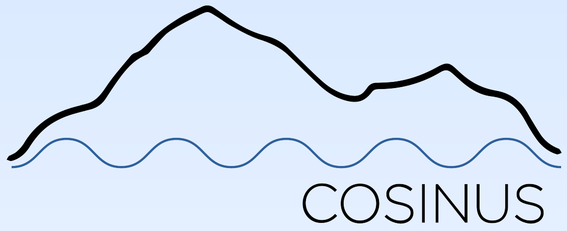
DPG Frühjahrstagung
Dresden 2023

Studies on the effects of Tl% to quenching factor measurements in NaI

Mukund Bharadwaj | On behalf of the COSINUS collaboration
15.03.2023



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Overview

1. Motivation
   - QF primer
   - Current status of NaI QF
   - Impact on experimental inferences
2. Experimental setup
   - Crystal characterization
   - Accelerator facility
   - Test setup
3. Analysis
   - List cleanup and selection
   - QF extraction
4. Conclusion & future outlook

Motivation

QF primer

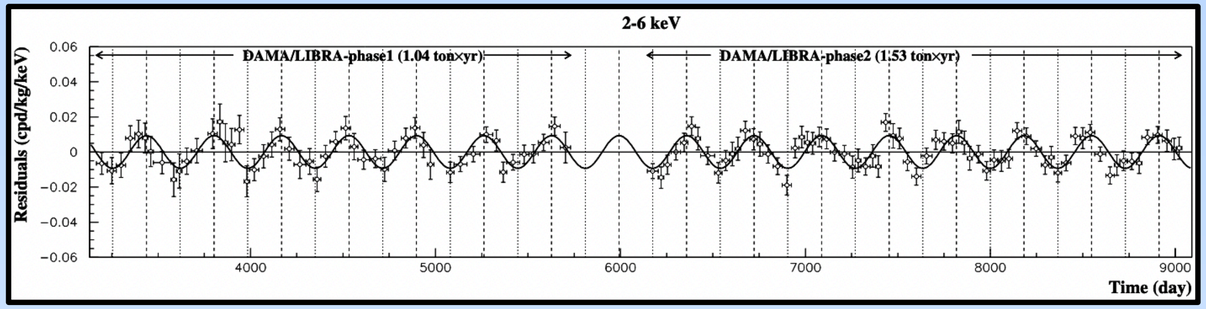
Electron recoil and a nuclear recoil of the same energy produce different intensities of scintillation light within the same target material.

Quenching Factor (QF): parameter introduced to help extract the "true" nuclear recoil energy.

