

Gamma-ray spectroscopy at RCNP, Osaka University

Eiji Ideguchi
RCNP, Osaka University

RCNP Research Activity




CANDLES
@ KAMIOKA

double
 β decay

LEPS@SPring8


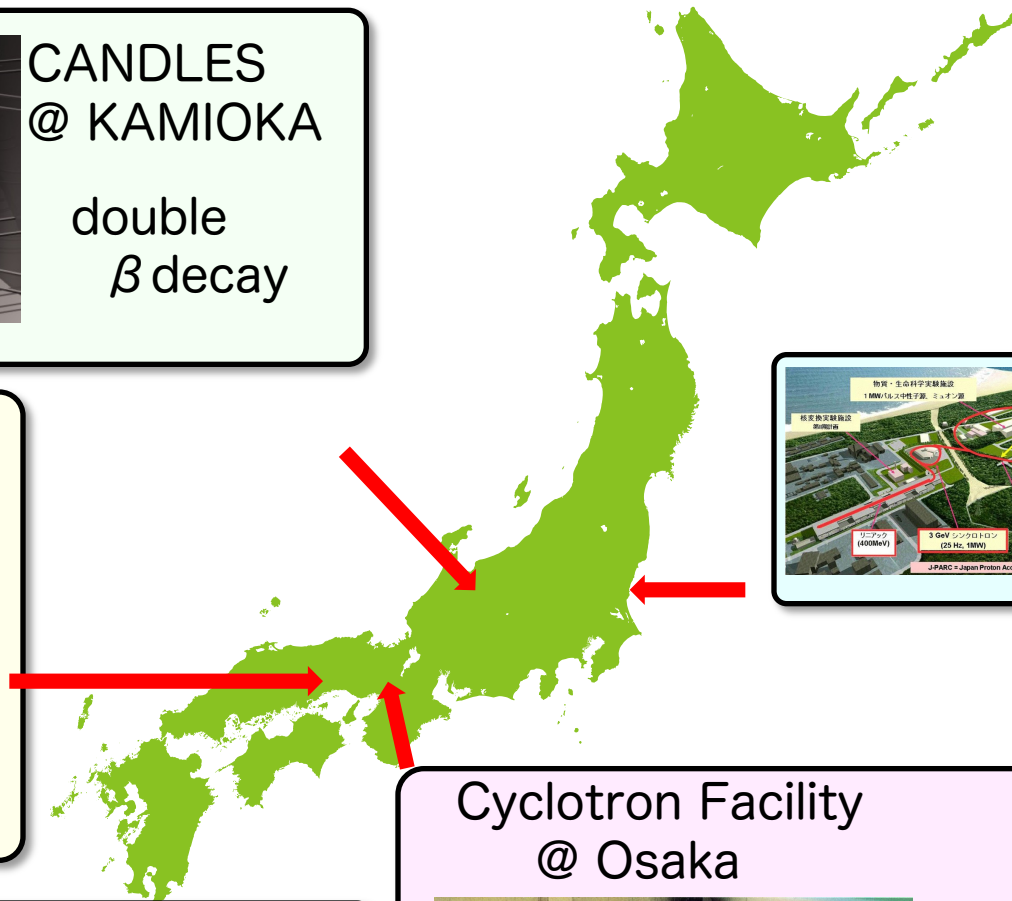


Hadron Physics
Penta-quark



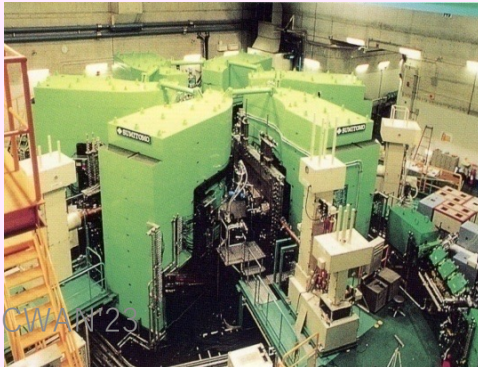
Theory

Hadron
Nucl. Phys.
Super Comp



J-Parc
Hadron
 Λ /Charm

Cyclotron Facility
@ Osaka



Nuclear Physics
Accelerator Phys.
 n EDM
 μ
Application

Physic Opportunities at RCNP Cyclotron Facility

K400 ring cyclotron



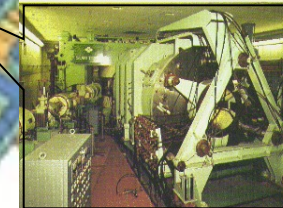
EN beam line for RI beam



p: 400MeV
HI: 100MeV/u



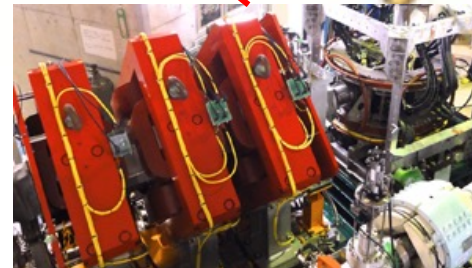
MuSIC



K140 AVF cyclotron
p ~ Xe
Pol. p & d



Double arm spectrometer (Grand Raiden & LAS)



MuSIC (DC Muon beam)

CAGRA Project at RCNP, Osaka University

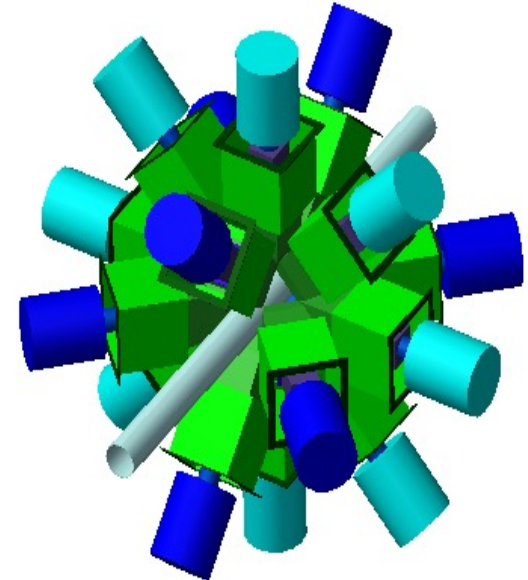
CAGRA (Clover Array Gamma-ray spectrometer
at RCNP/RIBF for Advanced research)

RCNP-Tohoku-ANL-ARL-IMP-Milano... collaboration

Eiji Ideguchi (RCNP, Osaka University)

Contents:

- Brief introduction of CAGRA project
- Recent highlight
- Future perspective



Collaborating Institutions and Personal on FOA Proposal

Argonne National Laboratory - M.P. Carpenter, C. Hoffman, R.V.F. Janssens, T.L. Khoo, F.G. Kondev, T. Lauritsen, C.J. Lister, E.A. McCutchen, D. Seweryniak, S. Zhu
CNS, University of Tokyo – (E. Ideguchi), S. Shimoura, S. Go
Lawrence Berkeley National Laboratory – P. Fallon, R. Clark, A. O. Macchiavelli
RIKEN – (N. Aoi), Y. Ichikawa, T. Motobayashi, S. Nishimura, H. Sakurai, H. Ueno, H. Watanabe
Yale University – Volker Werner, Rick Casten
Tohoku University – T. Koike, T. Sumikama,
Florida State University – S Tabor, M. Riley, I. Wiedenhoever
Kyushu University – T. Morikawa
Oak Ridge National Laboratory - C.-H. Yu, D. Radford
Osaka University – A. Odahara
Washington University – W. Reviol, D. Sarantities
Tokyo University of Science – (T. Sumikama)
University of Richmond – C. Beausang
University of Maryland – C. J. Chiara
University of Notre Dame – U. Garg
United States Navel Academy – D. Hartley
Mississippi State University – W. Ma
+ RCNP, Osaka University – E. Ideguchi, N. Aoi, A. Tamii, H.J. Ong, N. Kobayashi, J. Issak, S. Noji, T. Hashimoto, C. Iwamoto, Y. Ayyad, ...

➡ Expanding collaboration (+Europe, +Asia, ...)

CAGRA project

- By using the existing **Compton Suppressed Ge Clover detectors** from laboratories in **Japan** and **the U.S. + China**, it is assembled to the CAGRA array at RCNP/RIBF to be utilized in gamma-ray spectroscopy.
- Physics experiments at RCNP using EN, GR, MuSIC
- At RIBF using both energy degraded and stopped beams of exotic nuclei.
- **Mechanical Infrastructures** to be built
 - Self contained, trigger-less acquisition system using Gretina Digitizers
 - Liquid Nitrogen filling system
 - Support structure
- **Physics Scope**
 - Multi-Step Coulomb excitation
 - Transfer or Deep Inelastic reactions
 - Fusion Evaporation
 - Stopped Beams

Exp. at RCNP

- Exp. at EN beam line
- Exp. at Grand Raiden

Exp. at JAEA

Exp. at RIBF

Introduction

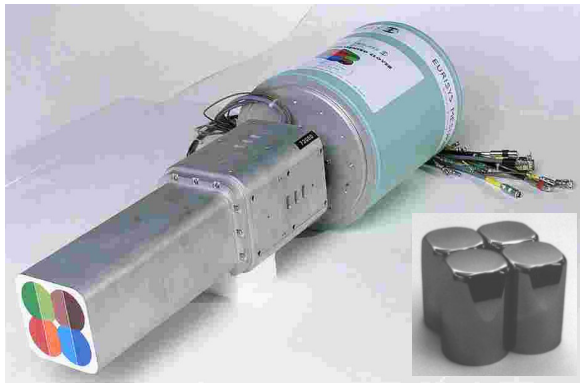
- Physics motivation

- Nuclear shell evolution across the nuclear chart
- Nuclear shape coexistence
- Nuclear triaxiality
- Superdeformation
- Astrophysical application
- Detailed nature of Pygmy dipole and Gamov-Teller resonances
- Isospin symmetry breaking

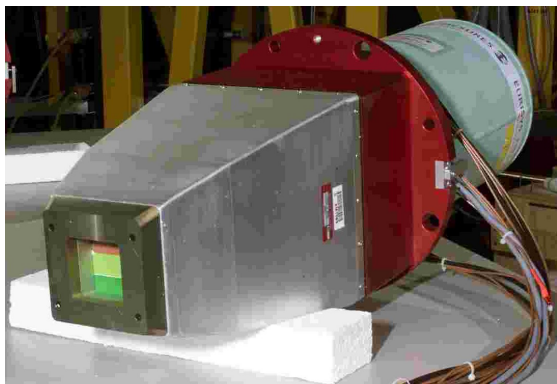
EN exp.
campaign

GR exp.
campaign

CAGRA status: Detector Inventory



6 clovers + Compton suppression shields from **Tohoku University**. Inventory from Hyper-Nuclei program at JPARC (T. Koike)



10 clovers + Compton suppression shields come from **CloverShare** in USA. These detectors originally comprised the Yrast Ball at the Wright Nuclear Structure Laboratory – Yale University (V. Werner and R. Casten).

2 Clovers from ARL (Jeff. Carroll)

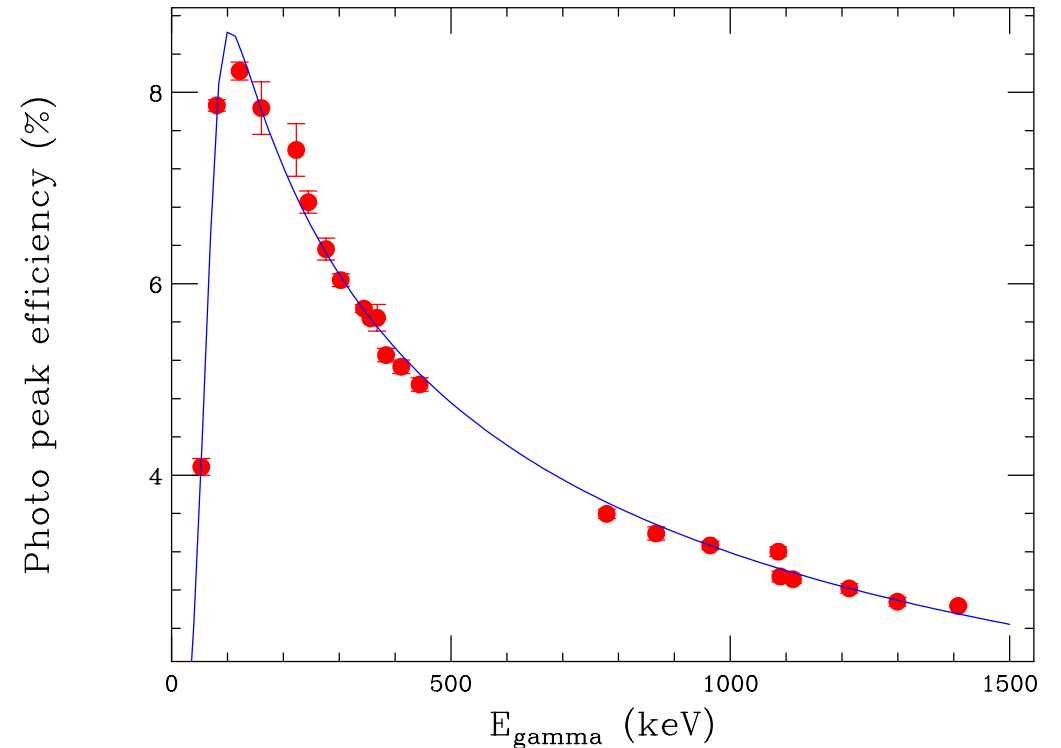
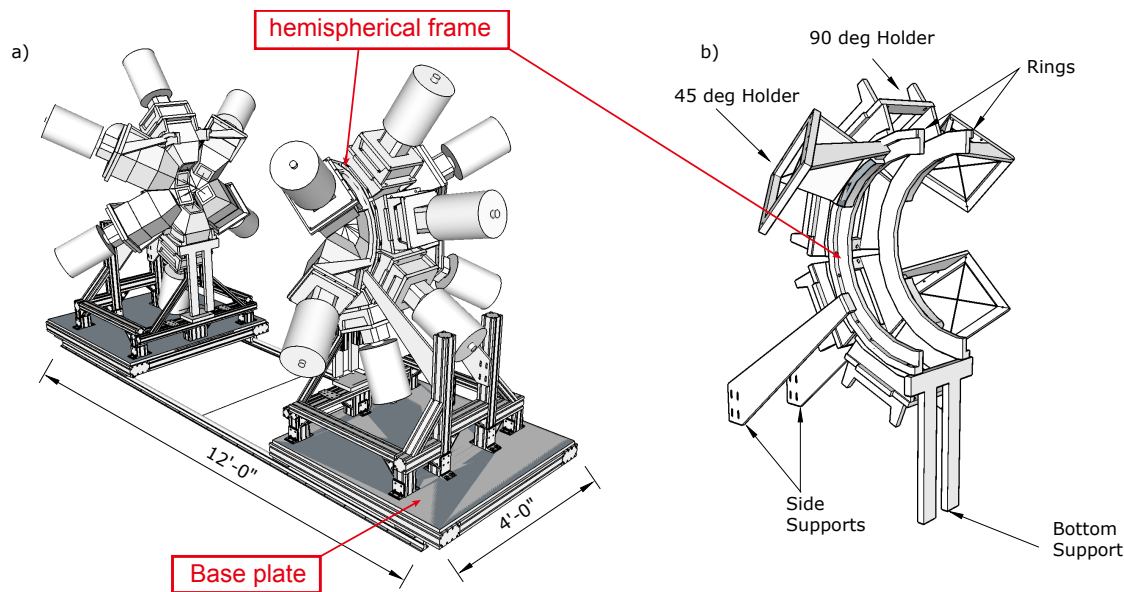
3 EXOGAM type Clover Detectors from **IMP**, China



