TAUP VIENNA 2023

Quenching factor measurement of low-energy Na recoils in ultra-pure NaI(Tl) crystal

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PICOLON project

PICOLON (Pure Inorganic Crystal Observatory for LOw-energy Neutr(al)ino)

- Dark matter search experiment using NaI(Tl) scintillator
- We succeeded in developing high-purity NaI(Tl) crystals with a low background equal to or less than the DAMA/LIBRA group.[1]

For more information, please see poster presentation by Kenta Kotera.

Quenching factor : QF

- Nuclear recoils are observed at lower energies than electron recoils with the same energy.
- Light yield ratio of nuclear recoil L_{nr} to electron recoil L_{er}

$$QF = L_{nr} / L_{er} = E_{ee} / E_{nr}$$

E_{ee} : Electron equivalent energy

E_{nr} : Nuclear recoil energy

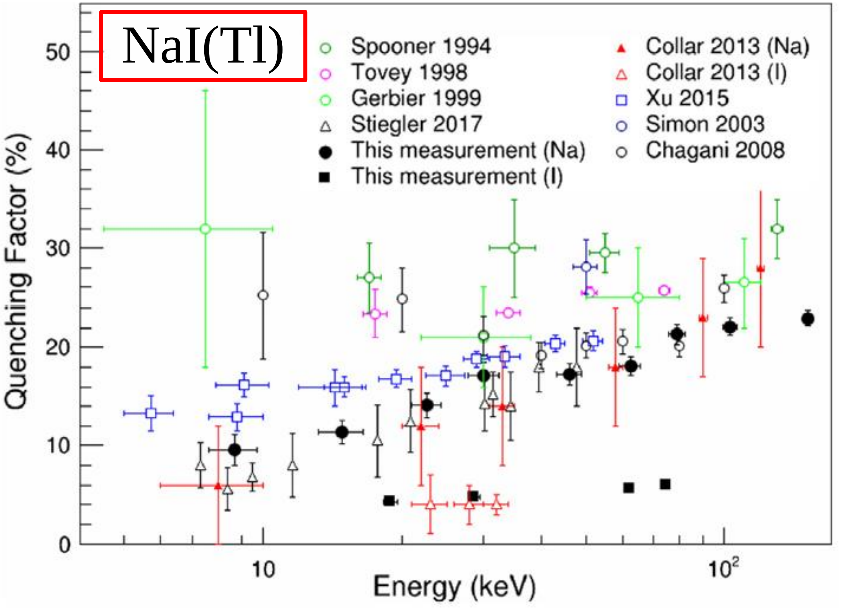
- Necessary to calibrate the nuclear recoil energy by WIMP

[1] K.Fushimi *et al.*, J Phys Conf Ser, **2156**, 012045, 2022

Experimental values of QF

It is necessary to measure the low-energy side with high accuracy for WIMP search.

- ➢ Smaller than theoretical value
- ➢ Discrepancy of the reported values from several groups
- ➢ QF absolute value and its energy dependence in the low-energy region (~100 keV) have been discrepant in previous studies.
- ➢ We should verify whether the variation is due to the individual crystal differences or the effect of systematic errors.



Experimental values of QF[2]

[2] H.W.Joo *et al*., Astroparticle Physics, **108,** 50, 2019

Motivation

- In general, the higher the impurity concentration in the crystal, the lower the light output.
- Necessary to measure using crystals with low radiation impurity concentration

We measure the QF of the NaI(Tl) scintillator developed by PICOLON group.

- We investigate individual crystal differences and the effect of different energy calibration methods on QFs.

Our crystal

2.54 cm

2.54 cm

	Our crystal[3]	DAMA/LIBRA
^{232}Th (ppt)	0.4 ± 0.5	0.5-0.7
^{238}U (ppt)	4.7 ± 0.3	0.7-10
^{210}Pb (μBq/kg)	29.4 ± 6.6	5-30

[3] K.Fushimi *et al.*, J Phys Conf Ser, **1468**, 012057, 2020

Setup

Neutron energy : 2.45 MeV (DD Nuclear Fusion)

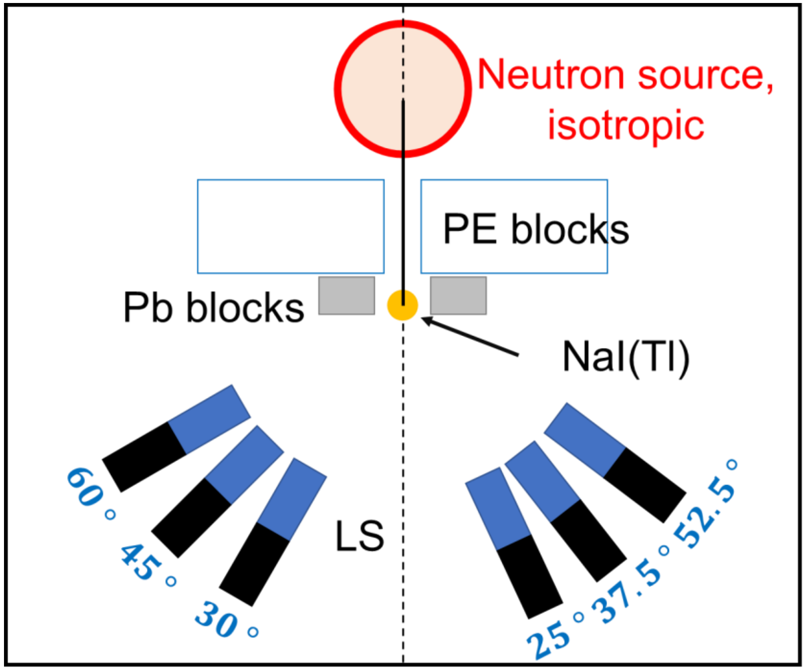
Neutron intensity : 5×10^6 n/s (Neutron source)

