Towards a better understanding of neutrino–^{16}O NCQE interaction: study of the gamma-rays from knocked-out neutron–^{16}O interaction

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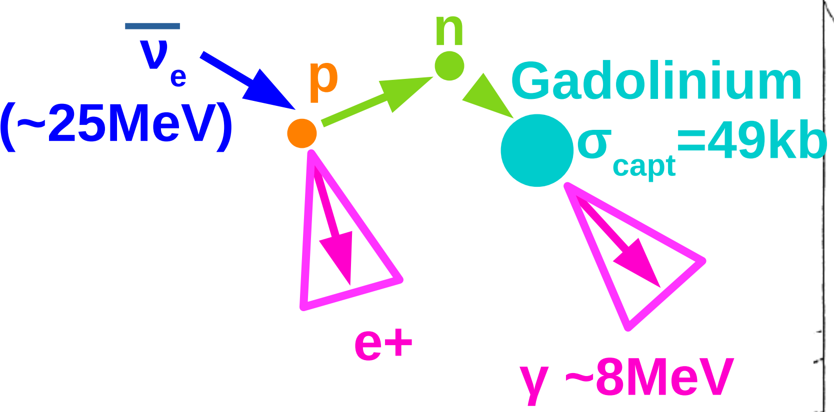
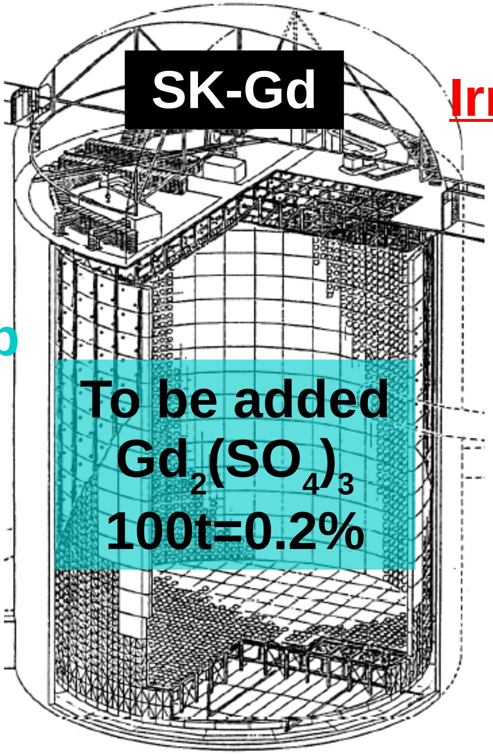
Motivation for the study of ν - ^{16}O NCQE interaction

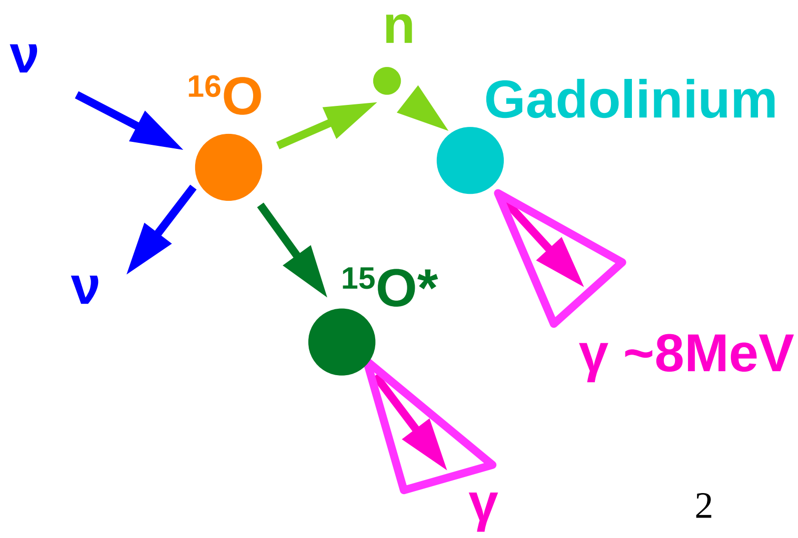
Crucial for many physics searches: sterile neutrino, dark matter, supernova relic neutrino (SRN), etc.

Expected detection of SRN in SK-Gd via IBD

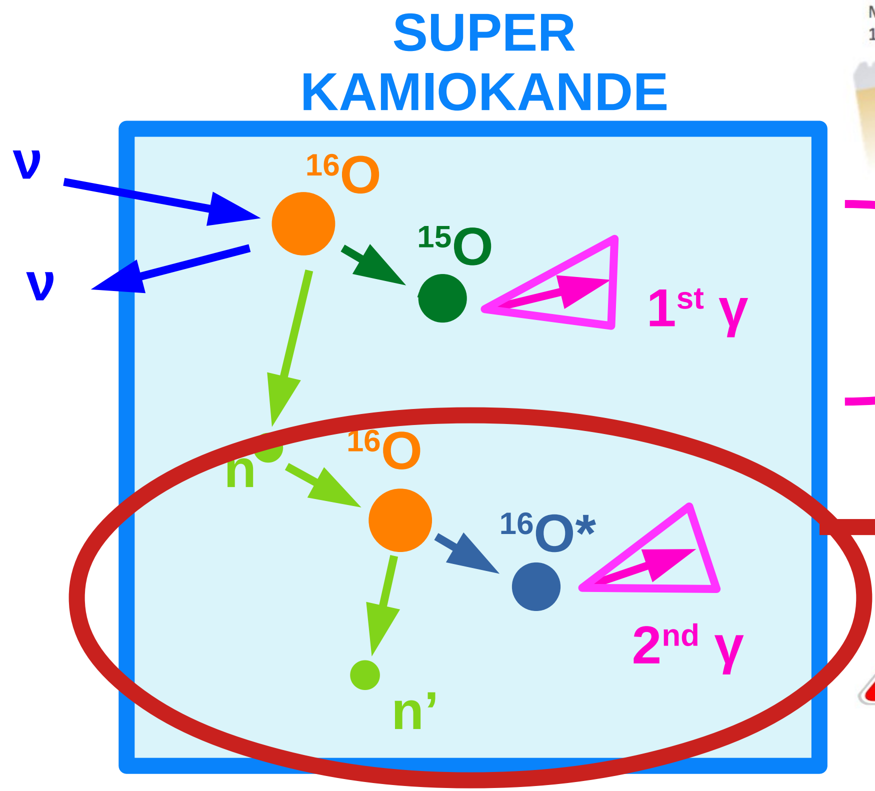


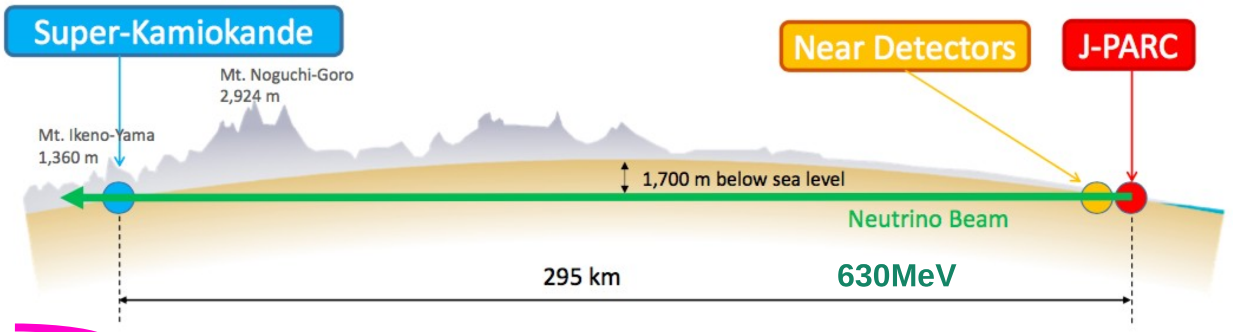


Irreducible background in SK-Gd: atmospheric neutrinos NCQE



Study of ν - ^{16}O NCQE interaction with T2K and SK





NCQE study via the observation of gamma rays (1-10MeV)

FOCUS

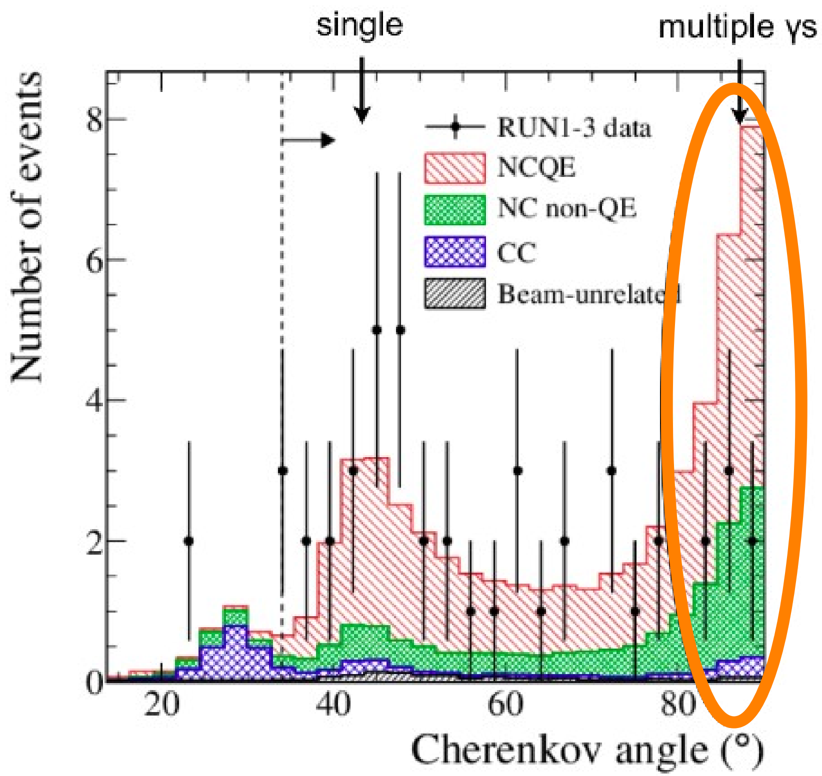
Secondary gamma rays

T2K MC simulation to get the rate

Major systematic error

Problem with secondary gamma in T2K simulation

GOAL: reducing secondary gamma systematic error



Systematics (K. Huang, Ph.D Thesis, Kyoto University (2016))

Systematic error	Signal	Background		
interactions	NCQE	NCothers	CC	beam-unrelated
fraction of events	68%	25%	4%	2%
Flux	11%	10%	12%	–
Cross-section	–	18%	24%	–
Primary γ production	10%	3%	6%	–
Secondary γ production	13%	13%	7.6%	–
Detector response	2.2%	2.2%	2.2%	–
Oscillation parameters	–	–	10%	–
Total systematic error	20%	25%	30%	0.8%

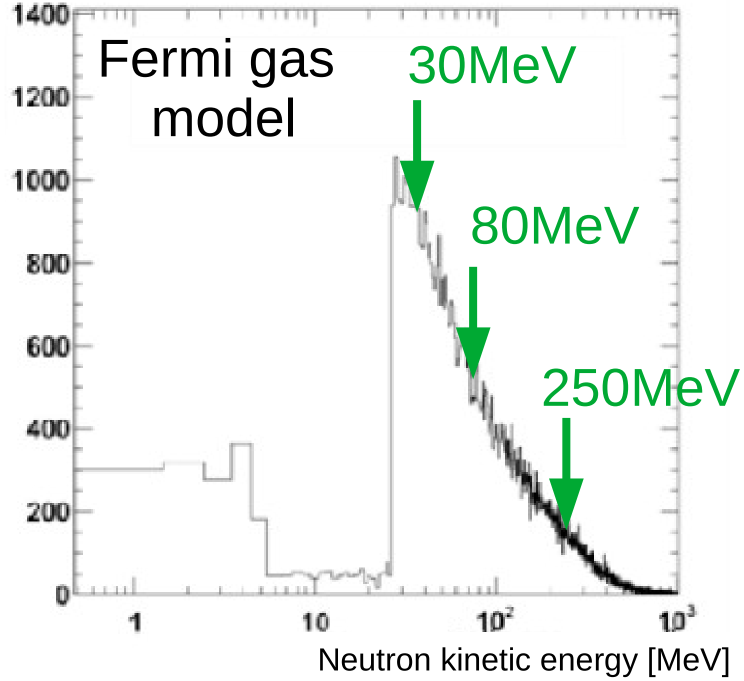
T2K simulation gives a higher number of events than experiment → **Hypothesis: too many neutrons generated in the simulation**

QE proton knockout	$^{16}O(n,np)^{15}N^*$
QE neutron knockout	$^{16}O(n,nn)^{15}O^*$

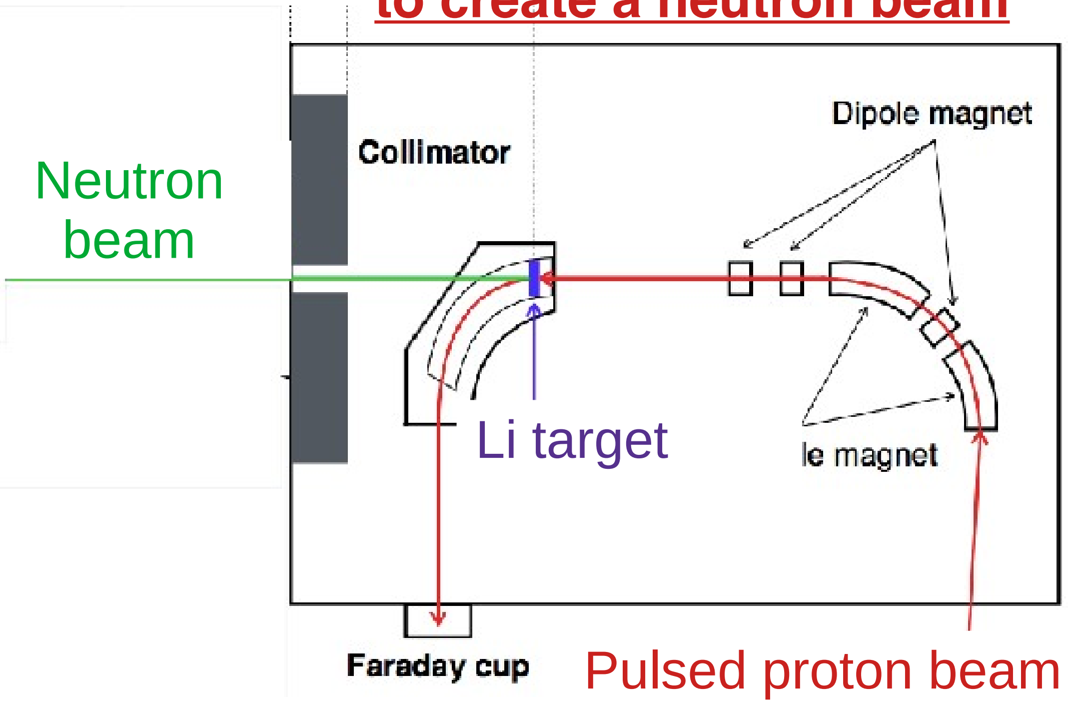
Solution: an external experiment

To measure production cross sections of gamma rays emitted by the knocked-out neutron–^{16}O interaction

