Quenching factor measurement in low-energy nuclear recoil of NaI(Tl) scintillator using monochromatic neutrons for dark matter search

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P21

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WIMPs direct search

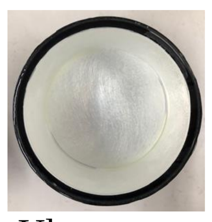
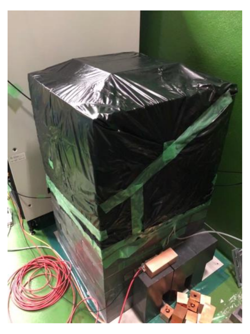
Nuclear recoil by WIMPs

$$E_{\rm nr} = \frac{4m_N m_\chi}{(m_N+m_\chi)^2} E_\chi \frac{1-\cos\theta}{2}$$

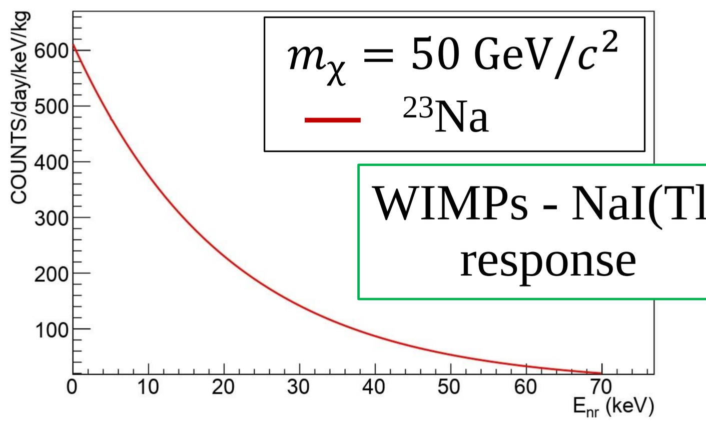
E_χ : Kinetic energy of WIMPs θ : Scattering angle in the center of mass frame

m_χ : Mass of WIMPs m_N : Mass of target nucleus

PICOLON @ Kamioka

Ultra-pure NaI(Tl) crystal



$E_{\rm nr}$ ~ less than several tens of keV

Model study by Lindhard

$$\mathrm{QF}(E_{\rm nr}) = \frac{kg(\varepsilon)}{1+kg(\varepsilon)}$$

$\varepsilon = 11.5\, E_{\rm nr}[\mathrm{keV}]\, Z^{-7/3}$

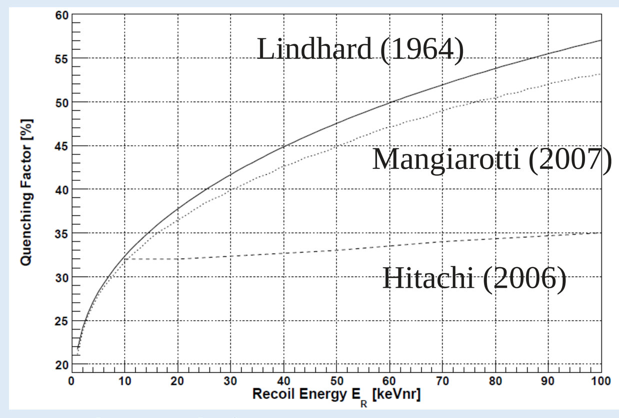
$k = 0.133\, Z^{2/3} A^{-1/2}$

$g(\varepsilon) = 3\,\varepsilon^{0.15} + 0.7\,\varepsilon^{0.6} + \varepsilon$

$\mathrm{QF_{Na}}(100\ \mathrm{keV_{nr}}) \sim 0.57$

$\mathrm{QF_{I}}(100\ \mathrm{keV_{nr}}) \sim 0.29$

Theoretical curves of QF of Na recoils



J. Lindhard *et al.*, Mat. Fys. Medd Dan.Vid. Selsk., **33**, 10, 1963 H. Chagani *et al.*, Journal of Instrumentation, **3**, P06003, 2008

