Nuclear recoil QF measurement for ANAIS-112

David Cintas on behalf of the ANAIS research team

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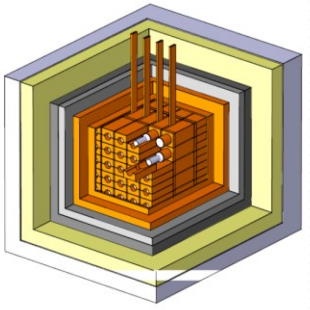
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN
CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza
MultiDark Multimessenger Approach for Dark Matter Detection

DAMA/LIBRA modulation signal

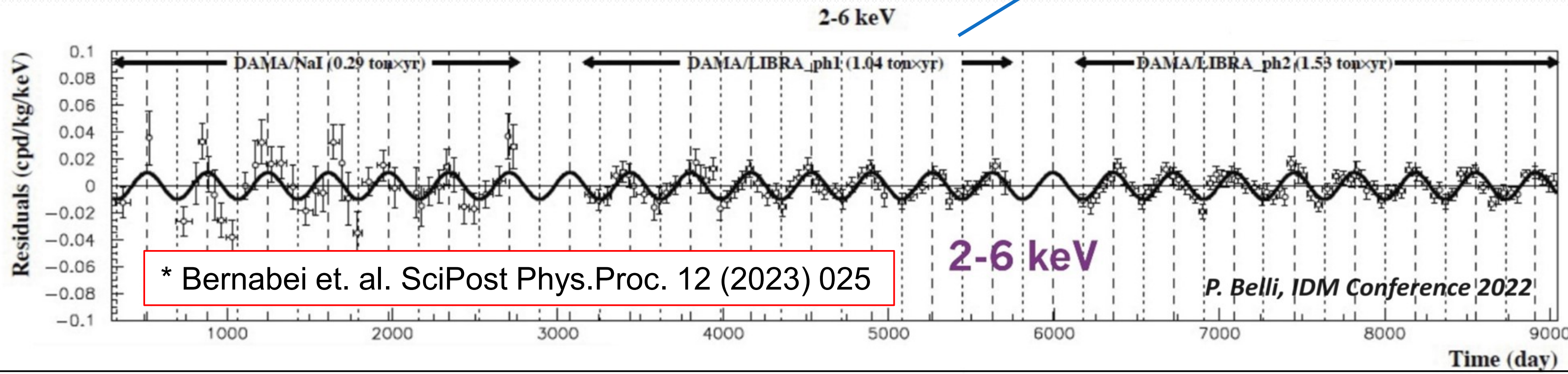
- At LNGS
- 5x5 NaI(Tl) crystals, 9.7 kg each



DAMA/LIBRA modulation signal

- At LNGS
- 5x5 NaI(Tl) crystals, 9.7 kg each
- Signal compatible with DM annual modulation considering SHM*
  - 13.7 σ C.L. in [2,6] keV
  - 11.8 σ C.L. in [1,6] keV

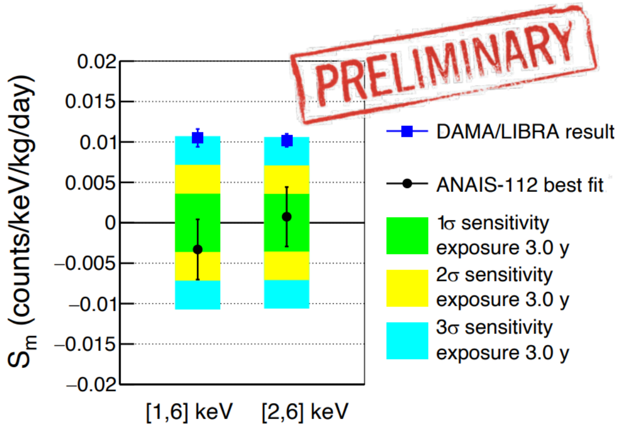
	ΔE	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
	(1-3) keV	0.0191±0.0020	0.99952±0.00080	149.6±5.9	9.6σ
DAMA/LIBRA-ph2	(1-6) keV	0.01058±0.00090	0.99882±0.00065	144.5±5.1	11.8σ
	(2-6) keV	0.00954±0.00076	0.99836±0.00075	141.1±5.9	12.6σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.00959±0.00076	0.99835±0.00069	142.0±4.5	12.6σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.01014±0.00074	0.99834±0.00067	142.4±4.2	13.7σ

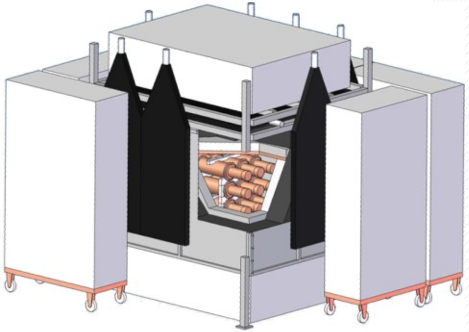


* Bernabei et. al. SciPost Phys.Proc. 12 (2023) 025

Model independent test with ANAIS-112

- Taking data since August 2017 at LSC Hall B
- 3x3 NaI(Tl) crystal modules, 12.5 kg each
- Multi-component shielding
- 3 years results support an absence of modulation
- Incompatible with DAMA/LIBRA results with a sensitivity >2.5σ





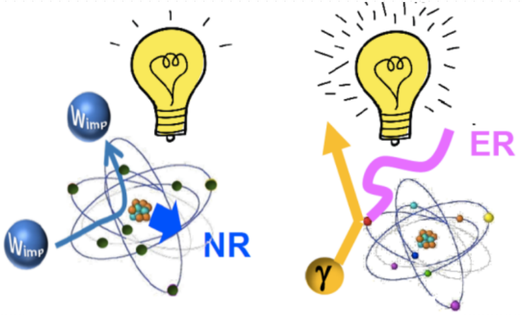
Amaré et. al. Phys.Rev.D 103 (2021) 10, 102005

Amaré et.al. Eur.Phys.J.C 79 (2019) 3, 228

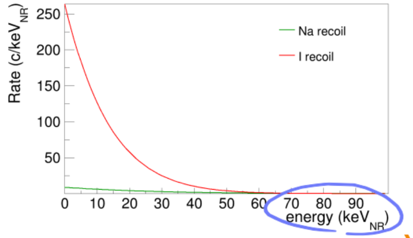
Model independent test with ANAIS-112

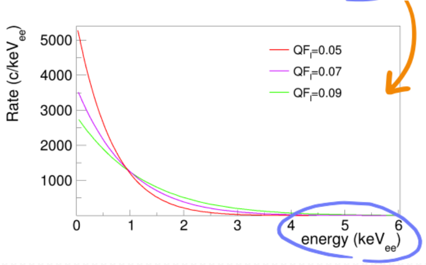
- Electron Recoils (ER) produce much more light than Nuclear Recoils (NR) of the same energy. The ratio of both light signals is the QF:

$$QF(E) = \frac{L_{nr}(E)}{L_{er}(E)}$$



- Experiments calibrated with ER, but DM particles are expected to produce NR
- Results must be compared in NR energies, which requires a precise knowledge of the QFs
- **Determining the QF is crucial to support the direct model independent testing of DAMA/LIBRA**

