Measurements of Low Energy Nuclear Recoil Quenching Factors for NaI(Tl) Scintillating Crystal

Presenter: Seo Hyun Lee

Based on the study

arXiv:2402.15122 (Accepted to PRC)

Measurements of low energy nuclear recoil quenching factors for Na and I recoils in the NaI(Tl) scintillator

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15th International Workshop on the Identification of Dark Matter

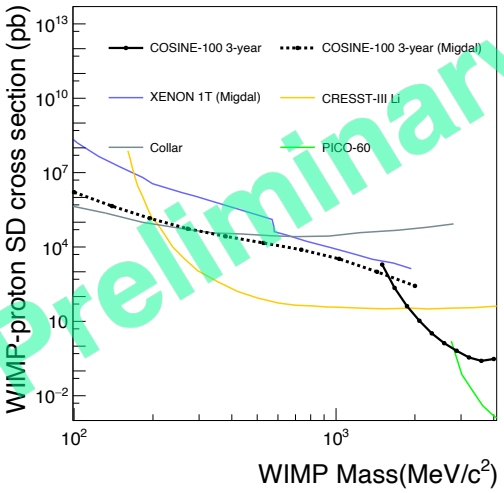
09 Jul. 2024

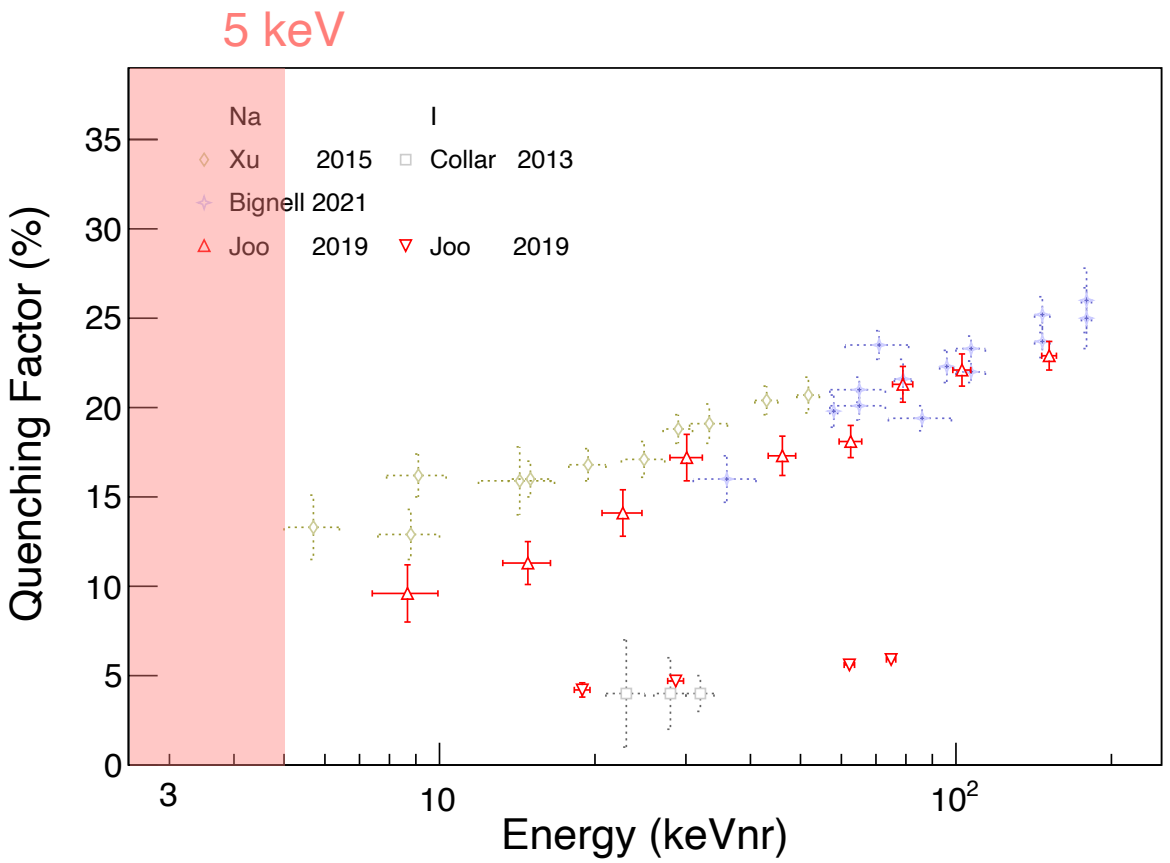
CENTER FOR UNDERGROUND PHYSICS

UST 과학기술연합대학원대학교 UNIVERSITY OF SCIENCE & TECHNOLOGY

Introduction

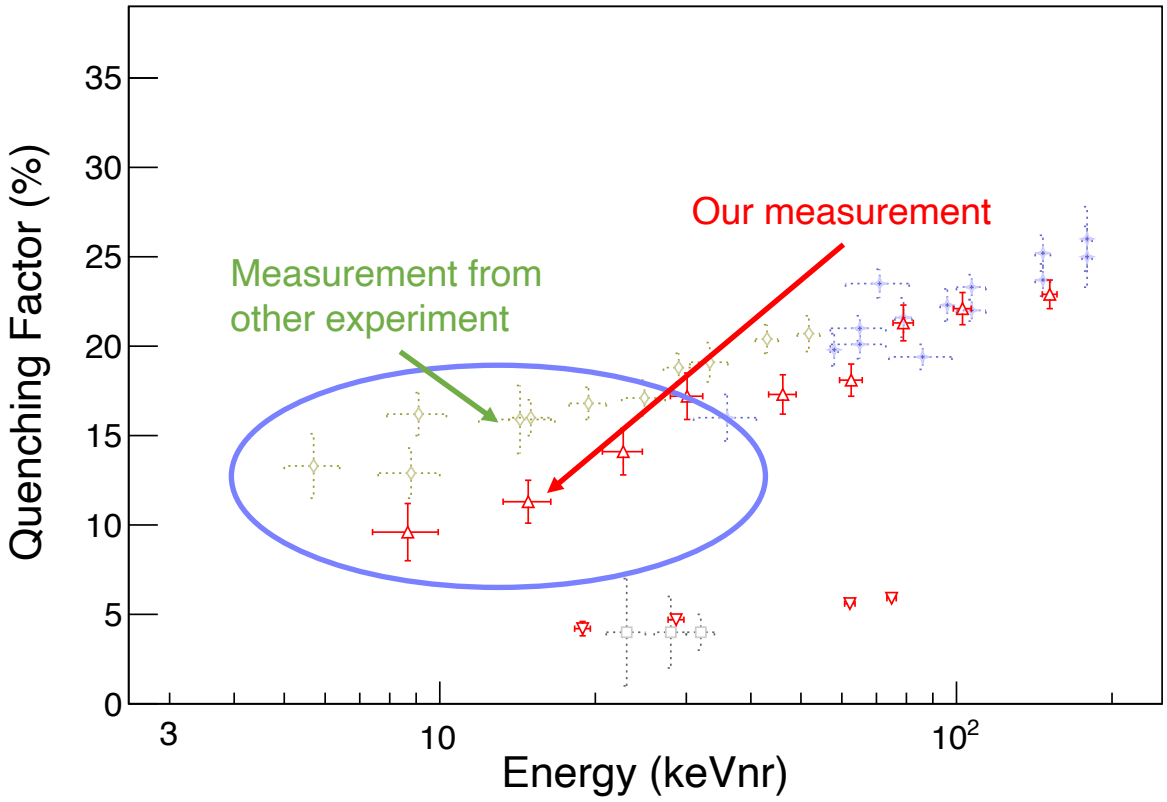
COSINE-100 sensitivity study





- Quenching factor: $\mathrm{QF} = \frac{E_{er}}{E_{nr}}$
- Important in rare event search experiments on low mass dark matter or CEνNS
  - NaI(Tl) crystal is suitable for low energy searches
  - Low energy measurement is needed considering energy thresholds