4 Large volume LaBr₃ detectors from **Milano**: 3.5" ϕ - 8" L

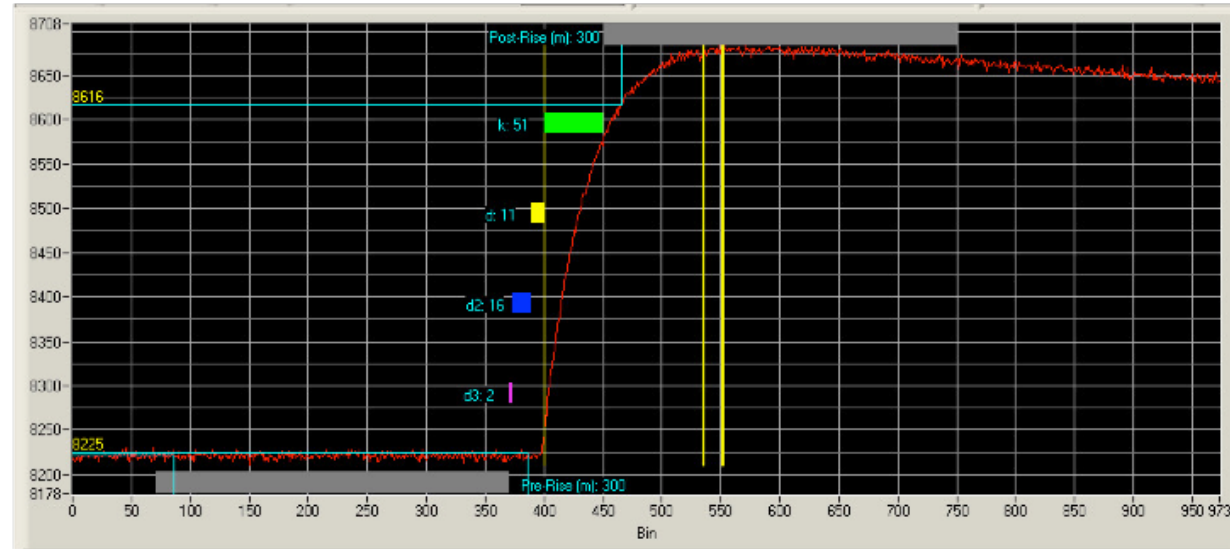
CAGRA specification

- 16 Compton suppressed Clover Ge detectors
 - 4 detectors at 45°
 - 8 detectors at 90°
 - 4 detectors at 135°
- **Target – Ge : 202mm**
- $\epsilon_{\text{ph}}(1\text{MeV}) \sim 3\%$



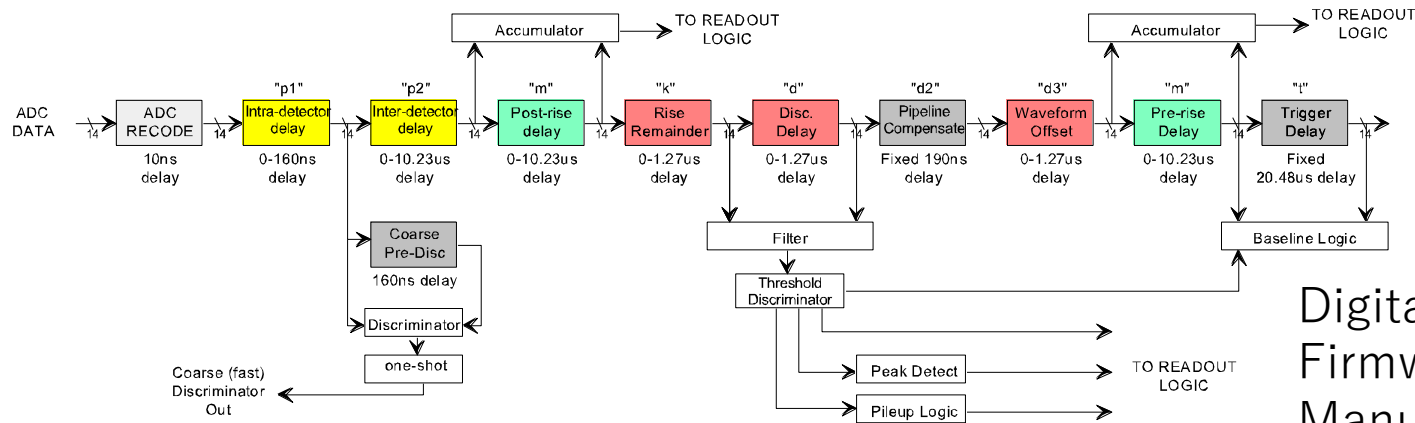
CAGRA Digital Data taking

Post rise



Pre rise

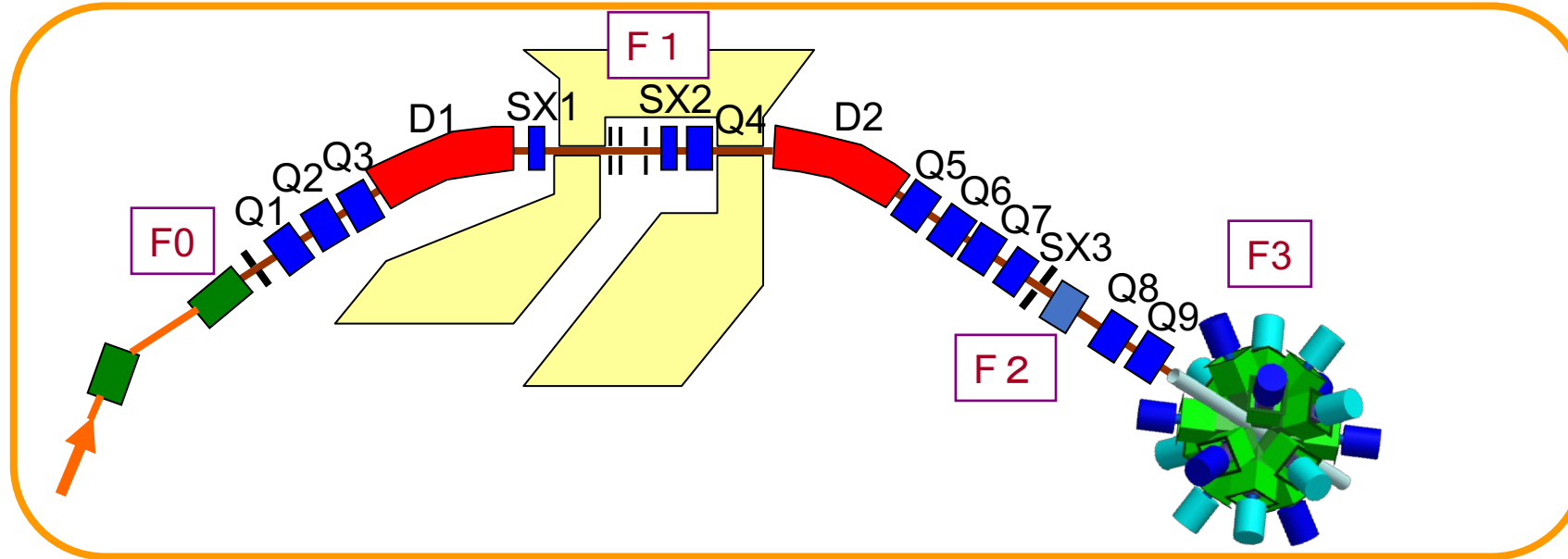
$$E = (\text{Post rise} - \text{Pre rise})/M$$



Digital Gammaphere
Firmware User's
Manual
J. Anderson, ANL

Campaign at RCNP-EN beam line

RCNP Exotic Nucleus beam line using Heavy Ion Beams



T. Shimoda et al., NIM B70 (1992) 320.

S. Mitsuoka et al., NIM A372 (1996) 489.

RI beam with beam energy
from low (~a few MeV/u)
to high (~several tens MeV/u)
can be delivered.

Maximum rigidity	3.2 Tm
Energy acceptance	$\Delta E/E = 16\%$
Angular acceptance	$\Delta\theta = 40$ mrad
	$\Delta\phi = 28$ mrad
Path length	16.8 m

Experiments at EN beam line

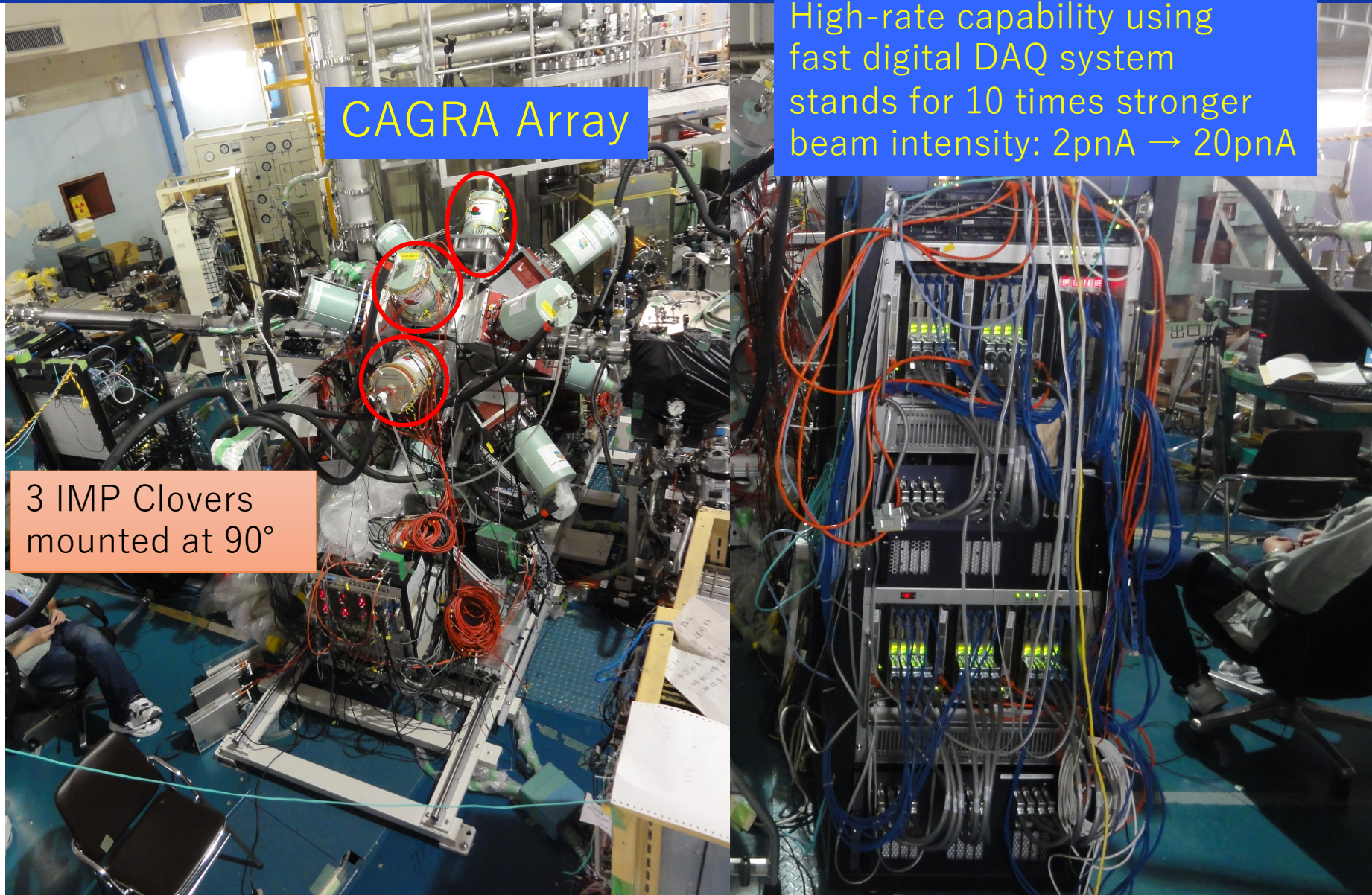
Experiments using stable beam

1. Study of superdeformed structure in ^{44}Ti , ^{45}Sc (E438: E. Ideguchi, RCNP)
2. Structure of excited states above the long-lived ($T_{1/2} \sim 1.5 \times 10^5 \text{y}$), $K^\pi = 8^+$ isomer in ^{186}Re (E435: F.G. Kondev, ANL)

Experiments using unstable beam

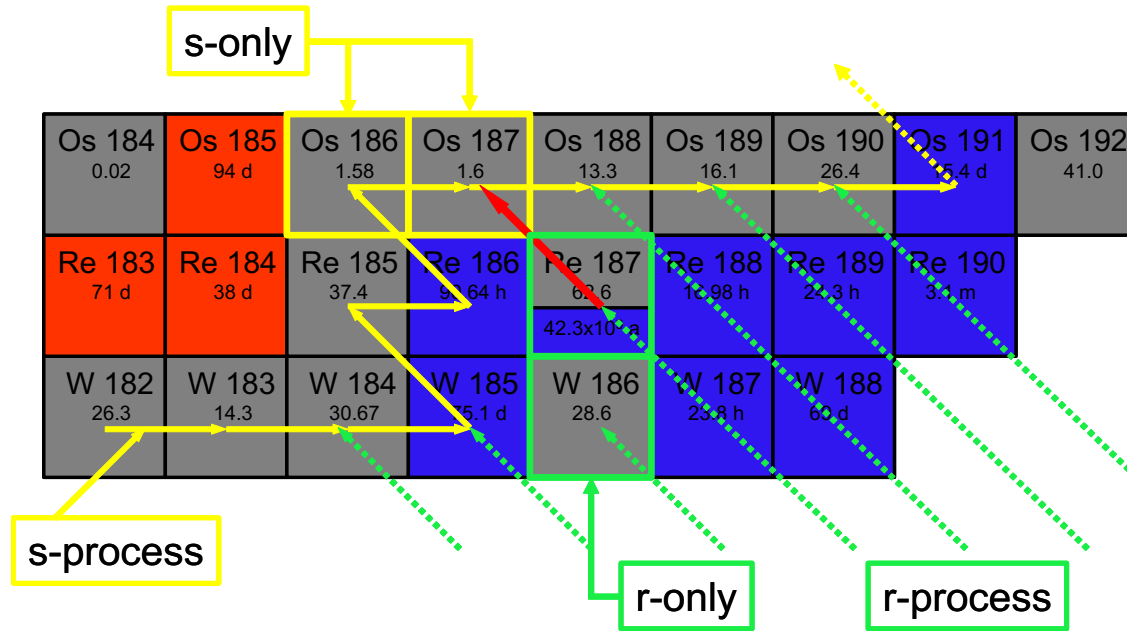
1. Probing High-Spin States in $^{61,62}\text{Fe}$ Using the $^{48}\text{Ca}(^{17}\text{N}, \text{pxn})$ Reaction (E436: M.P. Carpenter, ANL)
2. Study of High-Spin States by RI Beam Induced Fusion Reaction (E448: A. Odahara, Osaka)
3. Study of shell evolution at $N=20$ in neutron-rich region through nucleon transfer reaction (E439: T. Yamamoto & N. Aoi, RCNP)
4. Spectroscopy of ^{15}B : A search for unexpected bound states (E437: C.R. Hoffman, ANL)

CAGRA campaign experiments at EN beam line



E435

Structure of excited states above the long-lived ($T_{1/2} \sim 2.0 \times 10^5 \text{y}$), $K^\pi = 8^+$ isomer in ^{186}Re



^{187}Re - ^{187}Os cosmochronometer can be used to date the r-process

D.D. Clayton, Ap.J. 139 (1964) 637.

