Impact of Tl dopant concentration on the Quenching factors in NaI(Tl) crystals

TAUP VIENNA 2023

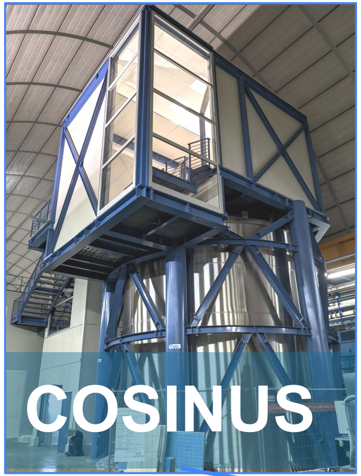
Rituparna Maji on behalf of the COSINUS collaboration
TU Wien and HEPHY, Vienna, Austria | E rituparna.maji@oeaw.ac.at

NaI-based experiments in the field

- ➢ Single channel readout
- ➢ room temperature scintillators
- ➢ detects light using NaI(Tl)

  - DAMA
  - ANAIS
  - COSINE
  - PICOLON
  - SABRE

- ➢ Dual channel readout
- ➢ cryogenic calorimeter
- ➢ detects light+heat using NaI



See contributions by
- Talk by V.Zema [30 Aug, 14:00]
- Talk by M. Bharadwaj [29 Aug, 14:45]
- Poster by M. Stukel
- Poster by M. Hughes

What is quenching factor?

COSINUS

- Nuclear recoil produce less amount of scintillation (L_{nr}) light than electromagnetic interaction (L_{ee}) of the same energy within the same target material

- Quenching Factor: $QF(E) = \frac{L_{nr}(E)}{L_{ee}(E)}$

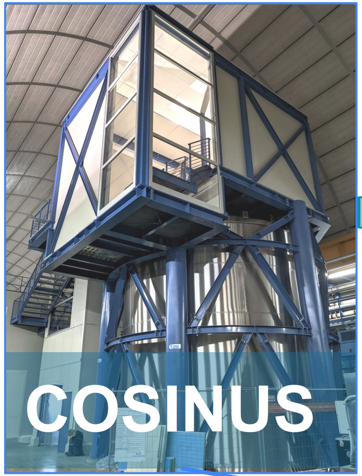
NaI-based experiments in the field

- ➢ Single channel readout
- ➢ room temperature scintillators
- ➢ detects light using NaI(Tl)

Incapable of in-situ measurement of QF

- DAMA
- ANAIS
- COSINE
- PICOLON
- SABRE

- ➢ Dual channel readout
- ➢ cryogenic calorimeter
- ➢ detects light+heat using NaI



Capable of in-situ measurement of QF in cryogenic temperature

See contributions by
- Talk by V.Zema [30 Aug, 14:00]
- Talk by M. Bharadwaj [29 Aug, 14:45]
- Poster by M. Stukel
- Poster by M. Hughes

Why is QF important?

COSINUS

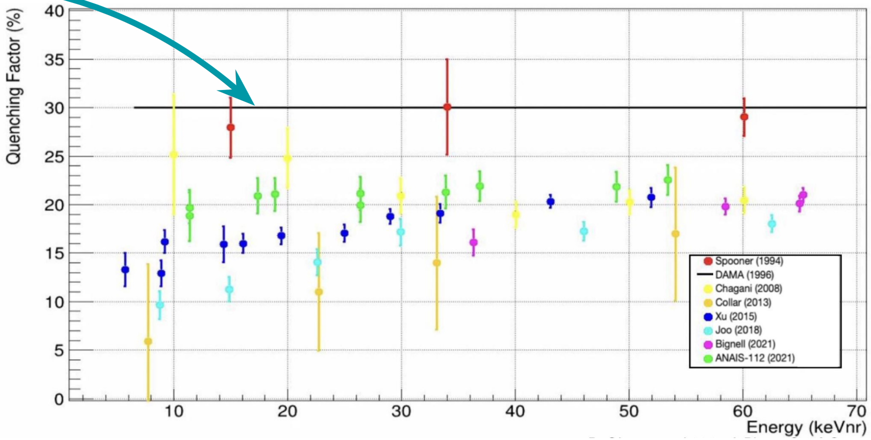
- For **scintillation-only experiments** crystals are **calibrated with electron/gamma** sources
- Energy of **nuclear recoil events gets quenched** and hence needs to be re-scaled using QF
- **Precise QF measurement is crucial** to get the correct nuclear recoil energy in **scintillation-only experiments**
- **Prior investigations** have shown that variable QF, linked to energy, has the **potential to influence modulation signals** [1]

[1] PhysRevC.92.015807

Motivation and goals

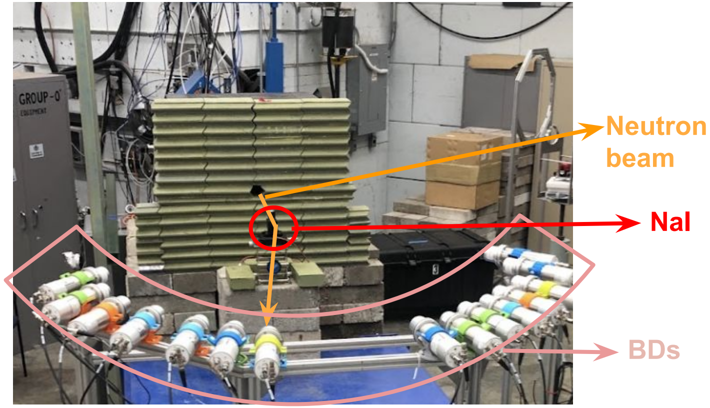
- DAMA reports(1996) a **constant QF** for different nuclear recoil energy:
    - **QF of Na: 0.3, QF of I: 0.09**
- **Quenching factor mystery** in the field: room temperature QF measurement of NaI(Tl) do not agree, especially below 30 keV_{nr}
    - **Goal 1: systematic study of QF in low energy range**
- Tl dopant concentrations (added for room temperature scintillation in NaI) in tested crystals often not precisely known
    - **Goal 2: systematic study of QF with different Tl dopant concentration**
- **Goal 3: Compare results with the cryogenic measurement @COSINUS**

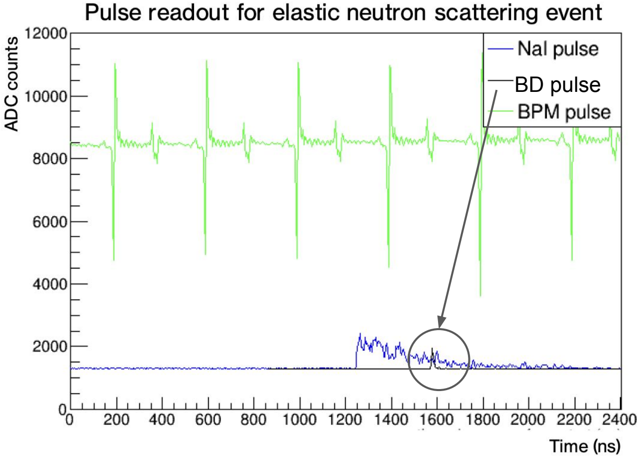
Reported Quenching factor values for Na recoils



D. Cintas et al 2021 J. Phys.: Conf. Ser. 2156 012065

QF measurement setup @ TUNL





- **Measurement done at TUNL, USA**
- Special thanks to **P. Barbeau, S. Hedges et. al** for their **invaluable contribution and support :)**
- Collimated **quasi-monoenergetic neutron beam(~1500 keV)** induces **nuclear recoils** in **NaI(Tl)** crystals
- **14 backing detectors (BDs)** [liquid scintillators coupled with PMTs] are placed at a distance of **1-1.5 m** from NaI covering **7-40 degrees** of angles
- **Coincidence window** between the NaI(Tl) and any backing detector for **triggering neutron-induced nuclear recoil events**