Introduction

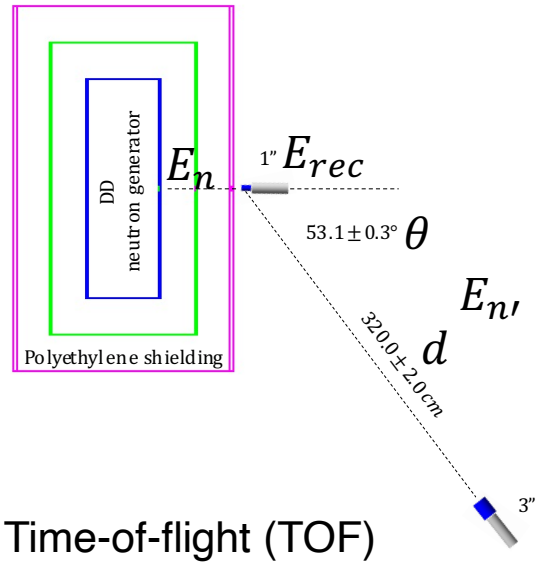


- Old measurement of ours shows different behavior in low energy QF
- Check for our old measurement is needed

Reexamination of Previous Measurement

Neutron Energy Measurement

Neutron beam from Deuteron-Deuteron (D-D) neutron generator

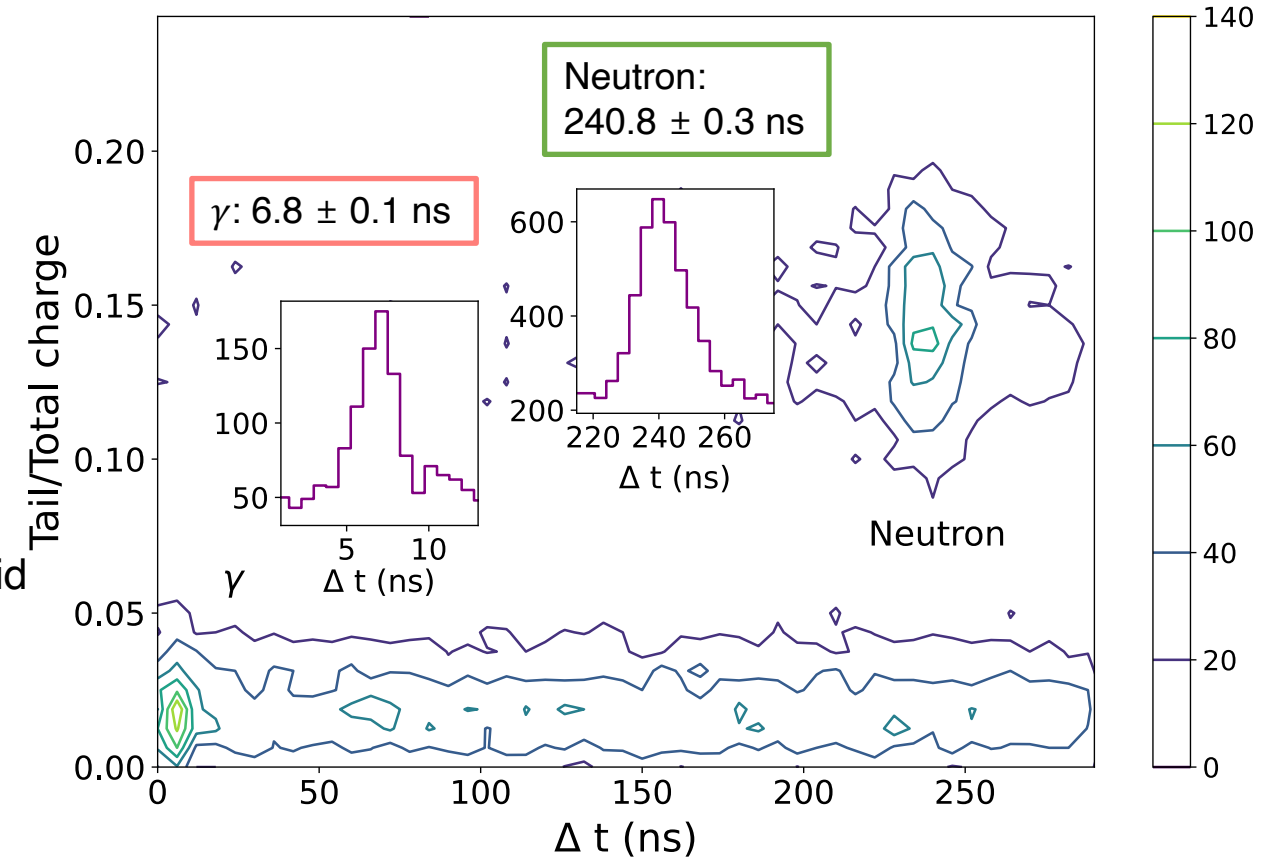


- Time-of-flight (TOF) measurement between 2 liquid scintillator (LS) detectors

$$E_n = E_{rec} + E_{n'}$$

$$E_{n'} = \frac{M_n}{2}\left(\frac{d}{c\Delta t}\right)$$

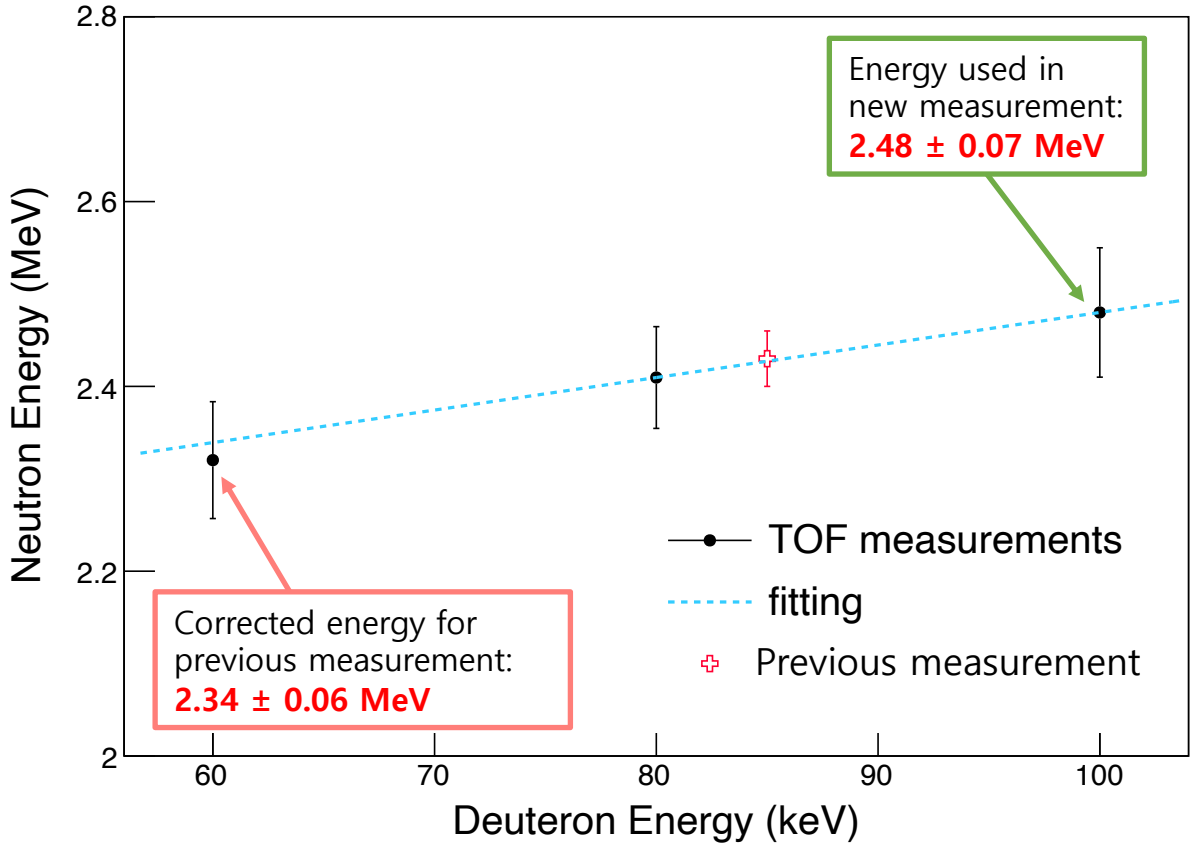
$$E_{rec} = \frac{2(1 + A - cos^2\theta - cos\theta\sqrt{A^2 - 1 + cos^2\theta})}{(1+A)^2} E_n$$



