10 CEνNS events/kg/day/GW
  - He: ~ 2 CEνNS events/kg/day/GW

- Contamination from SPC shell and shielding under study.
- Include background from reactor and cosmic muons.



Conclusion

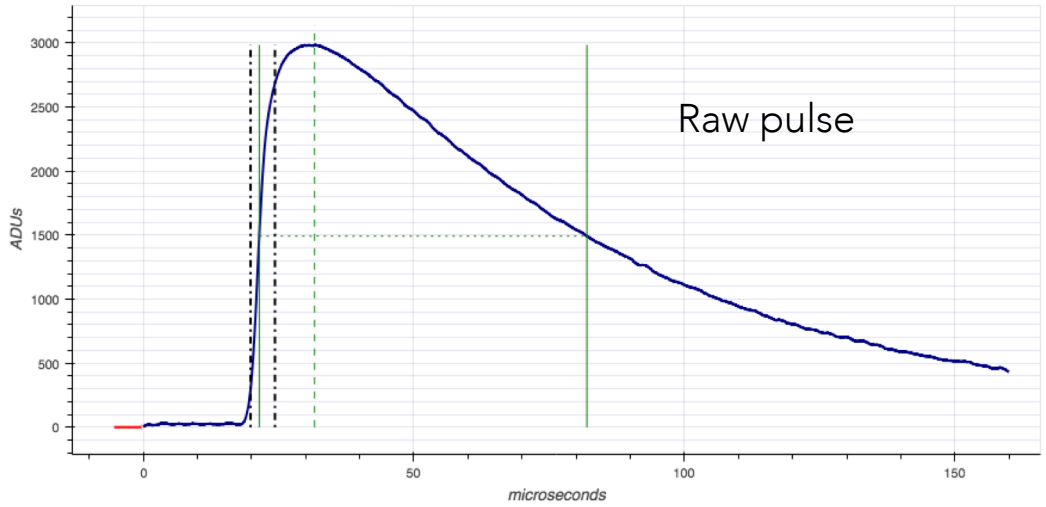
- Low energy recoils QF measurements in neon gas at the TUNL facility using SPC.
  - 1st measurements in neon gas
  - Developed a new method to extract QF
  - Paper soon to be published
- Studying the feasibility of an experiment using SPC to detect CEνNS at a nuclear reactor.
  - Expected signal in detector
  - Developing Geant4 simulation to account for background and assess the feasibility of the experiment.

Thank you

Questions?

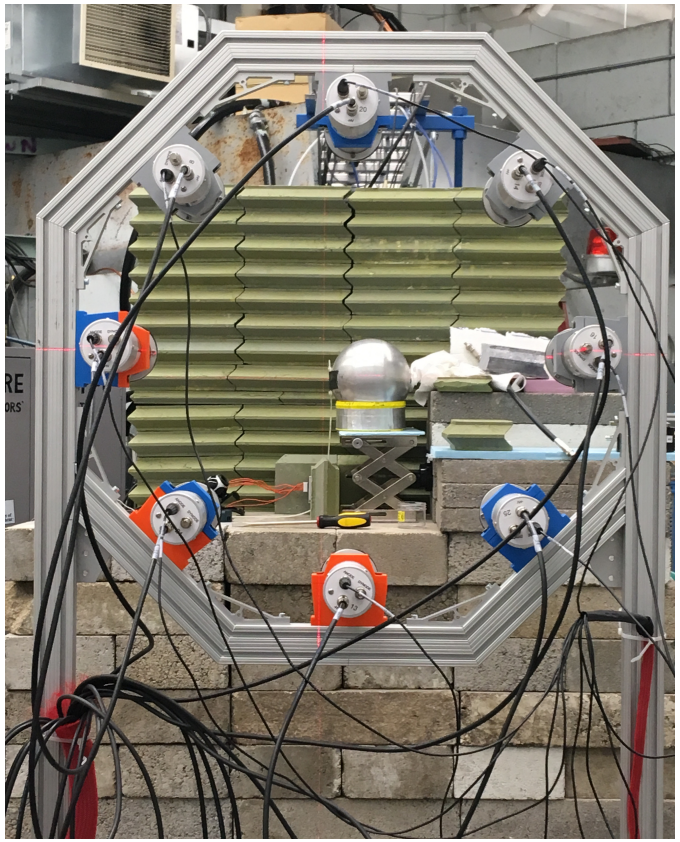
Back up slides

SPC: example of pulse treatment

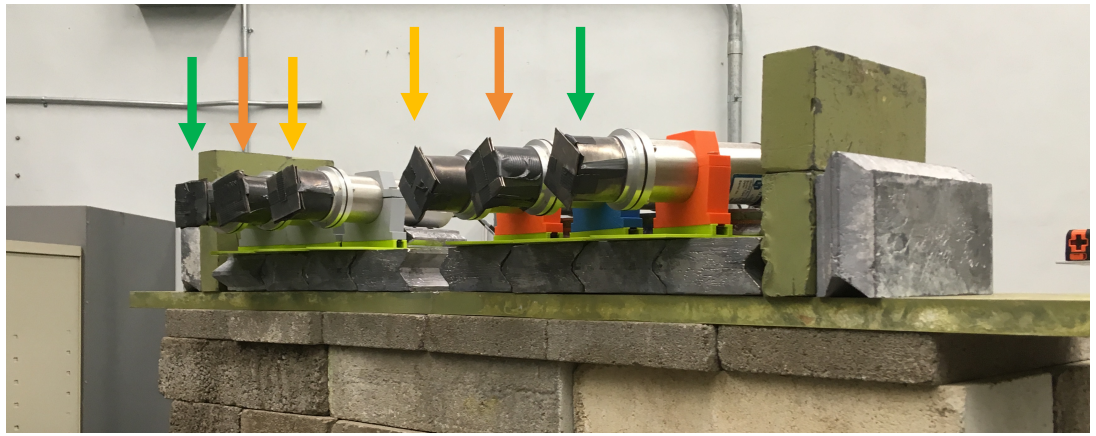


- RC sensitive preamplifier provides an output voltage signal.
- Data are processed by deconvolving the response of the preamplifier and the drift of the secondary ions from the pulse.
- Amplitude provides estimation of the energy of the event.
- Rise time provides an estimation of the radial distance of the event → Rise time linked to diffusion of the pe along their drift toward anode.

Quenching factor: 2 Experimental Set Ups



Annulus configuration



Multiple energy configuration

- Annulus configuration:
  - 8 BDs at the same scattering angle → same E_{nr}
  - 5 energy runs: from 6.8 keV_{nr} down to 0.7 keV_{nr}
- Multiple energies configuration:
  - To reach 0.3 keV_{nr}
  - 3 nuclear recoil energies recorded: 0.3, 1 and 2 keV_{nr}

Summary of the cuts

- PSD (pulse shape discrimination): discriminate gamma and neutron events, $psd_n > 1.35$
- Time of Flight (TOF): $T_{n,BD} - T_{n,BPM}$, TOF specific to each energy run.
- Onset time:
  - is the time between the interaction (SPC) and the start of the pulse: ~ drift time of the pe^-
  - time the pulse takes to reach 10% of its amplitude.
  - Expect to see excess of events at 40 μs because of DAQ configuration: recoils events.
- Rise time:
  - reject surface and unphysical events.