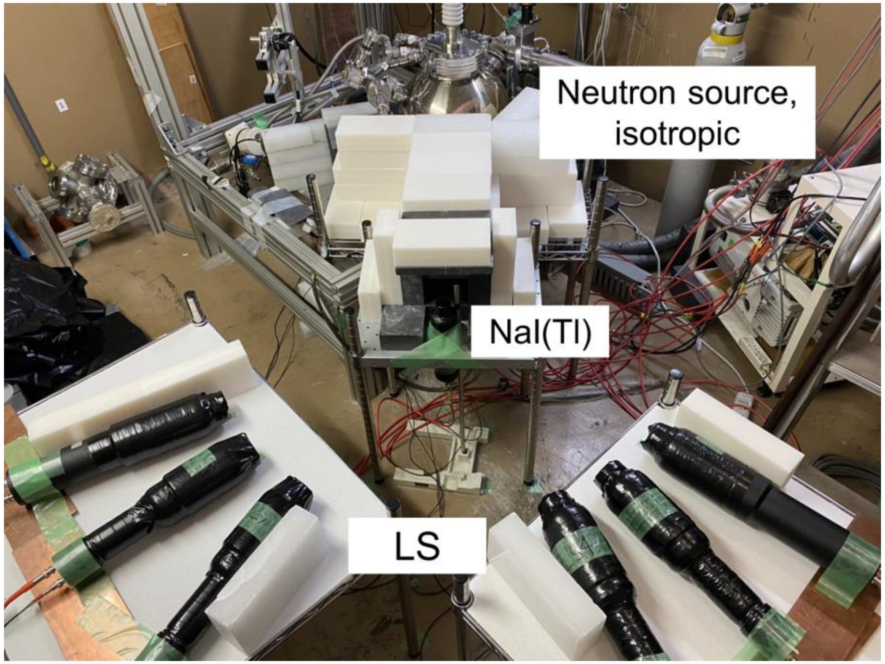
NaI(Tl) scintillator : developed by PICOLON + H11284-100 (PMT, Hamamatsu)

Liquid scintillator (LS) : EJ-301 (Eljen Technology) + R6091 (PMT, Hamamatsu)

Distance Neutron source - NaI(Tl) : 90 cm

Distance NaI(Tl) - LS : 50 cm (TOF)





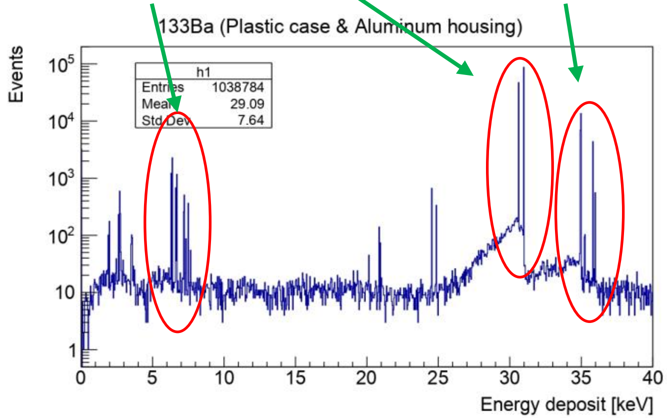
Institute of Advanced Energy, Kyoto Univ.

Energy calibration method

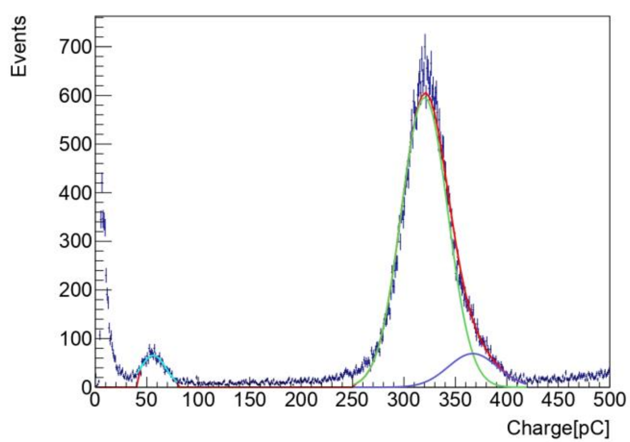
NaI(Tl) detector calibration

- Source:

^{133}Ba (6.5 keV, 30.8 keV, 35.1 keV)



Simulation of ^{133}Ba source (Geant4.10.5)



Fitting result for the three peaks of ^{133}Ba

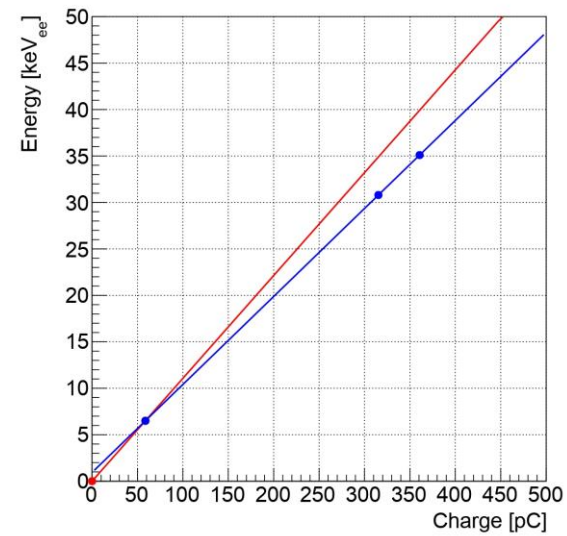
- NaI(Tl) detector was energy calibrated separately at 0-6.5 keV_{ee} and 6.5-35.1 keV_{ee}.