Crystals produced by SICCAS

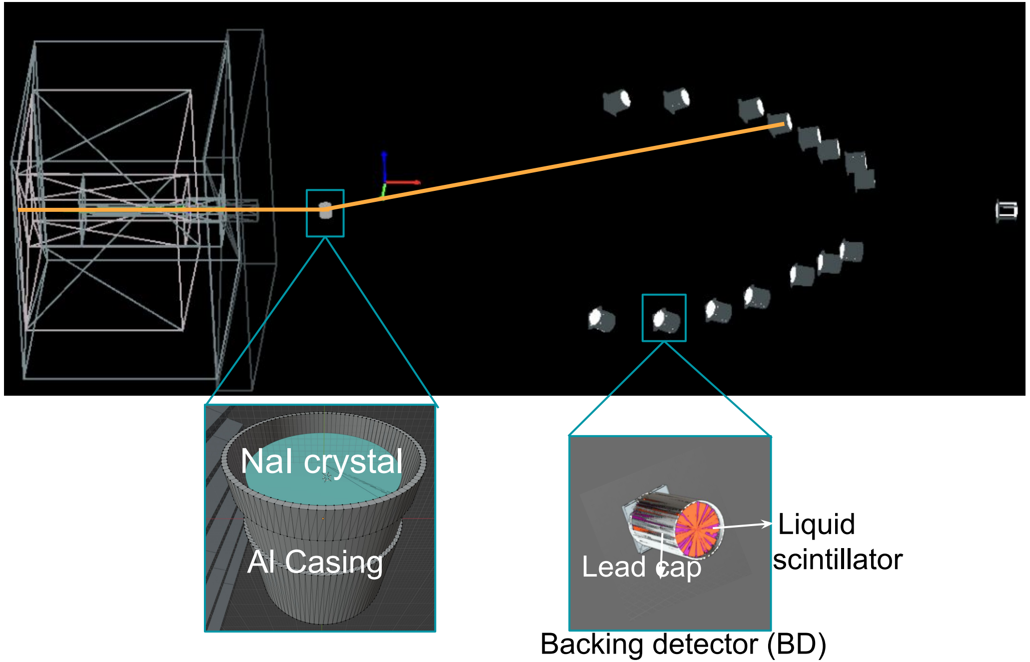
- **5 ultra-pure NaI crystals** each with **unique Tl dopant concentration**
- Crystals were produced by **SICCAS**, China using **Astro-Grade powder** *[arXiv: 1909.11692]*
- Small cylindrical crystals (diameter and height of 1 inch) to reduce multiple scattering
- As NaI is hygroscopic, each crystal is sealed in Al casing of ~1.5mm thickness
- ICP-MS studies @LNGS, Italy showed
  - Potassium: **10 ppb**
  - Uranium: **0.2 ppb**
  - Thorium: **0.1 ppb**
  - Radioactive contamination comparable or better than the crystals used at DAMA

- **28-36 hours exposure** on each crystal, placed on a rotating stand to ensure uniform neutron flux to reduce ion channeling effect
- A PMT (H11934-200) attached to the NaI crystal

Simulation goals

COSINUS

Geant4 simulation using *ImpCRESST(EPJC:(2019)79:881)*



A

Goal 1: Set up the experiment

To determine the optimal angular range for BD placement, ensuring sufficient neutron flux and an adequate number of events reaching each backing detector

B

Goal 2: Find true nuclear recoil energy

To simulate the true nuclear recoil energy → to be compared against the measured electron equivalent energy to calculate QF

C

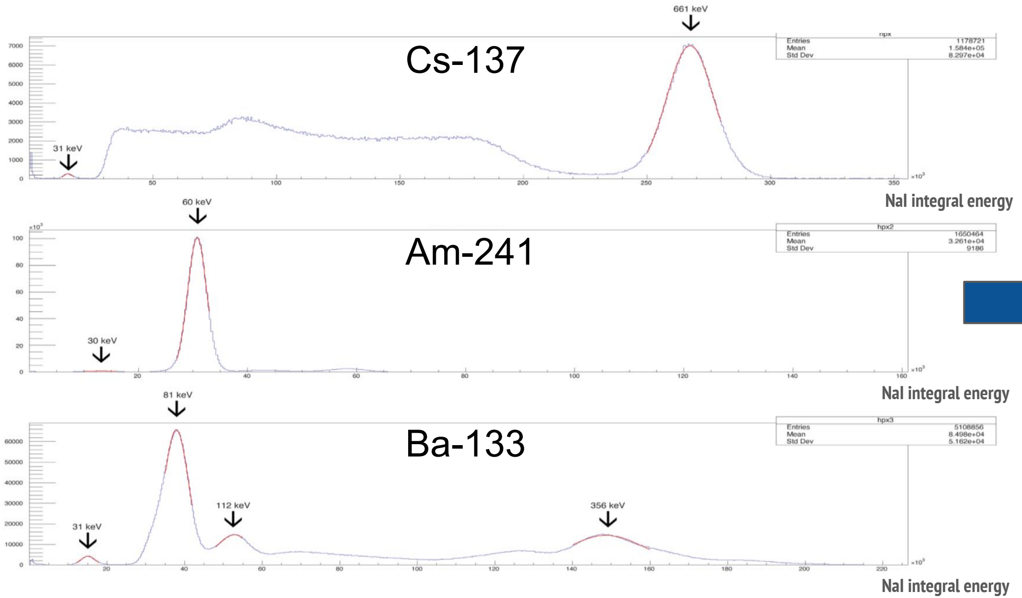
Goal 3: Compare measured calibration spectra

To simulate energy deposition on NaI using different calibration sources → compare simulated spectra to the fitted (measured) calibration spectra