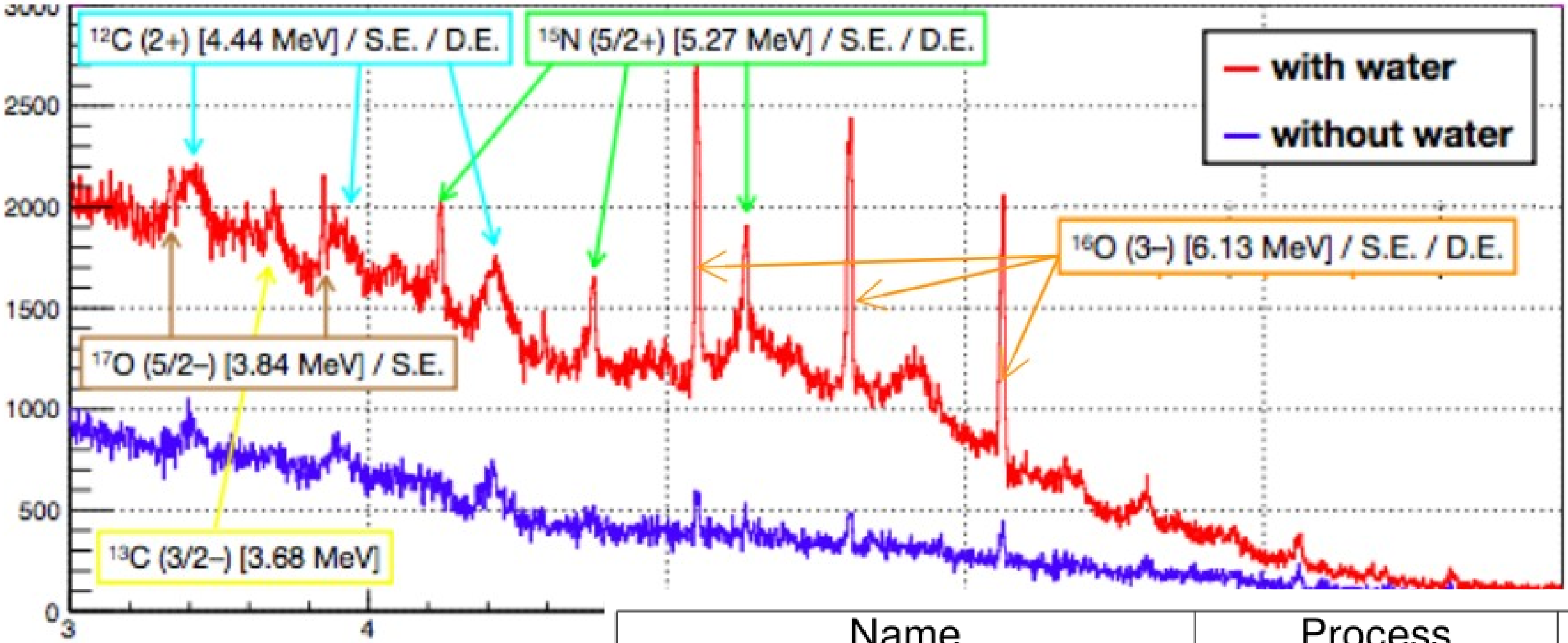
T2K: simulated kinetic energy for knocked-out neutrons



Use RCNP proton beam (30, 80, 250 MeV) to create a neutron beam

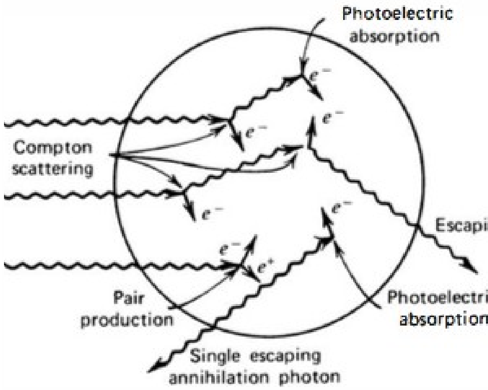


80 MeV proton beam - Gamma energy spectrum



arXiv:1902.08964cl

[nucl-ex] 24 Feb 2019



Name	Process	Gamma energy
Coherent inelastic scattering	$^{16}O(n,n')^{16}O^*$	6.13 MeV
Proton emission	$^{16}O^* \to p +^{15} N^*$	5.27 MeV
Alpha emission	$^{16}O^* \to \alpha +^{12} C^*$	4.44 MeV
QE proton knockout	$^{16}O(n,np)^{15}N^*$	6.32 MeV
QE neutron knockout	$^{16}O(n,nn)^{15}O^*$	6.18 MeV

Clearly observed and dominant

Not clearly seen

80 MeV proton beam - Gamma energy spectrum

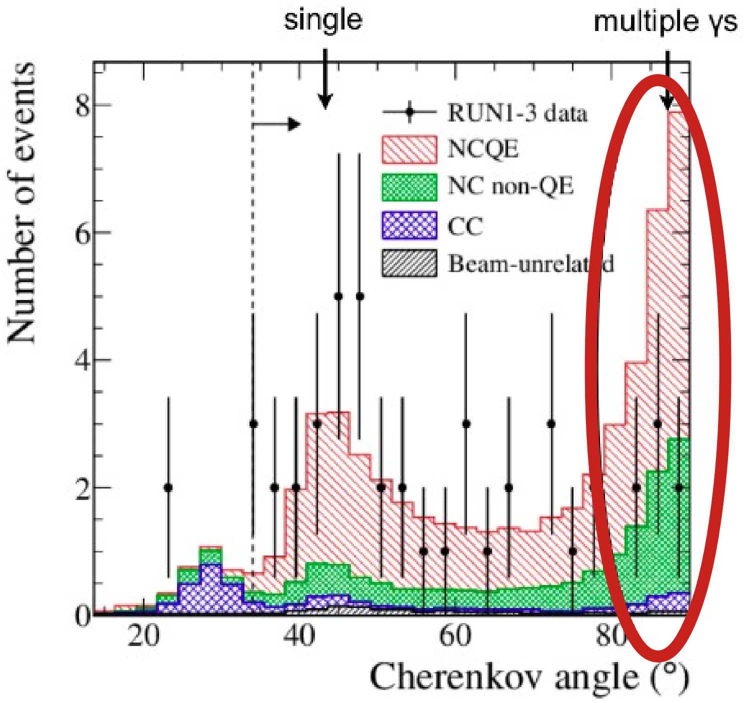
Final state p and α invisible in water Cherenkov detectors

Inelastic dominant

Name	Process	Gamma energy
Coherent inelastic scattering	$^{16}O(n,n')^{16}O^*$	6.13 MeV
Proton emission	$^{16}O^* \to p + ^{15}N^*$	5.27 MeV
Alpha emission	$^{16}O^* \to \alpha + ^{12}C^*$	4.44 MeV
QE proton knockout	$^{16}O(n,np)^{15}N^*$	6.32 MeV
QE neutron knockout	$^{16}O(n,nn)^{15}O^*$	6.18 MeV

Likely to produce additional neutrons (important for SK-Gd using neutron tagging)

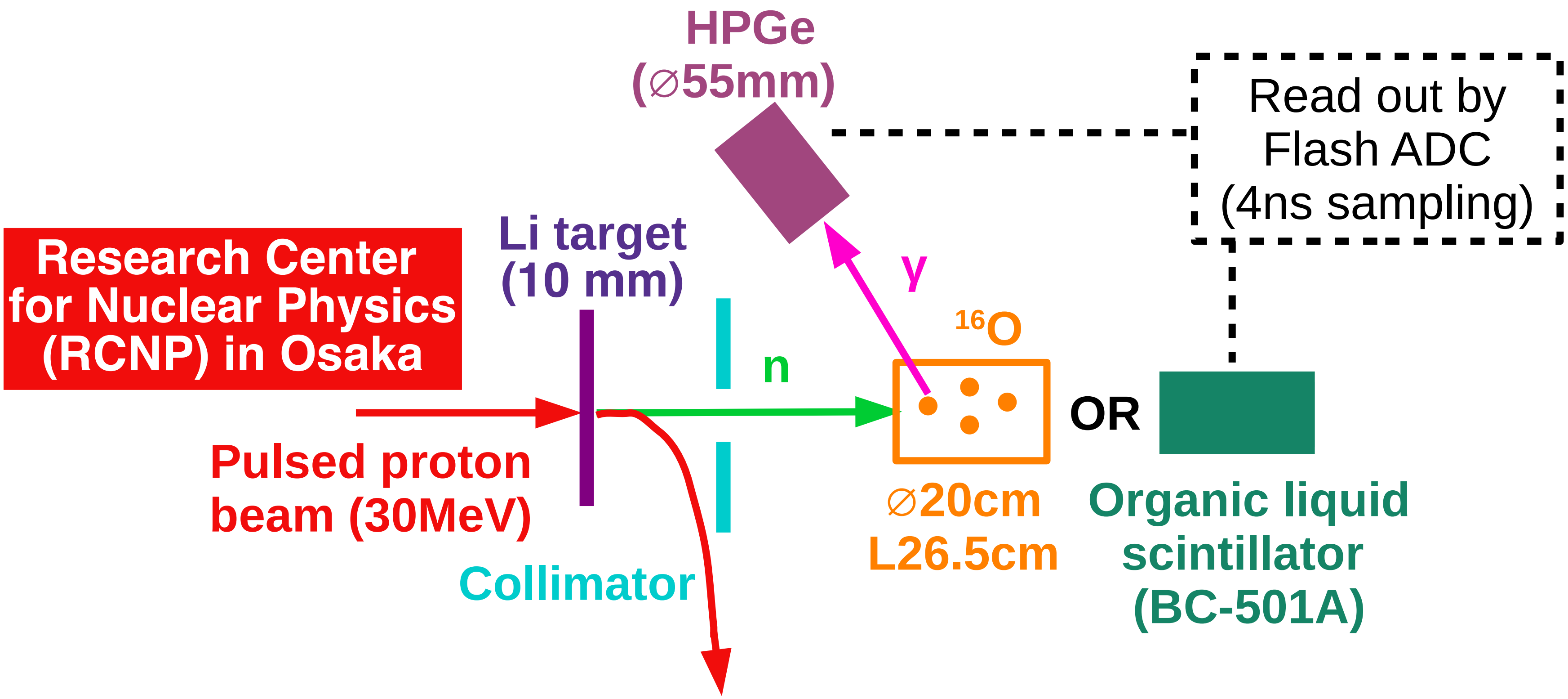
QE not clearly seen



Lower production of additional neutrons

30 MeV proton beam - Setup

Today talk will focus on 30MeV data analysis



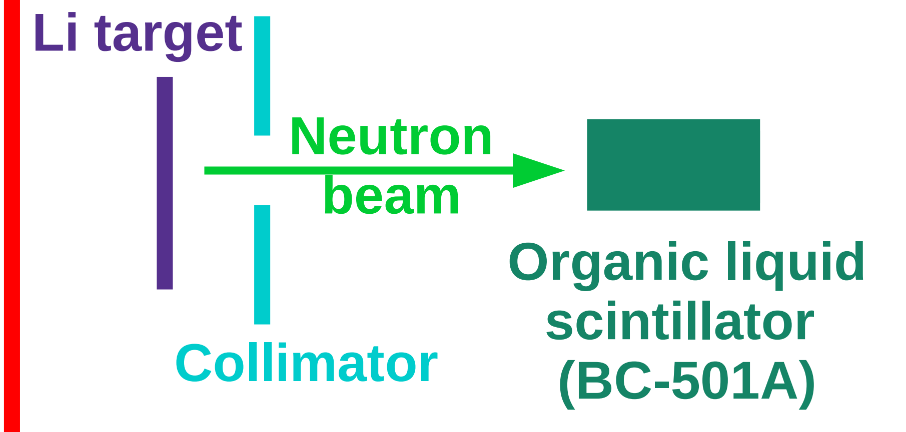
Step 1: Neutron flux measurement

$$\sigma_\gamma = \frac{N_{sig}}{\phi_n \epsilon_\gamma T}$$

Gamma ray production cross section

Neutron flux measurement

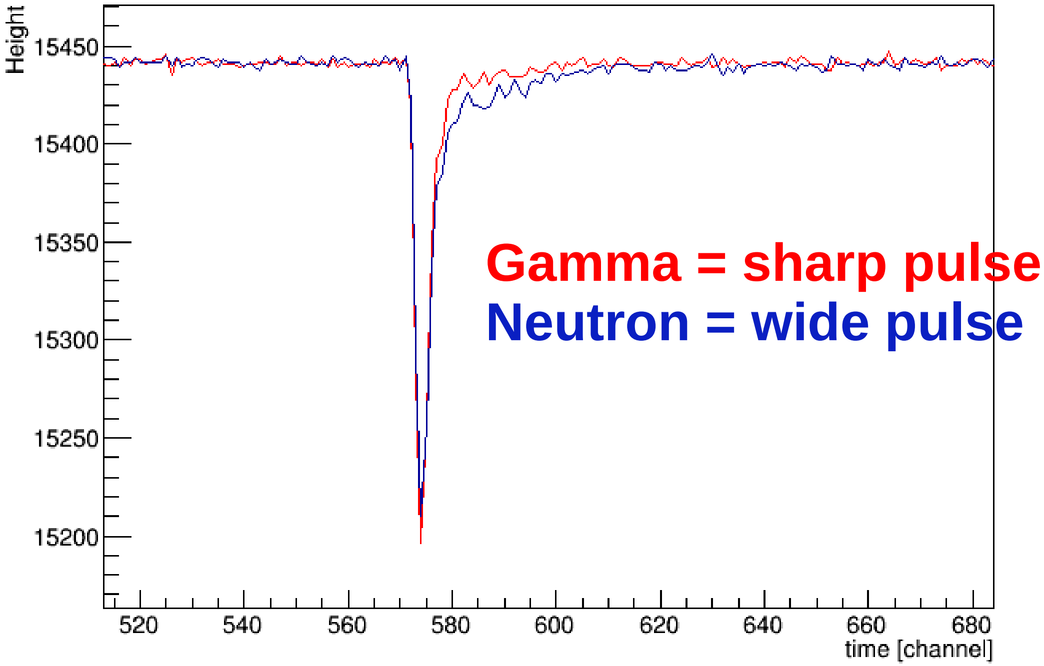
Gamma ray energy spectrum



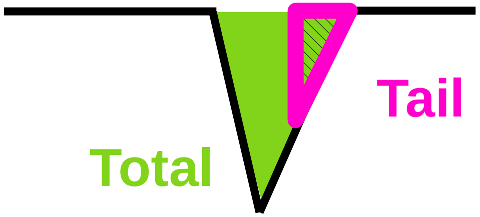
Neutron flux measurement - PSD

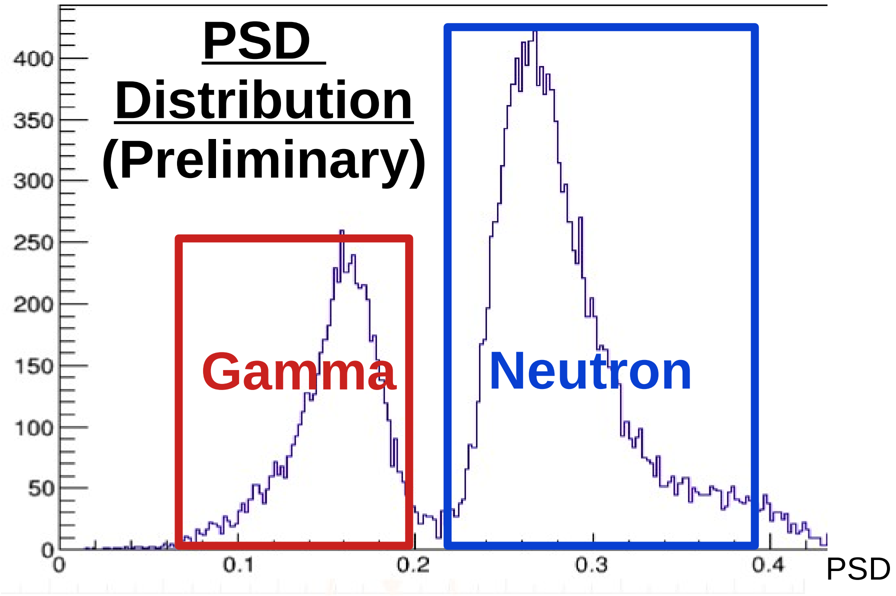
Distinguish gamma and neutron with Pulse Shape Discrimination

