Decay experiments and techniques at fragmentation facilities

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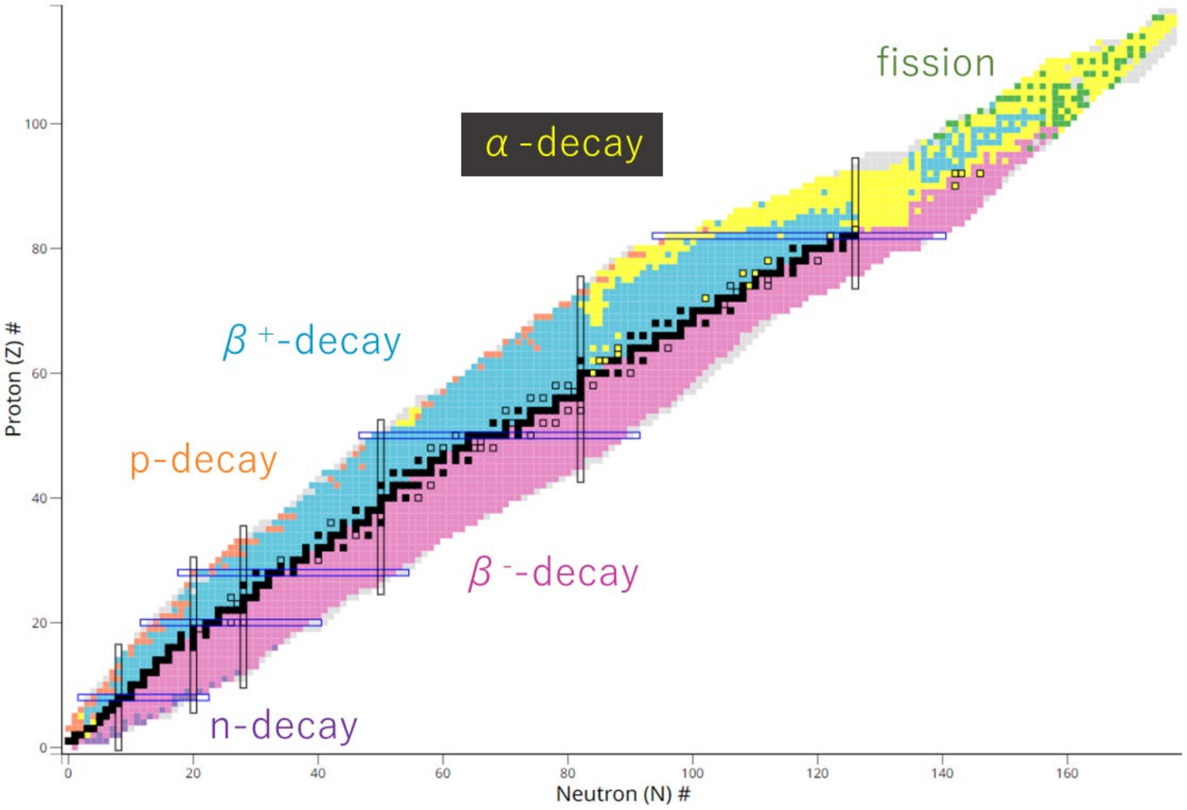
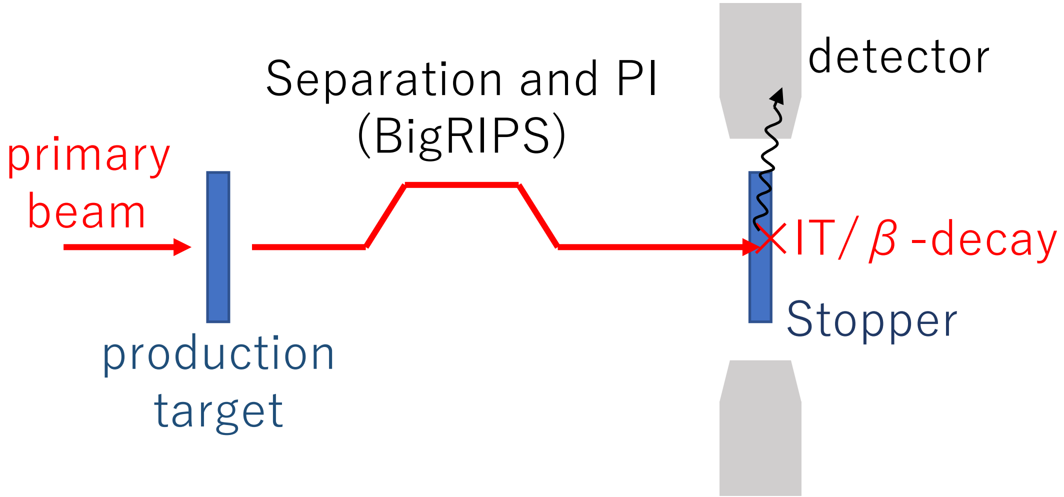
Contents

- Overview of decay spectroscopy at RIBF
- Study of β-delayed neutron emission
- New scintillator material for active stoppers
- Utilization of Apache Spark for efficient β-implant correlation analysis

Decay spectroscopy



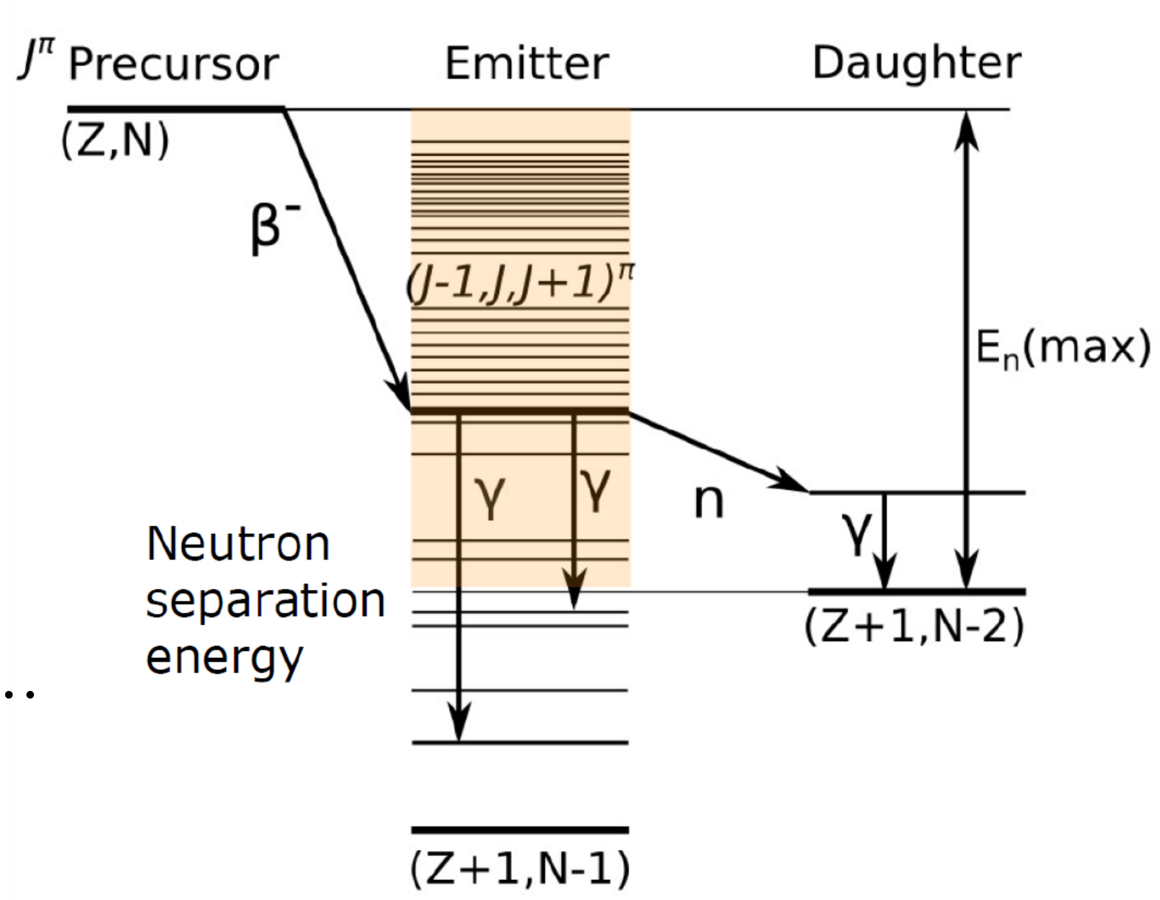


- Most of the atomic nuclei except for stable ones decay.
- 100% of the stopped nuclei decay
- Feasible on very exotic isotopes with a limited yield (from 100 counts).
- β -decay Q-values increase as N goes away from stable isotope.

- β -decay spectroscopy is a useful tool to study nuclear structure of very exotic nuclei
- Important information for astrophysical r-process calculation

Decay measurements

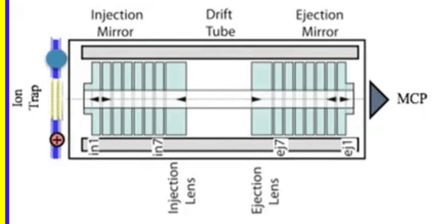
- Half-lives
- α / protons
  - Q values
- β rays
  - Energy (continuum) shape factor
- Delayed γ rays
  - Singles, γ - γ , Total absorption,…
- Delayed particles
  - Energy spectrum
  - Branching ratio



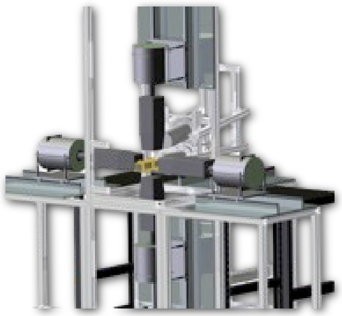
Decay Experiments at RIBF

ZeroDegree Program
Decay
Mass
In-beam
Interaction cross-section

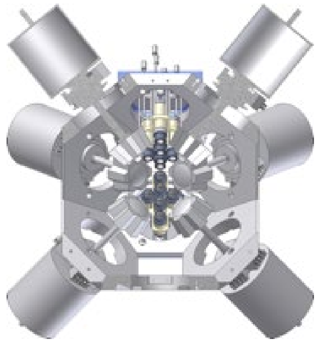
MR-TOF



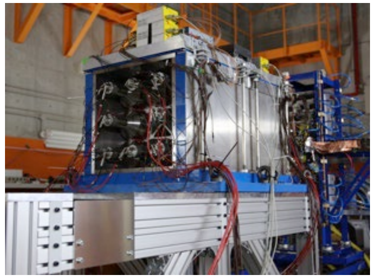
① beta-gamma spectroscopy



(2009)

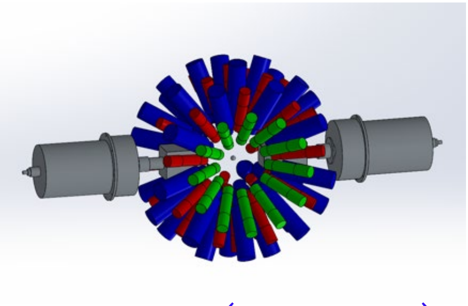


EURICA (2012 - 2016)



DTAS (2018 -)

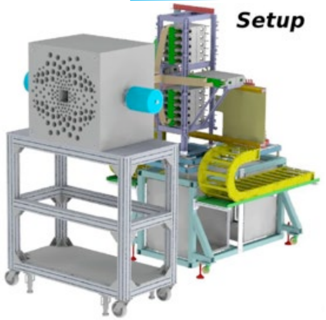
Total absorption spectroscopy



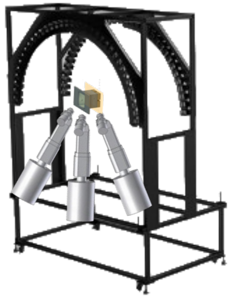
IDATEN (2024 -)

Lifetime of excited states

② beta-gamma-neutron spectroscopy



BRIKEN (2017 - 2021)



CAITEN II (2024-)

Other experiments

- VANDLE: β-delayed n spectroscopy of 78Ni region
- RIBF168: Super allowed α-decay of ^{104}Te
- RIBF104: Two-proton decay of ^{54}Zn
- SHARAQ03: Mass and p-decay of 45Fe region

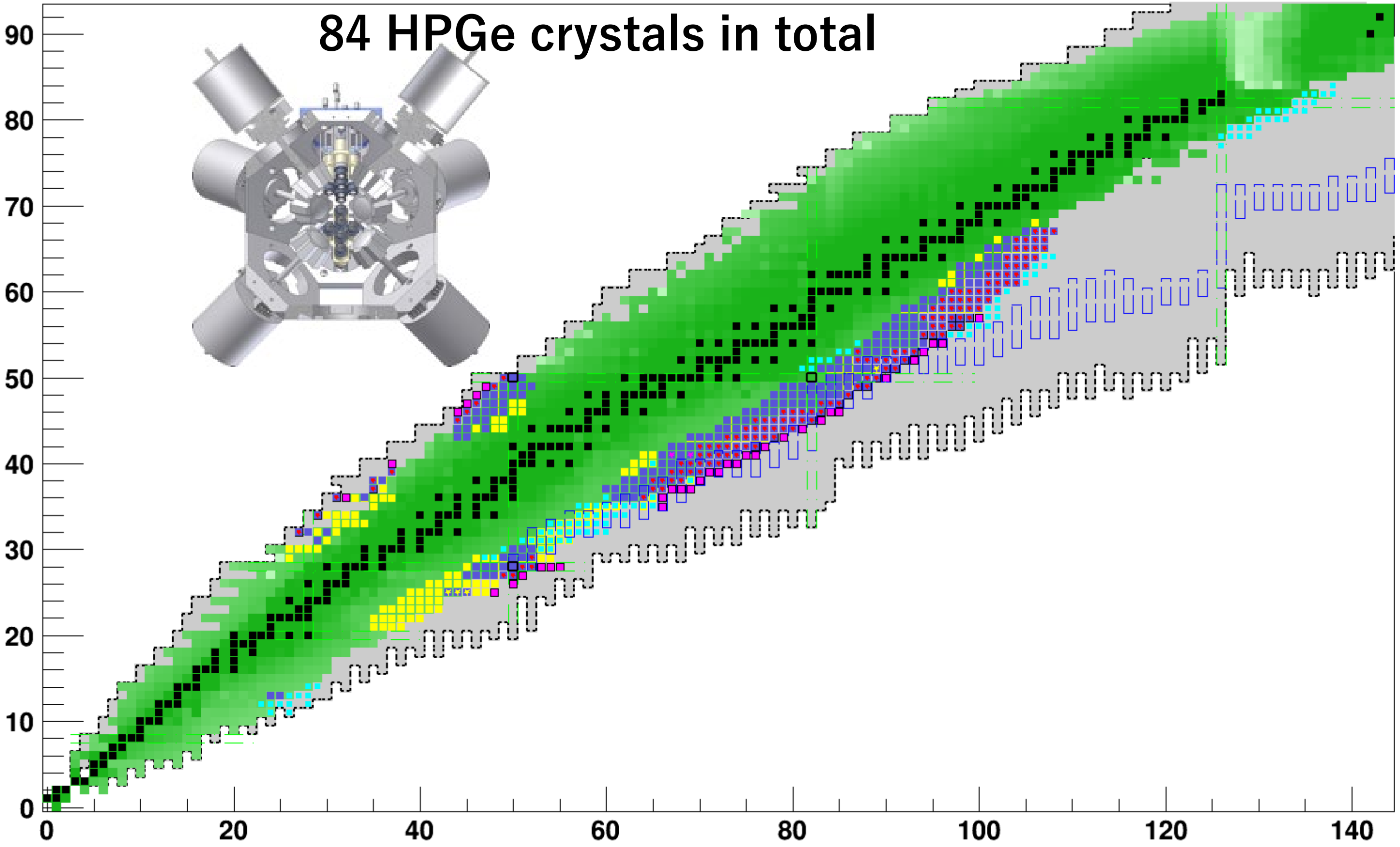
etc.

EURICA project (EUroball Riken Cluster Array)

Significant supports from GSI, GAMMAPOOL, ibs, and RIKEN Nishina Center

77 papers
- 16 in Phys. Rev. Lett.
- 16 in Phys. Lett. B
- 4 Phys. Rev. C (R)
- 35 Phys. Rev. C
- 3 EPJ
- 2 PTEP
- 1 JPSJ

EURICA (2012 - 2016)



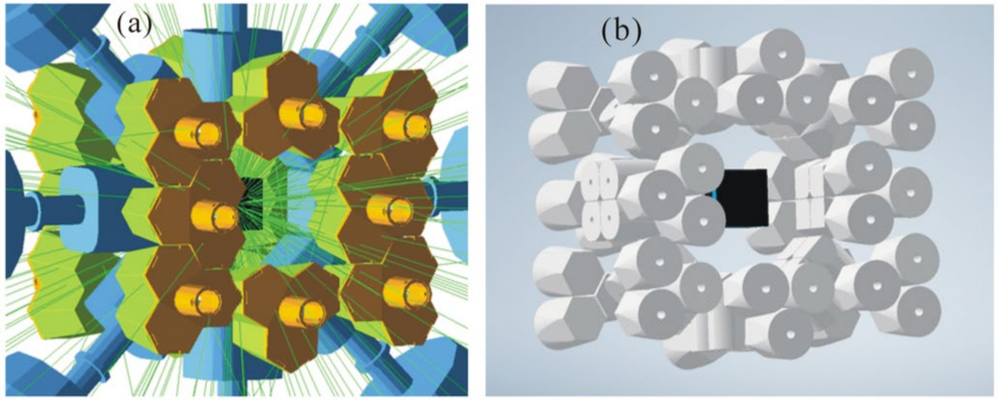
- New Isotopes: 63 (+9)
- New Half-Lives : 150 (+16)
- Half-Lives (updated): 315 (+60)

★	★
New P_{1n}: 4	updated: 6 (+ 2)
New P_{2n}: 1	updated: 1
New P_{1p}: +1	updated: +15
New P_{2p}: 1	updated: 1

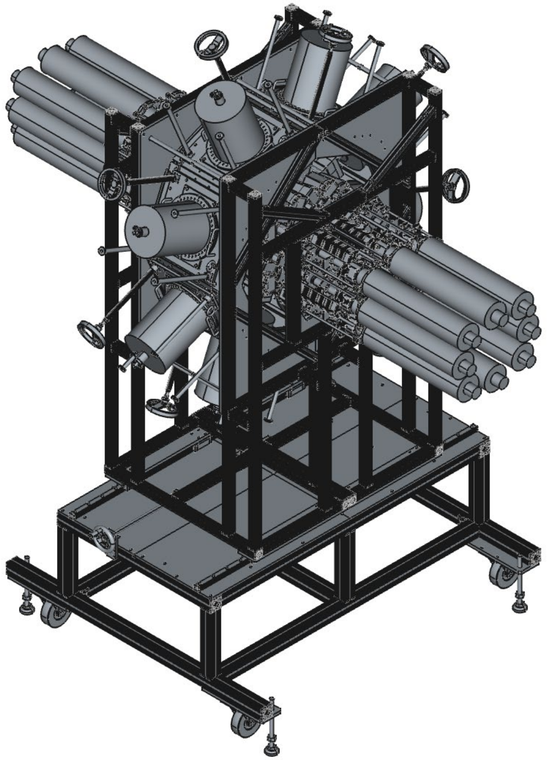
Many new β-γ and isomer spectroscopy Data were obtained

C2URIE (Clover and Cluster Units for the RIBF's Implantation Experiments)

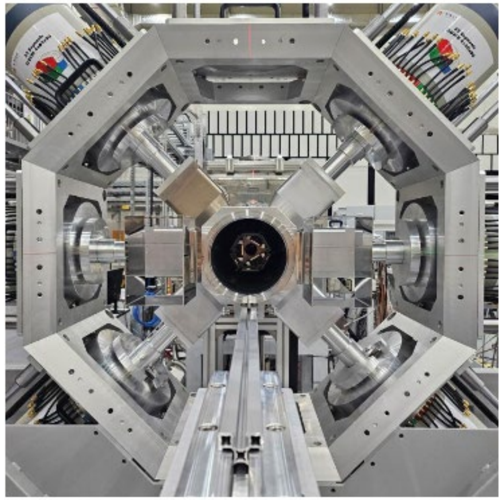
16 DEGAS cluster from GSI
Suer-Clovers from CENS and IMP



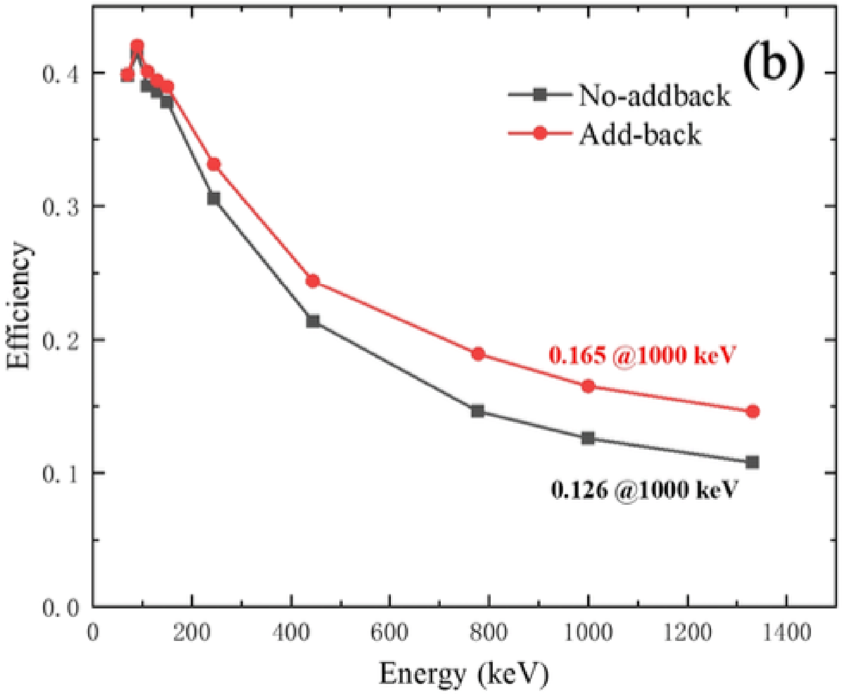
☑ High efficiency detector: 16.5 % @ 1000 keV (x 1.7)
☑ Digital electronics with self-trigger
☑ Minimum dead-time for short-lived isomers



Decay station frame @ RAON



Simulated γ-ray efficiency



Upgrades from the EURICA Project

◯ Primary Beam Intensity

^{78}Kr ... 30pnA → 500 ~ 690 pnA (x 20)
^{124}Xe ... 20 pnA → 140 ~ 173 pnA (x 7)
^{238}U ... 5 ~ 15 pnA → 70 ~ 100 pnA (x 15)

◯ Newly Available Beams

^{70}Zn ... 500 ~ 826 pnA
^{208}Pb? ... Unknown (~100 pnA)

◯ PID capability

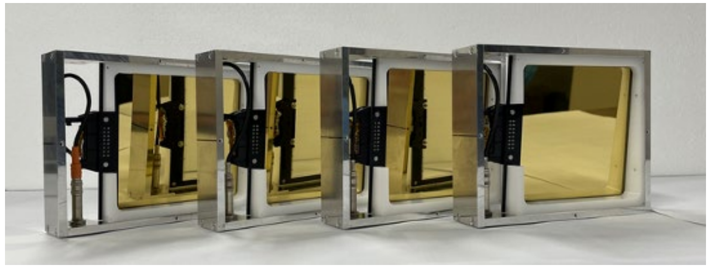
Two stage separation (F1-F3, F3-F7)

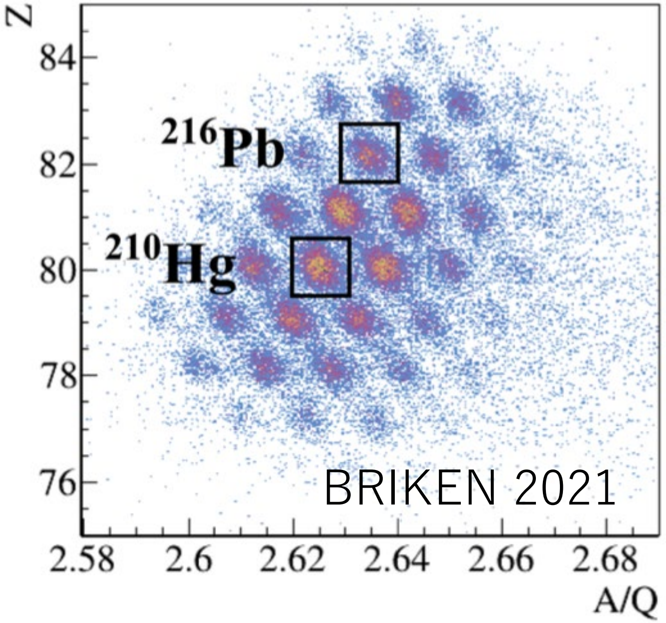
- Diamond detectors
- Xe-filled ionization chamber
- DAQ upgrades (MPV, digitizers, etc.)

