November 24-26, 2022
Focused Workshop on Rare Isotope Physics

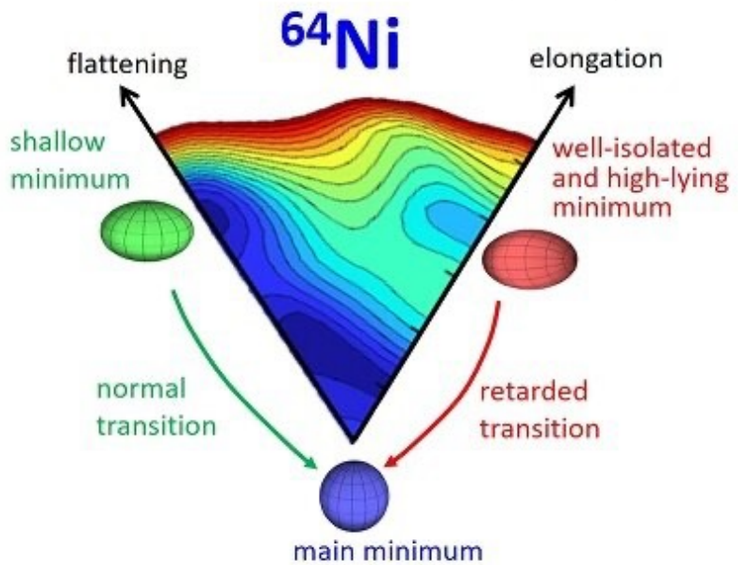
The IDATEN project: New approach to nuclear structure of exotic nuclei

Byul Moon
Center for Exotic Nuclear Studies, Institute for Basic Science

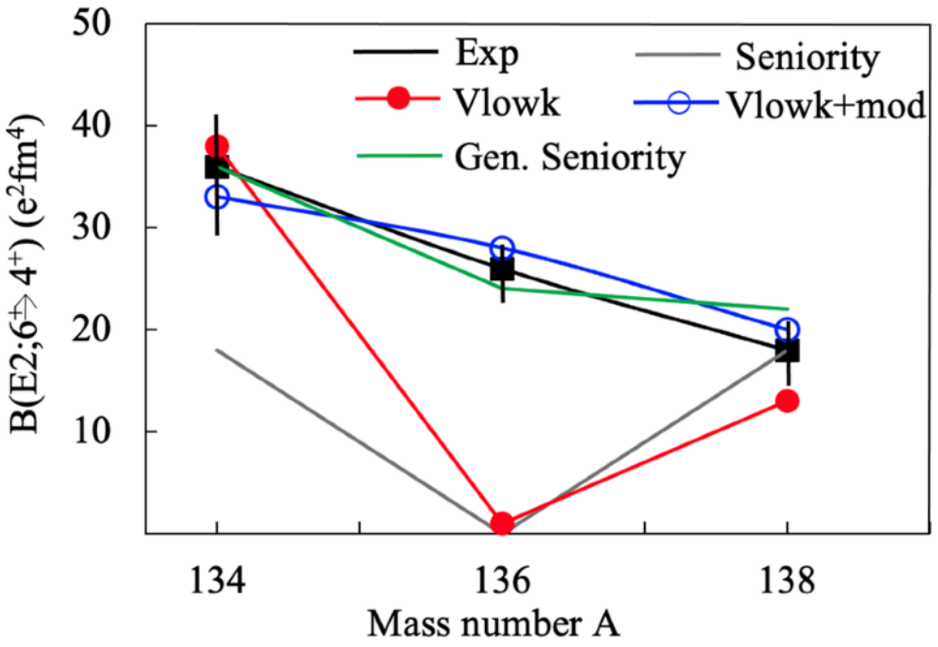
CENS CENTER FOR EXOTIC NUCLEAR STUDIES

Why fast-timing measurement?

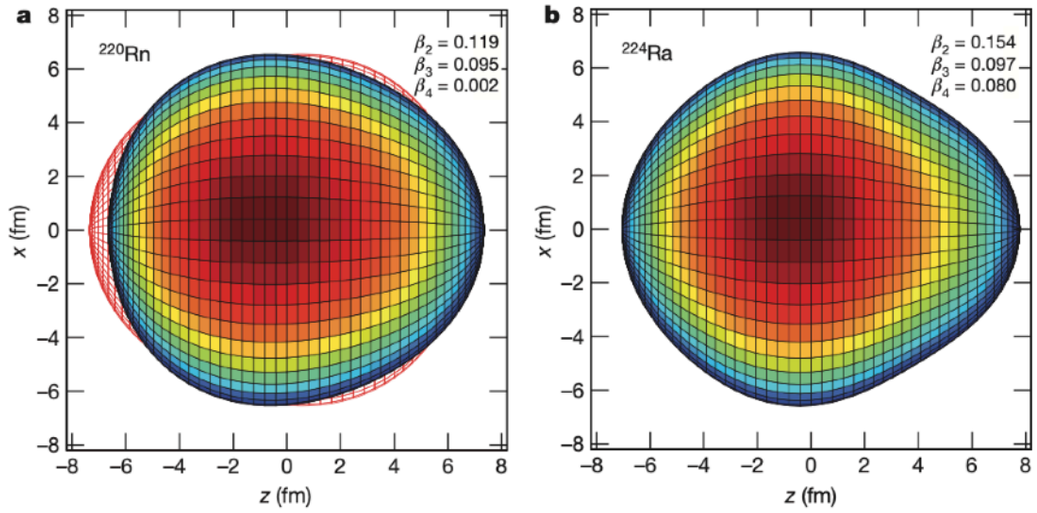
PRL **125**, 102502 (2020).



PRL **113**, 132502 (2014).

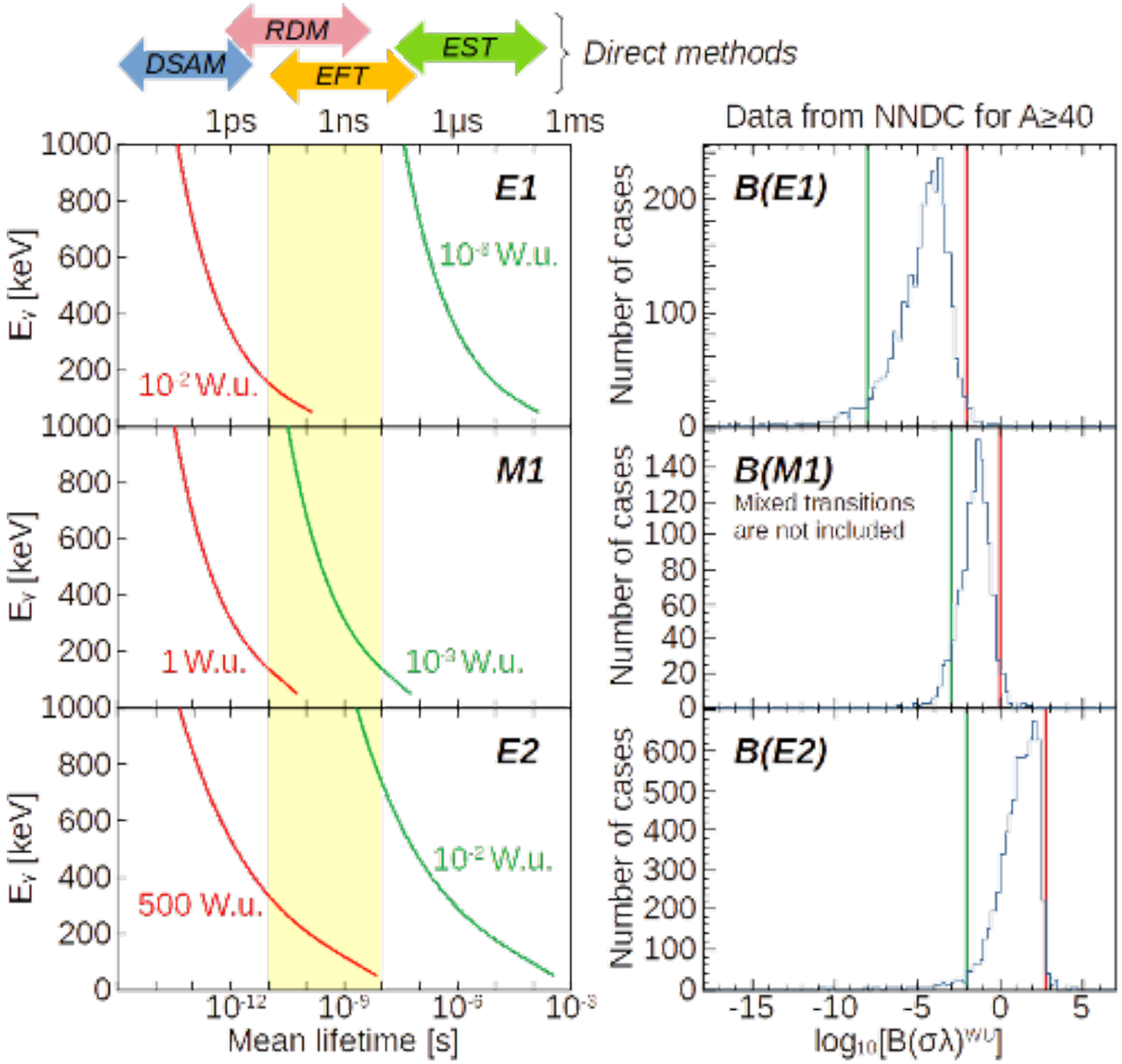


Nature **497**, 199 (2013).



- Energy information is not sufficient to investigate nuclear structure.
- Transition rate information is necessary and it can be derived by lifetime measurements.
- Discriminate the nuclear shape: prolate, oblate, triaxial
- Seniority studies near magic numbers
- Nuclear shape coexistence
- Asymmetric reflection like octupole deformation

Then why $LaBr_3(Ce)$ detector?



Credit by H. Watanabe

DSAM: Doppler-Shift Attenuation Method
RDM: Recoil Distance Method
EFT: Electronic Fast Timing
EST: Electronic Slow Timing

- Different lifetime sensitivity with different methodology.
- $LaBr_3(Ce)$ based EFT is sensitive to the range of a few tens of picoseconds to a few tens of nanoseconds.

Then why $LaBr_3(Ce)$ detector?

Transition type	Transition rate (W.u.)	Transition energy	Physics case
Strongly enhanced E2	~100 W.u.	< 300 keV	2^+_1 to 0^+_1 in even-even well-deformed nuclei in medium mass region
Moderately enhanced E2	~30 W.u.	300 - 700 keV	2^+_1 to 0^+_1 in even-even vibrational nuclei in medium-heavy mass region
Hindered E2	0.1 - 1 W.u.	400 - 1000 keV	Same seniority multiplet in single closed shell nuclei
Highly hindered M1	10^{-3} - 10^{-2} W.u.	A few tens to hundreds of keV	Single-particle states of different l in closed-shell region
Hindered E1	10^{-6} - 10^{-5} W.u.	Several hundreds of keV	$\Delta K = 1$ or 2 in well-deformed nuclei
Enhanced E1	10^{-4} - 10^{-2} W.u.	Several hundreds of keV	Yrast positive- and negative-parity states in reflection asymmetric nuclei

IDATEN project at RIBF

NP2112-RIBF212

Title: **Fast-timing γ-ray spectroscopy of exotic nuclei at RIBF**

Spokesperson(s): **Hiroshi Watanabe**

Approved — Grade A

1.5 days

1.5 days(including 0.5days for BigRIPS tuning)

A construction proposal of the fast-timing measurement at RIBF was approved.