$$QF = \frac{L_{nr}}{L_{ee}}$$

Motivation

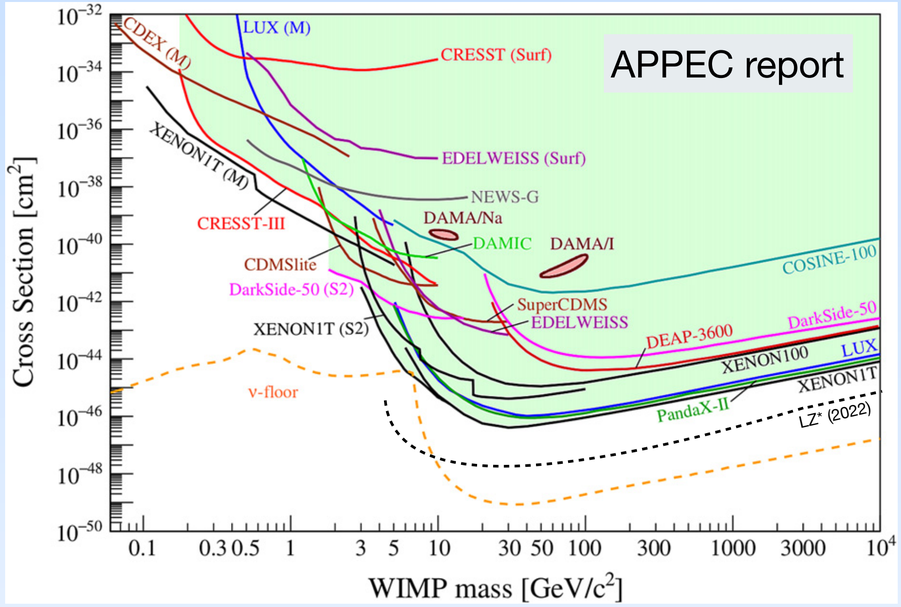
Direct DM searches



R. Bernabei et al., Nucl. Phys. At. Energy, 22(4):329–342, 2022.

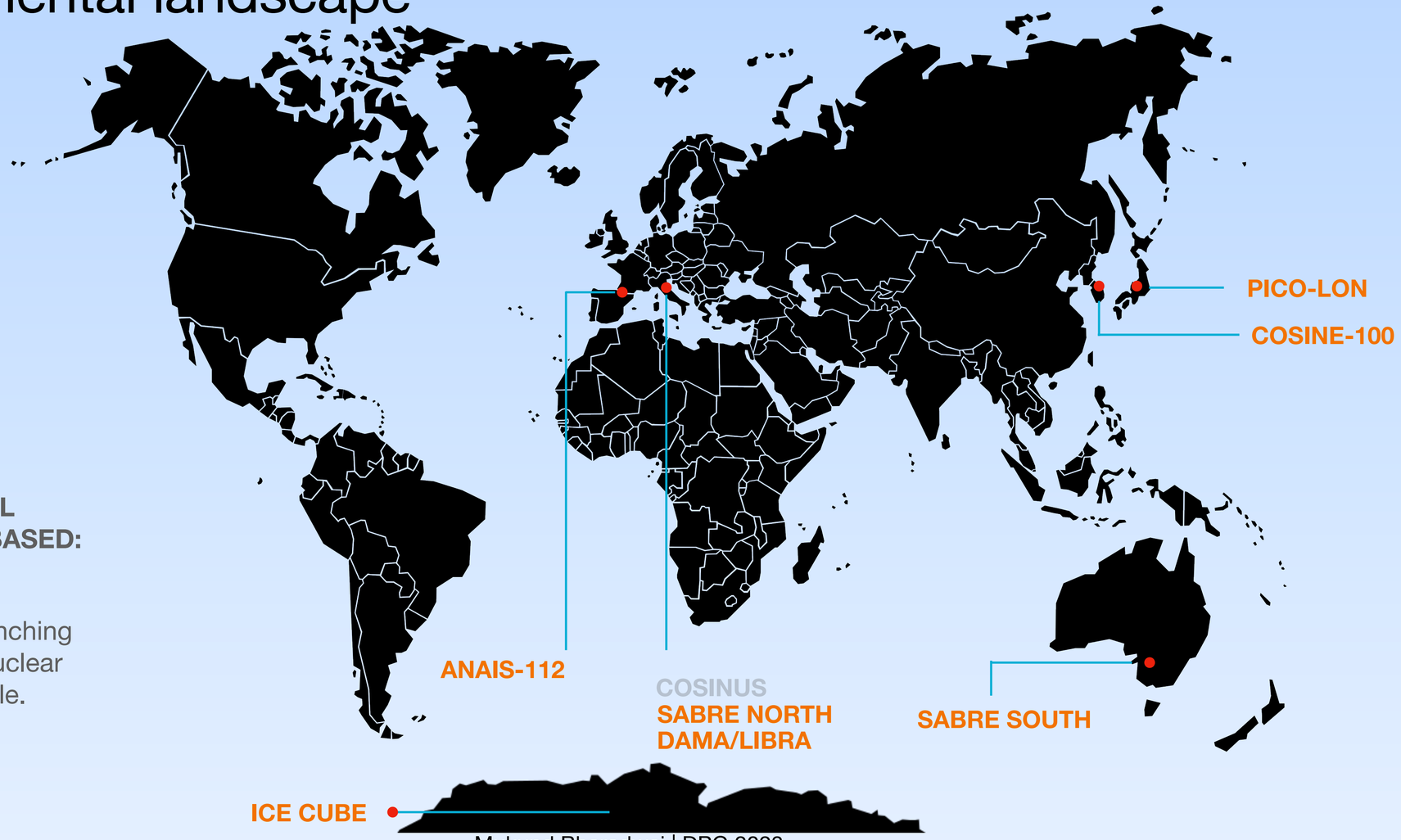
- Target material: NaI
- Total exposure: 2.86 tonne years
- C.L: 13.7 sigma in (2-6 keV_{ee})
  11.6 sigma in (1-6 keV_{ee})

Julien Billard et al 2022 Rep. Prog. Phys. 85 056201



Motivation

NaI experimental landscape

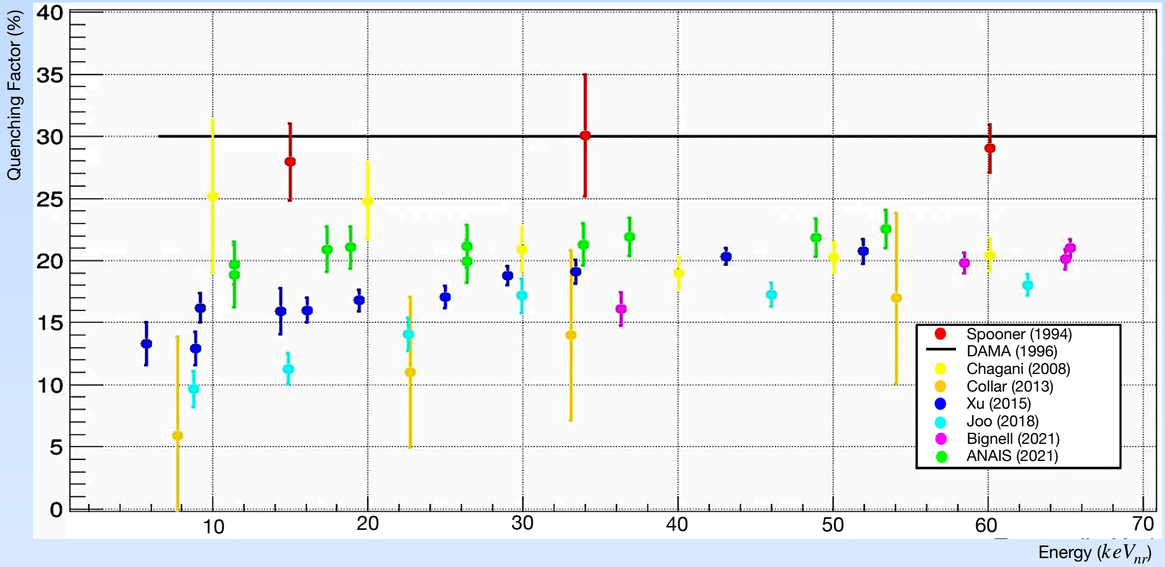


SINGLE-CHANNEL SCINTILLATION BASED:

- Influence of Quenching Factor (QF) on nuclear recoil energy scale.

Motivation

QF of Na recoils



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

- Strong influence of QF on signal interpretation on nuclear recoil energy scale of scintillation-only experiments.
- Measurements of quenching factors (QF) at room temperature disagree.

Experimental setup

Dependence on Tl dopant on QF?