For higher rate at F3

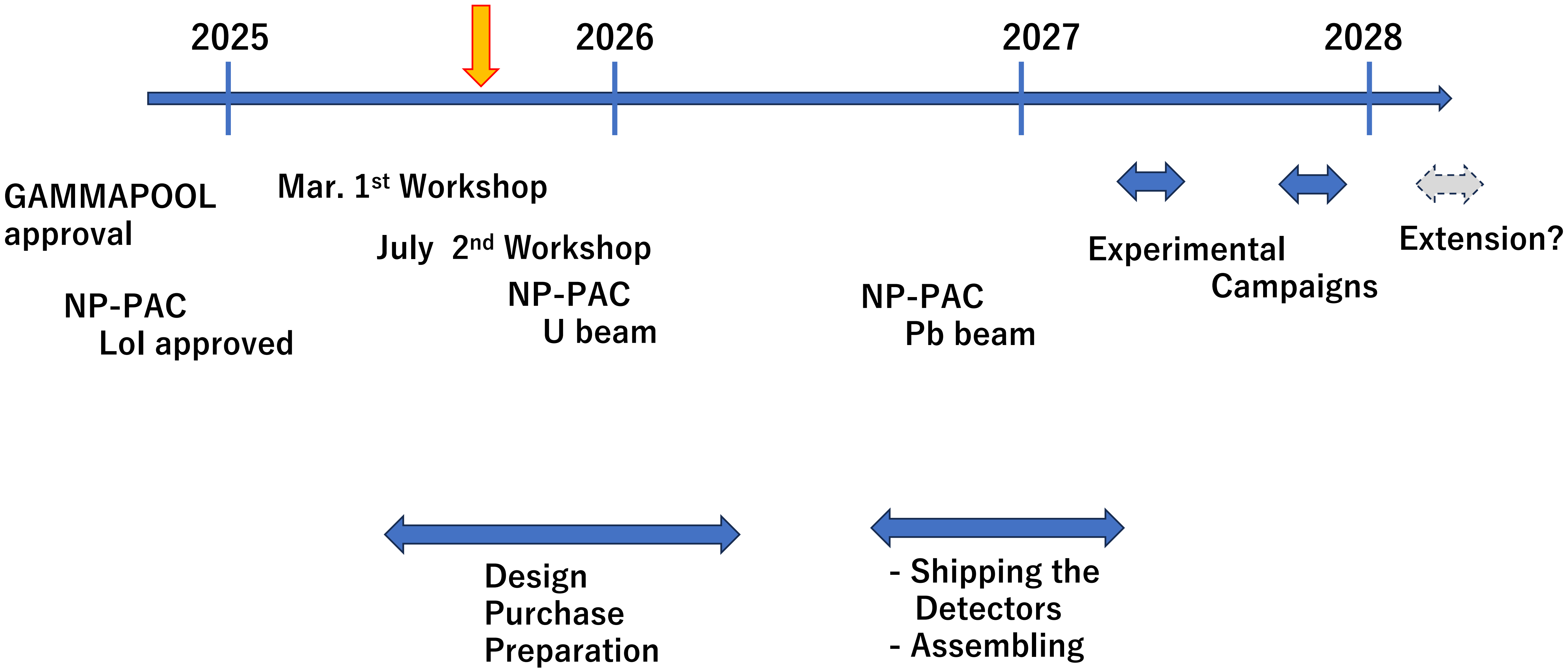
heavy/neutron-deficient region

Active stopper for Heavy region





Tentative Schedule (C2URIE)



https://ribf.riken.jp/C2URIE/

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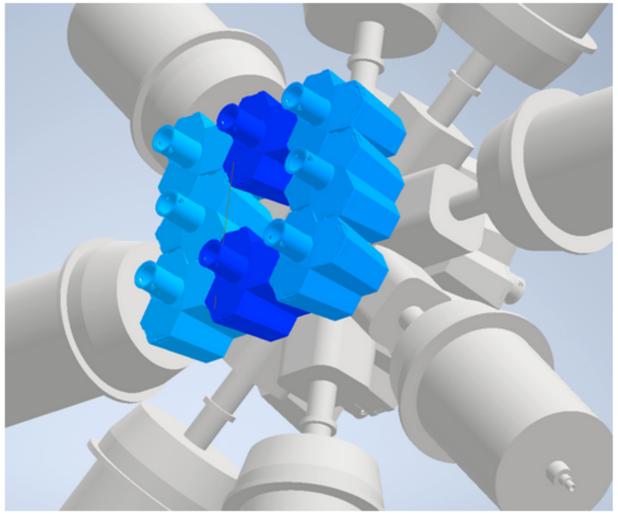
Welcome to our new website C2URIE!

C2URIE (Clover and Cluster Units for the RIBF's Implantation Experiments)



Following the success of the EURICA (Euroball-RIKEN Cluster Array) experiments, which were carried out from 2012 to 2016, we are now looking ahead to the next phase of decay spectroscopy at RIBF. Currently, a new array is in the planning, composed of 8 Clover detectors from CENS and IMP Lanzhou, along with up to 16 DEGAS detectors from the HISPEC/DESPEC project of FAIR, including GAMMAPOOL germanium capsules. This array will provide enhanced efficiency and open new avenues for research in nuclear structure and astrophysics, using the world's strongest radioactive ion beams. The array will feature about 20 % efficiency at 1 MeV, and it is envisaged that experiments will take place in 2026 and 2027.

Supported by Grant-in-Aid for Transformative Research Area (A) (No. 25H01273).

RECENT ENTRIES

2nd C2URIE Workshop on July 28, 2025 (Zoom)

Dear Colleagues, We ...

on C2URIE Page

By Shunji Nishimura | Comments (0)

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S. Nishimura	RIKEN	Japan
K.L. Wang	IMPCAS	China
K. Wimmer	GSI	Germany

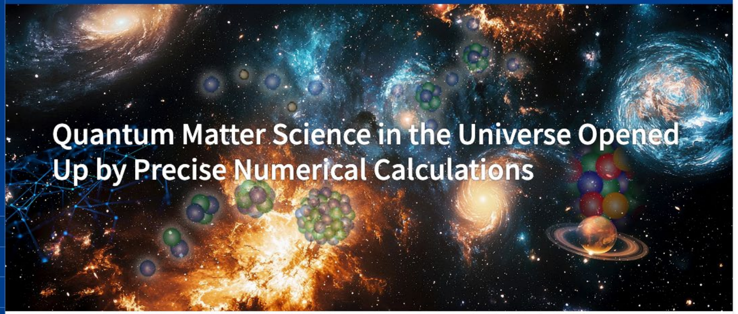
https://qm-science.org/en/

Quantum Matter Science in the Universe Opened Up by Precise Numerical Calculations

- TOP
- Introduction of this research area
- Research Groups
- Proposal of KAKENHI
- Organization
- General control group

Japanese

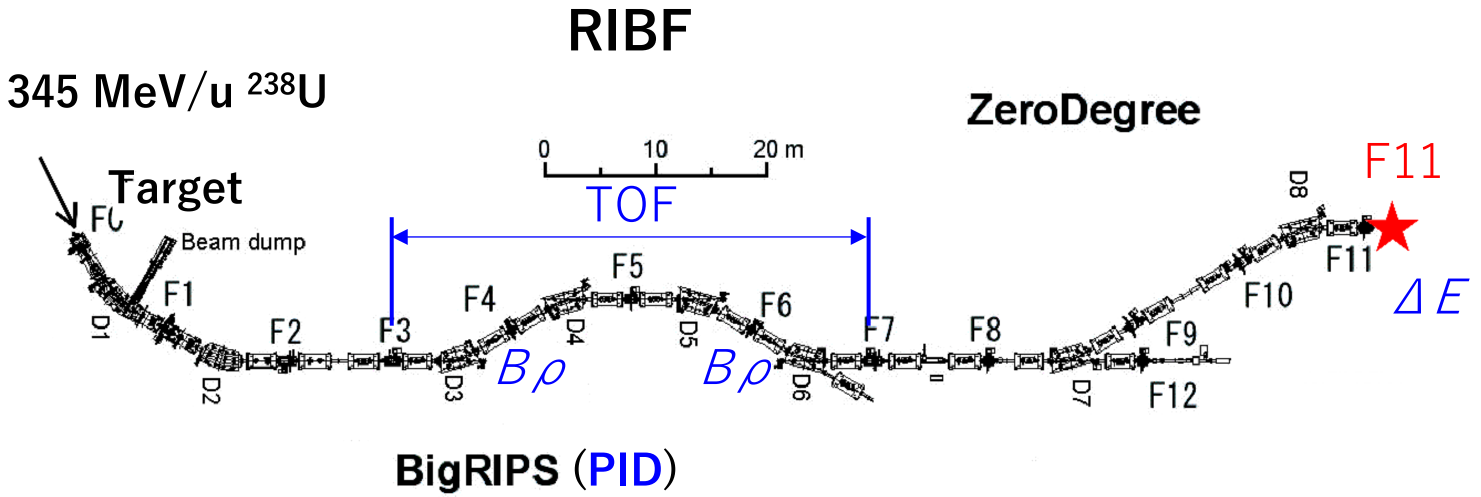
Members Only



Project overview

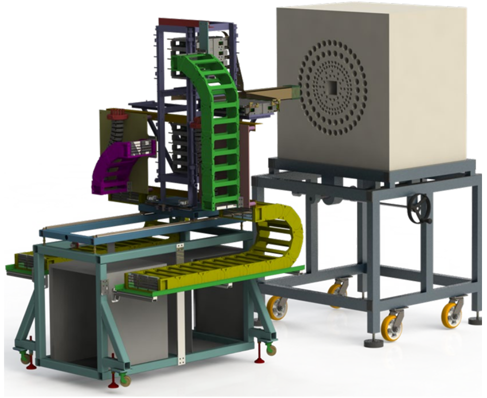
We aim to construct a “unified platform for finite quantum many-body computation” based on the infinitesimally shifted Gaussian Lobe expansion method (GEM) proposed and developed by the project leader, and to describe the formation and evolution of matter in the universe from the fundamental particle level by using this platform. The goal is to obtain precise solutions for quantum many-body systems ranging from 3 to 100 particles by unifying GEM and other computational methods. Using this platform, we try to elucidate the internal materials of neutron stars and the interstellar molecular evolution process. We work on these issues in collaboration with experiments using the J-PARC accelerator and other facilities and with ultra-precise molecular spectroscopy experiments to determine heavy particle interactions and to verify the accuracy of calculations in order to improve the predictive power of calculations. We also collaborate with experiments on heavy-element nuclei to elucidate the heavy-element synthesis process in space. In addition, as a social contribution use of the unified platform, we support the development of RIKEN’s compact

Beta-delayed neutron experiments at RIBF, RIKEN



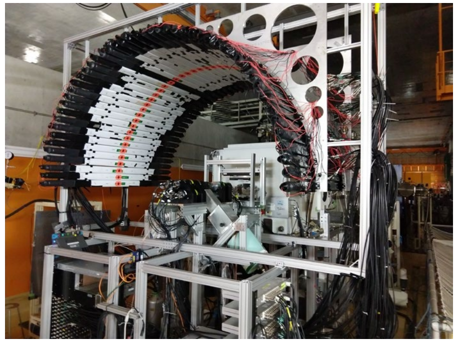
- In-flight fission of 345 MeV/u ^{238}U for production of very exotic nuclei
- ZeroDegree beamline for decay measurements

BRIKEN



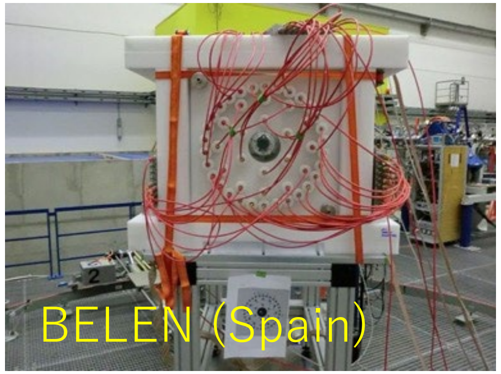
- HDPL moderator + 140 ^{3}He tubes
- High efficiency (>60% for 1MeV n)
- Pxn measurement

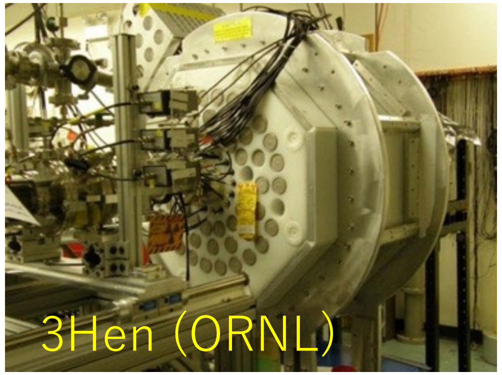
VANDLE (ToFU)

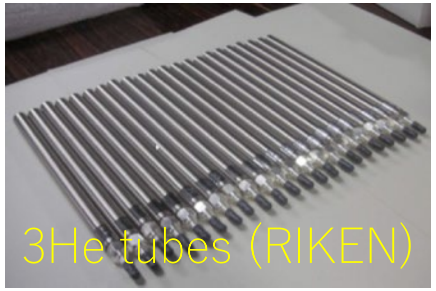


- Fast β-detector (YSO) + 48 plastic bars for ToF measurement
- Gamma-detectors
- Neutron energy spectra

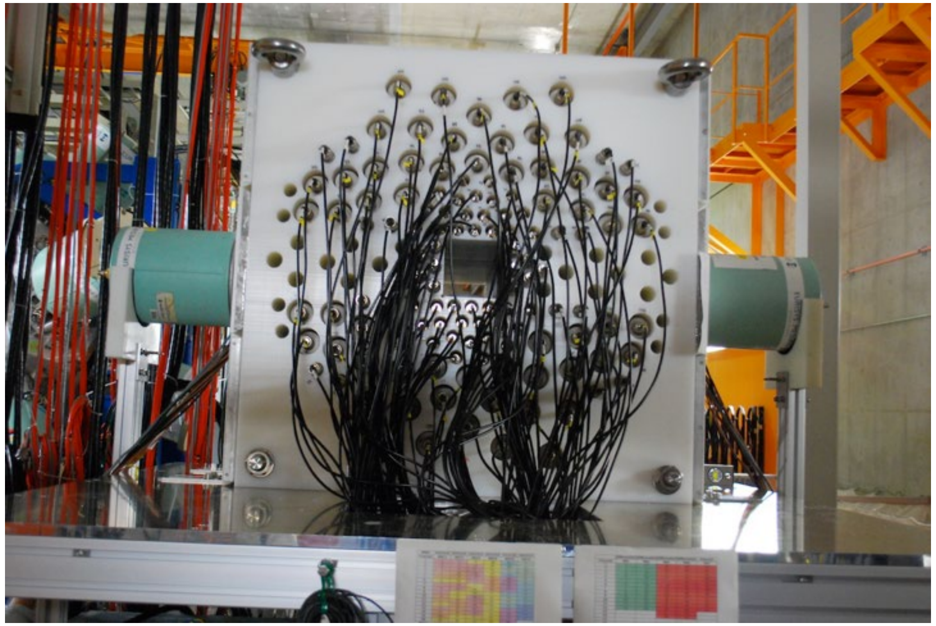
BRIKEN experiment at RIBF, RIKEN







- Implantation-decay detector array, WAS3ABi, AIDA, and YSO at F11
- Efficient neutron detection by 140 ^{3}He tubes (nearly all ^{3}He gas available for nuclear spectroscopy)
- Two ORNL clover Ge detectors for gamma-rays

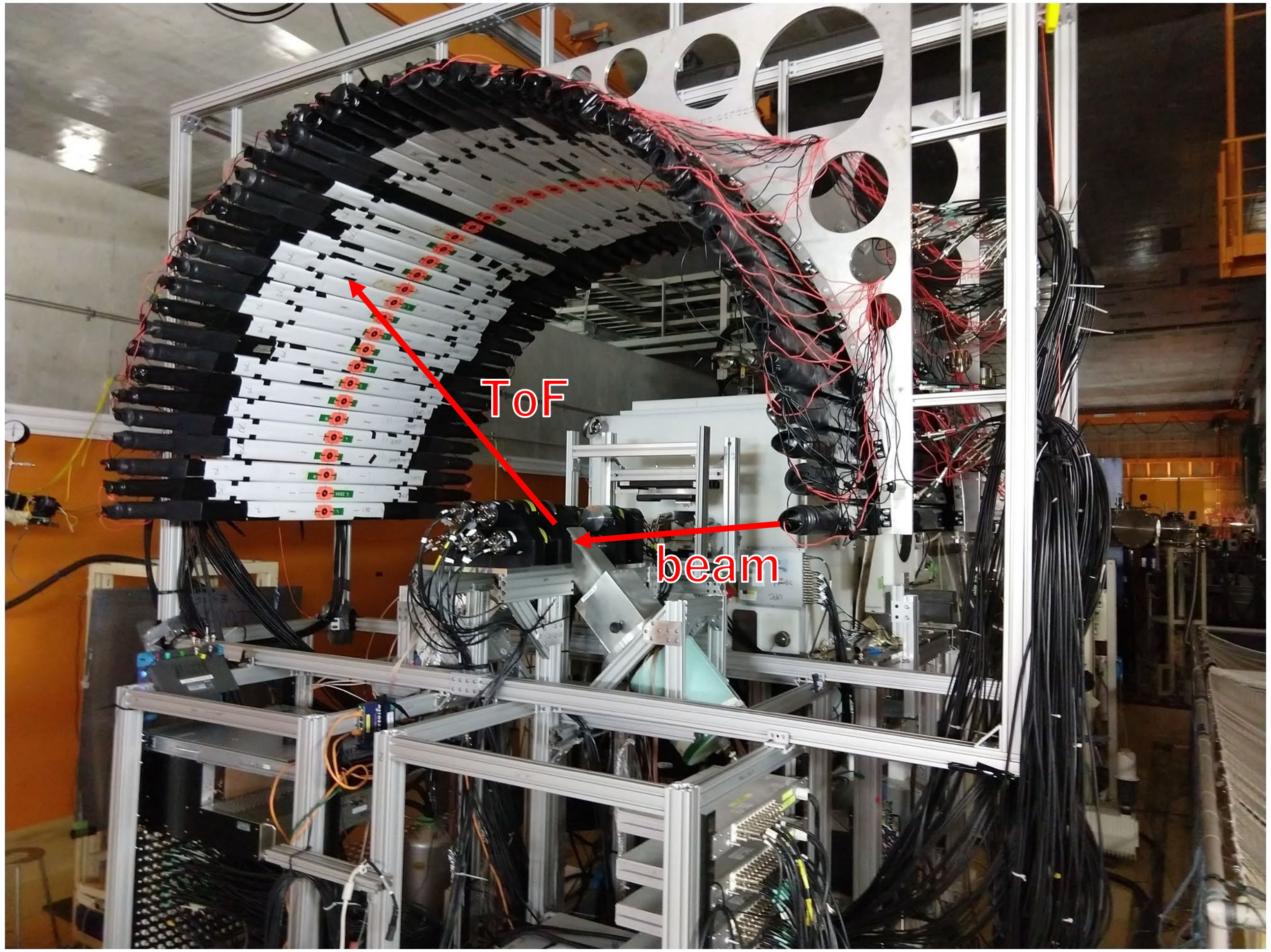


~66% efficiency for 1 MeV neutrons

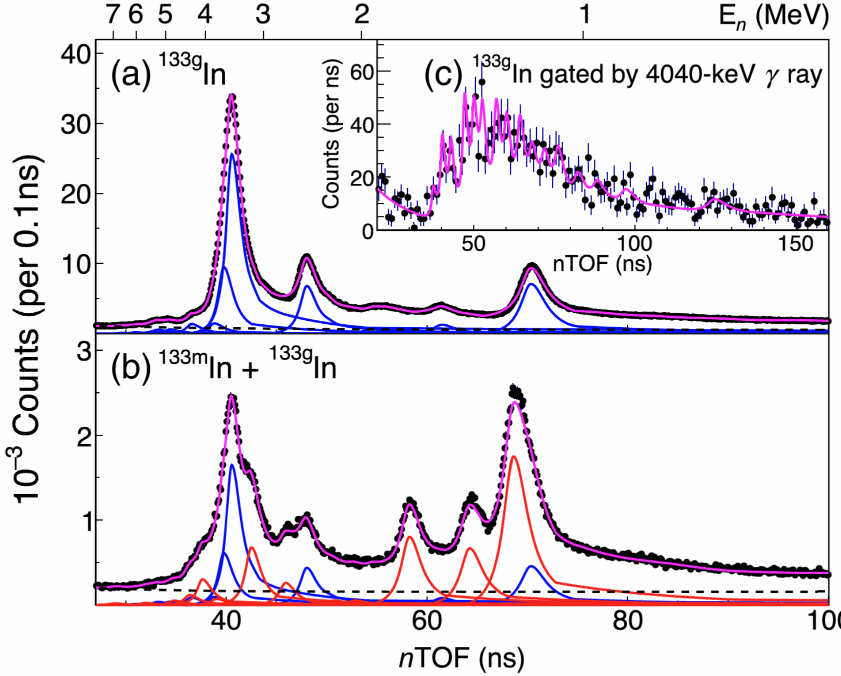
Systematic beta-delayed neutron emission branching ratio (Pxn) measurements