0 – 6.5 keV_{ee}

Energy [keV_{ee}] = 0.1107 × *Charge* [pC]

6.5 – 35.1 keV_{ee}

Energy [keV_{ee}] = 0.09471 × *Charge* [pC] + 0.9376



- The relationship between light intensity and energy of the NaI(Tl) scintillator is not perfectly linear at low energies.

Analysis methods

PSD (Pulse Shape Discrimination)

NaI(Tl)

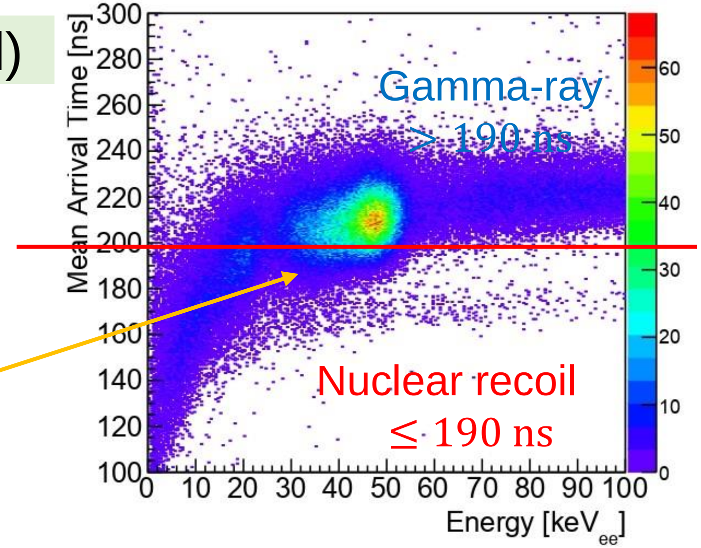
- Mean arrival time $< t >$ was used to discriminate the waveforms.

$$< t > = \frac{\sum_{i=0}^{838} t_i a_i}{\sum_{i=0}^{838} a_i}$$

a_i : Voltage [mV]

t_i : Time [ns]

Bremsstrahlung X-rays from neutron source



TOF (Time of Flight)

- Time of flight was used to discriminate the particles.

$$\mathrm{TOF} = L\sqrt{\frac{m_{\mathrm{n}}}{2E}} = t_{\mathrm{LS}} - t_{\mathrm{NaI}}$$

m_{n} : Mass of neutron

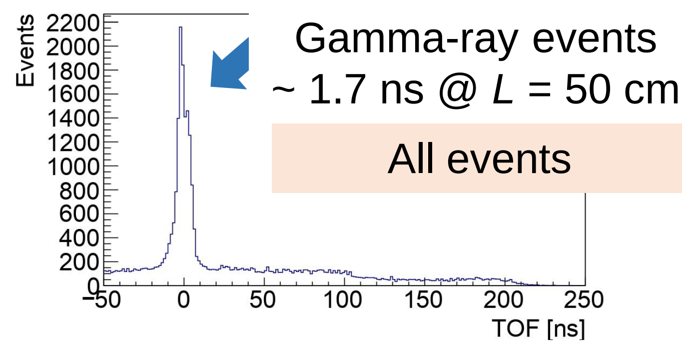
L : Distance NaI(Tl) - LS

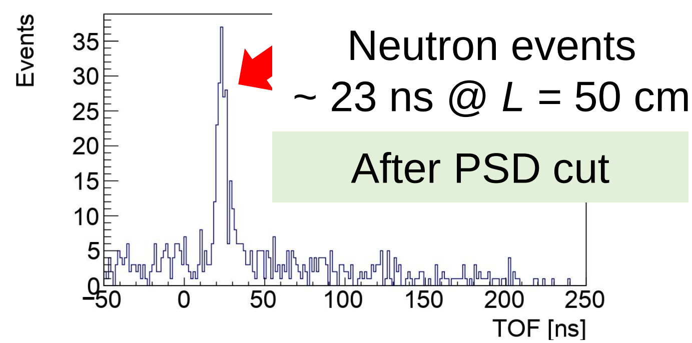
E : Energy of incident neutrons

t_{NaI} : Signal start time of NaI(Tl)

t_{LS} : Signal start time of LS

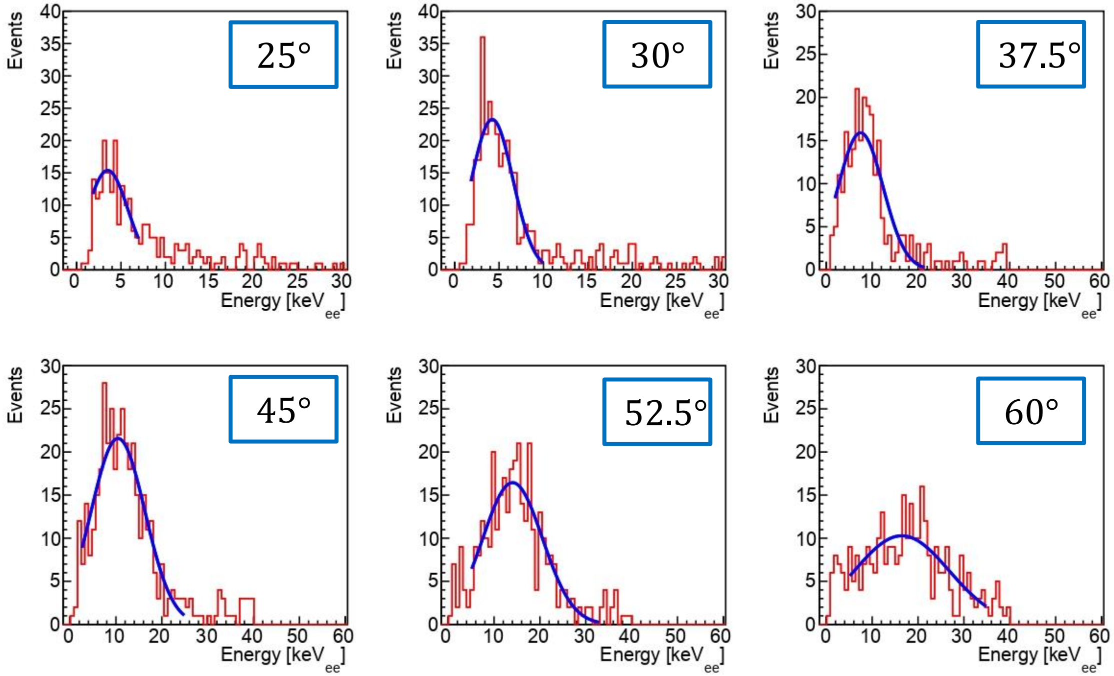
~ 23 ns @ L = 50 cm (Neutron TOF)