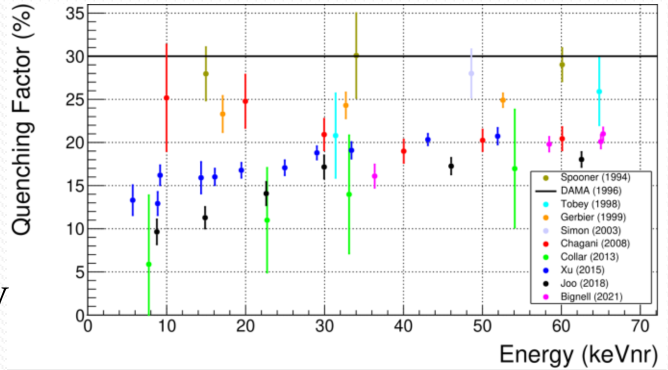




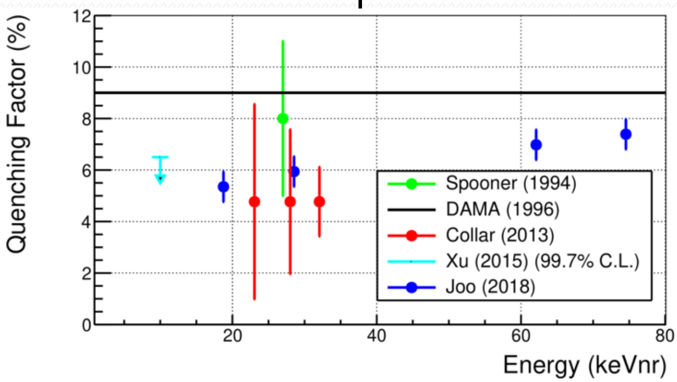
Quenching Factor in NaI(Tl) crystals

- High dispersion in QF meas. in NaI(Tl)
- Systematic in the result comparison with DAMA/LIBRA
  - DAMA QF are assumed constant: $QF_I = 9\%$, $QF_{Na} = 30\%$
  - Most recent measurements: QF increasing with NR energy
- Better understanding of the QF in NaI(Tl) requires the evaluation of
  - Possible systematics in the measurement and analysis procedures applied
  - Possible intrinsic differences in the QF because of impurities, Tl doping, etc.

^{23}Na

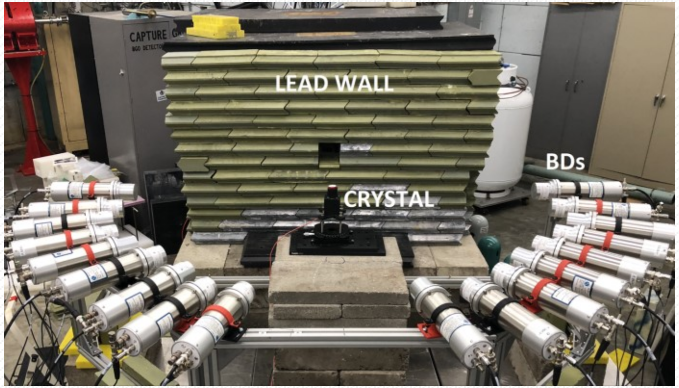


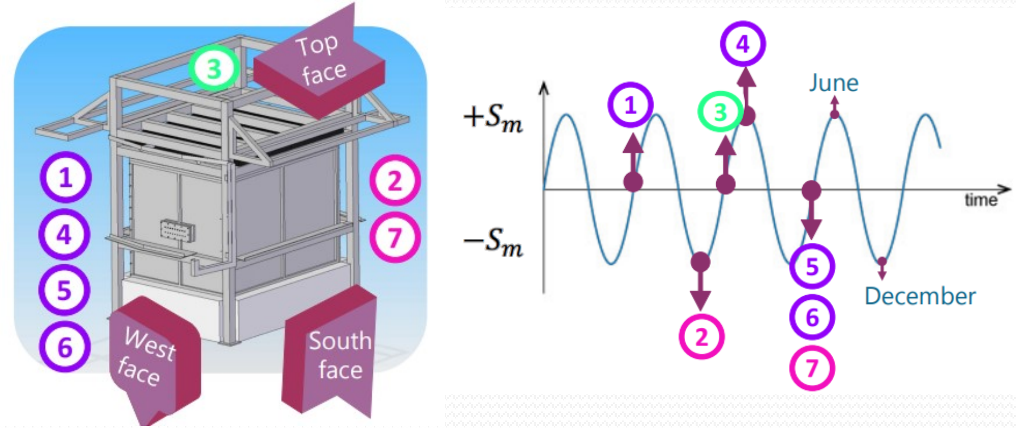
^{127}I



ANAIS-112 Neutron calibration program

- Complementary strategies followed in parallel
  - QF measured with monoenergetic neutrons at TUNL
  - ^{252}Cf calibrations in ANAIS NaI(Tl) crystals onsite



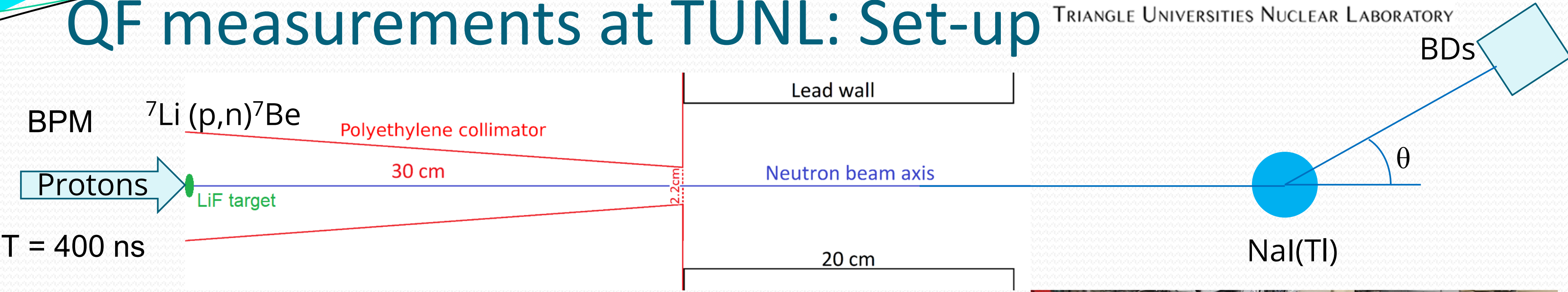


QF measurements at TUNL

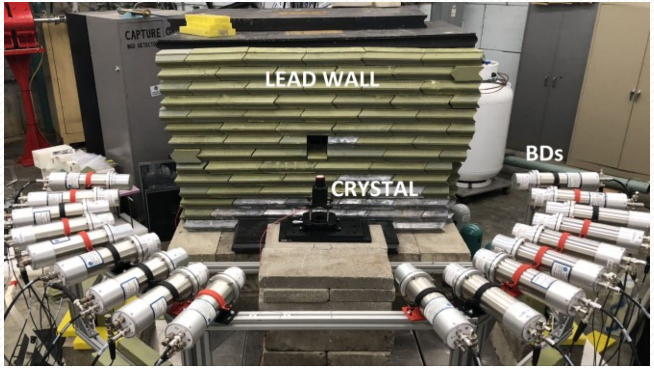
- Goal: to determine the Na and I QF of 5 NaI(Tl) crystals, analyzing a possible crystal dependence and reducing systematics affecting measurements and analysis
- Performed at TUNL (USA) in August and October 2018
- Collaboration between COSINE, COHERENT and ANAIS members
- Measured 5 different NaI(Tl) crystals
  - Different powder quality
  - Cylindrical and small
  - Same set-up

Crystal #	Run	Group	Powder quality	Length and ϕ (mm)
1	August	Yale	WS-I	25
2	August	Yale	WS-II	25
3	October	Yale	WS-III	25
4	October	Zaragoza	Std.	15
5	October	Zaragoza	WS-III	15

