Nuclear recoil calibrations for sub-GeV Dark Matter

SNOWMASS CF1

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Outline

- Neutron kinematics
- Low-energy mono-energetic neutrons
    - p-Li Accelerator Source
    - Portable DD/DT Sources
    - Tagged Reflection of Neutron Sources
    - Photo-neutron Source
- Addition of Energy Filters to Sources
- Neutron energy from Time-of-Flight only
- Backing detectors for low-energy neutrons
- Coherent High Energy Gamma Scattering from Nuclei

SNOWMASS LOI: Nuclear Recoil Calibration Techniques for Dark Matter and Neutrino Experiments (link)

Neutron Target Scattering Kinematics

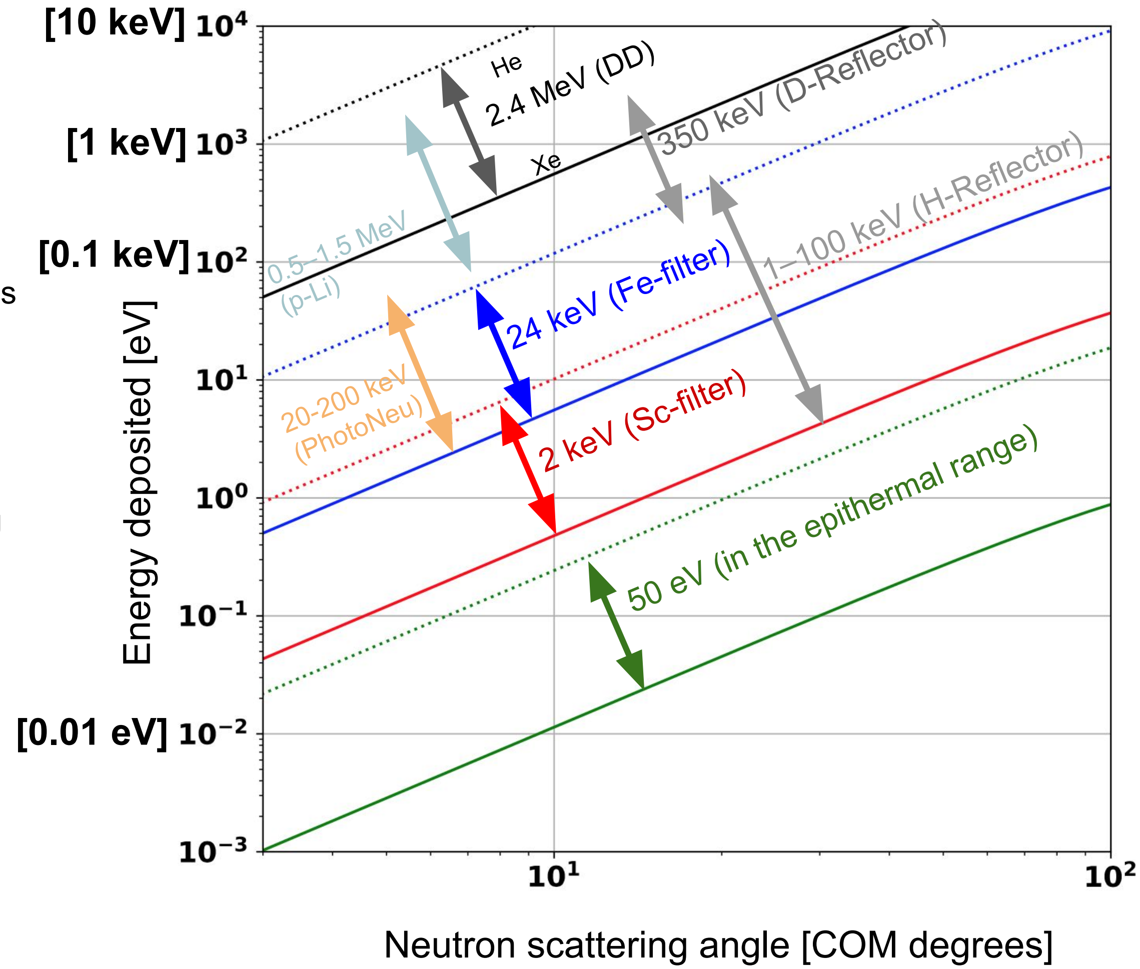
Using Neutrons of known energy significantly decrease systematics in calibrations