(under deuteron energy of 100 keV)

Reexamination of Previous Measurement

Neutron Energy Measurement

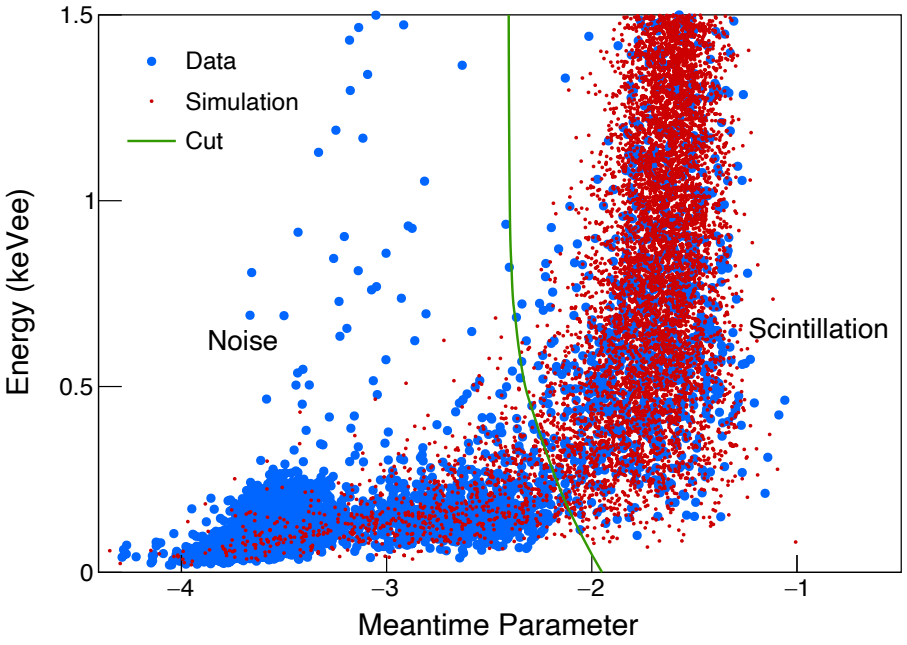


- TOF measurements preformed at Deuteron energy 60 keV, 80 keV, 100 keV
  - Old measurement: deuteron energy 60 keV
  - New measurement: deuteron energy 100 keV

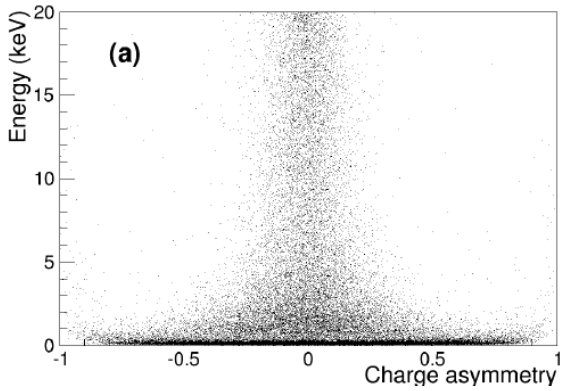
Reexamination of Previous Measurement

Updates on Event Selection

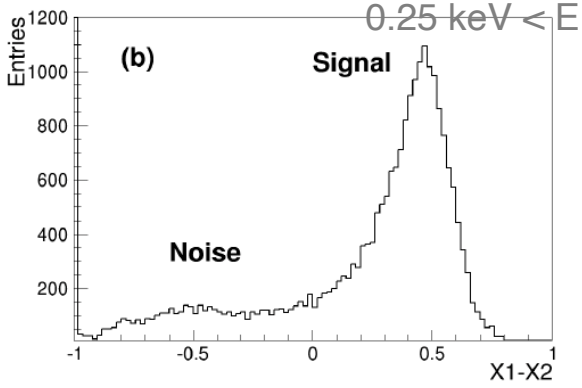
~ 0.2 keV threshold



Old selection



0.25 keV < E < 20 keV



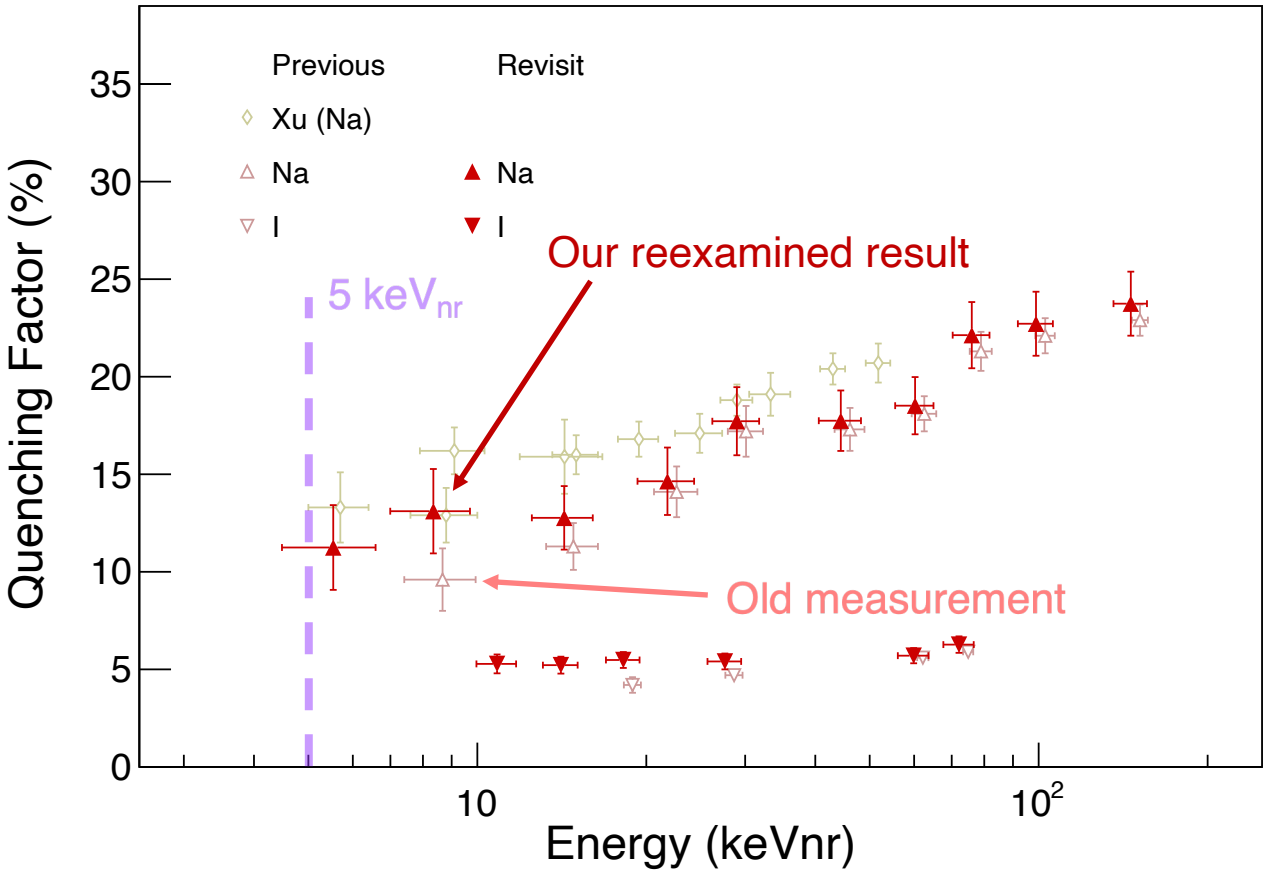
Astropart. Phys. (2019) 108, 50-56

- Event selection update
  - Previous selection w/ noise contamination in selected scintillation event
  - Removal of noise event in scintillation sample → Improved efficiency