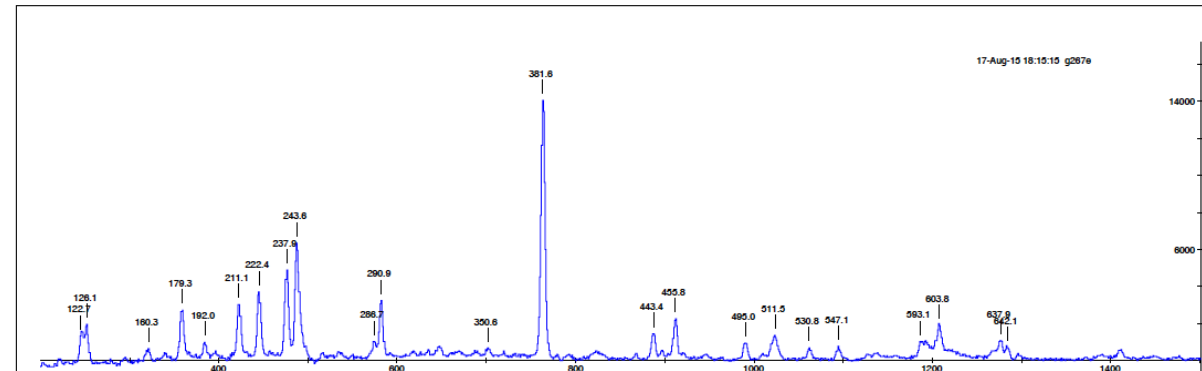
the existence of long-lived isomeric state
the production & destruction CS for the isomer are poorly known, but badly needed!

$^{186\text{m}}\text{Re}$ could contribute to the production of ^{187}Re in s-process nucleosynthesis

$^{186}\text{W}(d,2n)$

✓ at Osaka U & CAGRA

✓ γ - γ coin. at 14 MeV – identification of structures above the very long-lived $K^\pi = 8^-$ isomer ^{186}Re



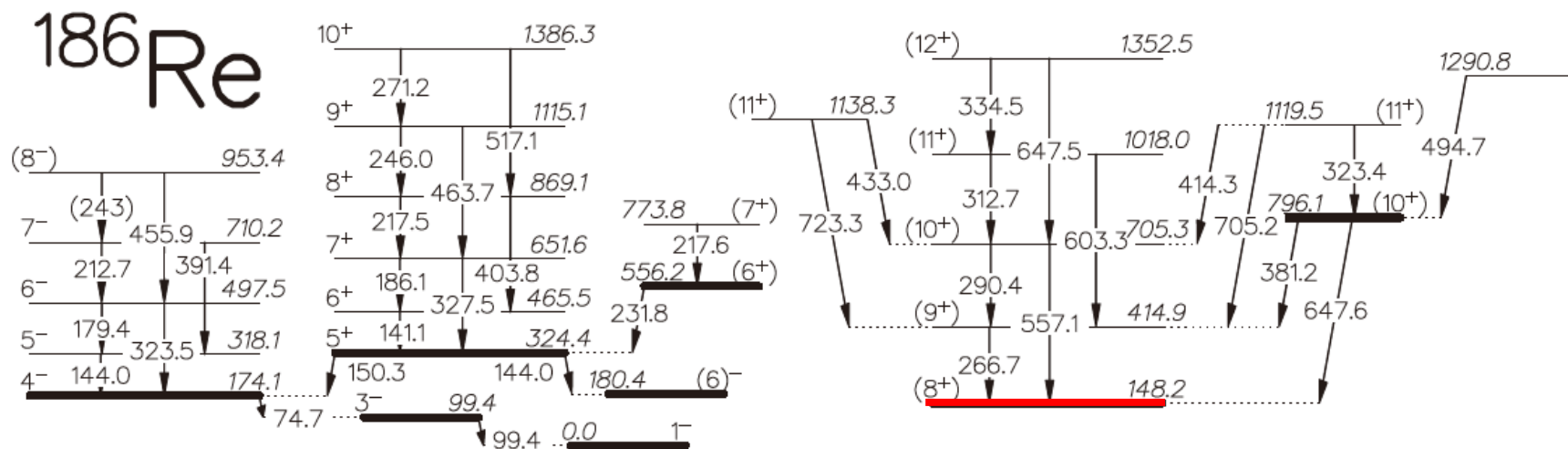
gamma rays above the $K^\pi = 8^+$ isomer

Recent CAGRA result

PHYSICAL REVIEW C 96, 014318 (2017)

In-beam γ -ray spectroscopy studies of medium-spin states in the odd-odd nucleus ^{186}Re

D. A. Matters,^{1,*} F. G. Kondev,² N. Aoi,³ Y. Ayyad,^{4,†} A. P. Byrne,⁵ M. P. Carpenter,⁶ J. J. Carroll,⁷ C. J. Chiara,⁸
P. M. Davidson,⁵ G. D. Dracoulis,^{5,‡} Y. D. Fang,³ C. R. Hoffman,⁶ R. O. Hughes,⁵ E. Ideguchi,³ R. V. F. Janssens,⁶ S. Kanaya,⁹
B. P. Kay,⁶ T. Kibédi,⁵ G. J. Lane,⁵ T. Lauritsen,⁶ J. W. McClory,¹ P. Nieminen,⁵ S. Noji,^{3,8} A. Odahara,⁹ H. J. Ong,³
A. E. Stuchbery,⁵ D. T. Tran,³ H. Watanabe,^{10,11,12} A. N. Wilson,⁵ Y. Yamamoto,³ and S. Zhu⁶



E439

Study of shell evolution at $N = 20$ in neutron-rich region through nucleon transfer reaction

Spokes person : Tetsuya Yamamoto (RCNP), Nori Aoi(RCNP)

Beam Time - 2015/05/02 ~ 2015/05/10

Purpose

- ◆ Study of the mechanism of shell evolution around $N = 20$ neutron rich region.

→ Measurement of the $N = 20$ ($f_{7/2} - d_{3/2}$) neutron shell gap.

→ We choose ^{29}Mg , ^{31}Mg , ^{33}Si which are locating across the “island of inversion”.

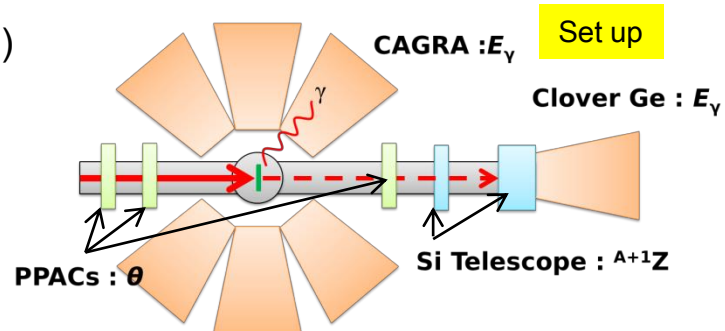
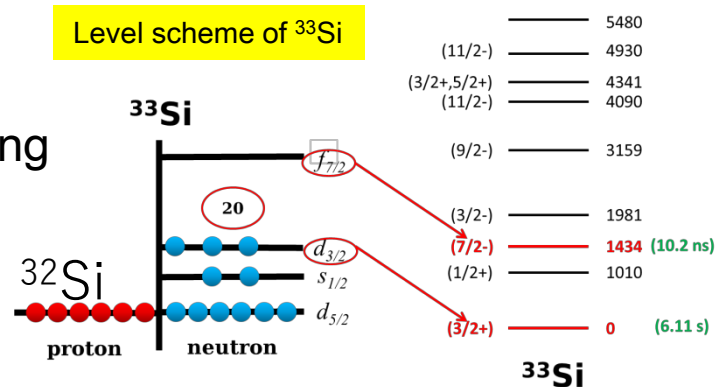
- ◆ Study of proton and neutron collectivity in ^{32}Si

Experiment

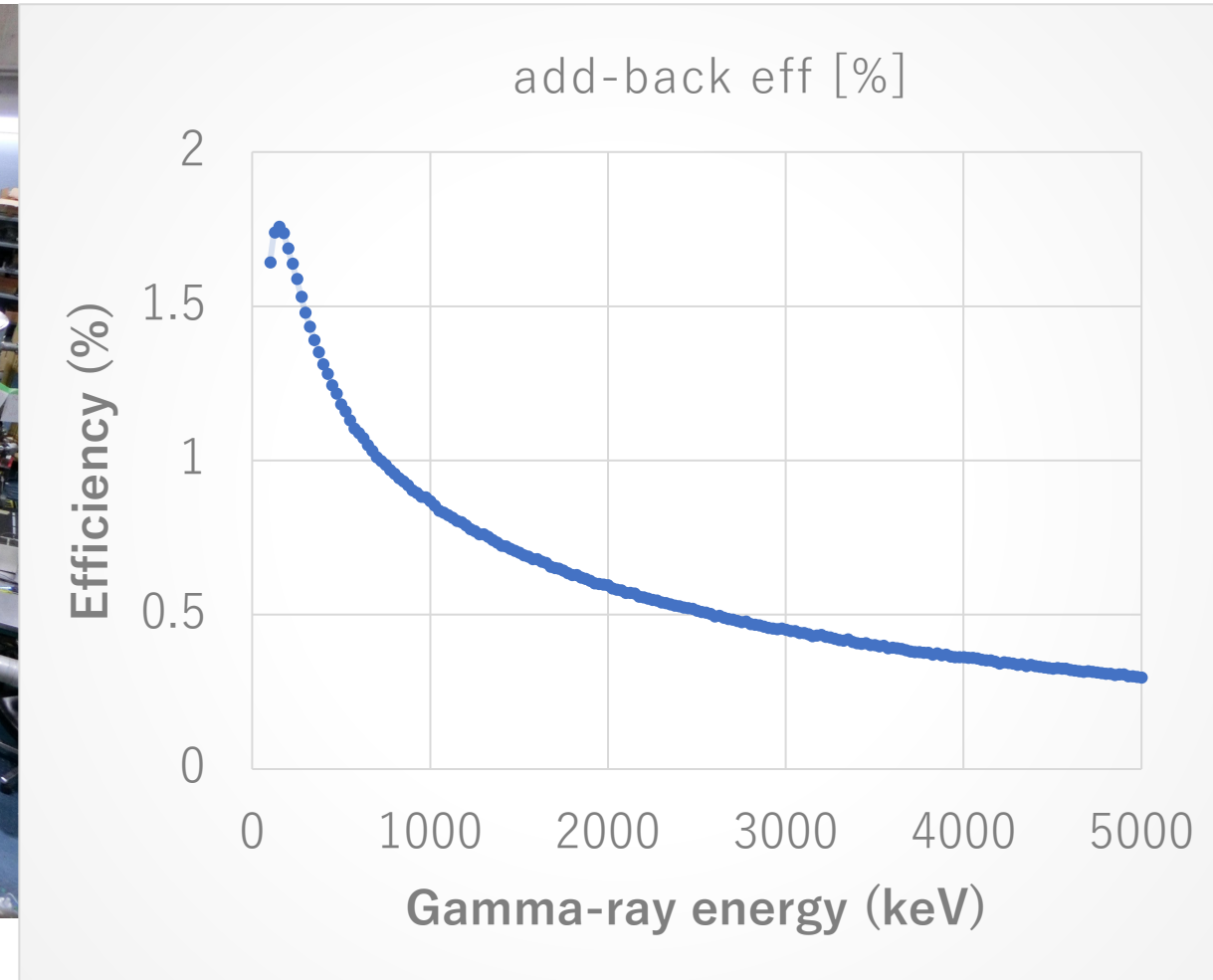
- ◆ Beam : (primary) ^{40}Ar , (secondary) $^{28,30}\text{Mg}$, ^{32}Si
- ◆ Reaction : $^{28}\text{Mg}(d,p)^{29}\text{Mg}$, $^{30}\text{Mg}(d,p)^{31}\text{Mg}$, $^{32}\text{Si}(d,p)^{33}\text{Si}$, $^{32}\text{Si}(d,d')^{32}\text{Si}$
- ◆ Measurement : θ_{sc} , γ (especially $7/2^- \rightarrow 3/2^+$)