- *Monoenergetic* source
- ToF (for lower energies)

Monoenergetic neutrons enable the deposited energy to be known on an event-by-event basis (assuming scattering angle also measured)

Scattering angle measurement:
-for large detectors, can be performed with the target mass (LUX/LZ)
-for small detectors, requires separate backing detector (perhaps more the model for <GeV detectors)

Neutron energy selection:
-depends on scattering energy of interest and target mass
-< GeV pushes to lower and lower neutron energies



p-Accelerator on 7Li Target

$^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$

Quasi-monoenergetic neutrons,
energy set by incident proton energy

Requires 2-2.5 MeV protons
(dedicated accelerator facility)

Endothermic so allows effective
tuning of n energy in range
500 keV – 1.5 MeV

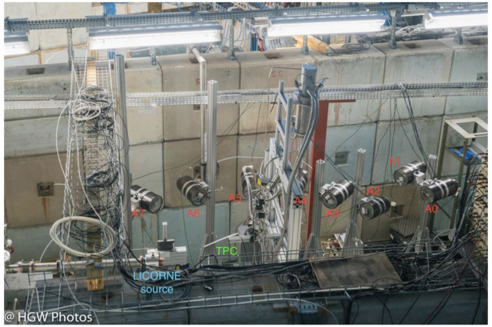
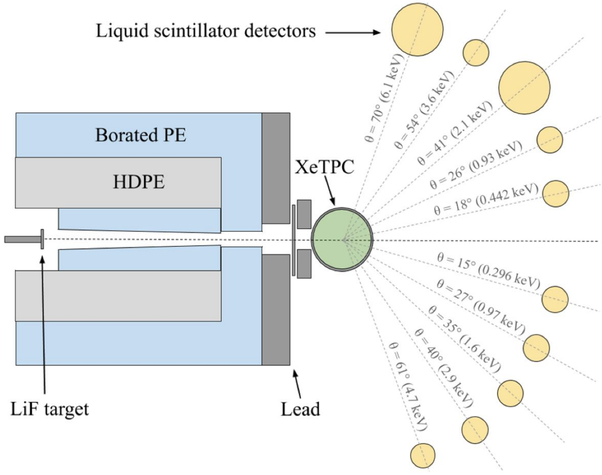
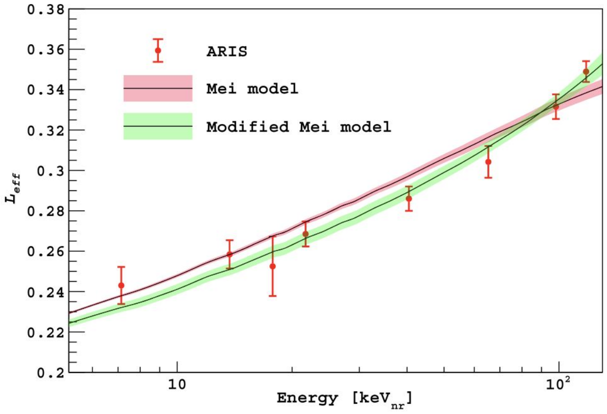


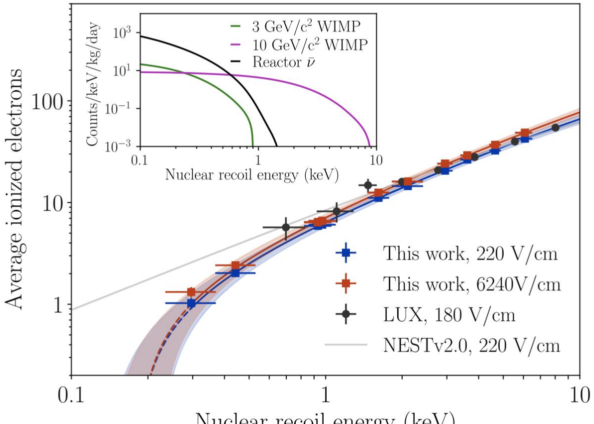
FIG. 1. Picture of the ARIS setup in the LICORNE hall.