Reexamination Previous Measurement

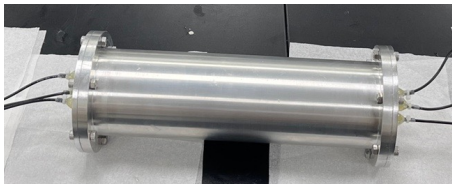
Corrected Quenching Factor

- Obtained lower recoil energy result with event selection update
- Revisited measurement shows similar behavior compared to other studies

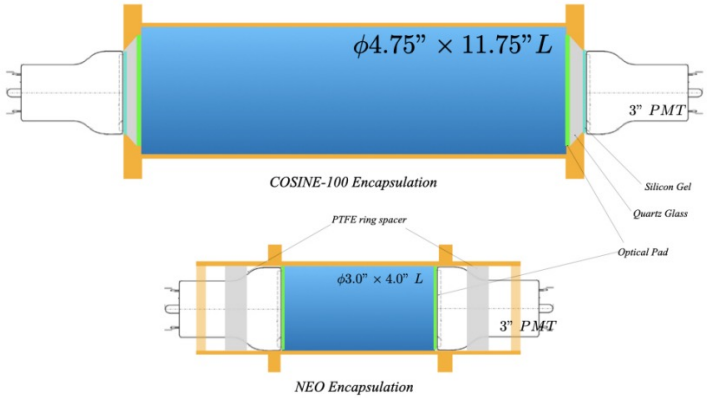


New Measurement

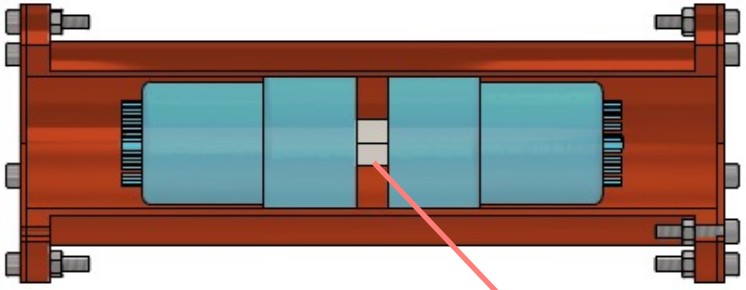
Detector Encapsulation



Our detector

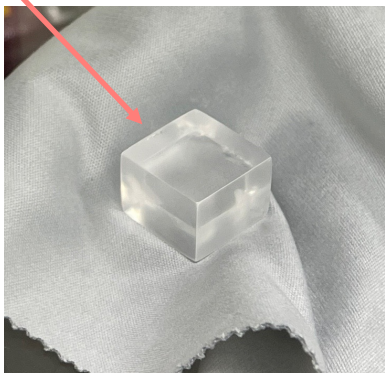


NIM-A (2020) 981:164556



w/ quartz window

w/o quartz window

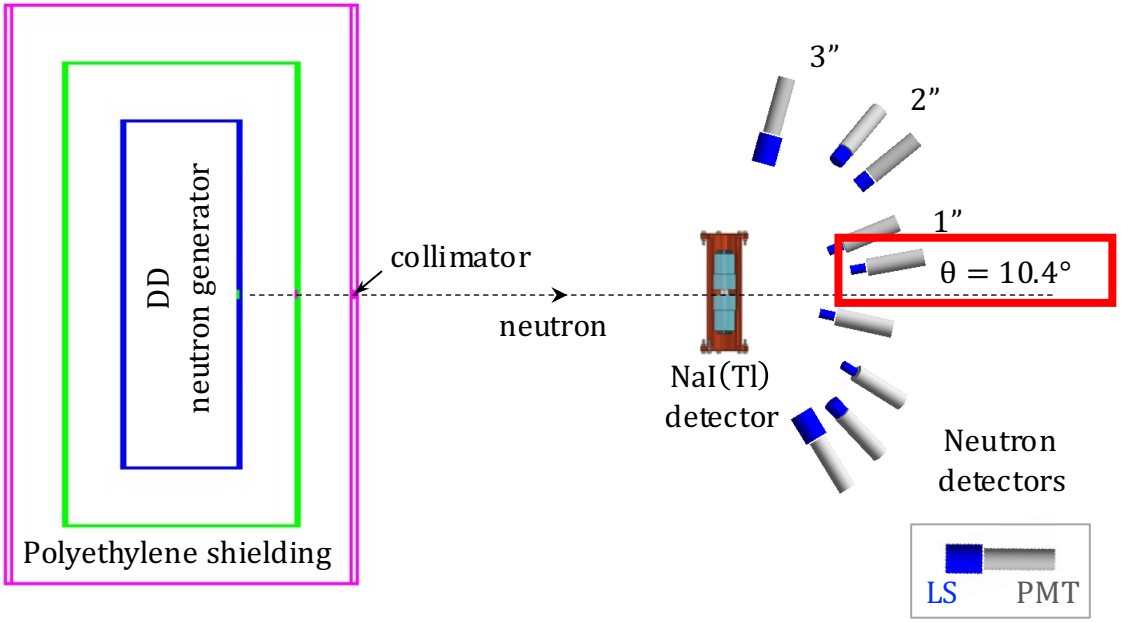


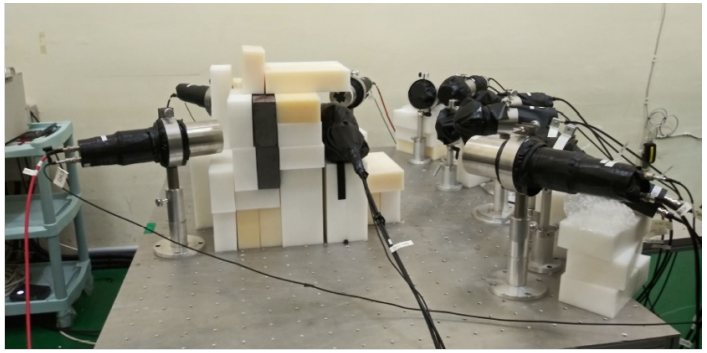
1.8 cm × 1.8 cm × 1.4 cm

- New encapsulation design for high light yield
  - Now ~ 26 NPE/keV (previously ~18 NPE/keV)
  - Low energy measurement possible
- Directly coupling PMT and the crystal without quartz window to reduce light loss