Motivation

Necessary to calibrate the nuclear recoil energy by WIMPs

Quenching factor : QF

◆ Light yield ratio of nuclear recoil $C_{\rm nr}$ to electron recoil $C_{\rm er}$

$$\mathrm{QF} = C_{\rm nr} / C_{\rm er} = E_{\rm ee} / E_{\rm nr}$$

$E_{\rm ee}$: Electron equivalent energy

$E_{\rm nr}$: Nuclear recoil energy

◆ Discrepancy of the previous measurements

→ **Individual differences in crystals ?? or Unknown systematic errors ??**

Major improvements from last year's experiment

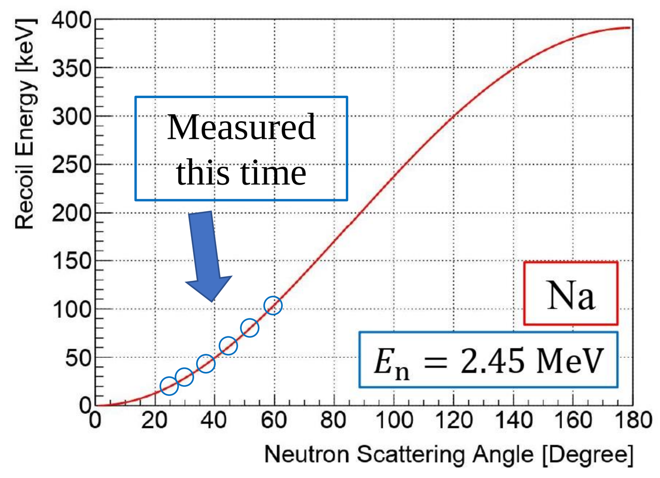
- Optimization of threshold setting by TFA
- Increase in measurement points (3 points → 6 points)
- Increase in statistics
- Improvement of BG shielding

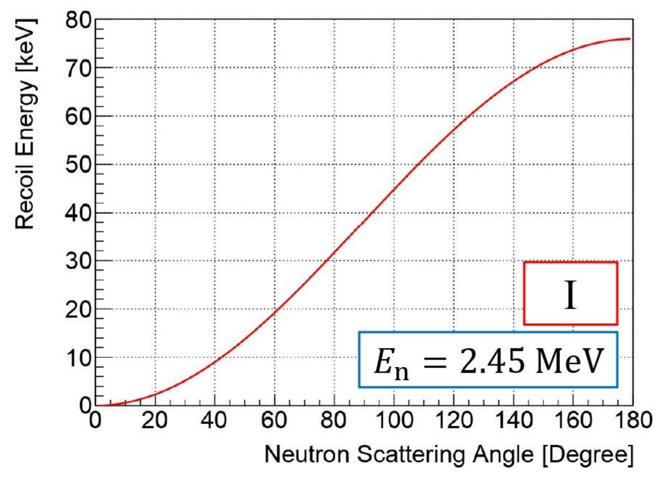
$$E_{\rm nr} = E_{\rm n}\cdot\left\{1-\left(\frac{m_{\rm n}\cos\theta_{\rm L}+\sqrt{m_{\rm N}^2-m_{\rm n}^2\sin^2\theta_{\rm L}}}{m_{\rm n}+m_{\rm N}}\right)^2\right\}$$