ARIS / Agnes et al. PhysRevD97,112005 (2018)



Lenardo, Xu et al. PhysRevLett.123.231106





DD and DT neutron generators

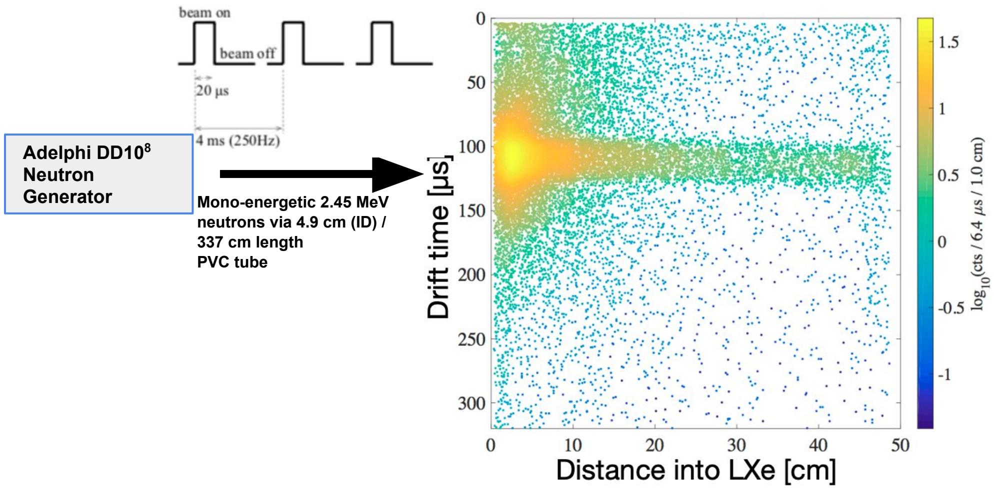
Portable mono-energetic high intensity neutron generators
- Very low associated gamma yields
- Brem x-rays blocked with few mm of Pb

DT KE n = 14 MeV
- In situ. Used to probe NR regime relevant for recoils predicted in Effective Field Theory (EFT) interactions
  - e.g. Xe Max Recoil 430 keVnr

DD KE n = 2.45 MeV
- In situ. Used to probe NR regime for regular and low mass (<GeV) DM
  - Used to measure Xe Recoils 0.3 keVnr - 75 keVnr

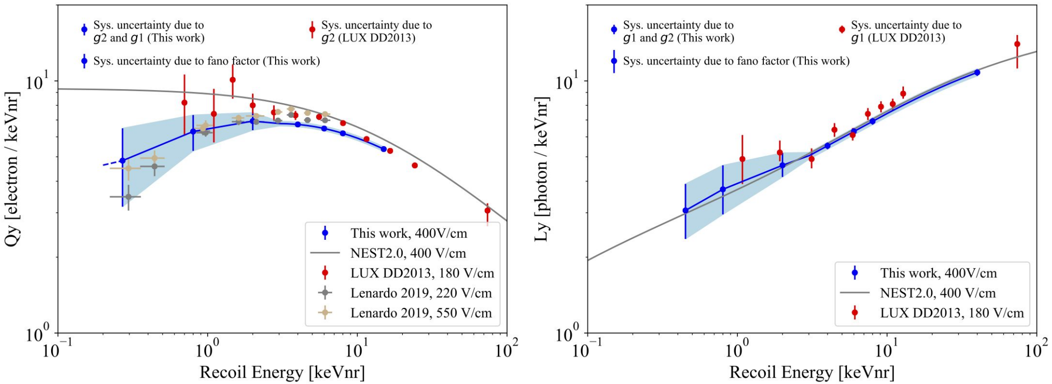
Great practical benefits from being both portable and pulsable.

Adelphi DD Accelerator LUX Experiment, Huang / Verbus (Brown University)
arXiv:1608.05381 / arXiv:1608.05309 / Nucl. Instrum. Methods A851, 68 (2017)



