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A systematic study on the effects of Tl dopant contribution to quenching factor measurements in NaI crystals

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on behalf of the COSINUS collaboration

MAX-PLANCK-INSTITUT FÜR PHYSIK

COSINUS

Motivation

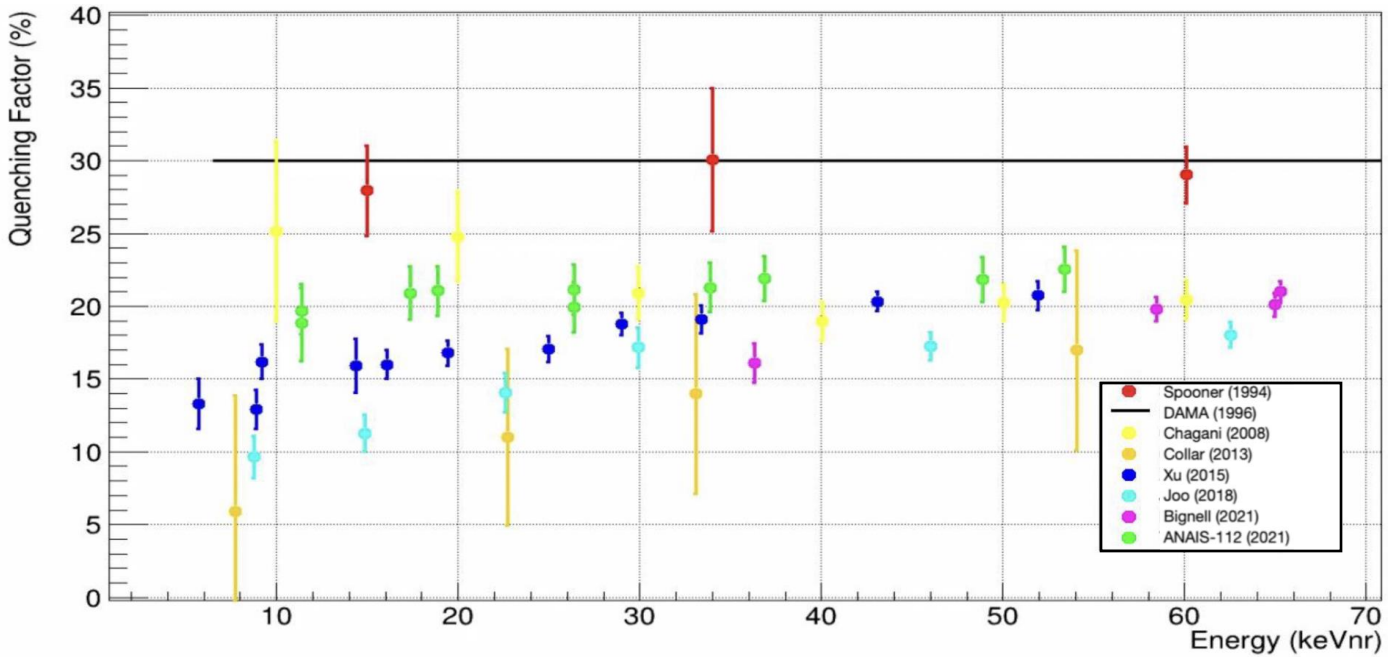
- Electron recoil and a nuclear recoil of the same energy produce different intensities of scintillation light within the same target material.

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

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

Motivation

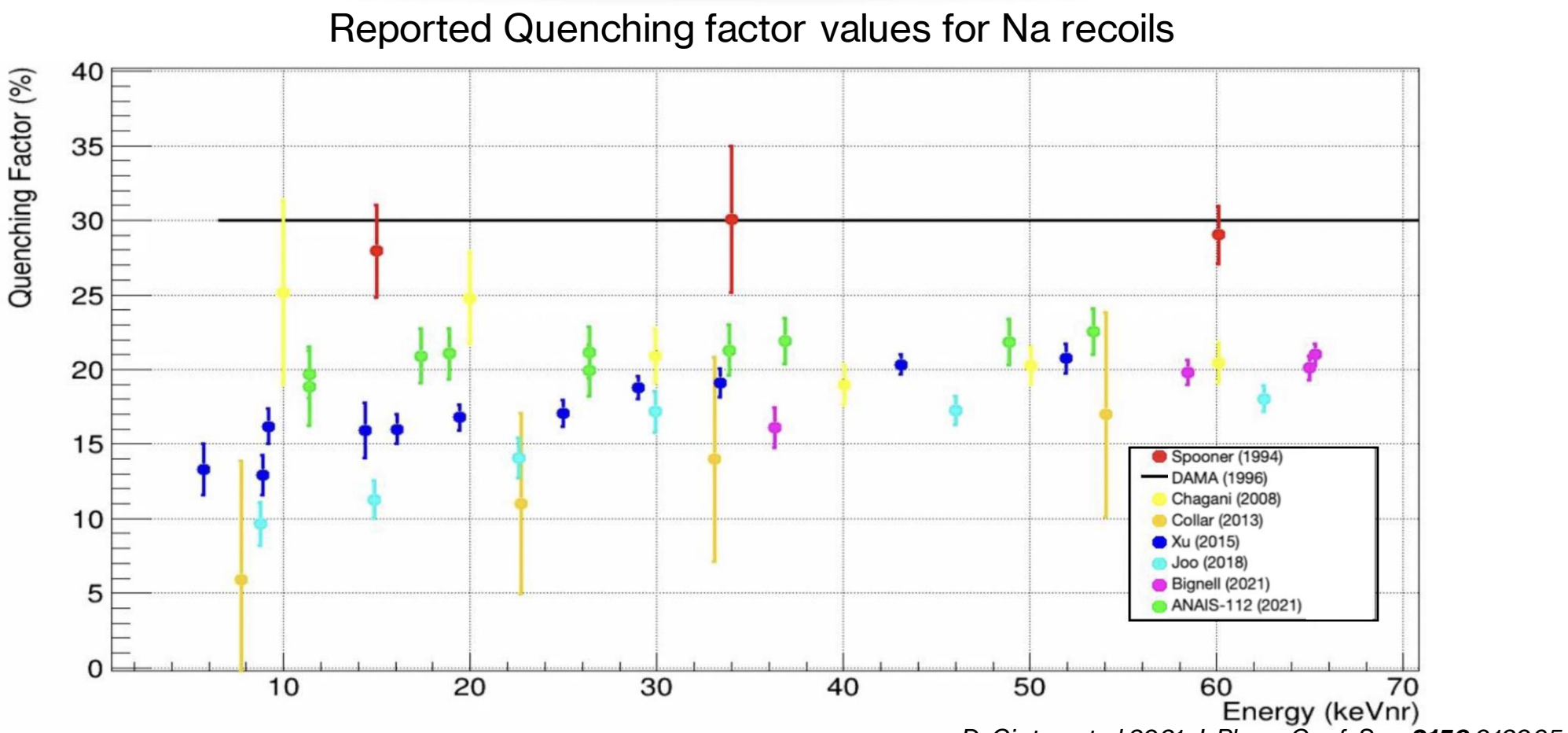
Reported Quenching factor values for Na recoils