$$E_{\text{ex}}, \frac{d\sigma}{d\Omega}, J^\pi, S_f$$

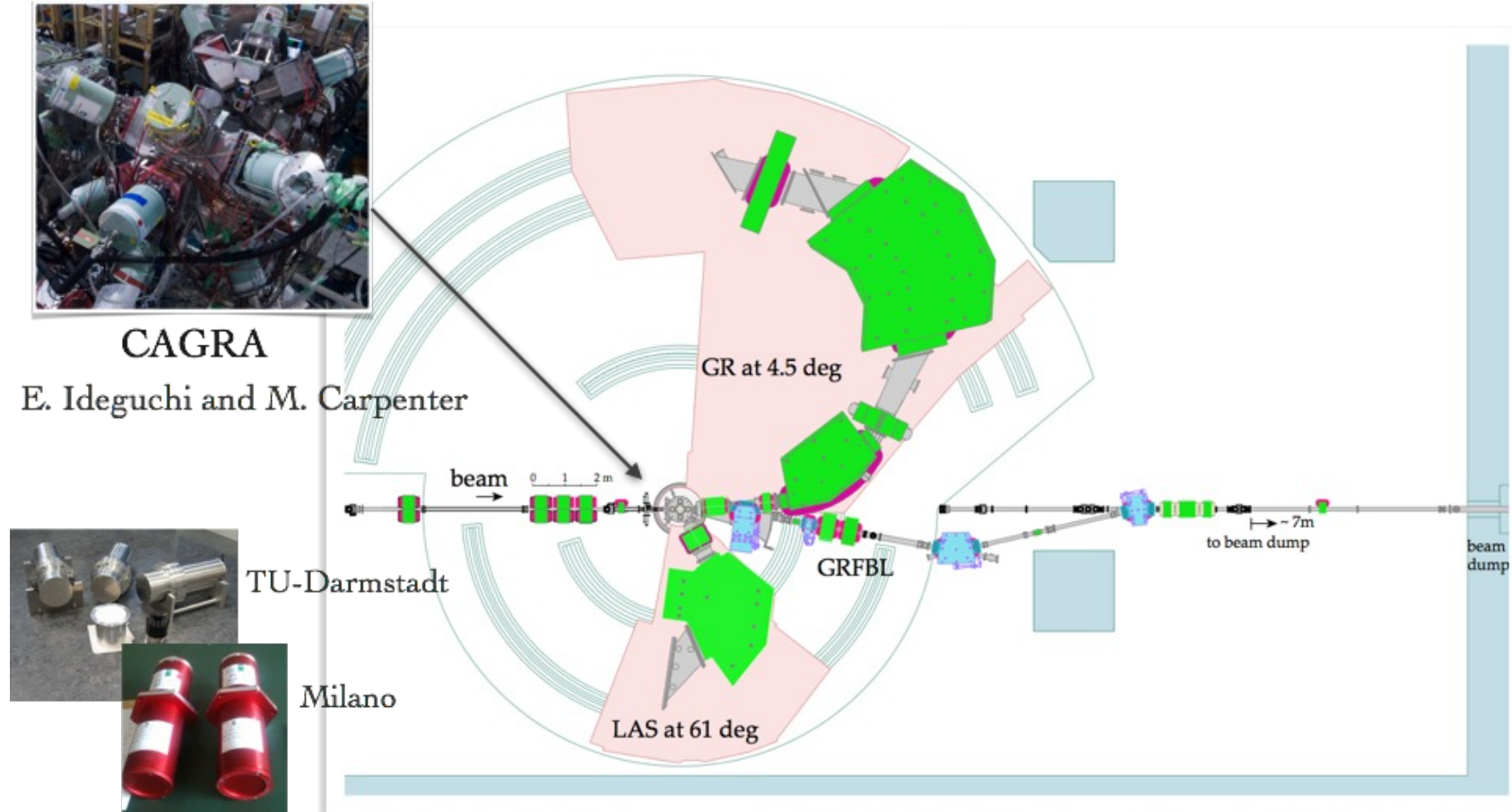


GAGRA (Clover Ge's with Gretina Quad Ge)



CAGRA-Grand Raiden Campaign at RCNP

Purpose: To perform high-resolution coincident measurements between reacting light-ions (Grand Raiden) and de-excitation γ -rays (CAGRA).



RCNP, Tohoku, ANL, LBNL, Milano, TU-Darmstadt, GSI, Köln, KVI, IFJ-PAN, IMP, York, ARL, ...

CAGRA+GR Campaign Exps. in Oct-Dec 2016

- E441:** The (${}^6\text{Li}, {}^6\text{Li}'$ [3:56MeV]) reaction as a novel probe for studying the inelastic neutrino-nucleus response in astrophysical scenarios 5.0 days
C. Sullivan, R.G.T.Zegers *et al.*:
PRC98, 015804 (2018)
S. Noji, R.G.T. Zegers *et al.*
Isvector spin-transfer response by tagging 3.56MeV γ
Gamov-Teller transition strength: relevance for inelastic neutrino-nucleus scattering cross section \rightarrow important to understand core-collapse supernovae
- E450:** Study of the Structure of the Pygmy Dipole Resonance States via the ($p, p'\gamma$) and ($\alpha, \alpha'\gamma$) Reactions 25.0 days
A. Bracco, F. Crespi, N. Pietralla *et al.*
A. Zilges, V. Derya, D. Savran, M.N. Harakeh, P. von Neumann-Cosel, N. Pietralla *et al.*
D. Savran, A. Zilges, V. Derya, M.N. Harakeh, P. von Neumann-Cosel, N. Pietralla *et al.*,
C. Iwamoto, A. Tamii, T. Hashimoto, P. von Neumann-Cosel *et al.*,
- E454:** Study of the Structure of the Pygmy Dipole Resonance States in ${}^{64}\text{Ni}$ via the ($p, p'\gamma$) and ($\alpha, \alpha'\gamma$) Reactions 6.0 days
D. Savran, A. Zilges, *et al.*,
- E470:** Search for superdeformed states in ${}^{28}\text{Si}$ via γ -particle coincidence measurements 6.0 days
D. Jenkins, D. Montanar, *et al.*,
- E471:** Study of high-spin state population by light-ion reactions 3.0 days
E. Ideguchi, A. Tamii, *et al.*,

Courtesy of A. Tamii



CAGRA+GR in the GRAF Setup



Completion with the full-configuration
2016.9.29

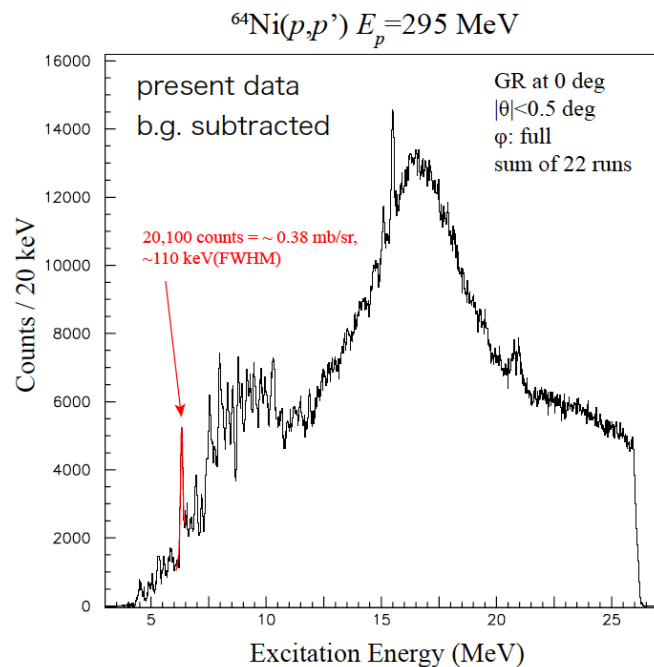
12 Clovers from ANL, Tohoku, ARL and IMP
4 large volume LaBr₃ from Milano



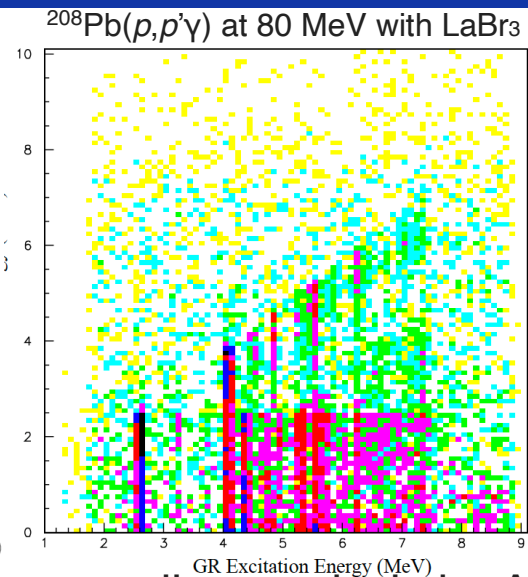
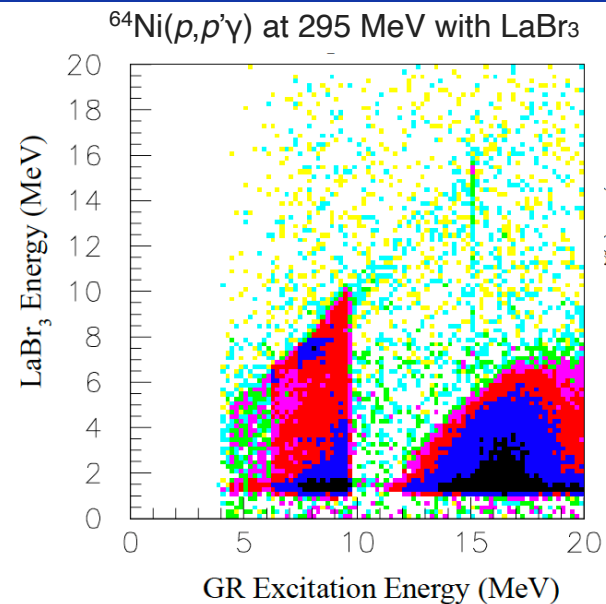
Courtesy of A. Tamii

CAGRA+GR in the 0-deg Setup

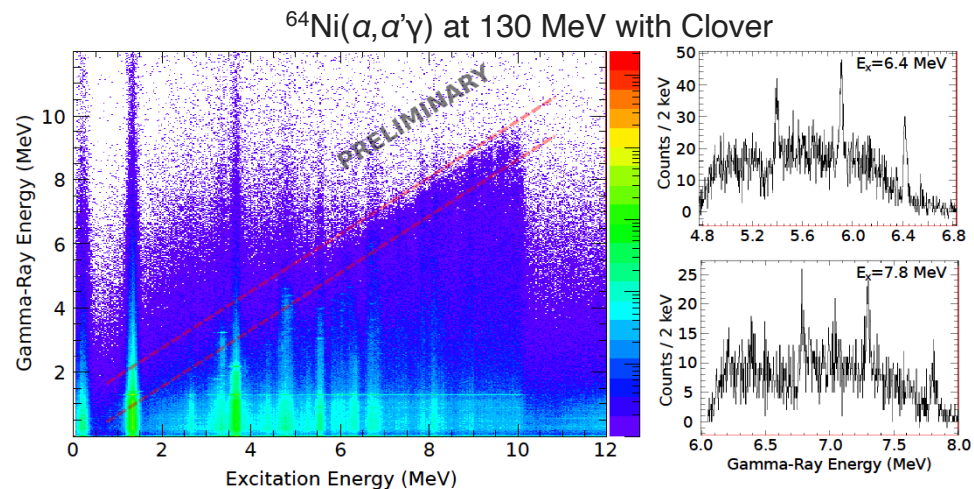
Analysis in Progress



online-analysis by AT



online-analysis by AT



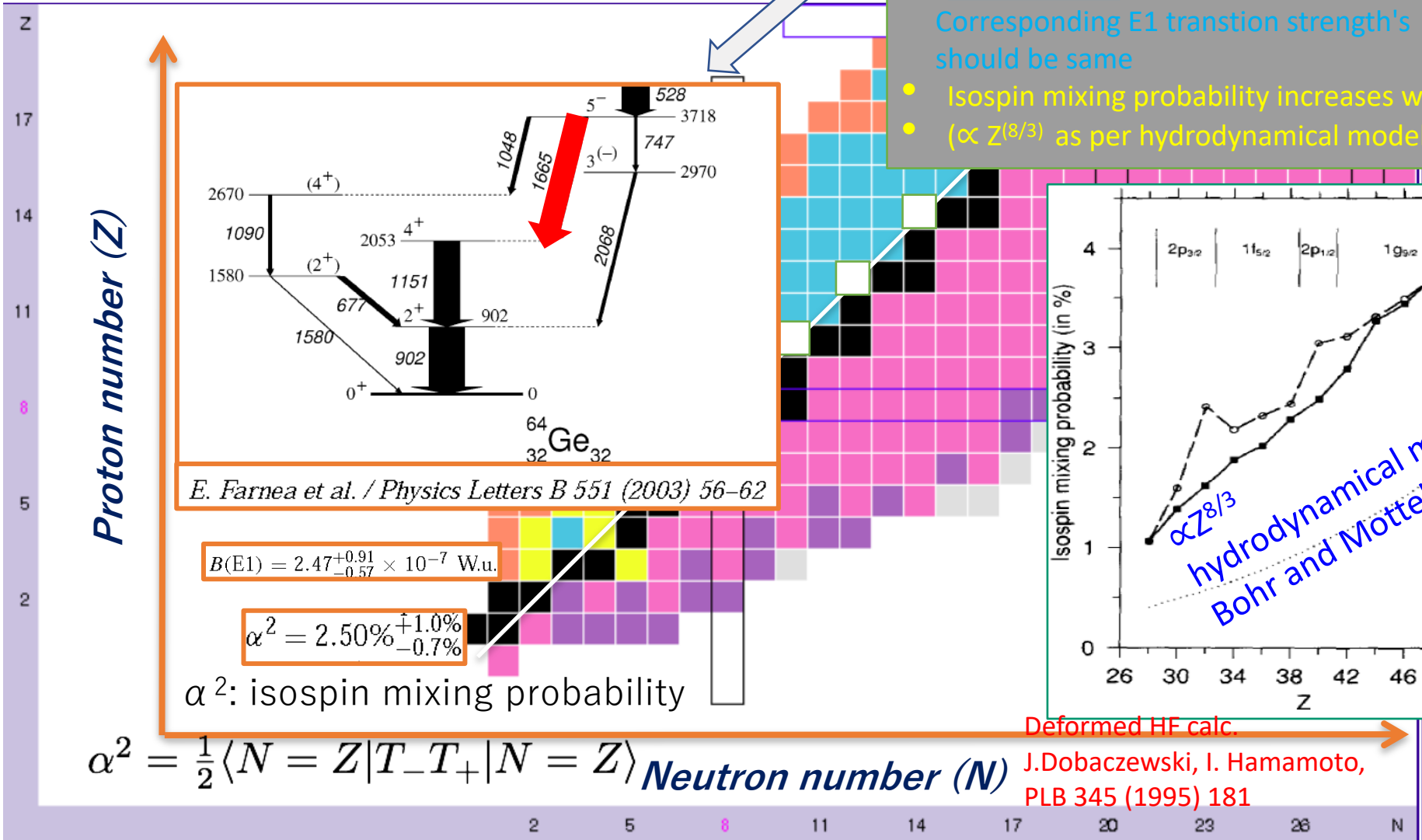
offline-analysis
by J. Isaak

Courtesy of A. Tamii

Figure 1: Left: Coincidence matrix in the $(\alpha,\alpha'\gamma)$ experiment. Right: γ -ray spectra after applying energy gates on the excitation energy of 6.4 MeV and 7.8 MeV, respectively.