Nuclear recoil energy spectra

Energy spectra after analysis by PSD and TOF



- ➢ Energy spectra depending on the neutron scattering angles were obtained.

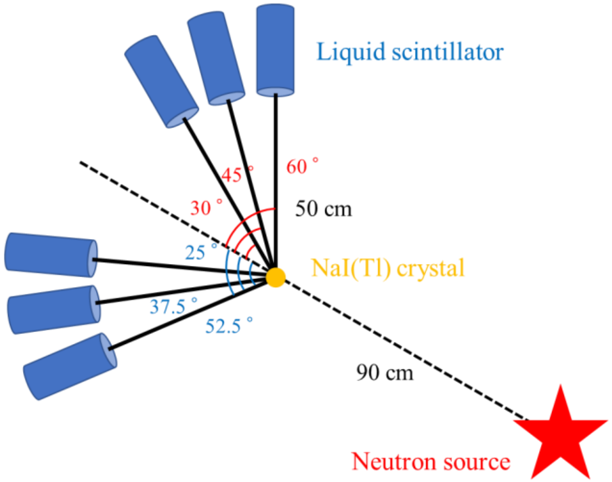
Systematic errors

- ➢ Energy calibration error (5 %)
- ➢ Liquid scintillator placement error (11.5~4.7 %)

Calculation of QF

- The same setup, detector size, and neutron beam structure as in the present experiment were reproduced by Geant4 simulation.

- Nuclear recoil energies without quenching effects were calculated by Monte Carlo (MC) simulation.

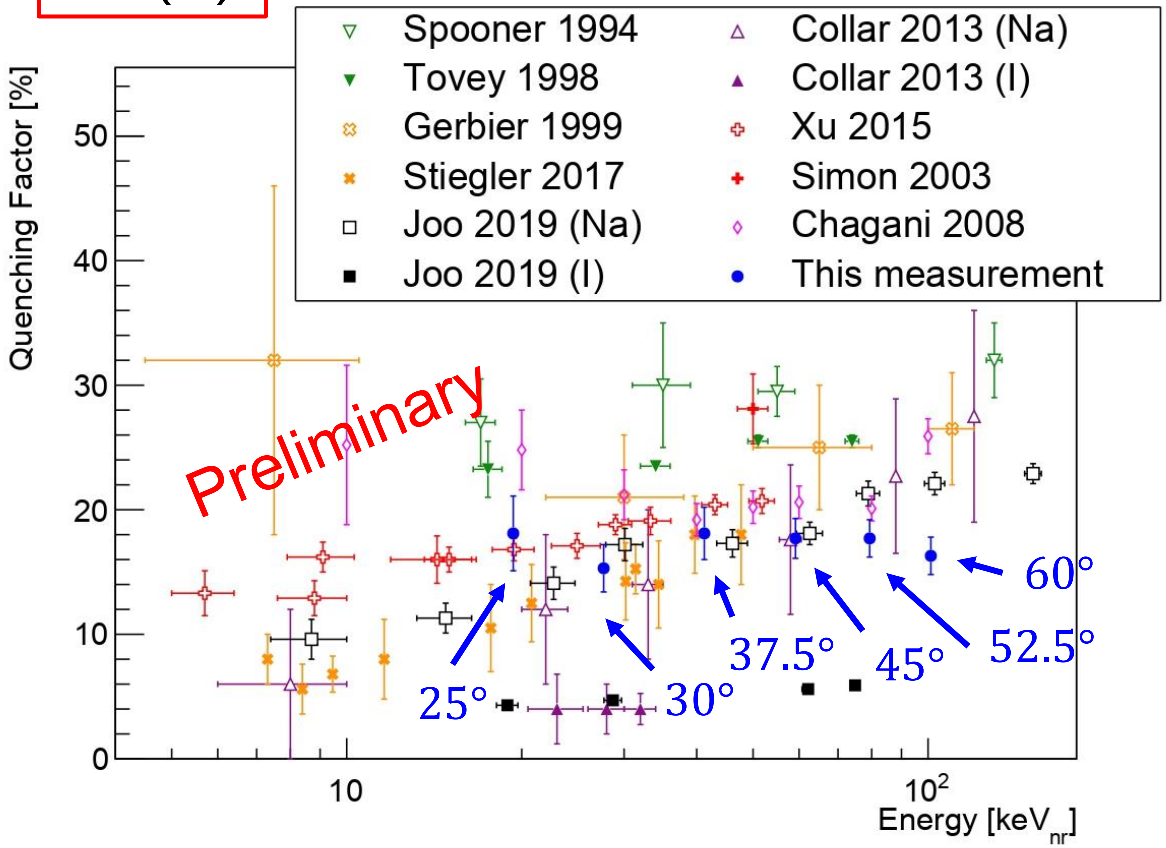


Calculation results of nuclear recoil energy E_{nr} by Geant4 (version 4.10.5) simulation