$E_{\rm nr}$: Nuclear recoil energy $m_{\rm n}$: Mass of neutron

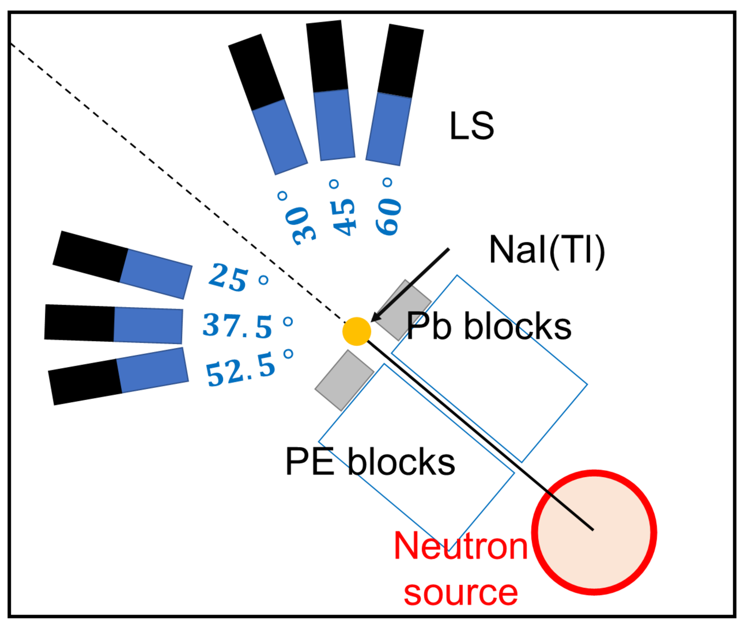
$E_{\rm n}$: Energy of incident neutron $m_{\rm N}$: Mass of target nucleus

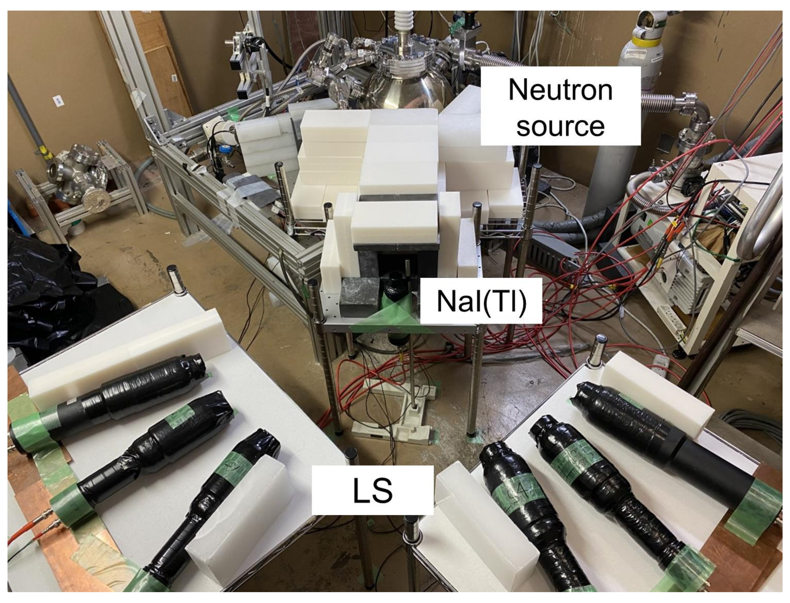
$\theta_{\rm L}$: Neutron scattering angle





Setup & Data acquisition system





Supported by Zero-Emission Energy Research (ZE2021-C12)

Neutron energy : 2.45 MeV (deuteron-deuteron fusion)

Neutron intensity : 5.0 ×10[6] n/s

Distance NaI(Tl) - LS : 50 cm (**TOF** : Time Of Flight)

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

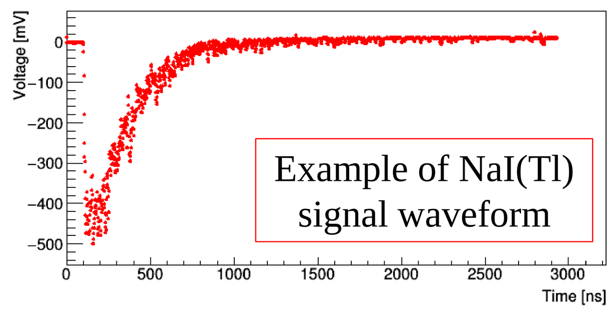
Liquid scintillator (LS) : EJ-301 + Hamamatsu R6091 (PMT)