Beta-delayed Neutron ToF measurements

VANDLE *W.A. Peters et al. (2016)*



- Neutron spectroscopy is a powerful tool to study neutron-rich nuclei

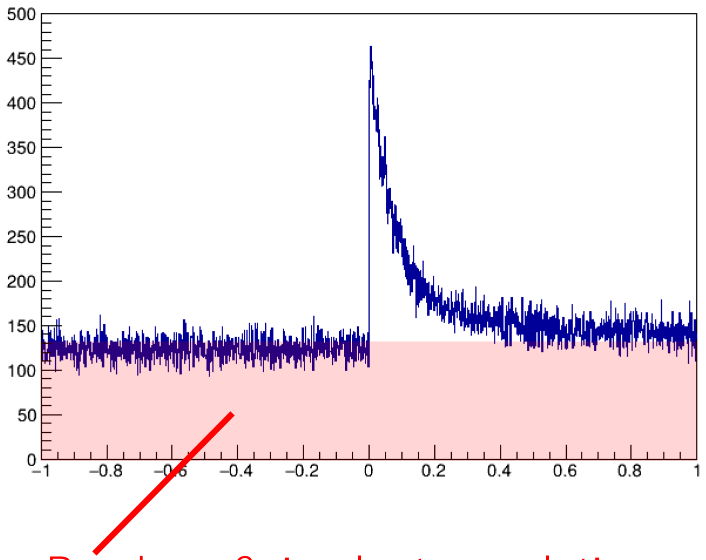


Z.Y.Xu et al., Phys. Rev. Lett. 131 022501 (2023)

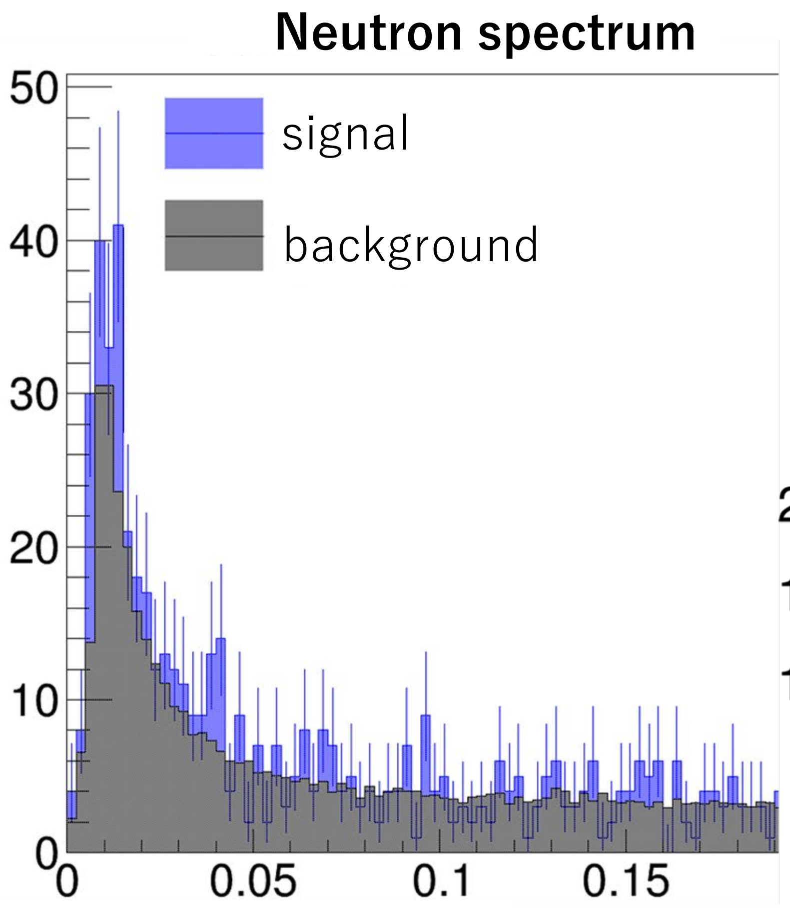
- Requires fast β detector for the start timing of nToF

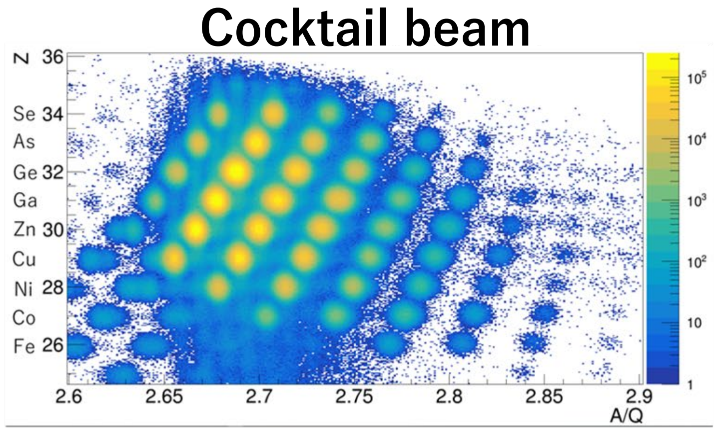
β-implant correlation background

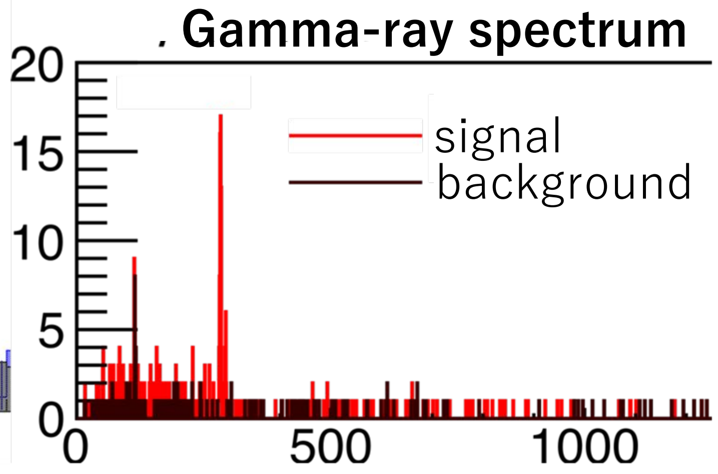
Decay curve



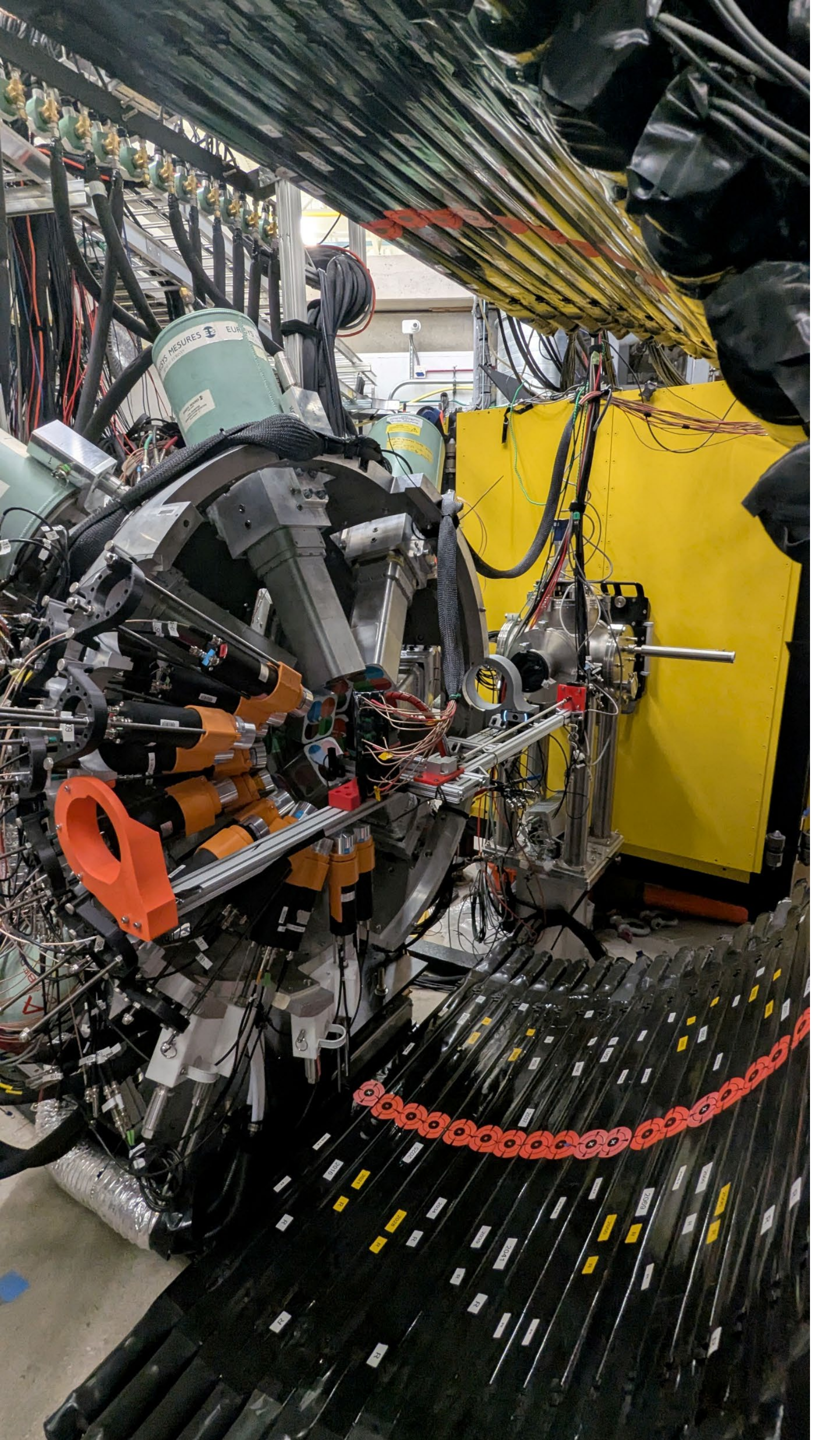
Random β-implant correlation



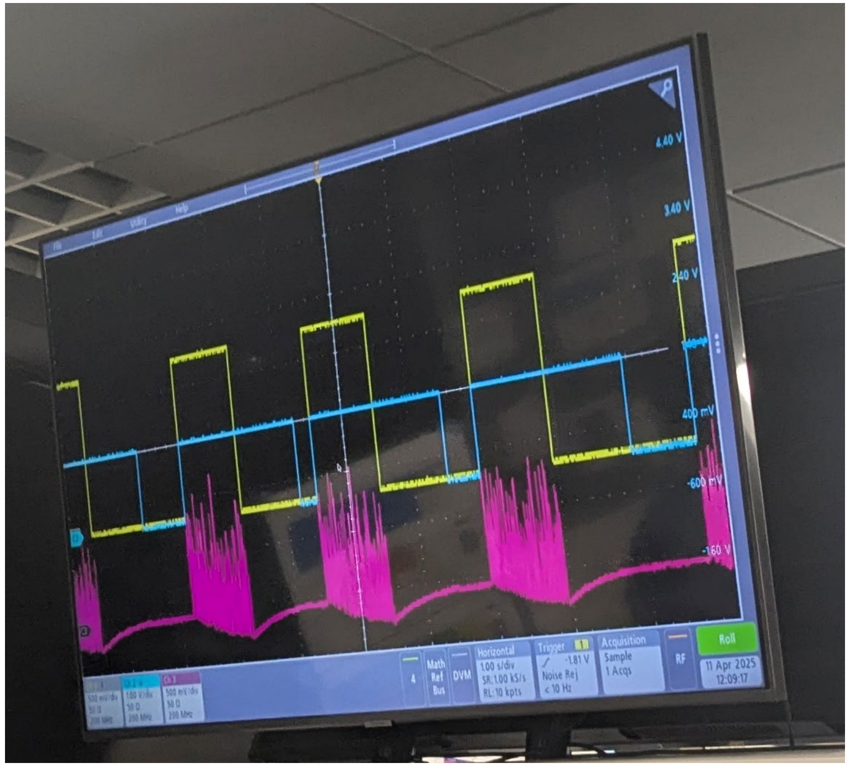




Random β-implant correlation affect neutron spectroscopy much more than high resolution γ-ray spectroscopy

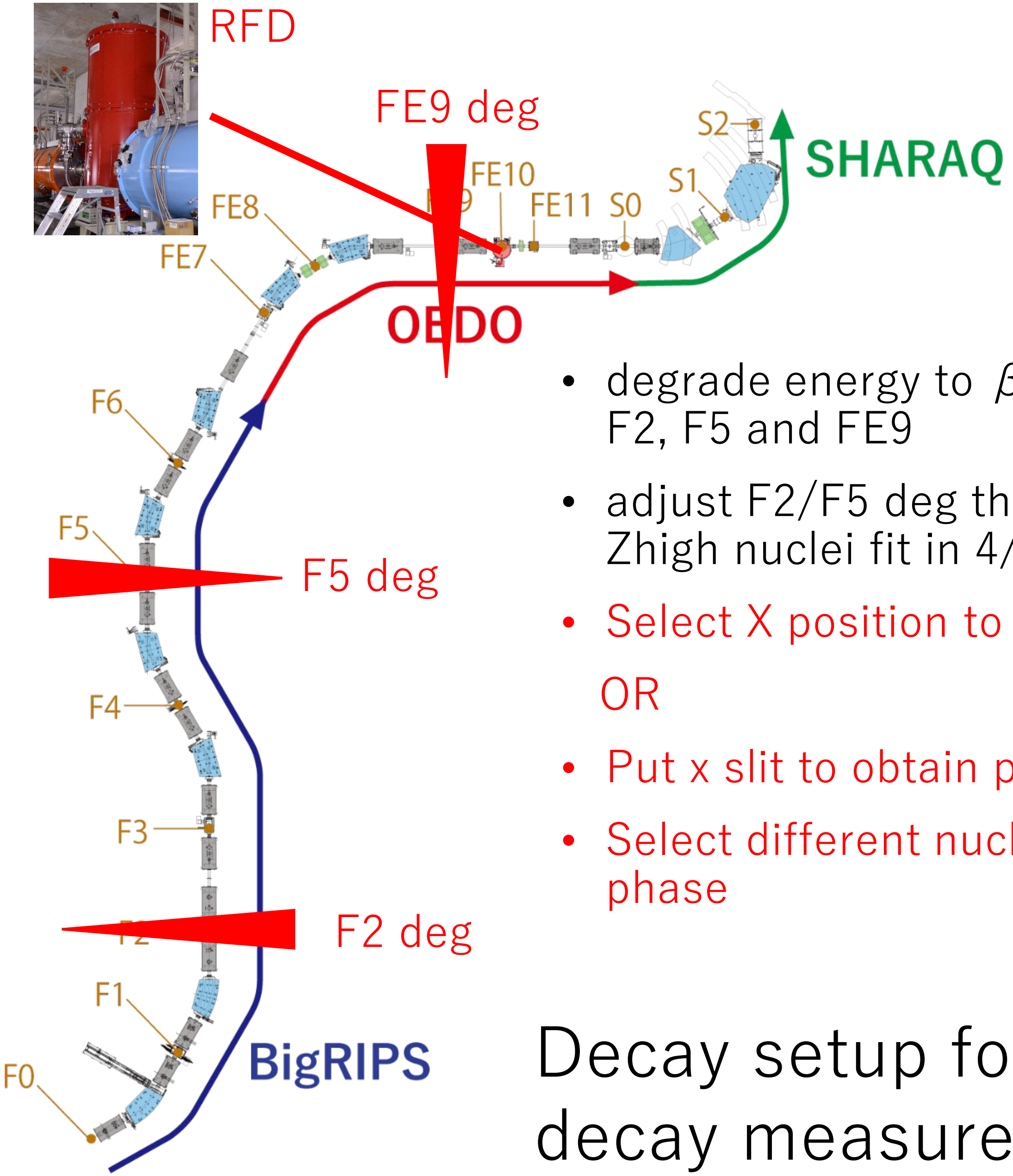


E23076 experiment at FRIB



- beam pulsing to measure the decay curve without implant correlation

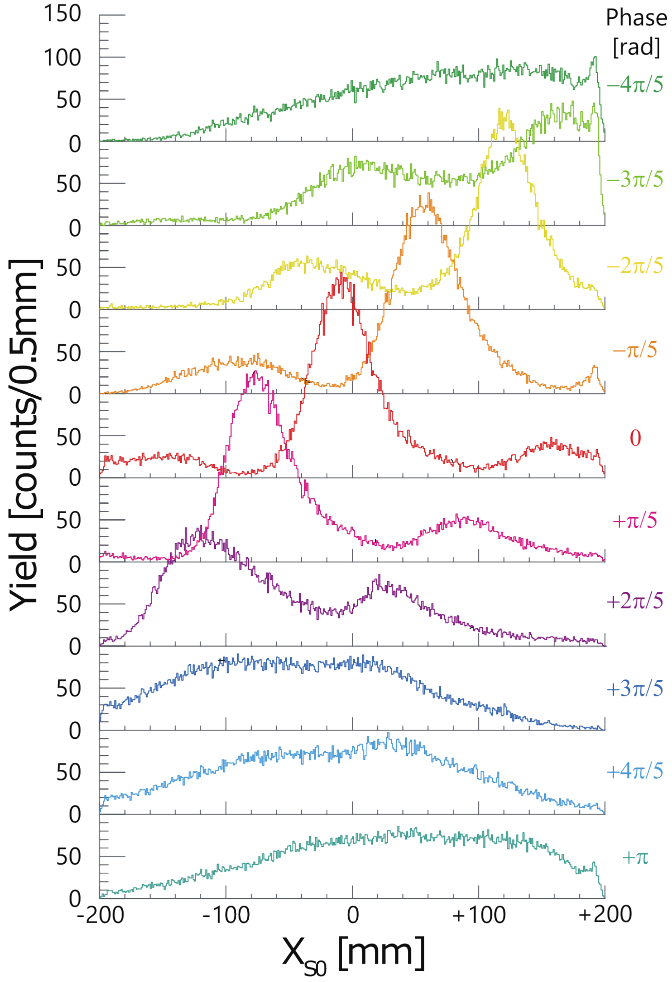
- Beta-decays of less neutron-rich Co isotopes by using pure beam
- Cannot applied to nuclei with lower production



low-background decay spectroscopy at OEDO

- degrade energy to $\beta \sim 0.2$ (designed velocity) at F2, F5 and FE9
- adjust F2/F5 deg thickness so ToFs of Zlow ~ Zhigh nuclei fit in $4/5\pi$ of the RF
- Select X position to look at different nuclei

  OR
- Put x slit to obtain pure beam
- Select different nuclei only by changing RFD phase



Decay setup for clean beta-decay measurement

low-background decay spectroscopy at OEDO

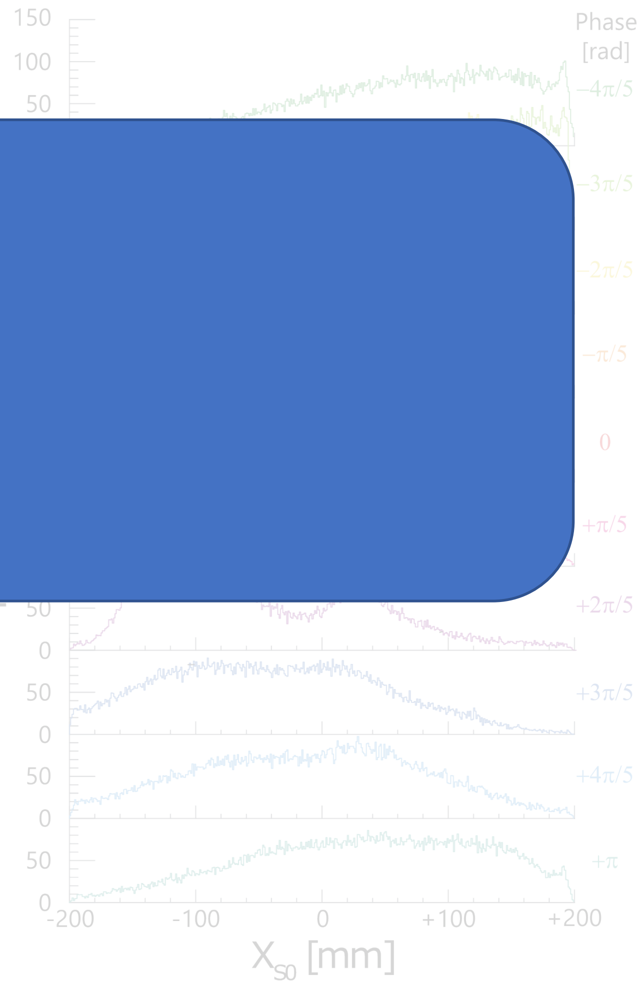
- degrade energy to $\beta \sim 0.2$ (designed velocity) at F2, F5 and FE9

Please contact me if

Pure 78Co beam

become available at HIAF!!!