Scattering angle	E_{ee} (keV_{ee})				E_{nr} (keV_{nr})		QF_{Na} [%]
	Fit mean	Fit error	Cal error	Place error	MC mean	MC error	
25°	3.50	±0.39	±0.18	±0.27	19.34	±0.16	18.1 ± 3.0
30°	4.23	±0.24	±0.21	±0.34	27.67	±0.19	15.3 ± 1.9
37.5°	7.47	±0.52	±0.37	±0.49	41.22	±0.23	18.1 ± 2.1
45°	10.45	±0.43	±0.52	±0.61	59.15	±0.23	17.7 ± 1.6
52.5°	14.05	±0.50	±0.70	±0.73	79.36	±0.33	17.7 ± 1.5
60°	16.45	±1.00	±0.82	±0.89	101.12	±0.36	16.3 ± 1.5

Comparison with previous studies of QF

NaI(Tl)



Scattering angle	QF_{Na} [%]
25°	18.1 ± 3.0
30°	15.3 ± 1.9
37.5°	18.1 ± 2.1
45°	17.7 ± 1.6
52.5°	17.7 ± 1.5
60°	16.3 ± 1.5

There were differences in QF results in the low-energy region (< 30 keV_{nr}).

- ➢ The radiation sources used in previous studies were varied.

→ Non-linearity in the low energy region of the detector response should be considered.

Conclusions

- We have experimented to measure the QF of the ultra-pure NaI(Tl) scintillator developed by PICOLON group.

- We have succeeded in calculating the QF_{Na}.

- We tried to identify the causes of the variation in the previous studies.

  Differences in QF results at lower energy region due to different energy calibration method

  Individual crystal differences may be the factor.

< *Future prospects* >

- Tl concentration dependence, temperature dependence, and readout photodetector dependence of QF, measurement of QF_I
- Radioactive impurity concentration dependence

Backup

PICOLON project

PICOLON (Pure Inorganic Crystal Observatory for LOw-energy Neutr(al)ino)

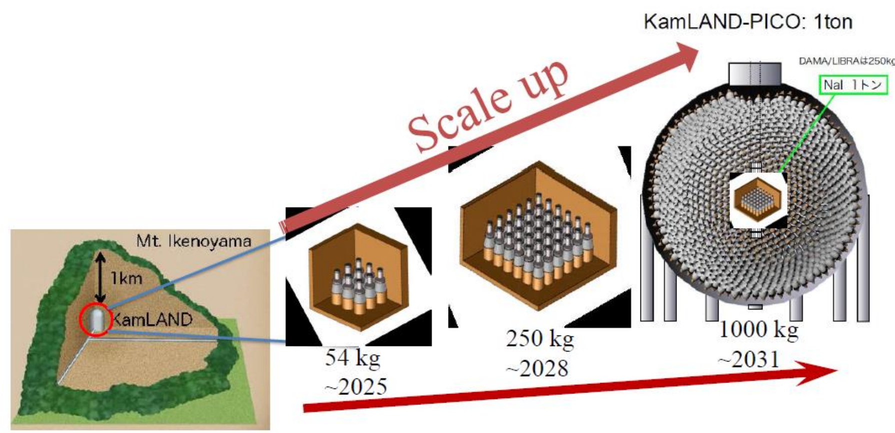
- Dark matter search experiment using NaI(Tl) scintillator

	DAMA/LIBRA (NIM A592 (2008) 297.)	Ingot #85 (2020)	Ingot #94 (This work)	Goal
Crystal size	$10.2\times10.2\times25.4$ cm^3	$7.62\phi\times7.62$ cm^3		
^{232}Th [μBq/kg]	2~31	0.3 ± 0.5	4.6 ± 1.2	<10
^{226}Ra [μBq/kg]	8.7~124	1.0 ± 0.4	7.9 ± 4.4	<10
^{210}Po [μBq/kg]	5~30	<5.7	19 ± 6	<50

K.Kotera, "Result and analysis for Ingot#94 of PICOLON ultra-pure NaI(Tl) crystal" (ICRC2023)

- We succeeded in developing high-purity NaI(Tl) crystals with a low background equal to or less than the DAMA/LIBRA group.

We are planning to construct 250 kg of NaI(Tl) detector within 5 years.[1]