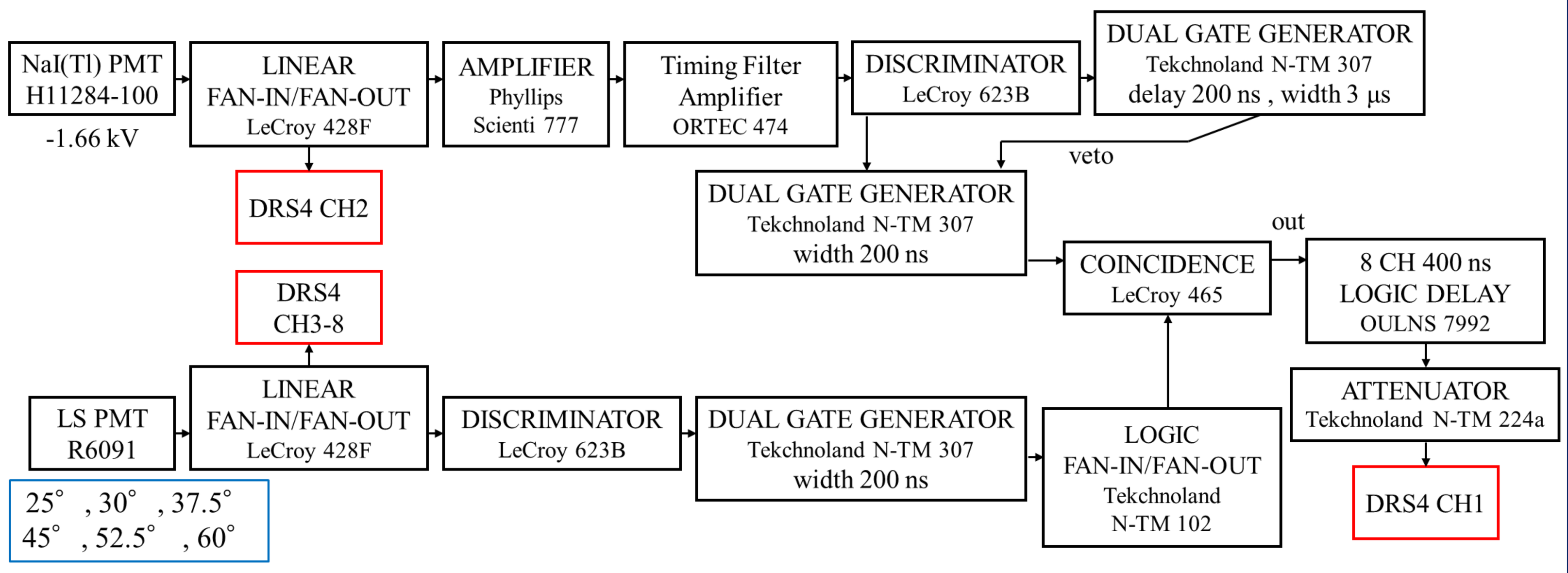
DRS4 (Domino-Ring-Sampler 4)