Spokespersons: H. Watanabe (Beihang U.), P. H. Regan (U. Surrey), and B. Moon (IBS CENS)
In-house contact person: S. Nishimura (RNC)

The world largest fast-timing array is coming…

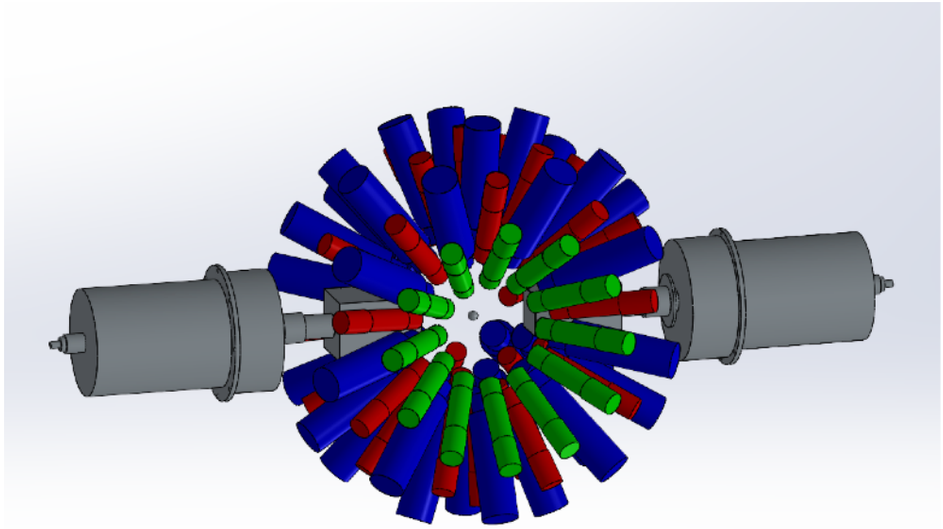
What is IDATEN?

International Detector Assembly for fast-Timing measurements of Exotic Nuclei

IDATEN is a Japanese word for the god of speed from Buddhism and Hinduism.

韋馱天 / 위타천 / स्कन्द् / Iskandar / Alexander the Great

In Japanese baseball pro games, a speedy player is called as Idaten.



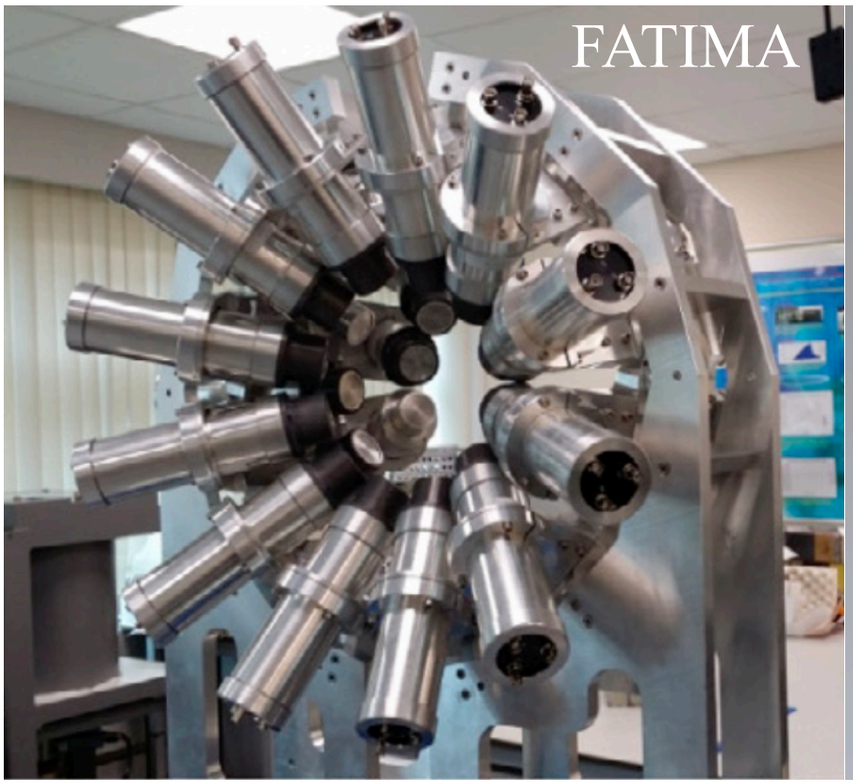
A large array of 82 $LaBr_3$(Ce) detectors

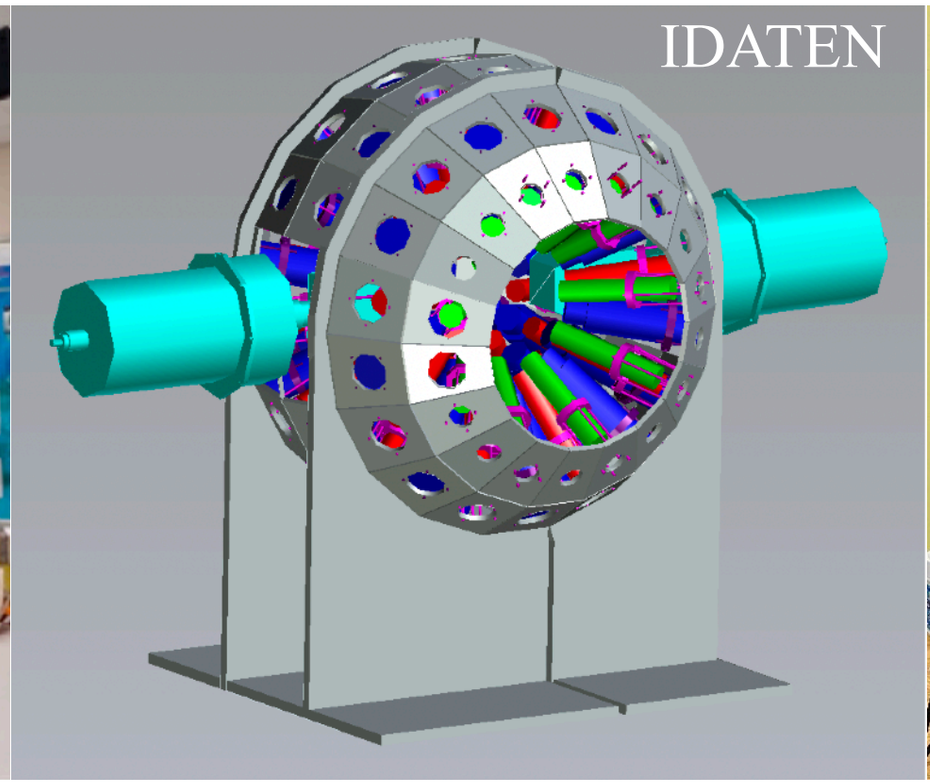
36 FATIMA (FAst-TIMing Array)

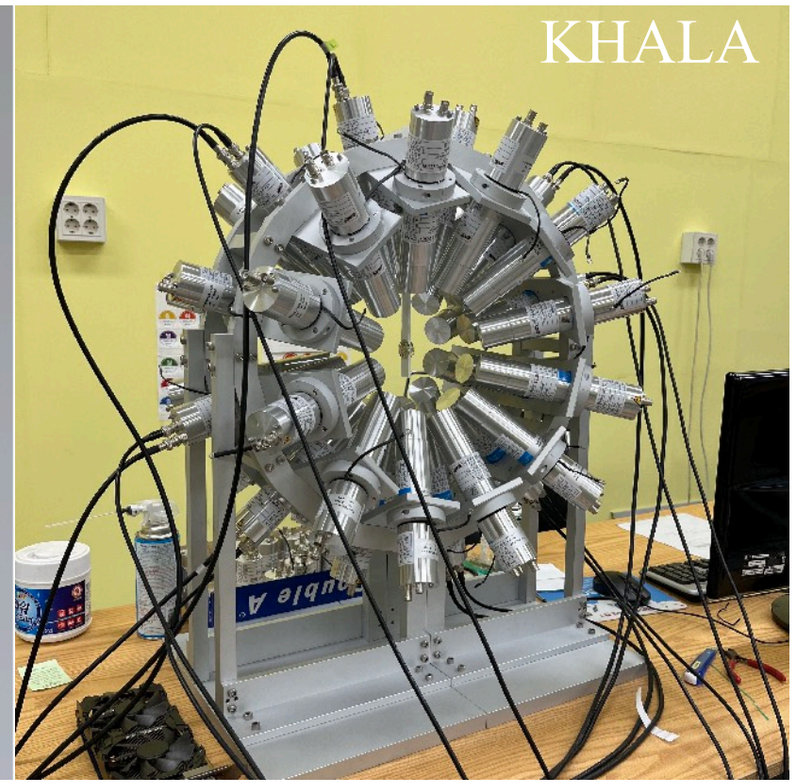
36+10 KHALA (Korea High-resolution Array of $LAbr_3$)