Adelphi DD10^8 Neutron Generator

Mono-energetic 2.45 MeV neutrons via 4.9 cm (ID) / 337 cm length PVC tube



Huang, Thesis (Brown University), paper in preparation

Neutron Reflectors (Scintillators)
Tagged Neutrons from Portable DD Source

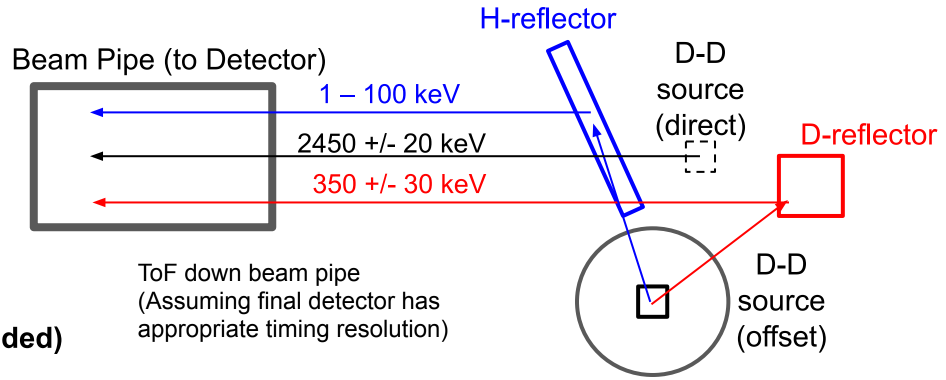
Reflecting the mono-energetic 2.45 MeV neutron beam by a fixed angle allows lower energy tuned neutron source

- D-Reflector: **KE n 350 keV** high intensity demonstrated
- H-Reflector: Continuum source **KE n 1-100 keV**

Method has very low x-ray / gamma contamination
(<1% of n flux, after 2 mm of Pb)

Reflector can be active scintillator: e.g. NE301 (CH) or NE315 (D loaded)
This allows individual tagging of each neutron

- ToF is directly available (100 keV => ToF 0.23 us/m, 1 keV => 2.3 us/m)



Beam Pipe (to Detector)

H-reflector

1 – 100 keV

2450 +/- 20 keV

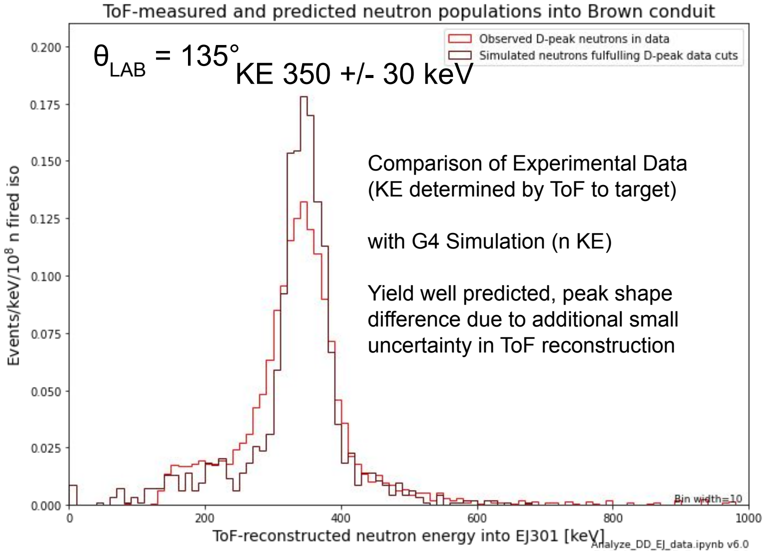
350 +/- 30 keV

D-D source (direct)

D-reflector

D-D source (offset)

ToF down beam pipe
(Assuming final detector has appropriate timing resolution)



θ_{LAB} = 135°

KE 350 +/- 30 keV

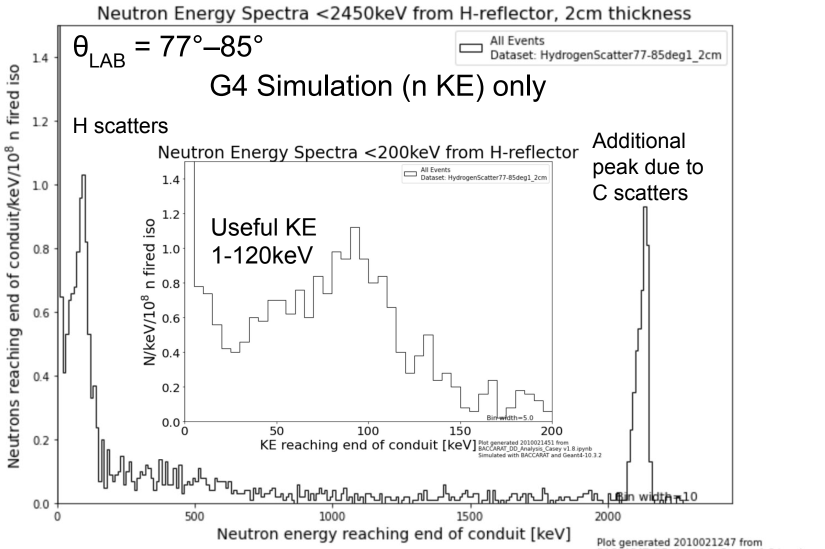
Comparison of Experimental Data (KE determined by ToF to target)

with G4 Simulation (n KE)