RFD phase



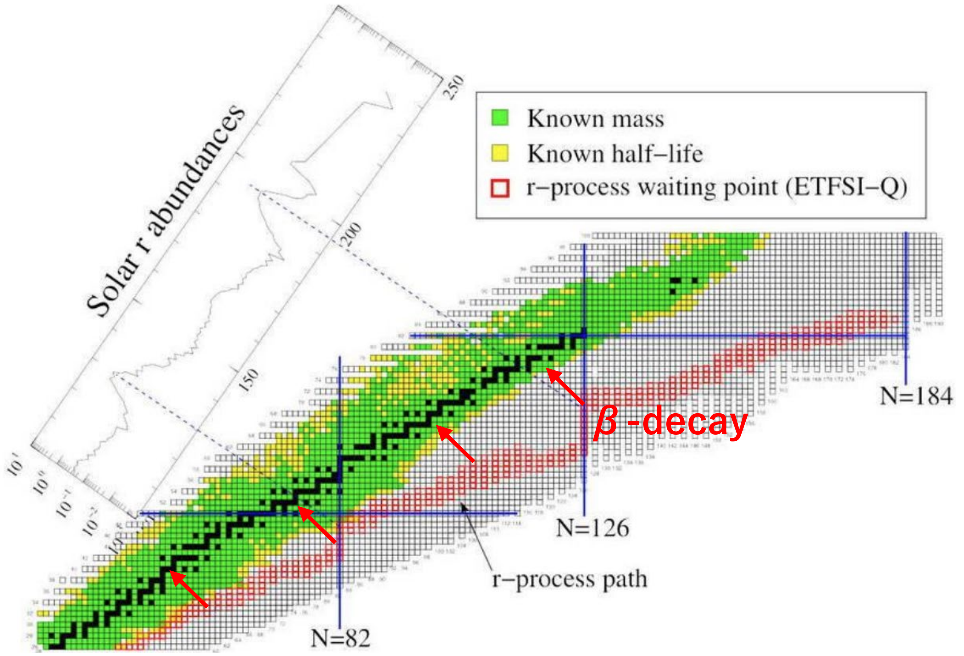
Decay setup for clean beta-decay measurement

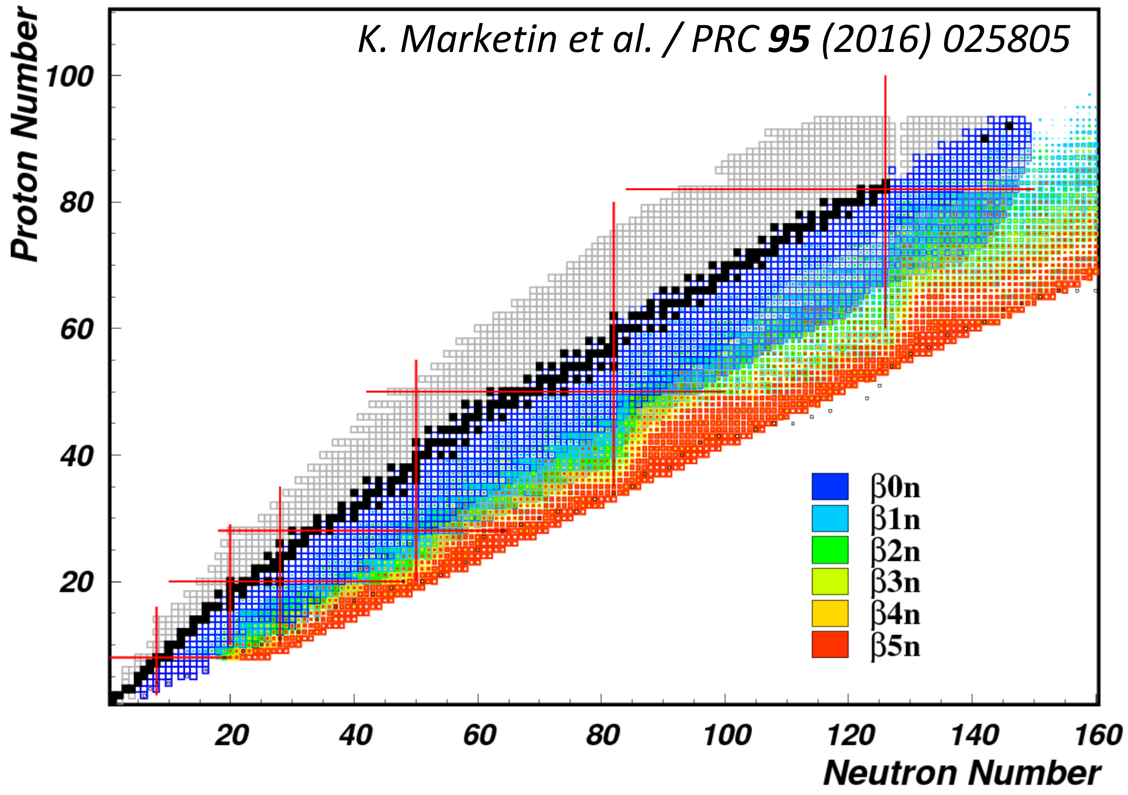
Contents

- Overview of decay spectroscopy at RIBF
- Study of β-delayed neutron emission
- New scintillator material for active stoppers
- Utilization of Apache Spark for efficient β-implant correlation analysis

Beta-delayed multi-neutron emission

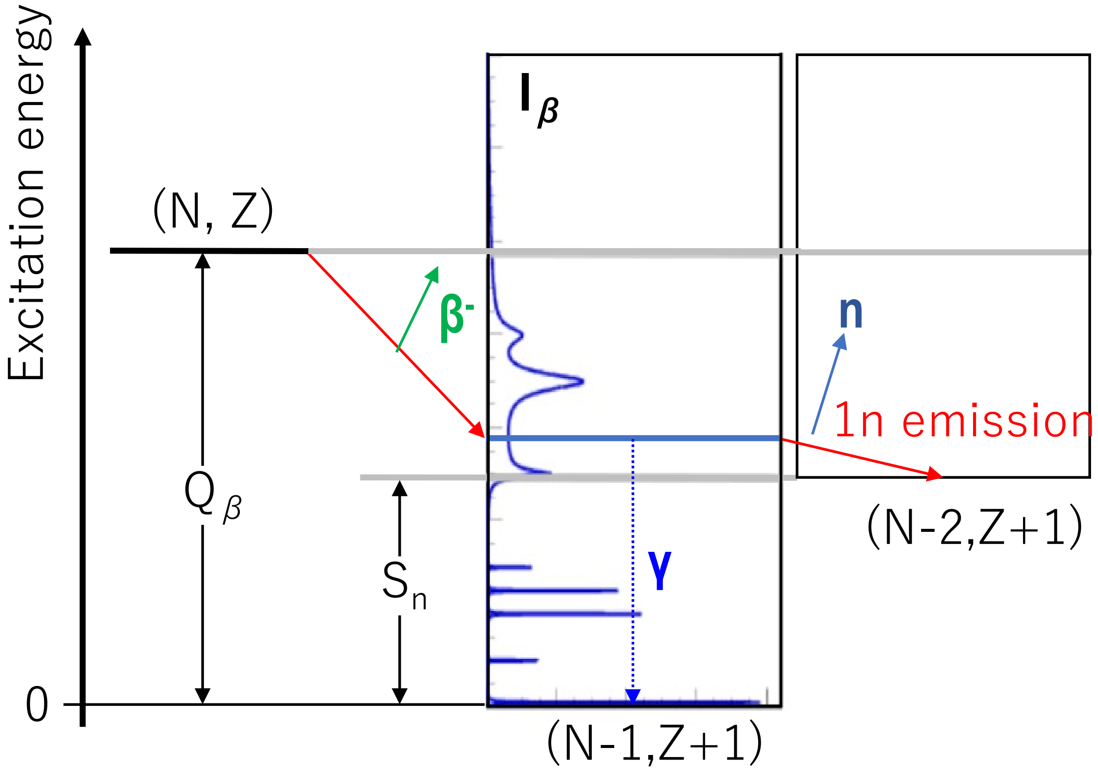
- Multi-neutron emission will occur when $Q_{\beta} > S_{2n}$
- Multi-neutron emission will be a dominant decay mode in r-process nuclei





Complexity of multi-neutron emitters

In the case of one-neutron emission



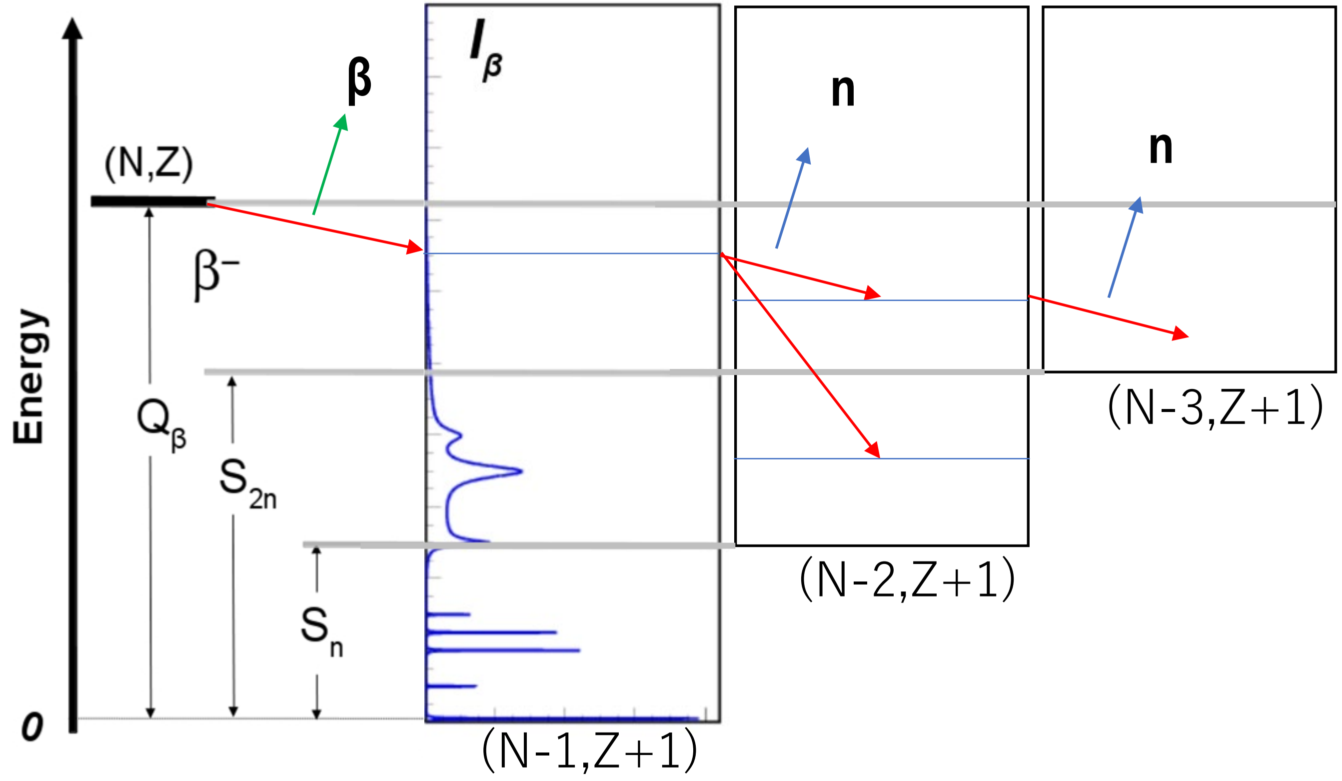
- Relative position of the beta decay strength (I_β) and the neutron separation energy (S_n) in the daughter nucleus controls P_n

- **In the case of 1n emission, gamma decay is the only competition.**

- Until recently, γ-competition is considered to be only important for the states just above S_n.

Complexity of multi-neutron emitters

In the case of multi-neutron emission

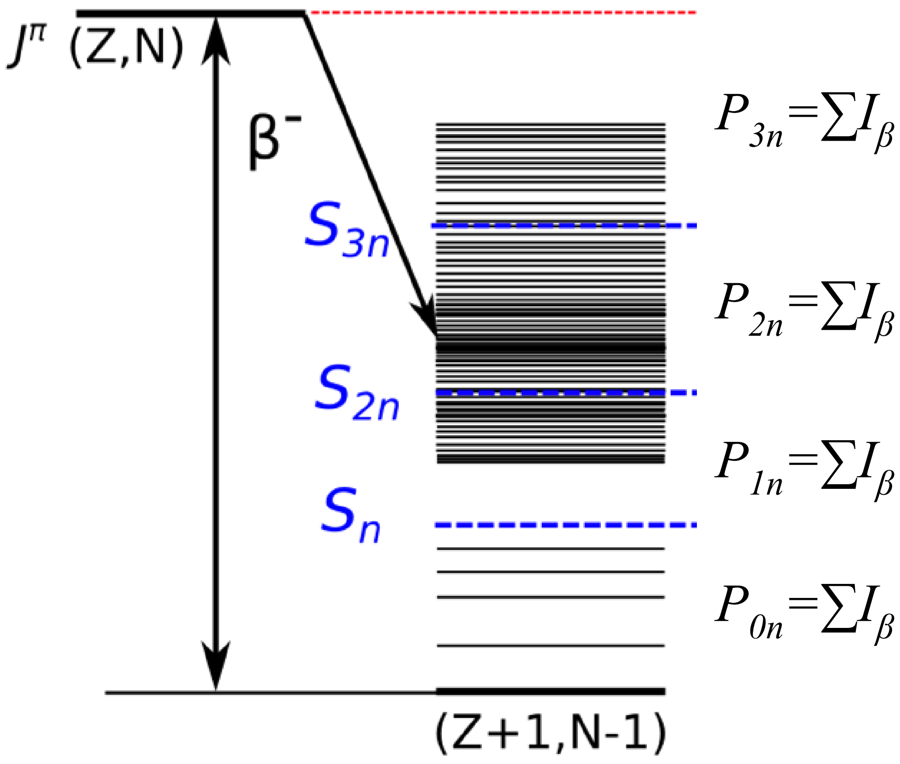


- Above S_{2n}, not only β_{2n} but also β_{1n} may take place.
- Competition between 1n and 2n decay reduces P_{2n} value.
- Multi-neutron emitters are much more complicated and sensitive to the nuclear properties than one-neutron emitters.

Theoretical models of neutron emission

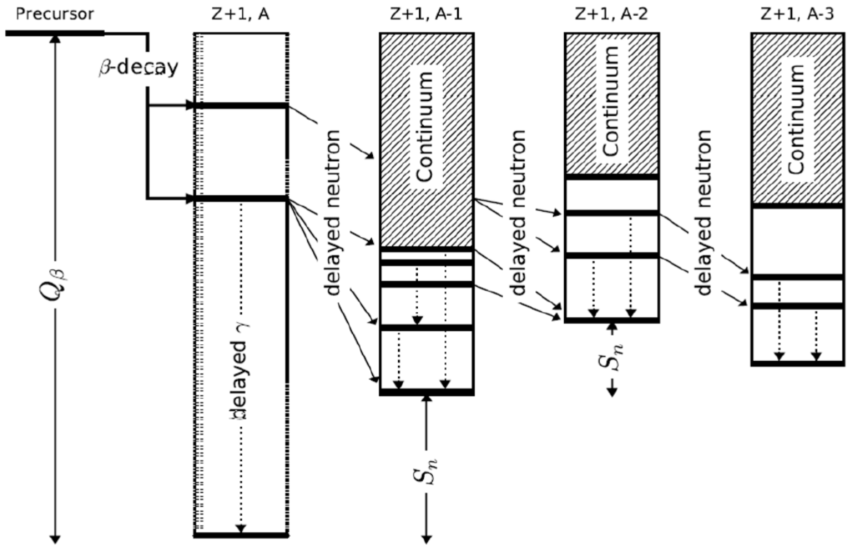
Cut off model *P. Möller et al. (2003)*

P_{xn} proportional to the integrated β-feeding in the respective energy window



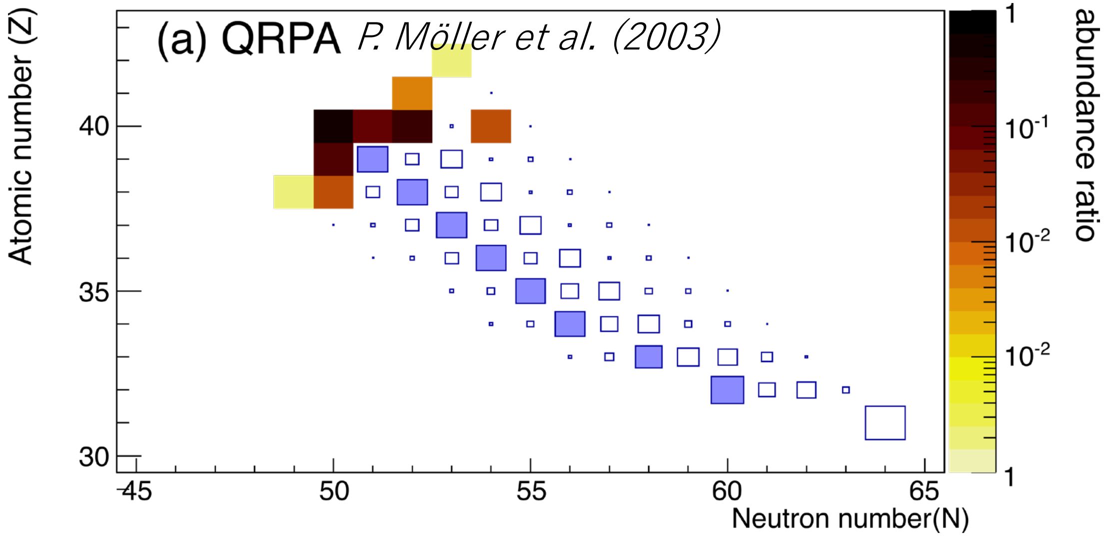
Statistical model T. Kawano et al. PRC 78, 054601 (2008)

- Implemented the Hauser-Feshbach statistical model for particle and γ-ray emission from compound nucleus.
- "only a slight improvement in neutron emission probabilities near stability"
  "Towards the neutron drip line we find substantial differences from older model predictions"

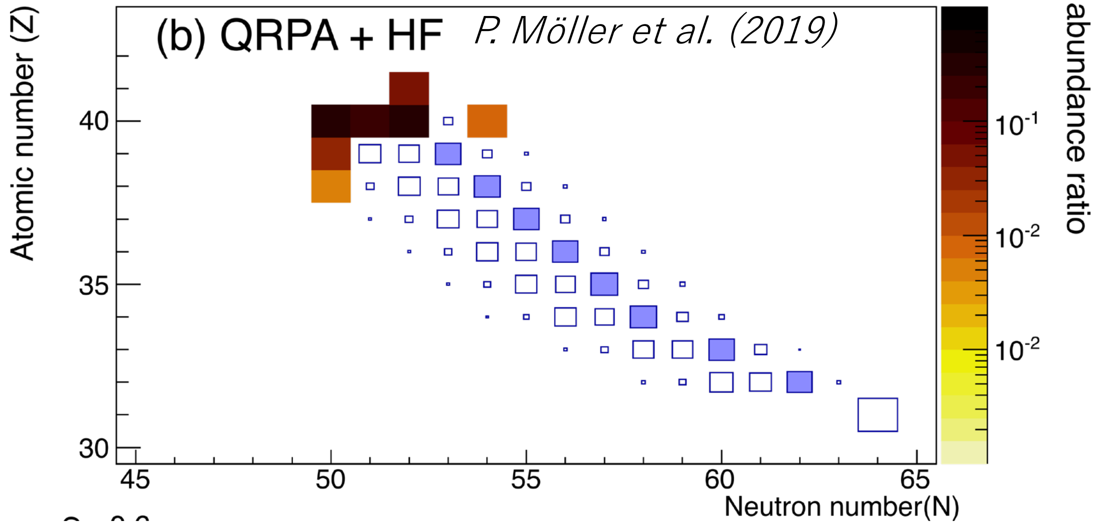


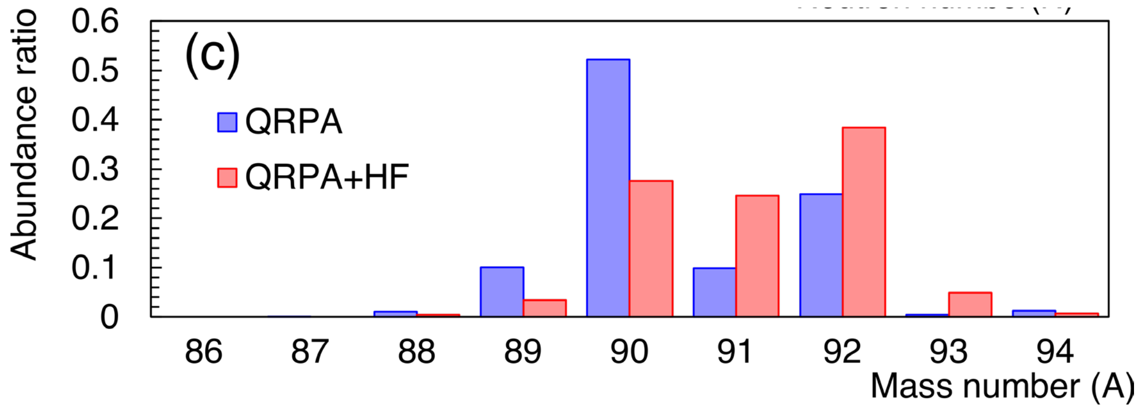
Decay paths of ^{95}Ga with the two models

Cut off model (no competition)



Statistical model

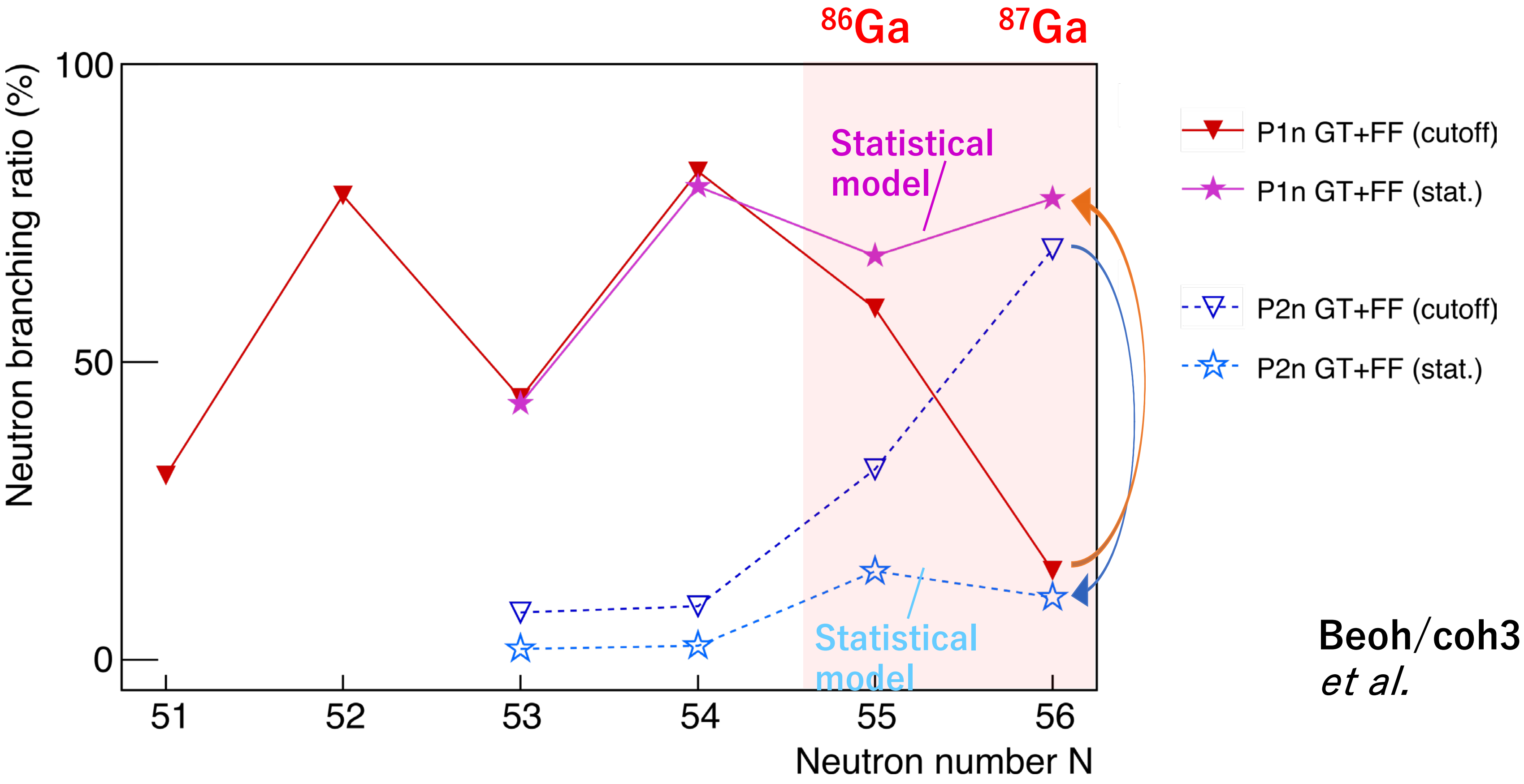




*R. Yokoyama et al. PRC **100**, 031302(R) (2019)*

- statistical model predicts less neutron emission which ends up in larger A nuclides.
  →Impact on r-process calculations.