New Measurement

Experimental Setup

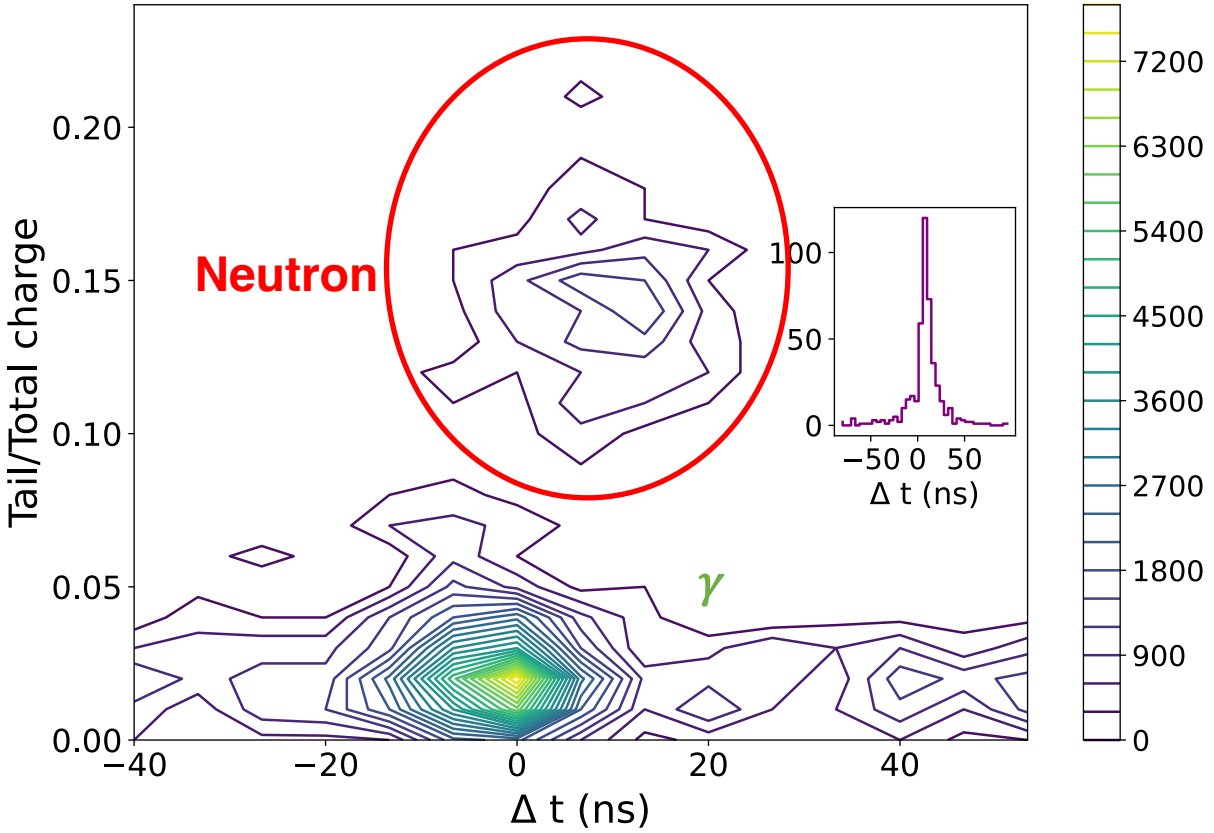




- Neutron energy: 2.48 ± 0.07 MeV
- 9 liquid scintillator neutron detectors at each recoil angle (EJ301, Eljen Tech.)
  - size 1” inch to 3”
  - Smallest angle: 10.4° (3.8 keV_{nr} for Na)
- Energy calibration: 59.54 keV gamma from ^{241}Am

New Measurement

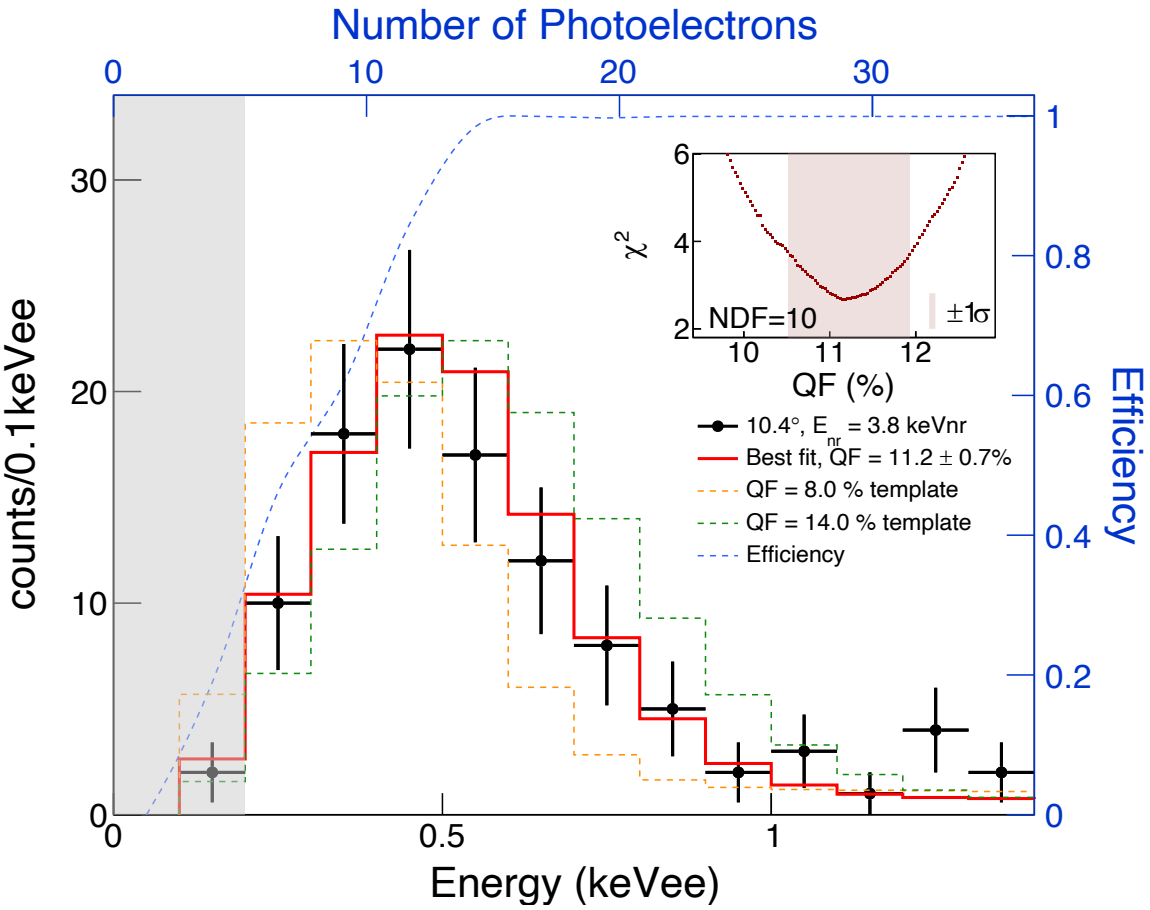
Event Selection for Neutron



- Parameters for neutron and gamma event separation
  - Pulse shape discrimination parameter (charge ratio)
  - TOF between NaI(Tl) crystal and LS neutron detector