Yield well predicted, peak shape difference due to additional small uncertainty in ToF reconstruction

Analyze_DD_EJ_data.ipynb v6.0
DAQ: Acquire_DD_Data.py v5.0
File: D-ref_1E7_EJ301_5mV_AC_adv_tr_castle_v3

Adelphi DD Accelerator + D-Reflector, Casey Rhyne (Brown University)



θ_{LAB} = 77°–85°

G4 Simulation (n KE) only

H scatters

Useful KE 1-120keV

Additional peak due to C scatters

Plot generated 2010021247 from
BACCARAT_DD_Analysis_Casey v1.8.ipynb
Simulated with BACCARAT and Geant4-10.3.2

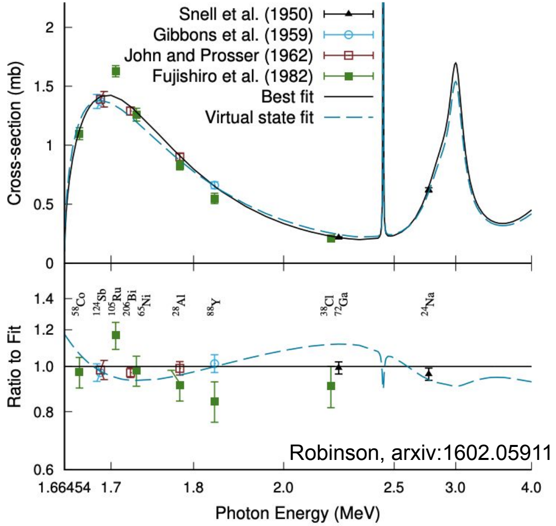
G4 Simulation (n KE), Eamon Hartigan-O’Connor, Casey Rhyne, Brown University

Photo-neutron sources

$$^{9}\mathrm{Be} + \gamma \rightarrow \ ^{8}\mathrm{Be} + n \quad (Q = -1.667\ \mathrm{MeV})$$

Gamma/n process can eject quasi-monoenergetic neutrons from 9Be nucleus. (requires intense monoenergetic gamma-ray source)

- Monoenergetic neutrons at a kinetic energy of Eγ–1.666 MeV, which allows for great tunability of neutron energies.
- Cross section is ~mb so yields ~ 0.1-1 neutron per 10^4 gammas



Robinson, arxiv:1602.05911

examples:

	^{88}Y-^{9}Be	**^{206}Bi-^{9}Be**	**^{124}Sb-^{9}Be**
Neutron energy	160 keV	48 keV	24 keV
Half-life	107 days	6.2 days	60.2 days

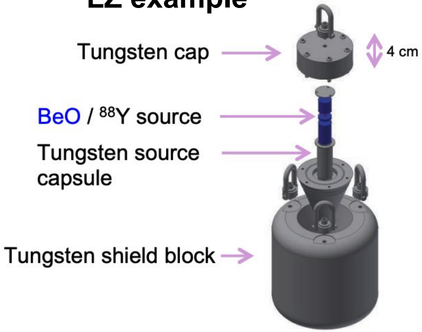
Challenge: gamma source must be ‘hot’ to produce useful n-flux.

Calibration still possible in two scenarios:

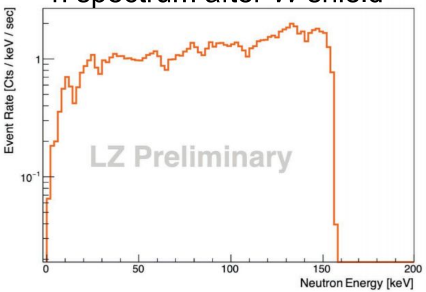
Scenario 1: detector technology of minimal ER response
(eg: bubble chamber)

Scenario 2: significant gamma shielding
(leads to moderation of neutron spectrum,
no longer monoenergetic)

LZ example



n spectrum after W shield



From https://lz.lbl.gov/wp-content/uploads/sites/6/2020/06/AB_AprilAPS2019_2.pdf

Neutron filters

Some nuclei have ‘notches’ in their neutron scattering cross sections, such that only a quasi-monoenergetic neutron population can leak through the material.