◆ Capable of recording waveforms of high-speed signals

◆ Record 2048 points during 2.9 μs Sampling rate : 700 MHz

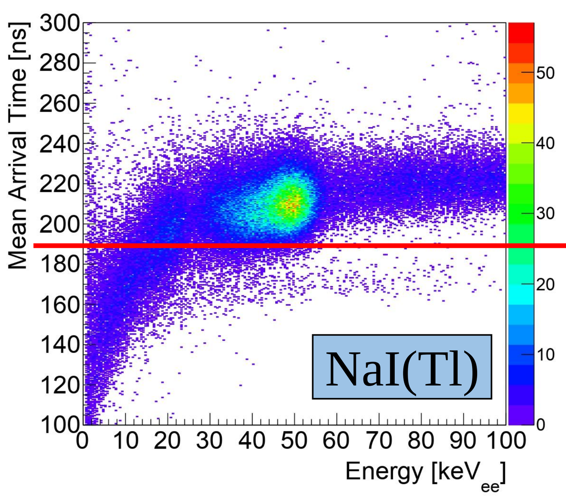
https://www.psi.ch/drs/drs-chip





Date of experiment : 2021/12/6-10

PSD (Pulse Shape Discrimination) analysis



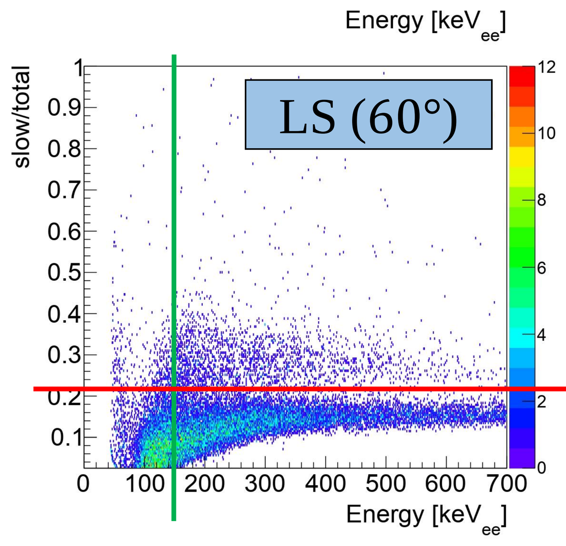
PSD by mean arrival time of scintillation photons

Gamma-ray ~ 230 ns

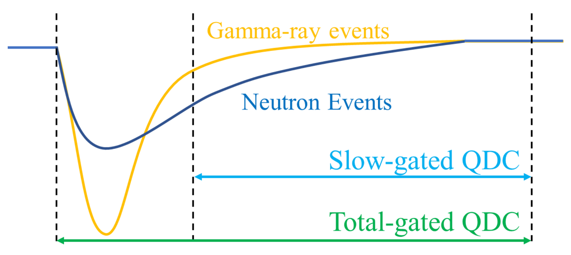
Nuclear recoil ~ 180 ns

$$<t> = \frac{\sum_{i=0}^{2047} t_i a_i}{\sum_{i=0}^{2047} a_i}$$

a_i : Voltage [mV] t_i : Time [ns]