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.

Motivation



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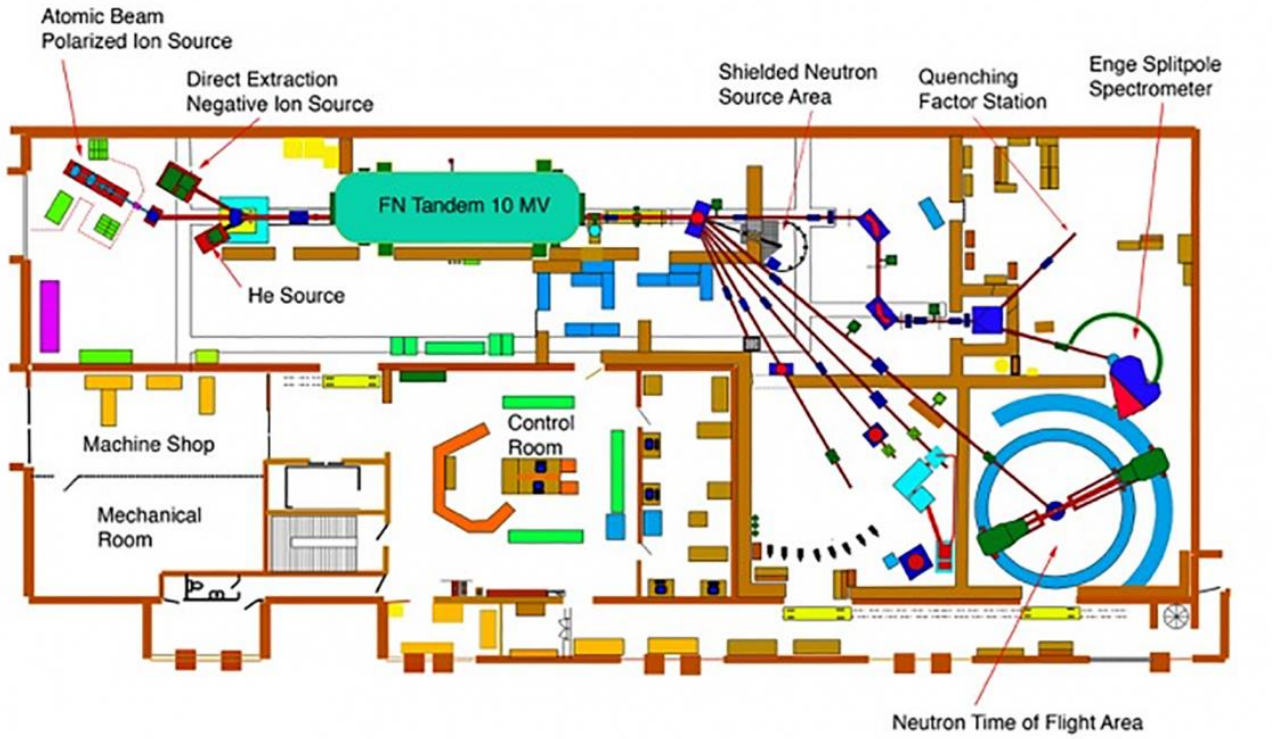
Experimental setup



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

Beam time: Aug-Sept. 2021

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

Dependence of QF Tl dopant concentration?