… and two clover detectors

Summary of IDATEN specification

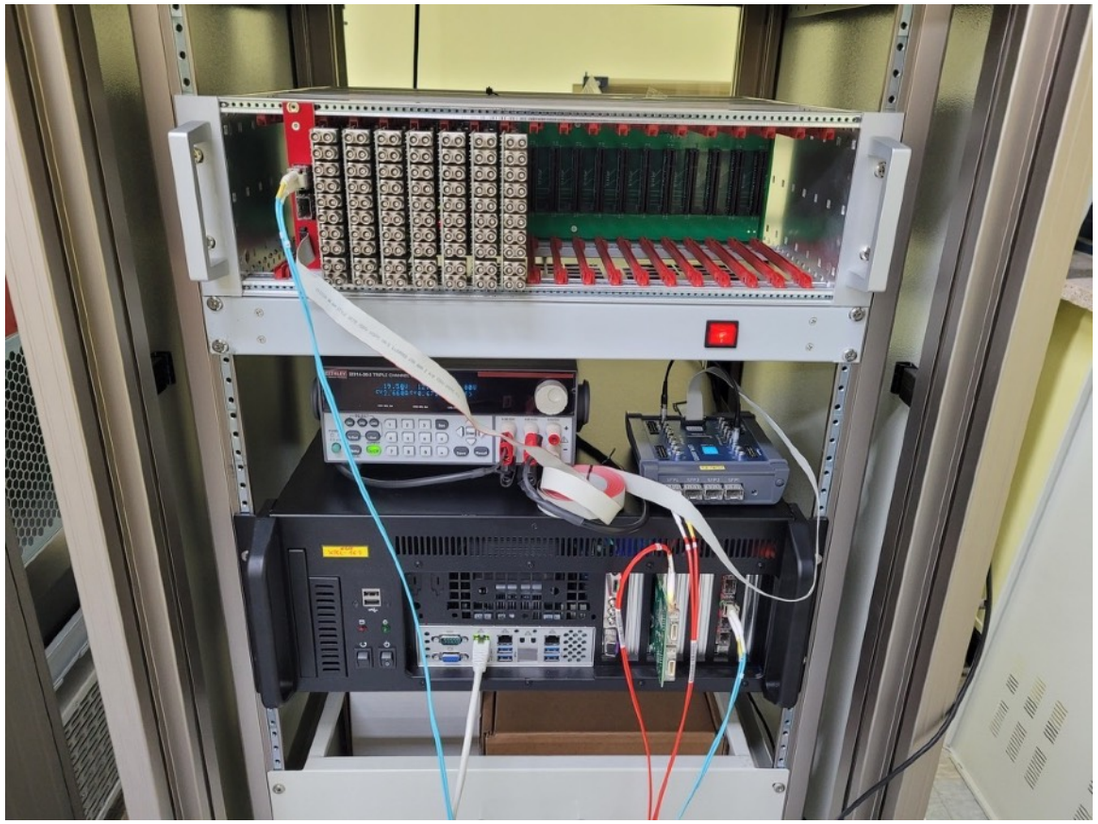






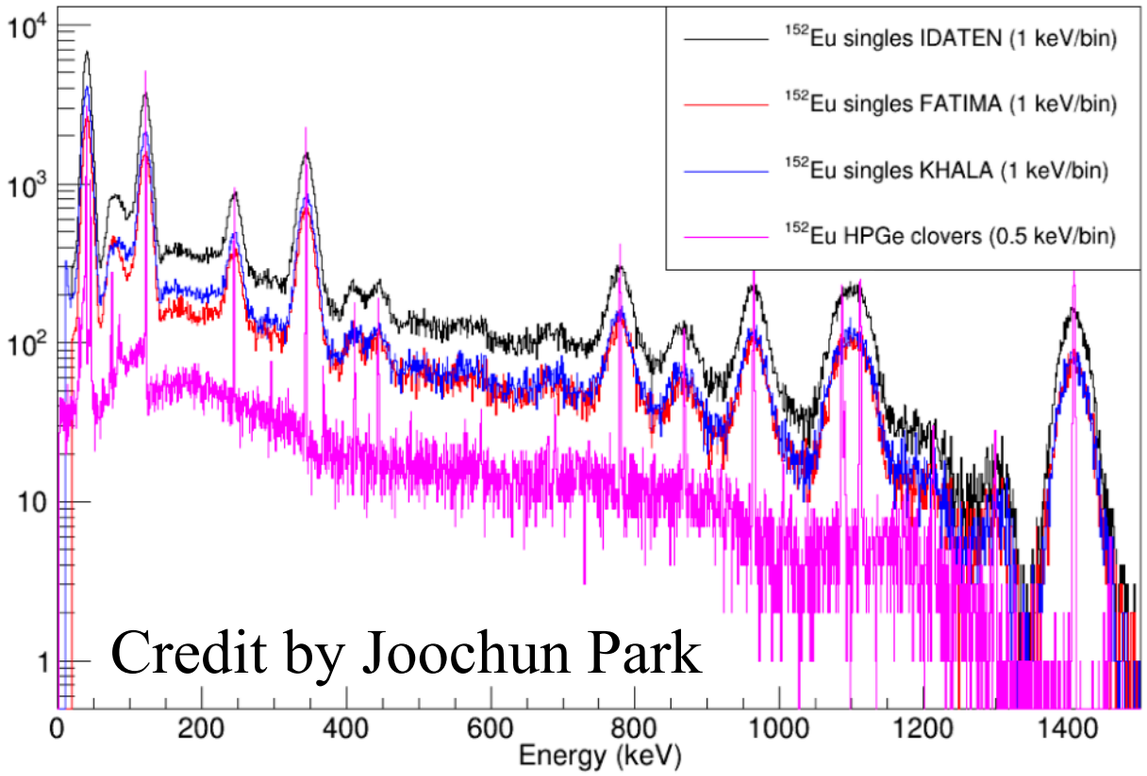
	FATIMA	KHALA
Number of detectors	36	36+10
$LaBr_3(Ce)$ crystal size	ϕ1.5”X2”-length	ϕ1.5”X1.5”-length
Energy resolution	3.4% @ 779 keV	3.3% @ 662 keV
Time resolution	334.3(4) ps @ 1332-1173 keV	335(1) ps @ 511-511 keV
Passive Pb shield	Optional	No
Owners	U. of Surry, U. of Brighton	KU, SNU

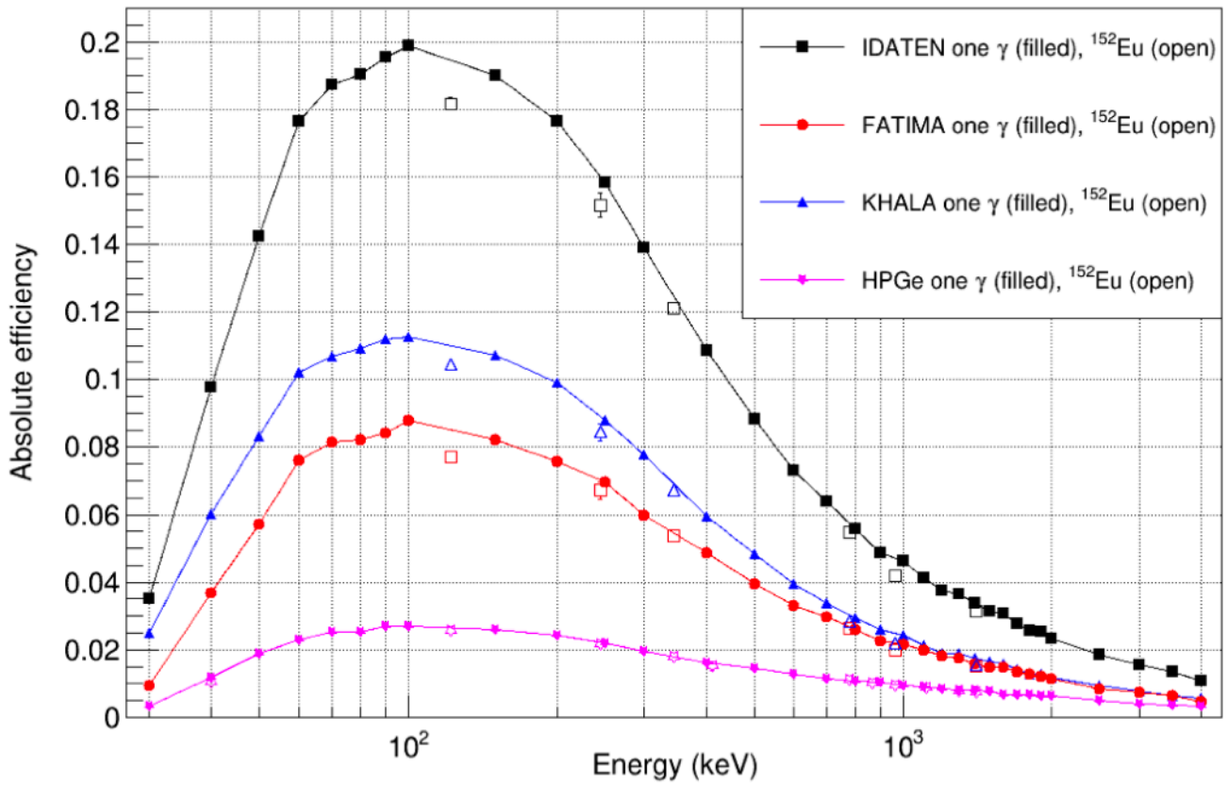
New DAQ electronics system



- Twinpeaks FEE + TAMEX TDC modules developed by GSI
- Capability of applying a long gate width (able to measure long-lived isomers)
- Advantage of the compact system, cheap price, and small dead time
- 16 input channels per a card with two amp types
- The system is arrived in Korea University and being tested.

IDATEN simulation





- Simulation based on NPTool
- Source data simulated with IDATEN-82 array
- Atomic and self-radioactive backgrounds are implemented.
- Helpful to prepare the RIBF PAC proposal.

Submitted IDATEN proposals

Study of shell structure, core-breaking and seniority-breaking effects close to ^{100}Sn with IDATEN
A. Blazhev, G. Zhang, Y. H. Kim, S. Guo et al.

Exploring the structure of the neutron-rich heavy nuclei beyond ^{208}Pb
A. Lopez, A. Gottardo, R. Lozeva, Z. Liu et al.

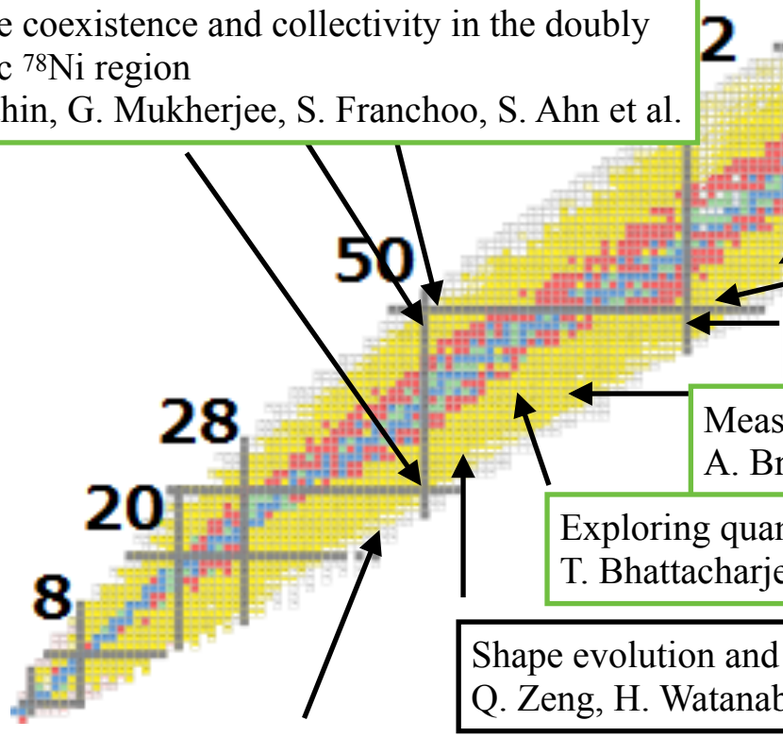
Fast-timing g-ray spectroscopy of excited states in N ~ Z nuclei below ^{100}Sn
J. Park, B. Das, Y. H. Kim, X. Liu et al.

First 2^+ state lifetime measurement for the neutron-rich Yb and Er
J. Ha, Y. H. Kim et al.