24keV (Fe) is the easiest practically
2 keV (Sc) is the lowest-energy that is *at all* practical

The fraction of neutrons that pass through the filter can be quite low; the traditional neutron source is a reactor.

Current R&D: pairing these filters with other more portable neutron sources.

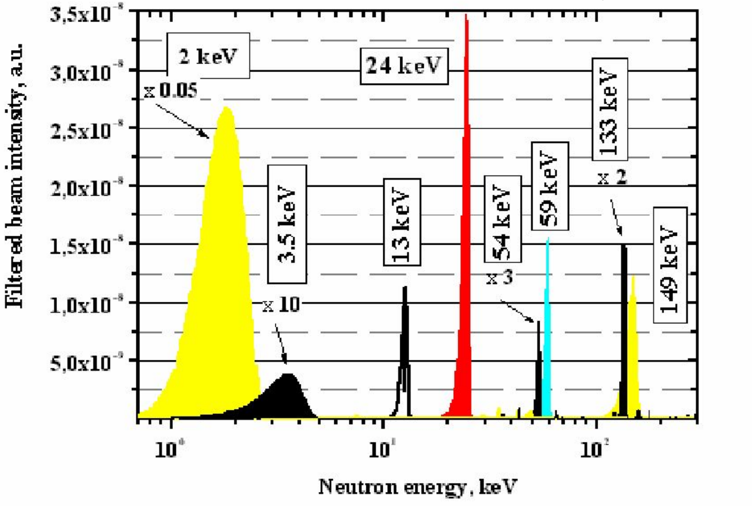
1: filtering a photo-neutron source (w/ moderation)

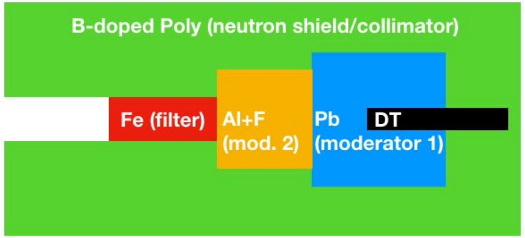
1) Neutron filter allows neutrons while shielding gammas
2) Completely avoids any higher-energy neutrons, useful for migdal or technologies without energy info)

Special case: 124SbBe matches Fe filter, Fe here not a n filter but a gamma blocker only.

2: filtering a DD/DT generator (w/moderation)
Benefit: can be pulsed to reduce backgrounds

Neutron Spectra for Various Filters, Gritzay et al, 2020





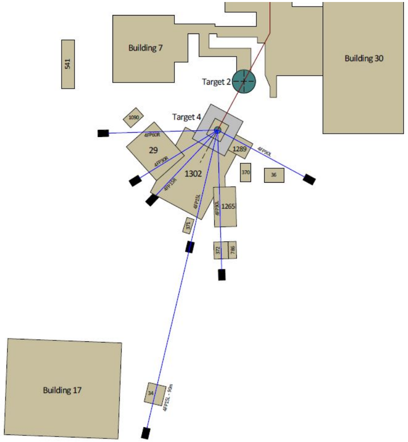
Non-monoenergetic neutrons (energy from Time of Flight only)

A spallation neutron source can provide
1) a short-duration pulse of large neutron flux 2) experiment sites at long distances (10s of meters)
This pairing gives *time-of-flight* methods great power.