Aim:

- Target low recoil energy region (1-30keV$_{nr}$)

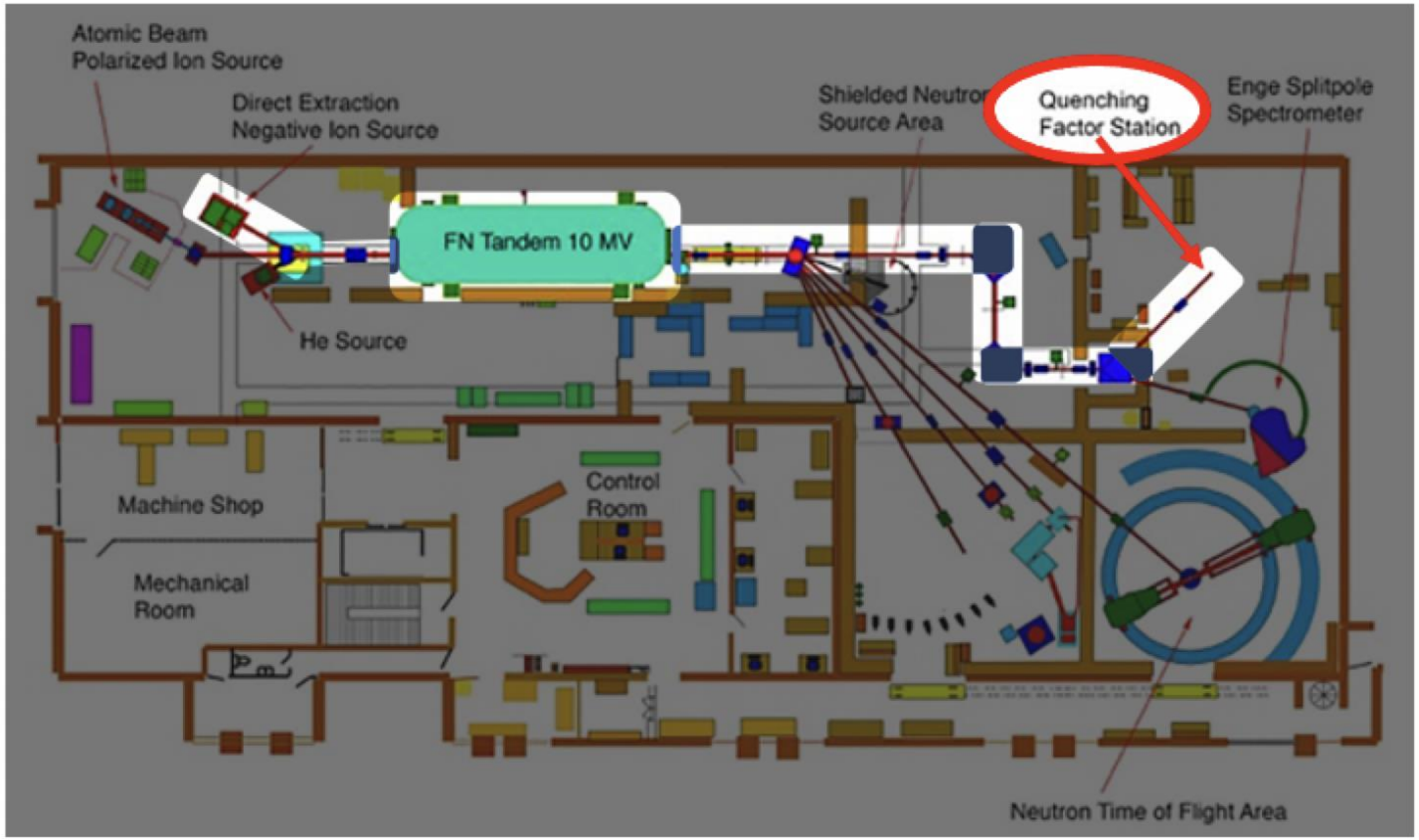
Requirements:

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

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

*arXiv: 1909.11692

Experimental setup



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

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.