Isospin mixing in N ~ Z nuclei

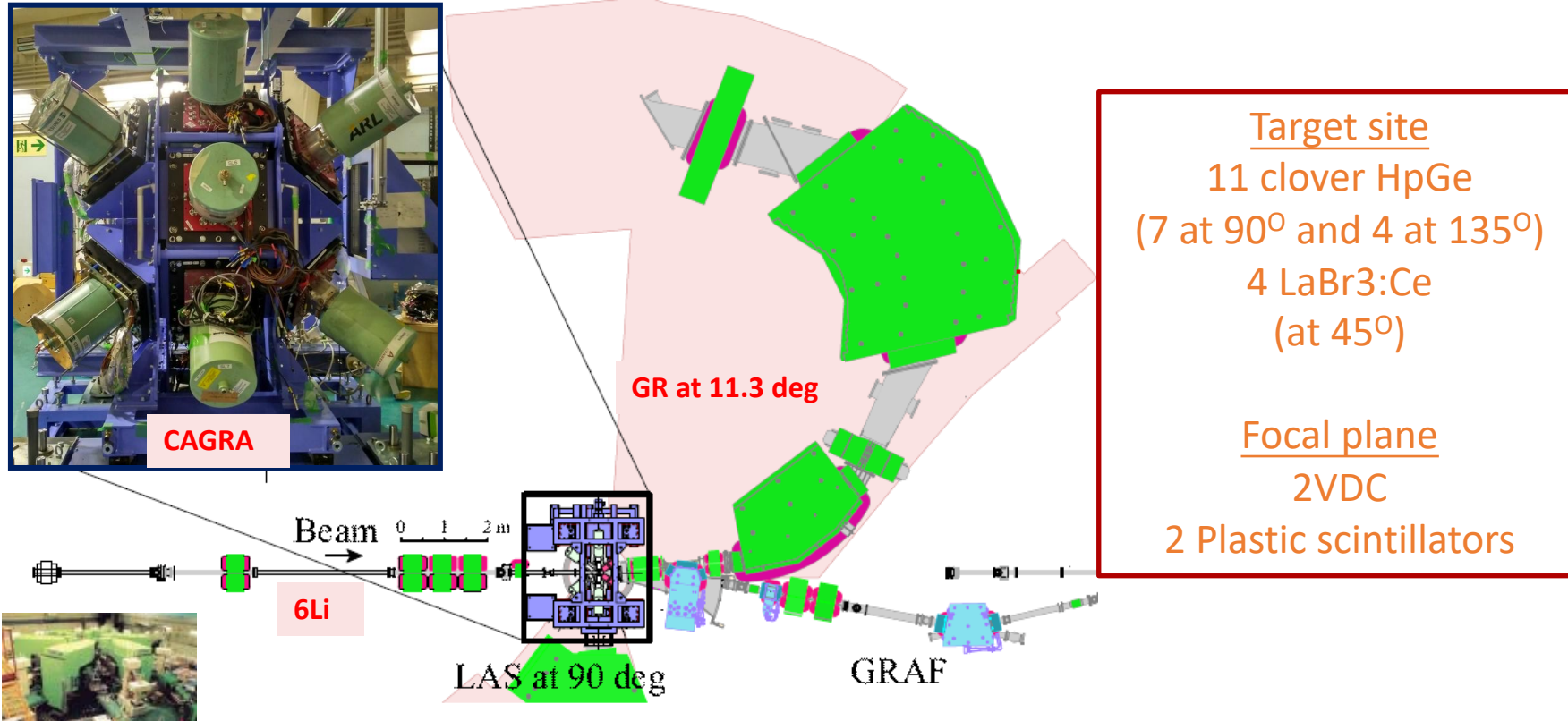
- Self conjugate nuclei (N = Z)
 $\Delta T = 0$, E1 transitions are forbidden
- Mirror nuclei:
 Corresponding E1 transition strength's should be same
- Isospin mixing probability increases with Z
 $(\propto Z^{8/3})$ as per hydrodynamical model



Experiment at RCNP

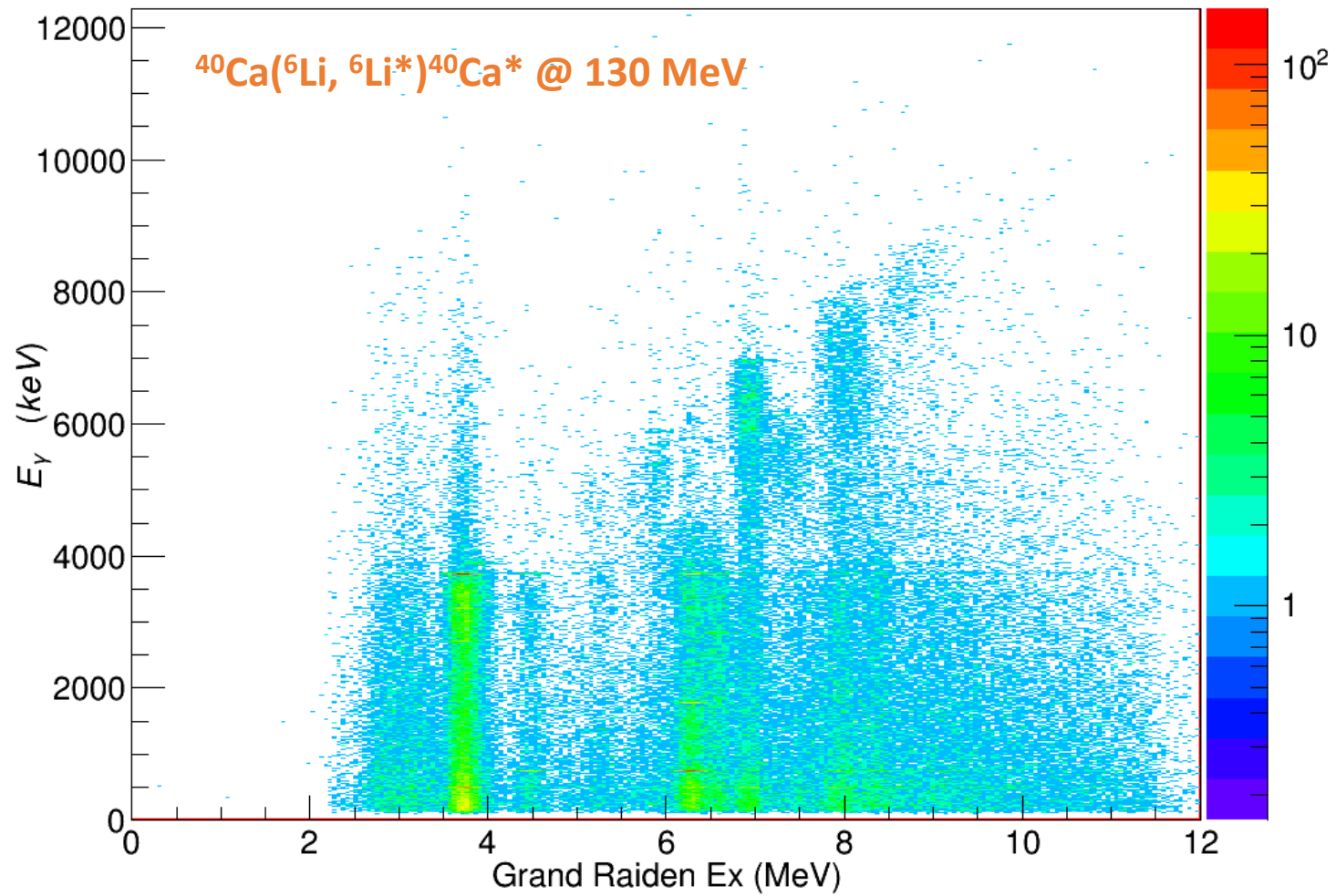
CAGRA:
Clover Ge array by
international collaboration
(Japan-US-China-..)

^{40}Ca (^6Li , $^6\text{Li}^*$) $^{40}\text{Ca}^*$ @ 130 MeV, 600 MeV
Target thickness : 1.6 mg/cm²
Beam current : ~ 5-10 nA

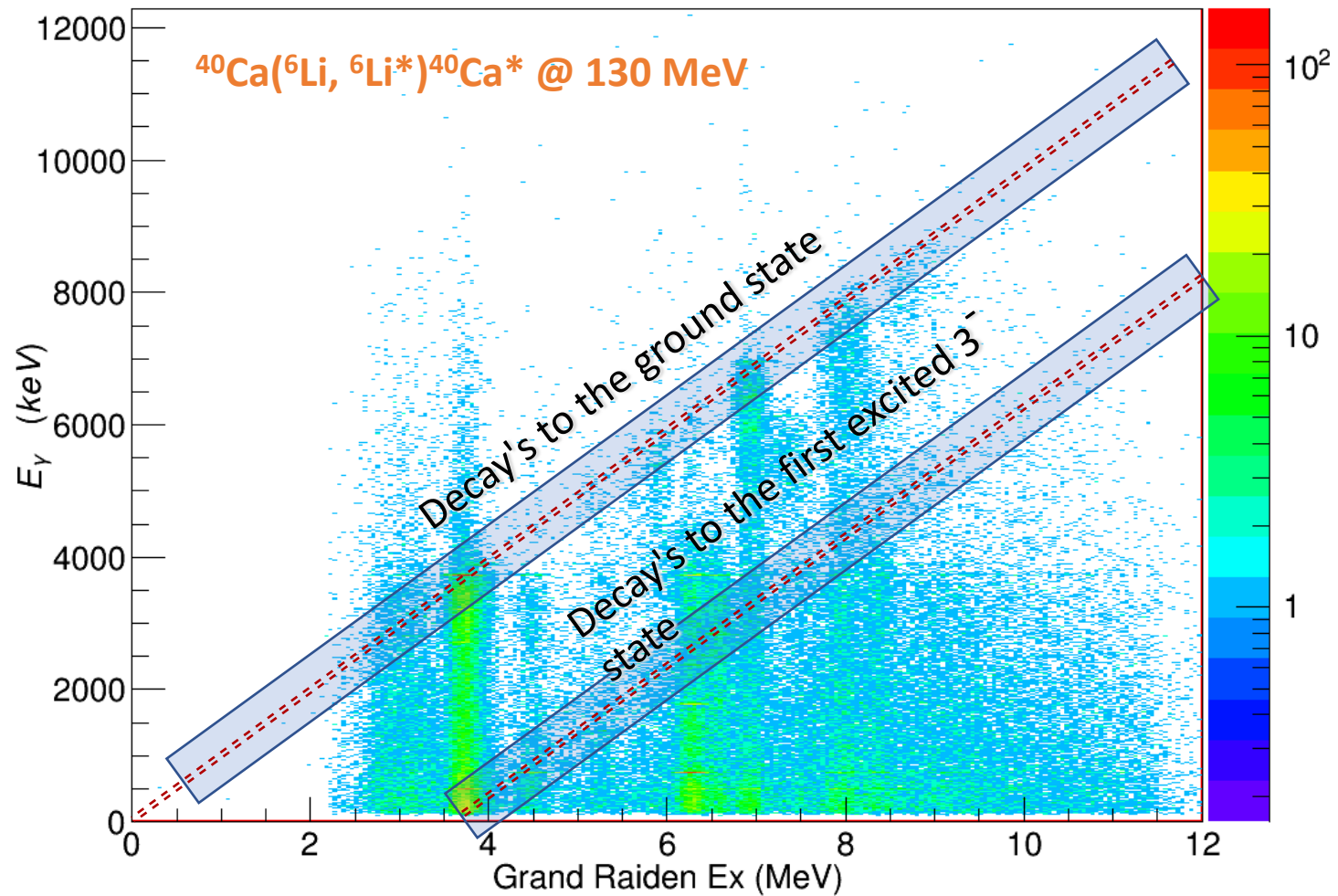


Measured excitation energy with GR and study γ de-excitation with CAGRA.

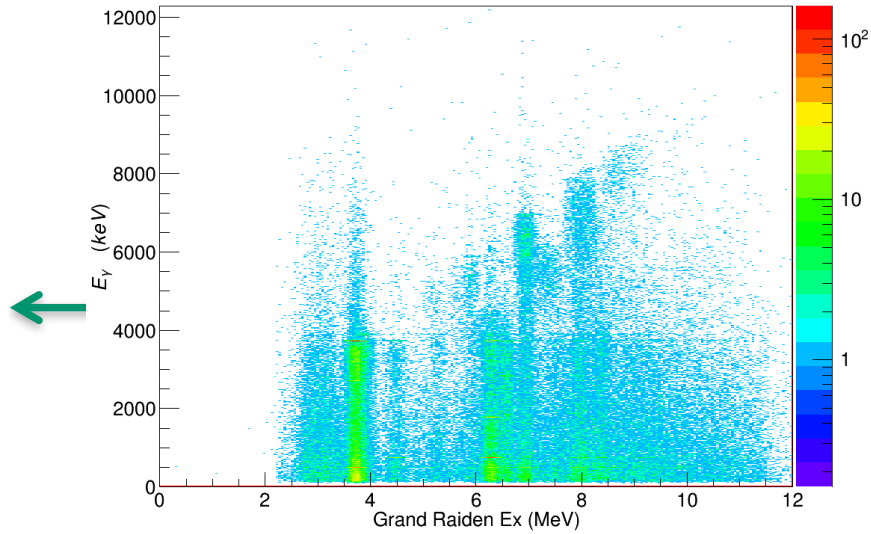
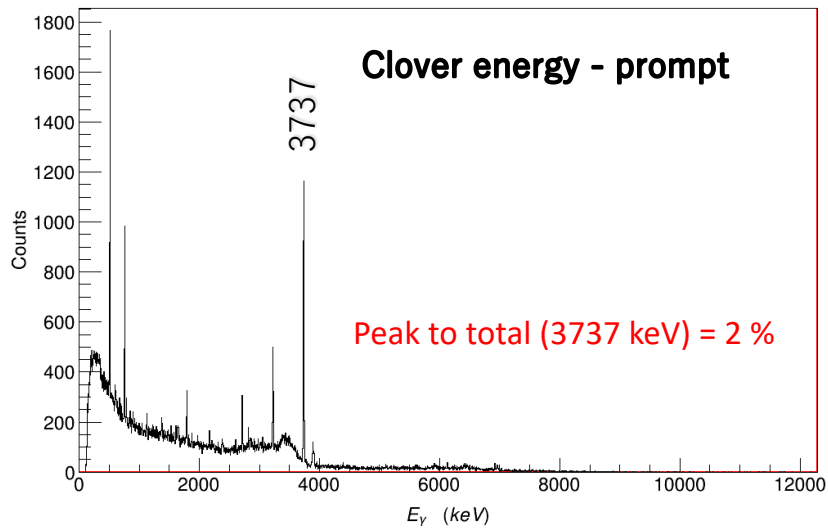
^{40}Ca excitation energy vs γ energy