Aim:

Target low recoil energy region (1-30keV_{nr})

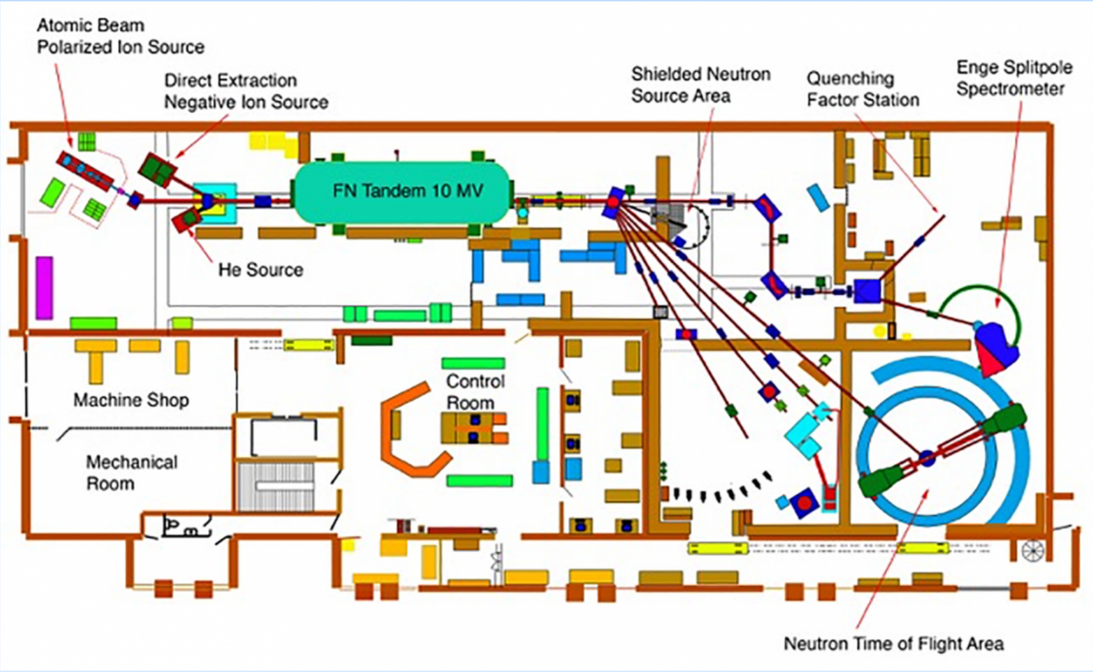
Crystal characteristics:

- Utilise extremely radio-pure* Tl doped NaI crystals manufactured by SICCAS, Shanghai:
- ^{40}K : <10ppb; ^{232}Th: ~10ppt; ^{238}U: ~20ppt
- Radioactive contamination comparable/better than DAMA crystals.

Special thanks to Y. Zhu, Z.W Ge, I.Dafinei and group!

Experimental setup

Accelerator facility

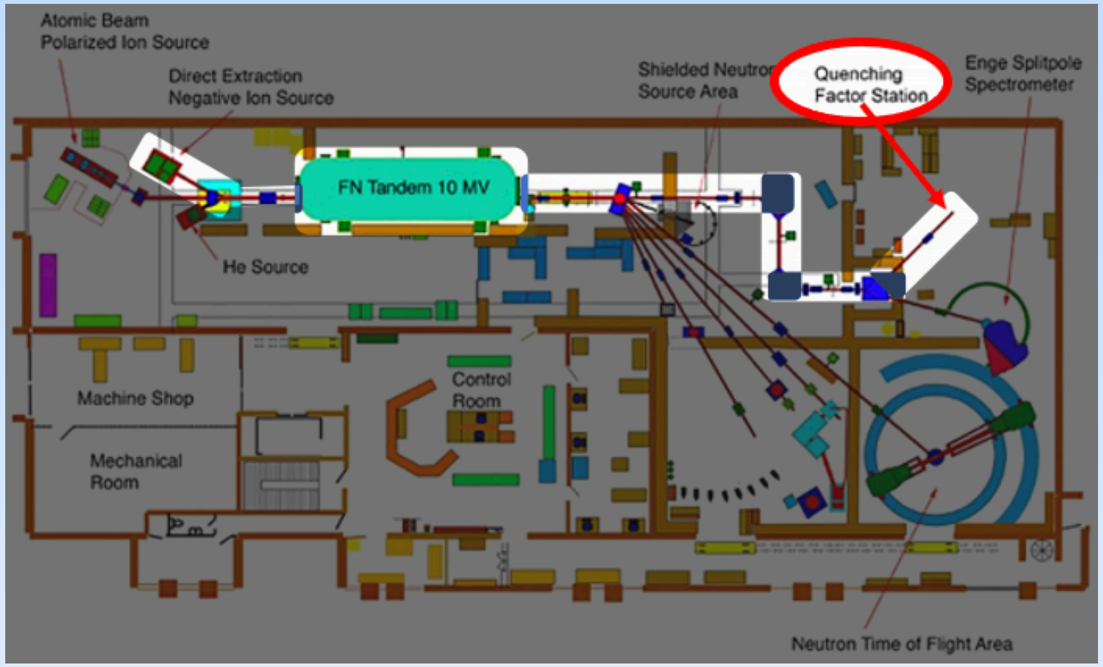


Experiment conducted in collaboration with Duke University at the Triangle Universities Nuclear Laboratory (TUNL).

Special thanks to P. Barbeau, S. Hedges et. al for all the help at various points along the way :)

Experimental setup

Accelerator facility



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

Experimental setup

Test setup

Detector No.	Tl conc. (initial powder)	Tl conc. (grown crystal)
8-1-01-B	0.1%	0.13%
8-2-03-B	0.3%	0.21%
8-3-05-B	0.5%	0.39%
8-4-07-B	0.7%	0.62%
8-5-09-B	0.9%	0.68%
Dummy	-	-

- Small crystal size -> Reduce multiple scatters (d:30.5mm, h:32mm)
- Crystal rotation -> Reduce ion channeling effects.