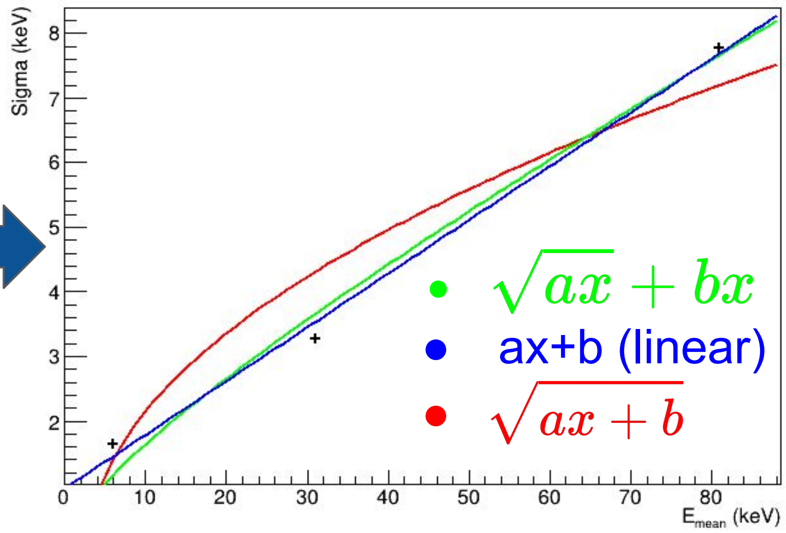
Calibration and Resolution

COSINUS

Measured calibration spectra from the PMT attached to NaI

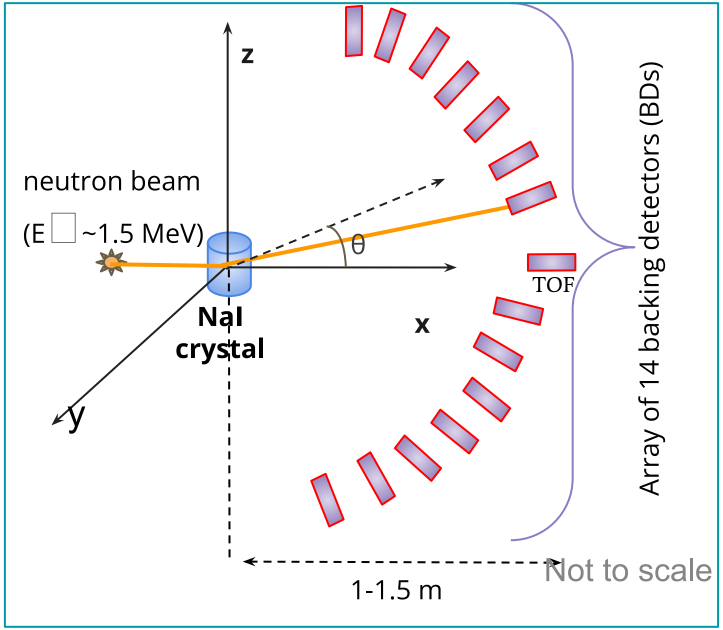


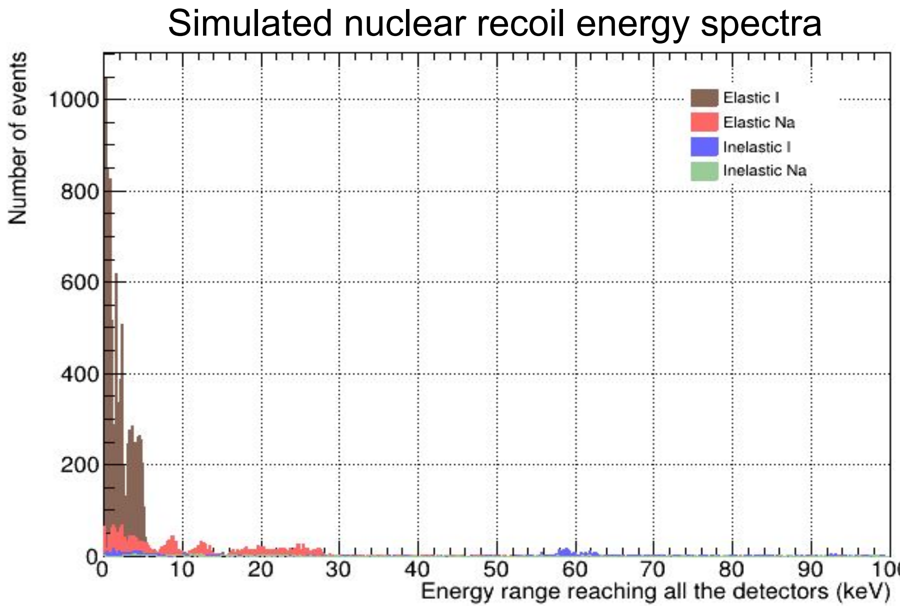
PMT Calibration + Resolution



- Gaussian fit to extract peaks and widths
- Fitted spectra compared to simulation

Simulated nuclear recoil energy



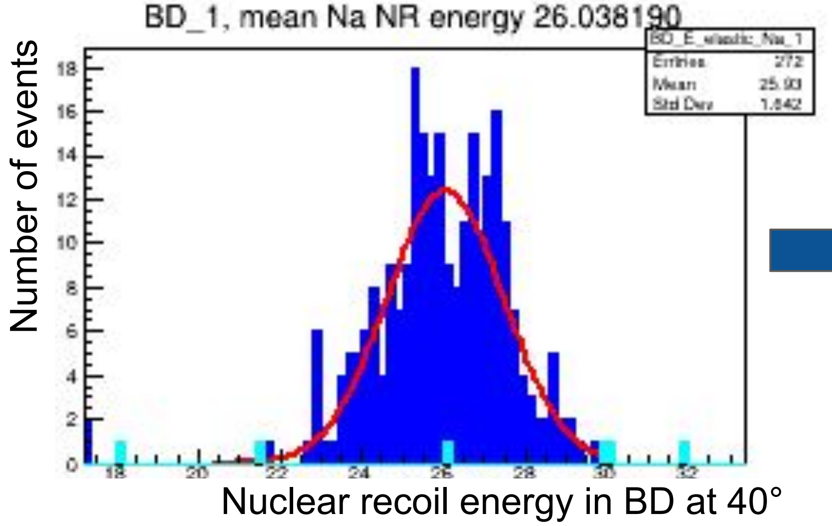


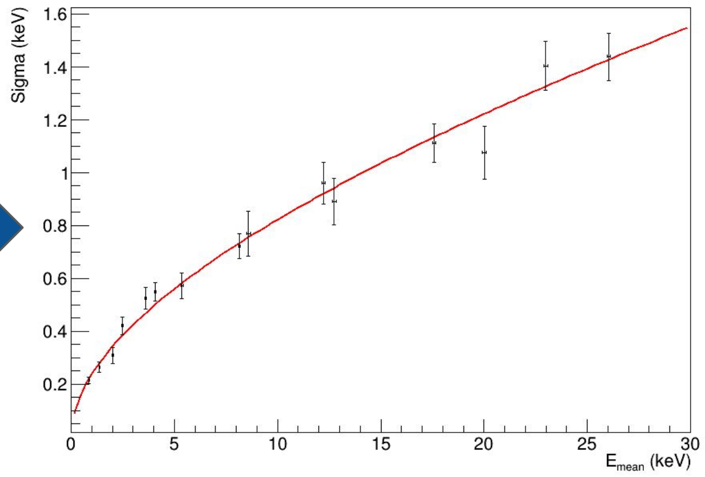
Energy deposition in a BD depending on the neutron scattering angle:

$$E_{nr} = 2E_n \frac{m_n^2}{(m_n + m_N)^2} \left(\frac{m_N}{m_n} + sin^2\theta - cos\theta \sqrt{(\frac{m_N}{m_n})^2 - sin^2\theta} \right)$$

m_n, m_N: mass of the neutron and target nuclide respectively

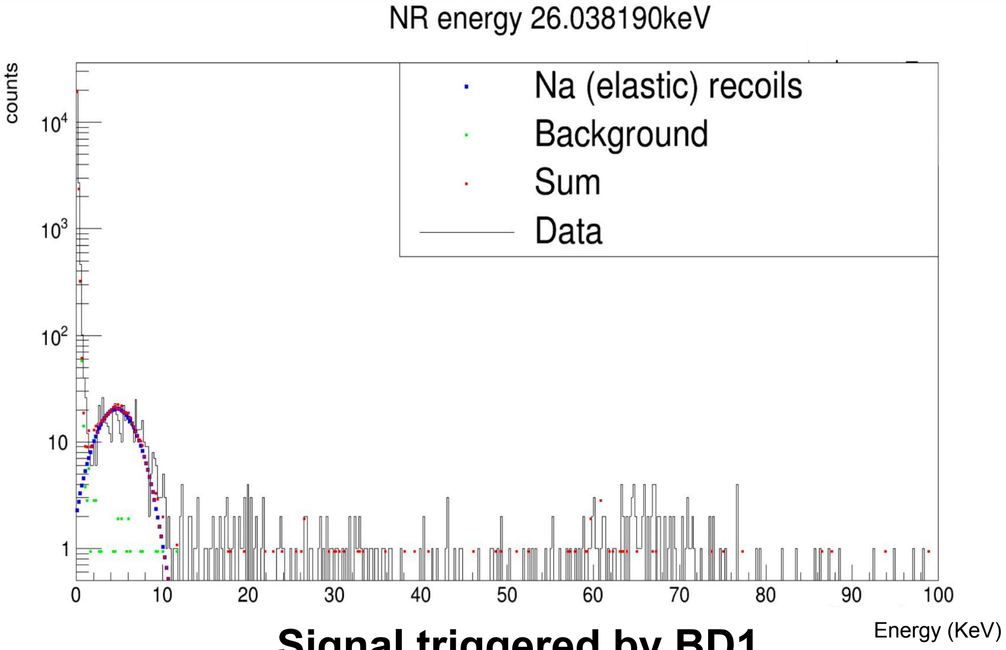
Resolution of simulated nuclear recoil spectra