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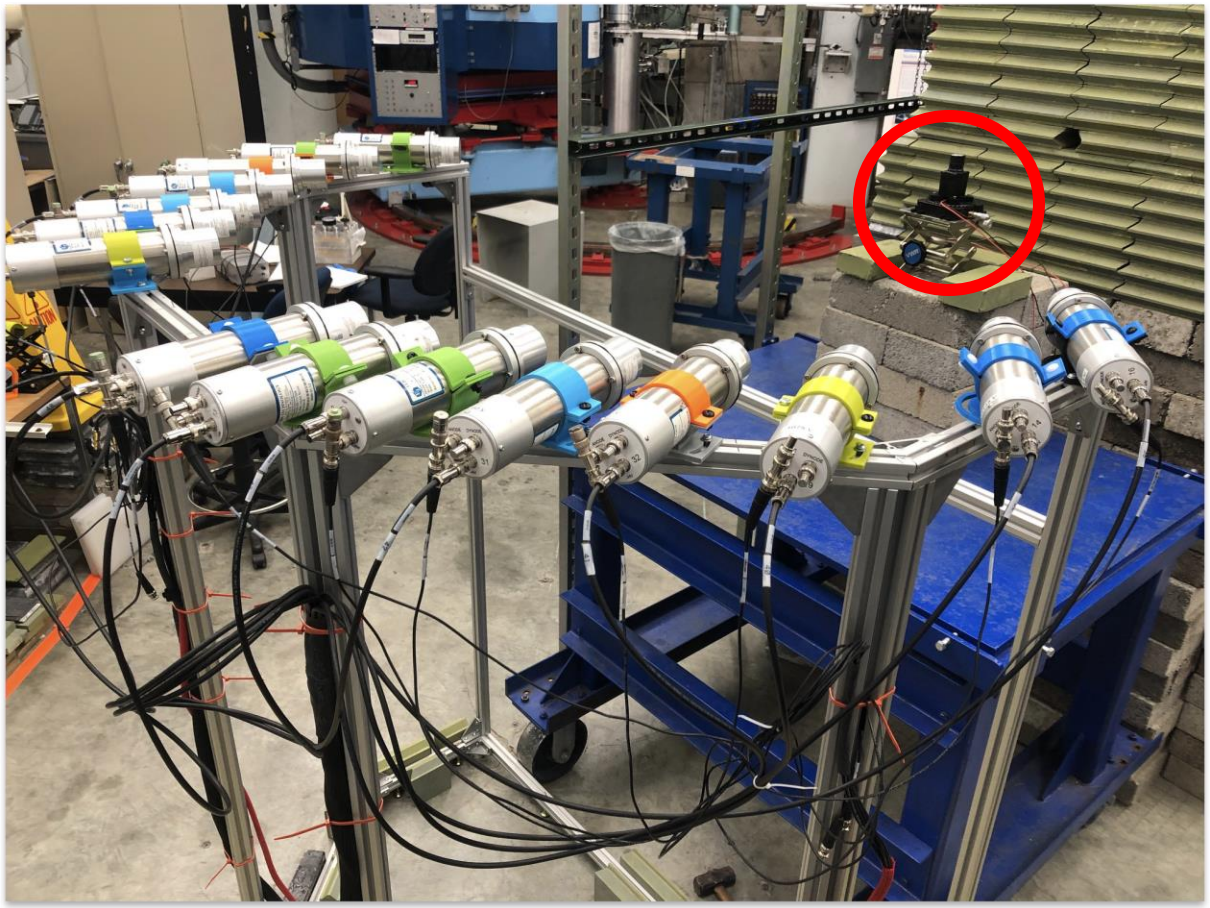
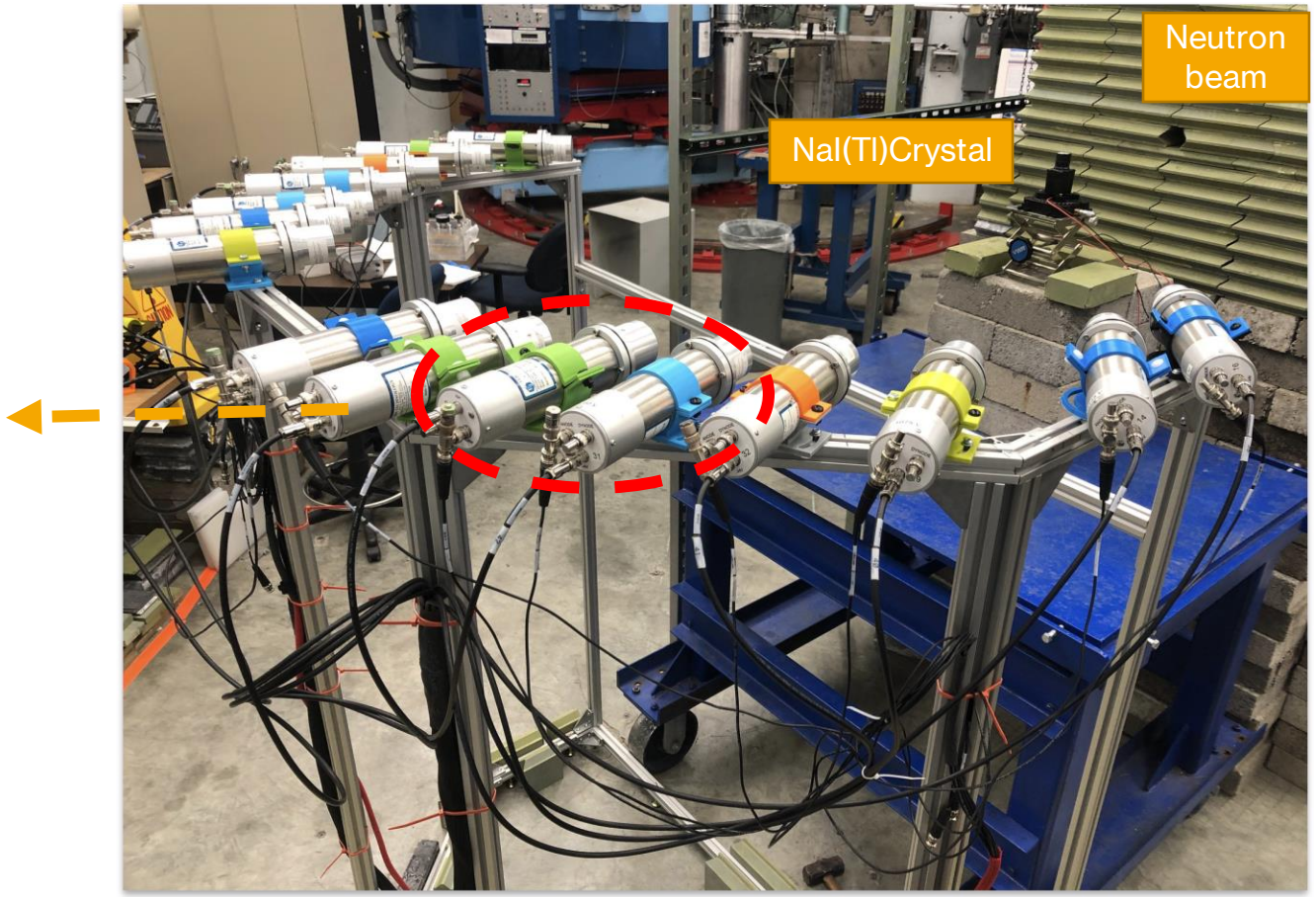
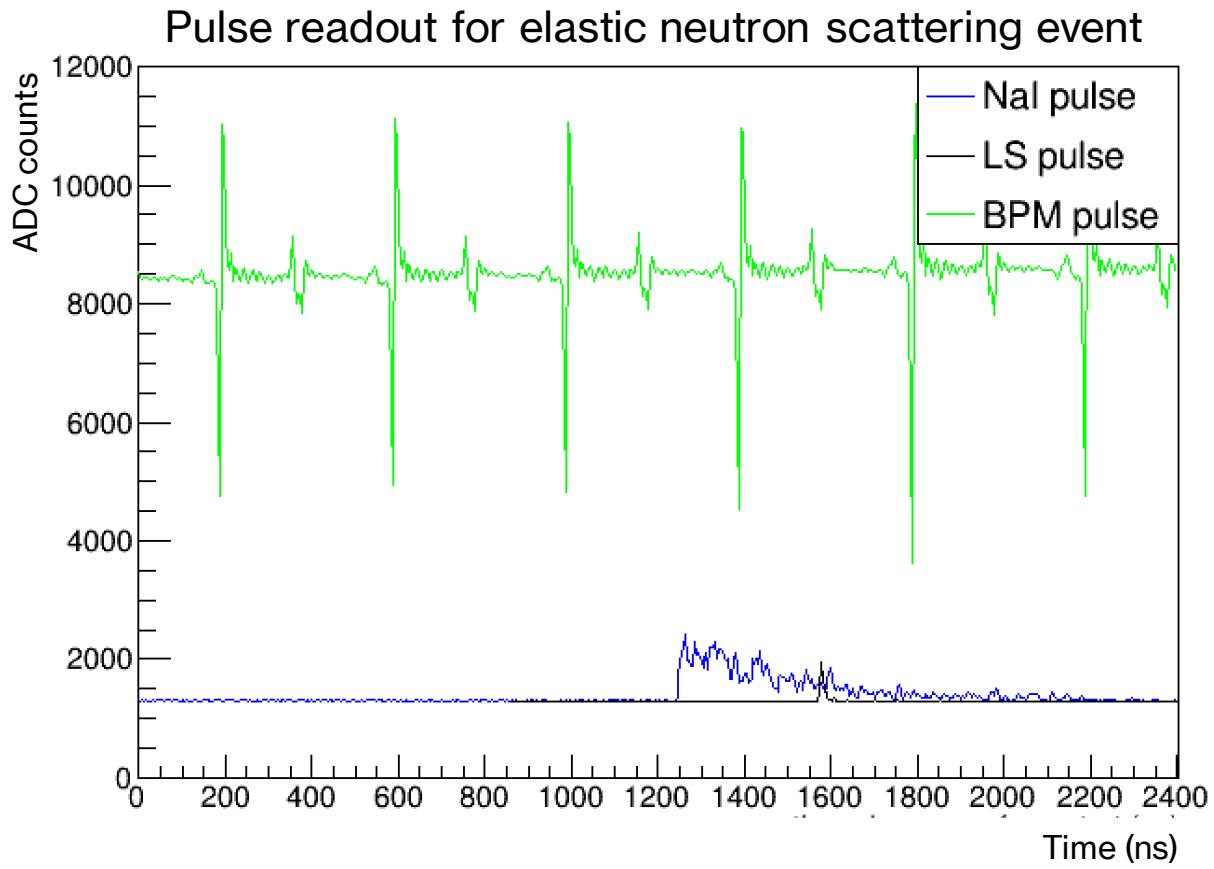