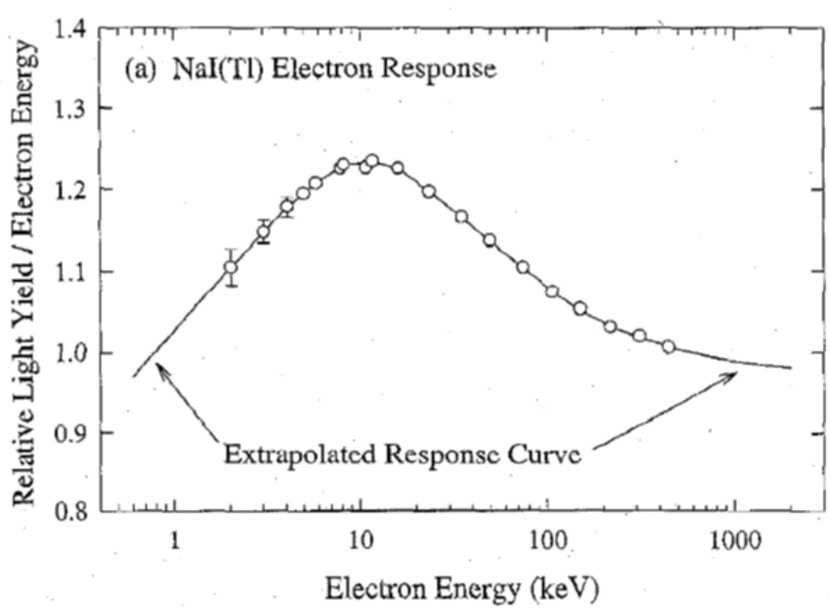
PICOLON's future plan

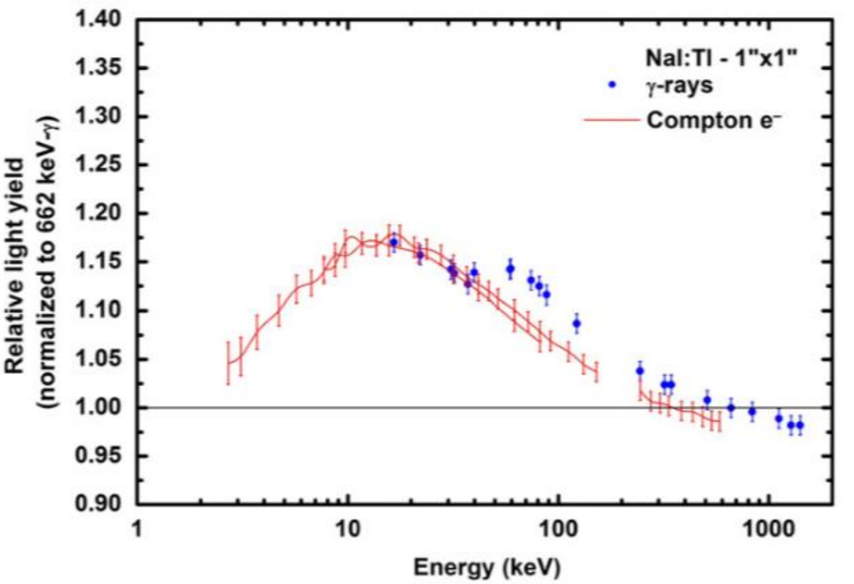
[1] K.Fushimi *et al.*, J Phys Conf Ser, **2156**, 012045, 2022

Non-linearity of NaI(Tl)

➢ The relationship between light intensity and energy of the NaI(Tl) scintillator is not perfectly linear at low energies.

➢ Non-linearity in the low energy region of the detector response should be considered.





B. D. Rooney *et al.*, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 44, NO. 3, JUNE 1997

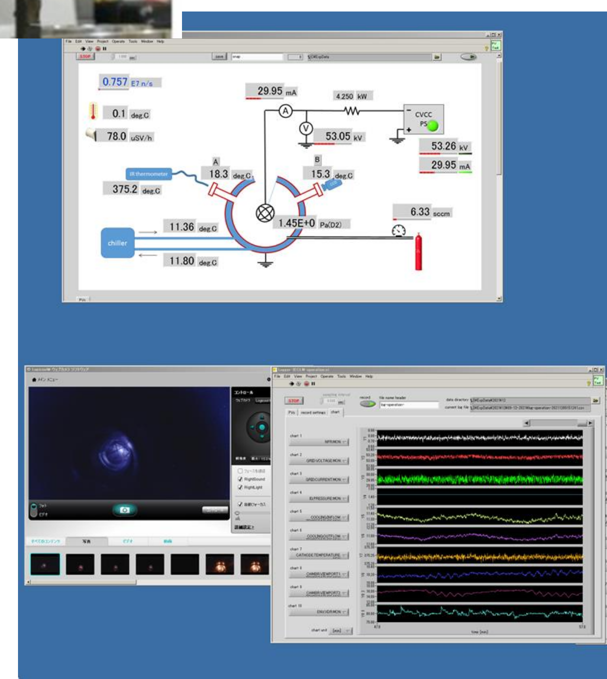
L.Swiderski *et al.*, Nuclear Instruments and Methods in Physics Research A 705 (2013) 42–46

Neutron source

Compact fusion D-D neutron source[4]

$$\mathbf{D + D \rightarrow {}^{3}He\ (0.82\ MeV) + n\ (2.45\ MeV)}$$

- ϕ 35 cm sphere
- ϕ 8 cm cathode in the center
- Cathode material: Molybdenum
- Water for cooling (5 cm thickness)



Neutron intensity (10^5-10^7) can be controlled by cathode voltage

Supported by Zero Emission Energy Research

Institute of Advanced Energy, Kyoto University

Dec. 6-10th, 2021

[4] K.Yoshikawa *et al*., Journal of Plasma and Fusion Research, **83**(10), 795, 2007

Nuclear recoil

Neutron scattering angle vs. Nuclear recoil energy

$$E_{\mathrm{nr}} = E_{\mathrm{n}} \cdot \left\{ 1 - \left(\frac{m_{\mathrm{n}} \cos\theta_{\mathrm{L}} + \sqrt{{m_{\mathrm{N}}}^2 - {m_{\mathrm{n}}}^2 \sin^2\theta_{\mathrm{L}}}}{m_{\mathrm{n}} + m_{\mathrm{N}}} \right)^2 \right\}$$