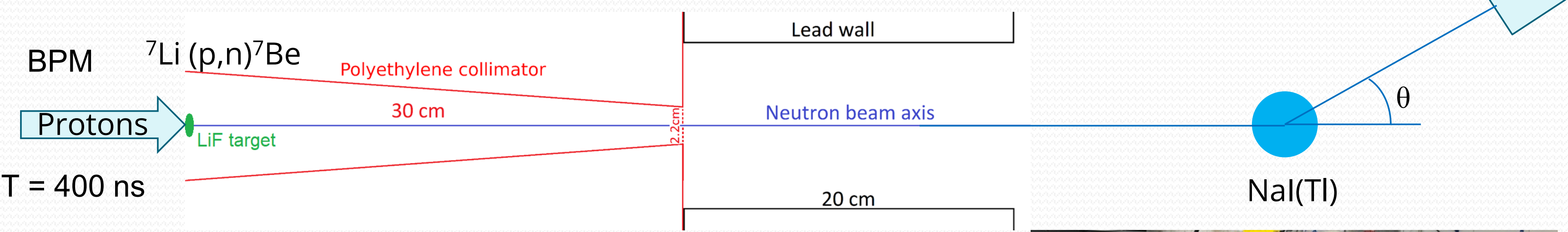
QF measurements at TUNL: Set-up

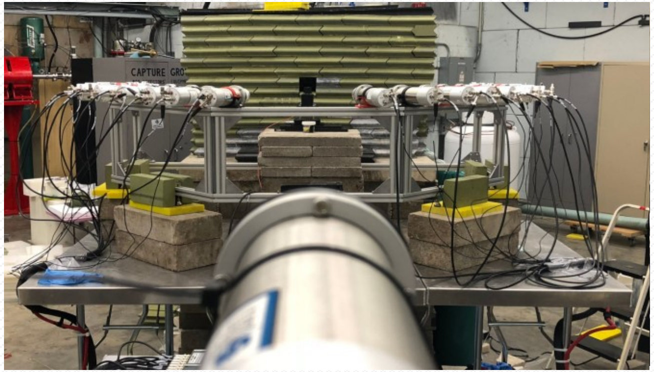


- Neutron detectors (LS, EJ-309)
  - 18 Backing Detectors (BDs)
    - To measure the scattering angle (θ), and then, the nuclear recoil energy



QF measurements at TUNL: Set-up

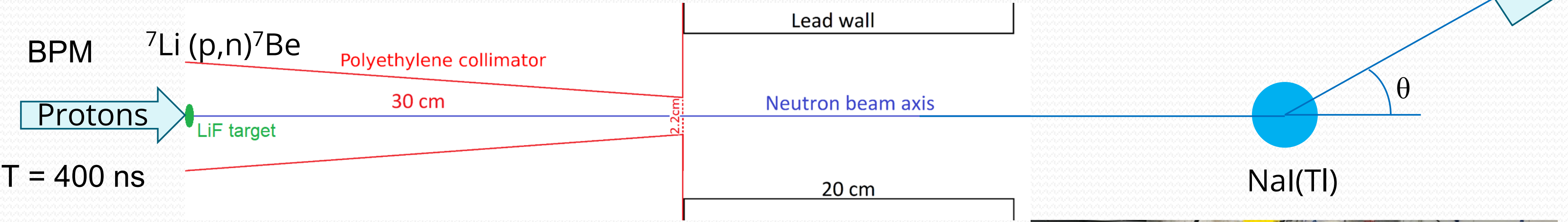




- Neutron detectors (LS, EJ-309)
  - 18 Backing Detectors (BDs)
    - To measure the scattering angle (θ), and then, the nuclear recoil energy
  - 0-deg Detector
    - Aligned with the neutron beam
    - TOF measurements for neutron beam energy distribution

QF measurements at TUNL: Set-up

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY



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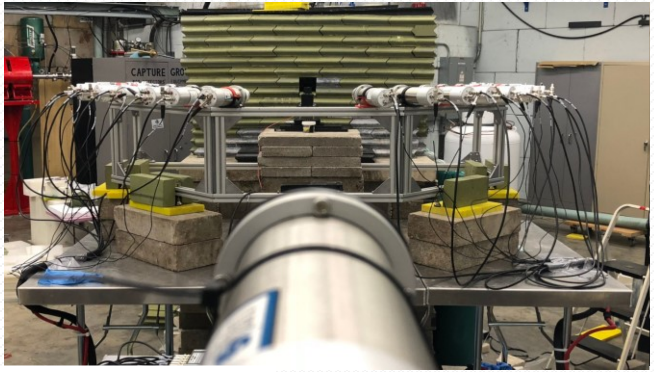
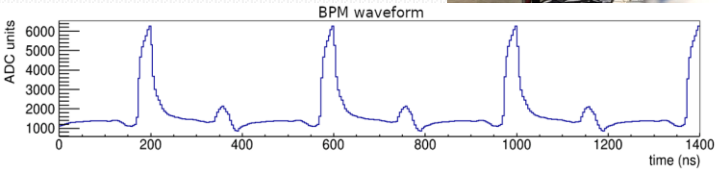
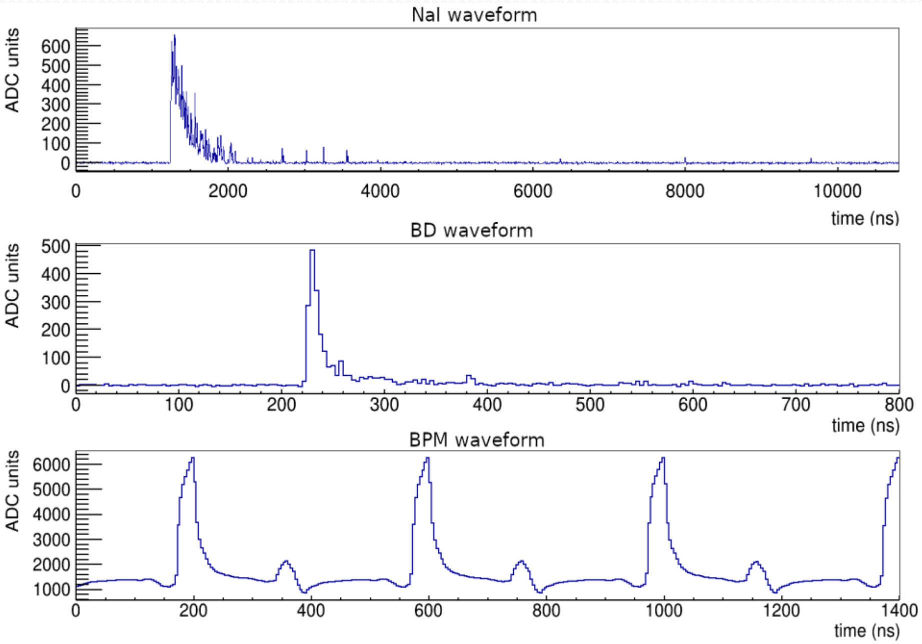
    - To measure the scattering angle (θ), and then, the nuclear recoil energy
  - 0-deg Detector
    - Aligned with the neutron beam
    - TOF measurements for neutron beam energy distribution
- Beam Pulse Monitor (BPM)





QF measurements at TUNL: DAQ

- 2 digitizers Struck33161
  - 4-bit, 250~MHz and 16-channels
  - Each one acts as a discriminator
- Trigger mode depends on measurement:
  - On-beam: any BD to avoid threshold effect
  - Calibrations: detector being calibrated
  - Background: any detector
  - Beam energy and TOF: 0-deg detector
- Data stored:
  - Timestamp
  - 21 signals:
    - NaI(Tl) crystal
    - All BDs
    - Beam pulse monitor (BPM)