Experimental setup

- 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.



Triggering scheme



- 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

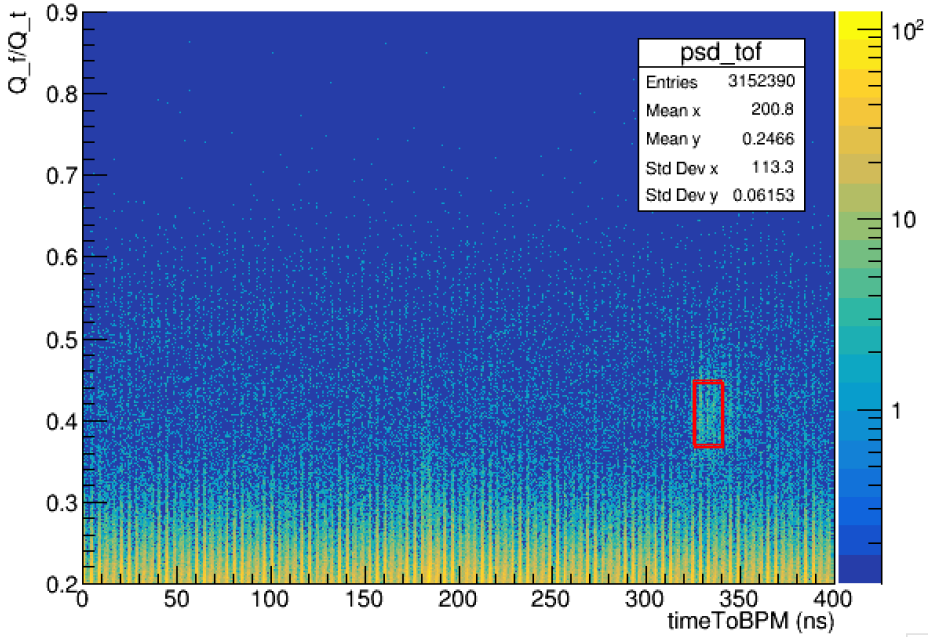
Analysis workflow

Applied cuts:
- PSD cut on BD.
- TOF cut w.r.t BPM.