Statistical model applied with the shell model strength distribution

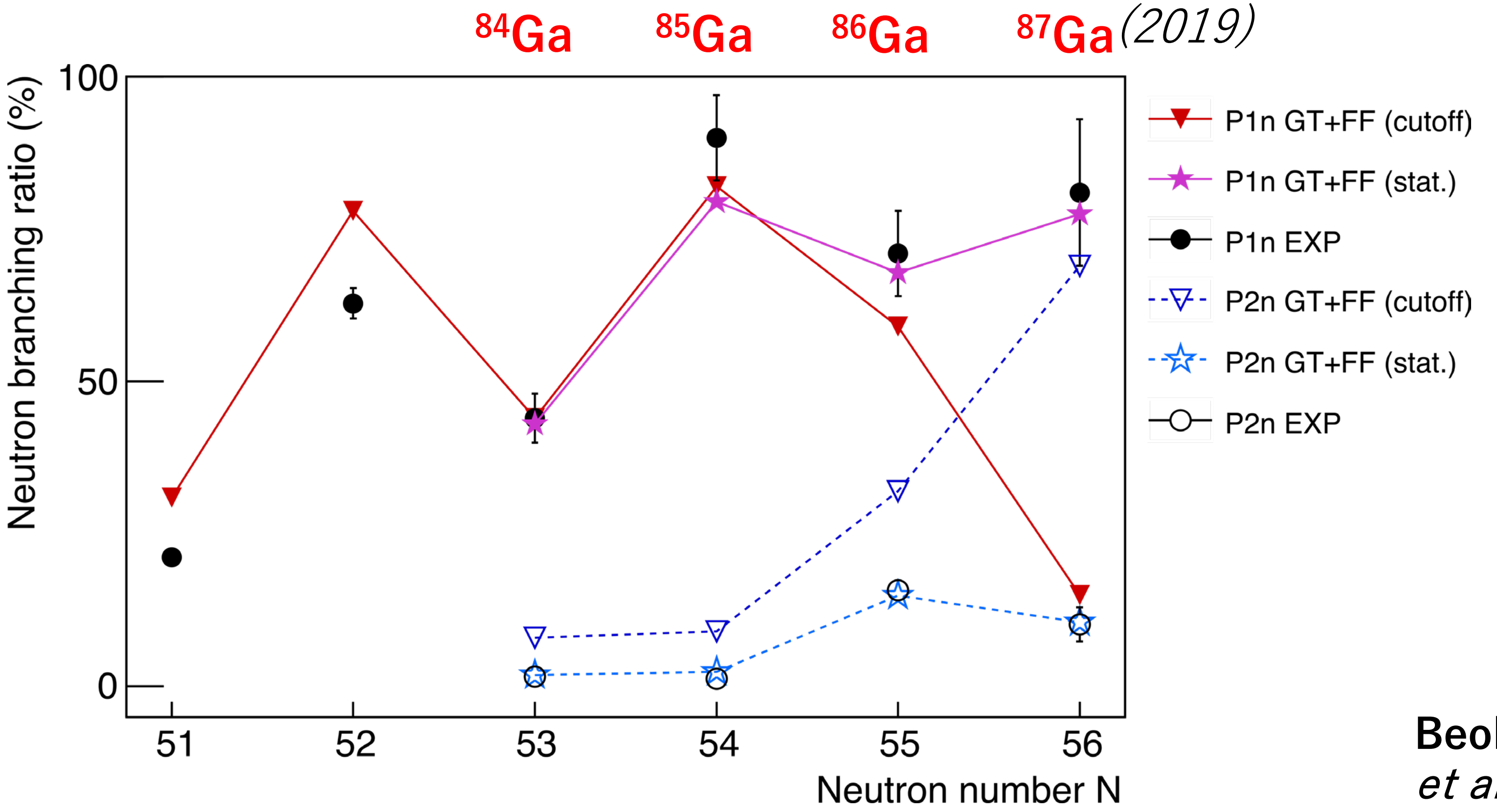


Beoh/coh3 T. Kawano *et al.*

- Inclusion of the statistical model reduces P_{2n} values and increases P_{1n} vales.

Pn values of Ga isotopes (experiment)

R. Yokoyama et al. PRC ***100****, 031302(R) (2019)*



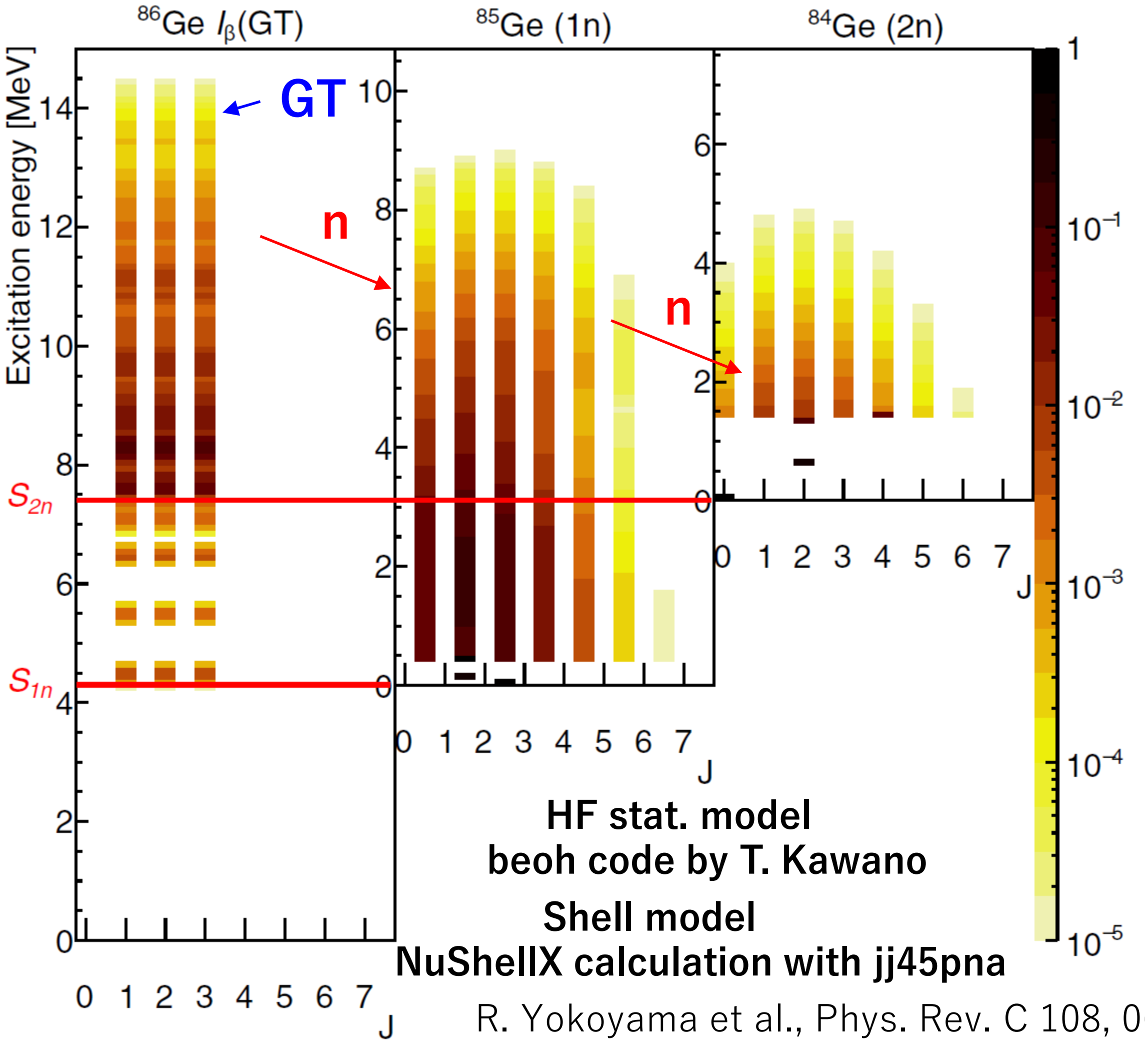
Beoh/coh3 T. Kawano *et al.*

- P_{1n} is still dominant in the ^{87}Ga decay
- P_{2n} values agree well with the statistical model

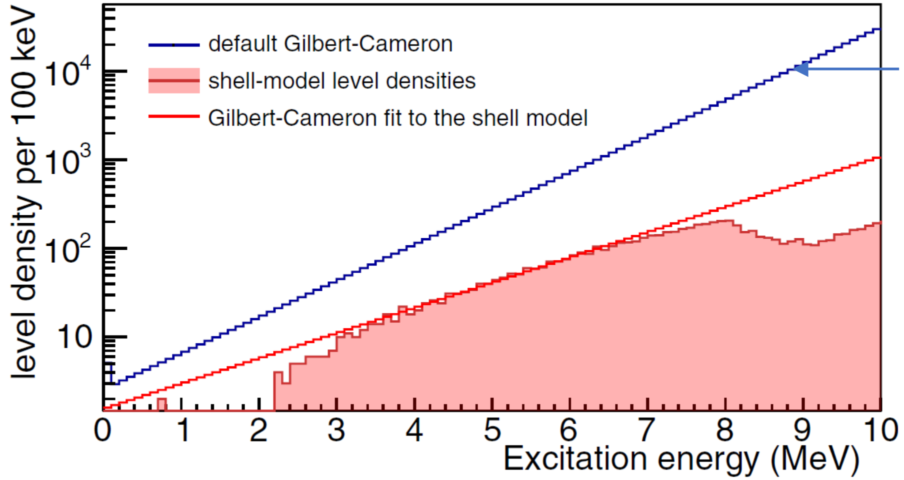
There is a competition between 1n and 2n channels

Impact of level densities to P_{2n}/P_{1n} ratio

Population of states in the HF calculation of ^{86}Ga decay (2- assumed for ^{86}Ga g.s.)

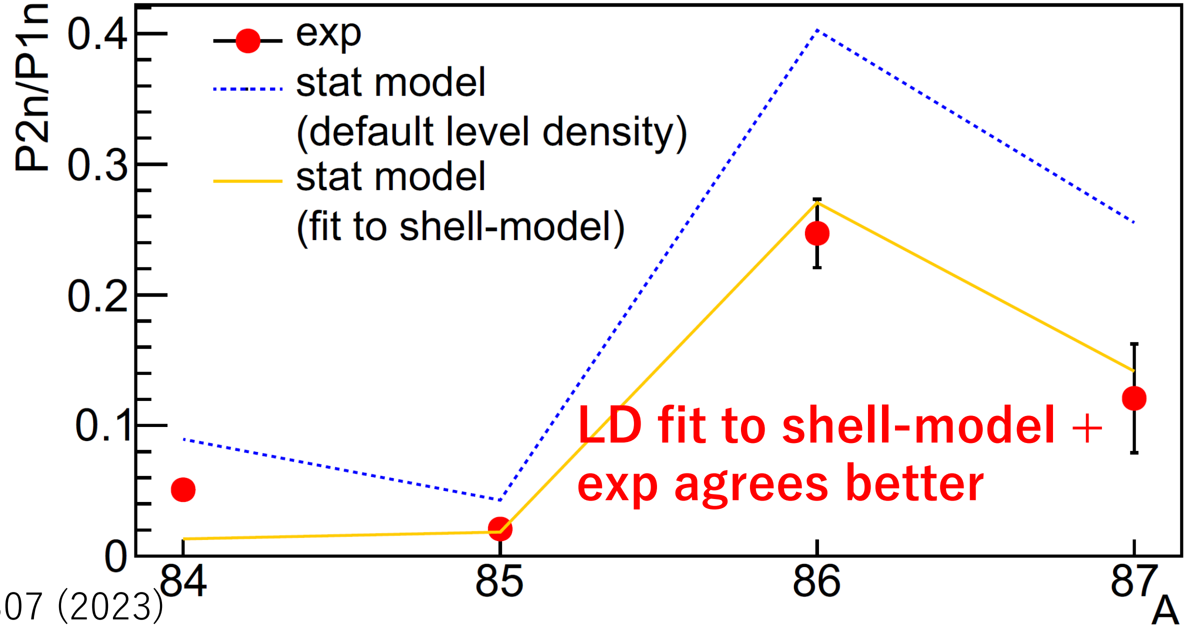


HF stat. model
beoh code by T. Kawano
Shell model
NuShellX calculation with jj45pna



$$\rho = \frac{1}{T}\exp\left(\frac{E-E_0}{T}\right),$$

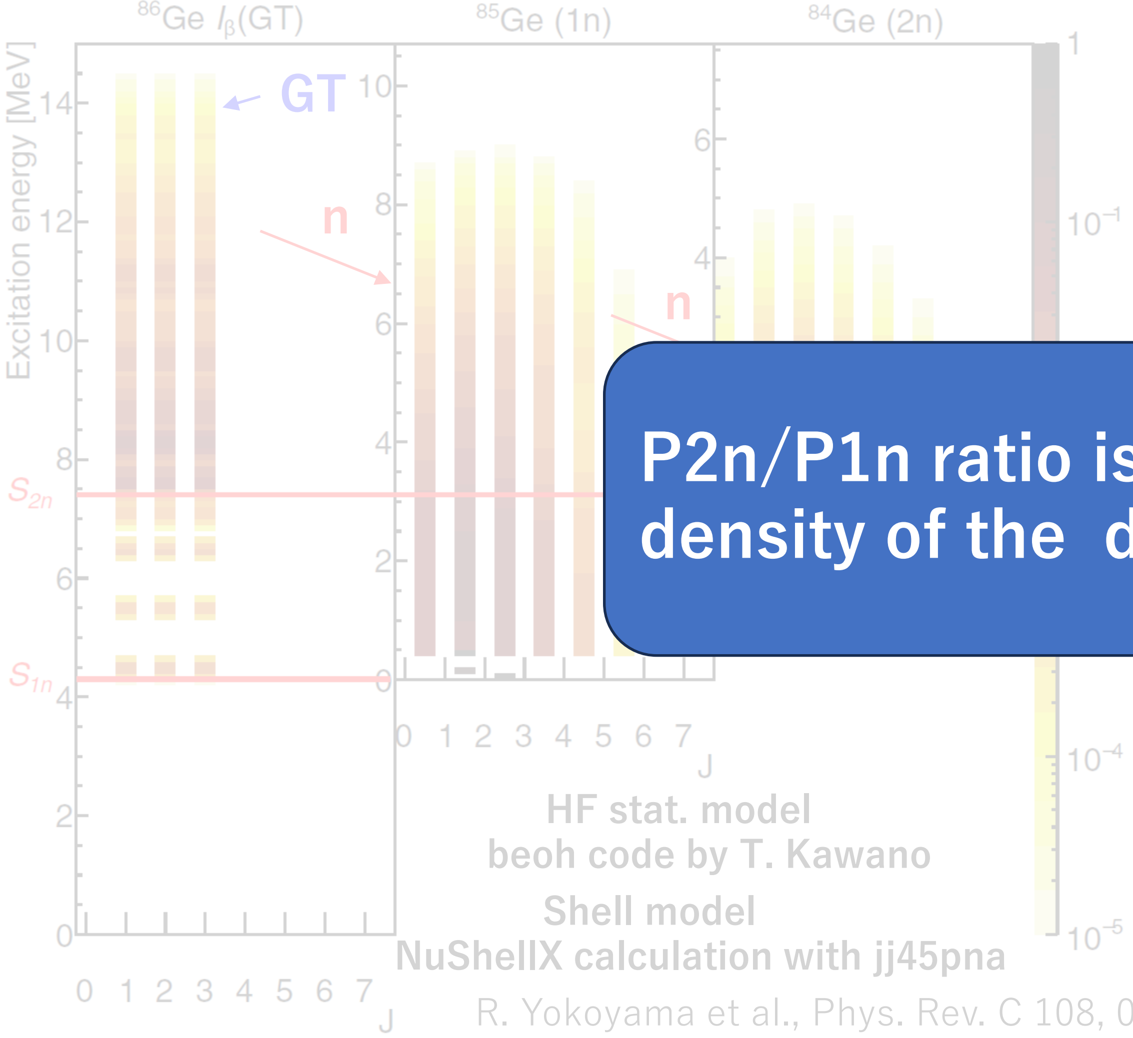
Pairing + shell corrections (KTUY05)



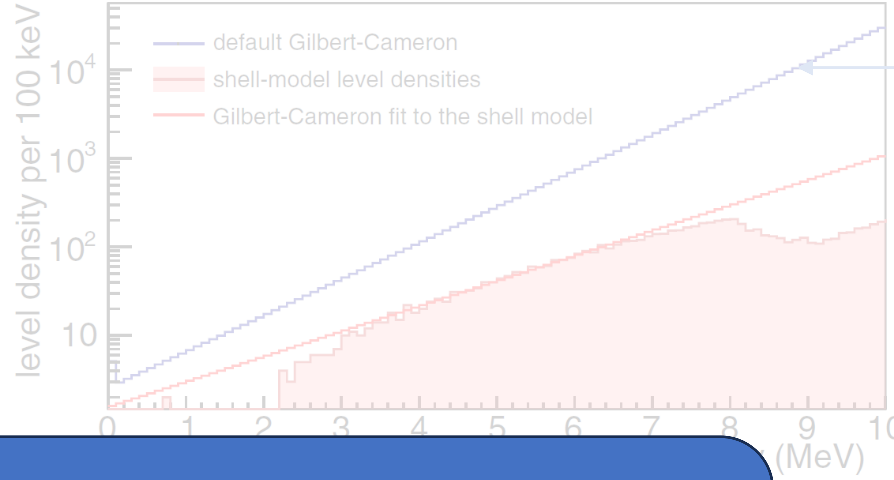
R. Yokoyama et al., Phys. Rev. C 108, 064307 (2023)

Impact of level densities to P_{2n}/P_{1n} ratio

Population of states in the HF calculation of ^{86}Ga decay (2- assumed for ^{86}Ga g.s.)

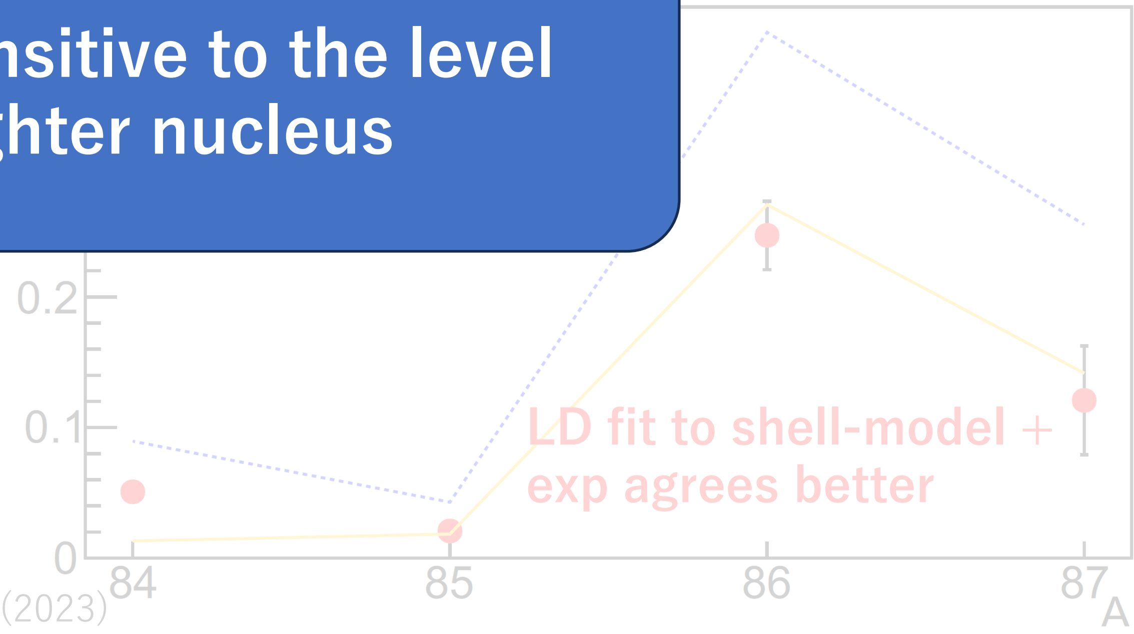


R. Yokoyama et al., Phys. Rev. C 108, 064307 (2023)



$$\rho = \frac{1}{T}\exp\left(\frac{E - E_0}{T}\right)$$

Pairing + shell corrections (KTUY05)

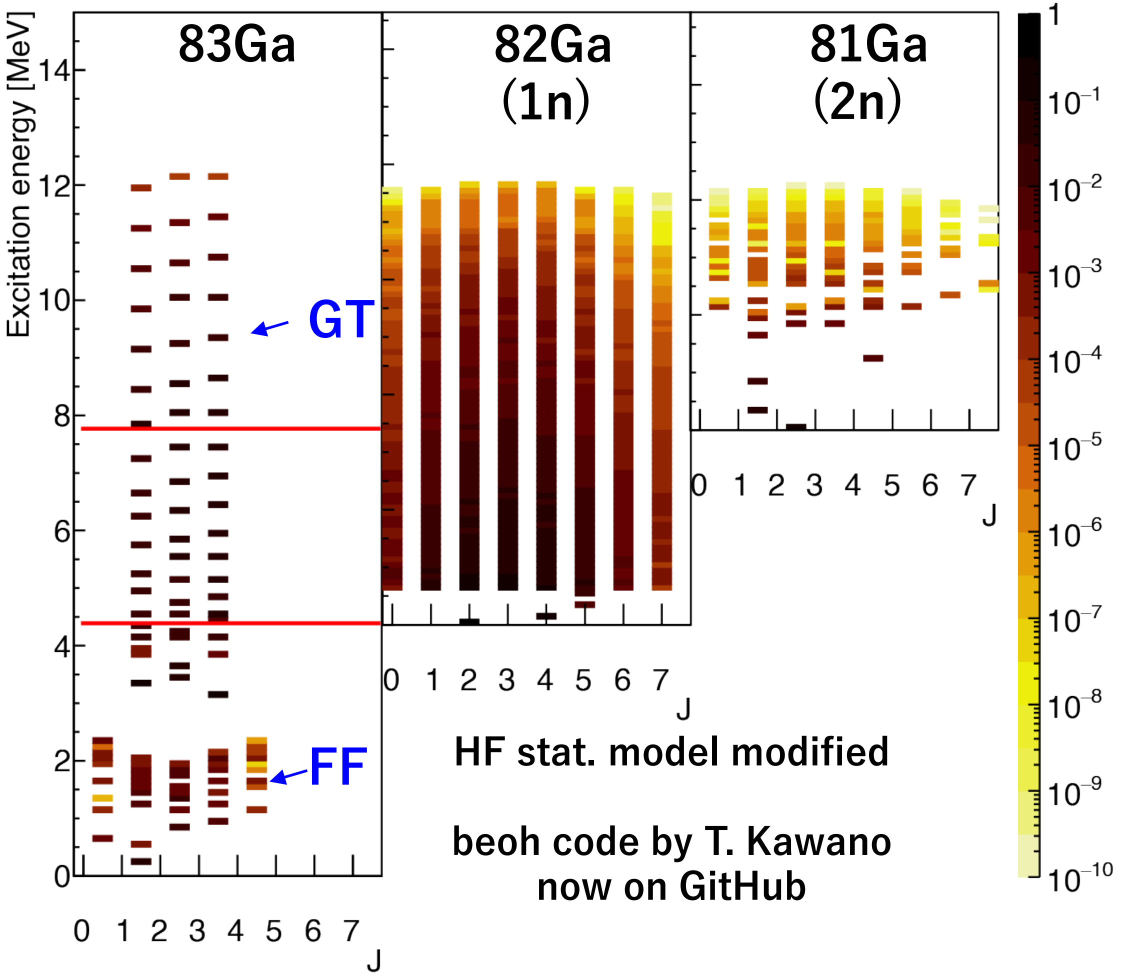


P2n/P1n ratio is sensitive to the level density of the daughter nucleus

Using KSHELL + stochastic estimation

N. Shimizu et al., Comp. Phys. Comm. 244, 372 (2019)

Population of states in the statistical model of ^{83}Zn decay (5/2- assumed for ^{83}Zn g.s.)