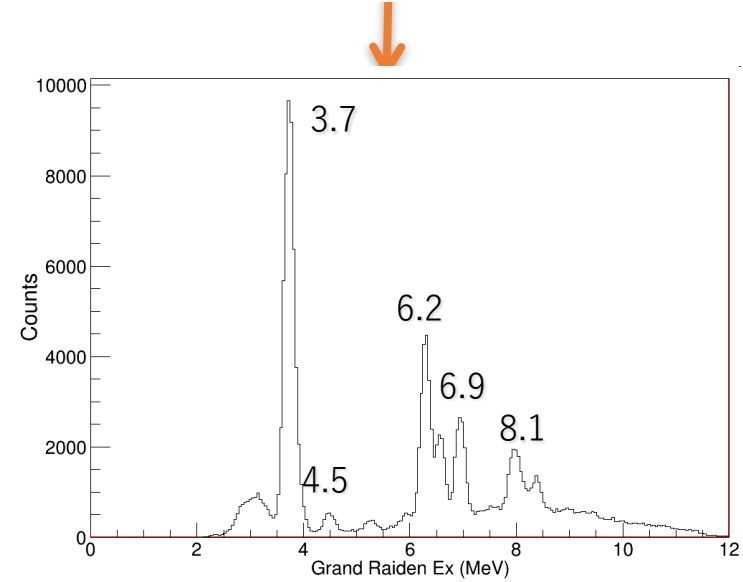
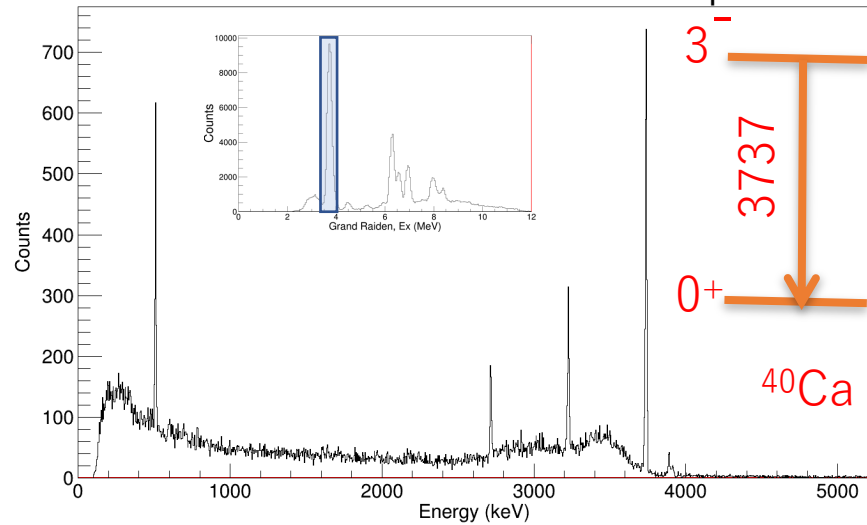
^{40}Ca excitation energy vs γ energy



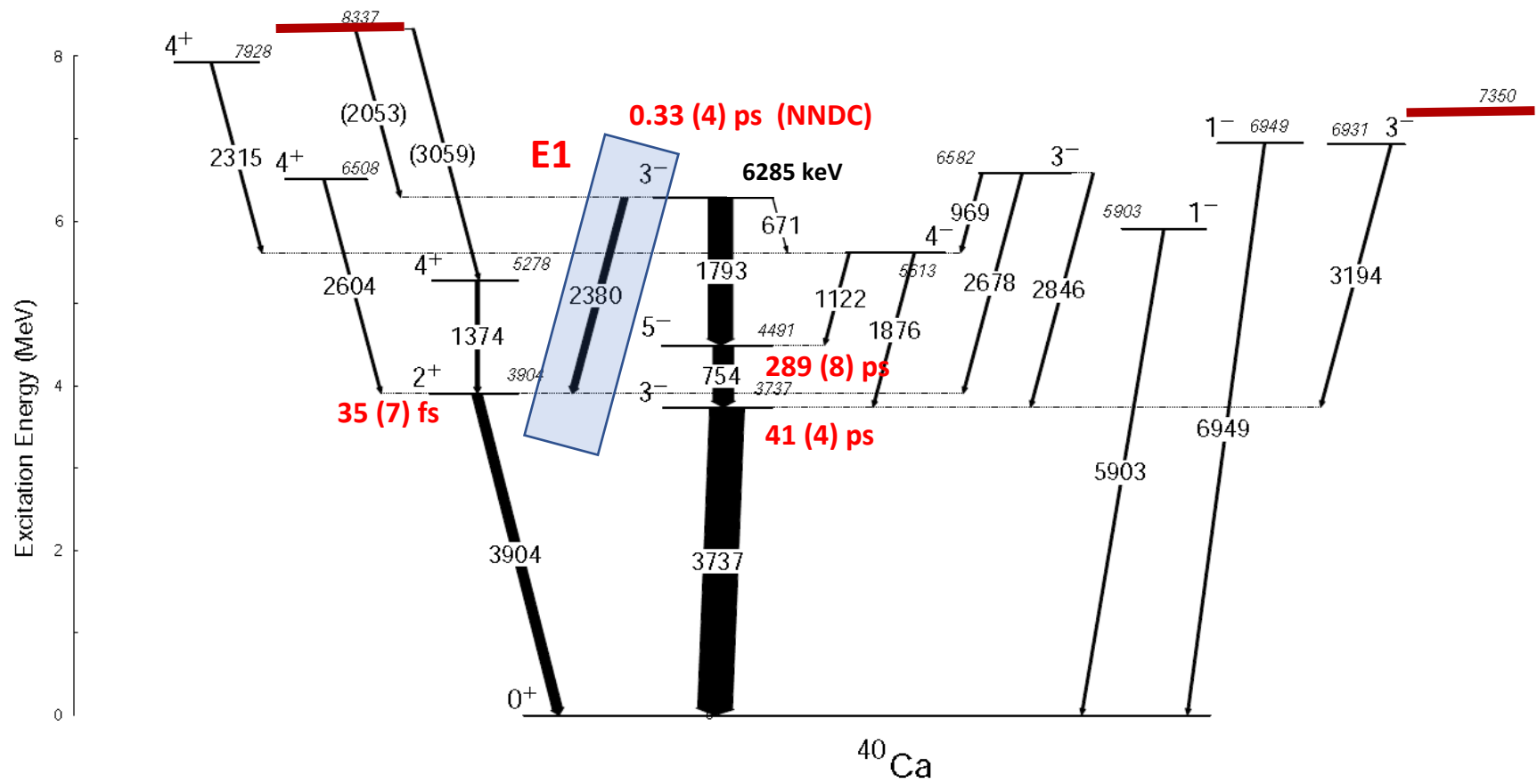
^{40}Ca excitation energy vs γ energy



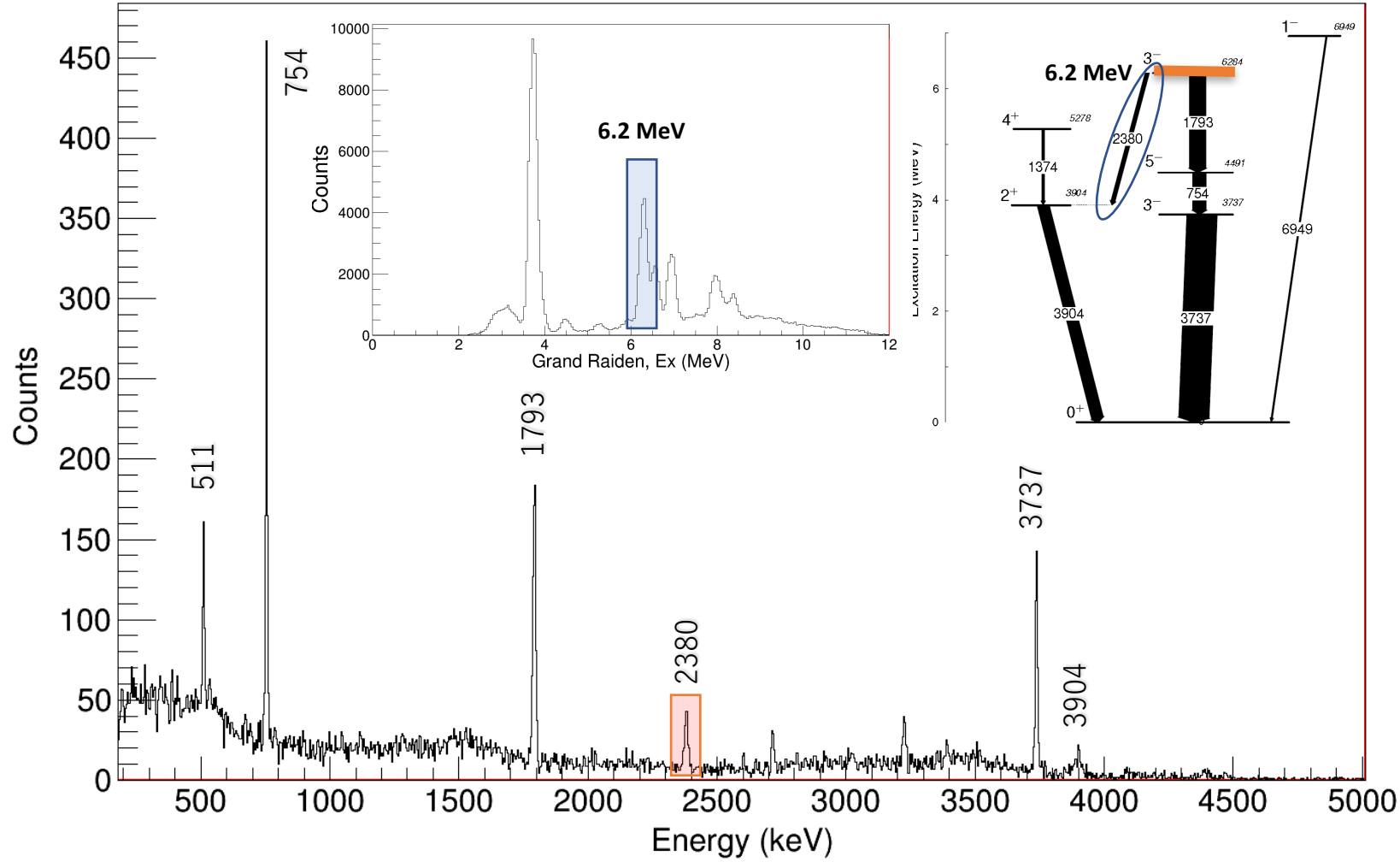
Gate on 3.7MeV on Ex. spectrum



Partial level scheme of ^{40}Ca



γ energy spectrum gated on 6.2 MeV



CAGRA at JAEA tandem accelerator facility

RCNP: *T.T. Pham, E. Ideguchi, N. Aoi, A. Kohda, R. Yanagihara*

ASRC, JAEA: *K. Nishio, R. Orlandi, H. Makii, M. Asai, K. Hirose, F. Suzuki, A. Andreyev, K. Tsukada, A. Toyoshima, T.K. Sato, Y. Ito*

QST: *T. Shizuma*

IMP CAS China: *Y. Fang, M. Kumar Raju, J-G. Wang, S. Guo, M. Liu, X. Zhou*

CNS Univ. of Tokyo: *N. Imai, N. Kitamura, S. Michimasa*

NSEC, JAEA: *Y. Toh*

ORNL: *K. P. Rykaczewski, J. Enzol, S.V. Cleve, J.B. Roberto, R.A. Boll*

Kyushu Univ: *S. Go, M. Tanaka*

Univ. of York: *A. Andreyev*



Japan Atomic Energy Agency
Sector of Nuclear Science Research
Advanced Science Research Center



中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

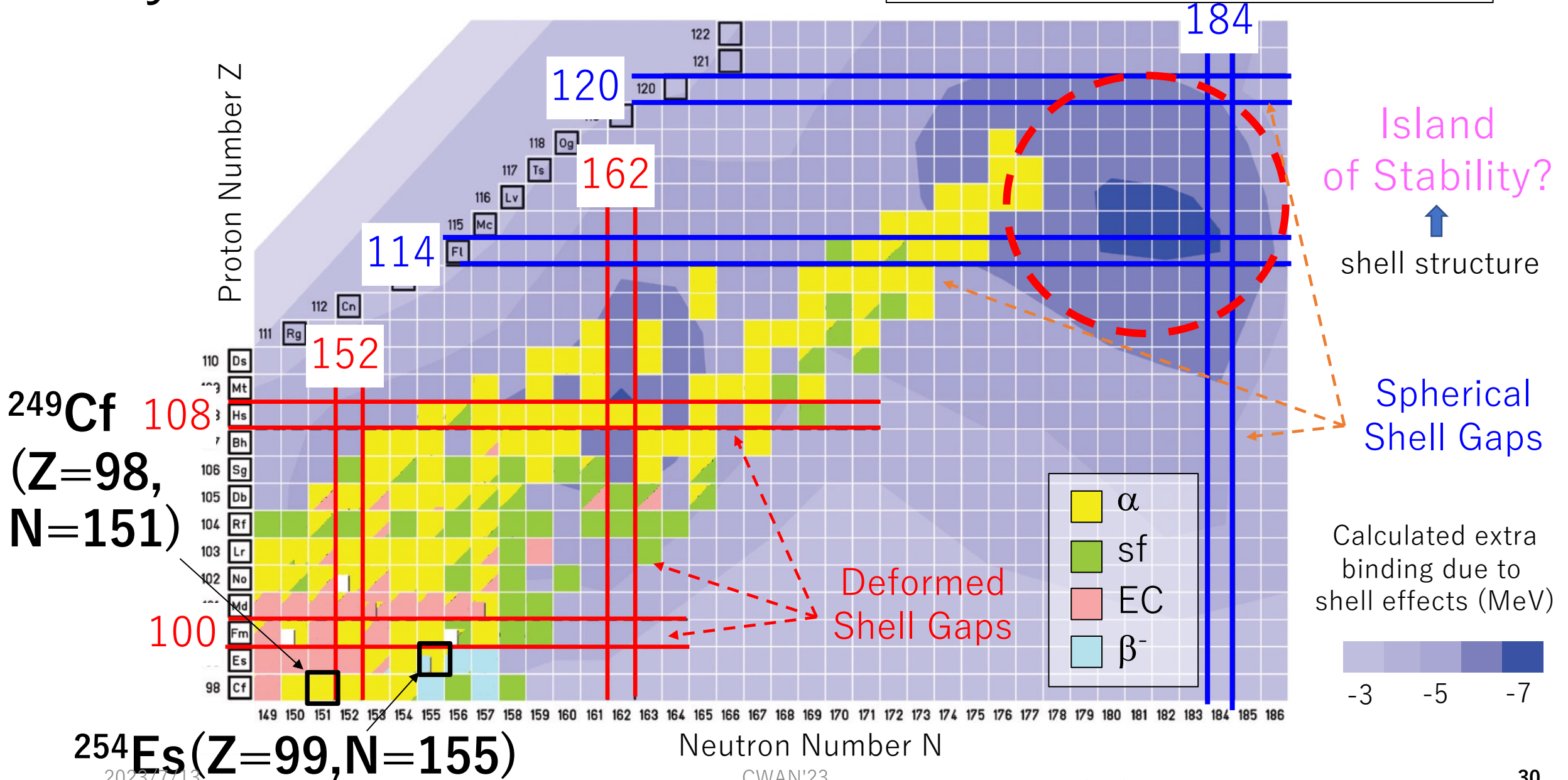


Japan Atomic Energy Agency
**Nuclear Science and
Engineering Center**



Physics Motivation

Where is the limit of nuclear stability?