Study of the deformation pattern in the rare-earth region
S. Pascu, S. Bae, V. Werner, Z. Podolyak et al.

Shape coexistence and collectivity in the doubly magic ^{78}Ni region
E. Sahin, G. Mukherjee, S. Franchoo, S. Ahn et al.

Probing octupole collectivity and electric dipole moments in neutron rich Ba, La, and Ce
B. Ding, H. Watanabe, S. Nag et al.



Seniority and collectivity of nuclei beyond doubly-magic ^{132}Sn nucleus
B. Moon, R. Lozeva et al.

Nuclear structure study of Pd, Ag, and Cd isotopes towards N = 82 with fast-timing lifetime measurements
H. Watanabe et al.

Measurement of lifetimes of excited states in ^{108}Zr
A. Bruce, B. Moon et al.

Exploring quantum shape phase transition around Z = 40 and N = 60 with g-g fast timing
T. Bhattacharjee, S. Bae et al.

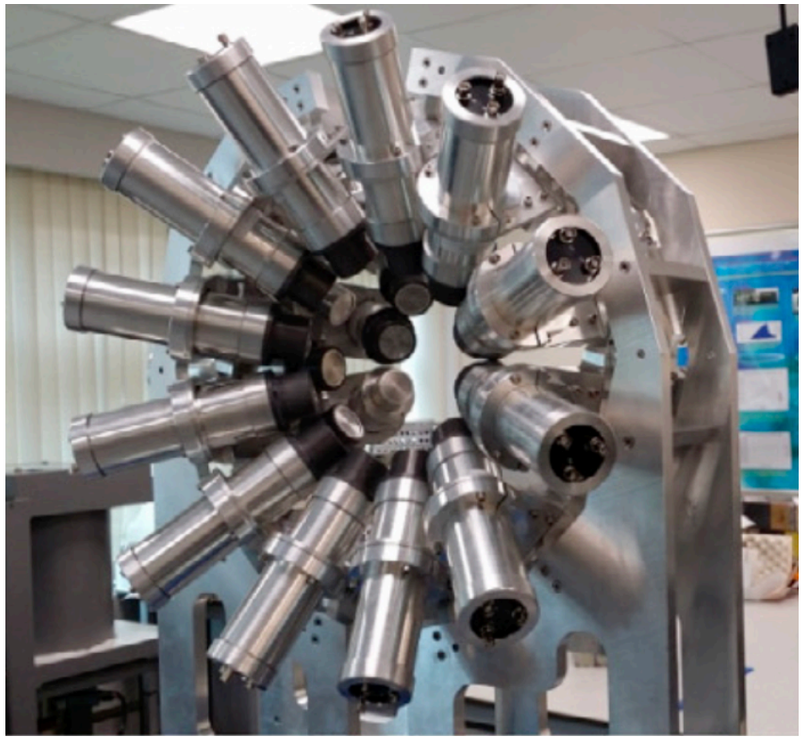
Shape evolution and new isomer in N ~ 60 neutron-rich Se Isotopes
Q. Zeng, H. Watanabe, Z. Liu et al.

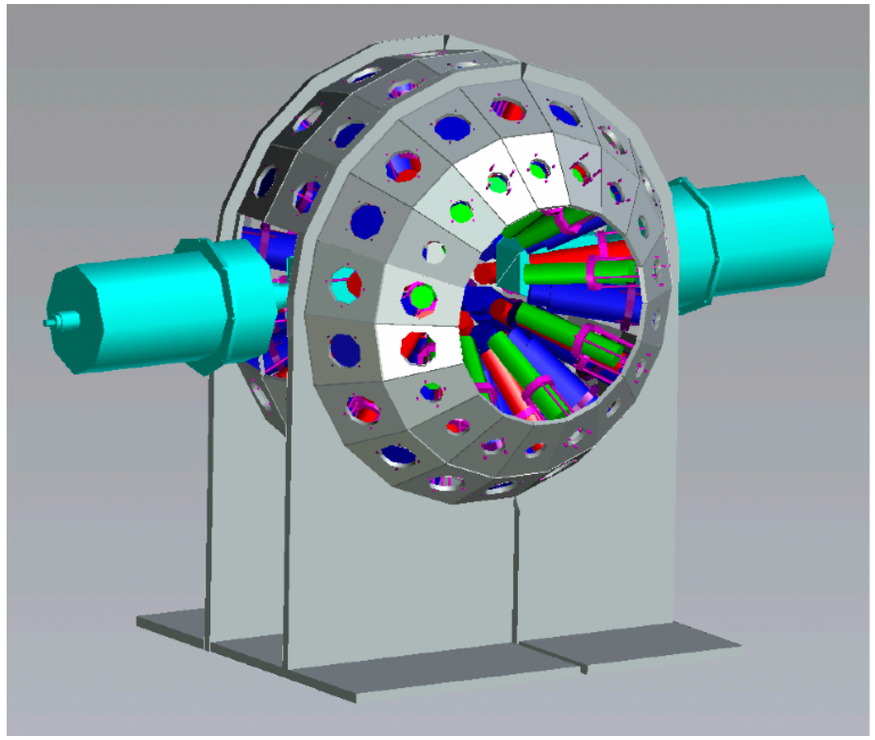
Locating the center of the N = 40 island of inversion
B. Olaizola, K. Wimmer et al.

13 proposals with various physics cases were submitted.
Stay tuned! (2 proposals as spokesperson, 6 proposals as co-spokesperson)

Summary

- Essential to measure the lifetimes of the excited state in nuclei to understand nuclear structure
- Fast-timing array composed of the $LaBr_3(Ce)$ detectors is one of the optimal measurements.
- The IDATEN project will be carried out at RIBF, RIKEN by combining FATIMA and KHALA.



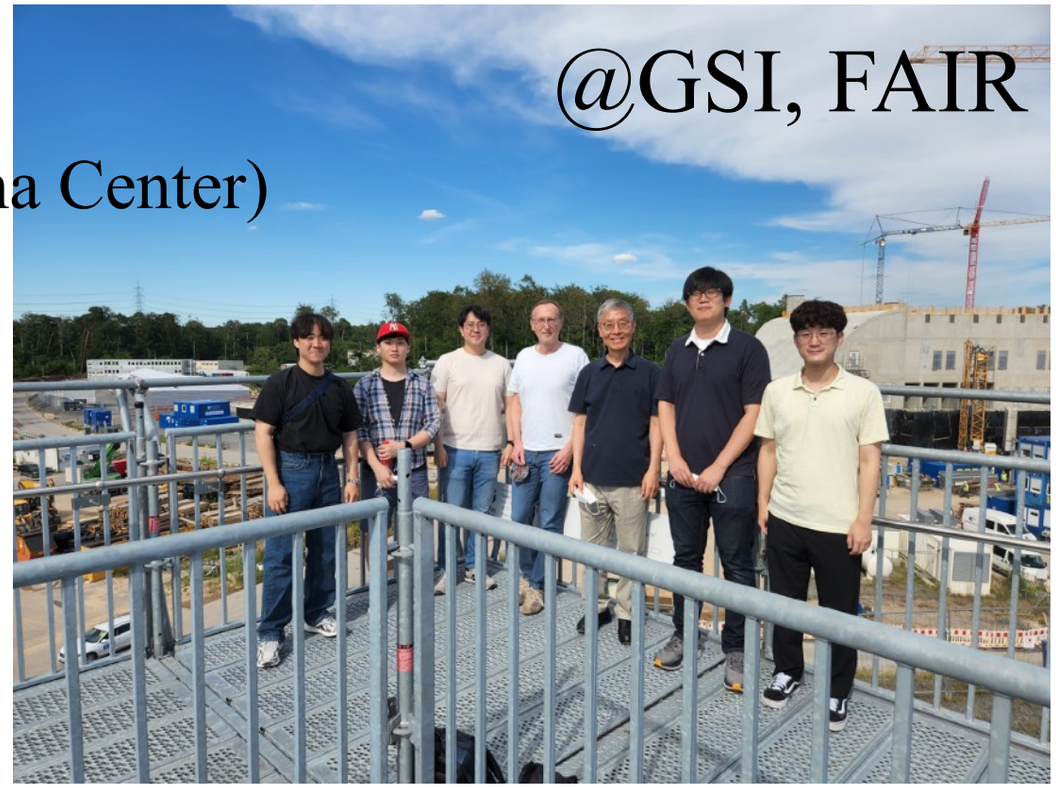


Collaborators

- Spokespersons
  Hiroshi Watanabe (Beihang U., RIKEN Nishina Center)
  Patrick H. Regan (U. of Surrey)
  Byul Moon (CENS/IBS)

- Core members
  Byungsik Hong, Youngseub Jang, Jaehwan Lee (KU, CENuM)
  Sunghoon Ahn, Sunghan Bae, Yung Hee Kim, Joochun Park (CENS/IBS)
  Sorin G. Pascu, Zsolt Podolyak (U. of Surrey)
  Alison Bruce (U. of Brighton)
  Shunji Nishimura, Vi H. Phong (RIKEN Nishina Center)

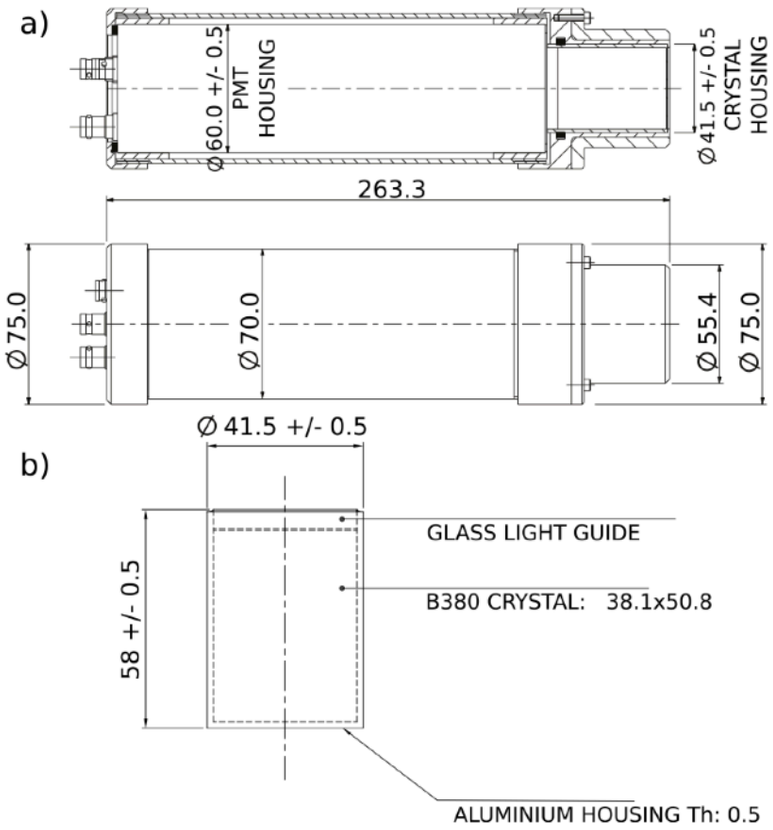
Thank you for your attention!