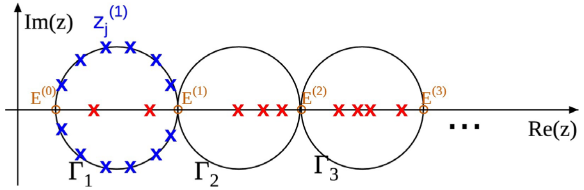


HF stat. model modified

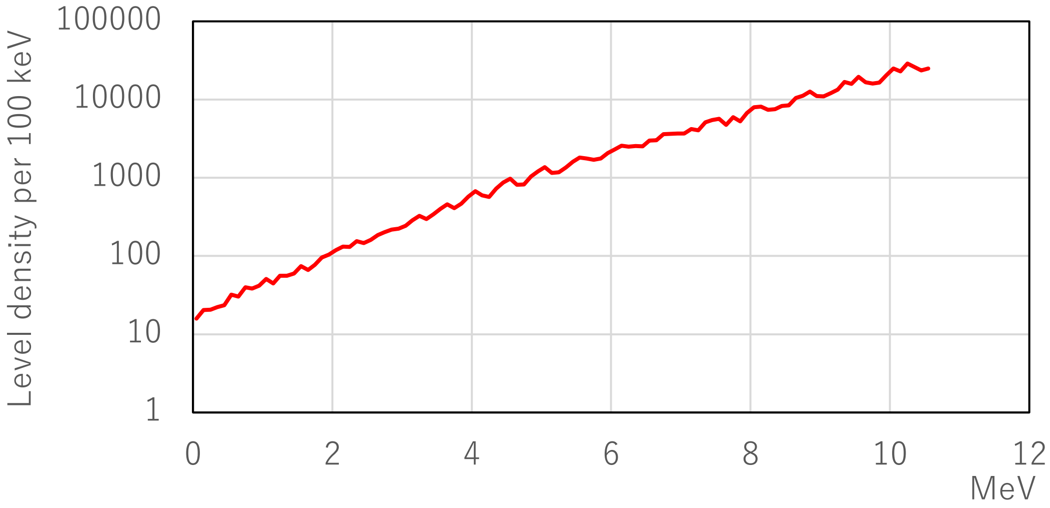
beoh code by T. Kawano now on GitHub

- KSHELL with jj4_45_VMU interaction is used to calculate both GT and FF transitions from the g.s. of the parent.
- Stochastic estimation method is used to calculate the level densities of daughter nuclides.

N. Shimizu et al., Phys. Lett. B 753, 13-17 (2016)



Estimates number of states in each energy bin



^{83}Zn decay (Exp. Vs HF+KSHELL)

Preliminary

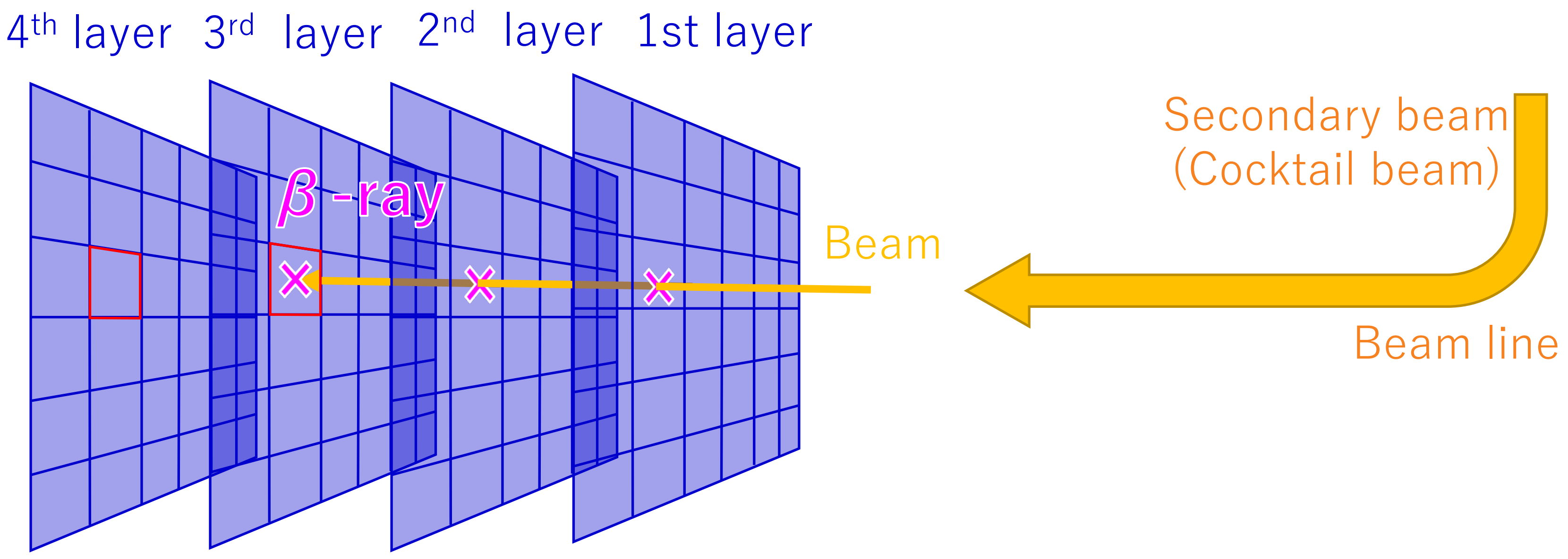
- We can now calculate neutron and gamma branching ratios

Contents

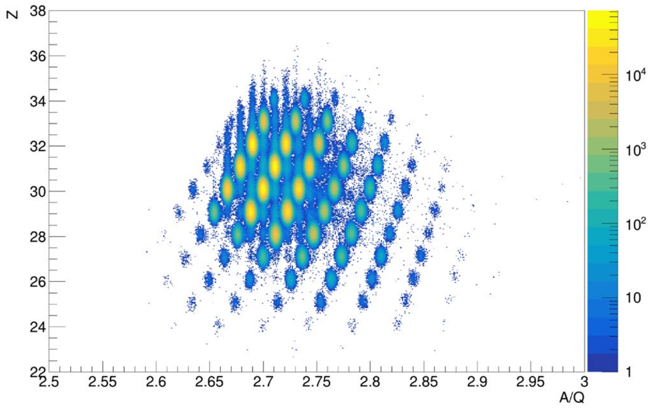
- Overview of decay spectroscopy at RIBF
- Study of β-delayed neutron emission
- New scintillator material for active stoppers
- Utilization of Apache Spark for efficient β-implant correlation analysis

β -decay experiments at a fragmentation facility

Implant detector (Stack of DSSSD)



PID



x-y position of an implant
x-y position of β-ray emission } Correlate β with PID

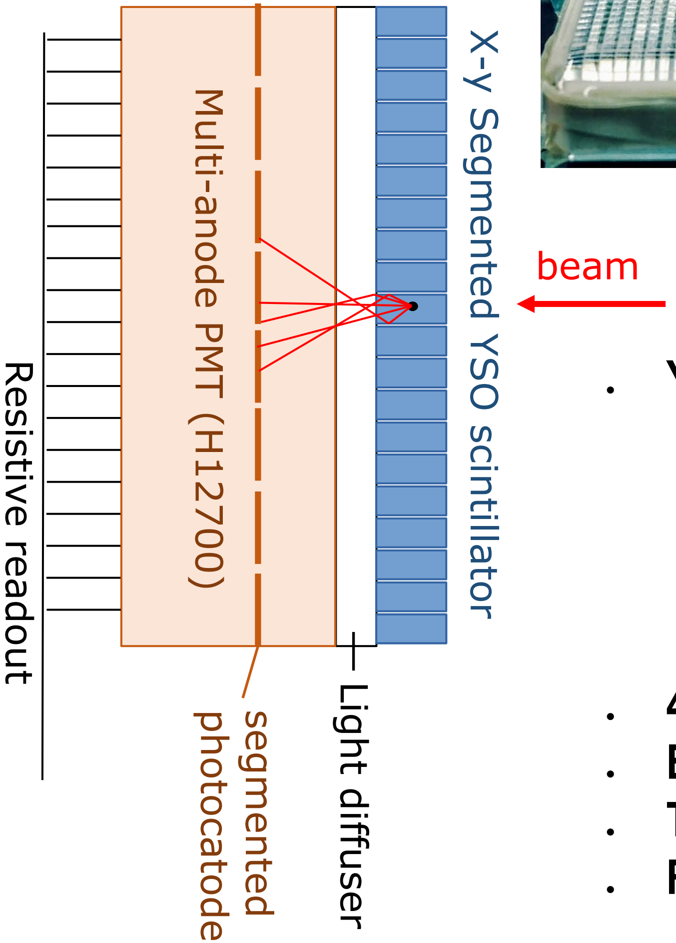
Implant detector requires

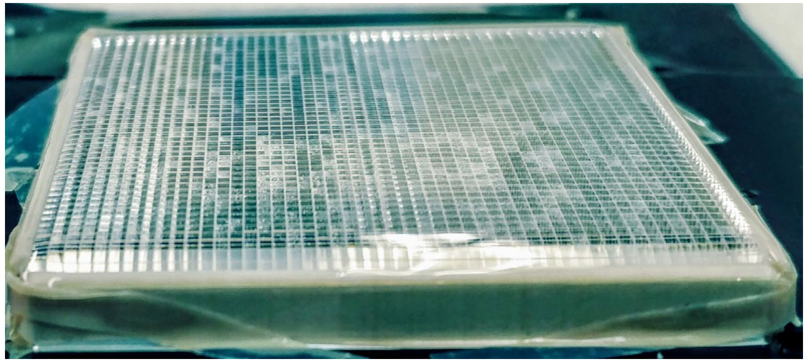
- Good position resolution for both ions and beta
- Implantation rate per pixel << $1/T_{1/2}$ of interest

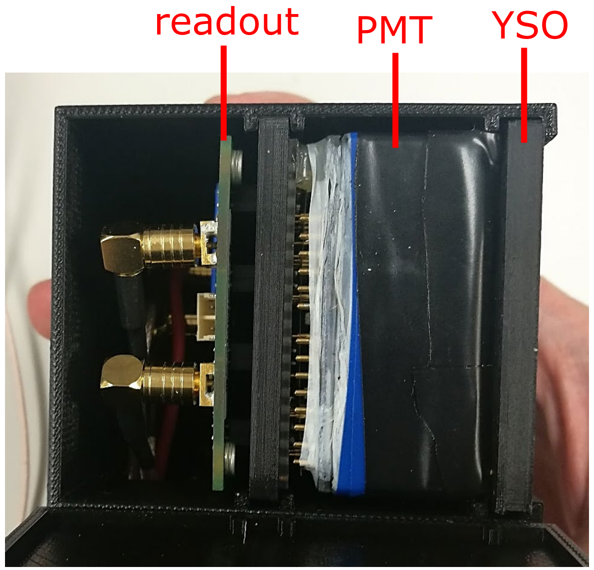
DSSSD is too slow for nToF measurements

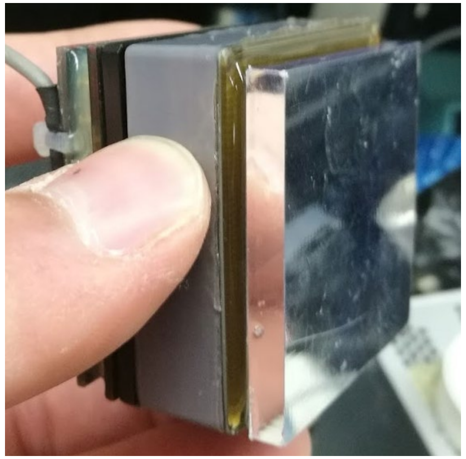
Segmented YSO detector

R.Yokoyama et al. NIM A 937, 93-97(2019)









- **YSO (Yttrium Orthosilicate, Y_2SiO_5) crystal**
  - **Effective atomic number: Z~39**
  - **Density: ~4.5 g/cm^3**
  - **Wavelength: 420 nm**
  - **Decay time: ~70 ns**

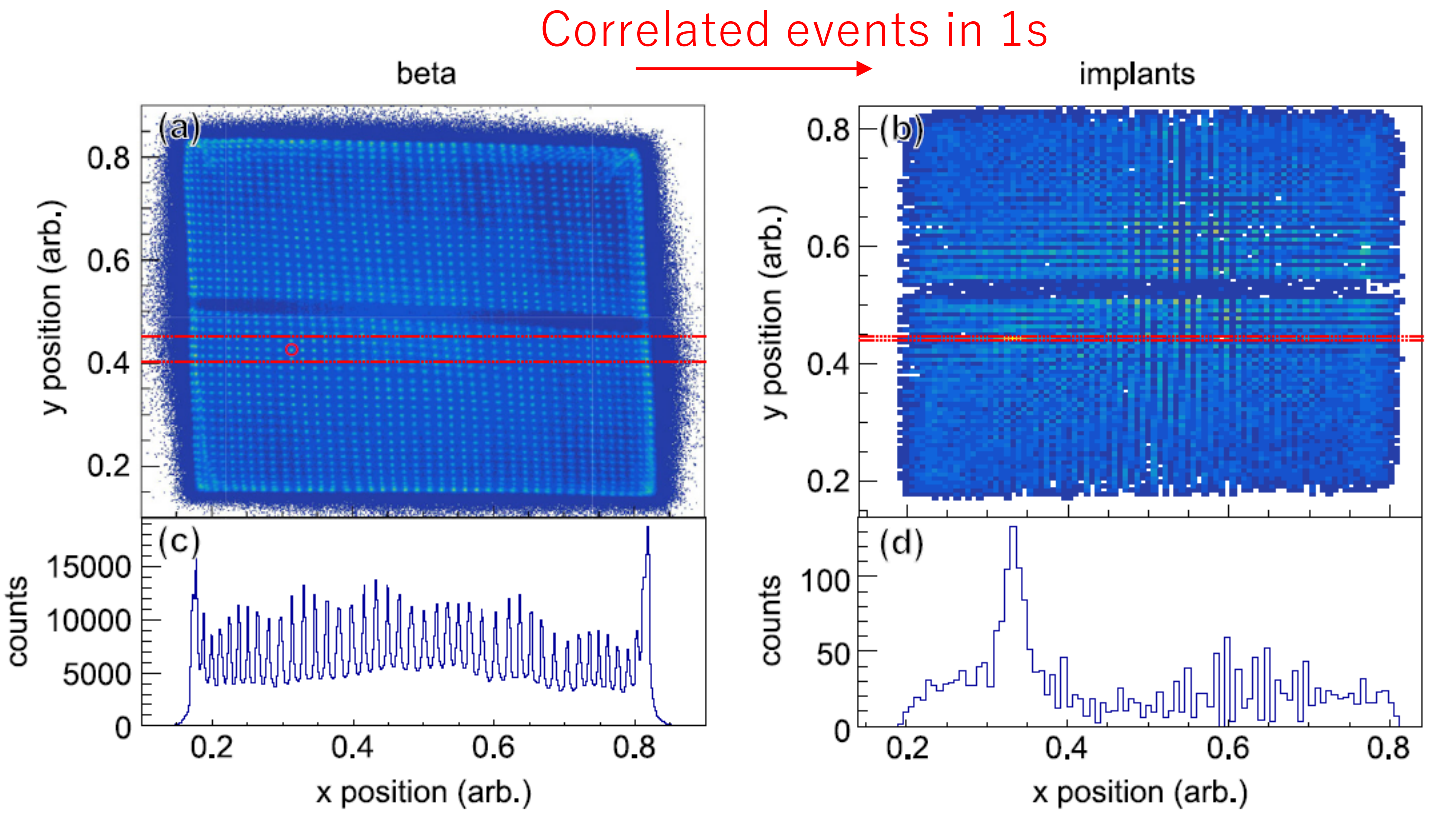
- **48 x 48 segments**
- **Each segment: 1 x 1 mm**
- **Thickness: 5 mm**
- **Reflective material: ESR**

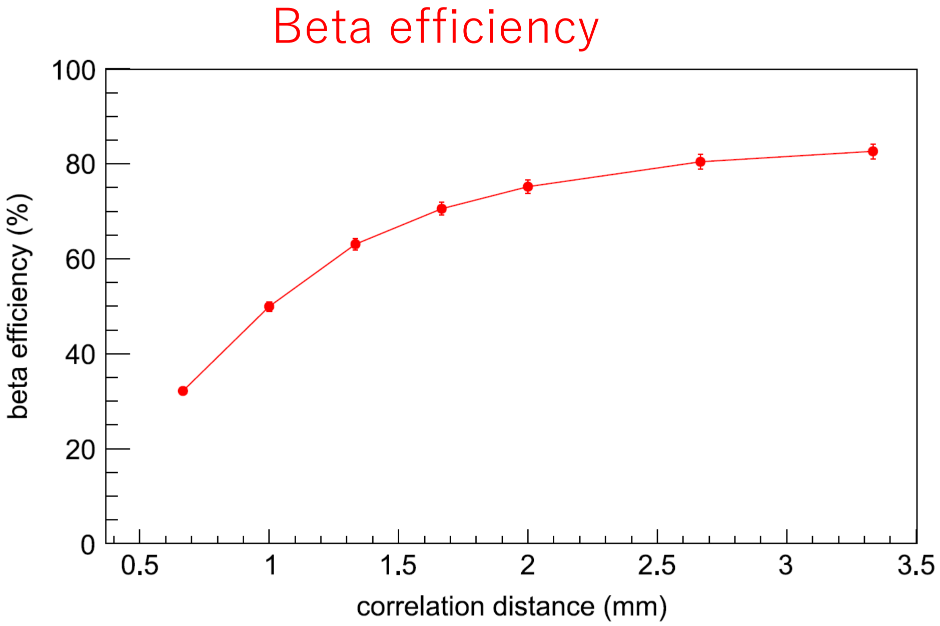
Compared to DSSSDs

- **Fast response time (~500 ps)**
- **Hard to radiation damage**
- **High stopping power**
  - **High beta efficiency**
  - **Good position correlation**
- **Can be thick**
- **Simple and compact**
- **More γ absorption**
- **~10% energy resolution for ions**

^{78}Ni region with YSO

R.Yokoyama et al. NIM A 937, 93-97(2019)

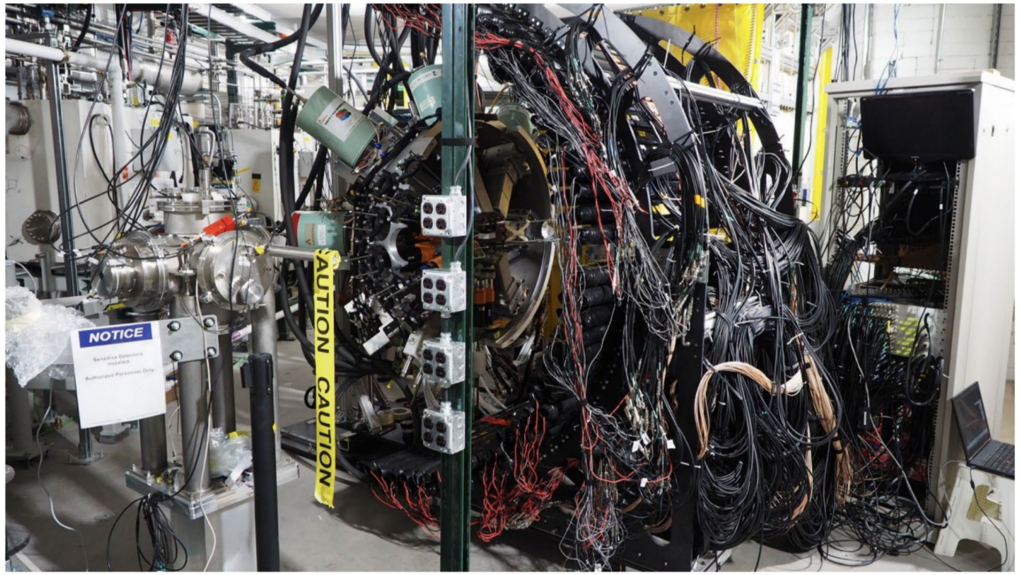




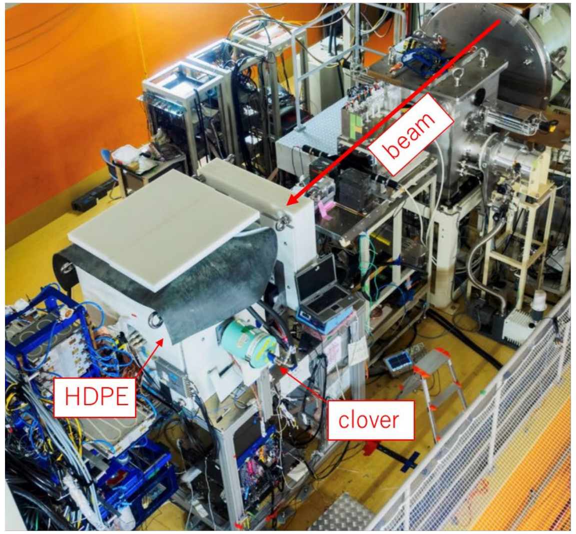
- Clear position correlation between beta and implant events
- Beta efficiency is as high as 80% at 3mm correlation radius (^{74}Co).