PSD by slow/total value



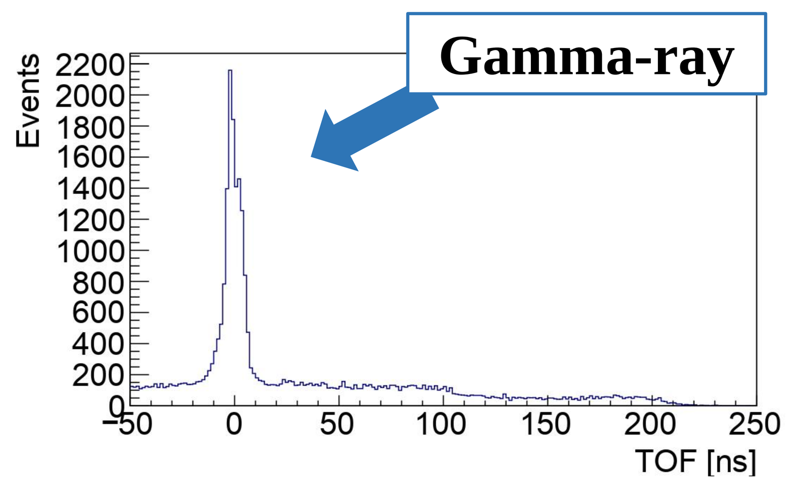
Neutron ≥ 0.22

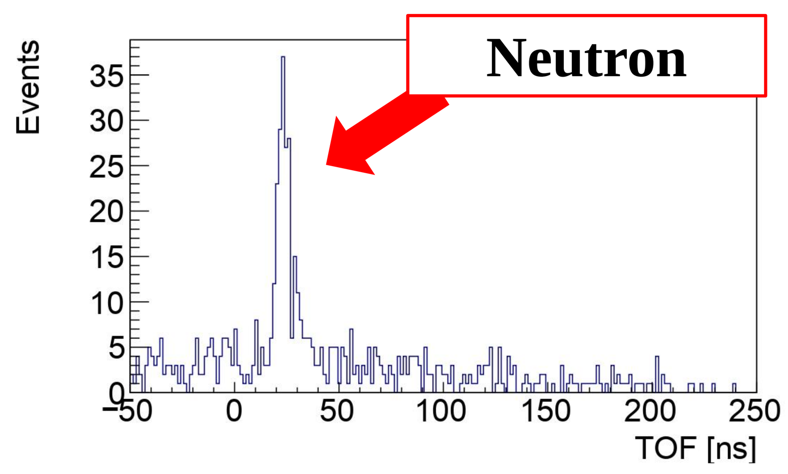
Gamma-ray < 0.22

slow : Light amount emitted at 30 ~ 300 ns

total : Total light amount emitted at 0 ~ 300 ns

TOF analysis





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

$m_{\rm n}$: Mass of neutron

L : Distance NaI(Tl) - LS

E : Neutron energy

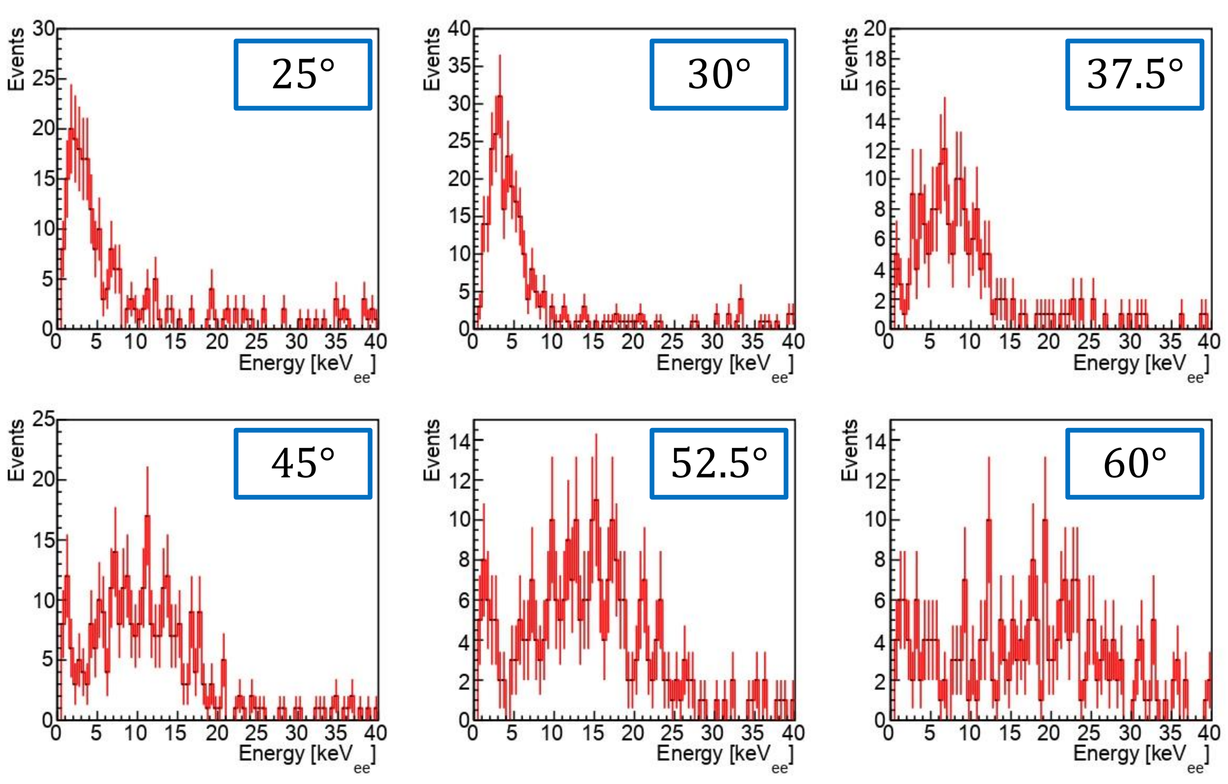
$t_{\rm NaI}$: Signal start time of NaI(Tl)