LqS typical raw waveforms



$$\text{PSD} = \frac{\text{Tail}}{\text{Total}}$$

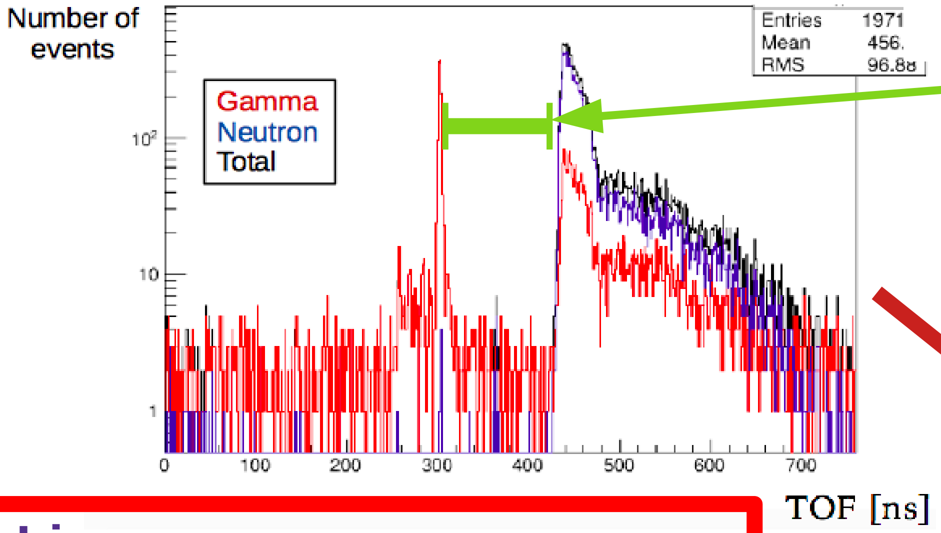


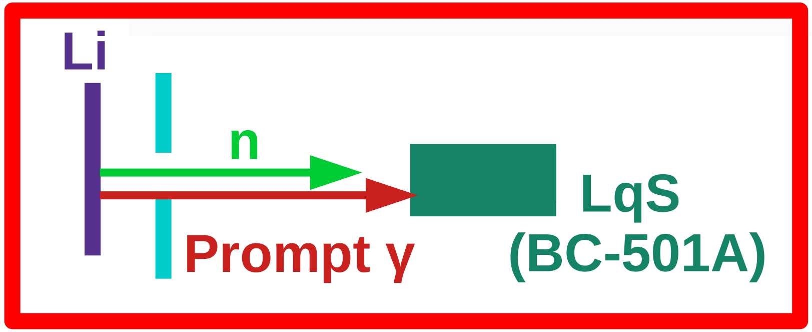


Neutron flux measurement - PSD

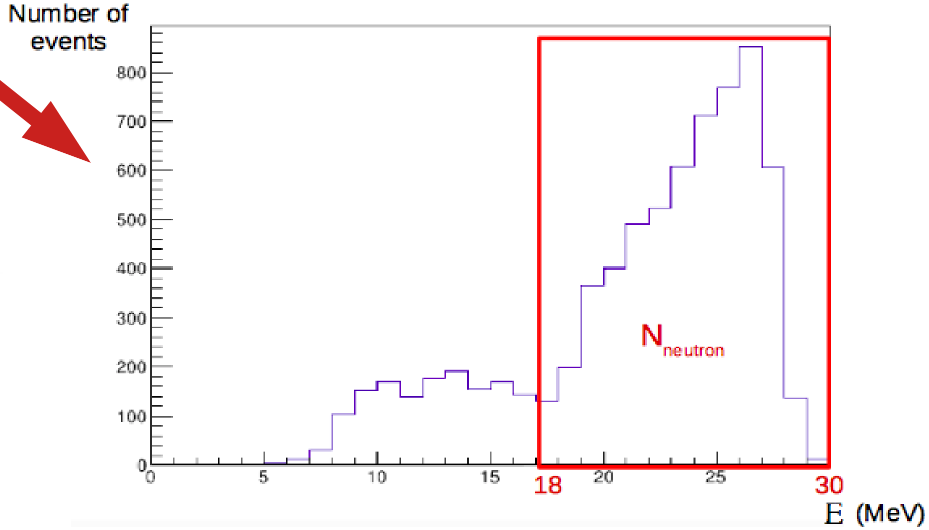
TOF distribution [ns] (Preliminary)

$$E_{kin} = mc^2\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) \text{ with } \beta = \frac{1}{1+\frac{c}{L}\left(TOF_n - TOF_{prompt\gamma}\right)}$$





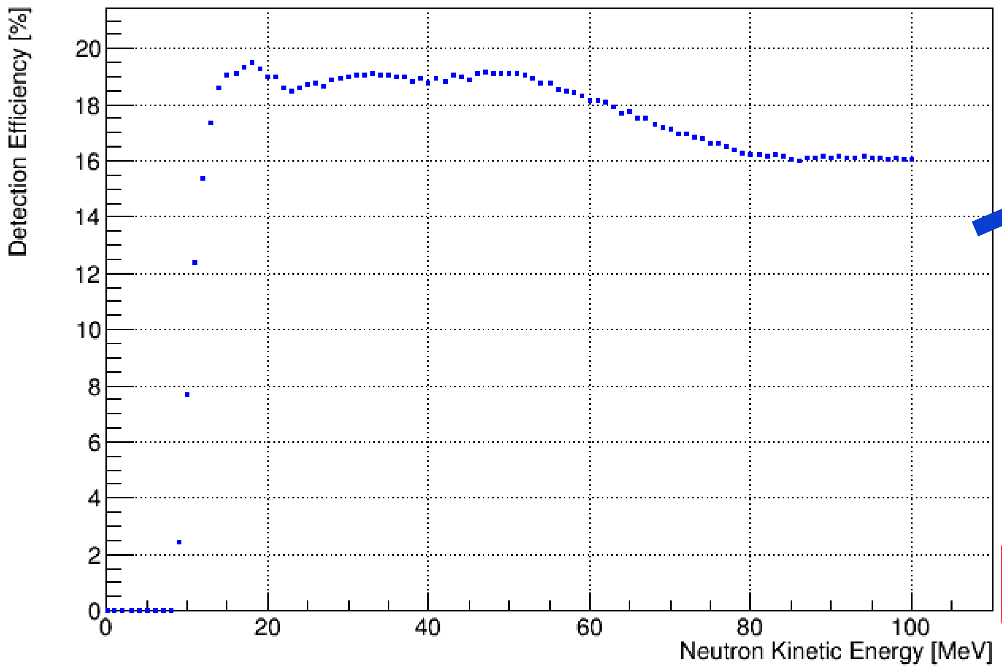
Neutron kinetic energy distribution [MeV] (Preliminary)



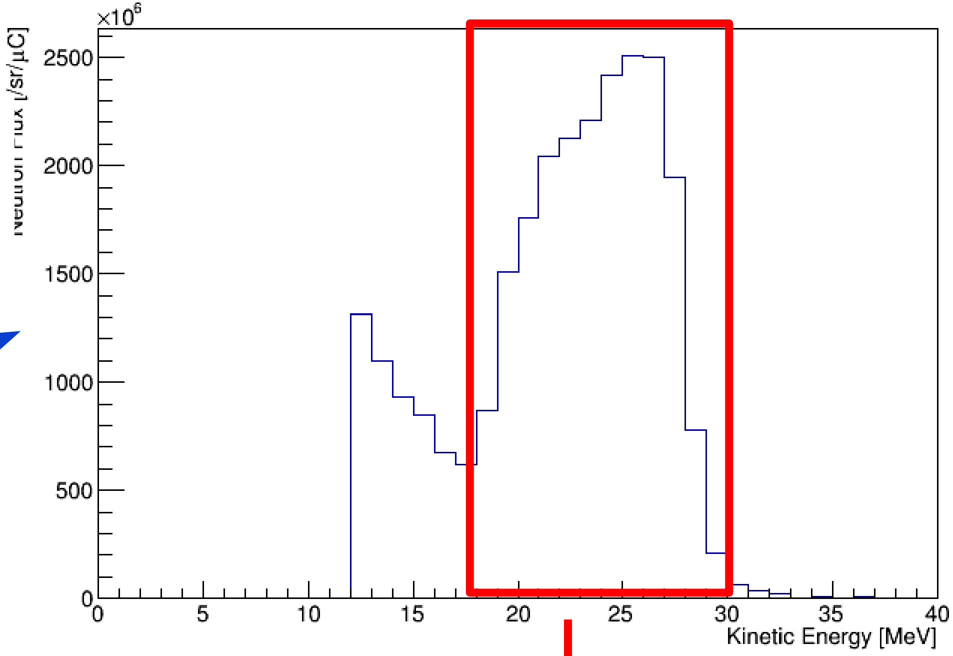
Neutron flux reconstruction

$$\phi_n[/sr/\mu C] = \frac{N_{neutron}}{\Omega * R * \epsilon_n * I_{beam}}$$

Efficiency [%] as a function of neutron kinetic energy [MeV] (Preliminary)



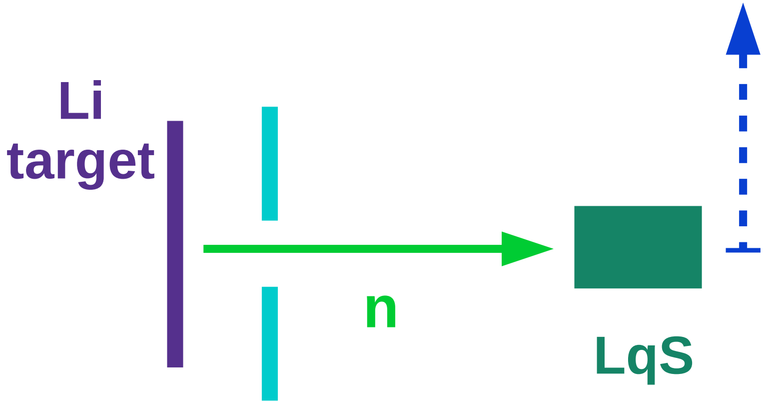
Neutron flux [/Sr/μC] as a function of neutron kinetic energy [MeV] (Preliminary)



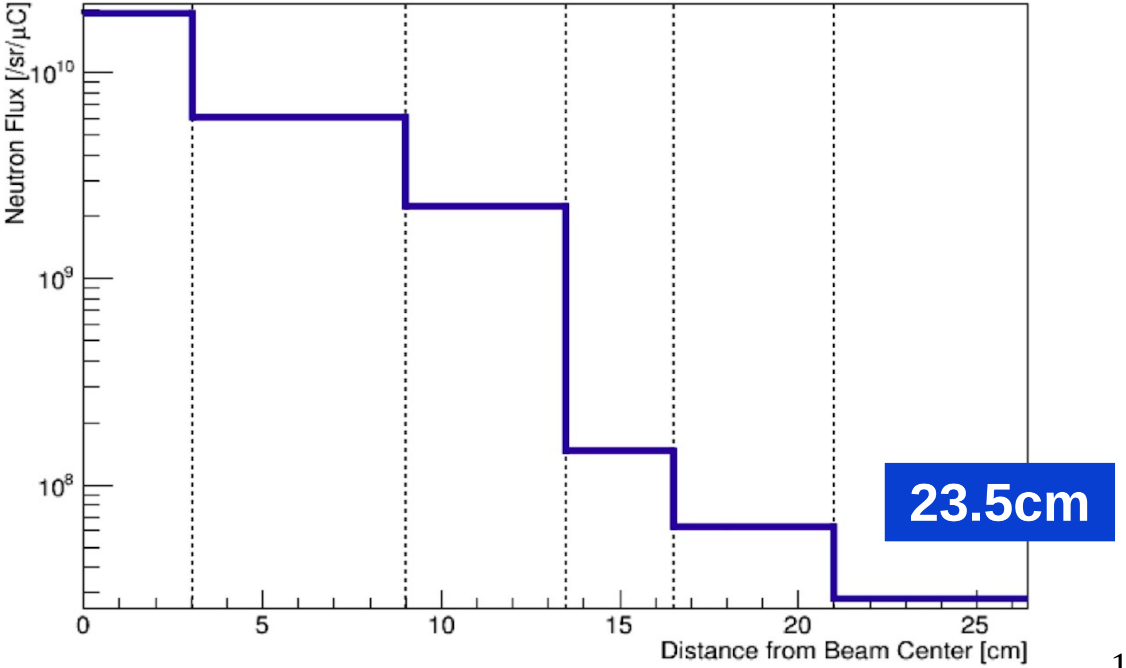
$2.1 * 10^{10} \pm 2.1\%(stat.) \pm 22\%(syst.)$ /Sr/μC

Neutron background measurement with LqS

Find position for HPGe with little neutron background



Neutron flux [/Sr/μC] as a function of the distance from beam center [cm] (Preliminary)