Success of YSO detector

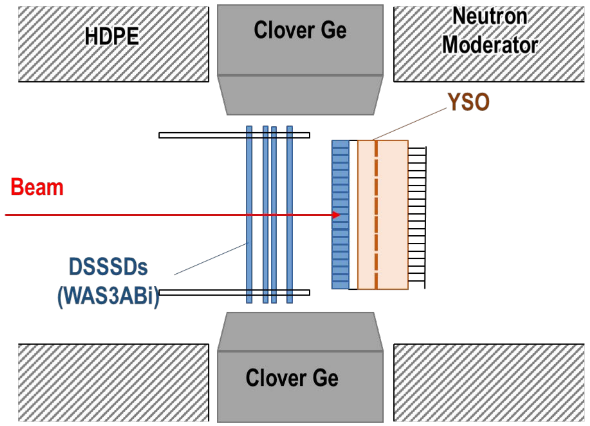
with FRIB Decay Station



with BRIKEN



- Setup inside the HDPE moderator

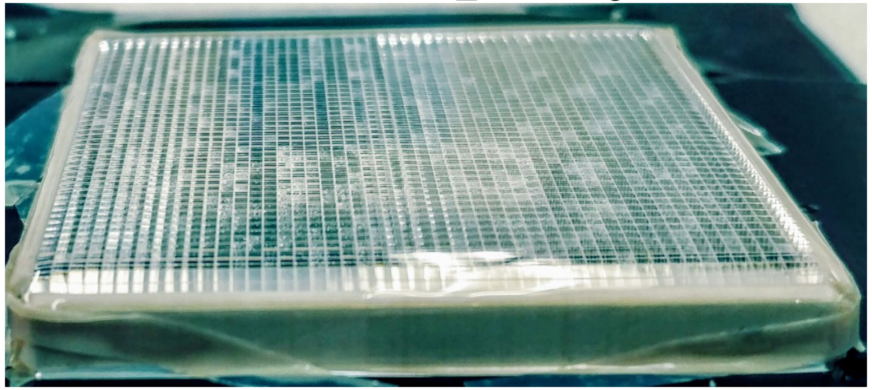


- Shared implantation between the conventional DSSDs and new YSO detector

[11] R. Yokoyama et al., Phys. Rev. C 100, 031302 (2019)
[12] R. Yokoyama et al., Phys. Rev. C 108, 064307 (2023)
[13] R. S. Lubna et al., Phys. Rev. C 108, 014329 (2023)
[14] T. J. Gray et al., Phys. Rev. Lett. 130, 242501(2023)
[15] M. Madurga et al., Phys. Rev. C 109, L061301 (2024)
[16] I. Cox et al., Phys.Rev. Lett. 132, 152503 (2024)
[17] S. Neupane et al., Phys. Rev. C 110, 034323 (2024)

New scintillator material for a β-implant detector

YSO (Y_2SiO_5:Ce)

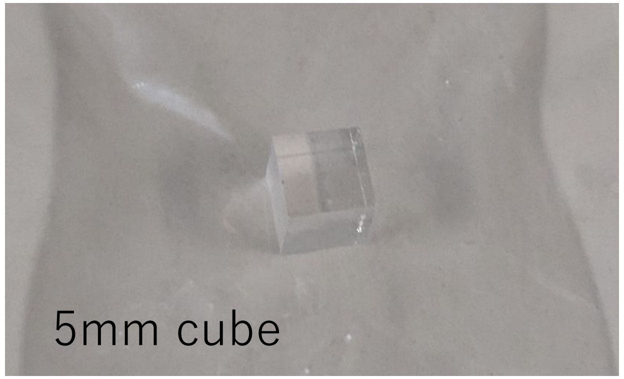


Zeff ~ 39, ρ ~4.5g/cm3

2MeV β range: ~2.7mm

La-GPS ($(Gd,La)_2Si_2O_7$:Ce)

A. Suzuki et al., Applied Physics Express 5 (10) (2012) 102601
S. Kurosawa et al., Nucl. Instrum. and Meth. A 744 (2014) 30–34
S. Kurosawa et al., IEEE TNS 65 (8) (2018) 2136–2139



Zeff ~ 51, ρ ~5.2g/cm^3

2MeV β range: ~1.8mm

Heavier material
→Shorter β range
→Smaller β-implant correlation radius
→Lower accidental background

La-GPS characteristics

Waveform

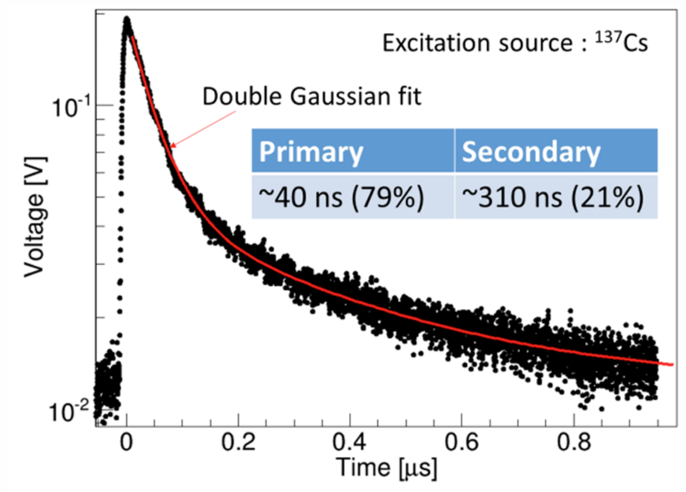


Fig. 6 Decay curve of Ce:La-GPS irradiated with gamma rays from a ^{137}Cs source.

Energy resolution

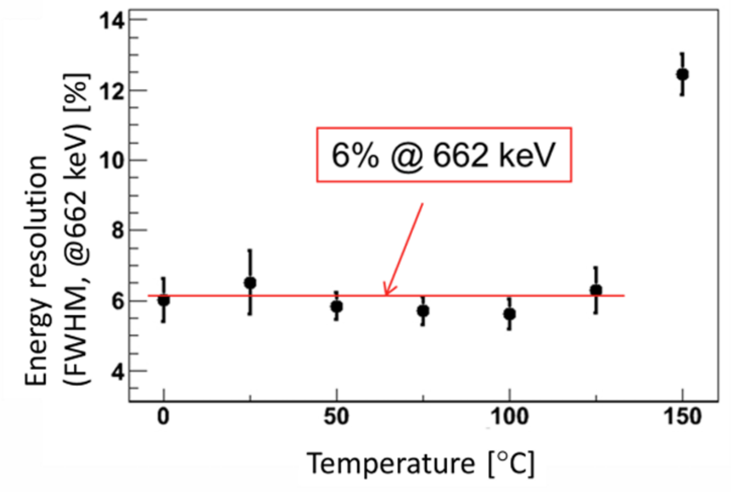
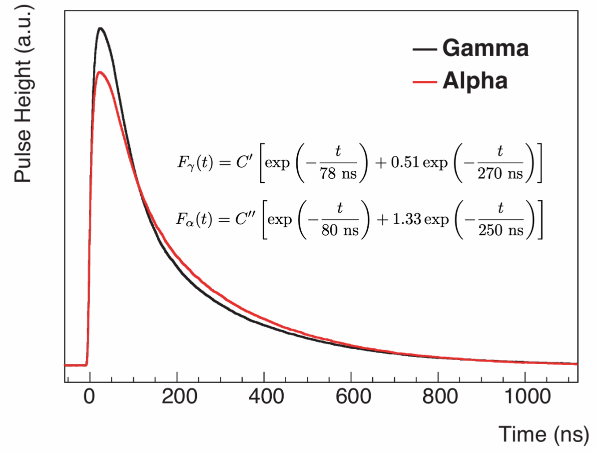
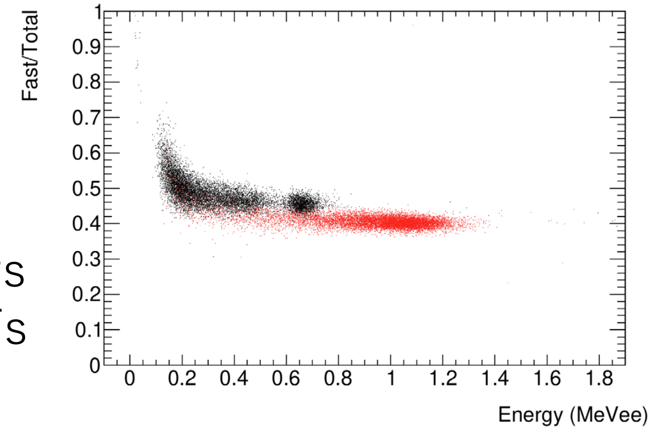


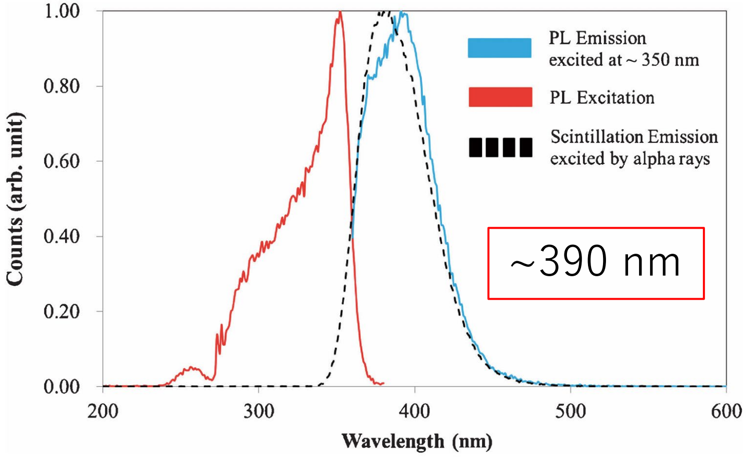
Fig. 9 Temperature dependence of energy resolution (FWHM, 662 keV) for Ce:La-GPS.

Pulse-shape discrimination capability





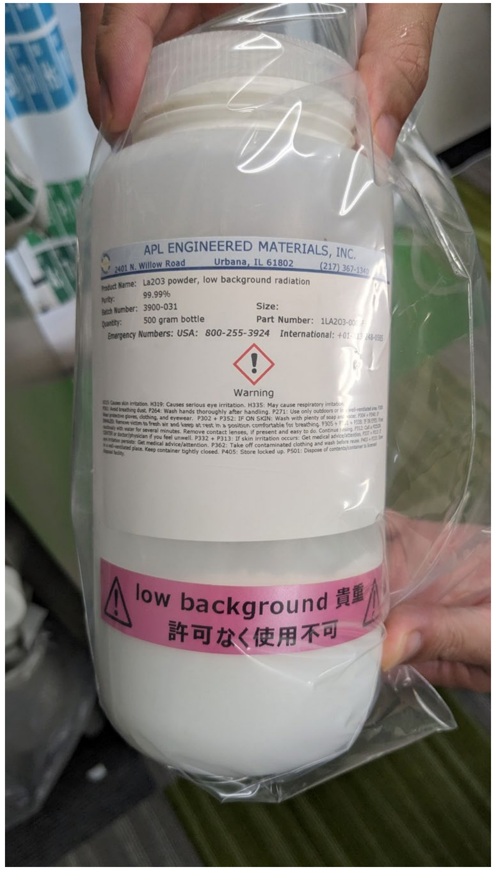
Emission wavelength



- High light output as halide scintillators (~36k photons/MeV)
- Fast time response as oxide scintillators
- Short wavelength that matches to PMTs unlike GAGG

S. Kurosawa et al.,日本結晶成長学会誌 Vol. 43, No. 1, 47-53 (2016)
K. Mizukoshi et al., Journal of Instrumentation 14, P06037 (2019)

2023/8/21 Tohoku



138La is radioactive

139-enriched La_2O_3
~350kJPY/500g
(70k for natural La)

~10% of total cost

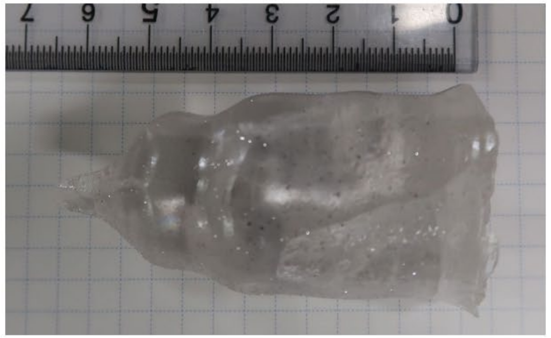
Heat and compress materials
in an iridium pod