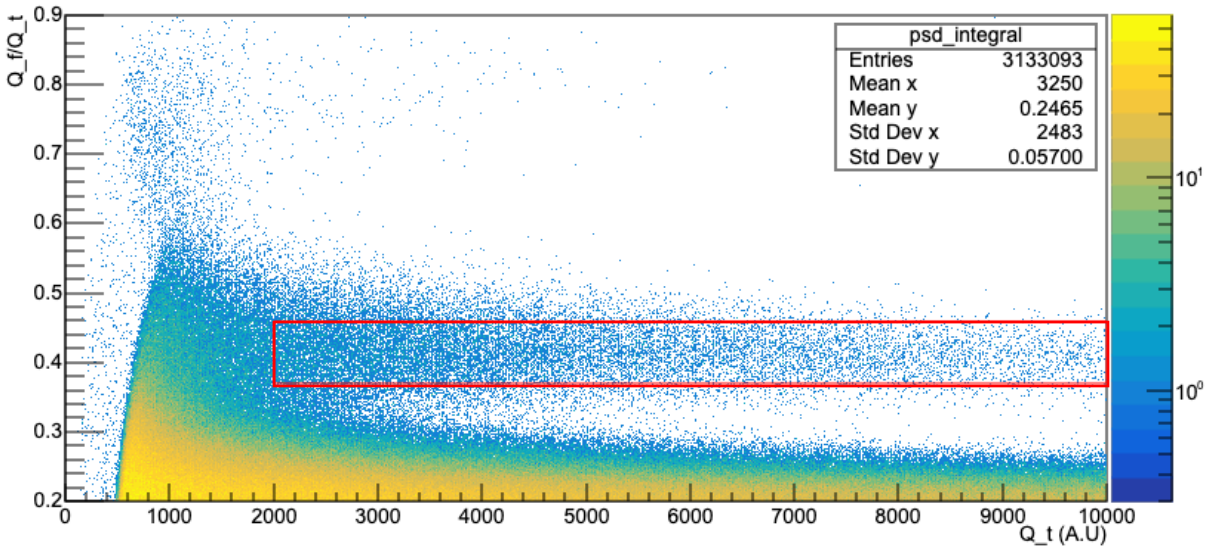
$$PSD = \frac{Q_f}{Q_t}$$

Q_f: Charge in second half of the pulse
Q_t: total pulse charge

Integral cut



PSD cut



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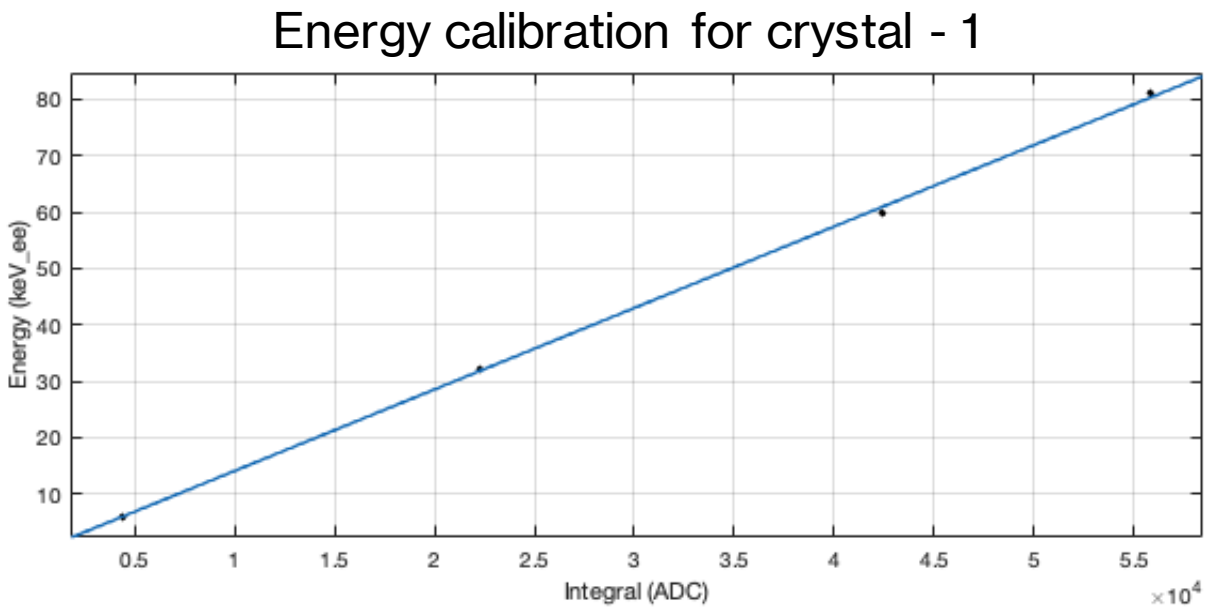