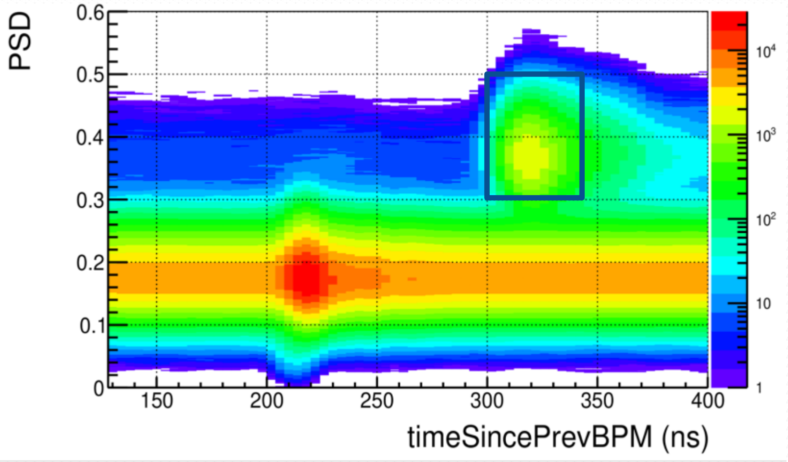


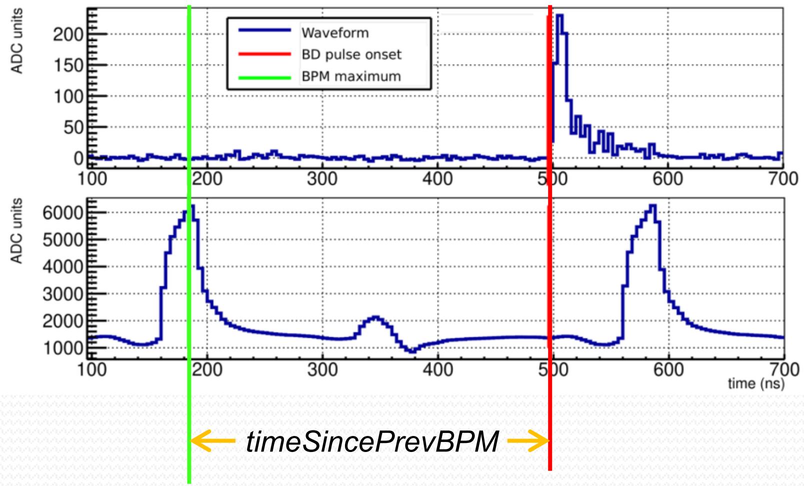
QF measurements at TUNL: Neutron selection in BDs

- Discrimination variables:
  - *PSD* variable
  - *timeSincePrevBPM*

$$PSD = \frac{\sum_{t=t_o+20\ ns}^{t=t_o+200\ ns} V_{BD}(t)}{\sum_{t=t_o}^{t=t_o+200\ ns} V_{BD}(t)}$$

- Neutron vs beta/gamma discrimination

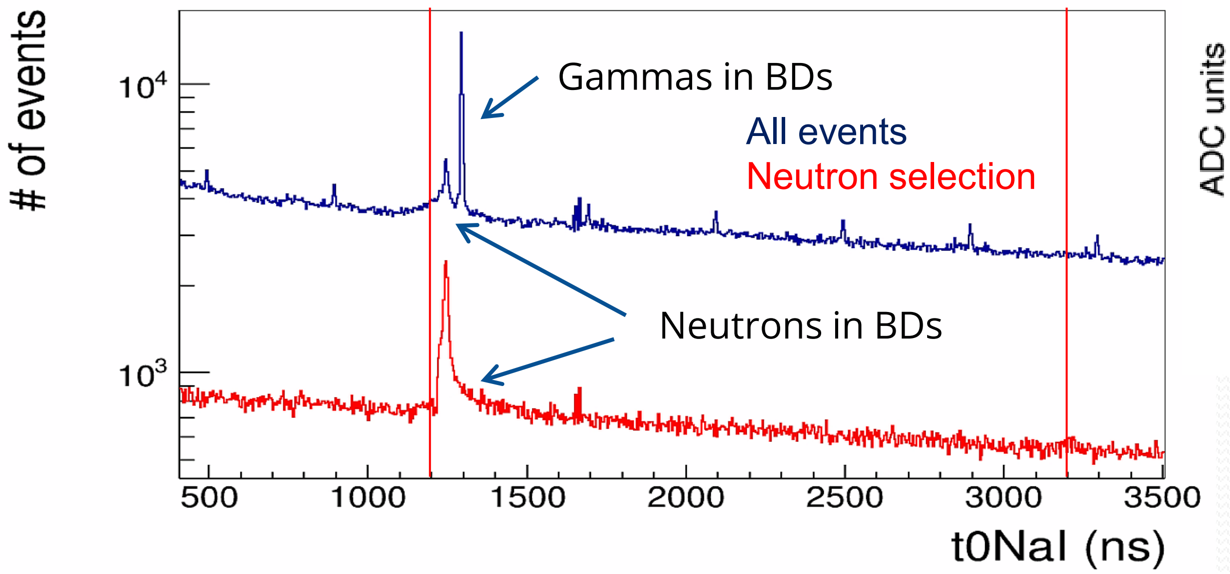


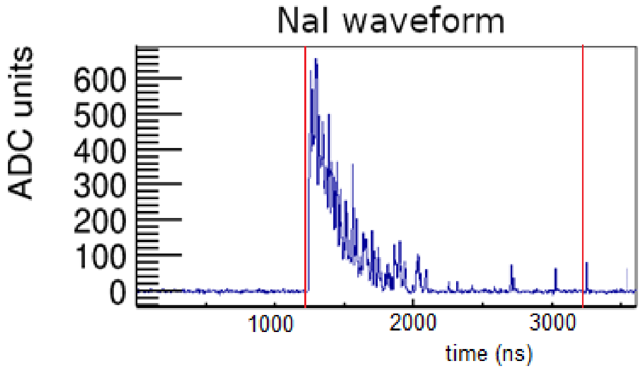


QF measurements at TUNL: NaI(Tl) energy estimator

- Integration window in the NaI(Tl) signal fixed to avoid threshold effect

Pulse onset distributions

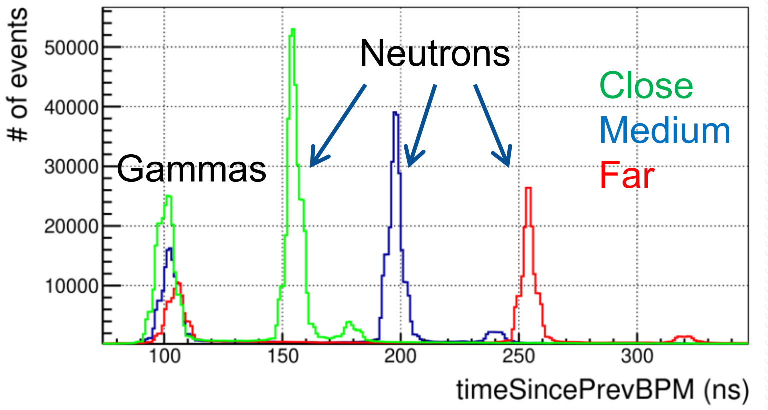




Integration window:
[1200,3200] ns

QF measurements at TUNL: Neutron beam energy

- Neutron energy calculated with TOF from Li target and 0-deg detector
  - 3 measurements at different distances
  - Neutrons and gammas identified

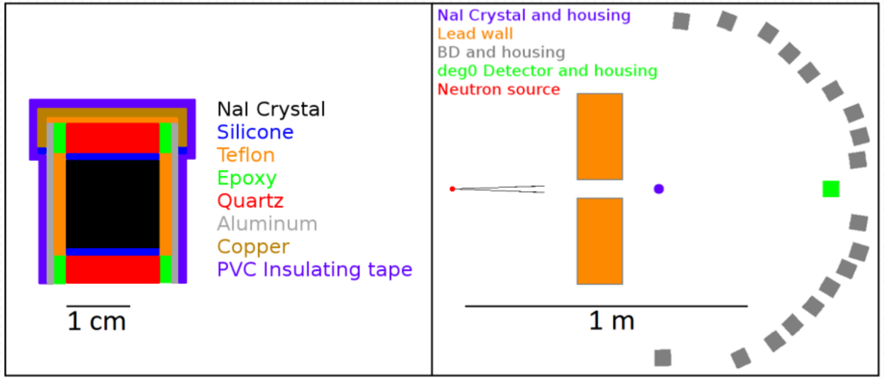


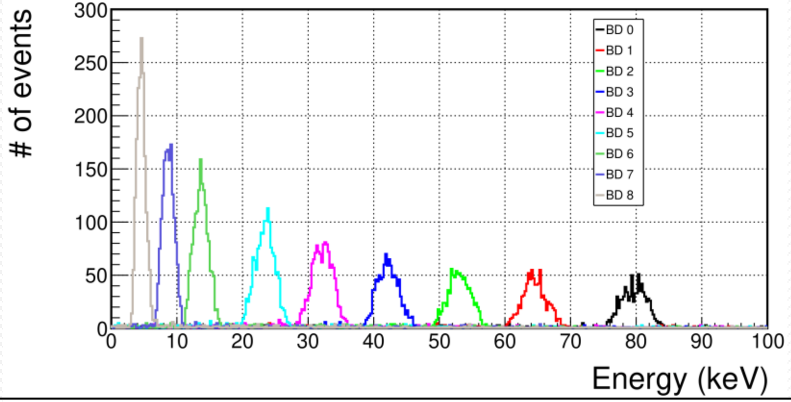
Samuel Hedges PhD thesis, Duke University, 2021