New Measurement

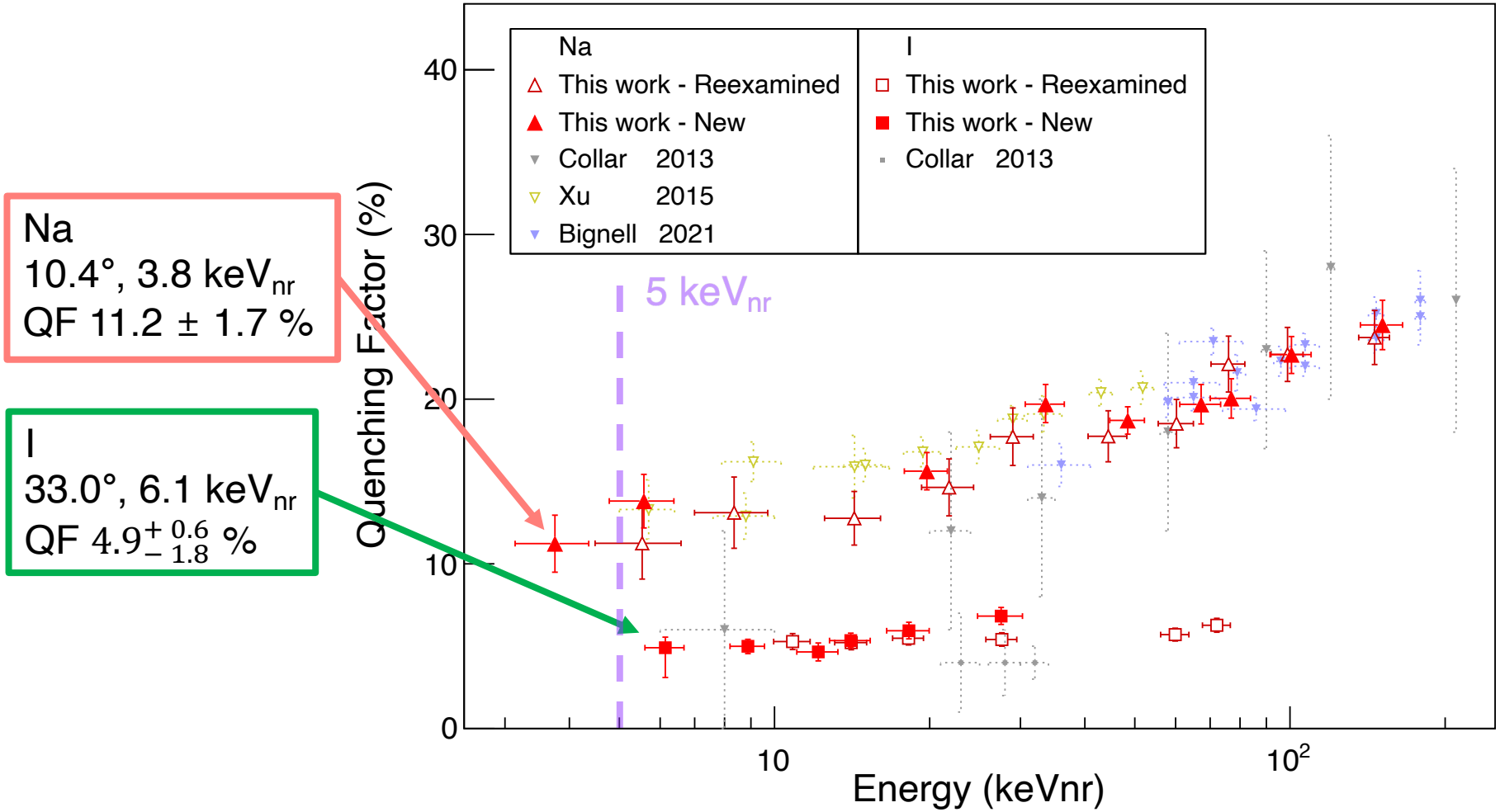
Quenching Factor Calculation



< 0.2 keV_{ee} not used in fitting

- Nuclear recoil data was compared with GEANT4 simulation templates
- Perform χ^2 template fit to the nuclear recoil data of the simulation template
- Fitting example on 10.4° (lowest angle)
  - E_{NR}: 3.8 keV_{nr}
  - Best-fit QF: 11.2 ± 1.7 % (error with systematics)

Quenching Factor Measurement Result

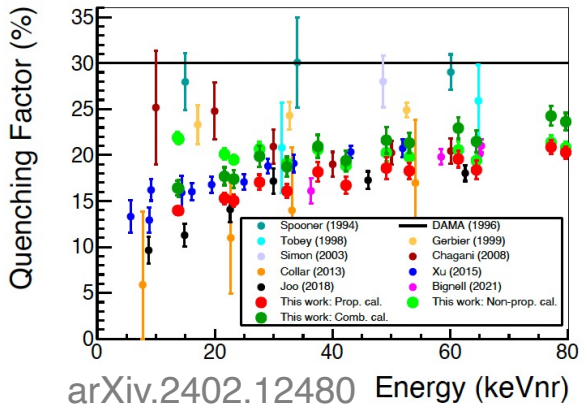


- New measurement well agrees with the other measurements
- Measured at very low energies

Quenching Factor Measurement Result

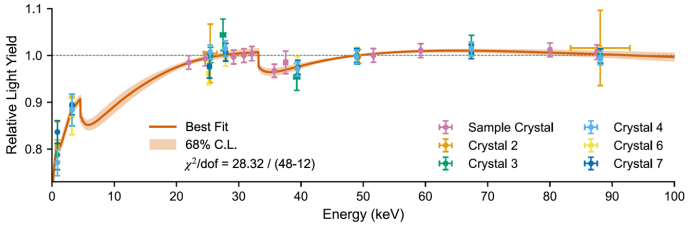
Considering Non-proportionality of the NaI(Tl) Crystal

QF measurement comparing different calibrations

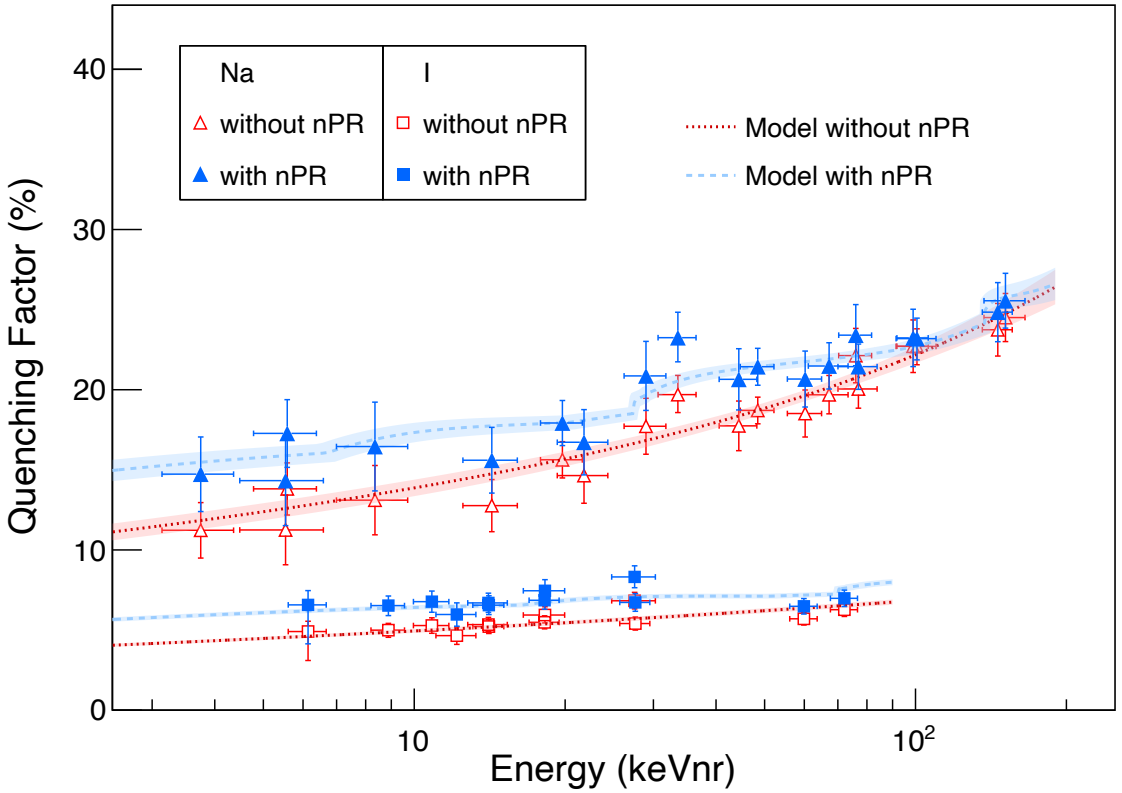


arXiv.2402.12480

nPR measurement for COSINE-100 crystals



Eur. Phys. J. C (2024) 84:484



- QF with non-proportionality (nPR) curve applied (blue)