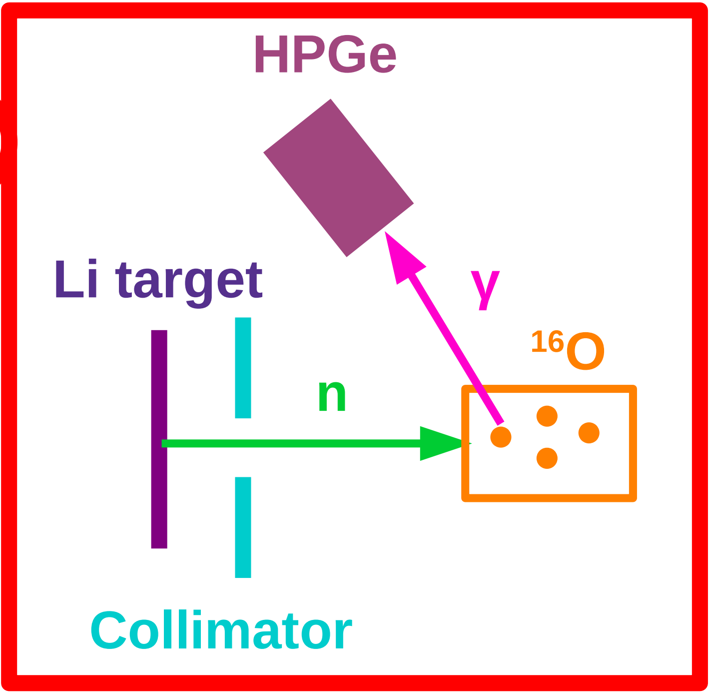
Step 2: Gamma ray energy spectrum

Gamma ray production cross section

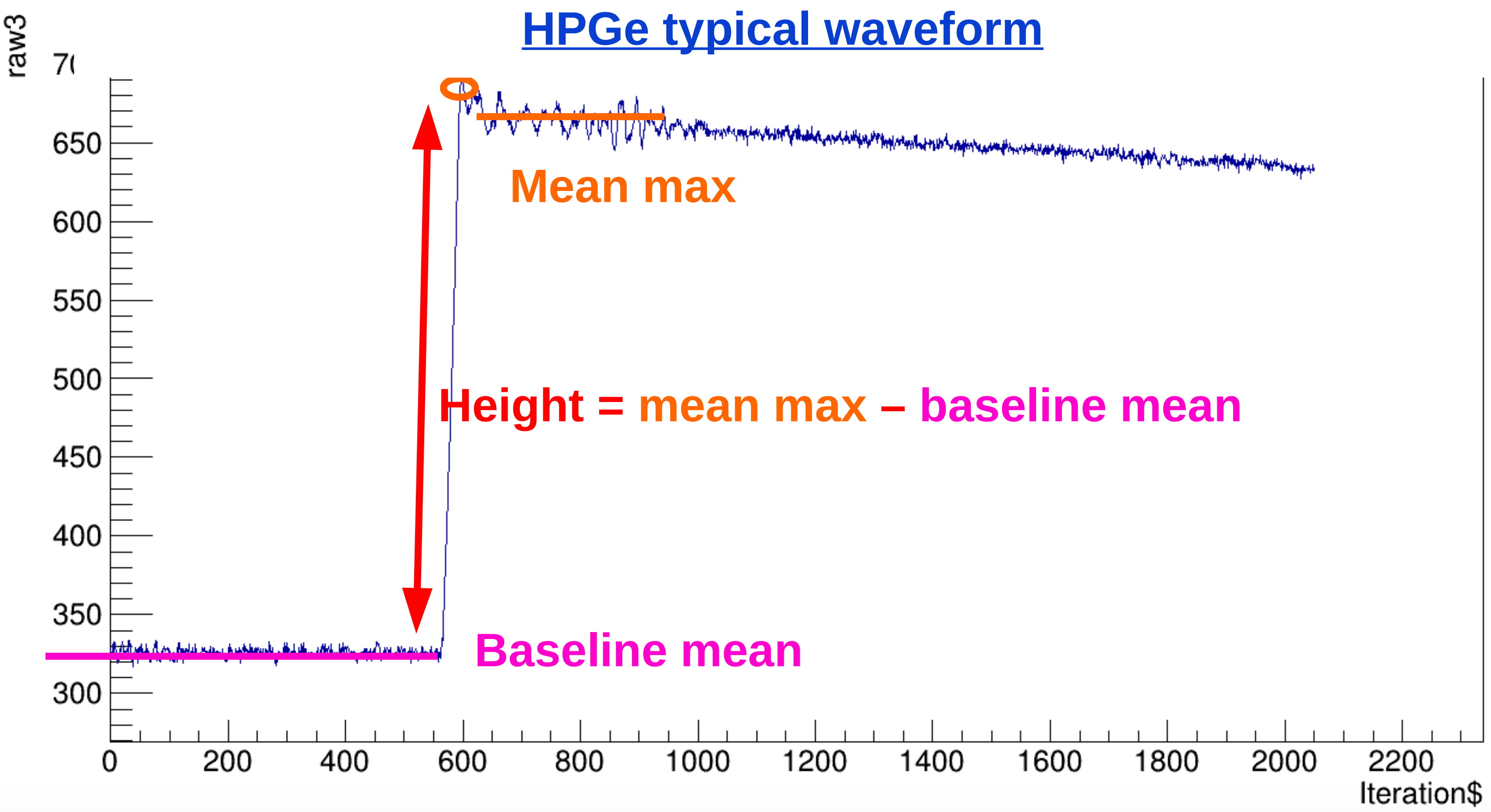
Neutron flux measurement

Gamma ray energy spectrum

$$\sigma_\gamma = \frac{N_{sig}}{\phi_n \epsilon_\gamma T}$$

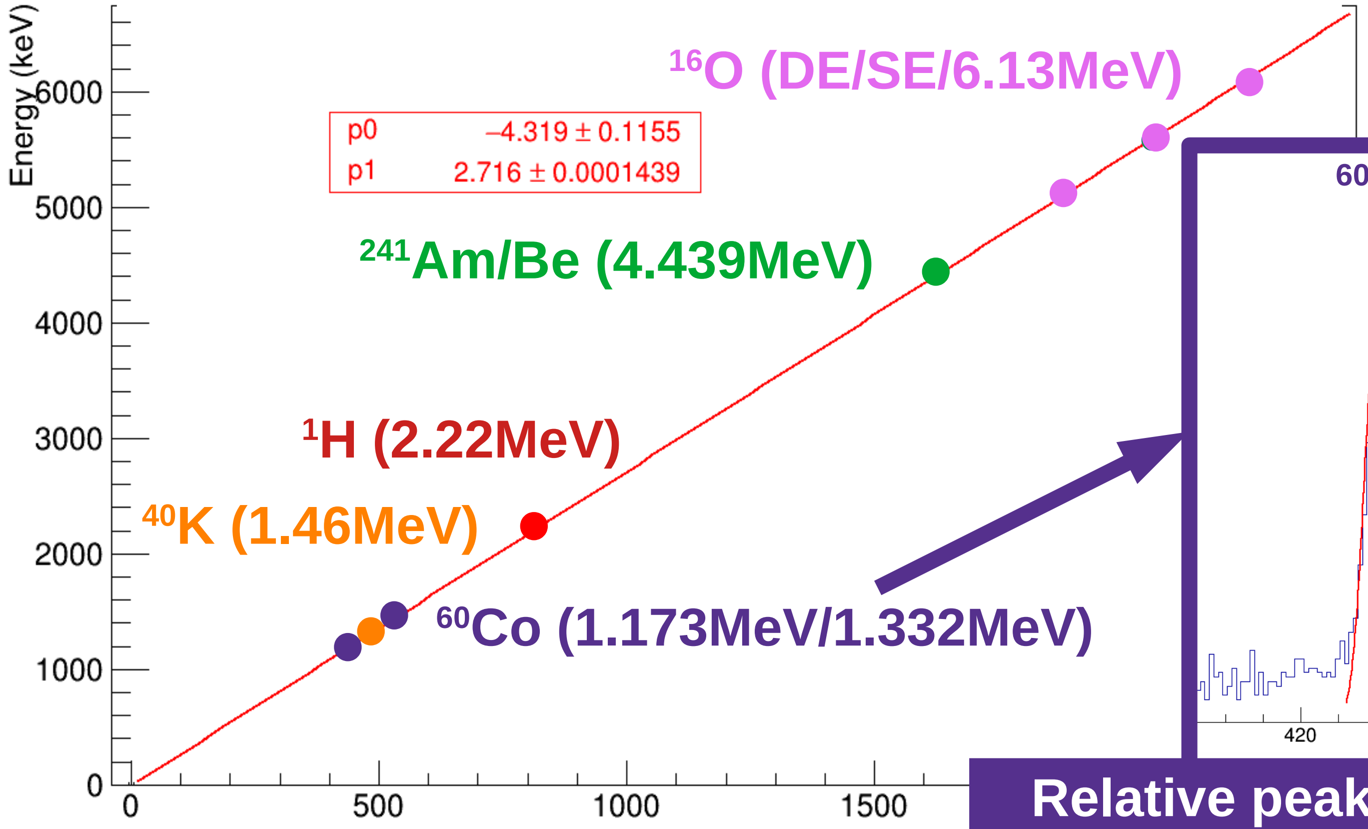


Step 2: Gamma ray energy spectrum

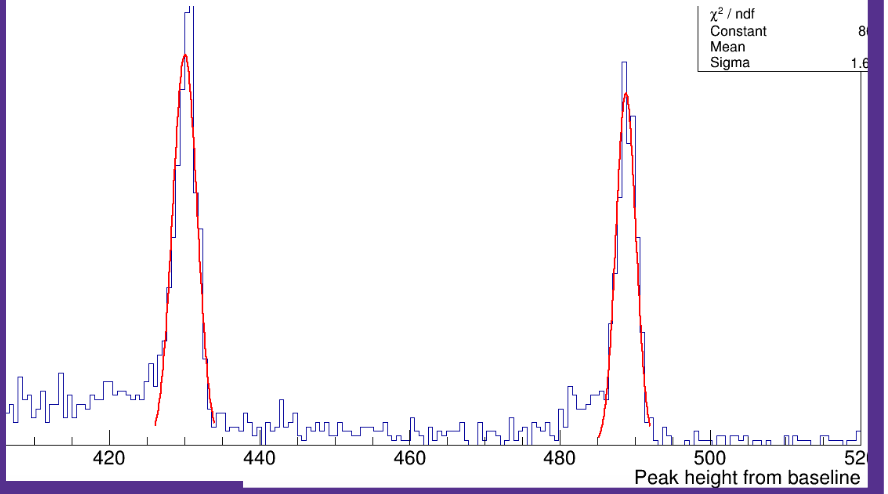


HPGe energy reconstruction method calibration

Energy [MeV] as a function of pulse height (Preliminary)



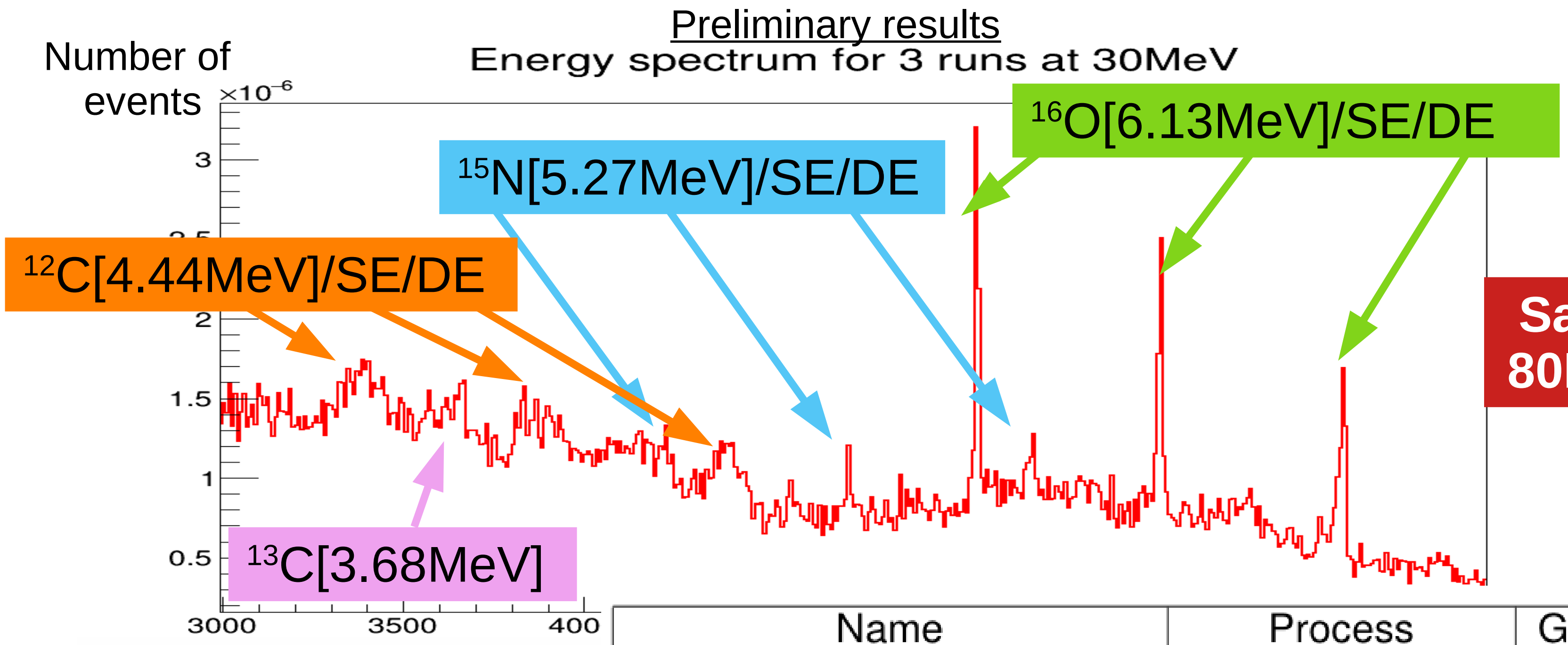
60Co height distribution (Preliminary)



Relative peak resolution < 1%

Preliminary HPGe spectrum and peak identification

Proton time: 84min
Events: 5×10^5



Clearly observed

Not clearly seen

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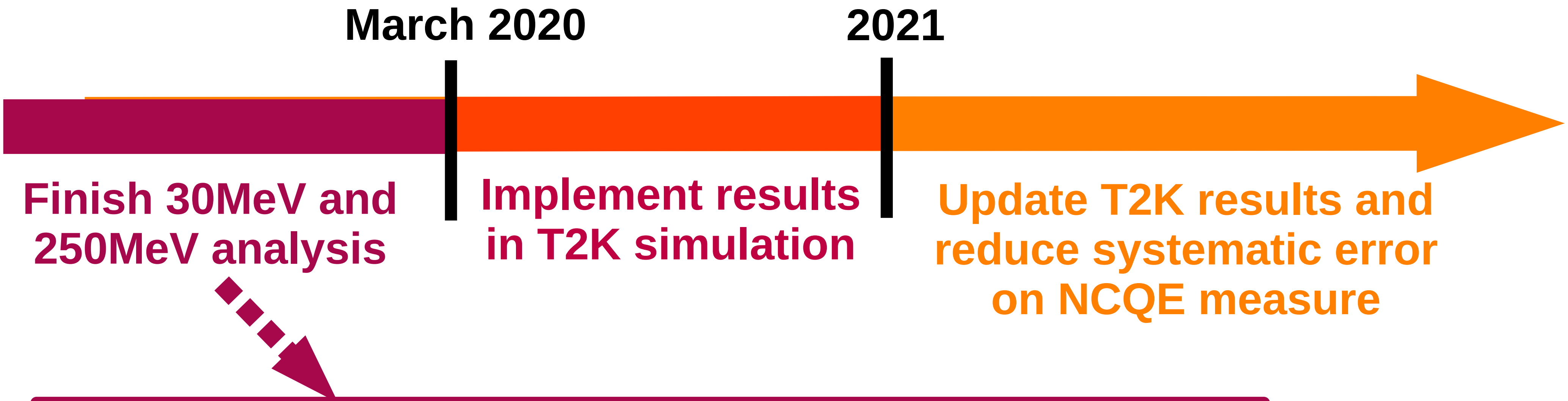
Prospects



HPGe TOF analysis near validation

After the TOF cut and accumulation of data, extraction of the gammas from 20-30 MeV neutron reactions

Same methods will be applied to 250 MeV data

Summary

ν - ^{16}O NCQE interaction: secondary gamma rays not well modeled

External experiment to measure production cross sections of gamma rays emitted by the knocked-out neutron–^{16}O interaction

<u>Experiment with a 80 MeV proton beam</u>
Coherent inelastic processes are dominant while QE nucleon knock out was expected to be dominant in many models

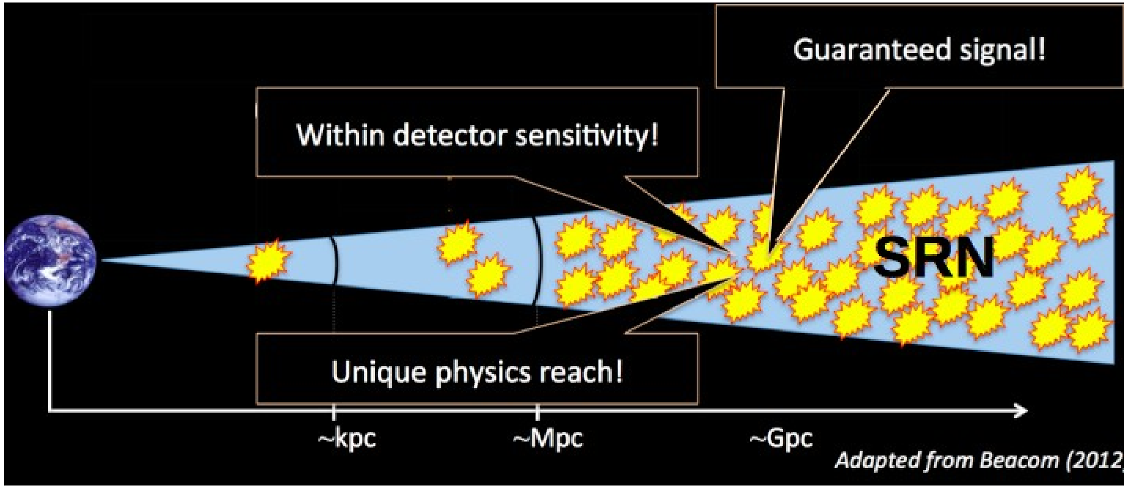
<u>Experiment with a 30 MeV proton beam</u>
Preliminary results seem to show that coherent inelastic processes are also dominant