Backup slides

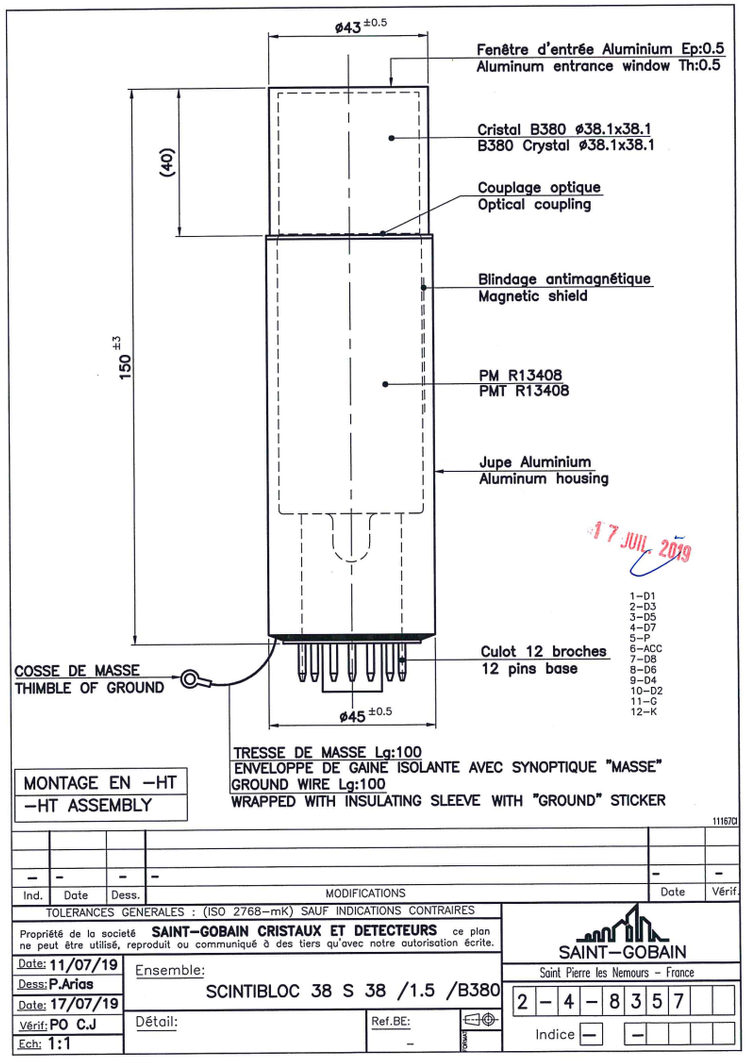
Detector module

FATIMA



M. Rudigier *et al.*, NIMA **969**, 163967 (2020)

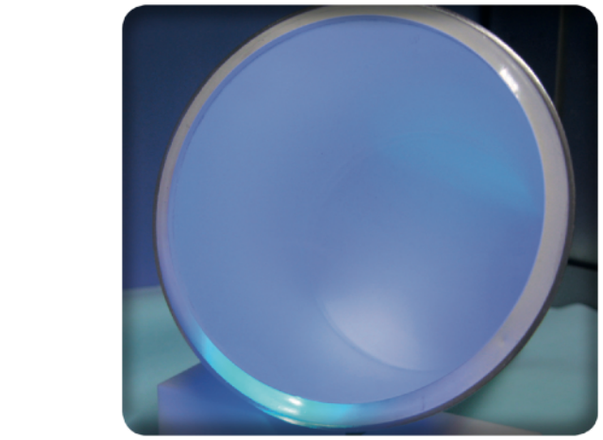
KHALA



- Both crystals are procured from Saint-Gobain. (B380)
- PMTs are from Hamamatsu, but different models and diameters.
- FATIMA is composed of individual crystal and PMT while they are combined in KHALA.

Specification of $LaBr_3(Ce)$ crystal

Scintillator	Light Yield (photons/keV)	1/e Decay time t(ns)	F.O.M. √(t/LY)	Wavelength of maximum emission λm (nm)	Refractive index at λm	Density (g/cm³)	Thickness (cm) for 50% attenuation (662keV)
NaI(Tl)	38	250	2.6	415	1.85	3.67	2.5
BrilLanCe™ 350	49	28	0.8	350	~1.9	3.85	2.3
BrilLanCe™ 380	63	16	0.5	380	~1.9	5.08	1.8
BaF2	1.8	0.7	0.6	~210	1.54	4.88	1.9
PreLude™ 420	32	41	1.1	420	1.81	7.1	1.1
BGO	9	300	5.8	480	2.15	7.13	1.0



- The $LaBr_3(Ce)$ scintillator crystal is BrilLanCe380 from Saint-Gobain.
- Excellent light yield, decay time, and density.
- Diameter: 1.5 inch / Height: 1.5 inch for KHALA
- Problem of self radioactivity

Specification of R13408 PMT

Type No.	Spectral response		Ⓐ	Ⓑ	Ⓒ	Maximum ratings		Anode to cathode supply voltage	Cathode characteristics			
									Luminous		Blue sensitivity index (CS 5-58) Typ.	Ⓓ Radiant
	Range (nm)	Peak wavelength (nm)	Photo-cathode material	Window material	Dynode structure / Stages	Supply voltage between anode and cathode (V)	Average anode current (mA)	(V)	Min. (μA/lm)	Typ. (μA/lm)		Typ. (mA/W)
R13478	300 to 650	420	BA	K	L/8	1750	0.1	1500	70	95	10.0	80
R13449	300 to 650	420	BA	K	L/8	1750	0.1	1500	70	95	10.0	80
R13408	300 to 650	420	BA	K	L/8	1750	0.1	1500	70	95	10.0	80
R13089	300 to 650	420	BA	K	L/8	1750	0.1	1500	70	95	10.0	80

NOTE: Ⓐ BA: Bialkali Ⓑ K: Borosilicate glass Ⓒ L: Linear-focused
Ⓓ Measured at the peak sensitivity wavelength.

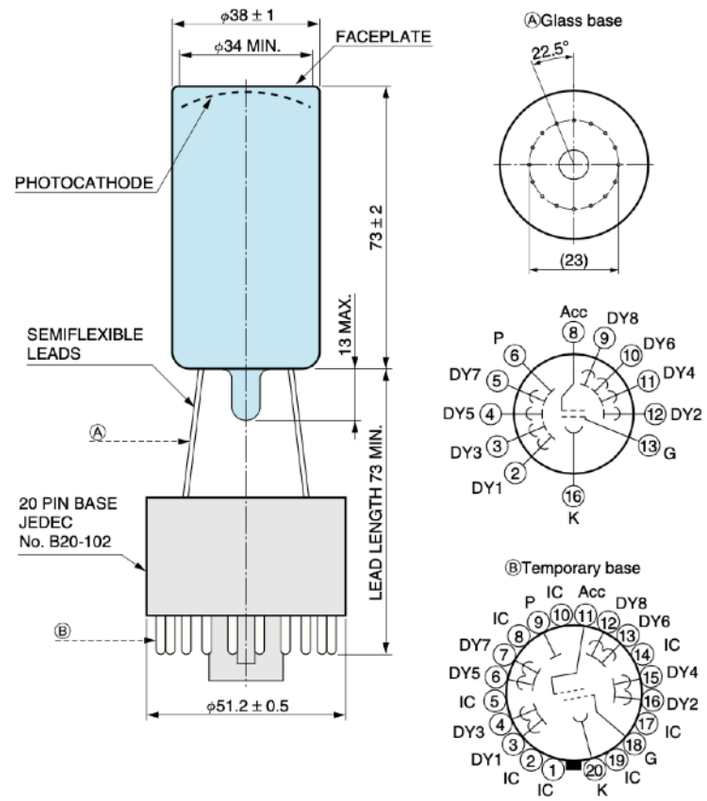
Anode characteristics								Pulse linearity		Storage temperature	Operating ambient temperature	Type No.
Luminous	Radiant	Gain	Dark current (After 30 min)		Time response							
					Rise time	Transit time	T.T.S. (Transit Time Spread) (FWHM)	±2 % deviation	±5 % deviation			
Typ. (A/lm)	Typ. (A/W)	Typ.	Typ. (nA)	Max. (nA)	Typ. (ns)	Typ. (ns)	(ps)	(mA)	(mA)	(°C)	(°C)	
50	4.2×10^4	5.3×10^5	3	30	0.9	9.1	130	10	25	-80 to +50	-30 to +50	R13478
50	4.2×10^4	5.3×10^5	3	30	0.9	10	170	10	30	-80 to +50	-30 to +50	R13449
50	4.2×10^4	5.3×10^5	3	30	1.2	13	190	20	50	-80 to +50	-30 to +50	R13408
30	2.5×10^4	3.2×10^5	10	50	2.0	20	230	30	60	-80 to +50	-30 to +50	R13089

VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrodes	K	G	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8(Acc)	P
Ratio	1.3	4.8	1.5	1.5	1	1	1	1	1	1	

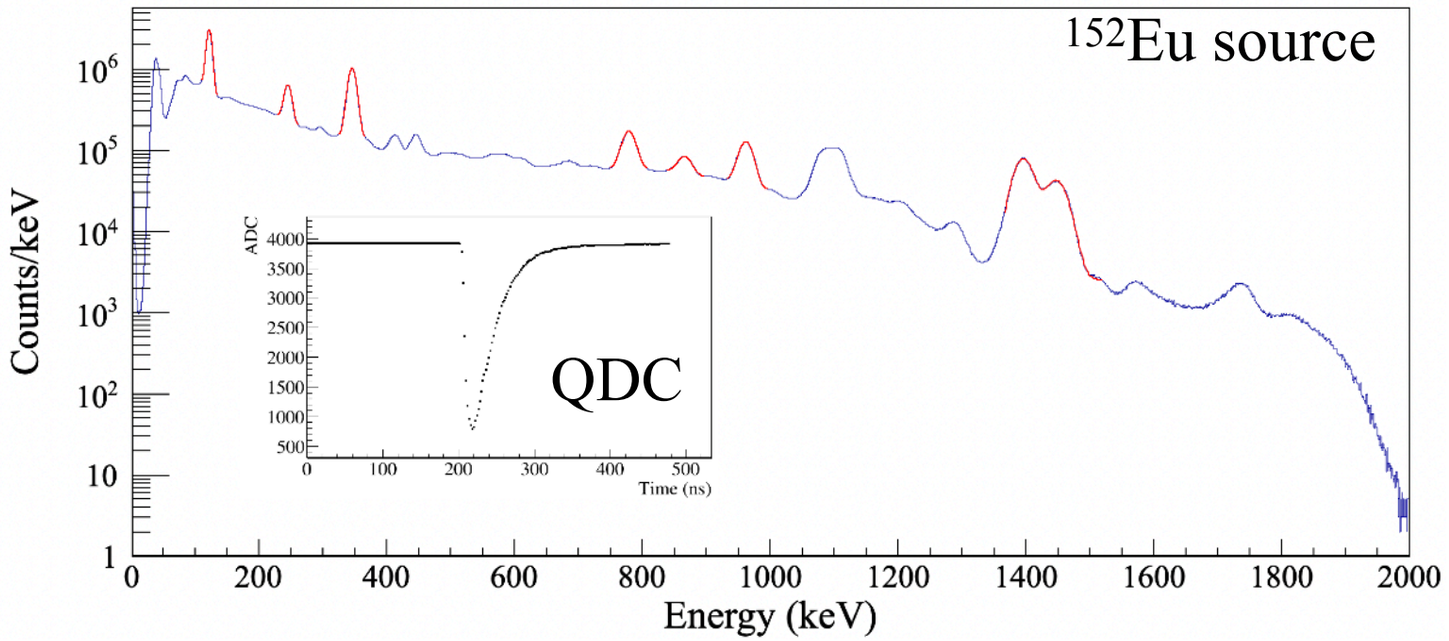
Supply voltage: 1500 V, K: Cathode, Dy: Dynode, P: Anode, G: Grid, Acc: Accelerating electrode
Acc to be connected to Dy8 with a protection resistor in series. (recommended resistance: 10 MΩ)