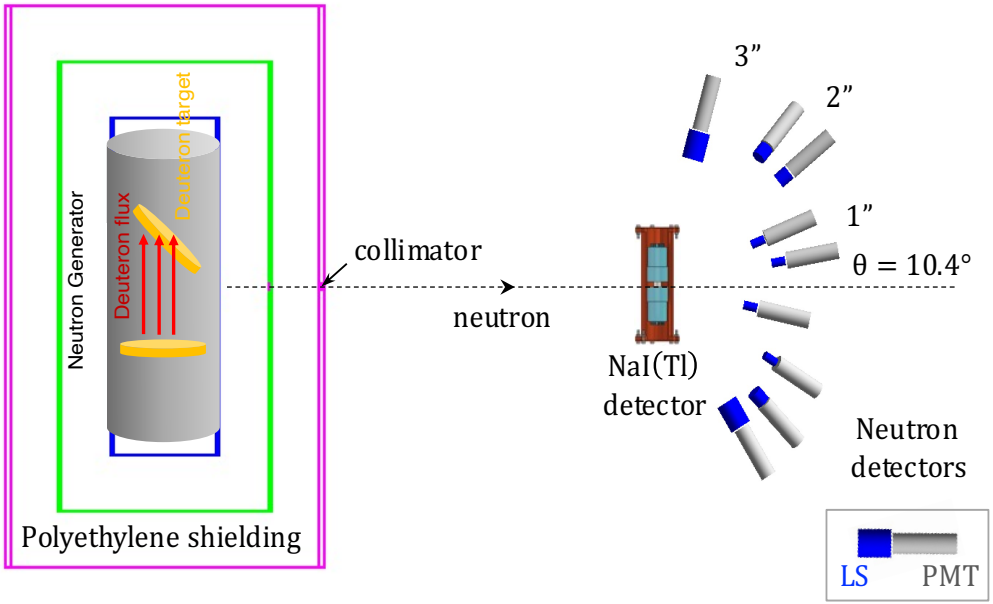
Summary

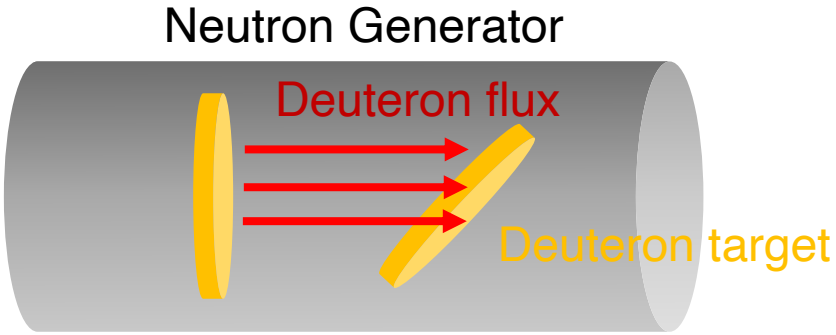
- Measurement of QF up to low energy region is important in rare event search experiments on low mass dark matter or CEνNS
- Previous measurement was revisited with updates on neutron energy measurement and analysis method
- New measurement was performed with high light yield crystal (26 PE/keV), including measurements on lower recoil energy
  - Na: 3.8 keV_{nr}, QF 11.2 ± 1.7 %
- Impact of non-proportional behavior on QF also investigated

Thank You!

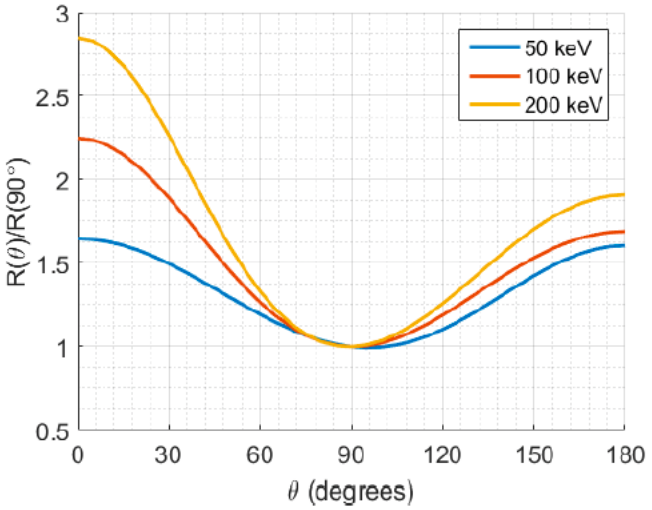
Backup

Deuteron-Deuteron Neutron Generator





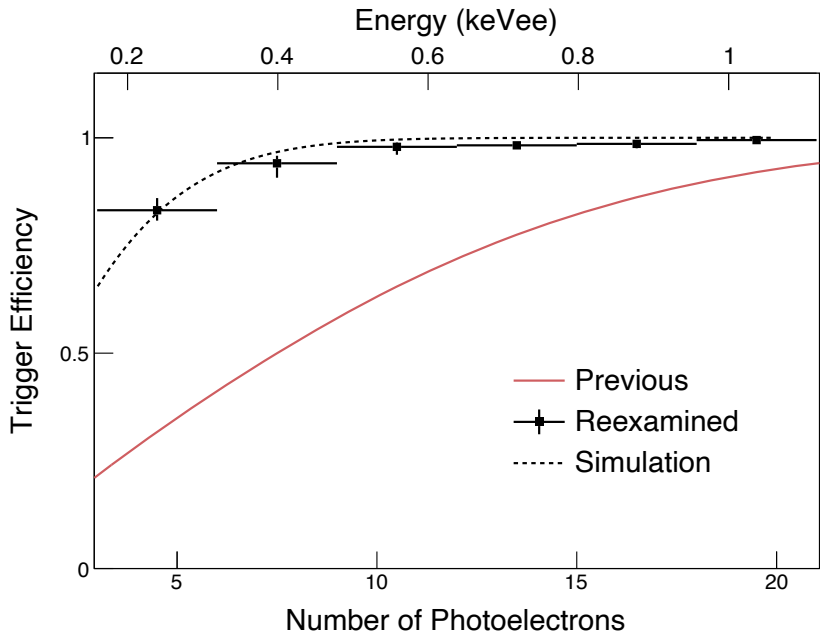
Cory Scott Waltz (2016),
Characterization of Deuteron-Deuteron
Neutron Generators