Resolution as a function of energy of simulated peaks fitted using $\sqrt{ax}+bx$

QF estimation (Na recoils)



Signal triggered by BD1

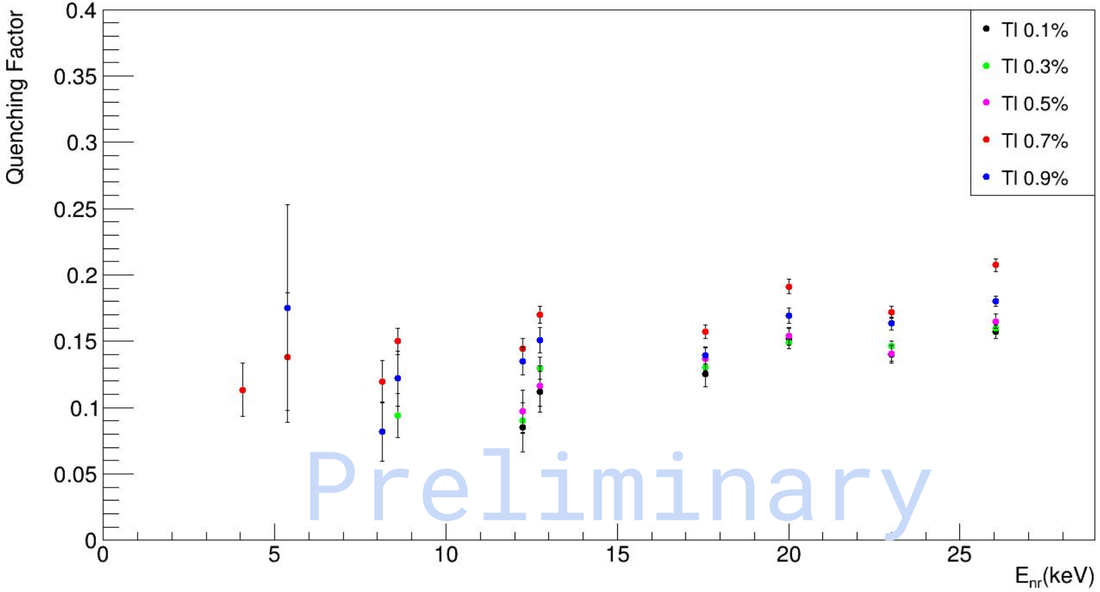
A — **Step 1:**
Calibration + resolution of PMT attached to NaI

B — **Step 2:**
True nuclear recoil energy simulated. Nuclear recoil energy resolution extracted from the simulated nuclear recoil energy

C — **Step 3:**
Measured energy from PMT attached to NaI converted to keV using step 1. Signal gaussian is fitted using the extracted background, width given by the 2 resolution functions

D — **Step 4:**
The fitted mean of the gaussian is compared against the mean of simulated nuclear recoil energy histogram → QF

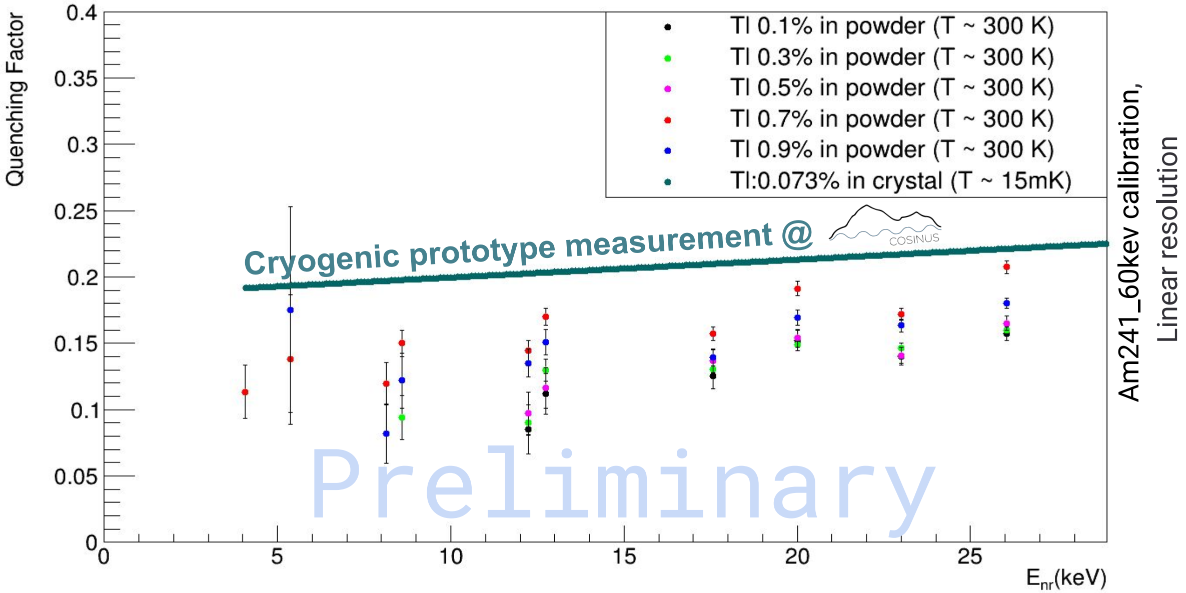
QF(Na): preliminary results



Am241_60kev calibration,
Linear resolution

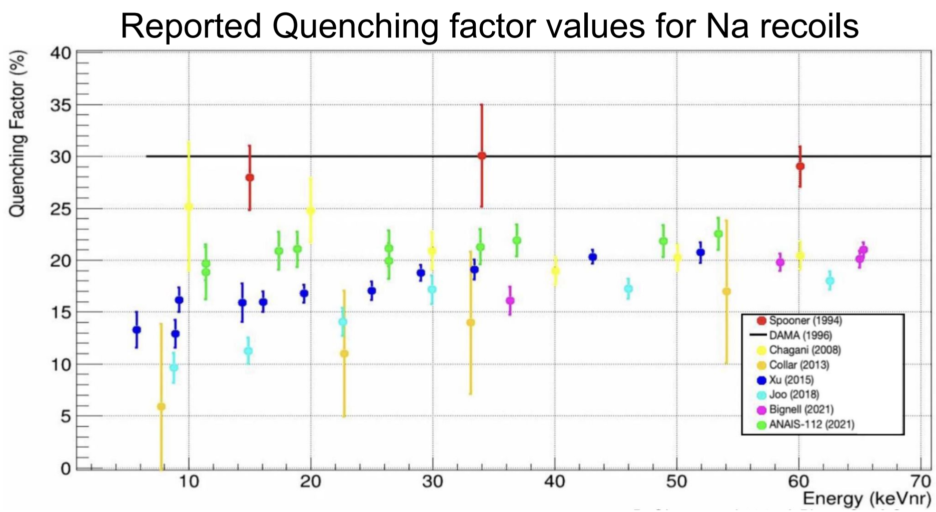
- An energy-dependent trend is observed in QF (Na recoils): QF decreases as nuclear recoil energy declines