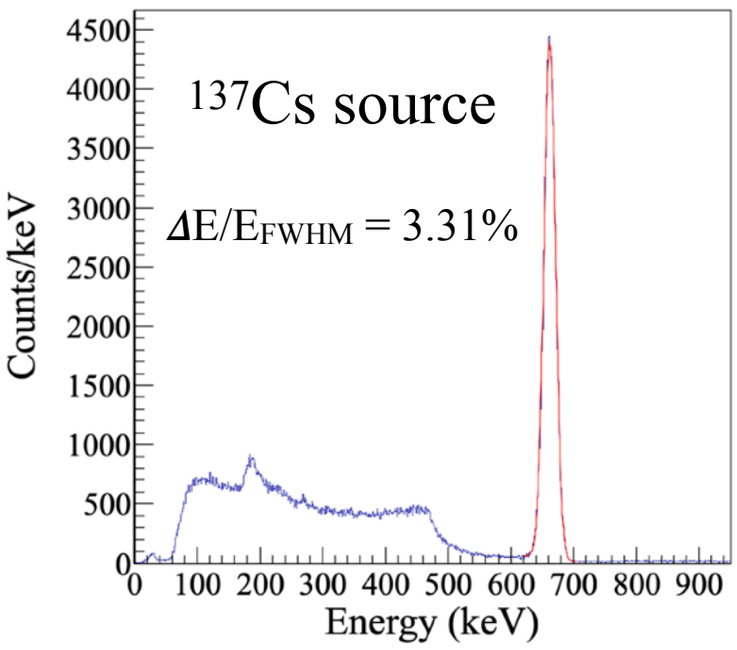
● R13408

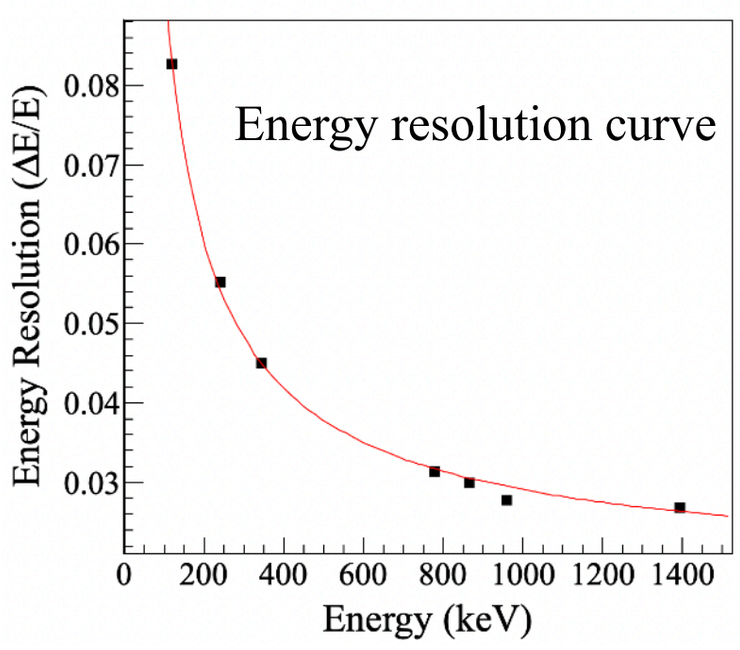


- Manufactured by Hamamatsu
- Specialized in fast-timing performance
- Diameter: 1.5 inch

Energy resolution

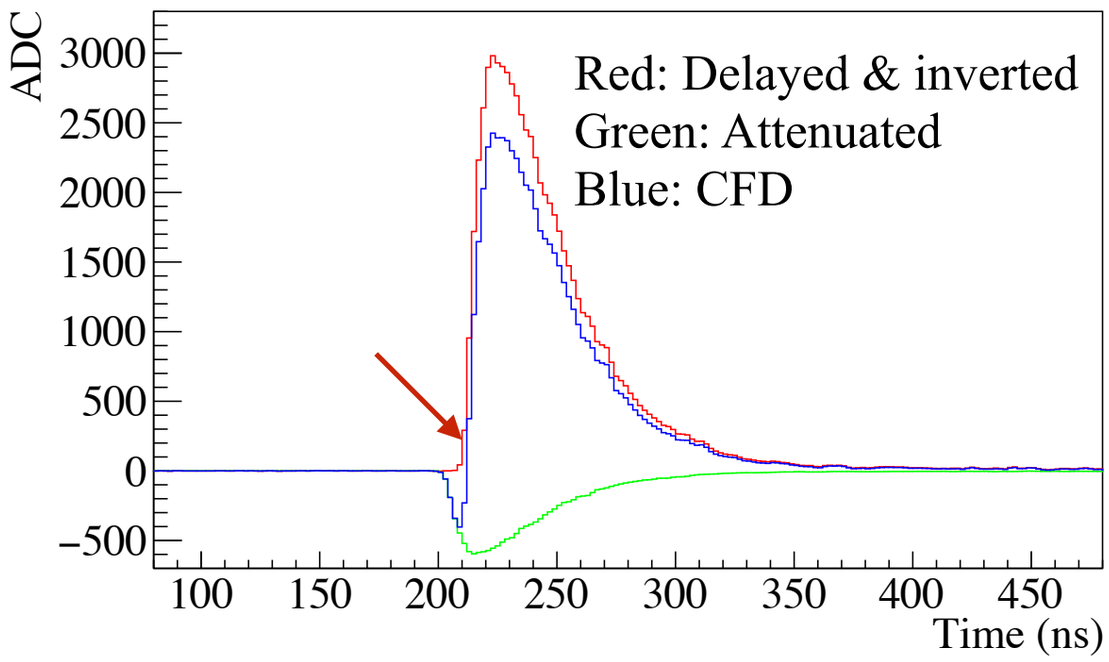


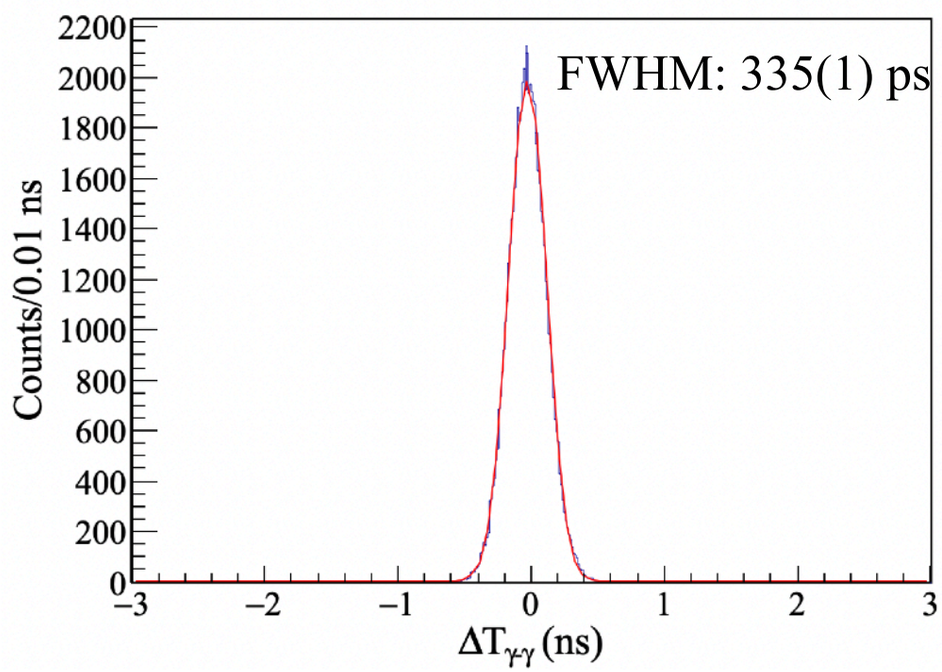




- Obtain energy information by integrating the pulse a.k.a QDC method.
- Data taken by using 12 KHALA detectors.
- Energy resolution at 662 keV: 3.31% in FWHM
- Energy resolution curve obtained from the ^{152}Eu source.