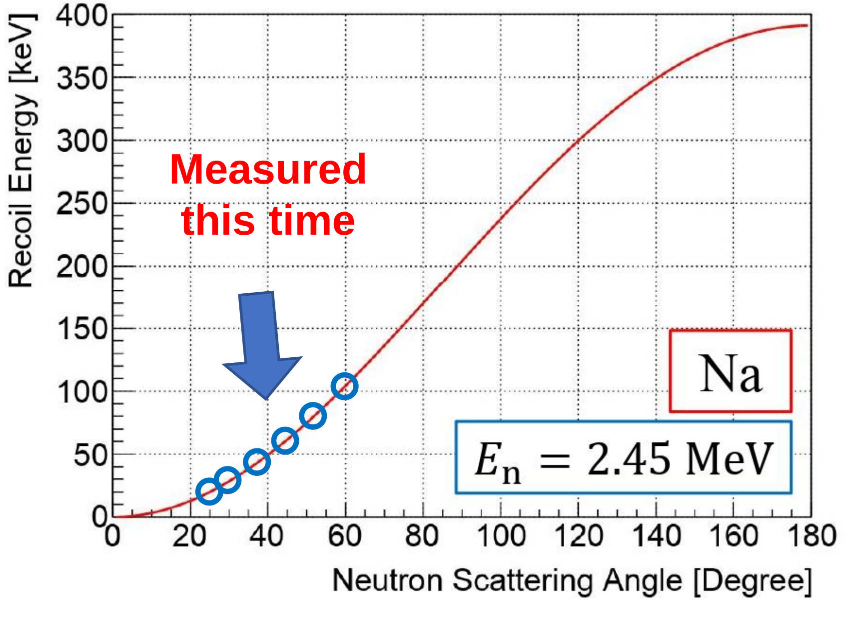
E_{nr} : Nuclear recoil energy

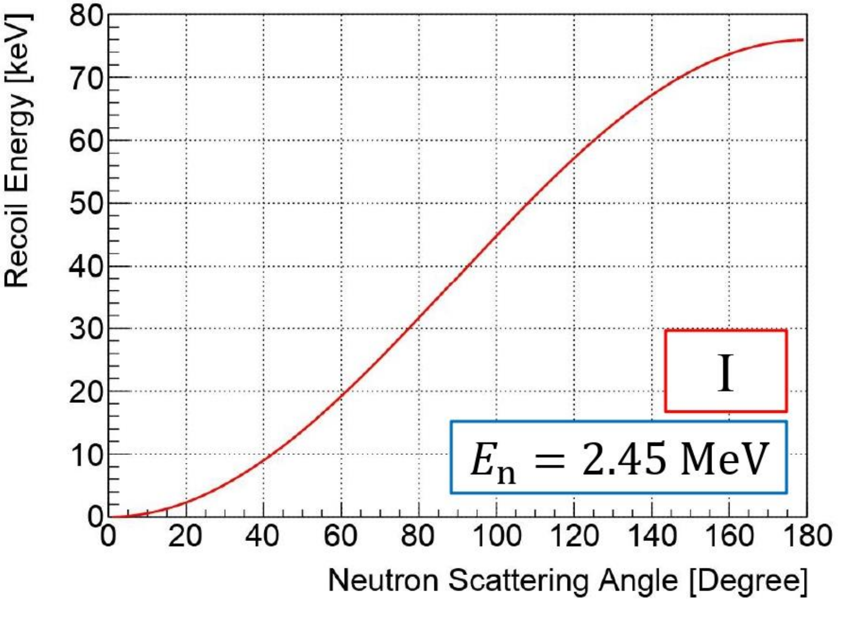
E_{n} : Energy of incident neutrons

θ_{L} : Neutron scattering angle

m_{n} : Mass of neutron

m_{N} : Mass of target nucleus



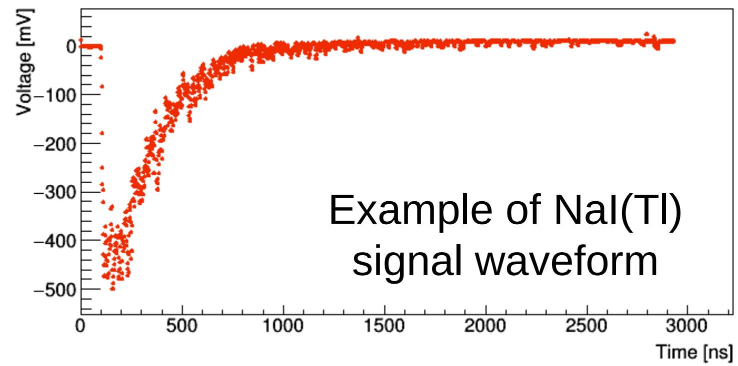


Data acquisition system

DRS4 (Domino-Ring-Sampler 4) Evaluation Board V5[5]

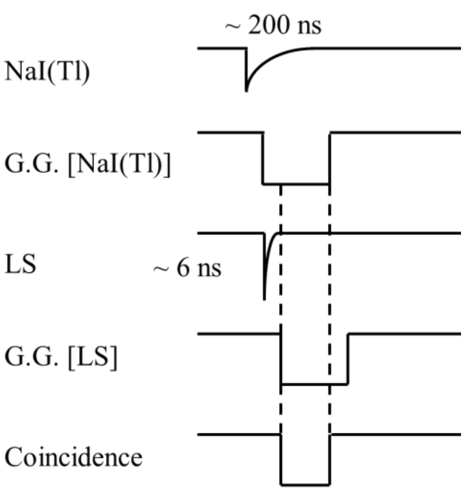
- ➢ Capable of recording waveforms of high-speed signals
- ➢ Sampling rate : 700 MHz
- ➢ Record 2048 points during 2.9 μs