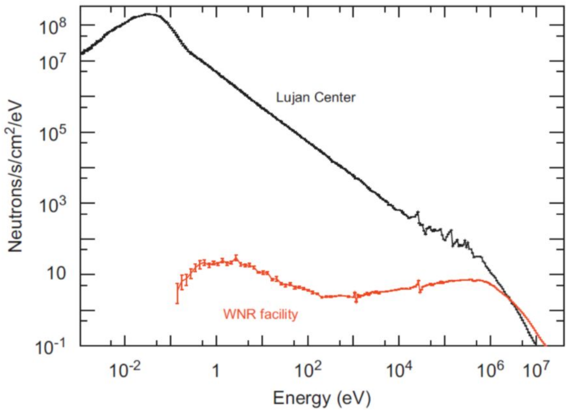
TOF methods eliminate the requirement of a mono-energetic source.
(Or put differently: the neutron source is monoenergetic *within each TOF time-bin*)

It is *very difficult* to make mono-energetic neutron sources with E<keV…
… it's possible these non-monoenergetic TOF techniques are the long-term future of neutron calibrations
(if neutrons of 100eV, 10eV, 1eV are required)

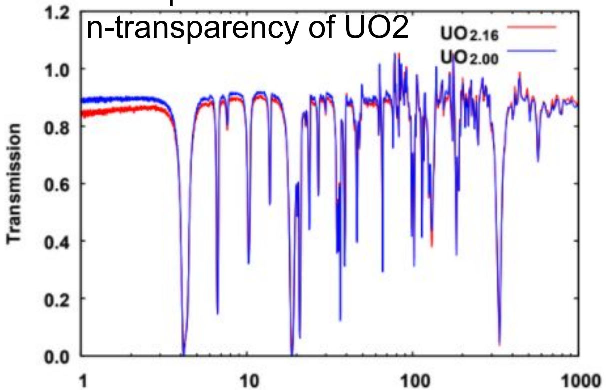
Primary challenge: wide energy flux, many neutrons far from the useful energy.
Required R&D: shaping the n spectrum to specific useful windows (using choppers, moderator/capture materials, etc.)



Neutron spectra at LANSCE



Example of eV-scale neutron work:
n-transparency of UO2



Neutron Energy [eV] (from time of flight)

Backing detectors for low energy neutrons

Many <GeV dark matter experiments will be small, requiring a separate detector for measuring the neutron scattering angle.

En > 10s of keV: backing detector based on neutron *scattering*

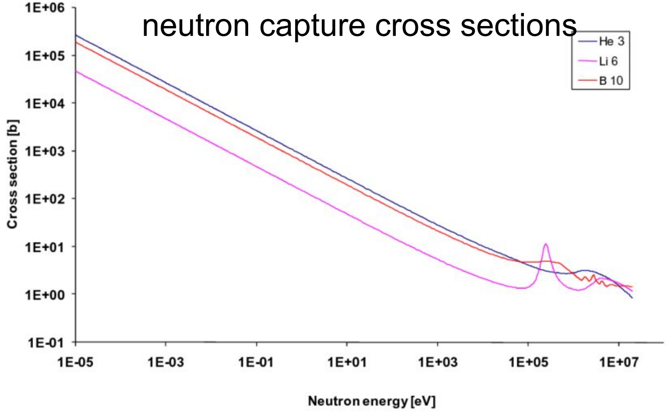
En < 10s of keV: backing detector must be based on *capture*

Capture introduces a time delay (order-µs and up) which damages the usefulness of time-of-flight techniques.

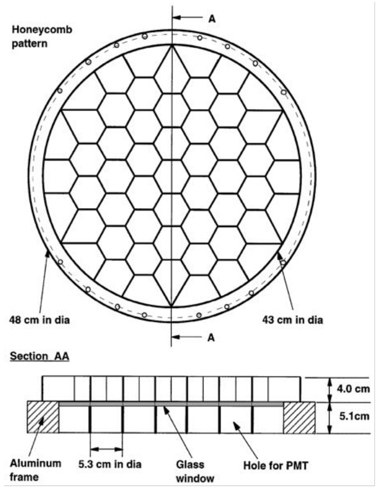
Capture requires doping with specific capture isotopes (6Li, 10B, 3He, etc.) which increases cost and decreases material choices.

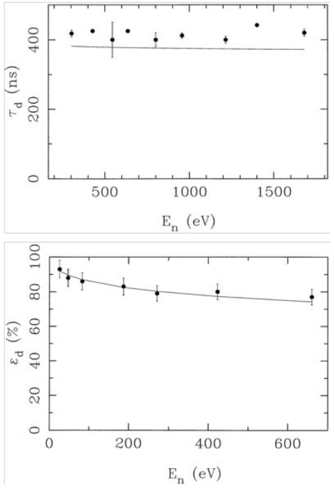
Note: some <GeV dark matter experiments have a slow response (for example, some bolometric techniques). The slower the technology being calibrated, the longer the calibration takes, and one has a strong motivation to maximize the area and capture efficiency of the backing detector. (so every neutron scatter ‘counts’).

neutron capture cross sections



example: finely partitioned B-doped liq. scintillator





Nuclear Recoils from Coherent Gamma Scattering

Photonuclear, or Coherent Gamma-ray Nuclear scattering can also be exploited at the lowest recoil energies.