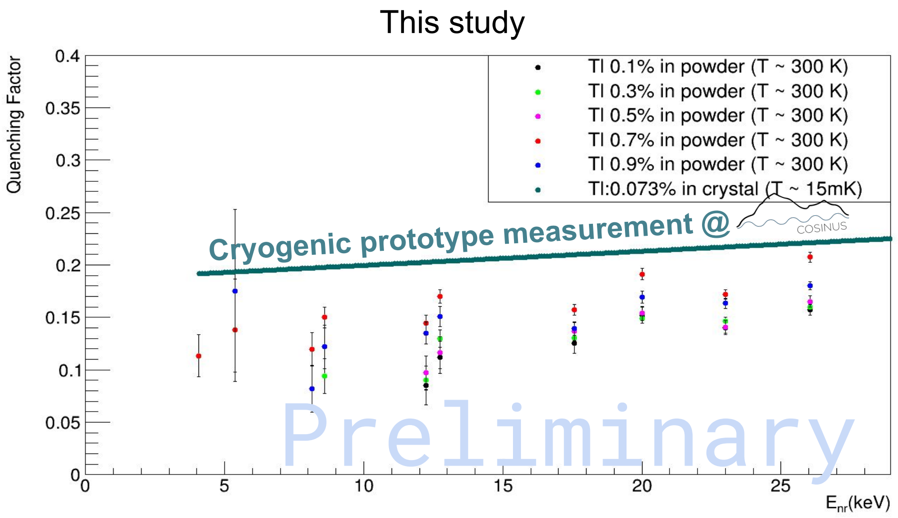
Comparison with cryogenic measurement



- An energy-dependent trend is apparent in QF (Na recoils): QF decreases as nuclear recoil energy declines
- In-situ cryogenic measurement with a prototype NaI(TI) remo-TES detector demonstrates a similar energy-dependent behaviour of QF [arXiv: 2307.11139]

Comparison of QF(Na) with other measurements

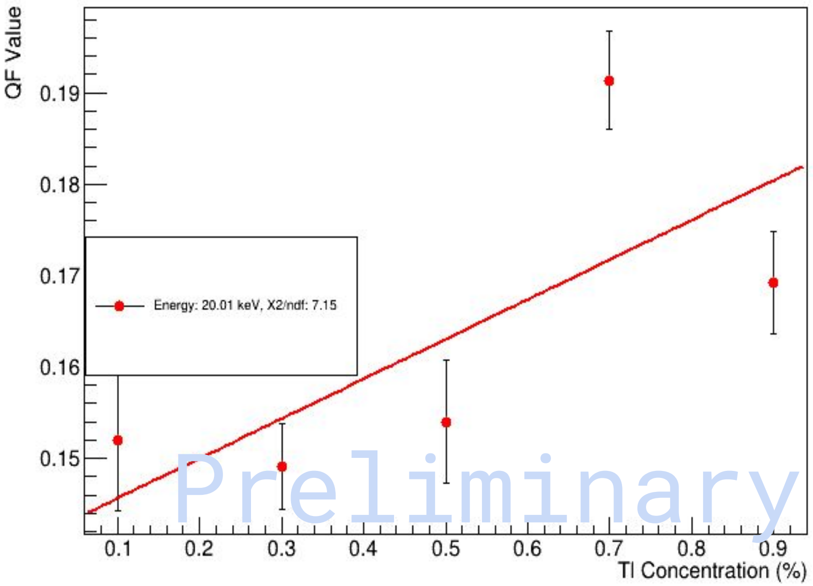




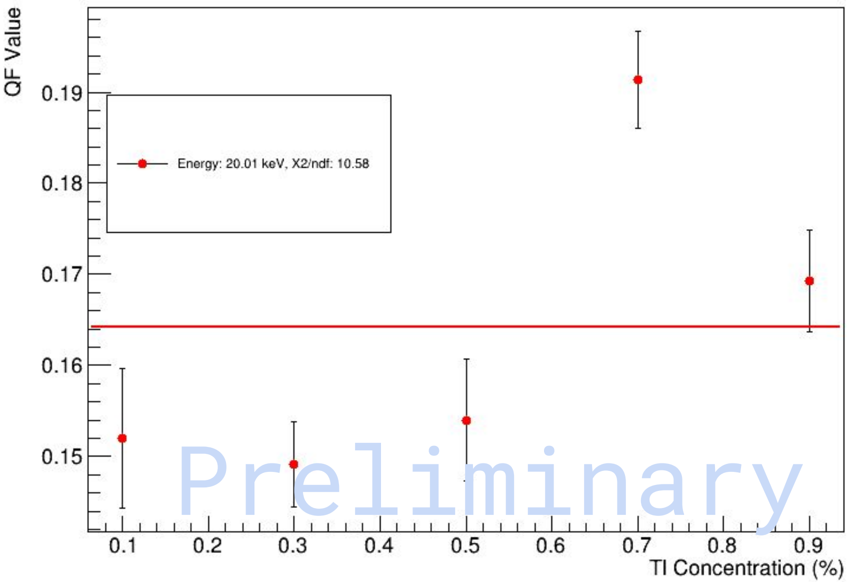
- This measurement aligns with other QF measurements that report energy-dependent behavior of QF

Tl dopant concentration dependence of QF(Na)

Linear fit



constant QF fit

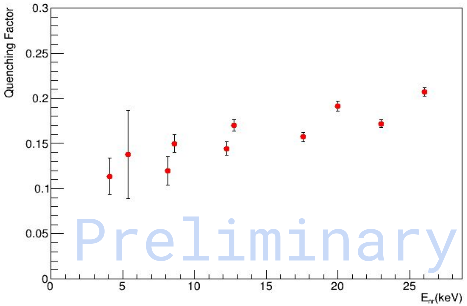
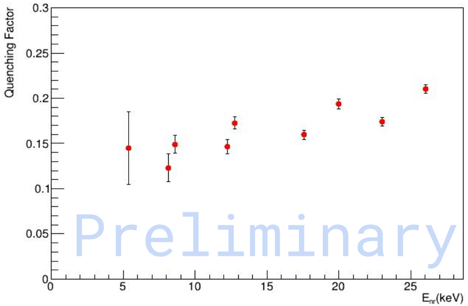
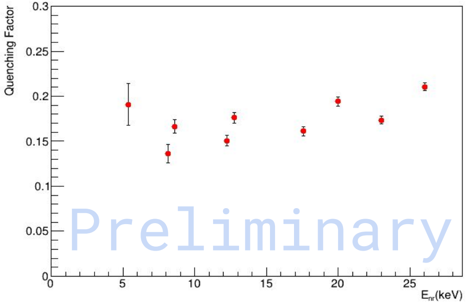
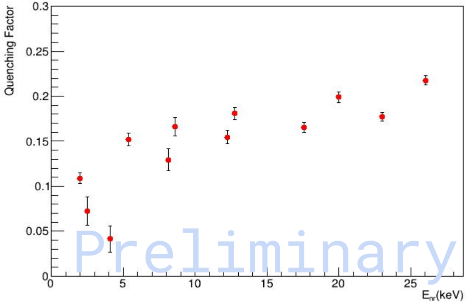


- Preliminary indication of Tl dopant concentration dependence on QF

Effect of different calibration and resolution on QF(Na)

COSINUS

Crystal with 0.7% Tl dopant concentration

	Am241(60 keV) calibration	Ba133(linear) calibration
$ax + b$ resolution		
$\sqrt{ax} + bx$ resolution		

Different calibration and resolution methods (shown in slide 9) influences the QF behavior