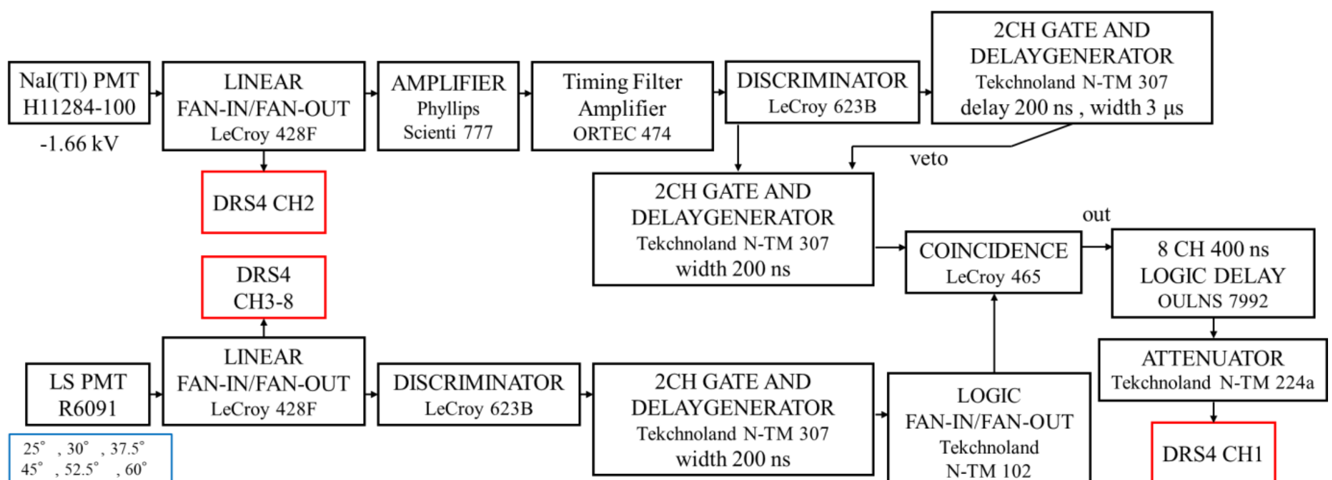
サイズ



DAQ Trigger

- ➢ NaI(Tl) and LS coincidence



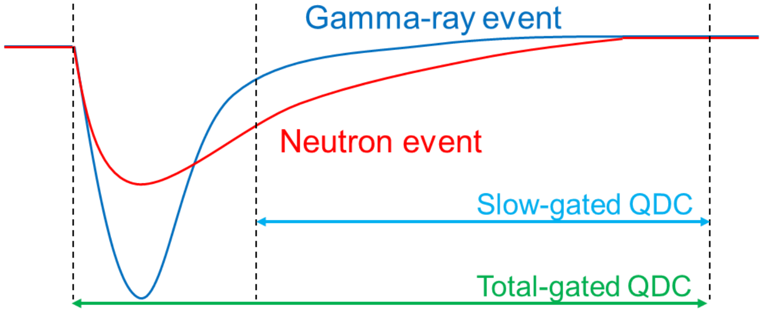


[5] https://www.psi.ch/drs/drs-chip

PSD analysis

PSD by the slow/total

➢ In liquid scintillators, neutrons have a more delayed component of scintillation light than gamma rays



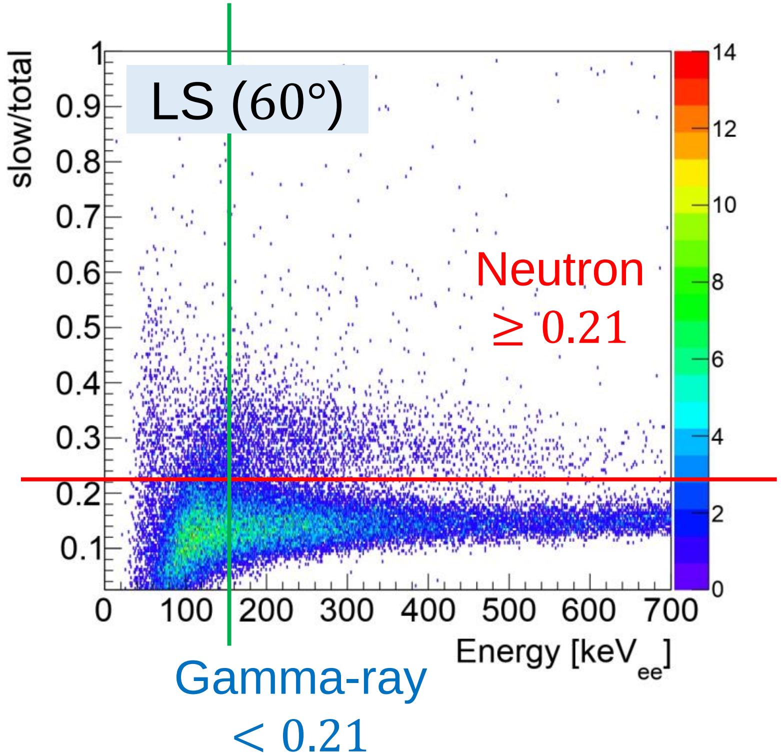
➢ slow/total was used to discriminate the waveforms.

$$\text{slow/total} = \frac{\int_{30\ \text{ns}}^{300\ \text{ns}} a_t\, dt}{\int_{0\ \text{ns}}^{300\ \text{ns}} a_t\, dt}$$

a_t : Voltage [mV]

slow : Light Amount emitted at 30 ~ 300 ns

total : Total Amount of light emitted at 0 ~ 300 ns



TOF analysis

TOF (Time of Flight)

➢ Particle time of flight was used to discriminate the particles.

$$\mathrm{TOF} = L\sqrt{\frac{m_{\mathrm{n}}}{2E}} = t_{\mathrm{LS}} - t_{\mathrm{NaI}}$$

m_{n} : Mass of neutron

L : Distance NaI(Tl) - LS

E : Energy of incident neutrons

t_{NaI} : Signal start time of NaI(Tl)

t_{LS} : Signal start time of LS

~ 23 ns @ $L = 50$ cm (Neutron TOF)