Experimental setup

Test setup

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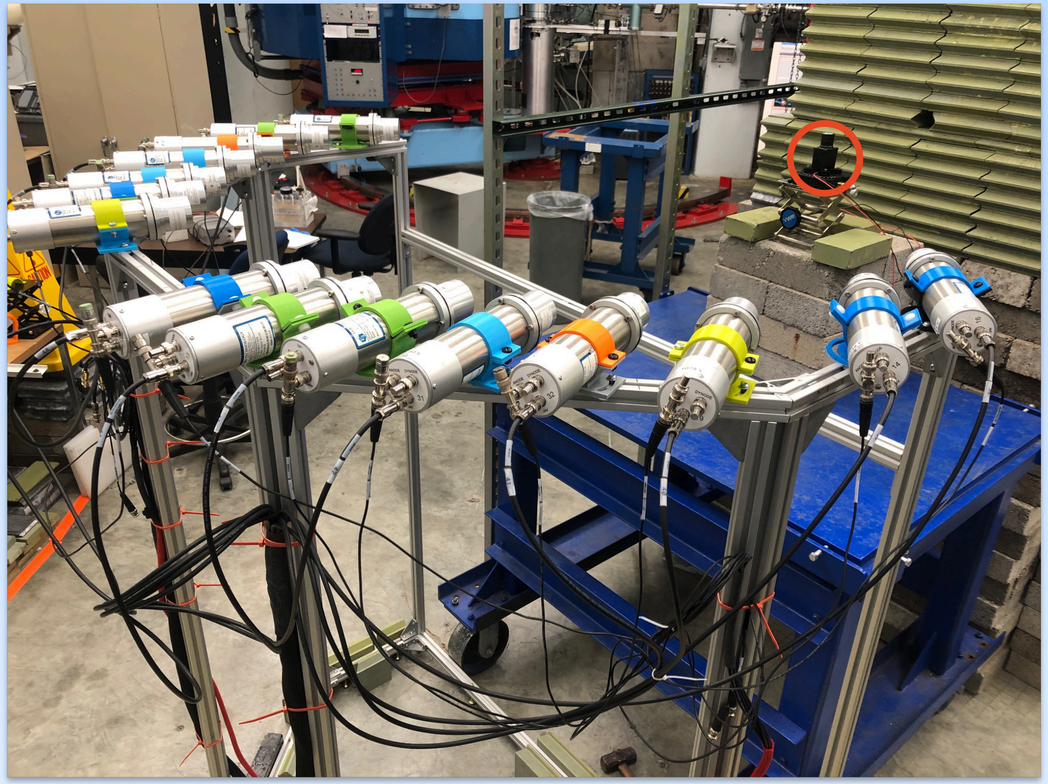

- Small crystal size -> Reduce multiple scatters (d:30.5mm, h:32mm)
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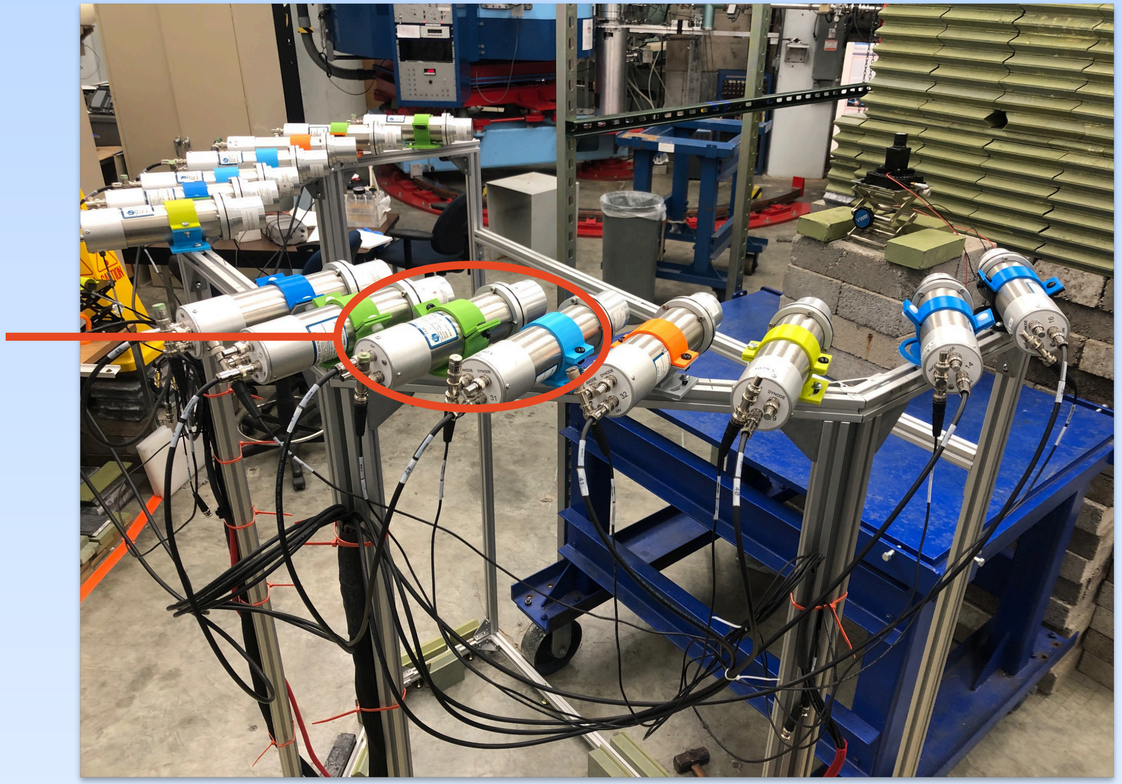
Experimental setup