Thank you for your attention

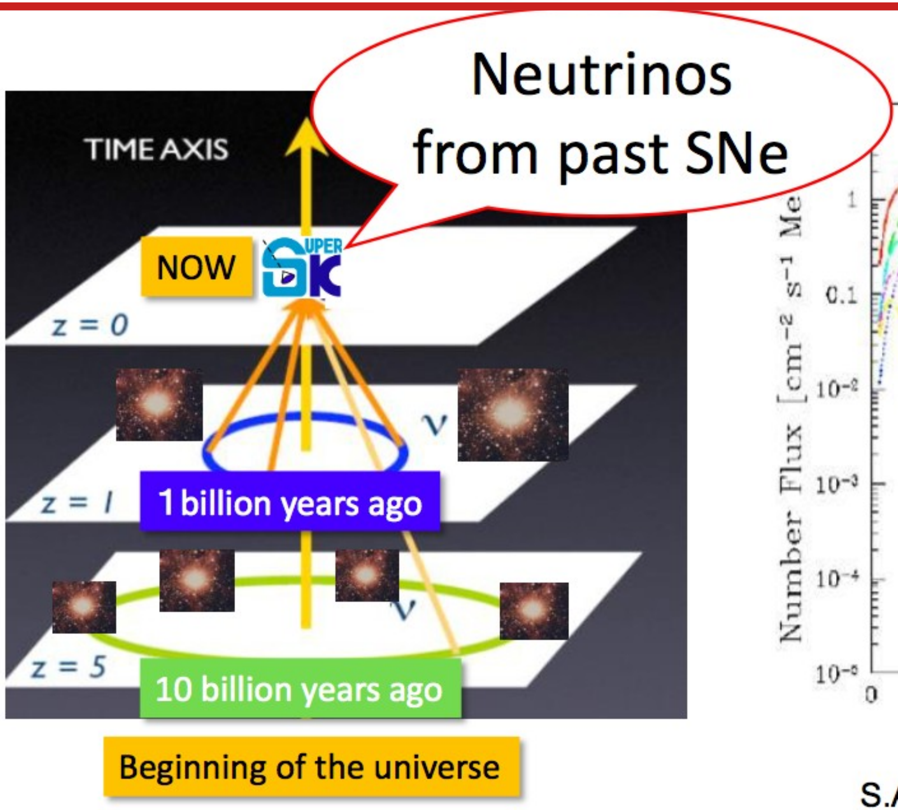
Back up

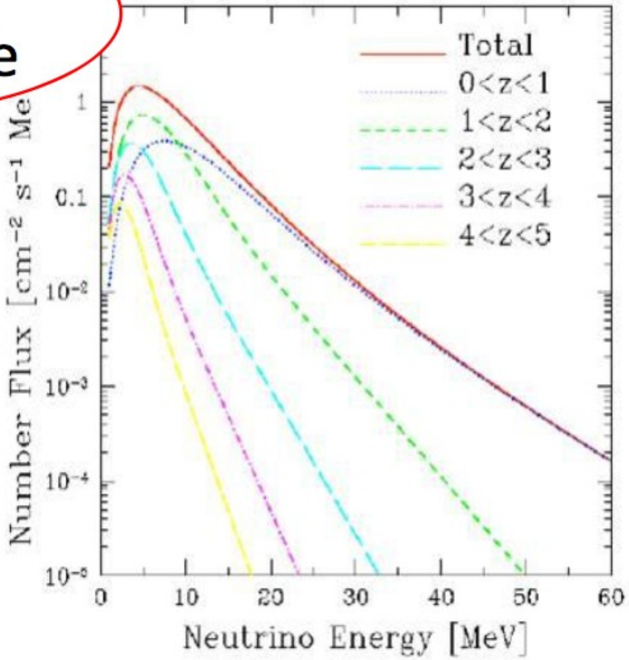
Supernovae relic neutrinos

- Cumulative emission of **MeV ν** from **all past core collapse supernovae**
- Also called **Diffuse Supernovae Neutrino Background (DSNB)**
- **At a distance of the order of Mpc** (SN1987A at a distance of 50kpc)
- **Continuous source of neutrino events** (10 supernovae explosions per second in the visible universe against 1-3 galactic core collapse supernovae per century)



Supernovae relic neutrinos





S.Ando, Astrophys.J. 607, 20(2004)

Theoretical flux prediction : 0.3~1.5 /cm2/s (17.3MeV threshold) 10

Slide from M.Ikeda (ICRR) for Super-K collaboration

SK-Gd

- SK-Gd project started in 2002
- EGADS started in 2009 to evaluate Gd effect to SK.
- In 2015, we achieved resolving 0.2% (target value) of Gd sulfate after PMT installation without a large loss of water quality.
- Most of listed items to study Gd effect were studied, and confirmed that there is no showstopper.
- Finally, SK-Gd was accepted by Super-K in June 2015.

Slide from M.Ikeda (ICRR) for Super-K collaboration

ν - ^{16}O NCQE interaction model – Ankowski's model

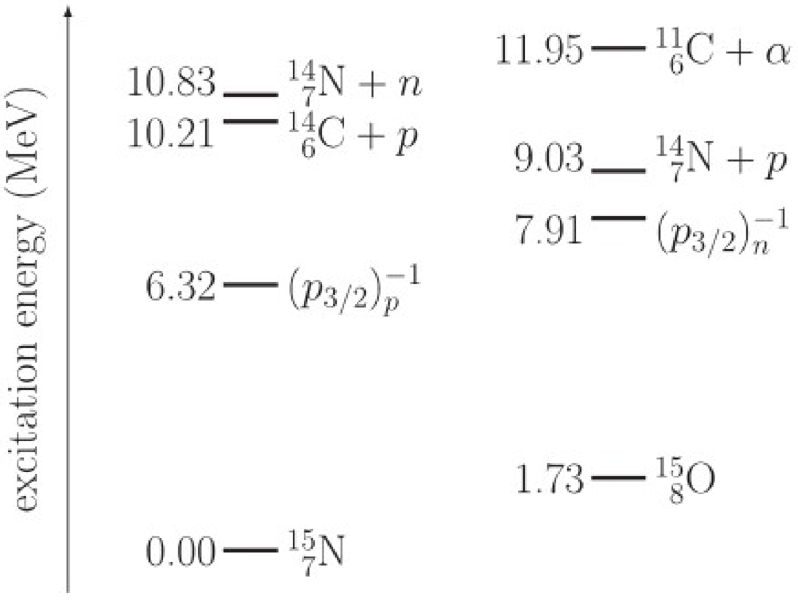


FIG. 2. Low-lying excited levels of the residual nuclei produced in $^{16}_{8}$O(ν, $\nu' N$) scattering. Energies are measured with respect to the $^{15}_{7}$N ground state.

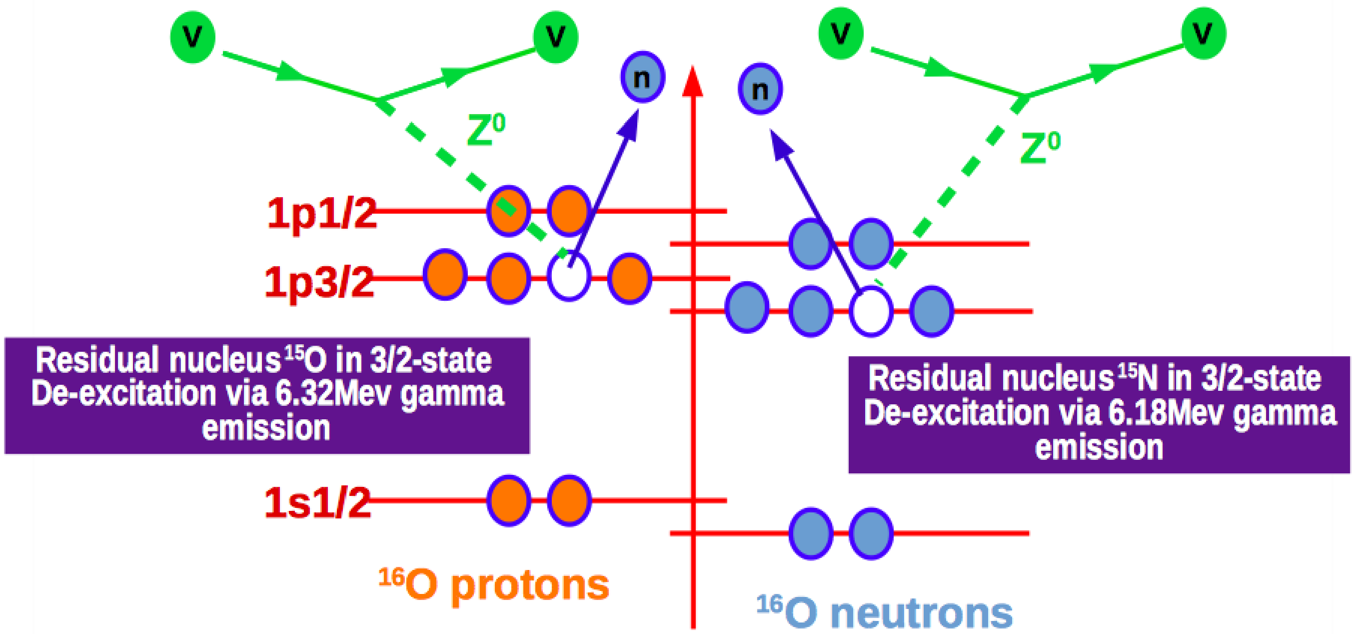
<u>Reference:</u> A. M. Ankowski, O. Benhar, T. Mori, R. Yamaguchi, and M. Sakuda, Phys. Rev. Lett. 108, 052505 (2012).

ν - ^{16}O NCQE interaction model – Ankowski's model

- For E_ν> 200 MeV, the single-nucleon knockout is the dominant reaction mechanism.
- Results obtained using for the first time a realistic model of the target spectral function, extensively tested against electron-nucleus scattering data.
- At E_ν=600 MeV, the contribution of the $p_{3/2}$ state is overwhelming.

Reference: A. M. Ankowski, O. Benhar, T. Mori, R. Yamaguchi, and M. Sakuda, Phys. Rev. Lett. 108, 052505 (2012).

ν - ^{16}O NCQE interaction



T2K simulation

- **FLUKA** is used to simulate hadron production in the target
- Particles are then transported through the magnetic horns, target hall, decay volume and beam dump with **GEANT3**
- **GCALOR is used for hadronic interactions**

Reference: K. Abe et al. (T2K Collaboration), Phys. Rev. D 90, 072012 (2014).

T2K simulation – GCALOR and INC

GCALOR is a combination of many models:

- **above 20 MeV** neutrons → intra-nuclear cascade model
- **below 20 MeV** neutrons → ENDF-V library: nuclear data file including data for neutron – ^{16}O

- The **INC models** treat the interaction of incoming projectile with the nucleus as **a series of independent collisions using on-mass-shell free particle-nucleon cross sections**

- INC may be justified for low energies (>50 MeV) considering reactions which take place primarily on **nuclear periphery like quasi-elastic** but we **may expect discrepancies**

Reference: **Intra-nuclear cascade** model Y. Yariv Soreq NRC, Yavne 81800, Israel Abstract.

80MeV experiment cross sections

$$\sigma_{\gamma(6.13\ \mathrm{MeV})} = 4.2 \pm 0.1(\mathrm{stat.}) \pm 0.9(\mathrm{syst.})\ \mathrm{mb},$$

$$\sigma_{\gamma(5.27\ \mathrm{MeV})} = 6.4 \pm 0.1(\mathrm{stat.}) \pm 2.2(\mathrm{syst.})\ \mathrm{mb},$$

$$\sigma_{\gamma(4.44\ \mathrm{MeV})} = 8.3 \pm 0.1(\mathrm{stat.}) \pm 1.6(\mathrm{syst.})\ \mathrm{mb}.$$

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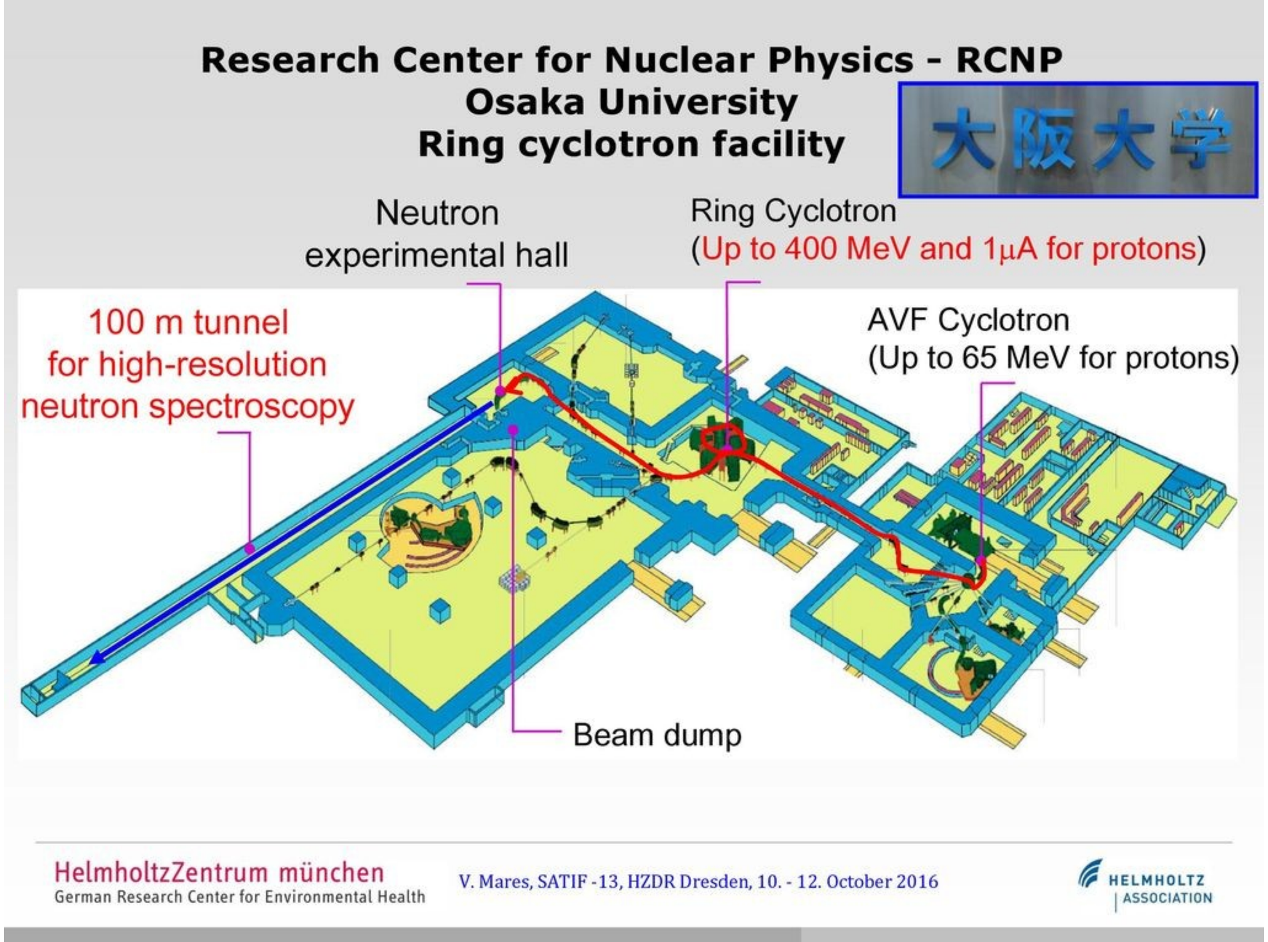
RCNP

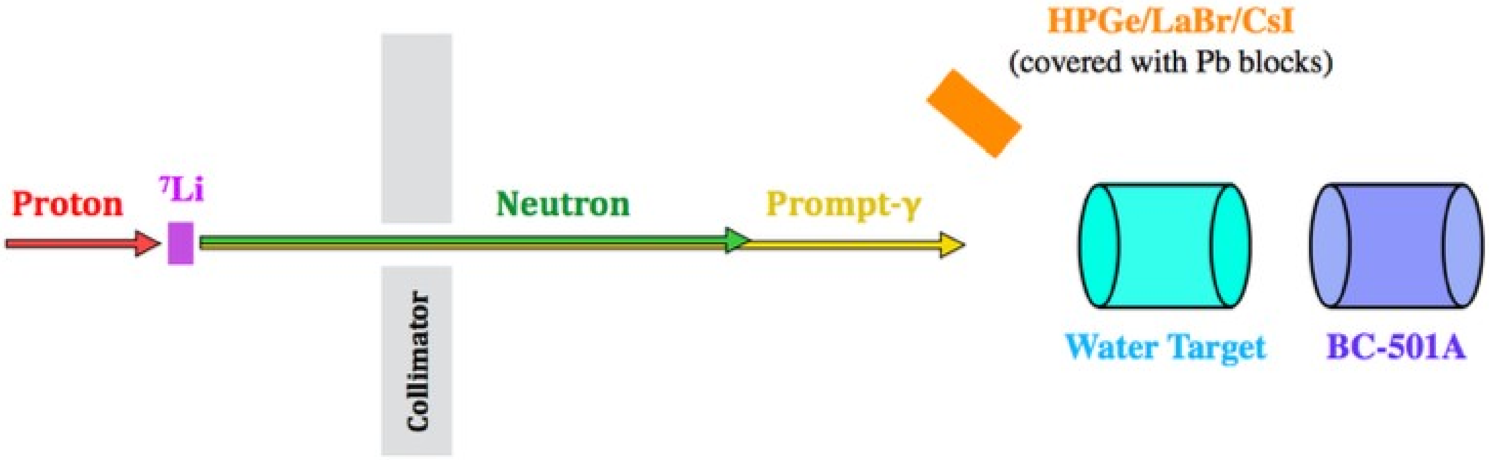


A proton beam accelerated using **two cyclotrons**, the K140 AVF cyclotron and the K400 ring cyclotron, and then directed onto a **10 mm thick lithium target** (^{nat}Li: 92.5% ^{7}Li and 7.5% ^{6}Li) to produce an almost mono energetic neutron beam via **the ^{7}Li(p, n)^{7}Be reaction**.