Conclusions

COSINUS

- **Five NaI crystals,** each with **unique Tl dopant concentration** measured at the neutron calibration facility at Triangle Universities National Laboratory (TUNL), USA
- **QF (Na recoils) decreases at lower nuclear recoil energy** → emphasizing the **need for energy-dependent calibration**
- **Lower Tl dopant concentration linked to reduced QF (Na recoils)**, indicating **Tl dopant's role in crystal response**
- Different **calibration and resolution methods demonstrated significant influence on QF behavior**, highlighting the **necessity of precise methodologies** while comparing dark matter results from different experiments
- A publication is currently under preparation
- QF (I recoils) unattainable in the current set up due to extremely low recoil energies

Thank you

for your attention

Accelerator facility at TUNL, USA

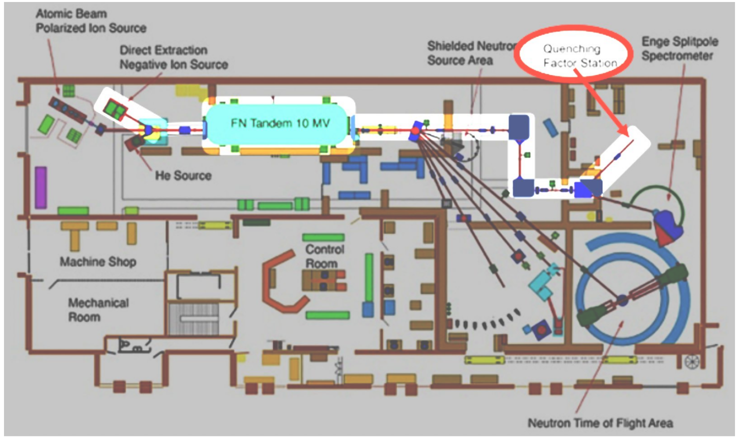
Triangle Universities Nuclear Laboratory

COSINUS

- Tandem Van de Graaff accelerator with maximum potential difference 10 MV
- Pulsed beam of protons interacts with the LiF target generating pulsed beam of quasi mono-energetic (~1500 keV) neutron
- A beam pulse monitor (BPM) records the time of neutron production (interaction of proton with LiF)

Additional details of the QF measurement setup

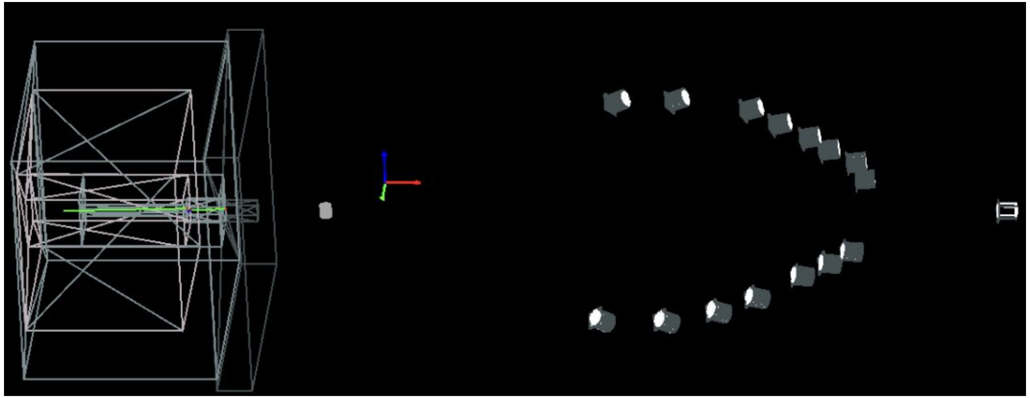
- A backing detector at 0 degree to measure time of flight (TOF) to monitor the spread of neutron energy
- A beam pulse monitor (BPM) records the time of neutron production (interaction of proton with LiF)

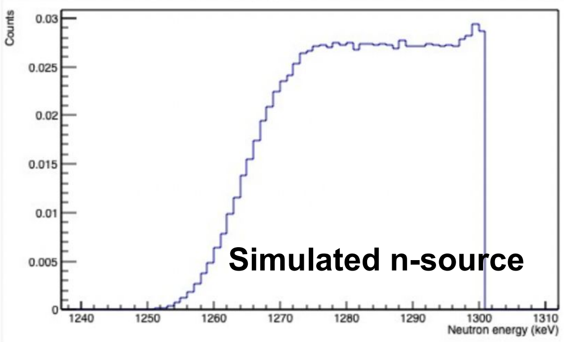


Beam parameters:

- Proton beam energy: 1495 keV
- Proton pulsing time: 400 ns
- Pulse width: 2ns FWHM
- Proton beam current: 900nA
- LiF target thickness: 1434 nm

Simulated geometry and n-source

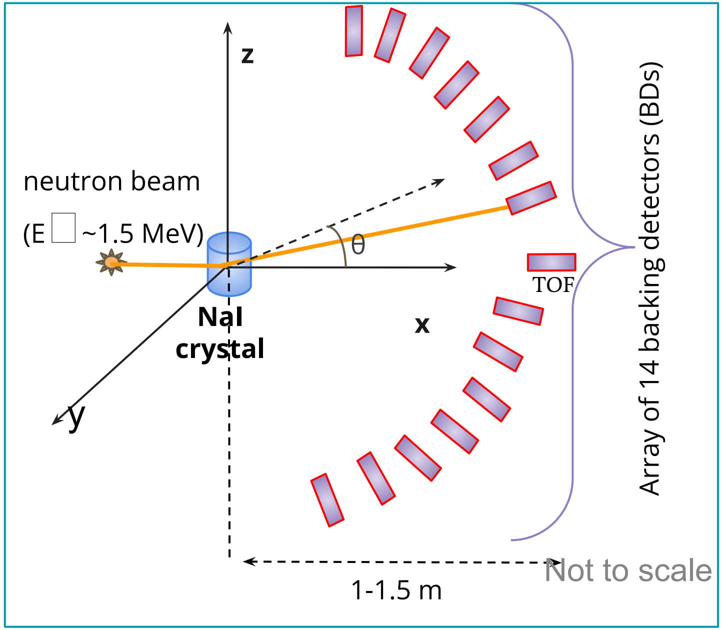




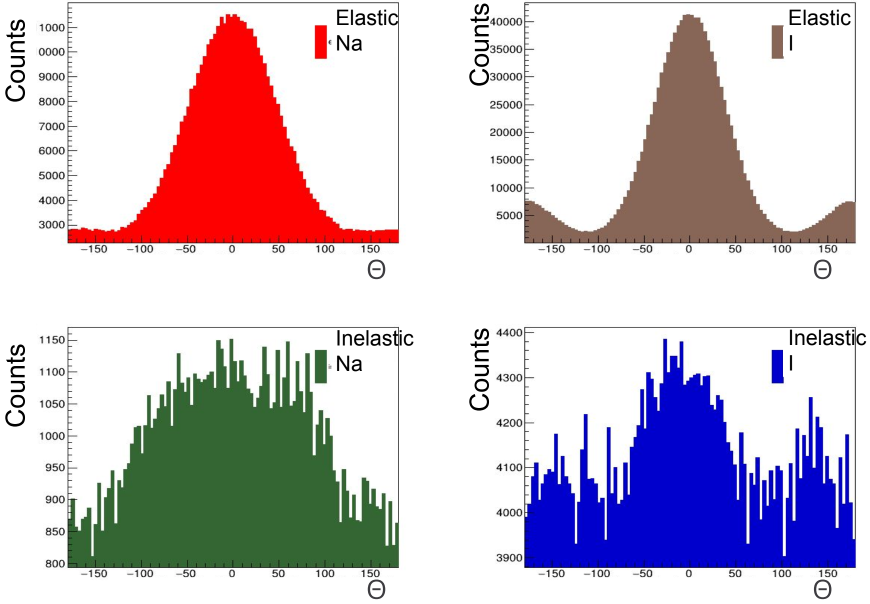
The following things were simulated:

- NaI(TI) crystal and complete housing
  - NaI cylindrical crystal
  - Al Casing
- Backing detector(s)
  - Liquid scintillator: cylindrical EJ-309
  - Al Casing
  - Lead cap (cylinder + square plate)
- Collimator made of BPE and HDPE
- Ba 133, Am 341, Cs 137 source for calibration
- Quasi-monoenergetic neutron source (~1500 keV)

Geant4 simulation to setup the experiment

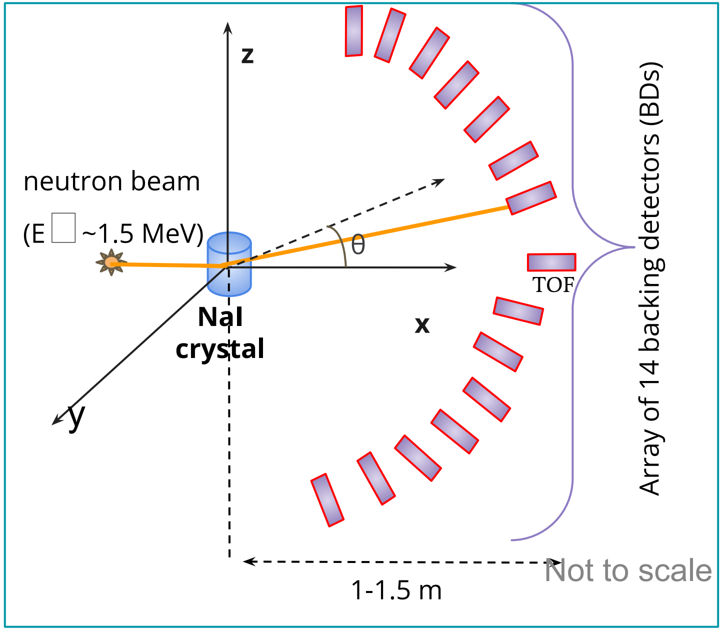


Finding suitable angular range to place the BDs:

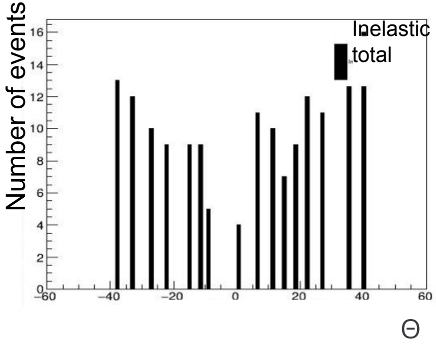


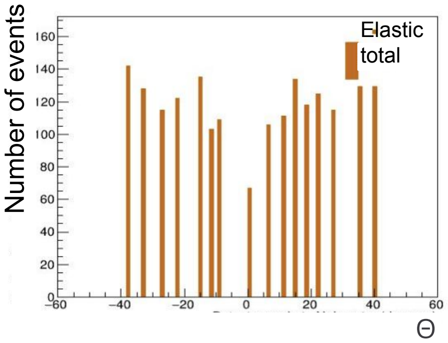
Based on the simulation the BDs are placed between -40 to 40 degrees

Geant4 simulation to setup the experiment



Ensuring enough neutro reaching each BD:



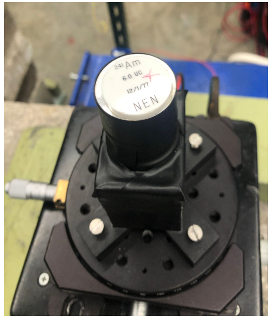


Simulation of the calibration spectra

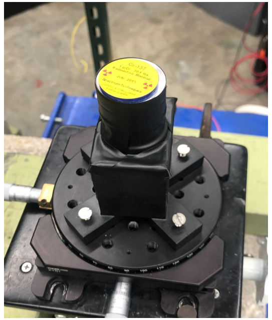
COSINUS

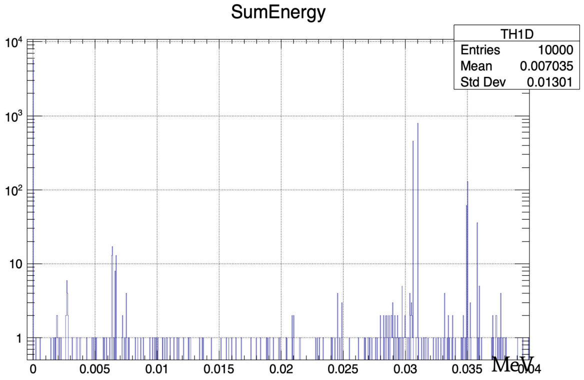
Ba-133

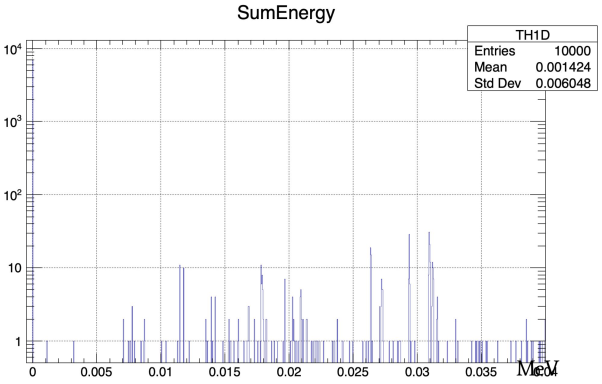
Am-241

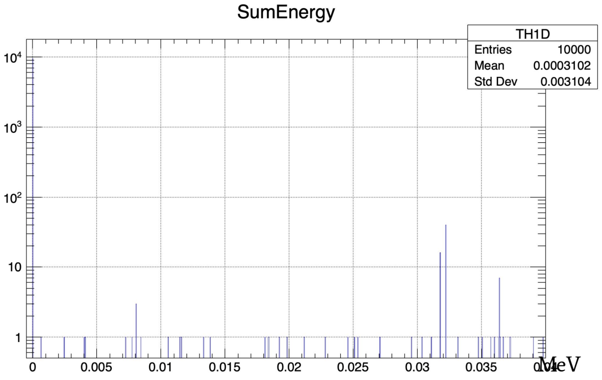


Cs-137



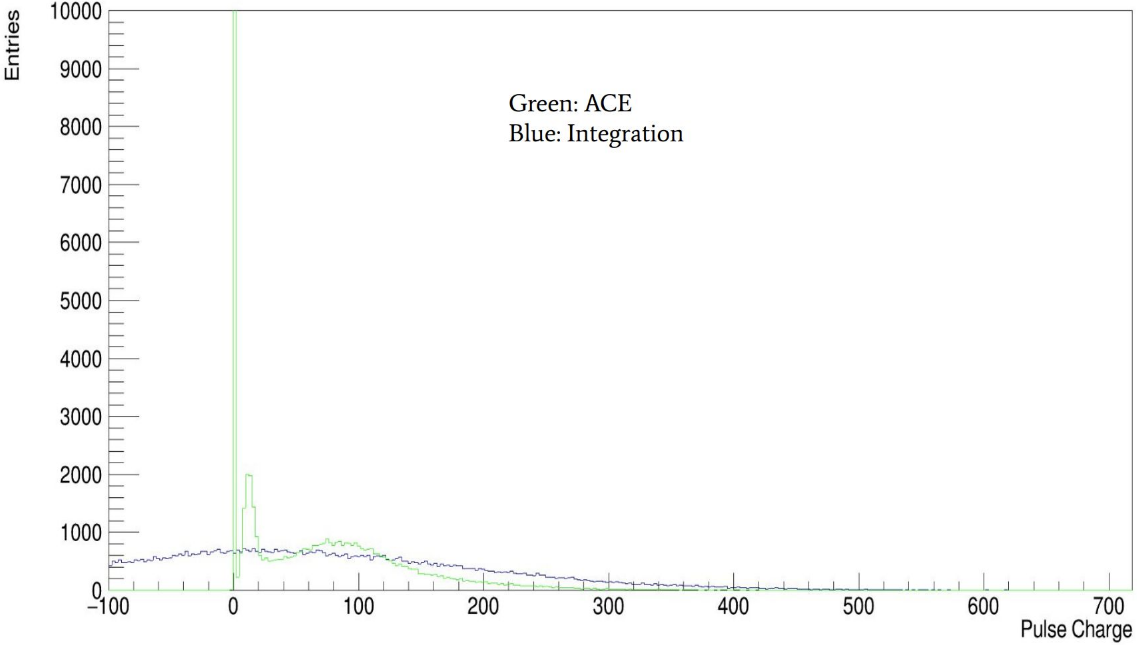






PMT energy estimation

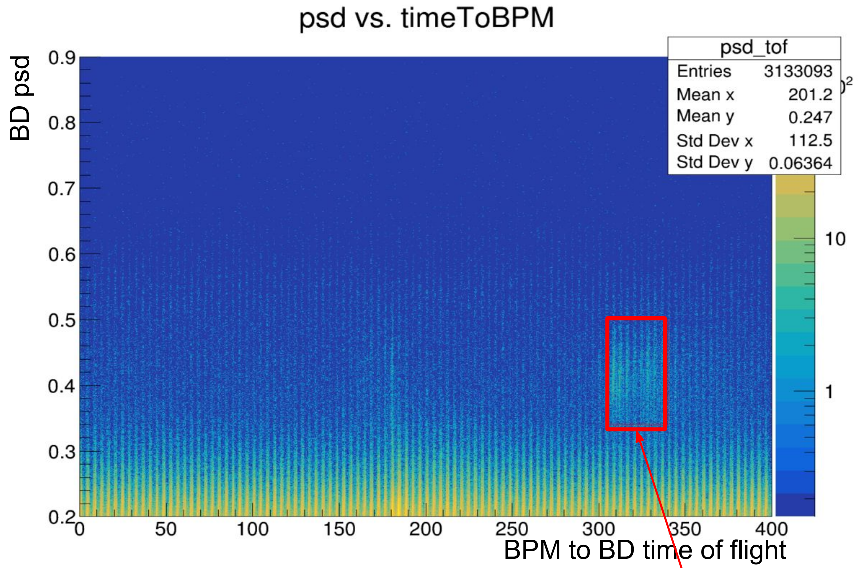
FWin (Fixed Window integration) V/S ACE (Adopted Charge estimation)

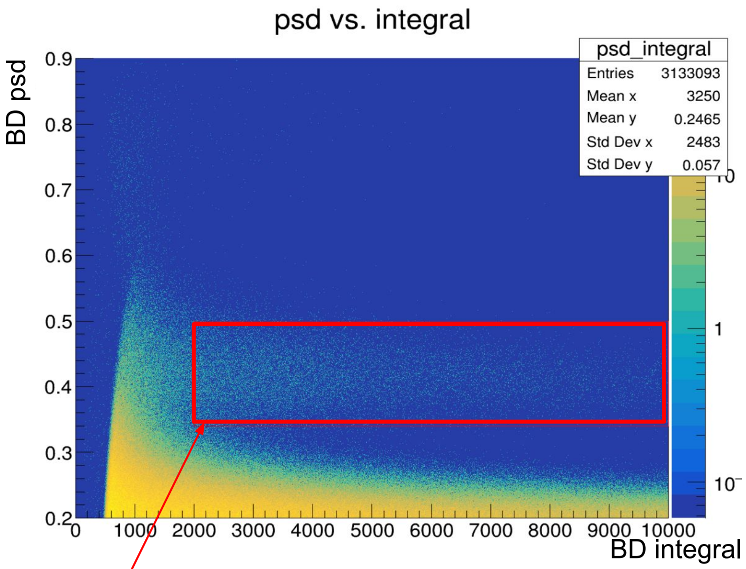


- ACE (arXiv:2102.02833) was used to estimate PMT charge

Neutron selection

- BPM to BD time-of-flight and pulse shape parameter (PSD) are used to select **neutrons** for further analysis
- Also used the digitizer pileup flag to remove double events

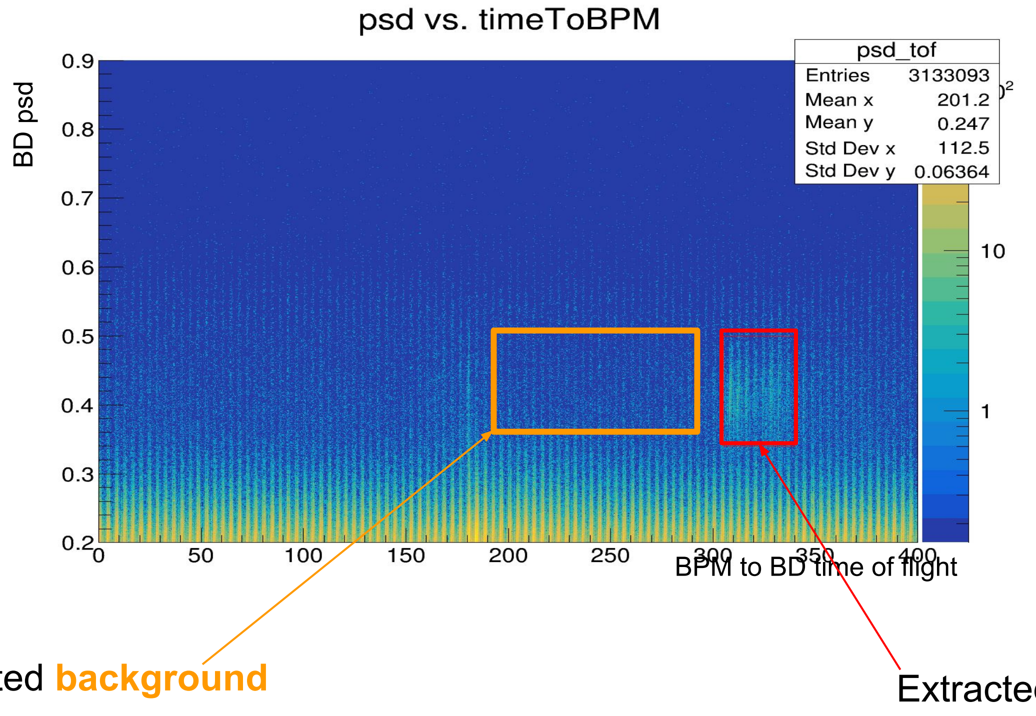




Extracted **neutron**

Background extraction

by shifting the BPM parameter



Systematic uncertainty due to beam shift

COSINUS

1. A beam shift could explain the systematic sawtooth pattern observed in the QF results
2. Solution (approach):
   a. Take rolling average of two points to find the optimum shift which best explains the sawtooth pattern
   b. If we change the angle by 0.7 degrees and recalculate the nuclear recoil energies, then the sawtooth pattern reduces
3. Remarks: While this method reduces the sawtooth pattern effectively, it makes it challenging to compare with other results