Run	Time resp. (ns)	E_P (keV)	Mean E_n (keV)	Std. dev. E_n(keV)
August	3.40 ± 0.06	$2670.9^{+1.5}_{-3.1}$	958 ± 5	4 ± 3
October	1.21 ± 0.03	$2696.8^{+0.3}_{-0.8}$	982 ± 7	7 ± 5

QF measurements at TUNL: GEANT4 simulation

- Objectives:
  - Obtain nuclear Na and I recoil energy distributions for each BD triggered taking into account the full geometrical effects
  - Obtain the average energies of the peaks in the NaI(Tl) crystal calibration with ^{133}Ba



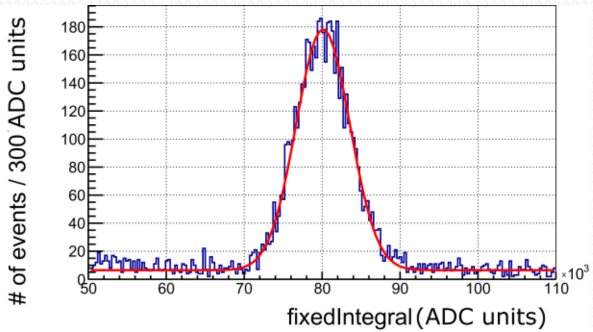


QF measurements at TUNL: NaI(Tl) energy calibration

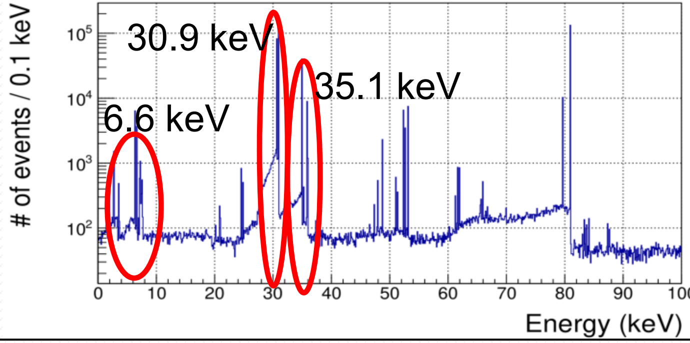
Analysis of the effect of calibration in the QF estimate:

- **Proportional:** using single energy as reference (inelastic peak of ^{127}I, at 57.6 keV)
  - Method followed by many of the previous experiments
  - Peak outside the ROI
- **Non-proportional:** linear response using three energy peaks of calibration with ^{133}Ba (average energies obtained with GEANT4 simulation)

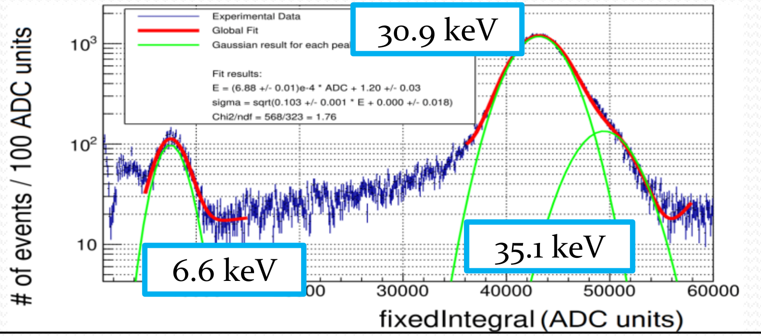
^{127}I inelastic scat. peak, at 57.6 keV



Calibration with ^{133}Ba: Simulation



Calibration with ^{133}Ba: Measurement



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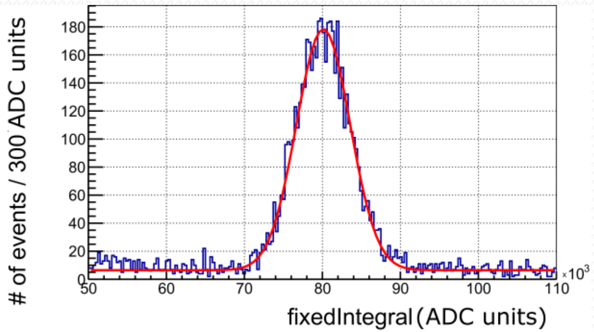
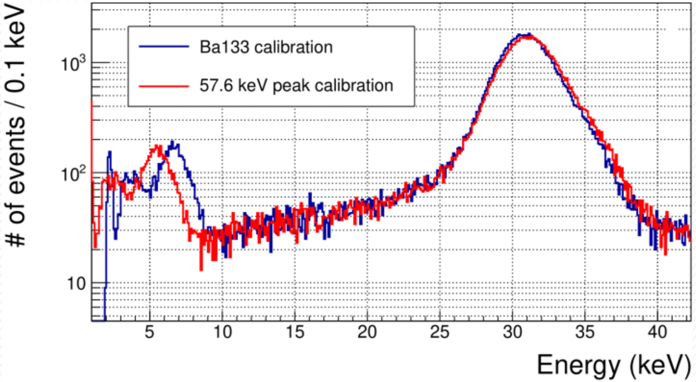
  - Three peaks inside the ROI

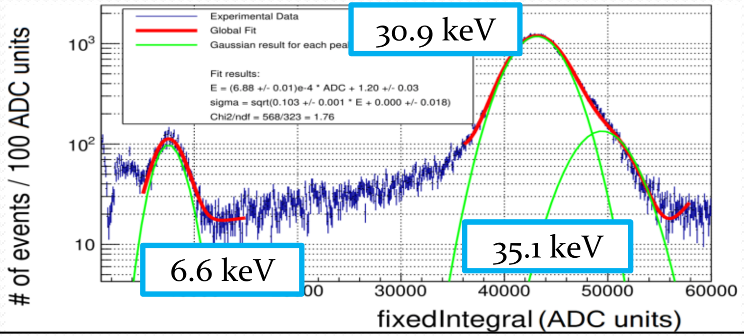
^{127}I inelastic scat. peak, at 57.6 keV



Important differences in response at LE

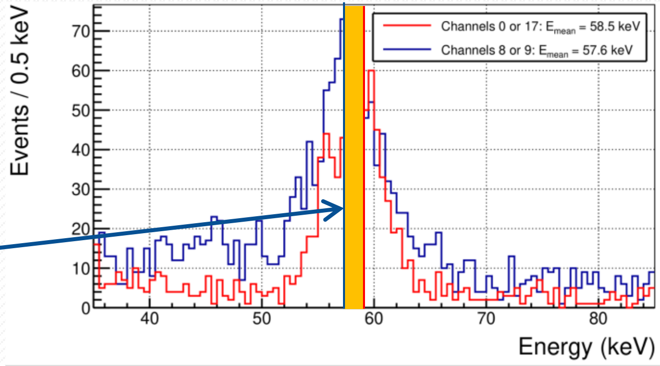


Calibration with ^{133}Ba: Measurement



QF measurements at TUNL: I QF result

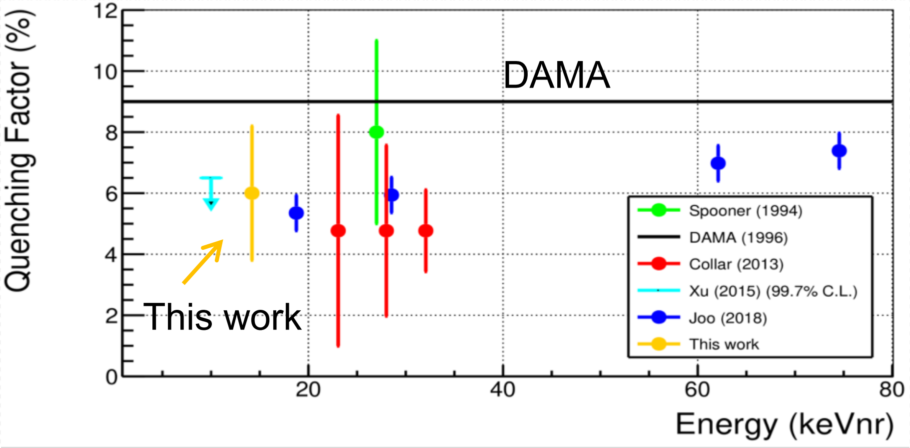
- Using ^{127}I inelastic peak built for each BD signal (because direct elastic iodine recoil spectrum could not be disentangled)
- Quenched energy obtained as the energy difference for max and min. scattering angles
- Applied proportional calibration