Predicted single-particle structure in transuranium region

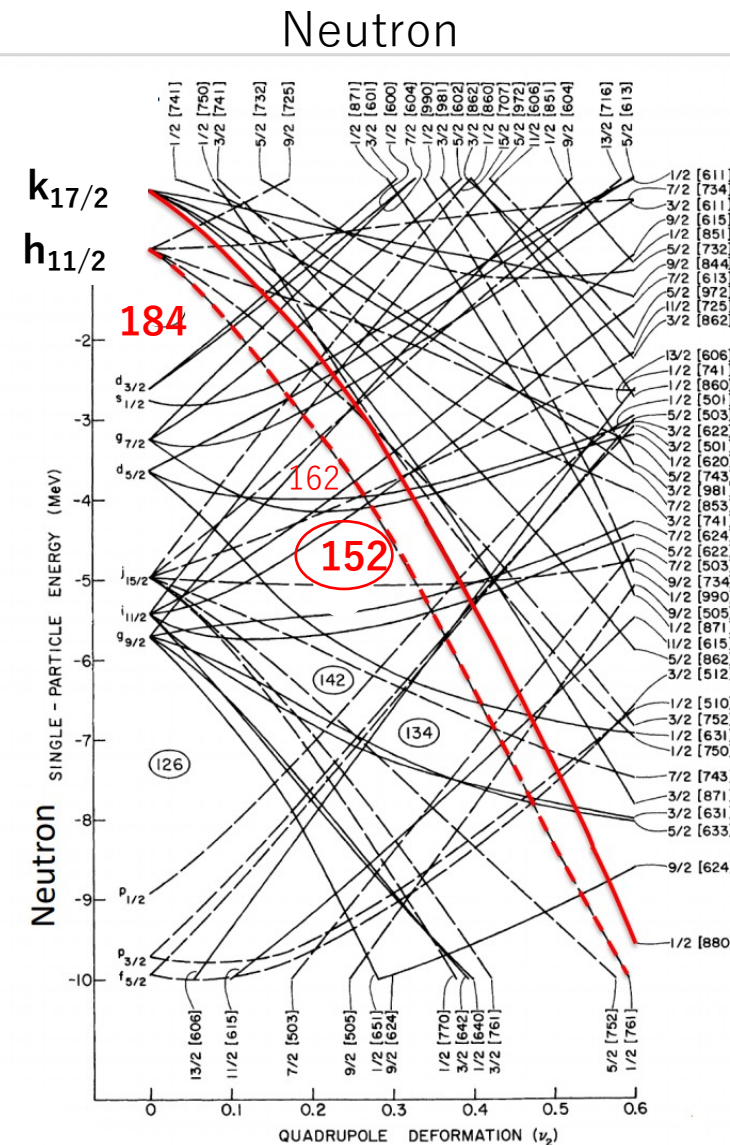
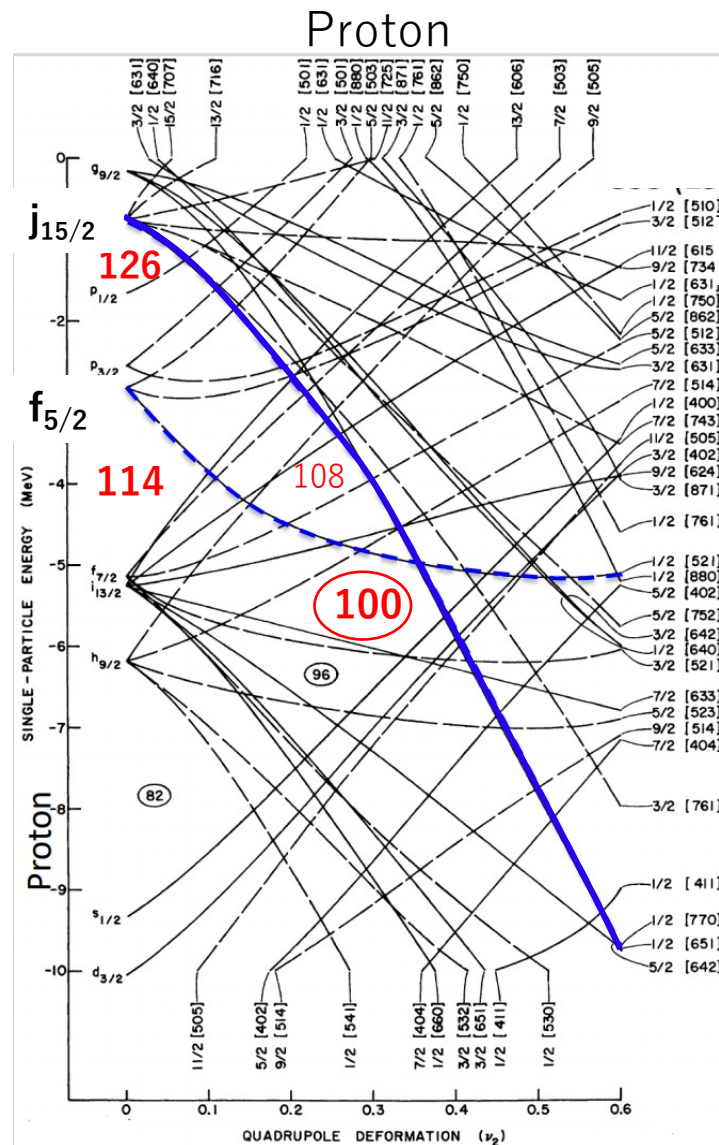
$\pi j_{15/2}$, $\pi f_{5/2}$ orbitals are important for $Z=114$, 126 shell gap
 $\nu h_{11/2}$, $\nu k_{17/2}$ for $N=184$ gap

Deformed shell gap at $Z=100$, $N=152$

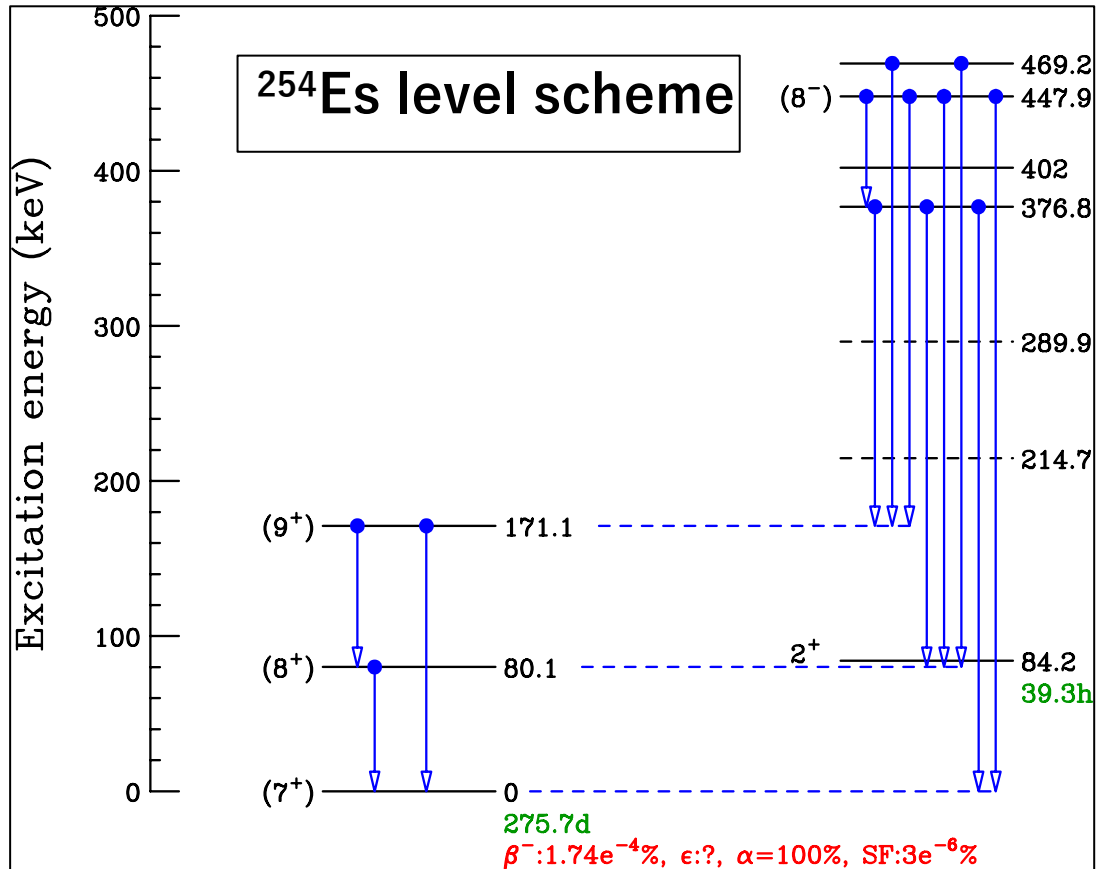
$\pi j_{15/2}$, $\pi f_{5/2}$, $\nu h_{11/2}$, $\nu k_{17/2}$ orbits are going down in the deformed region

Studies of **excited states** and **deformation** will be useful to understand the shell structure

R.R. Chasman, et al.,
 Rev. Mod. Phys. 49(1977)833



^{254}Es Target Coulomb excitation



K.J. Moody et al., Nucl. Phys. A 563, 21-73 (1993).

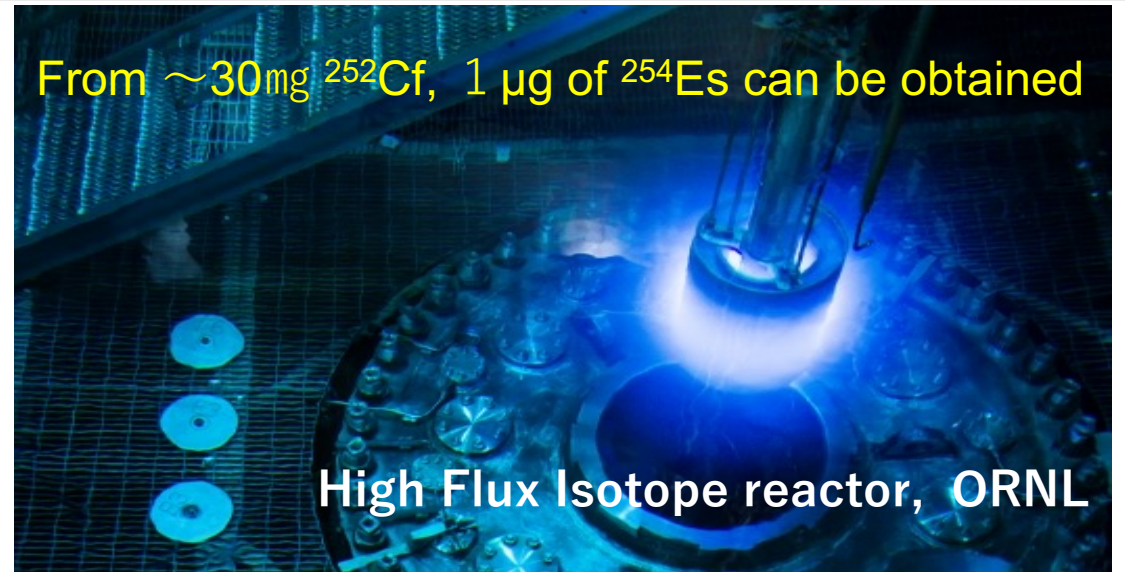
^{254}Es produced at High Flux Isotope Reactor at Oak Ridge National Lab, USA.