$t_{\rm LS}$: Signal start time of LS

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

Energy spectrum

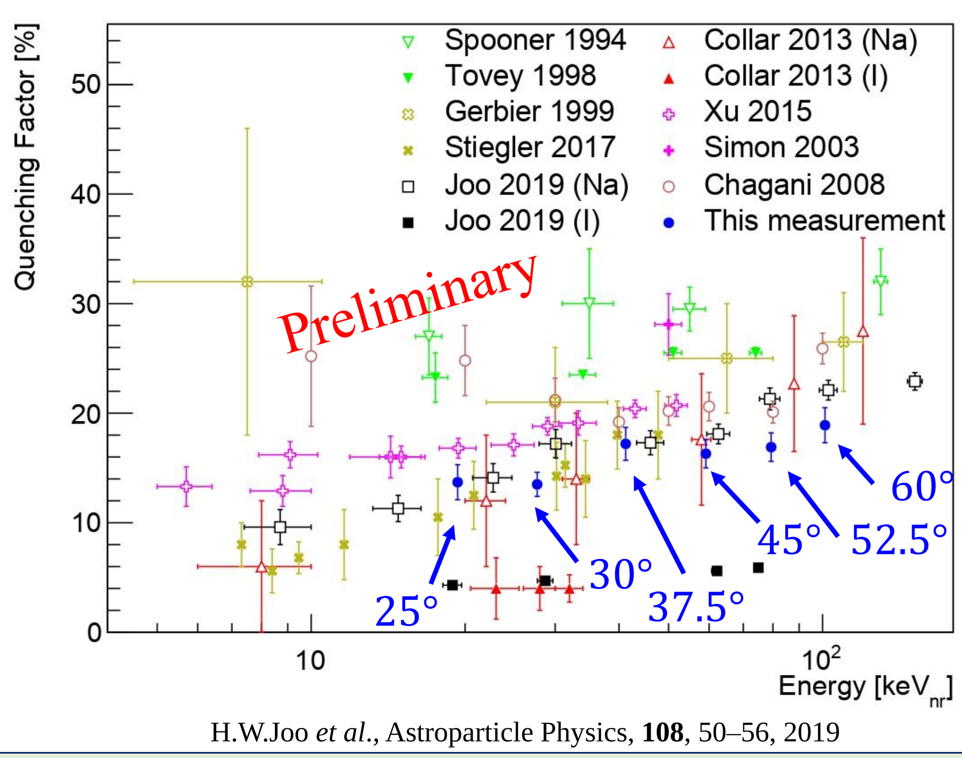
After PSD and TOF cut ~ 16 hours



Angular dependence of energy spectrum !!

Scattering angle [deg.]	$E_{\rm ee}$ [keV$_{\rm ee}$]
25	2.64 ± 0.24
30	3.73 ± 0.15
37.5	7.08 ± 0.42
45	9.64 ± 0.48
52.5	13.39 ± 0.68
60	19.1 ± 1.2

Result of QFs & Comparison with previous results



H.W.Joo *et al.*, Astroparticle Physics, **108**, 50–56, 2019

Geant4 calculation of $E_{\rm nr}$ at each scattering angle

Scattering angle [deg.]	$E_{\rm nr}$ (Na) [keV$_{\rm nr}$]	$\mathrm{QF_{Na}}$ [%]
25	19.34 ± 0.16	13.7 ± 1.6
30	27.67 ± 0.19	13.5 ± 1.1
37.5	41.22 ± 0.23	17.2 ± 1.5
45	59.15 ± 0.23	16.3 ± 1.3
52.5	79.36 ± 0.33	16.9 ± 1.3
60	101.12 ± 0.36	18.9 ± 1.6

Summary

◆ We have succeeded in calculating the $\mathrm{QF_{Na}}$.

◆ We are considering the measurement of the $\mathrm{QF_{Na}}$ dependence on Tl concentration and the measurement of the $\mathrm{QF_I}$.

◆ Investigation of the effect of different energy calibration methods on QFs in the low energy region

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