QF_I at 14.2 keV = 6.0 ± 2.2 %
(average of crystals 2 and 3)

Compatible with previous measurements

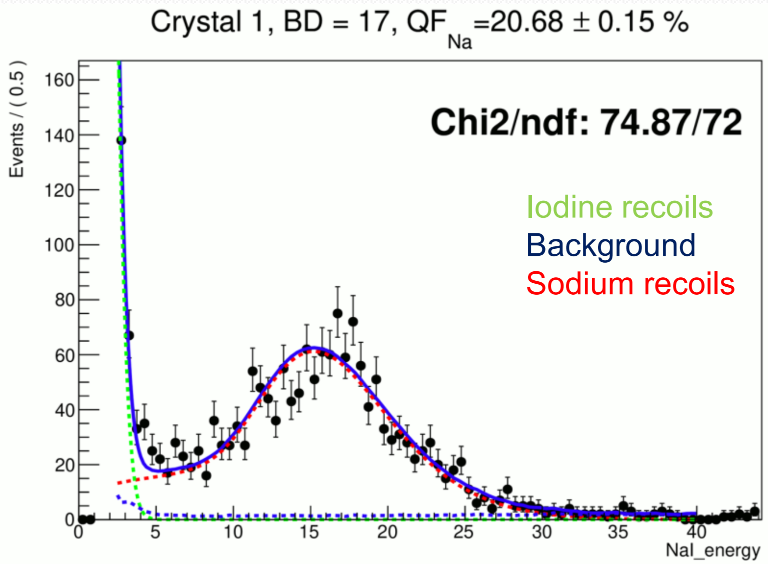
QF_I (DAMA) = 9 %



QF measurements at TUNL: Na QF calculation

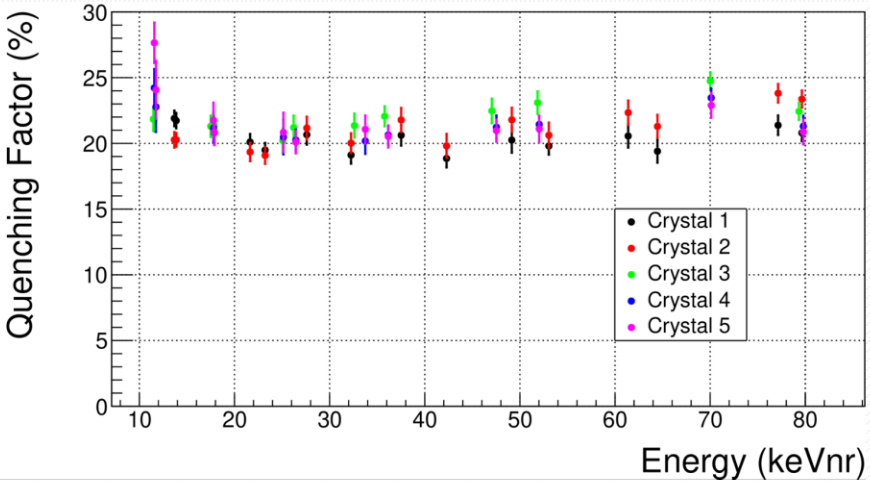
- Na QF value obtained by fitting energy calibrated spectrum to a PDF built by adding three contributions
  - S_I: Iodine nuclear recoil from simulation
    - Converted into Eee with a fixed QF
  - S_b: Background from experimental data
  - S_{Na}: Sodium nuclear recoil from simulation
    - Converted into Eee with a floating QF_{Na} for each BD
    - Gaussian convoluted considering two energy resolution models:
      - Constant with the energy
      - Poissonian energy dependence
- Systematic uncertainties from
  - Energy resolution
  - Calibration parameters uncertainties
  - Uncertainties in BD positions
  - Iodine QF value