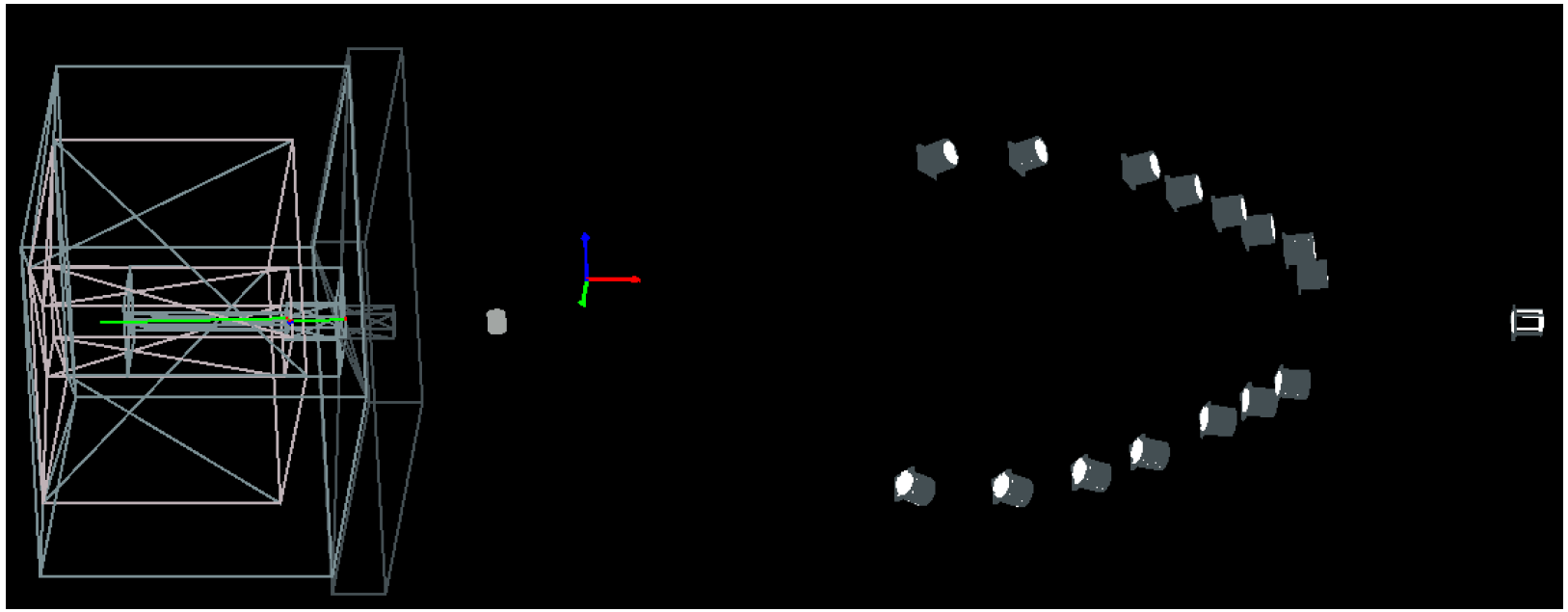
Linear calibration function: a*ADC + b

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

- 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 (analysis with the 59.7keV ^{127}I inelastic line also carried out).