arXiv:1902.08964cl

[nucl-ex] 24 Feb 2019

80MeV setup



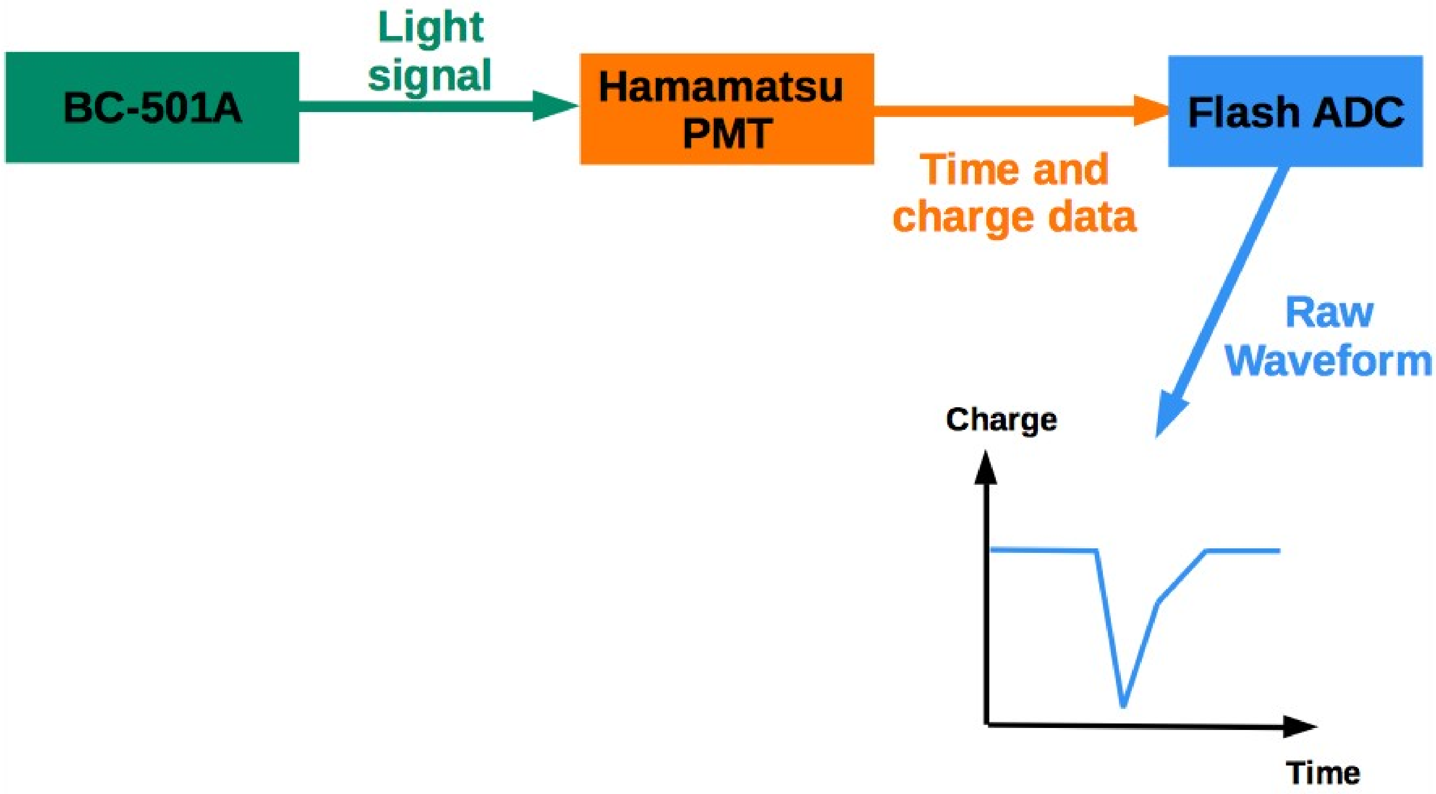
[Beam setting]

- beam time : 24 hours
- proton energy : 80.6 +/– 0.6 MeV
- Chopping : 1/9
- beam current (after 1/9) : 100 nA for gamma-ray, 5 nA for neutron flux

30MeV beam setting

- beam time: 24h
- proton energy: 30 ± 0.6 MeV
- Chopping: 1/9
- Beam current: 100 nA - 500 nA

Detailed setup LqS



PSD with organic scintillators

Prompt fluorescence (few ns)

Delayed fluorescence (10^{-3} s)

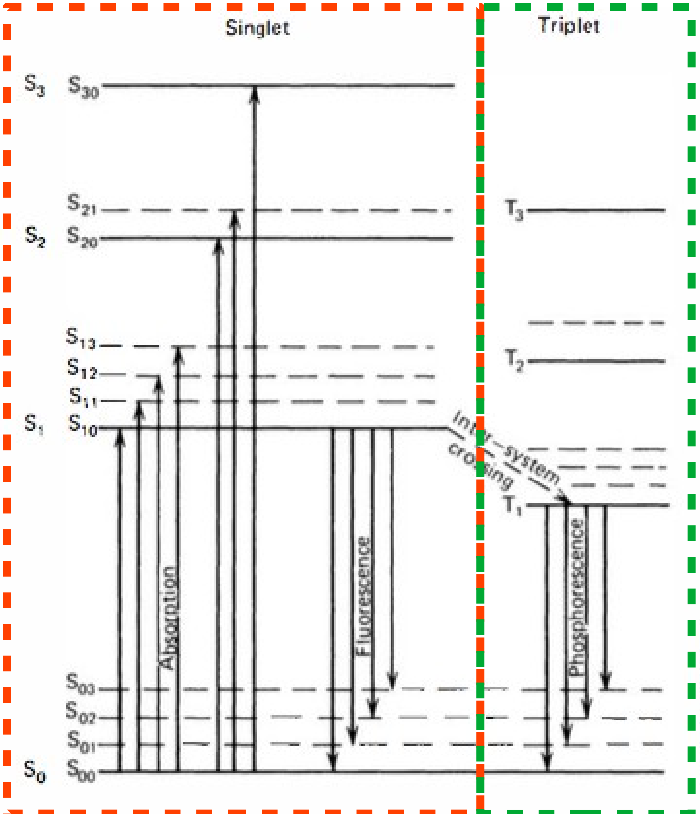


Figure 8.1 Energy levels of an organic molecule with π-electron structure. (From J. B. Birks, *The Theory and Practice of Scintillation Counting*. Copyright 1964 by Pergamon Press, Ltd. Used with permission.)

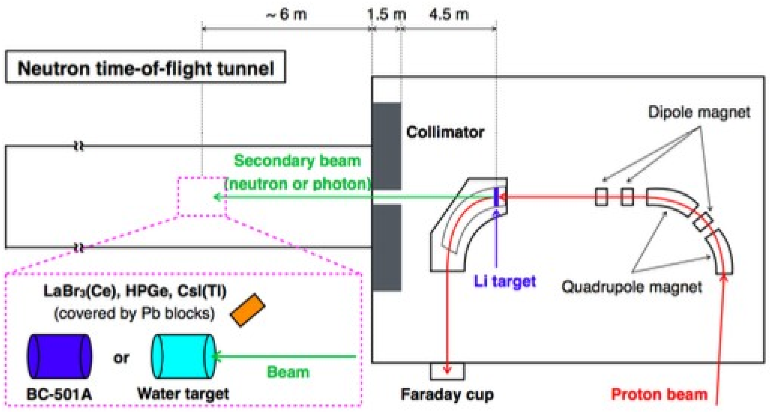
- The fraction of light corresponding to the slow component depends on the nature of the exciting particle.
- This dependence can be used to **differentiate between particles of different kinds that deposit the same energy in the detector**

Glenn F. Knoll Radiation Detection and Measurement

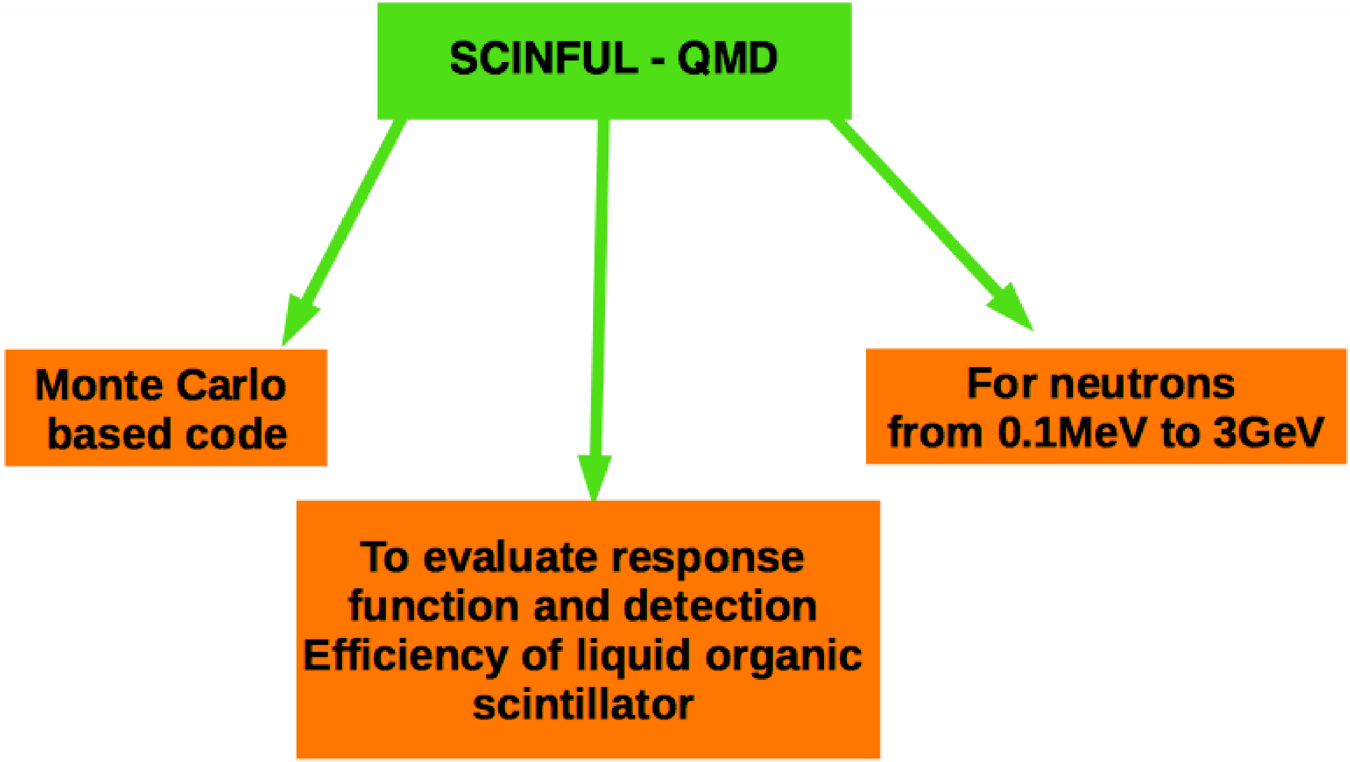
30 MeV neutron flux

$$\phi_n[/sr/\mu C] = \frac{N_{neutron}}{\Omega * R * \epsilon_n * I_{beam}}$$

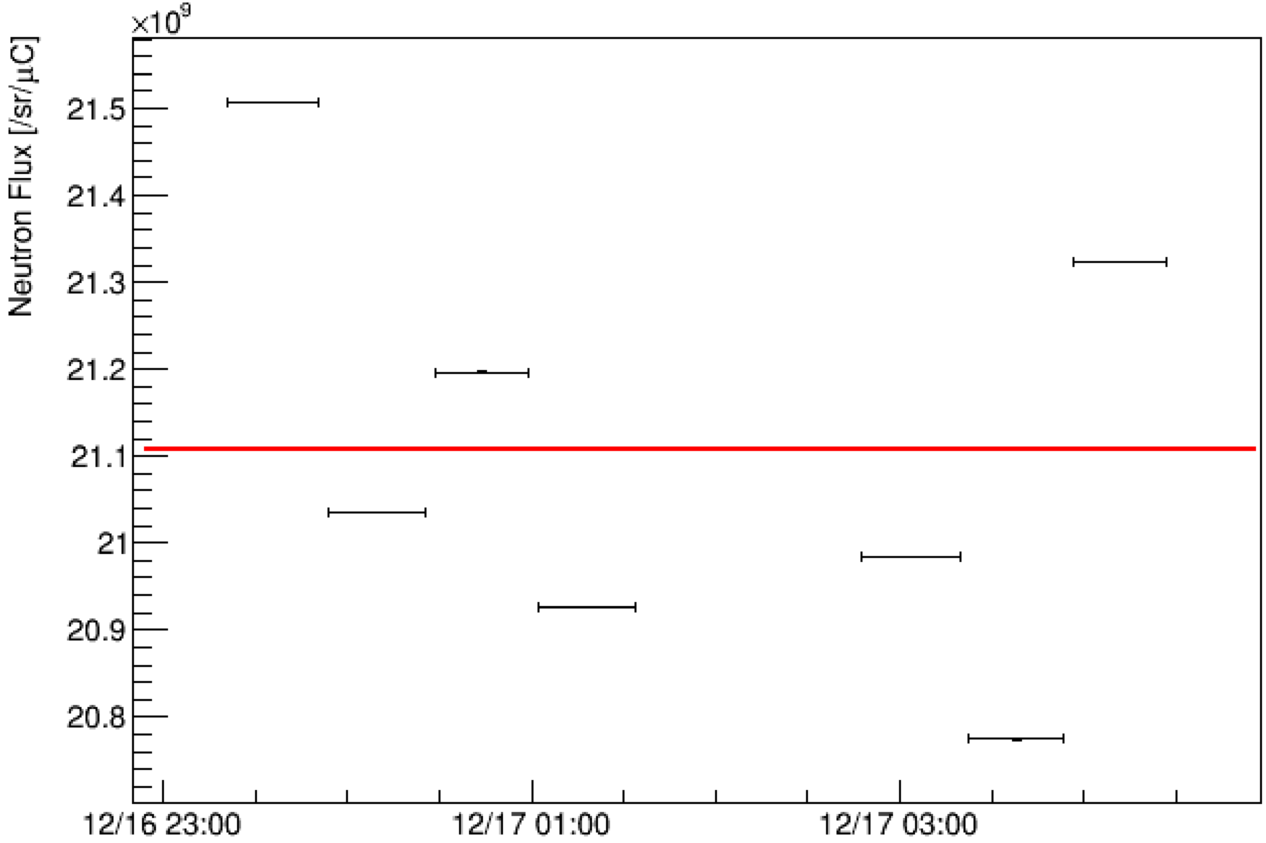
- Ω solid angle through which the water target is seen by the beam
- R flash ADC rate
- ϵ_n detector efficiency using MC simulation (SCINFUL-QMD)
- I_{beam} beam current [μC], Faraday cup information