$$PDF = N_I S_I + N_b S_b + N_{Na} S_{Na}(QF_{Na}, \sigma)$$

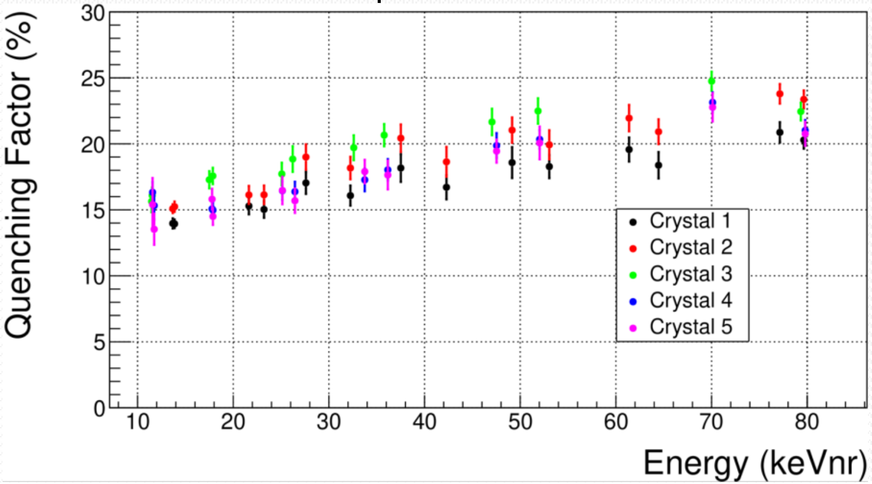


QF measurements at TUNL: Na QF results

Non-proportional calibration



Proportional calibration

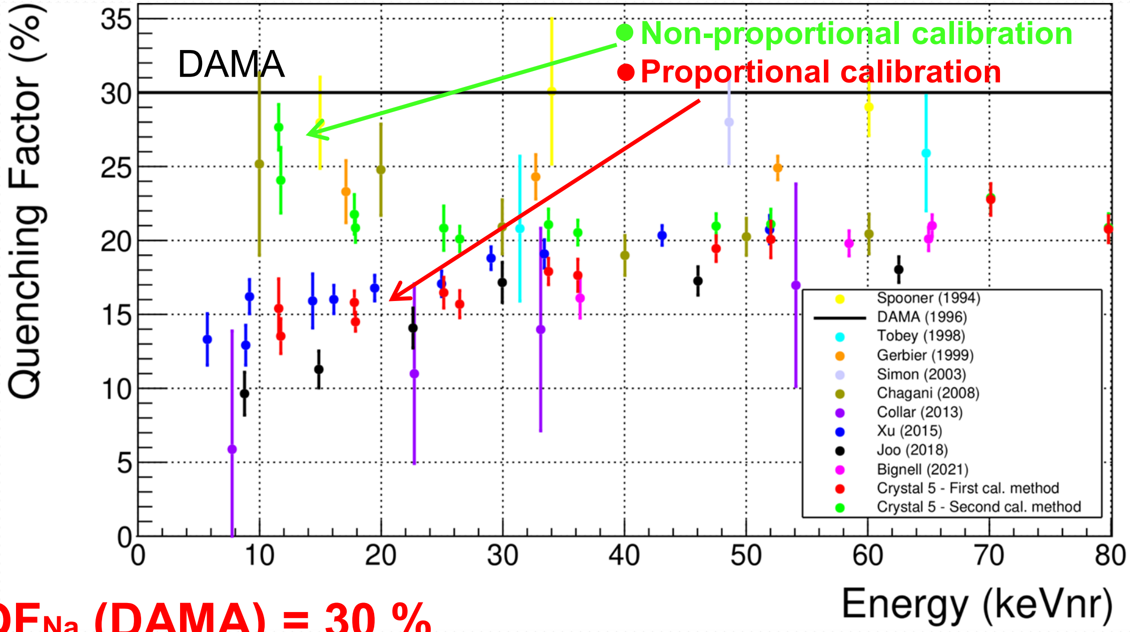


- Results for the 5 NaI(Tl) crystals are compatible with each other in both scenarios
- The **energy calibration is a critical issue** in the determination of the QF
  - Non-proportional calibration: constant with energy **(QF_{Na} = 21.2 ± 0.8 %)**
  - Proportional calibration: Increases with the energy

QF measurements at TUNL: Na QF results

- The dispersion in QF_{Na} could be related with the different calibration in energy applied
- Further work is required to better understand the conversion from energy deposited into light in NaI(Tl), considering
  - Non-linear response
  - Surface effects
  - Other systematics

Crystal 5 (same ingot of ANAIS-112) result comparison



QF_{Na} (DAMA) = 30 %
Different from our estimates

QF measurements at TUNL: Na QF results

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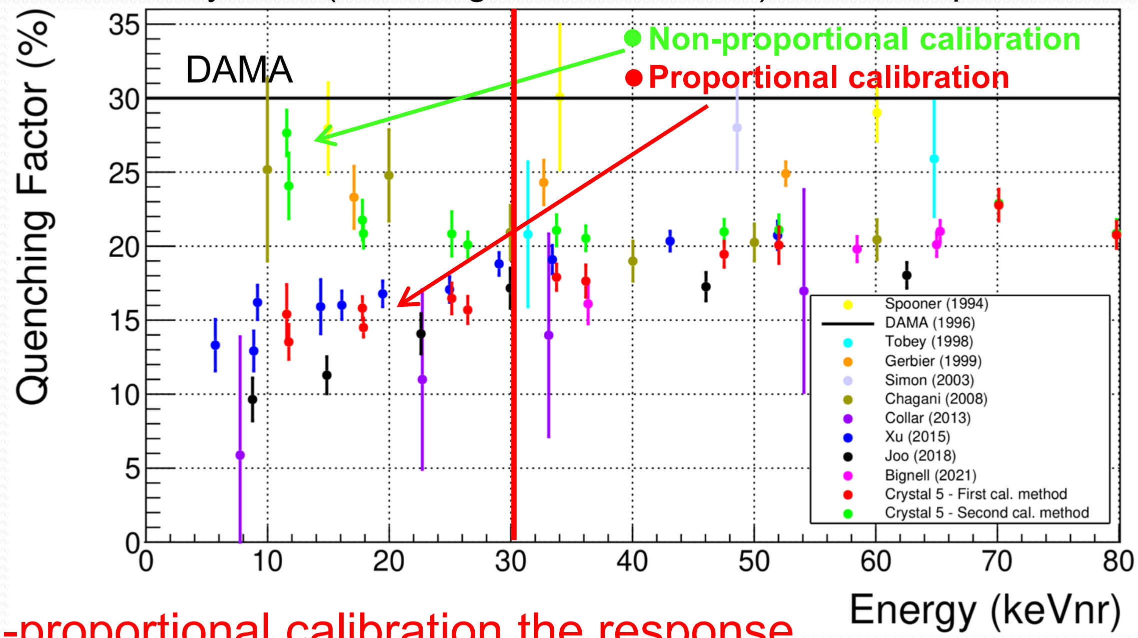
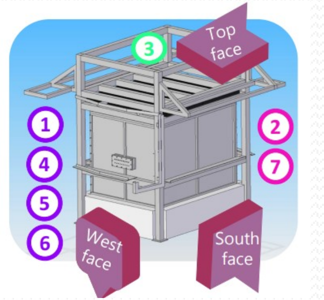
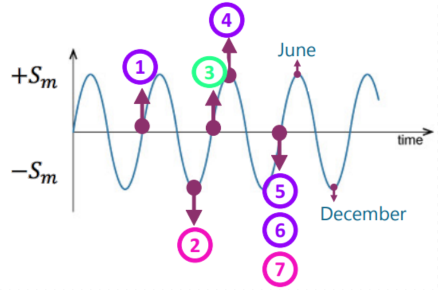


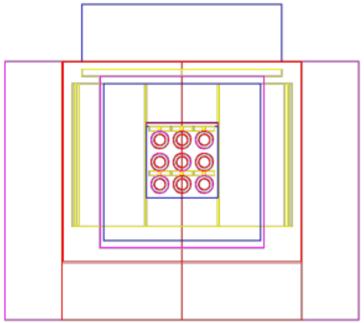
In non-proportional calibration the response is extrapolated below 6.6 keVee (below ~ 30 keVnr)

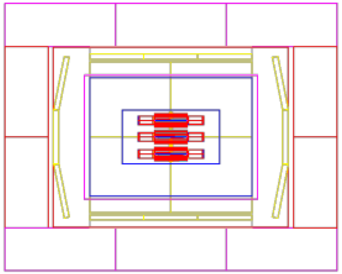
Neutron calibration program in ANAIS-112

- 7 calibrations runs with a ^{252}Cf neutron source in ANAIS crystals onsite
- GEANT4 model of ANAIS-112 allows to simulate these calibrations







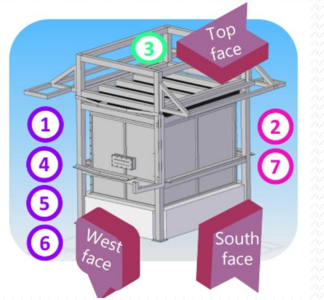


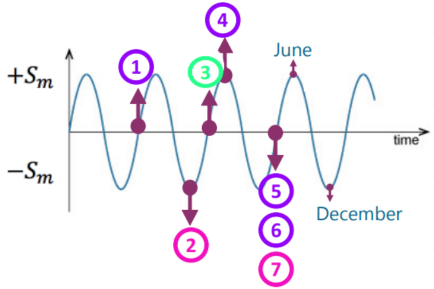
T.Pardo et.al. Contributed to TAUP 2023

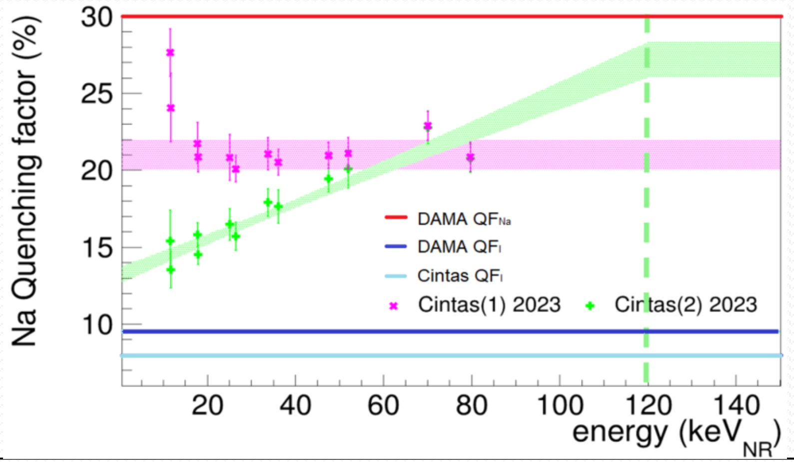
Neutron calibration program in ANAIS-112