At lowest energies, dominated by Rayleigh scattering (gamma scatters off all the electrons of the atom as a whole). Cross section scales as Z^3.

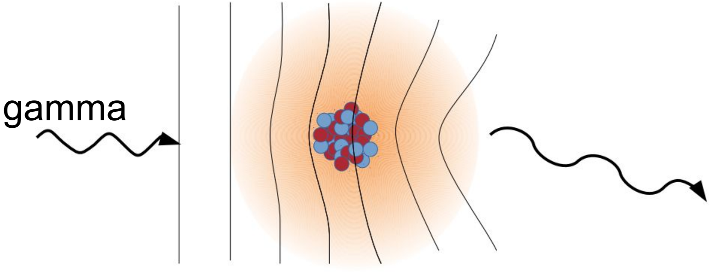
Example kinematics:

Target (gamma energy)	15 degree recoil	Recoil endpoint
4He (and 60 keV gamma)	32 meV	1.9 eV
Xe (and 9 MeV gamma)	23 eV	1.3 keV

Challenge: separating these useful coherent scatters from the *dominant* gamma processes (eg compton scattering). Possible in two regimes:

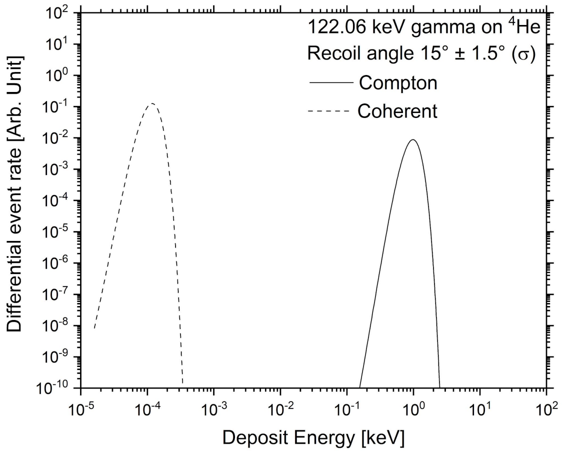
- Lack of ER response (for example: bubble chambers)
- Tagged gamma scattering angle (as in neutron scattering)

Useful reference: slides from A. Robinson



$$E_r = \frac{q^2}{2M} = \frac{(2p_\gamma \sin\frac{1}{2}\theta)^2}{2M}$$

[lab frame]



Summary

SNOWMASS LOI: Nuclear Recoil Calibration Techniques for Dark Matter and Neutrino Experiments (link)

- Broad array of existing methods (for scattering energies from keV down to meV scale)
  - Techniques have a various of pros and cons:
    - portable vs facility-based
    - mono-energetic vs time-of-flight
    - pulsed vs constant-flux
    - Different levels of neutron spectral purity / competing gamma backgrounds from source
  - As detector thresholds push lower for sub-GeV DM, NR calibration techniques need to keep pace

- We will likely continue to add to the list of techniques. Important and active region of R&D.
  - Important to demonstrate their effectiveness (as well as simulations)
  - Understand neutron spectrum (and ToF) properties - what fraction of total neutron flux is in useful range?
  - What unwanted source-related gamma signals compete for live time in detector being calibrated?

- Need to better define *requirements* for DM & neutrino nuclear recoil calibrations
  - Identify and Propose dedicated facilities including calibrations with dedicated detectors
    - Detailed studies / optimized geometries / high stats - no fear of activation of search experiment
  - Techniques for *in situ* calibrations (of live dark matter and neutrino experiments, underground)
    - Important to show that specific event searches have quoted response characteristics
      - Especially true for detectors that are exploiting sensitivity in lowest energy bins where start-to-end efficiency should be demonstrated (includes yields of signal quanta, their detection, and their treatment in analysis pipeline)
    - Lower systematic uncertainties in calibration source, ensures detector response can be unambiguously determined (minimize correlated errors and strong simulation dependencies)