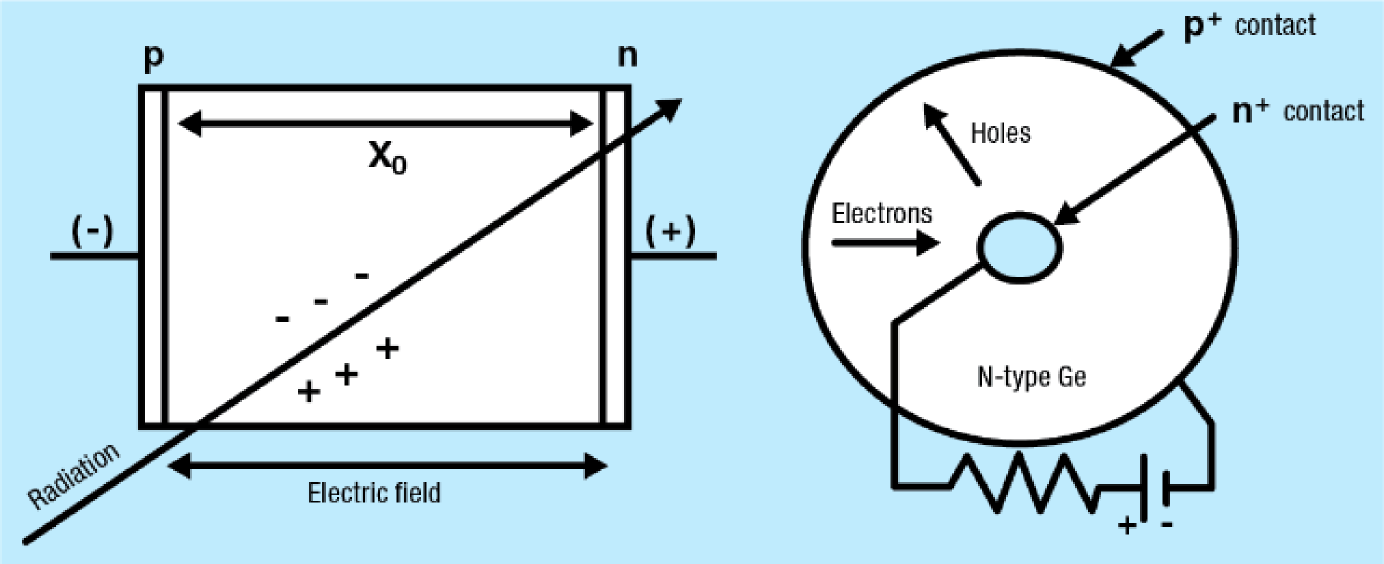
SCINFUL


SCINFUL - QMD
Monte Carlo based code
To evaluate response function and detection Efficiency of liquid organic scintillator
For neutrons from 0.1MeV to 3GeV

30 MeV neutron flux stability

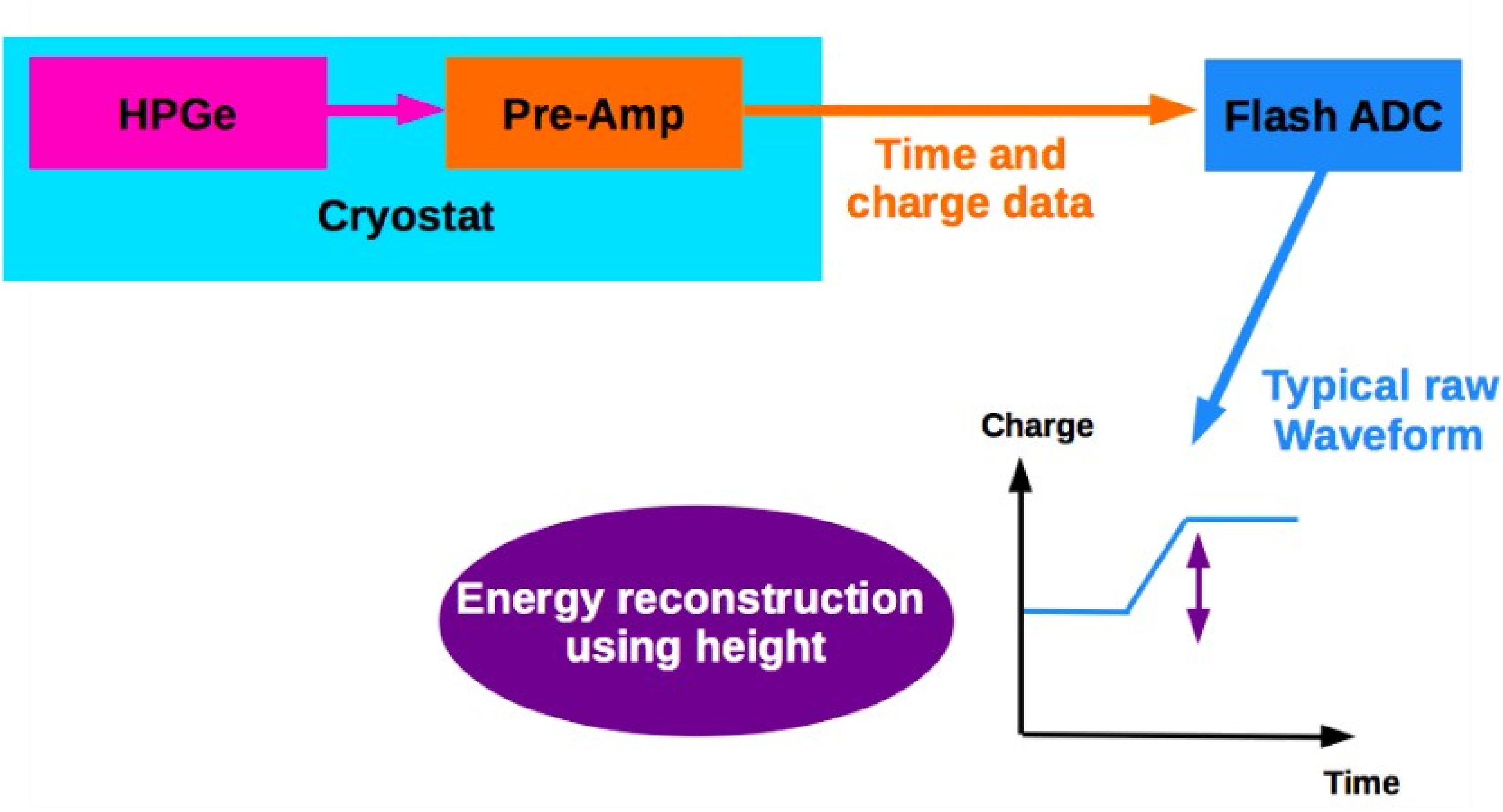


Advantages HPGe

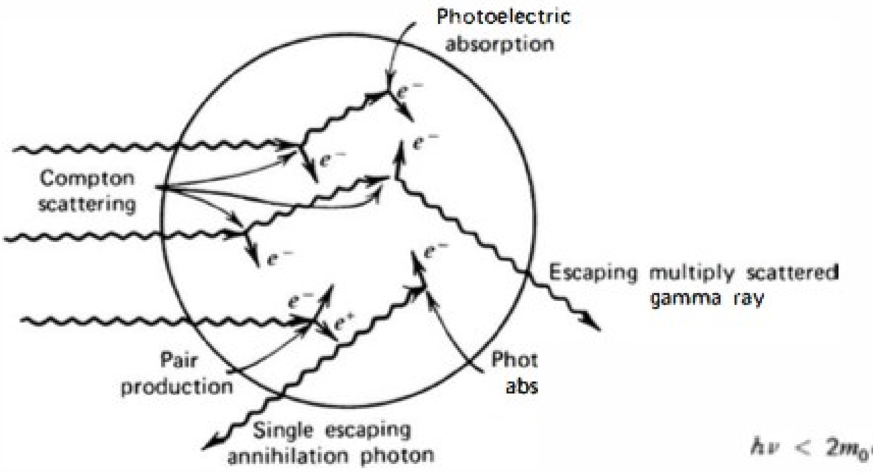


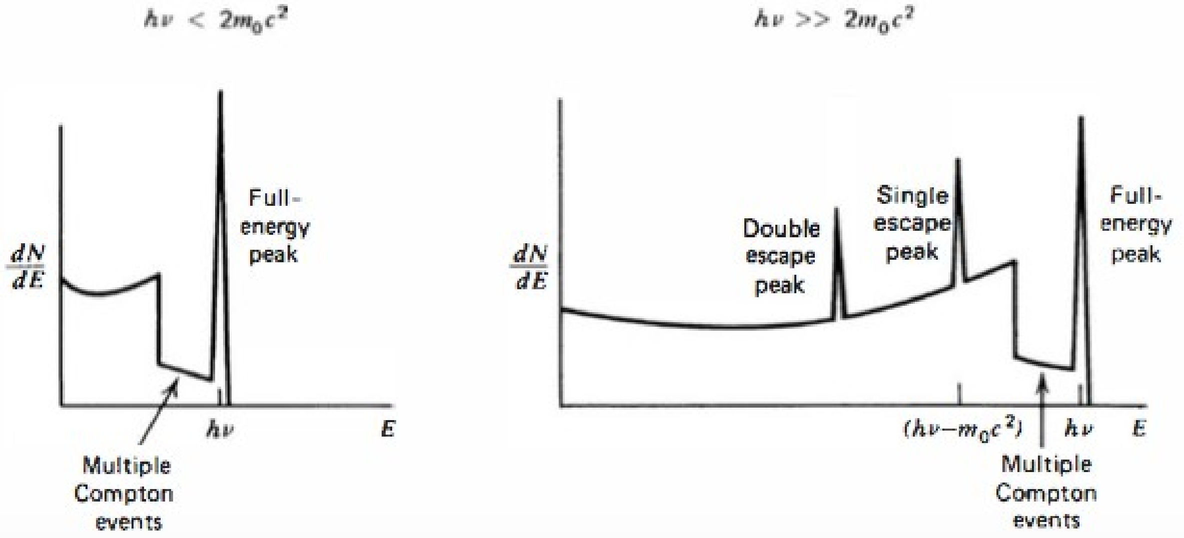
- Depletion depth: $X_0 = (\frac{2\epsilon V_0}{eN})^{\frac{1}{2}}$ with N is the impurity concentration of the material
- Energy needed to form an electron hole pair = 3eV $\rightarrow$ large number of electron-hole pairs $\rightarrow$ good statistics $\rightarrow$ good energy resolution

Detailed setup HPGe



SE/DE/photopeak

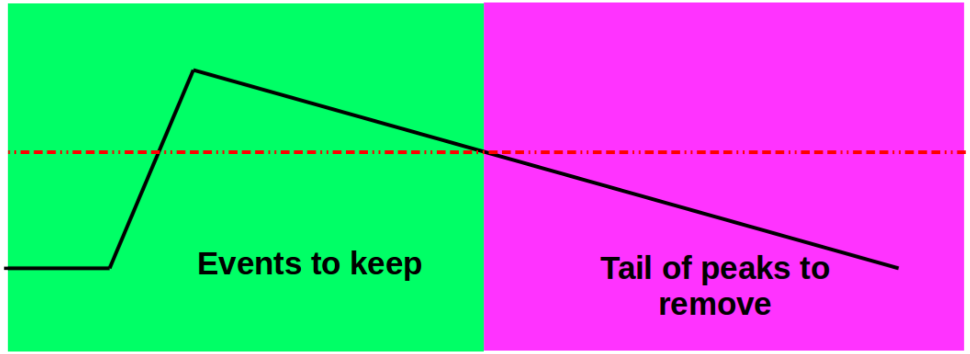




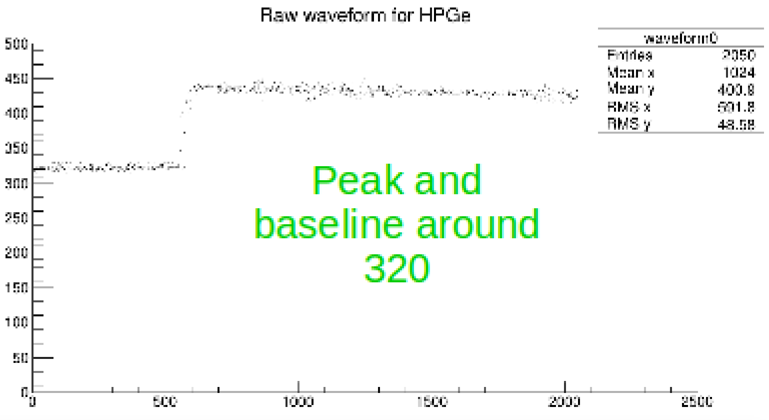
Glenn F. Knoll
Radiation
Detection and
Measurement

HPGe event selection

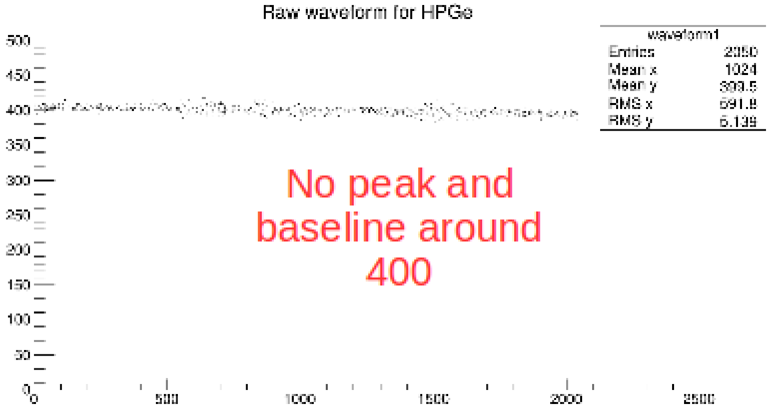
Two types of events



Events to keep



Events to remove



HPGe 30MeV calibration

- Conclusion: good linearity between energy and height

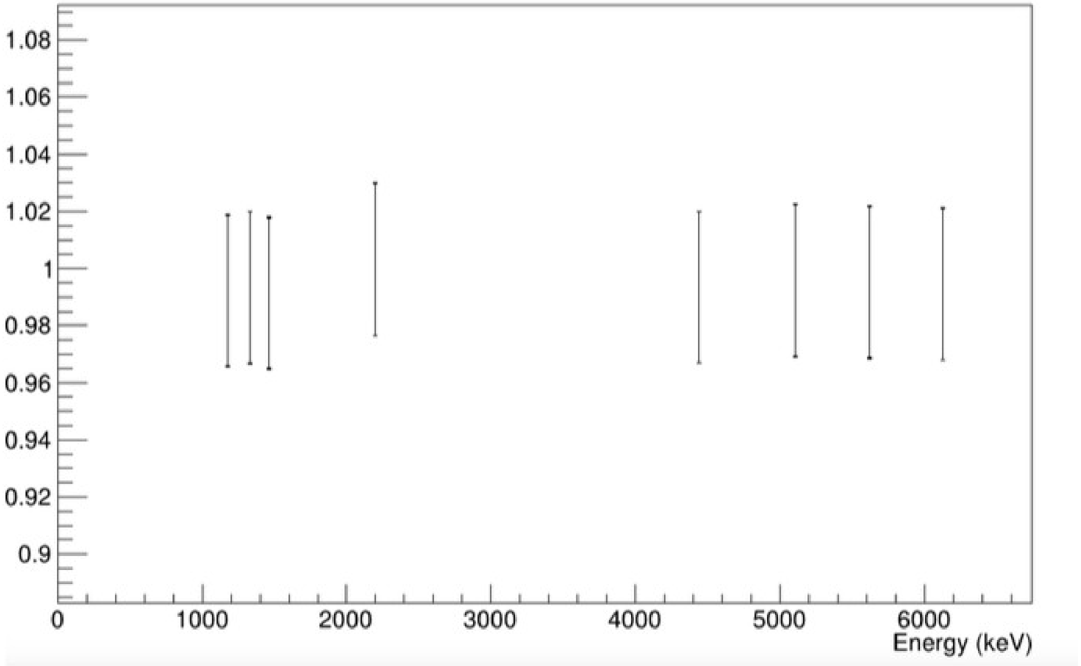
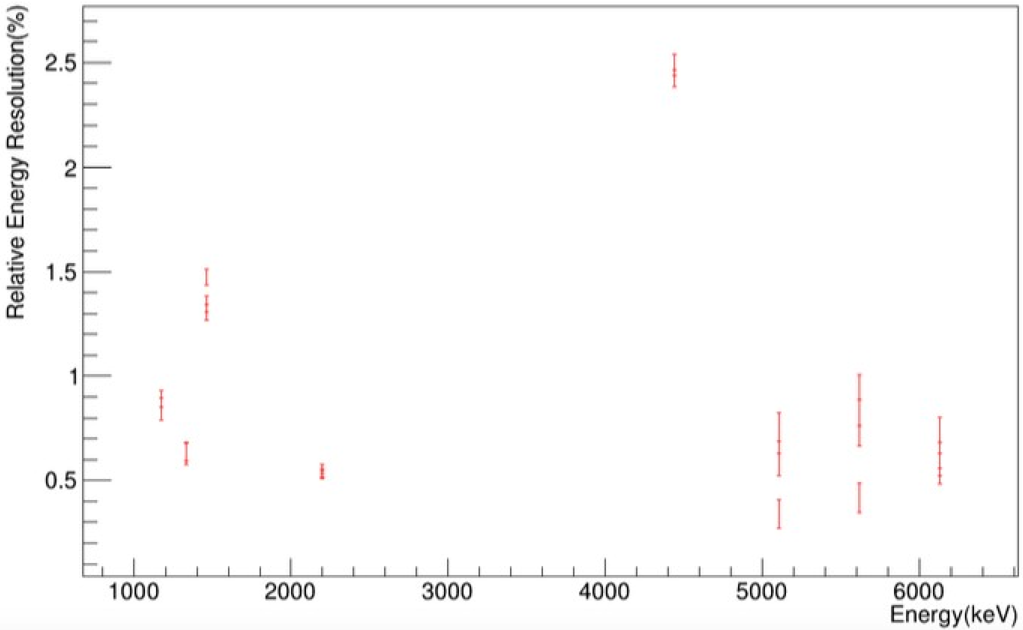