- 7 calibrations runs with a ^{252}Cf neutron source in ANAIS crystals onsite
- GEANT4 model of ANAIS-112 allows to simulate these calibrations
- Measured and simulated spectra have been compared considering different QF models
  - DAMA QF meas. (**QFNa = 30%**, **QFI = 9%**)
  - QF_{Na}cte
  - $QF_{Na}(E)$
- Work in progress

T.Pardo et.al. Contributed to TAUP 2023



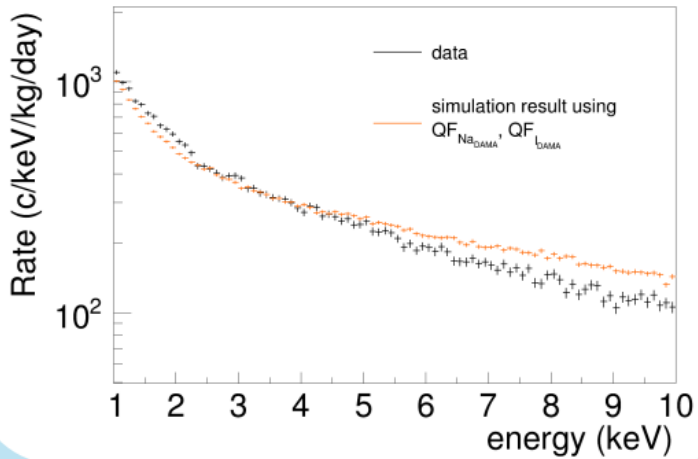


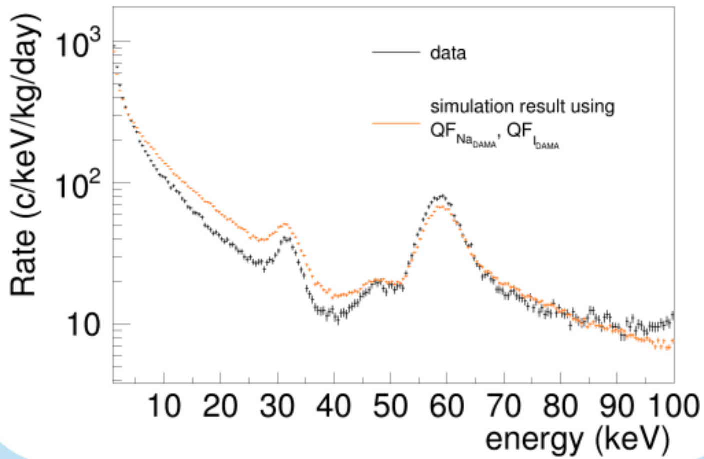


QF model comparison: Preliminary results

- DAMA QFs are not compatible with our data

Work in progress





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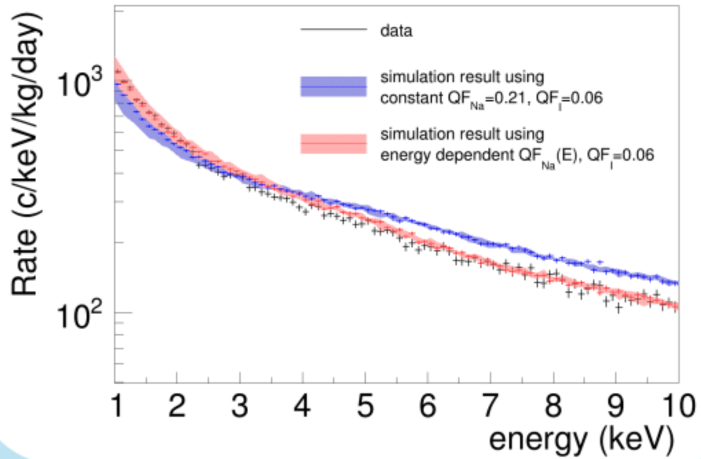
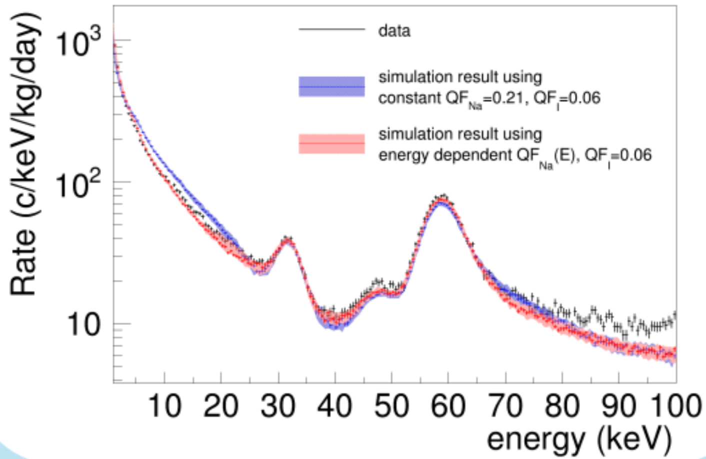
QF model comparison: Preliminary results

- $QF_{Na}(E)$ provides a robust agreement, better than QF_{Na}cte

Work in progress





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Further investigation is required to better **understand multiple-hit events** and **include non-proportionality** issues in the simulation

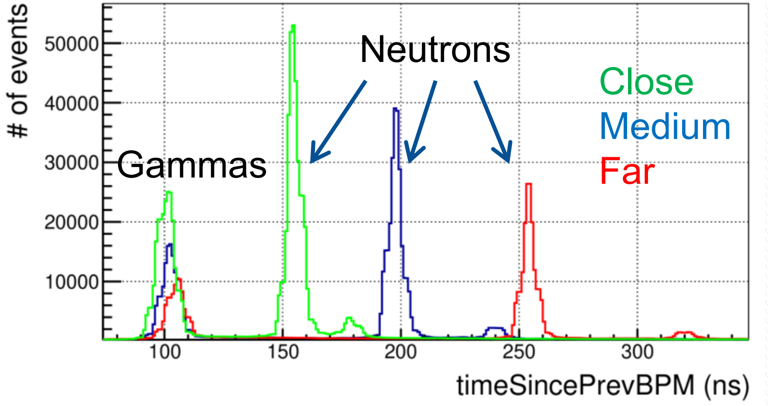
Conclusions

- Not observed a crystal dependence of the QF_{Na} in NaI(Tl) using the same analysis and experimental approach
- Calibration method is a critical issue in the QF_{Na} estimation:
  - Proportional calibration: QF_{Na} increases with the energy
  - Non-proportional calibration (response extrapolation below 6.6 keVee): QF_{Na} constant with average value of $QF_{Na} = 21.2 \pm 0.8$ %, between 10 and 80 keV
- GEANT4 simulation of ANAIS-112 allows to simulate the neutron calibration with ^{252}Cf sources and compare results with measurements considering different QF models
  - DAMA QFs are not compatible with our data
  - Energy-dependent QF_{Na} provides a robust agreement and seems to be favored over constant QF_{Na}
  - Plans to continue studying other energy dependences and to include the non-proportionality of detectors
- Further work is required to better understand the conversion from energy deposited into light in NaI(Tl) crystals
- Measurements of the QF for ANAIS detectors will be taken into account for the comparison with DAMA/LIBRA results and those from other targets

Thanks for your attention

QF measurements at TUNL: Neutron beam energy

- Neutron energy calculated with TOF from Li target and 0-deg detector
  - 3 measurements at different distances
  - Neutrons and gammas identified
- Procedure followed to get En distr (*):
  - Simulate gammas and neutrons going from Li target to 0-deg detector
  - Fit their TOF distributions considering the detector time response for different initial energies



Run	Time resp. (ns)	E_P (keV)	Mean E_n (keV)	Std. dev. E_n(keV)
August	3.40 ± 0.06	$2670.9^{+1.5}_{-3.1}$	958 ± 5	4 ± 3
October	1.21 ± 0.03	$2696.8^{+0.3}_{-0.8}$	982 ± 7	7 ± 5

* Samuel Hedges PhD thesis, Duke University, 2021

QF model comparison: Systematic uncertainties