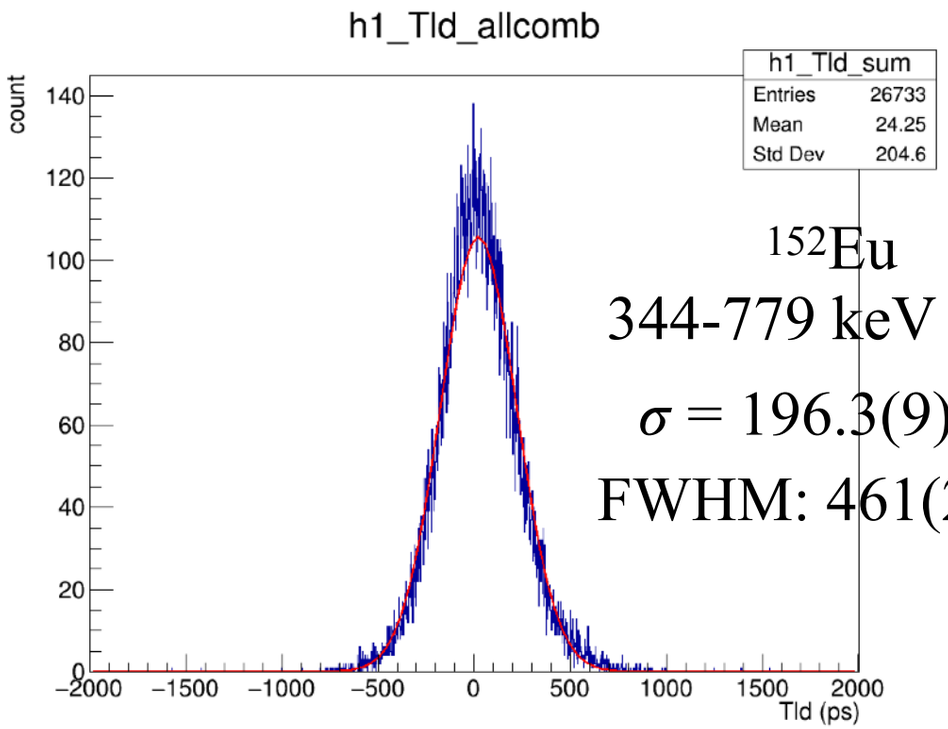
Timing resolution



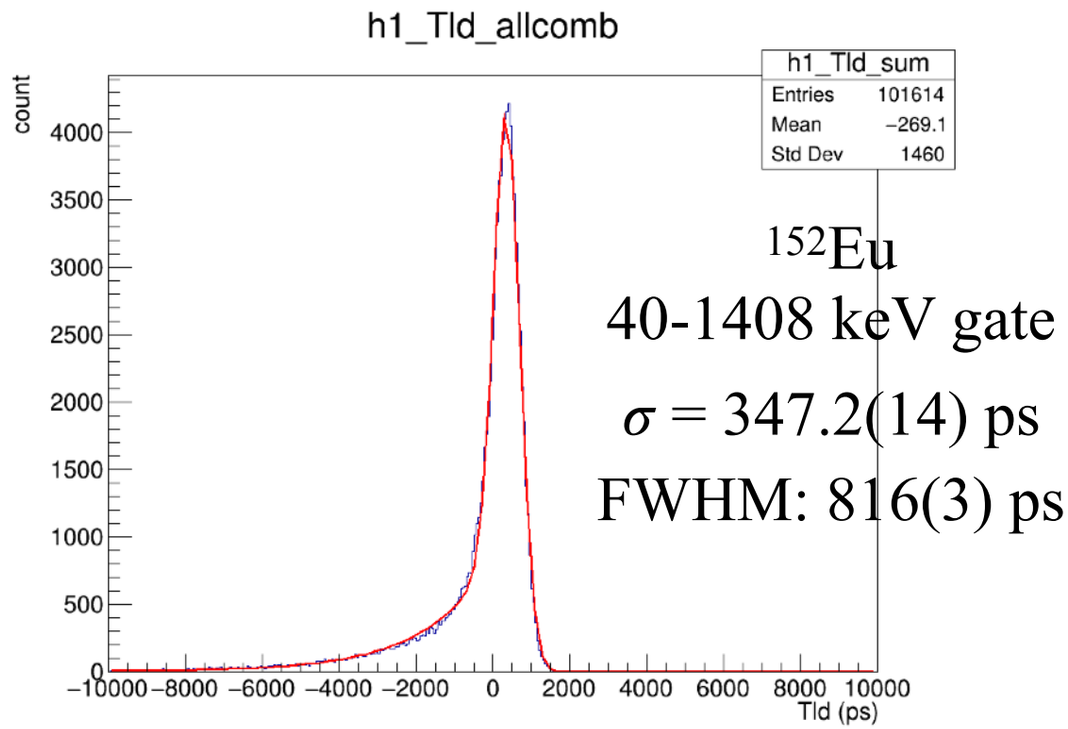


- Digital constant fraction discrimination method to obtain TDC information
- Use the offline pulse analysis.
- Data taken by using 12 KHALA detectors.
- ^{22}Na γ-ray source: 511-keV two photons
- Timing resolution of 335(1) ps in FWHM

Performances



^{152}Eu
344-779 keV gate
σ = 196.3(9) ps
FWHM: 461(2) ps



^{152}Eu
40-1408 keV gate
σ = 347.2(14) ps
FWHM: 816(3) ps

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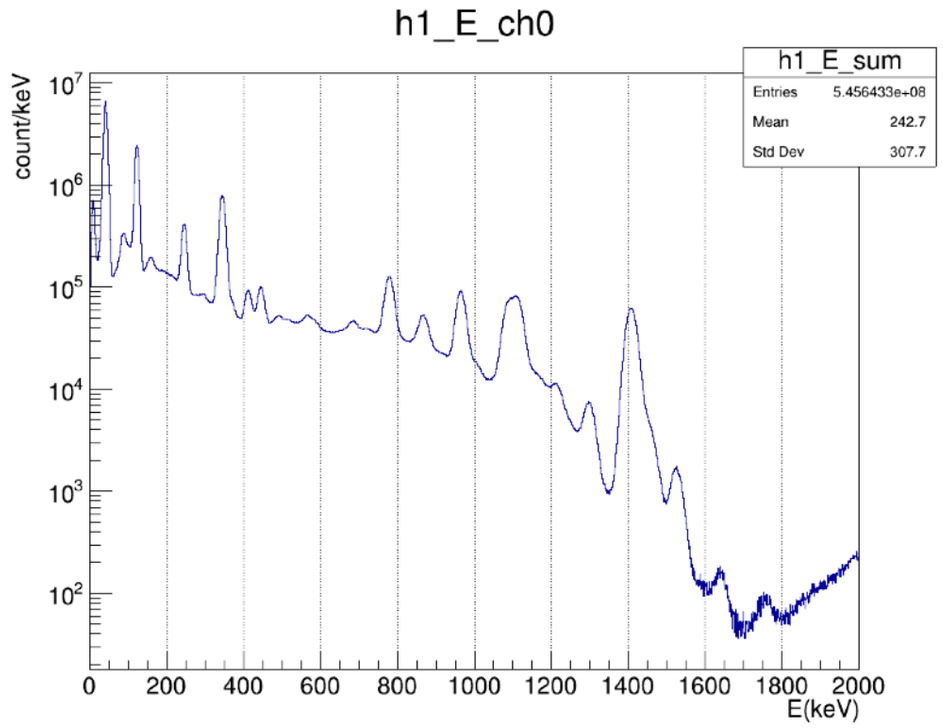
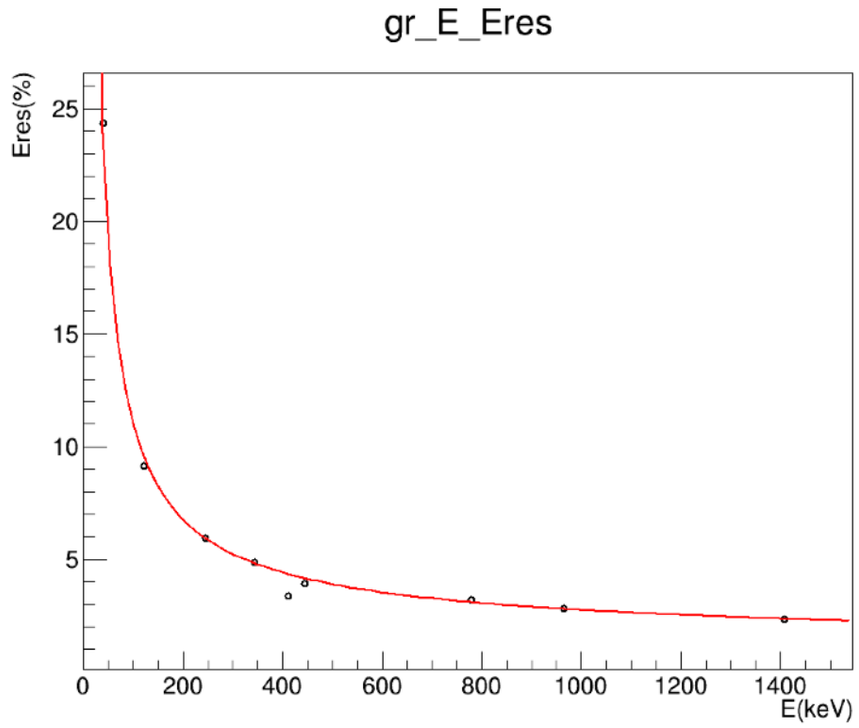
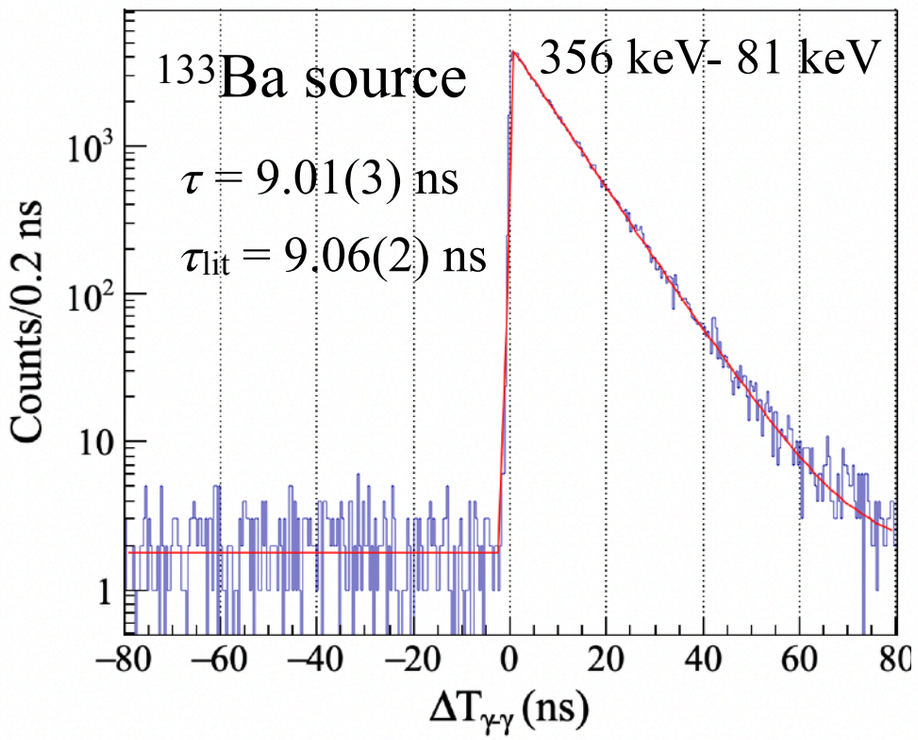
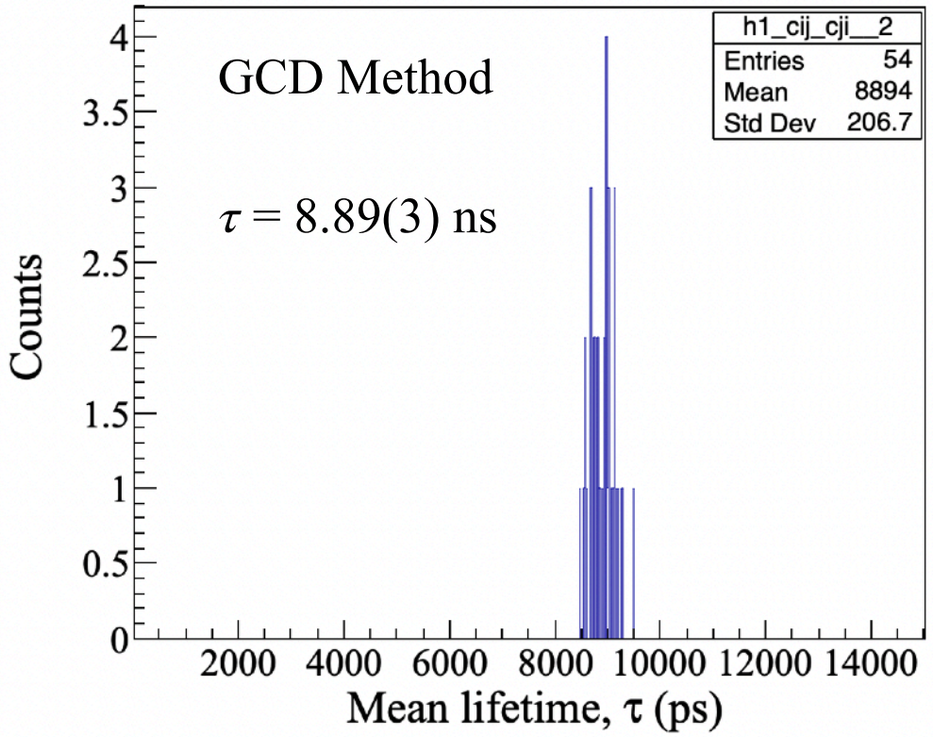
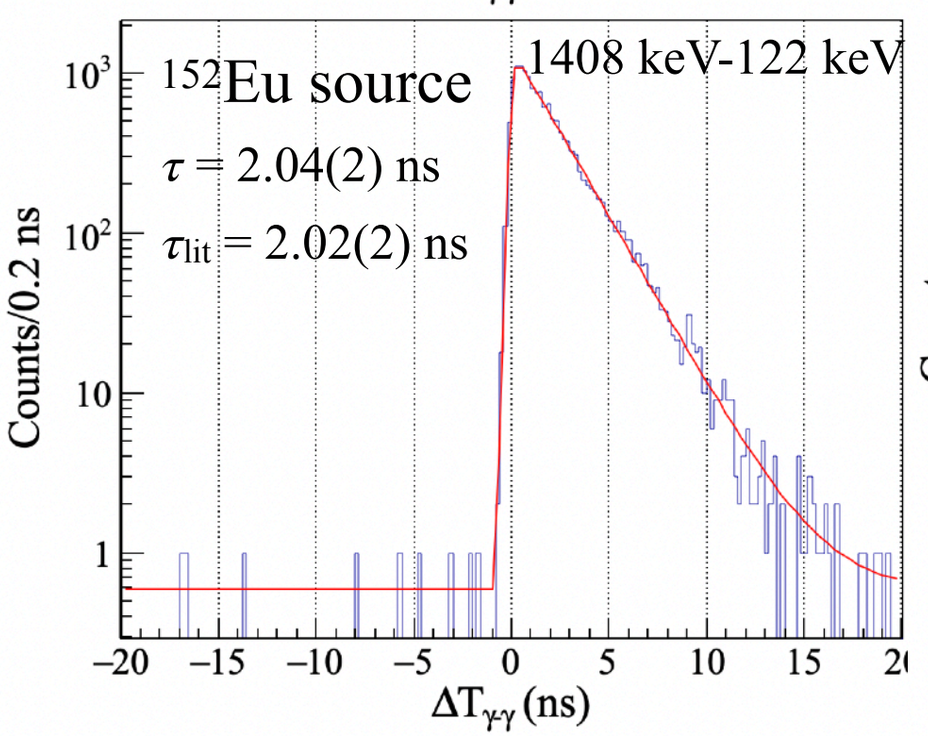