Test setup

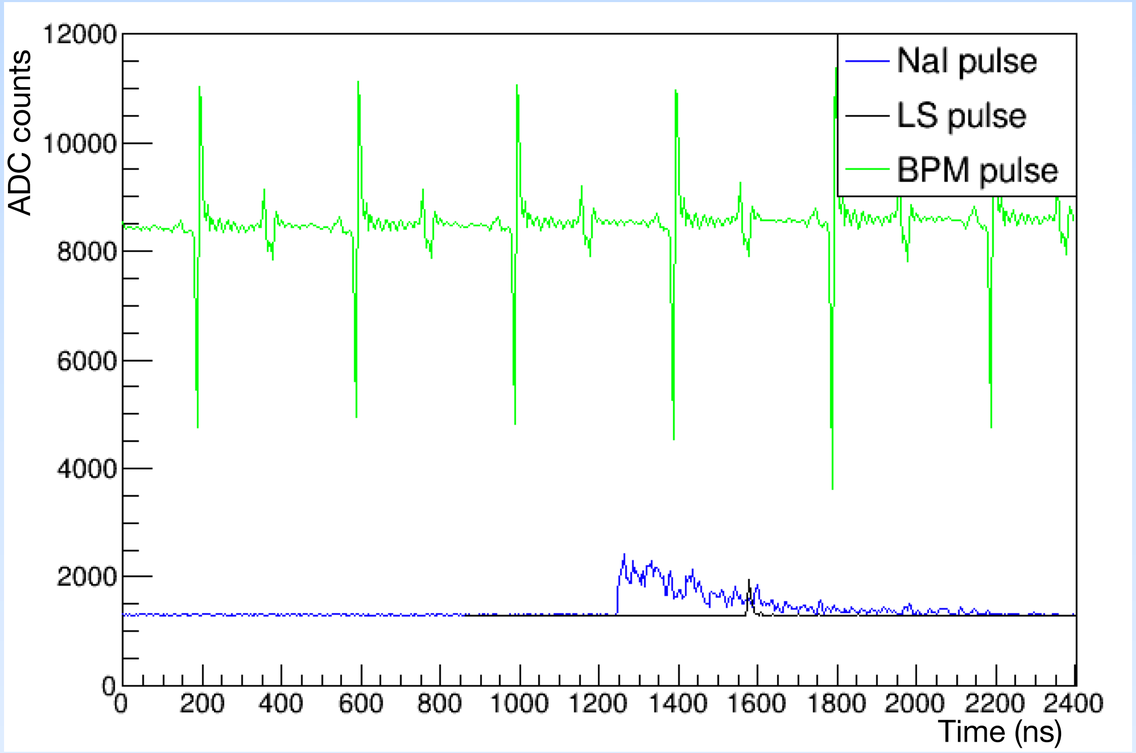
- 15 liquid scintillators, denoted as backing detectors (BD).
- Used to tag the scattered neutrons off the Na or I nuclei to determine energy deposition in the crystal.



Analysis

Trigger scheme

Pulse readout for elastic neutron scattering event



- Threshold free trigger scheme implemented.
- NaI pulses reconstructed using adopted charge estimate*, ensuring good reconstruction of low-energy NaI events.

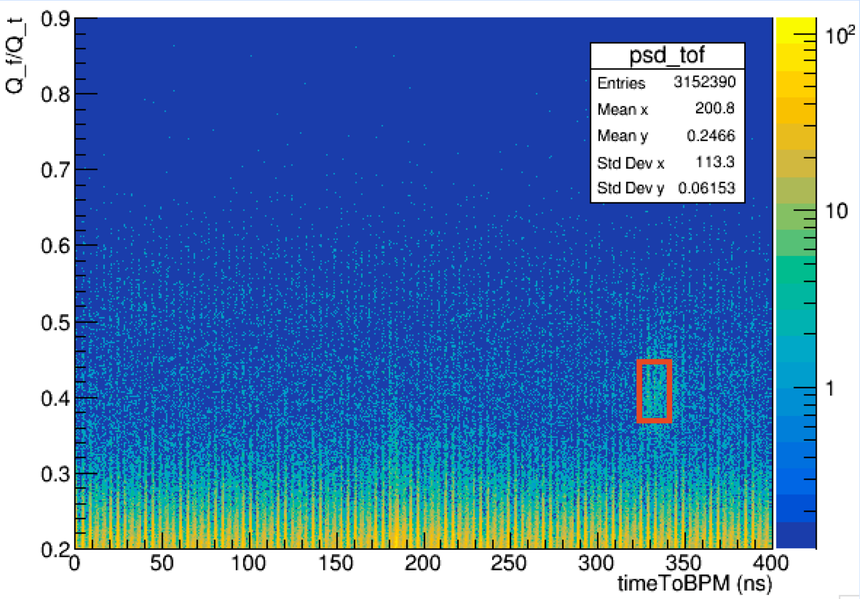
*L.J. Bignell et al 2021 JINST 16 P07034