Analysis workflow

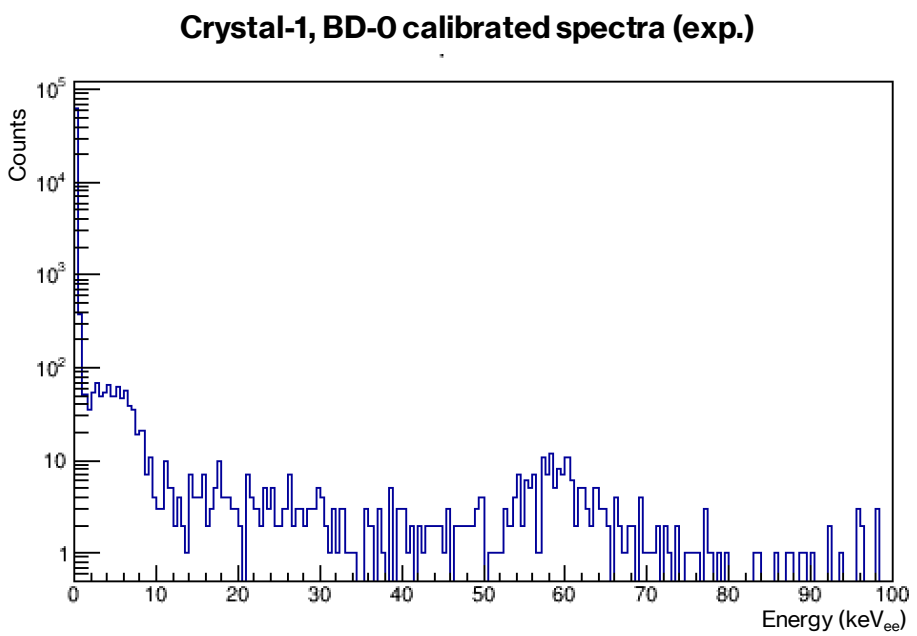
GEANT4 simulation of the entire setup

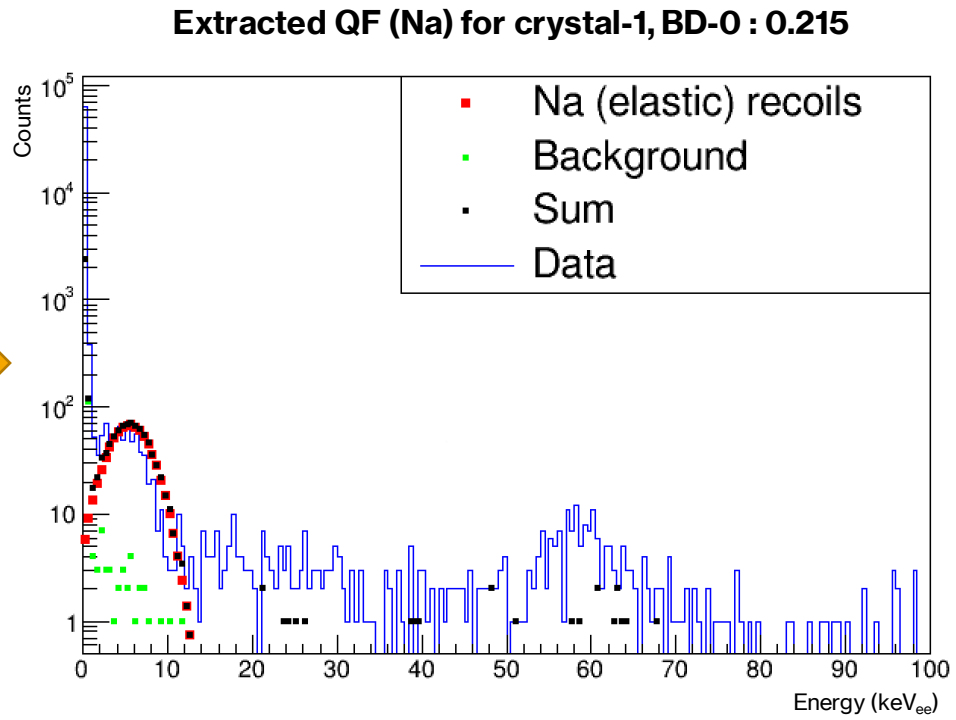


Used to extract "true" nuclear recoil energy scale (keV_{nr})

QF estimation (Na recoils)

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





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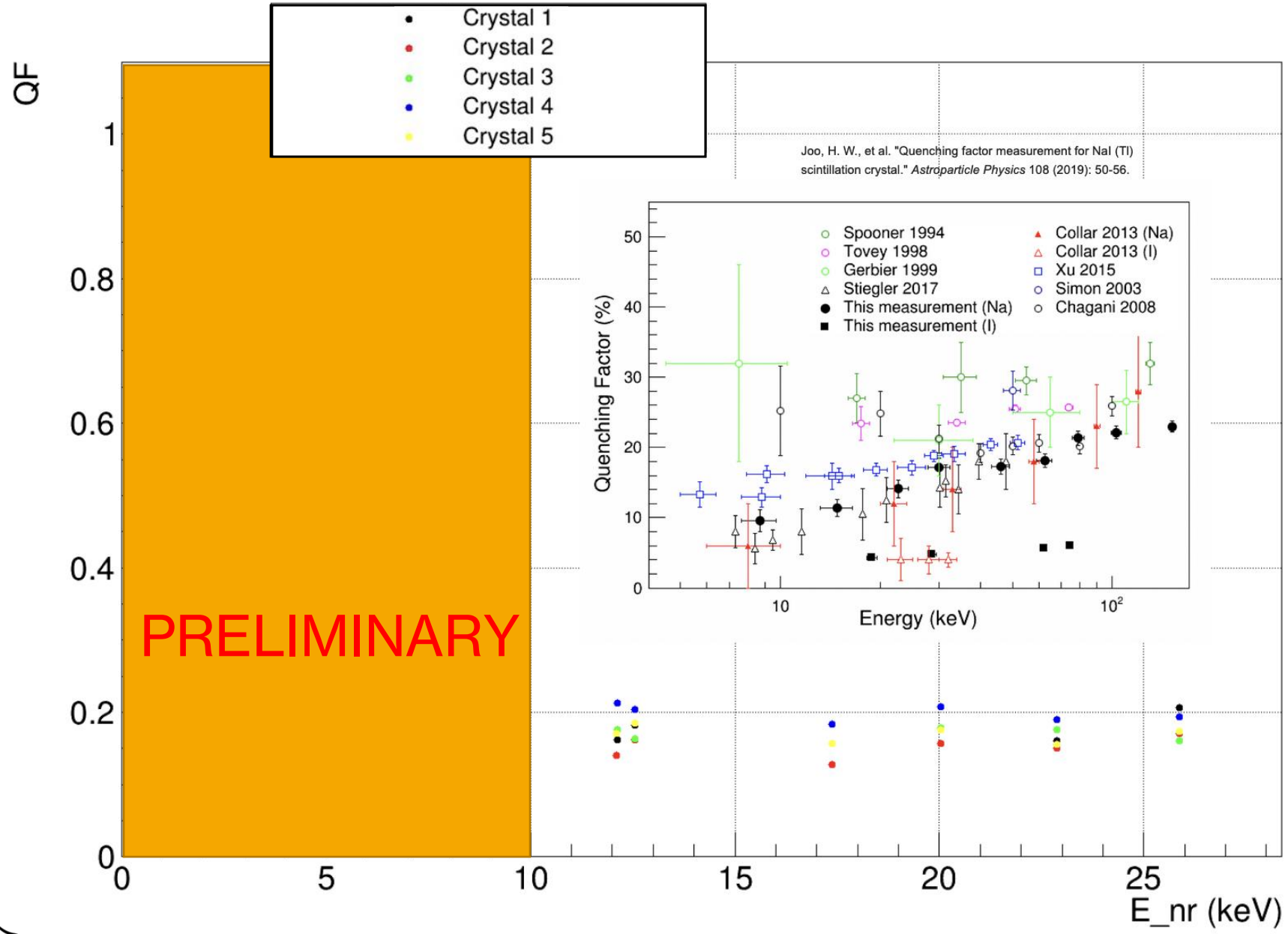

Conclusion

- 5 NaI crystals with differing TI dopants tested at neutron calibration facility at Triangle Universities National Laboratory (TUNL).
- For each individual crystal, no clear energy dependence of QF (Na recoils) is observed up until 10keV$_{nr}$.
- With different calibration scheme (57.6keV inelastic I line), energy dependence observed; Points to non-linear response of NaI(TI).
- QF (I recoils) could not be extracted in current setup due to extremely low recoil energies.

Backup – 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.

Backup – 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]

Backup – 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.