La-GPS crystal growth

Seed crystal

2.5” rod

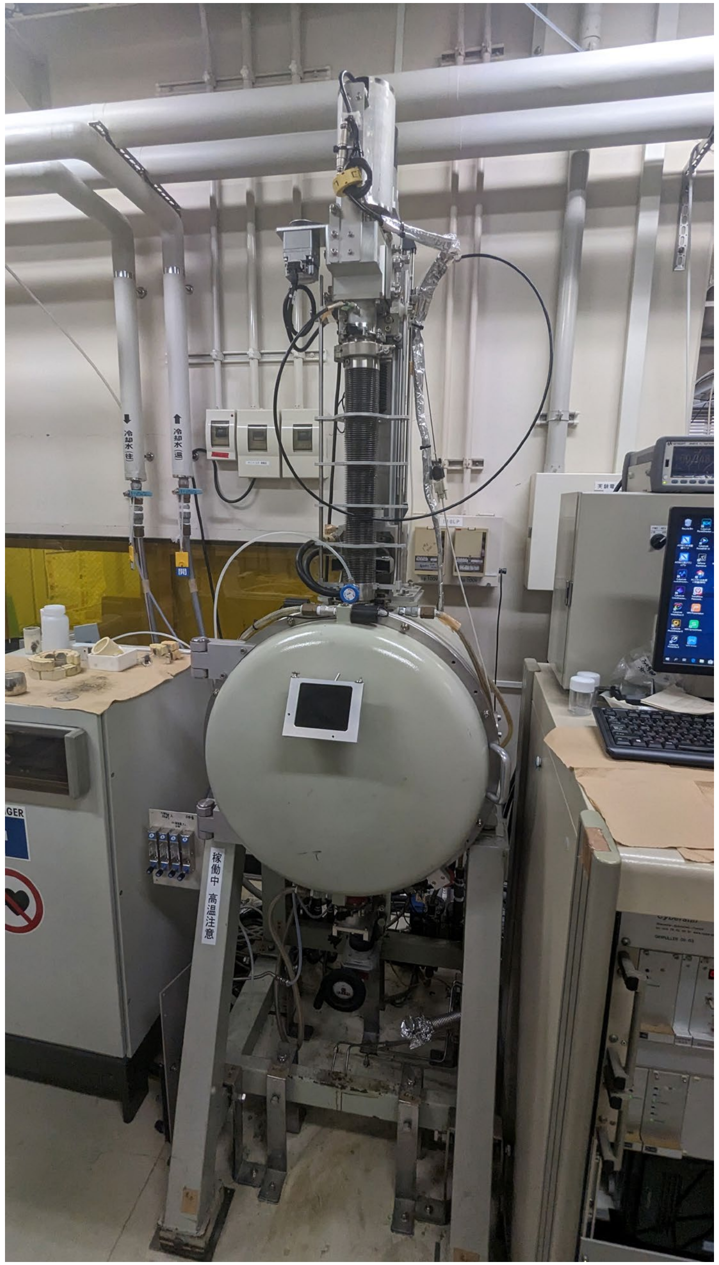
1st batch



2nd batch

3rd batch

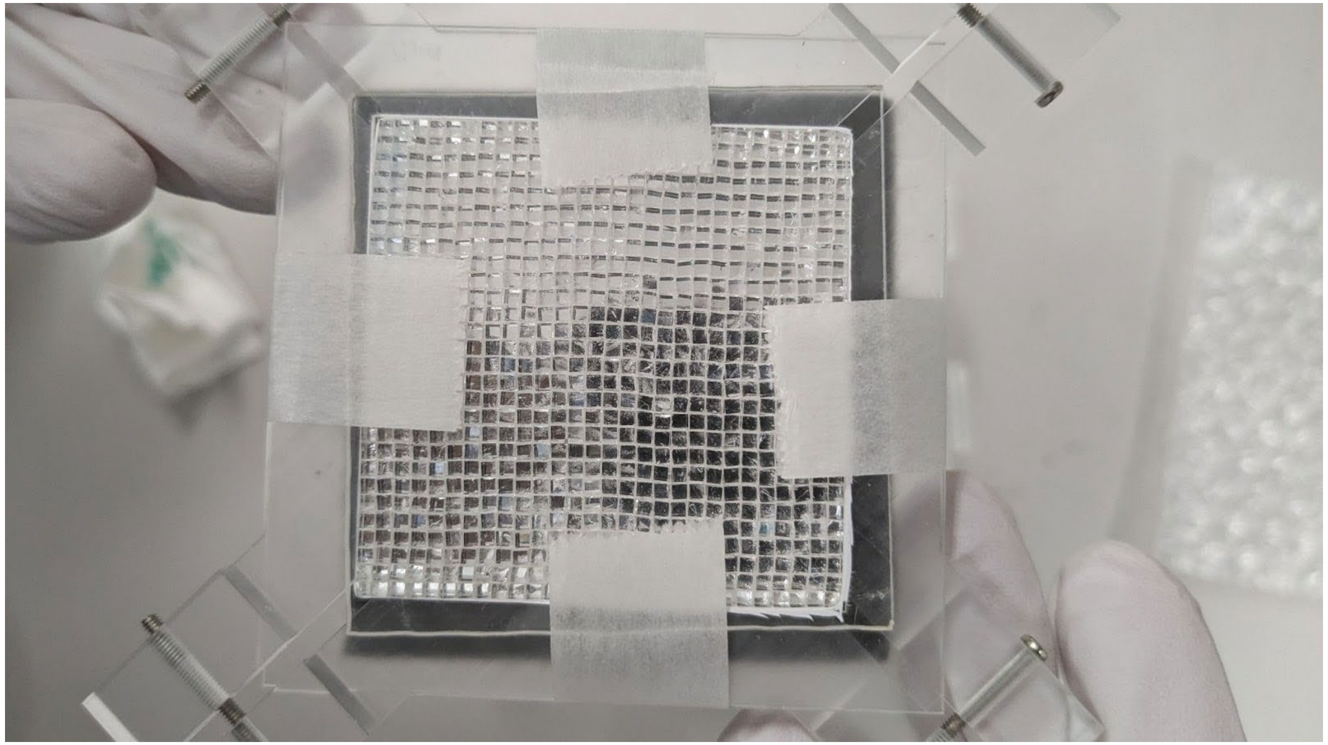
Heating chamber for Czochralski method



Making pixels

Cut into
1.5 mm x 1.5 mm x 2.5 mm pixels

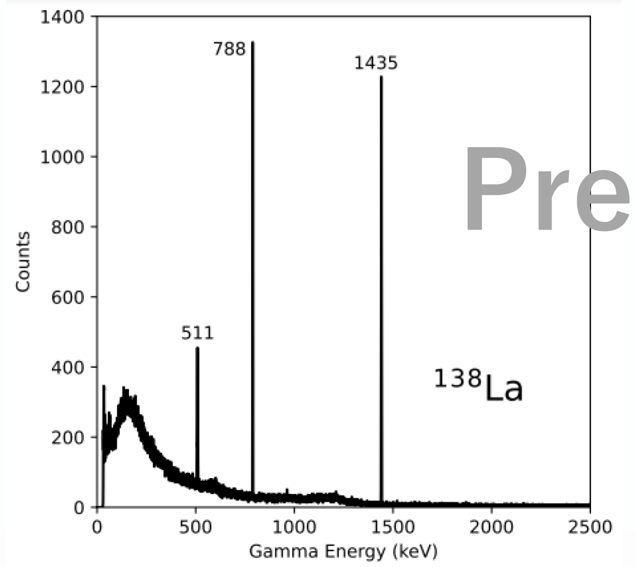
La-GPS Array



32 x 32 1.5mm x 1.5mmx2.5mm pixels
→Half the thickness of YSO

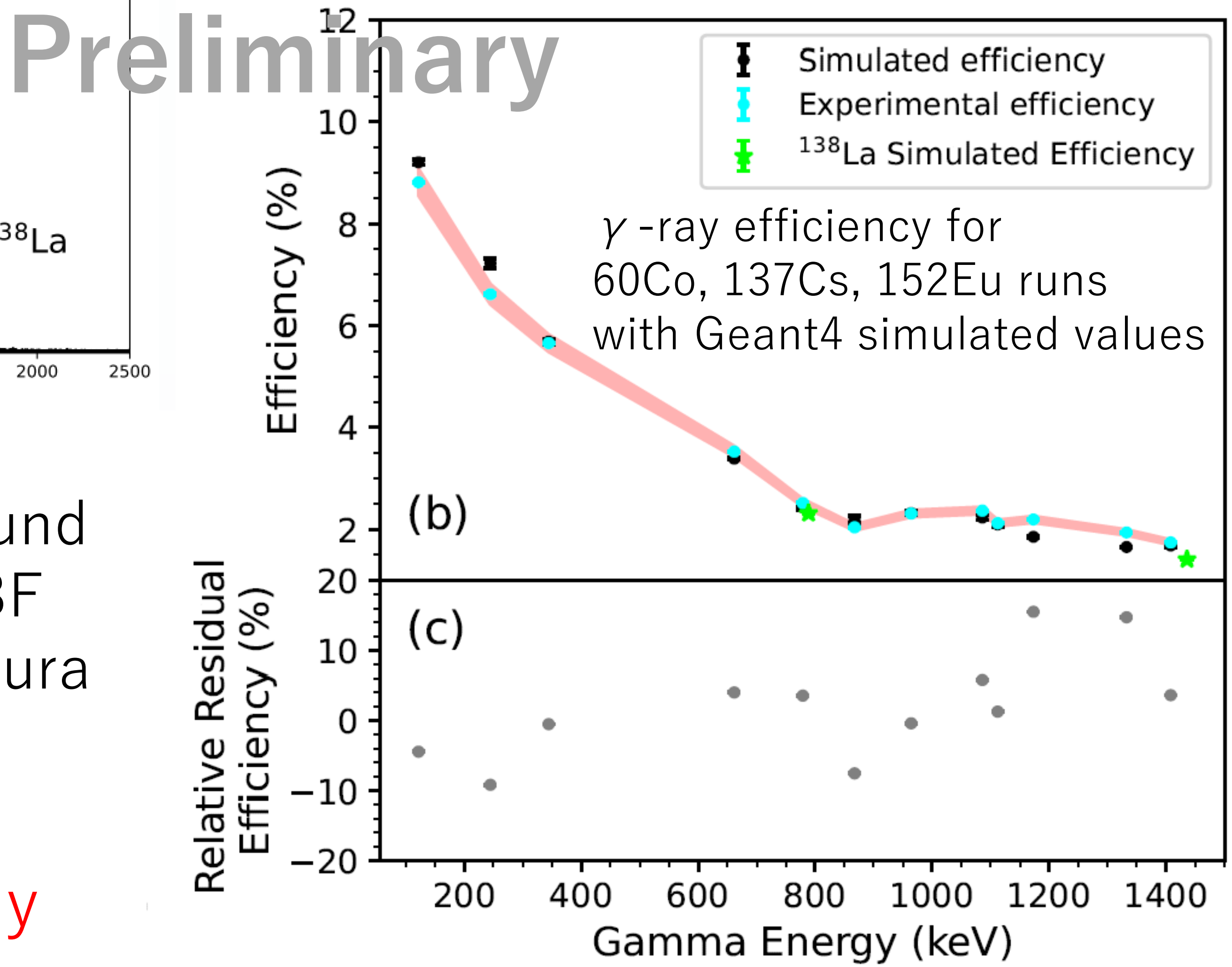
by Yasmin Anuar

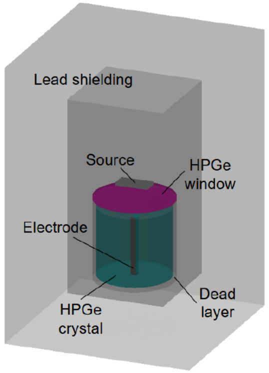
139La-GPS activity measurement



←Low background Ge setup at RIBF by Megumi Niikura

Geant4 simulation with Cascade γ emissions

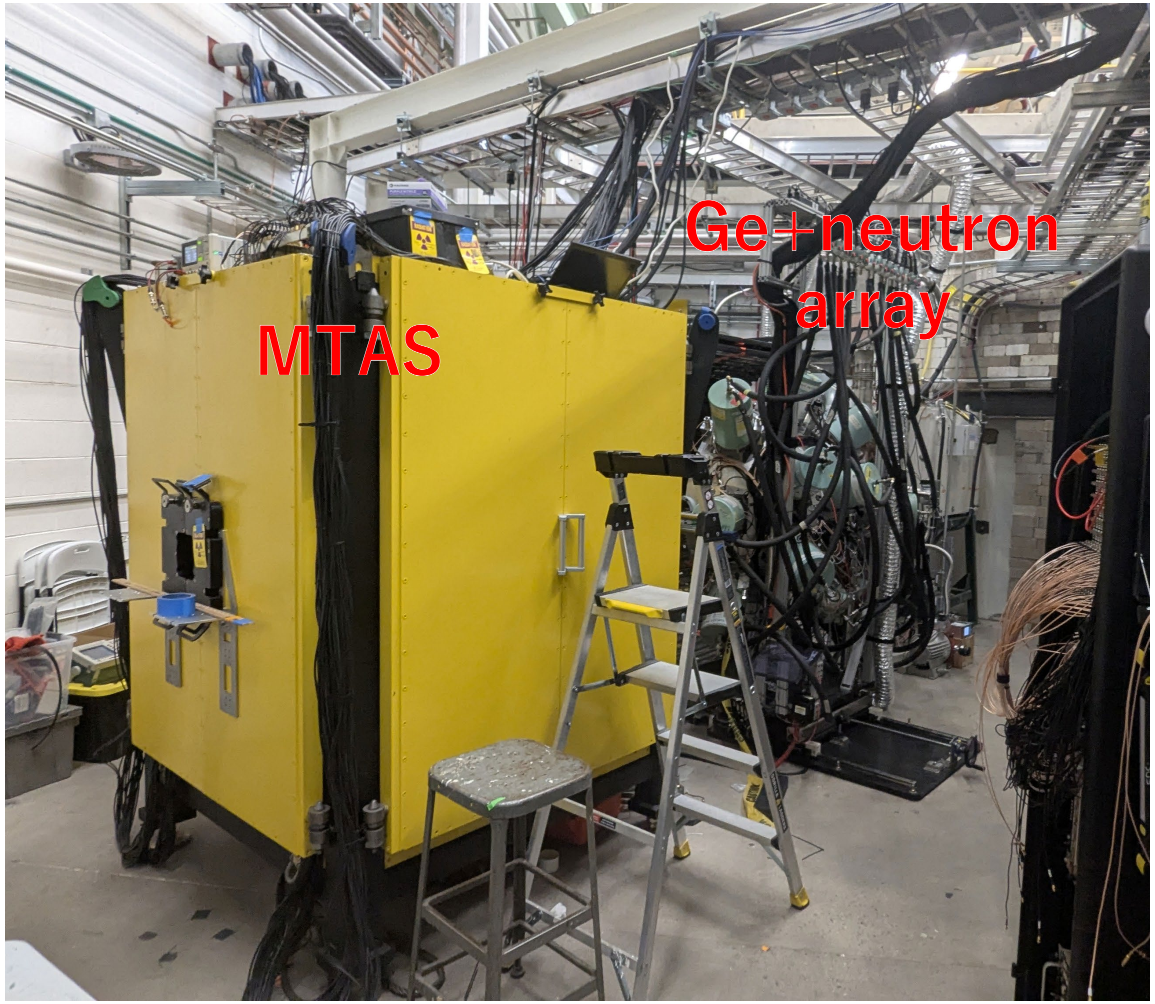


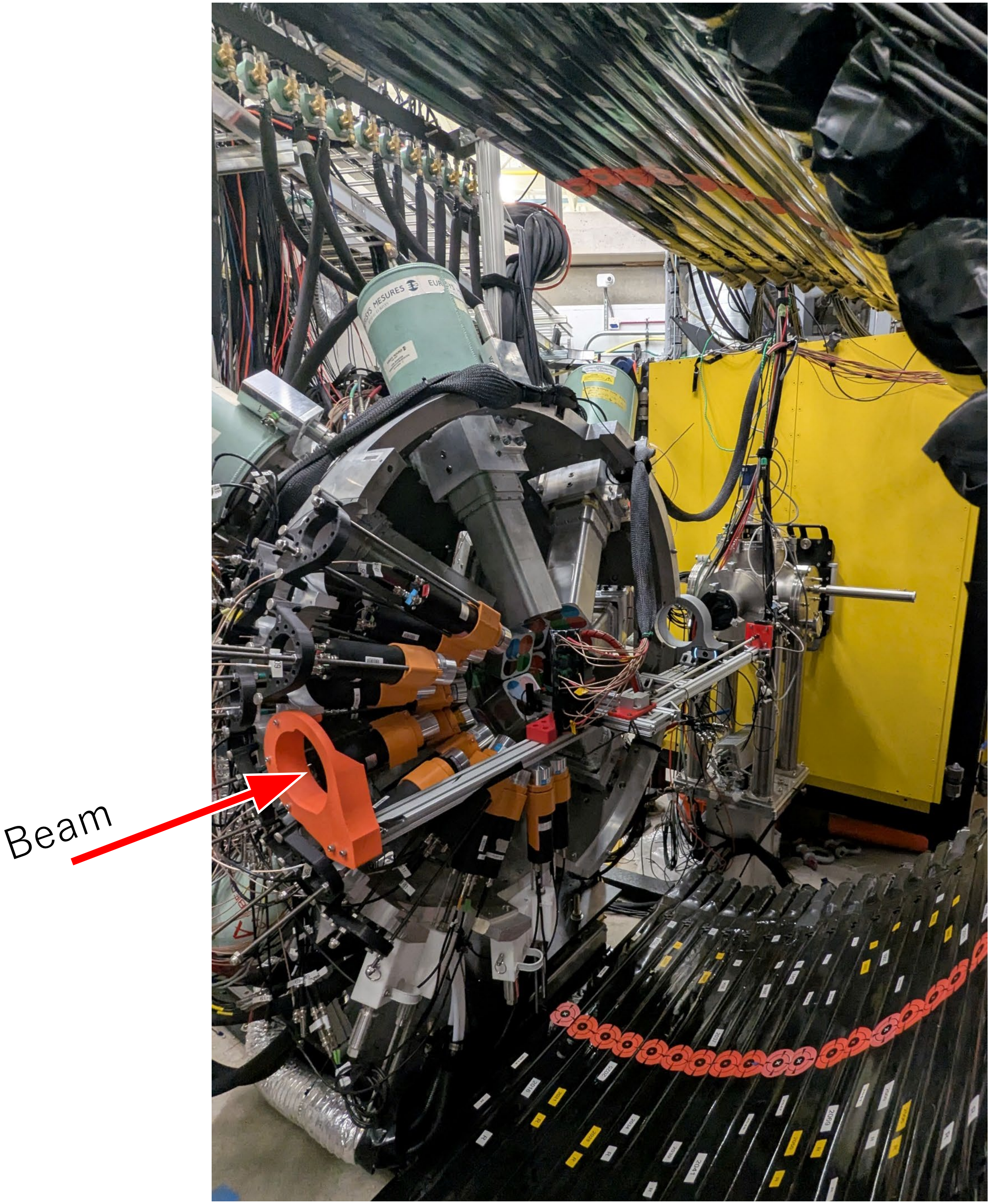


γ-ray efficiency for 60Co, 137Cs, 152Eu runs with Geant4 simulated values

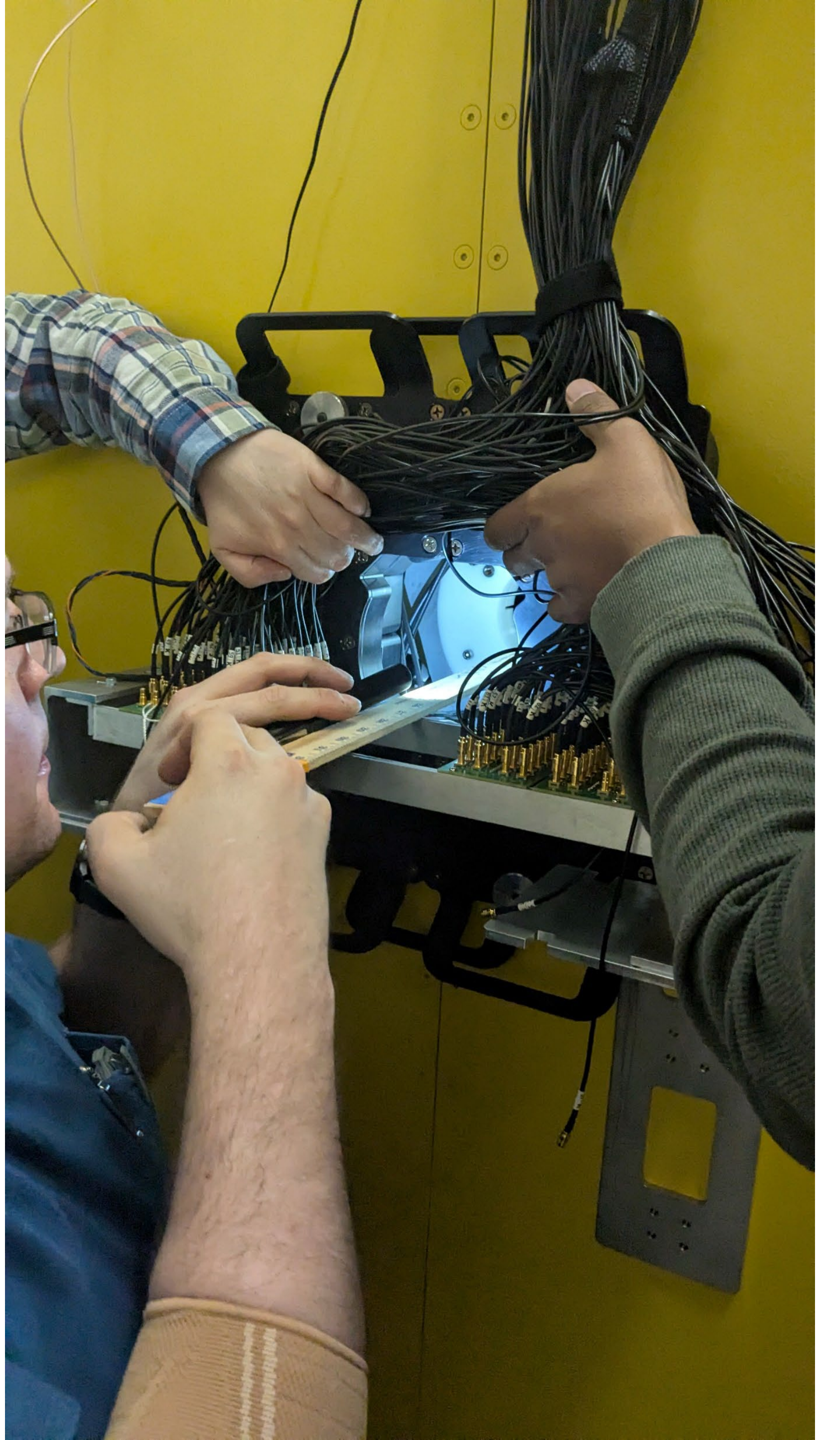
2.1(2)Bq for the entire array

La-GPS array at FRIB Decay Station





LaGPS Array for MTAS



La-GPS energy for implants

Preliminary

It has energy resolution
to see ΔE-TKE plot in the Z~28 region

Analysis ongoing

- β-implant correlation efficiency
- Quenching factor

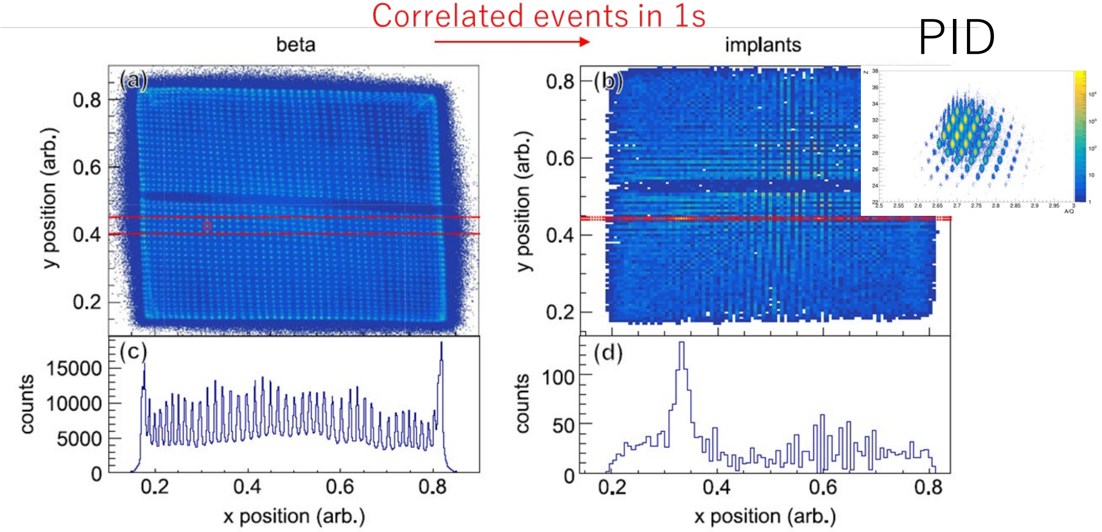
β-Implant detectors

- DSSDs
  - ✓Very good energy resolution
  - ❌Slow (not for neutron ToF)
- Plastic scintillator arrays
  - ✓Very fast/Cheap
  - ❌Low energy resolution
- YSO
  - ✓Fast (nToF)/Good β-implant correlation
  - ❌Low energy resolution/Low energy γ-ray absorption
- La-GPS
  - ✓Very good β-implant correlation/Good energy resolution/Fast (nToF)
  - ❌X-rays (49 keV)/Low energy γ-ray absorption

Contents

- Overview of decay spectroscopy at RIBF
- Study of β-delayed neutron emission
- New scintillator material for active stoppers
- Utilization of Apache Spark for efficient β-implant correlation analysis

Correlating β and implant events need computing power

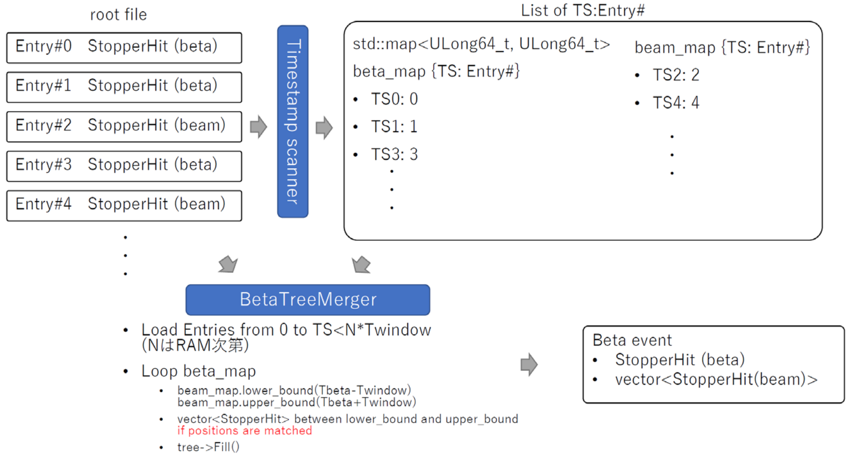


- 5 days of beam at RIBF
- 83Ga (2e7 implants)
- Took 238m49s with a 32-core server with my C++ code

- Beta-implant detector: 1-2 kHz
- Finding correlations with ±1s
- Distance between beta position and implant position < 3 mm

Also

Complicated coding
Requires quite some C++ knowledge



ROOT TTree → Apache Spark Dataframe

- Spark: Open-source distributed processing framework for big data
- Event building code became very simple

```python
from pyspark.sql import functions as F
RADIUS = 0.2
df_merged = df_beta.join(df_implant, \
                  on=[df_beta.beta_run==df_implant.imp_run, \
                      F.abs(df_beta.beta_ts-df_implant.imp_ts)<1e9, \
                      F.pow(df_beta.posXH-df_implant.posXL,2)+F.pow(df_beta.posYH-df_implant.posYL,2) < RADIUS**2 \
                     ], \
                  how='inner')
```

Python

Join dataframes of β and implant events

Conditions:

- ←Runnumber match
- ←timestamp difference ±1s
- ↑distance of β and implant event $<$ RADIUS

↑Only keep rows with both data

Automatically

- Multithreaded/lazy evaluation/Catalyst optimizer (plans algorithm to use)

238m49s with a 32-core server → 114m49.866s with a 16-core PC

PC Cluster

Spark + hadoop HDFS

miniPC1
(i7-13620H)
Driver+executor

miniPC2
(i7-13700H)
executor

desktopPC
(i7-14700F)
executor

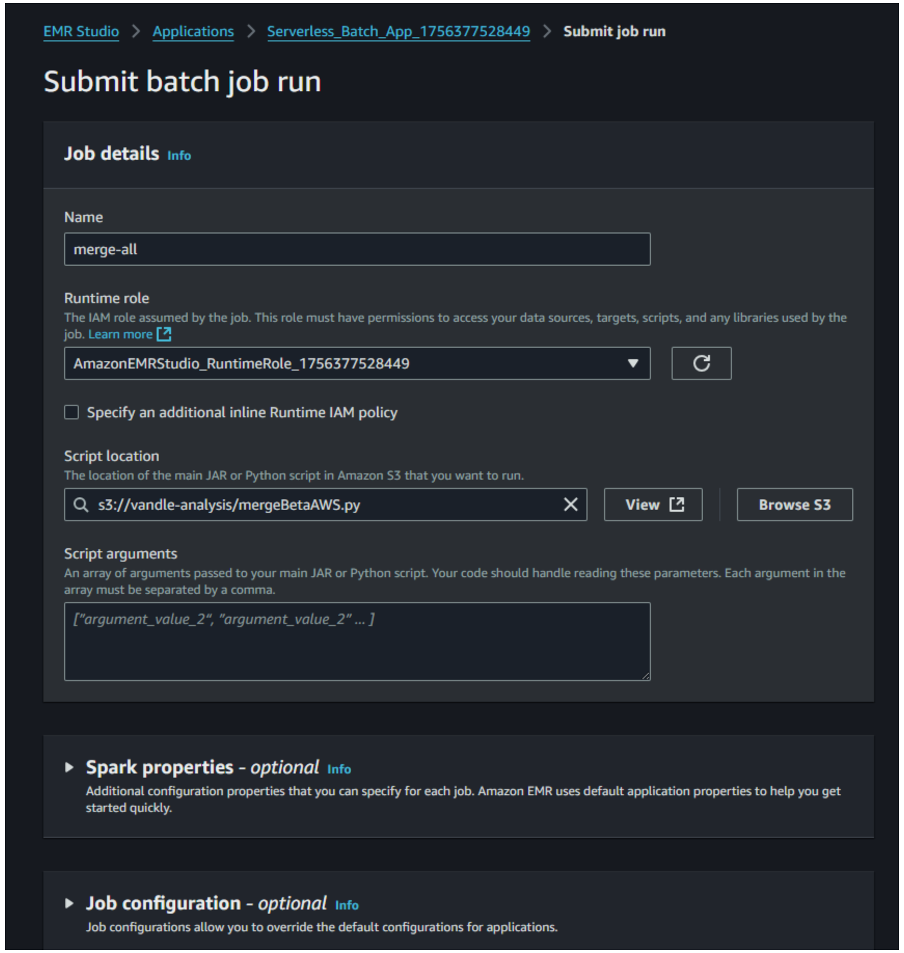
Executor ID	Address	Status	RDD Blocks	Storage Memory	Disk Used	Cores	Active Tasks
driver	192.168.0.9:40089	Active	0	381.3 KiB / 5.8 GiB	0.0 B	0	0
0 desktop	192.168.0.3:42203	Active	0	324.7 KiB / 5.8 GiB	0.0 B	28	28
1 miniPC2	192.168.0.4:39115	Active	0	290 KiB / 5.8 GiB	0.0 B	20	21
2 miniPC1	192.168.0.9:36581	Active	0	290 KiB / 5.8 GiB	0.0 B	16	17

- 64 cores in total
- 37m12.331s
  (miniPC1 local: 114m49.866s)

Amazon EMR Serverless

Amazon
S3

- Upload data and codes to S3(Amazon Simple Storage Service)



Spark 3.5.5-amzn-0 | Jobs | Stages | Storage | Environment | Executors | SQL / DataFr

Executors

Show Additional Metrics

Summary

	RDD Blocks	Storage Memory	Disk Used	Cores	Active Tasks	Failed Tasks
Active(128)	0	213.1 MiB / 1008.3 GiB	0.0 B	508	513	0
Dead(0)	0	0.0 B / 0.0 B	0.0 B	0	0	0
Total(128)	0	213.1 MiB / 1008.3 GiB	0.0 B	508	513	0

8 min, 44 secs

Billed resource utilization
33.077 vCPU-hours
132.307 memoryGB-hours
0 storageGB-hours

2.50USD

- 512 cores
- Took 8min 44s + 2.50USD

~ 4hours to 8min

What is EMR Serverless Spark?

Updated at: 2025-03-31 16:48 Product Community

E-MapReduce (EMR) Serverless Spark is a high-performance lakehouse service for data and AI scenarios. It provides end-to-end data platform services for enterprises, such as job development, debugging, scheduling, and O&M. This significantly simplifies data processing and model training workflows. EMR Serverless Spark is also fully compatible with the open source Spark ecosystem and can be seamlessly integrated with an existing customer-side data platform. EMR Serverless Spark helps enterprises improve efficiency by focusing on data processing and analysis and optimization of model training.

Features

Fully managed data platform services for enterprises

- **Ease of use**
  We are committed to providing optimal user experience. You can start to develop jobs without the need to build complex infrastructure.
- **High performance**
  Built based on Fusion Engine, formerly Spark Native Engine, EMR Serverless Spark provides up to four times the performance of open source Spark.
- **High scalability**
  Based on the serverless computing capabilities of Alibaba Cloud, EMR Serverless Spark provides highly scalable

Feedback

Contents

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Summary

- EURICA
- BRIKEN
  - 160 new half-lives, 70 new P_{1n}, 10 new P_{2n}, many papers…
- C2URIE project (HPGe detectors from Europe, China, and Korea)
  - Higher γ-ray efficiency with upgraded beam capabilities since EURICA
- Pure exotic RI beam for decay spectroscopy

- Multi-neutron emission process is complicated
- KSHELL+stochastic estimation + HF statistical model

- 139 enriched La-GPS scintillator as a new active stopper
- 2 Bq for entire array/good energy resolution/first implementation at FRIB

- Apache Spark for efficient β-implant correlation