Analysis

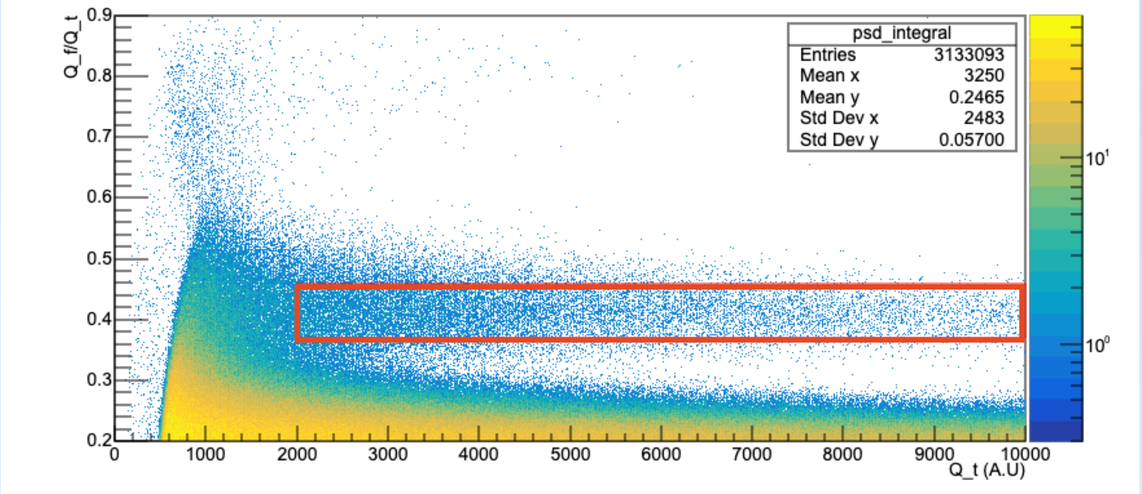
Neutron event selection

Applied cuts:

- Time Of Flight cut w.r.t BPM.



- Pulse Shape Discrimination cut on BD.



$$PSD = \frac{Q_f}{Q_t}$$

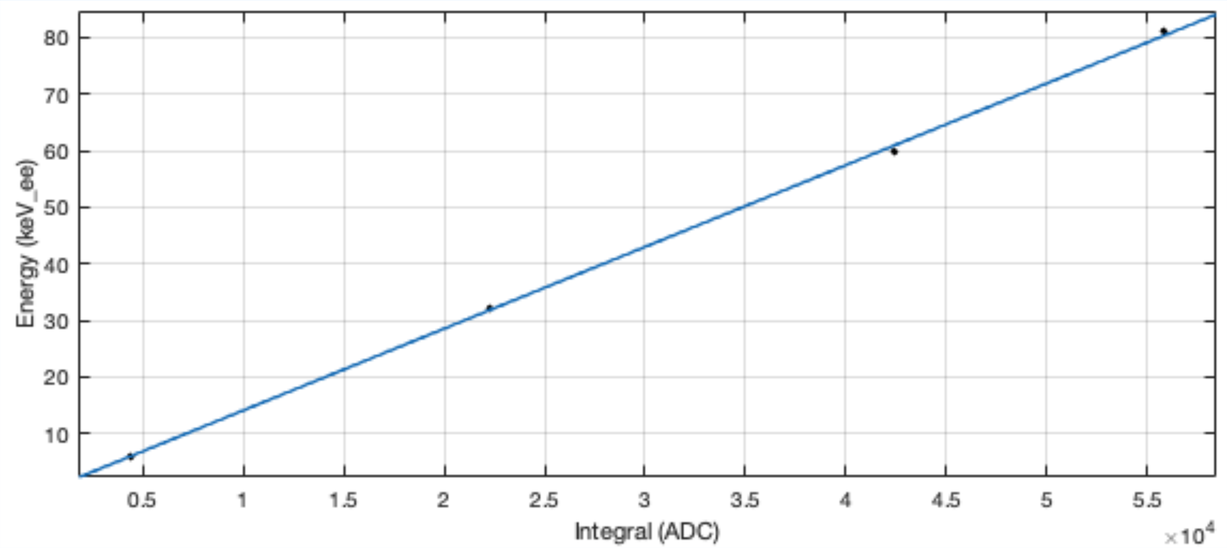
Q_f : Charge in second half of the pulse

Q_t : Total pulse charge

Analysis

Energy calibration for NaI PMT

Energy calibration for crystal - 1



- Low energy calibration peaks cross-checked with GEANT4 simulations to account for low-energy X-ray emission peaks.
- Linear calibration function chosen for the following analysis.