Figure: Ratio between the measured height and the fitted height according to energy in keV (preliminary results)

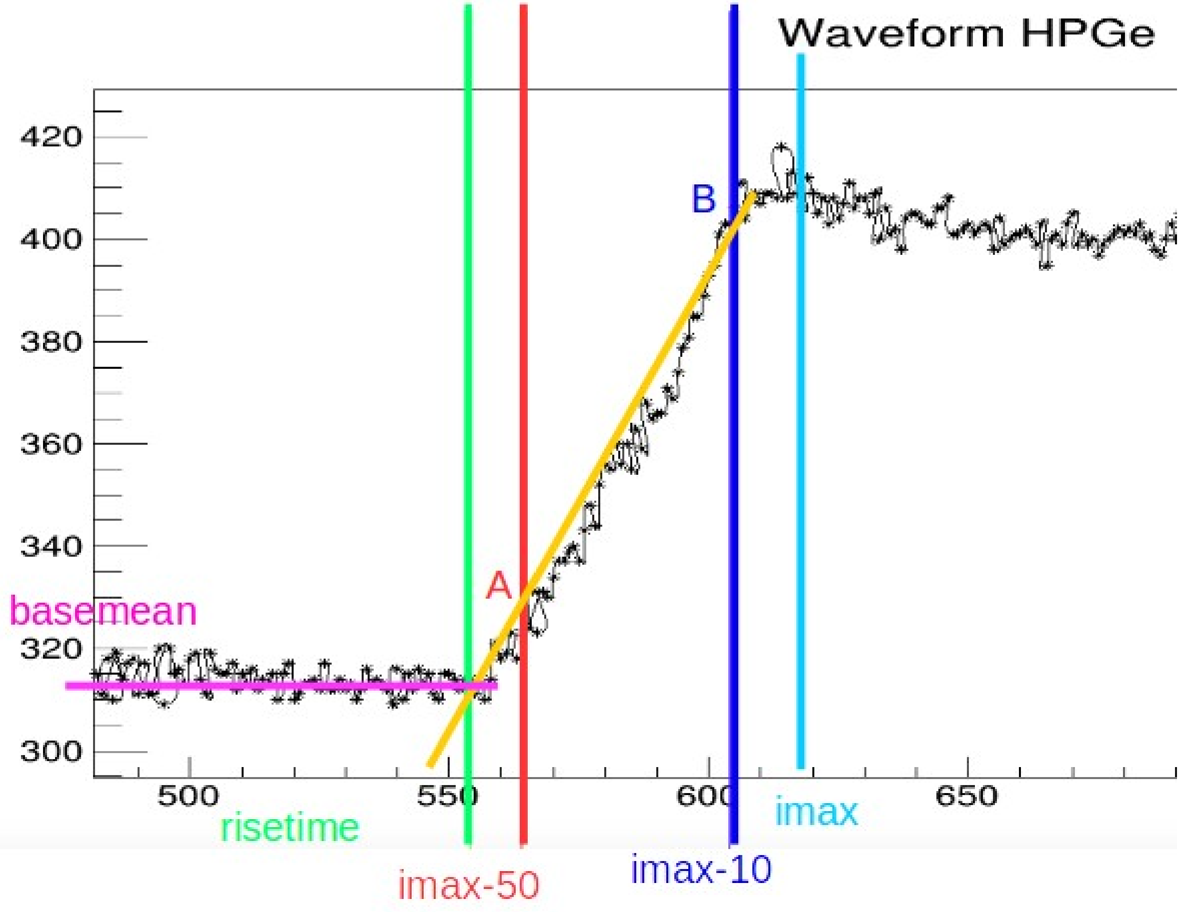
HPGe energy resolution

- Relative energy resolution R for a peak ($R = \frac{FWHM}{E}$)
- Am/Be photopeak (4.439MeV) resolution affected by Doppler broadening
- HPGe energy resolution the best among gamma detectors ($\leq 1\%$)

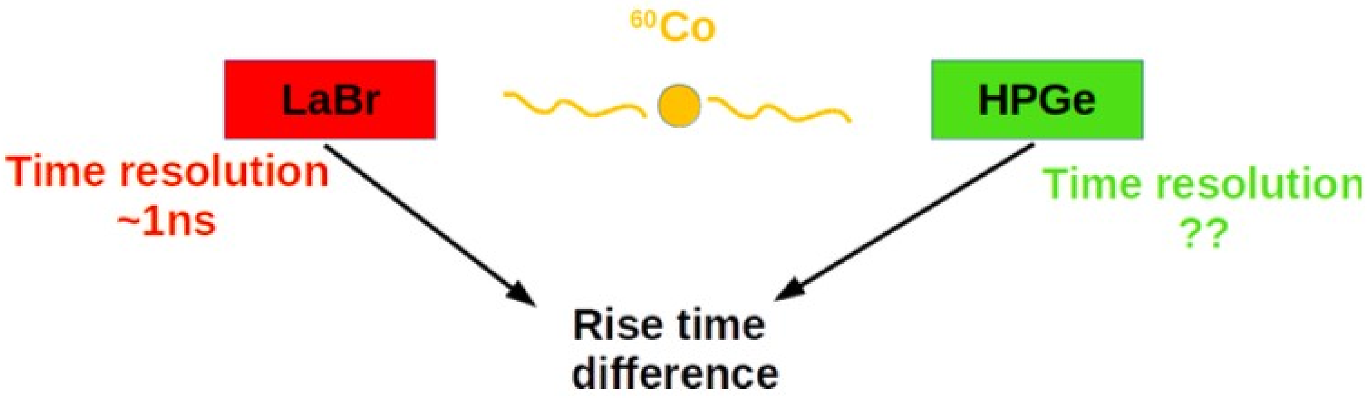
Resolution as a function of the energy for 30MeV runs (preliminary results)



TOF reconstruction: rise time determination method



Time resolution using coincidence measurement

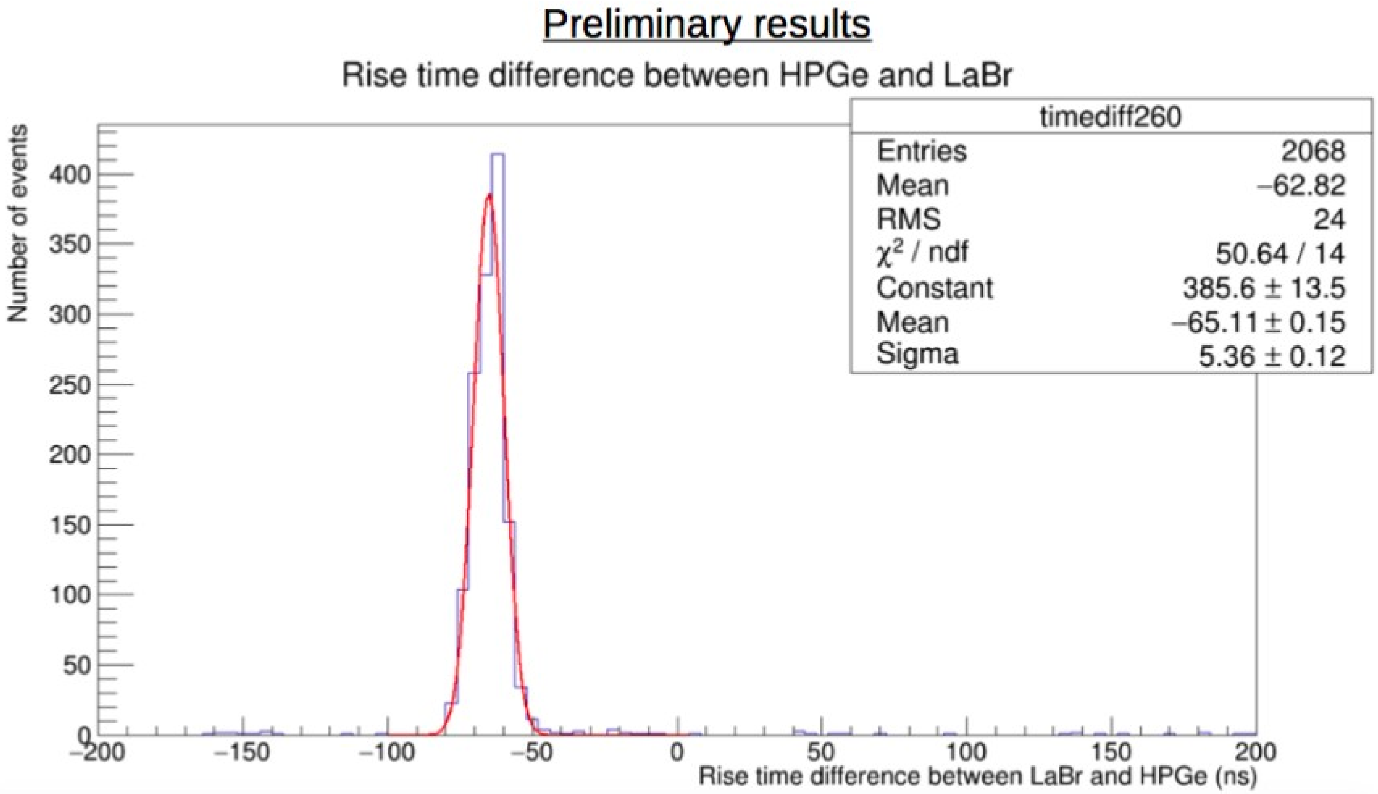


$$\delta t = t_{LaBr} - t_{HPGe}$$

$$\sigma_{\delta t} = \sqrt{\sigma_{LaBr}^2 + \sigma_{HPGe}^2} \sim \sigma_{HPGe}$$

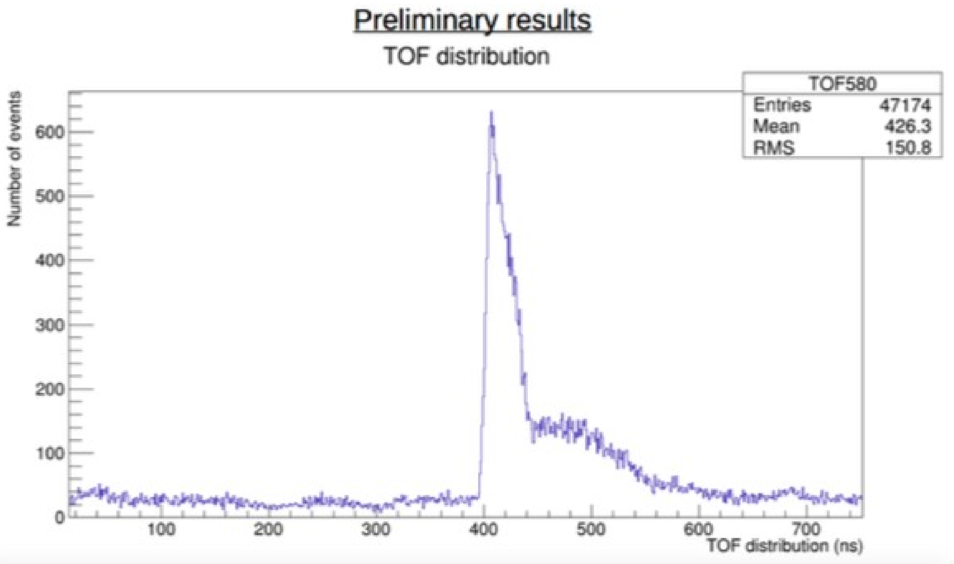
Time resolution using coincidence measurement

- Good time resolution: $\sigma_{HPGe} = 5.36ns$



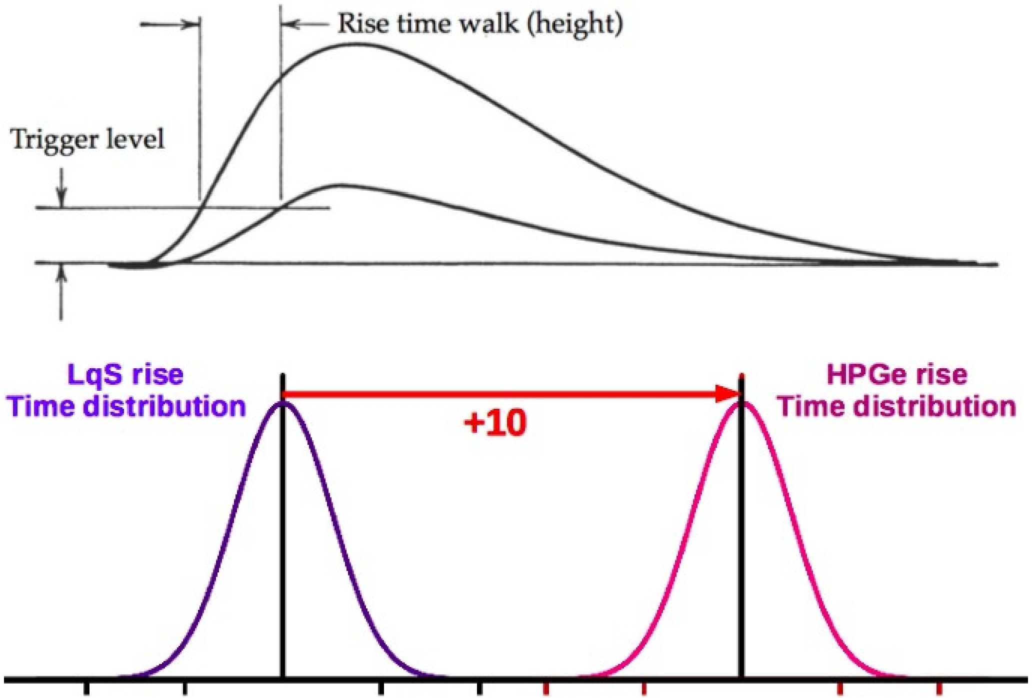
TOF reconstruction

- Using the same method as for the neutron flux
- No clear prompt gamma → use LqS data to see prompt gamma and reconstruct kinetic energy
- Need to apply time walk correction to HPGe TOF → on going validation



Time walk correction

- TDC recognizes trigger point as the rise timing
- The rise timing depends on the slope and on the height
- LqS has a faster response than HPGe → HPGe rise time has to be corrected accordingly



Neutron-^{16}O interactions and possible gamma rays

Name	Process	Gamma energy
Inelastic scattering	$^{16}O(n,n')^{16}O*$	6.13 MeV
Proton emission	$^{16}O^* \rightarrow p +^{15} N^*$	5.27 MeV
Alpha emission	$^{16}O^* \rightarrow \alpha +^{12} C^*$	4.44 MeV
QE proton knockout	$^{16}O(n,np)^{15}N*$	6.32 MeV
QE neutron knockout	$^{16}O(n,nn)^{15}O*$	6.18 MeV
Alpha knock out	$^{16}O(n,\alpha)^{13}C*$	3.68 MeV
Neutron capture by ^{16}O	$^{16}O + n \rightarrow^{17} O^*$	3.84 MeV