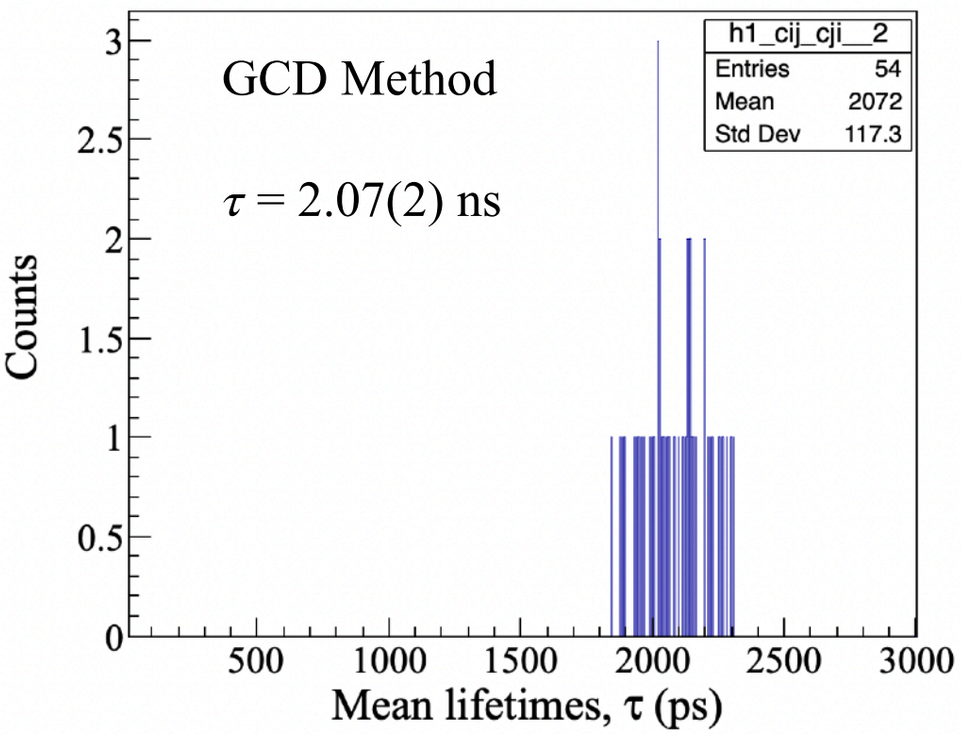


Lifetime measurement



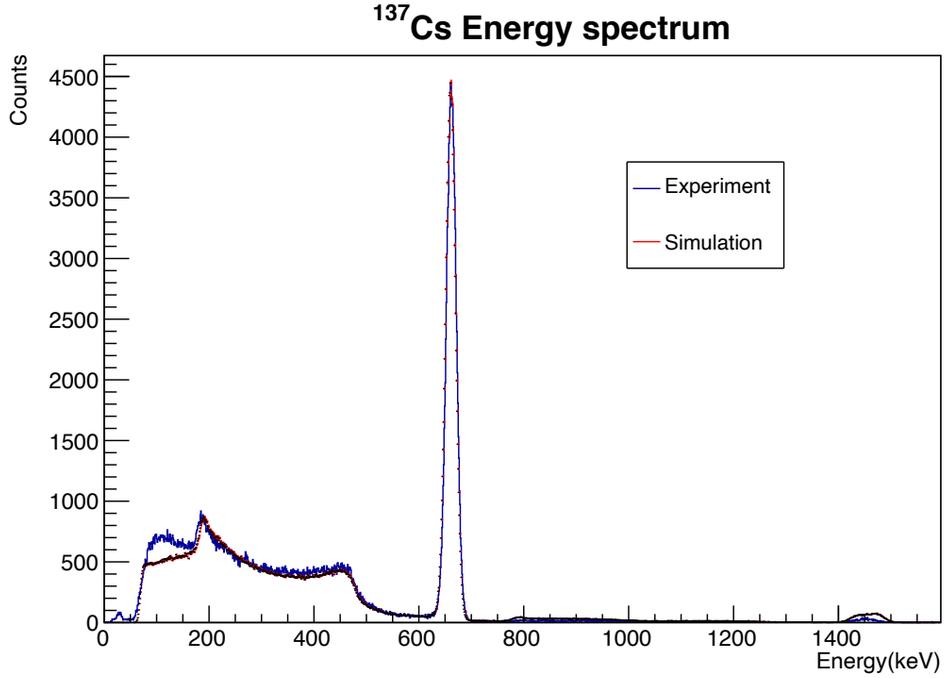


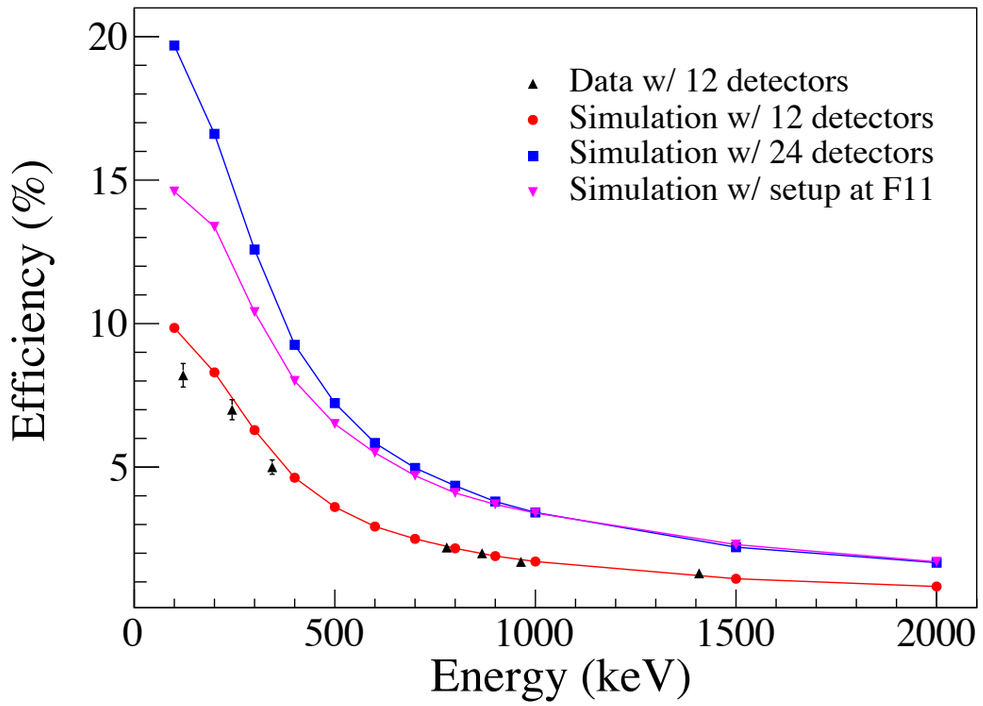




- Sufficient to deduce few nanosecond lifetime by using the convolution fit method
- Consistent results obtained by the generalized centroid difference (GCD) method

Geant4 simulation





- Geant4 simulation has been performed with the bench test setting.
- Distance from the center: 10 cm
- Verified the reliability by reproducing the ^{137}Cs source spectrum.
- Checked the expected results and verified with the experimental result with the 12-unit setup.
- Plan to examine the detection efficiency for the full system (36 units) with new electronics system.