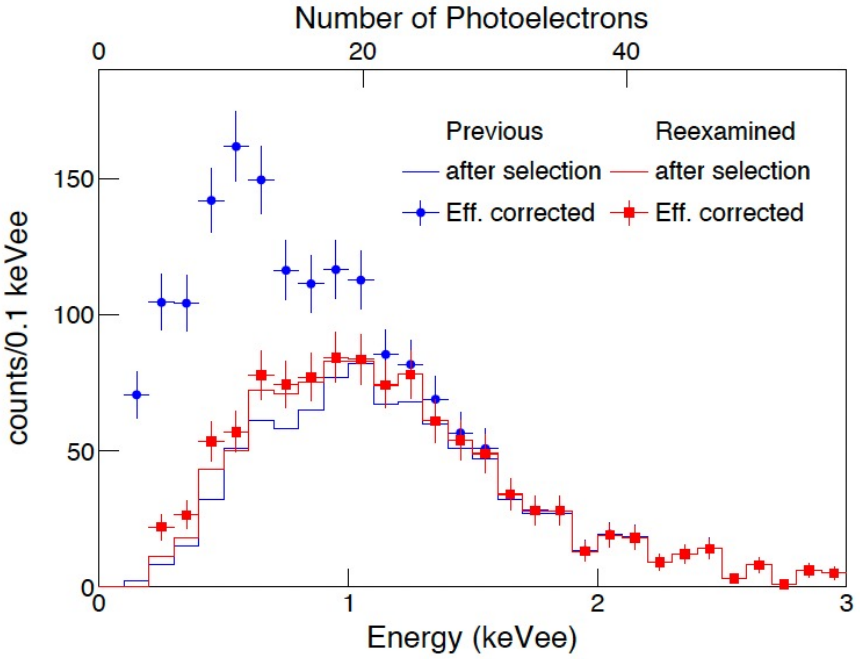


- D-D fusion reaction
  - $^{2}H + {}^{2}H \rightarrow {}^{3}He + n$

Reexamination of Previous Measurement

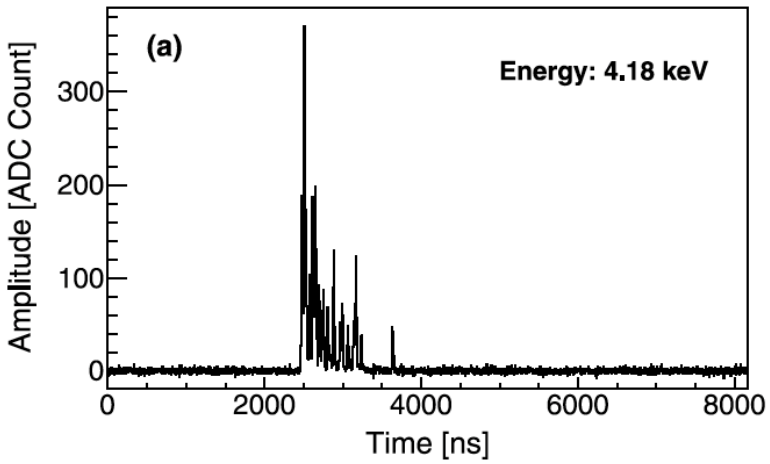
Updated Efficiency



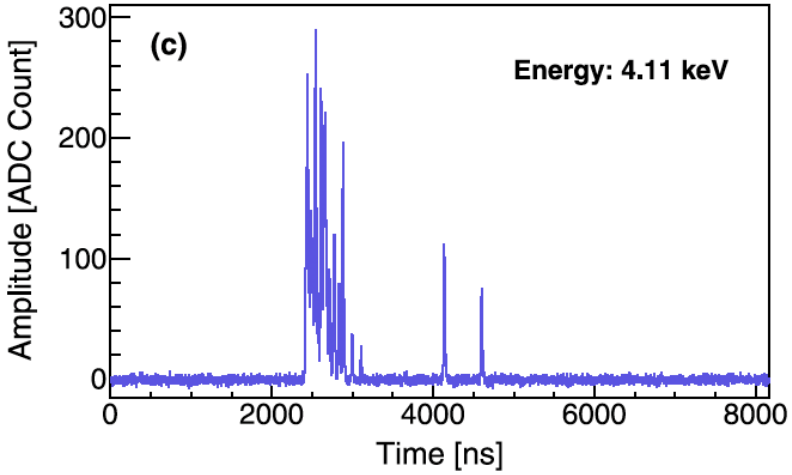


Event Selection

Waveform Simulation



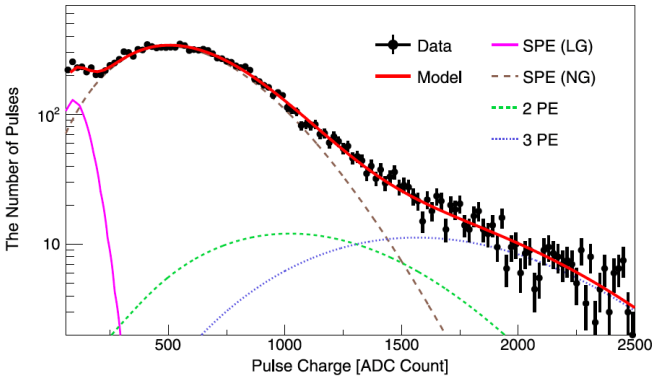
Experimental data



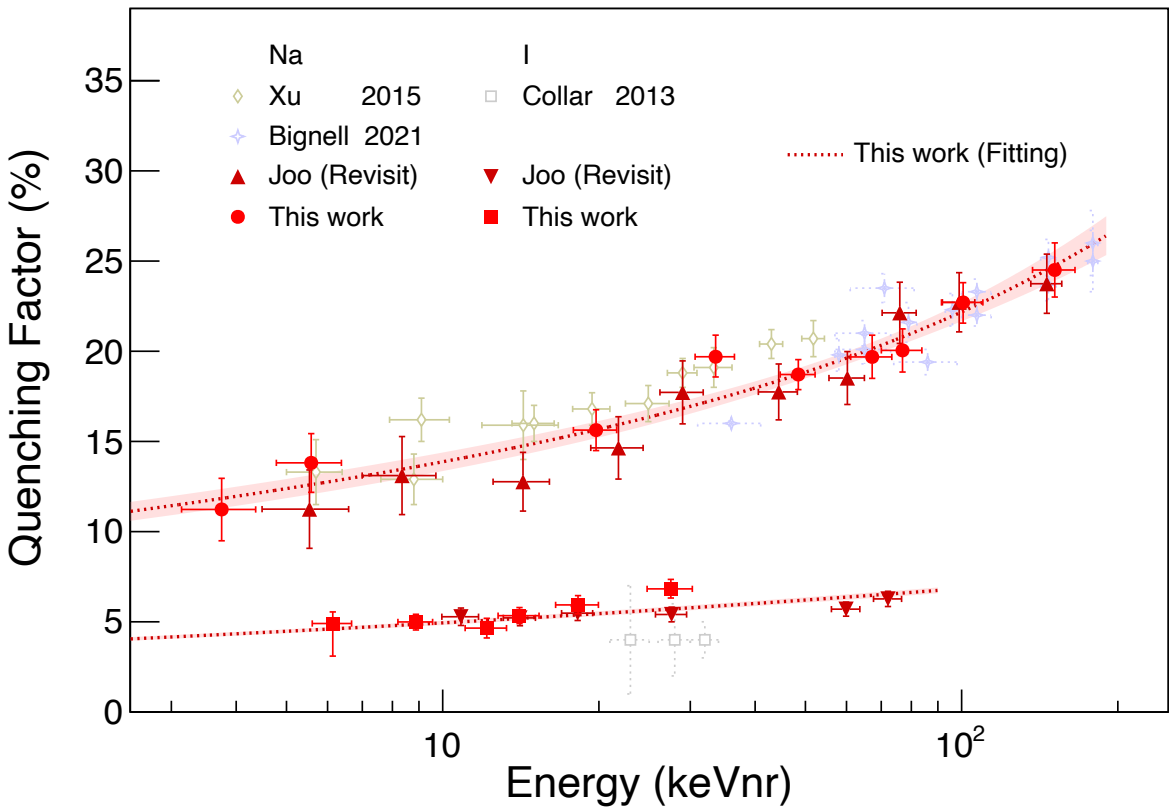
Simulation data

NIM-A 1065 (2024) 169489

SPE model



Fitting Quenching Factor Measurement Result



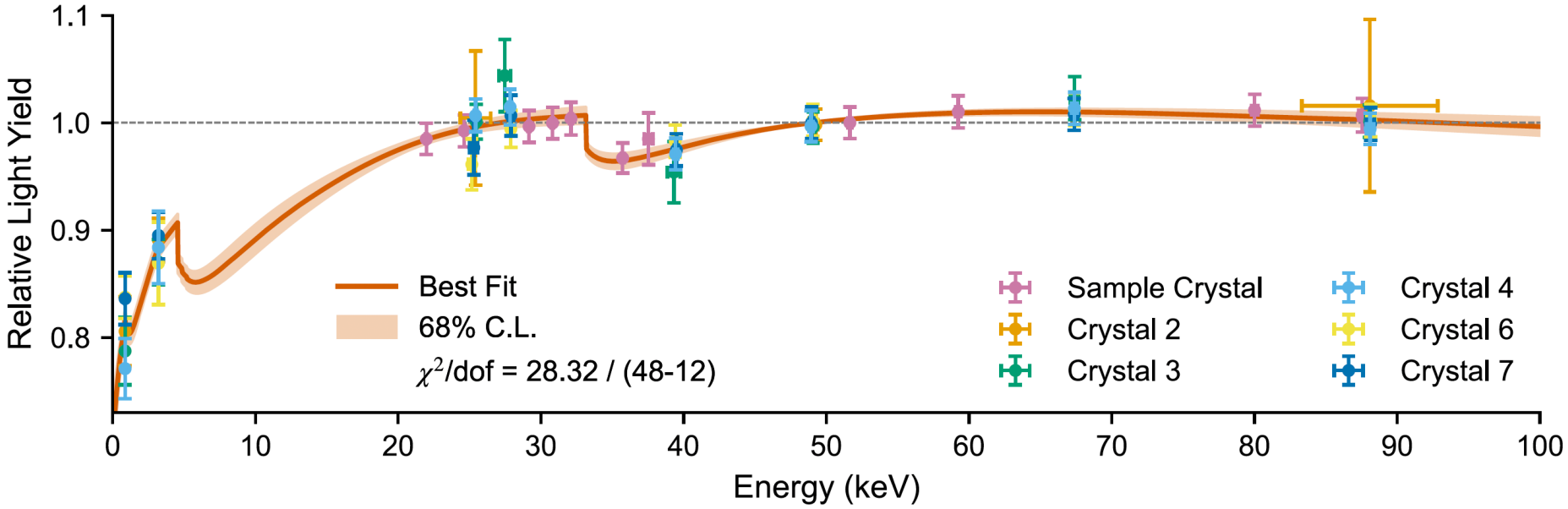
- QF result fitted with modified Lindhard model

$$f(E_R) = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

JCAP11(2019)008

$$g(\epsilon) = 3\epsilon^{0.5} + 0.73\epsilon^{0.6} + \epsilon$$

Applying Non-proportionality Curve



EPJC (2024) 84:484

- Internal radioactive gamma peak + external gamma ray source spectroscopy data
- nPR curve fitted by Payne's model