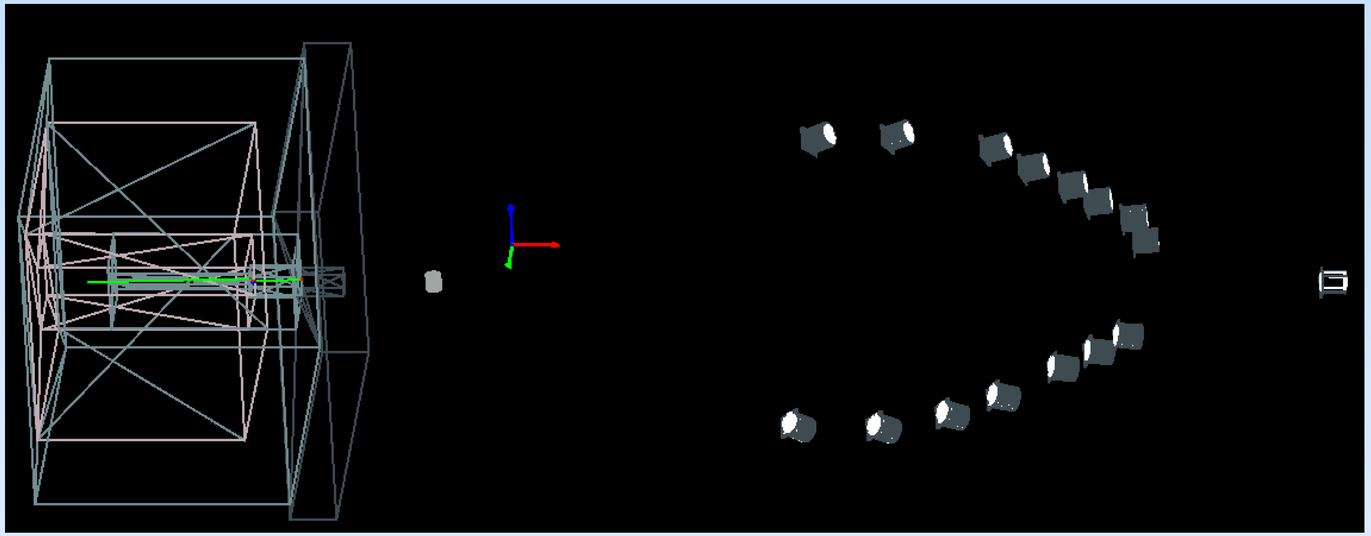
Linear calibration function: a*ADC + b

a: 1.446±0.08keV
b: (1.47)*10-4 keV/ADC

Analysis

Energy calibration for NaI PMT

GEANT4 simulation of the entire setup



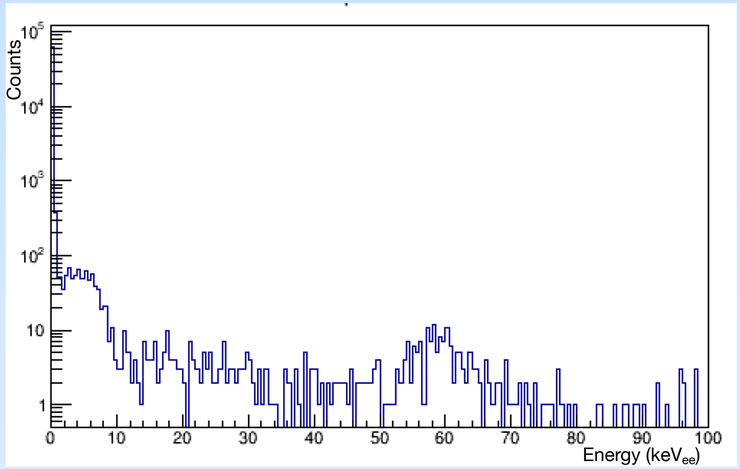
Used to extract "true" nuclear recoil energy scale (keV_{nr})

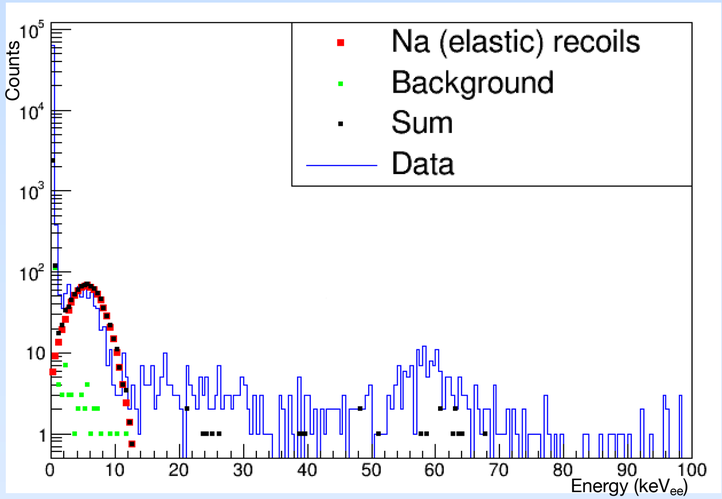
Analysis

QF estimation

Mean from simulated distribution + exp. bgd. distribution is fit with Gaussian function and QF as free parameters to exp. data.

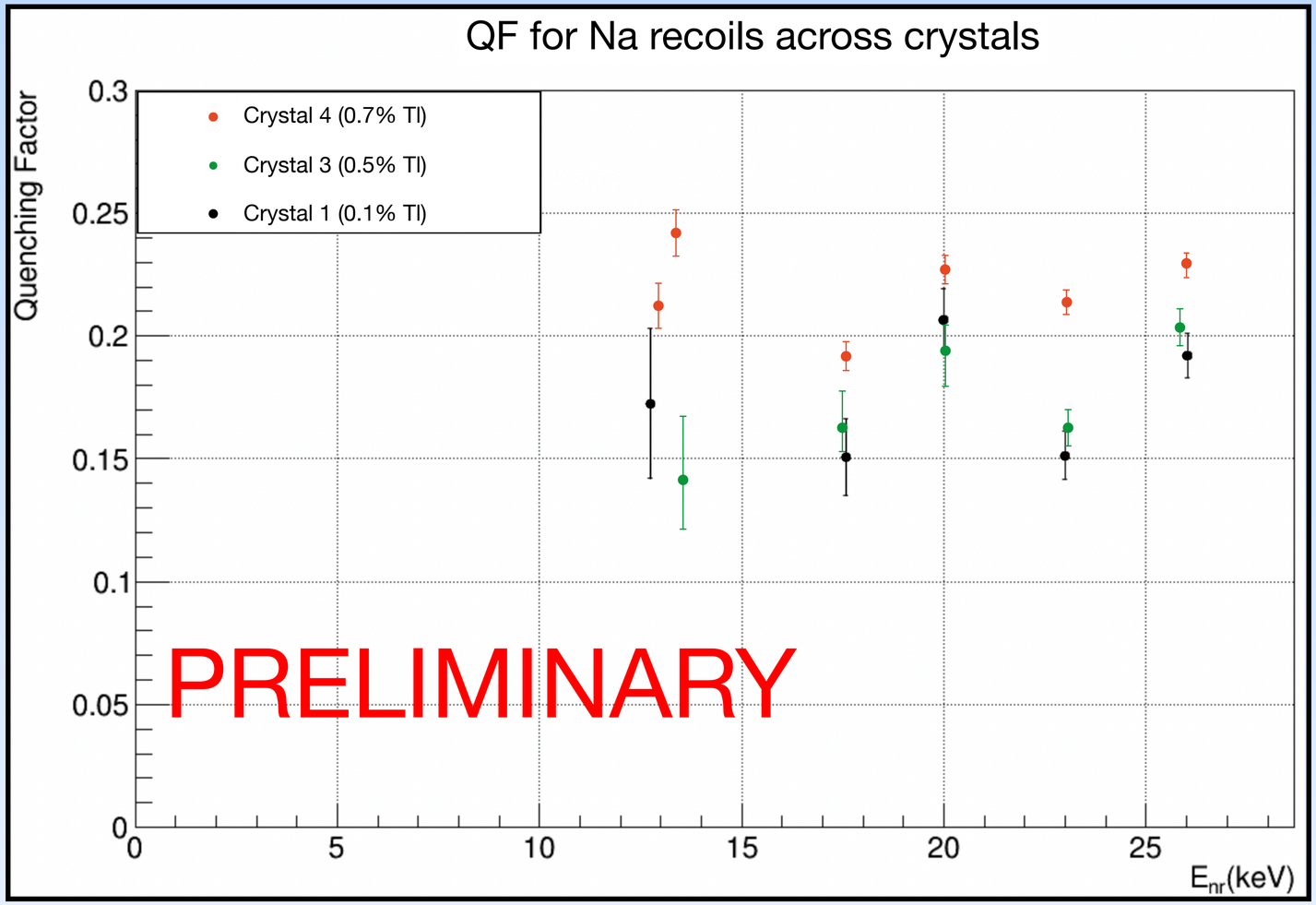
Crystal-1, BD-0 calibrated spectra (exp.)





Analysis

QF estimation



Conclusions

- 5 NaI crystals with differing Tl dopants tested at neutron calibration facility at Triangle Universities National Laboratory (TUNL).
- No clear energy dependence of QF (Na recoils) is observed in the energy range ~ 10keV$_{nr}$ - 30keV$_{nr}$
- Influence of Tl% on the QF of Na recoils observed.
- QF (I recoils) could not be extracted in current setup due to extremely low recoil energies.

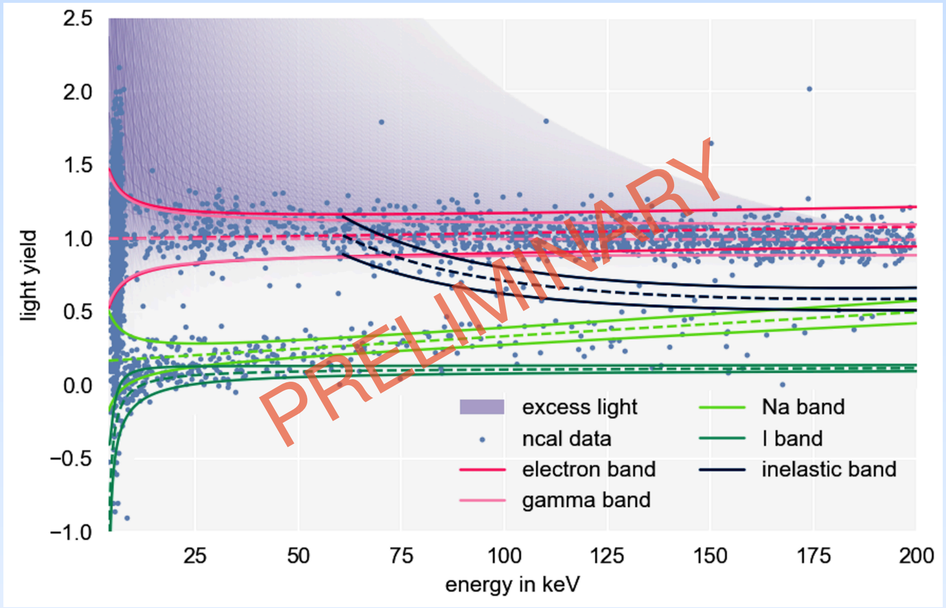
Conclusions

BONUS sneak peek:

- Cryogenic NaI calorimeter operated with ~0.07%Tl successfully (See M. Stahlberg talk T-11.4 on 02.03.23)

- QF of Na recoils empirically derived by comparing the light yield plots of neutron recoils and background/gamma recoils.

QF (Na recoils): ~0.2 in 10-30keV_{nr}



Appendix

Note on collimator

- Shielding with a collimated slit consisted of bi-layer of HDPE and borated-HDPE. Additionally, a lead wall was also consturcted in front of the collimator setup in order to reduce secondary gammas.
- Resultant neutron beam had an angular spread of 2.35° with an energy spread proportional to thickness of LiF film.

Appendix

Crystal growth cont.

- Initial NaI "Astro-grade" powder obtained from Merck and Co.
- Crystal production carried out by SICCAS in dedicated dry clean-room.
- Utilized modified Bridgman technique using double walled platinum crucibles for crystal growth. ["modified" as in allows for better control over the temperature gradient at the melt/crystal interface]

Appendix

Data acquisition

- PMT manufactured by Hamamatsu photonics (Model number: H11934-200) was optically coupled to NaI crystals; Quantum efficiency ~43%.
- BD were liq. scintillators produced by Eljen technology (Model number: M510); Scintillator medium was Gadolinium loaded in organic aromatic medium.
- Pair of SIS3316 14-bit digitizers by struck innovative systeme with a sampling frequency of 250MHz was utilized for overall data acquisition.