Performed in JAEA Tandem accelerator, Tokai, Ibaraki

Beam : ^{58}Ni - 250MeV

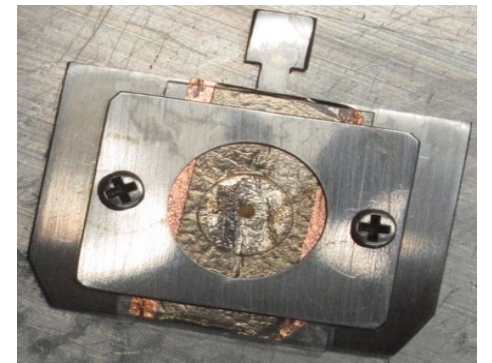
Target : ^{254}Es ~ 3 $\mu\text{g}/\text{cm}^2$

Backing & cover : natNi - 300 $\mu\text{g}/\text{cm}^2$ both side



^{254}Es target

Target prepared at JAEA using ~0.1 μg ^{254}Es
 Activity ~4.5 MBq



Detector System

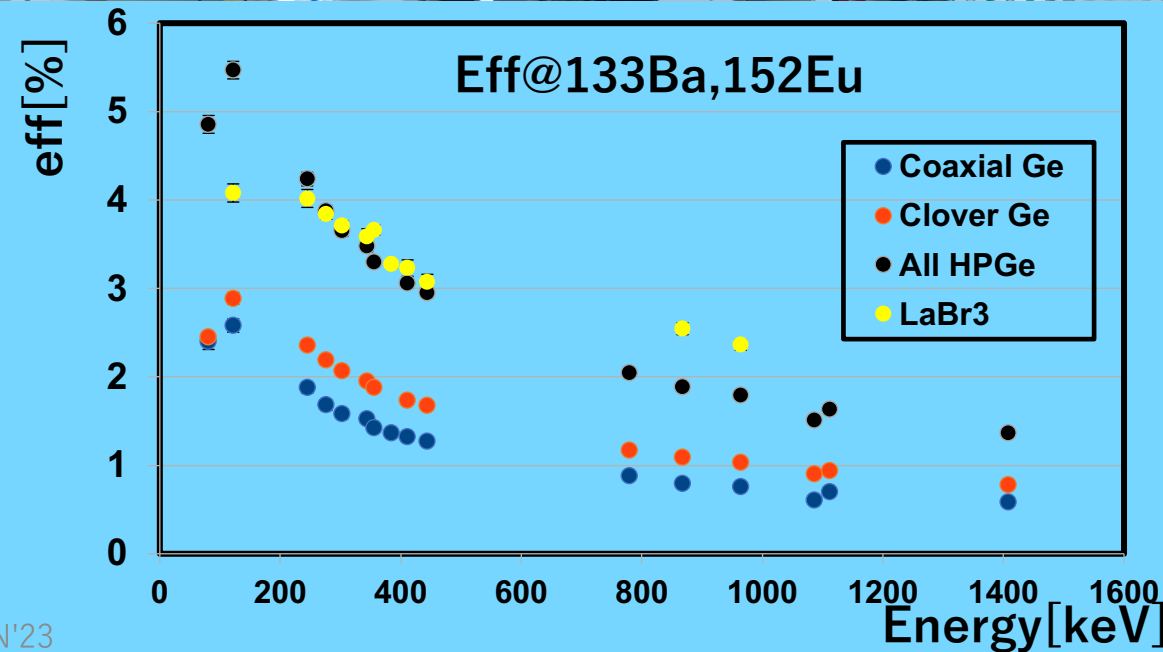
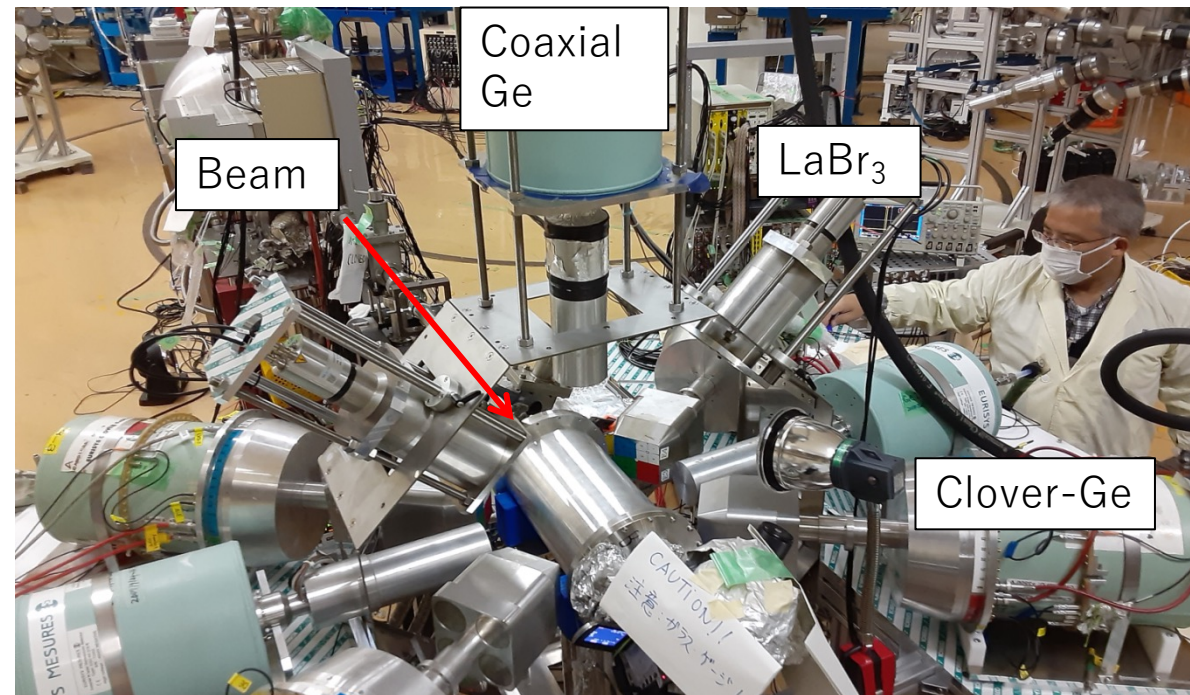
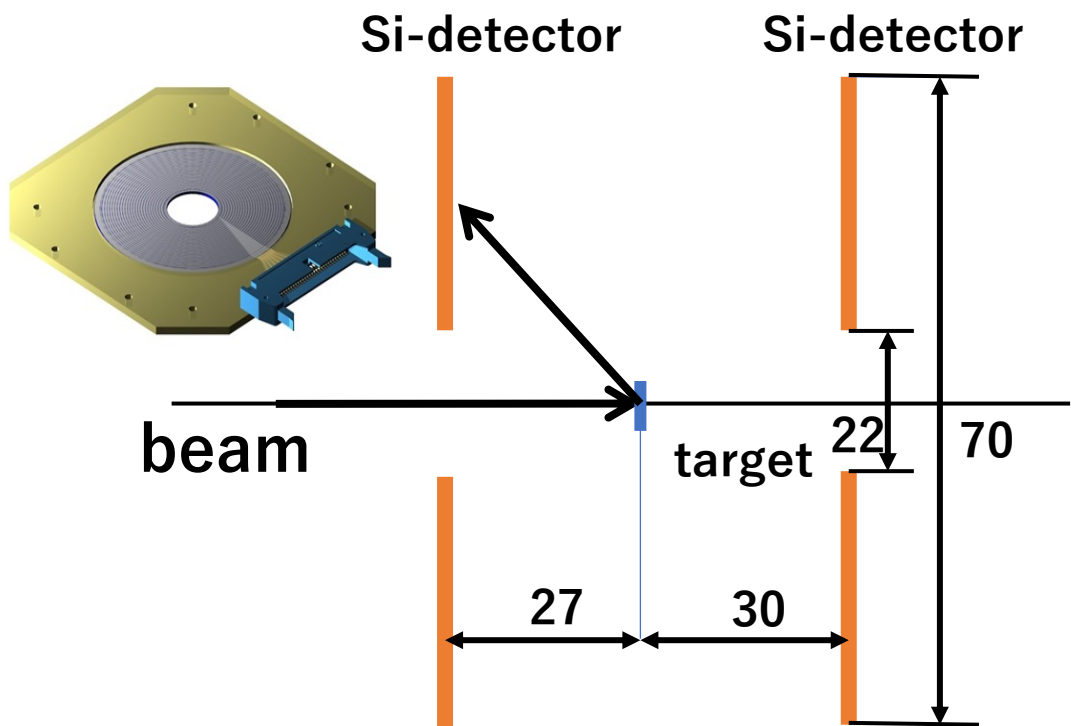
Silicon Detectors – 24 rings

Backward

Coverage angle : **127° – 157°**

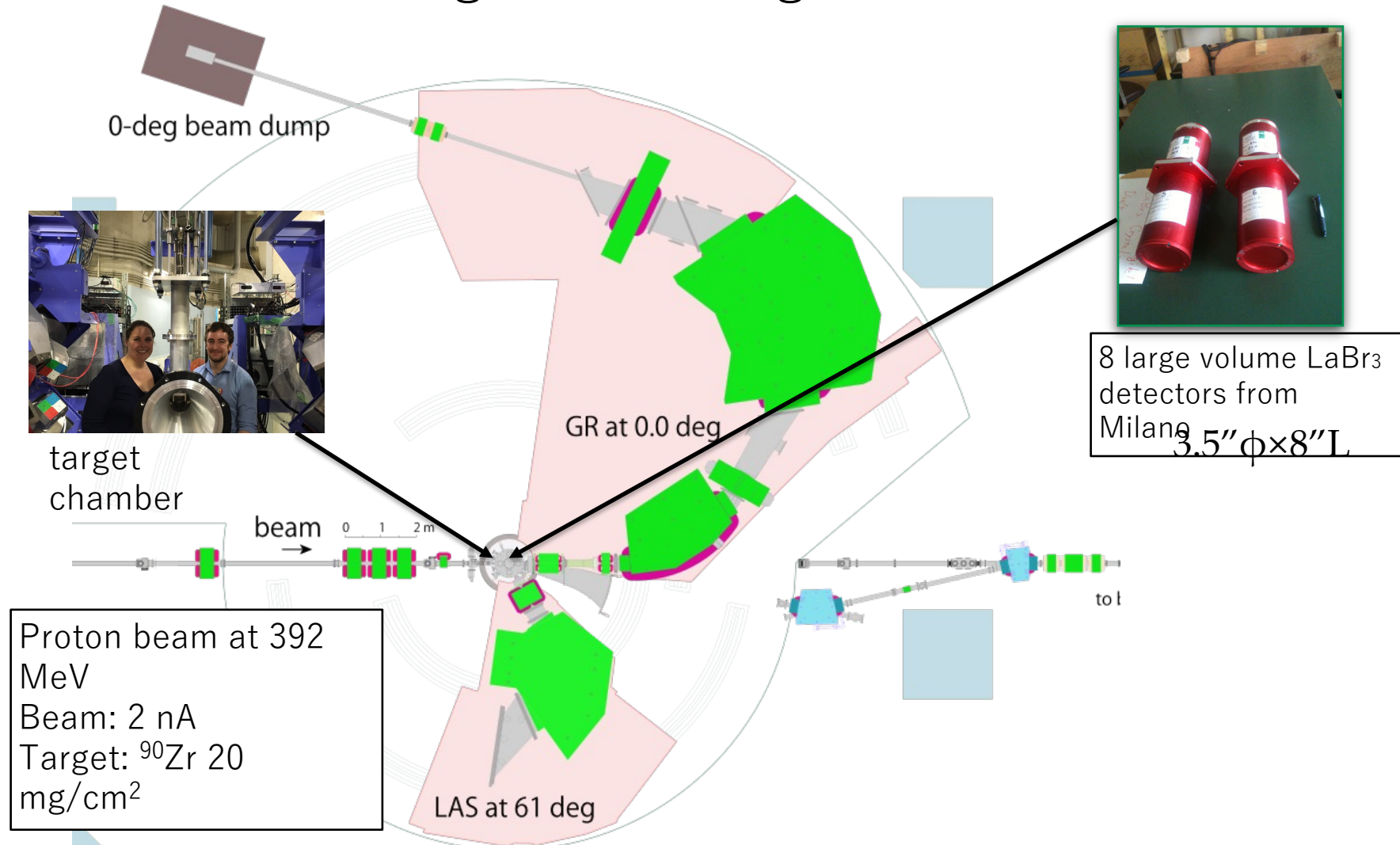
Forward

Coverage angle : **20° – 49°**



E498: Experimental Methods

GR 0-deg mode + large volume LaBr₃



Proton beam at 392 MeV
Beam: 2 nA
Target: ⁹⁰Zr 20 mg/cm²

8 large volume LaBr₃ detectors from Milang
3.5" φ × 8" L

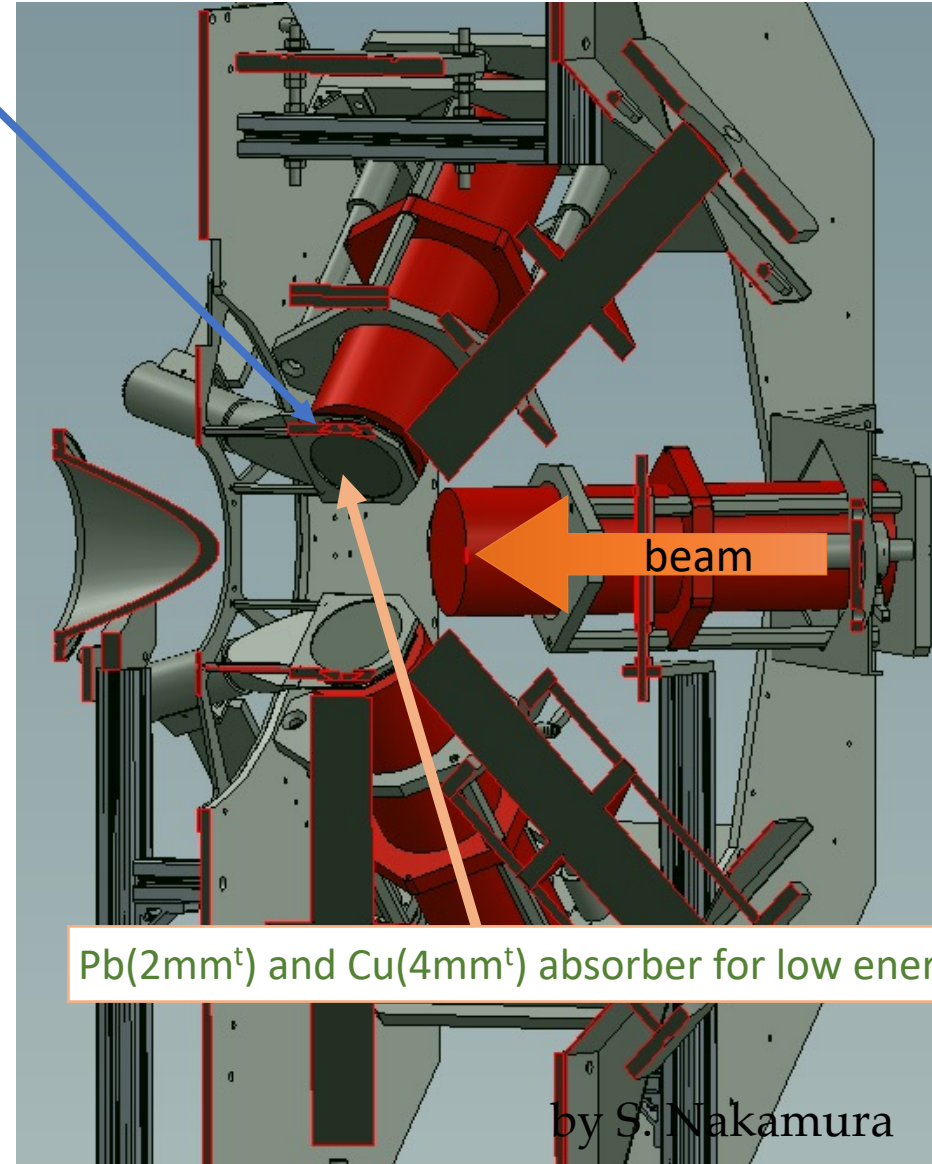
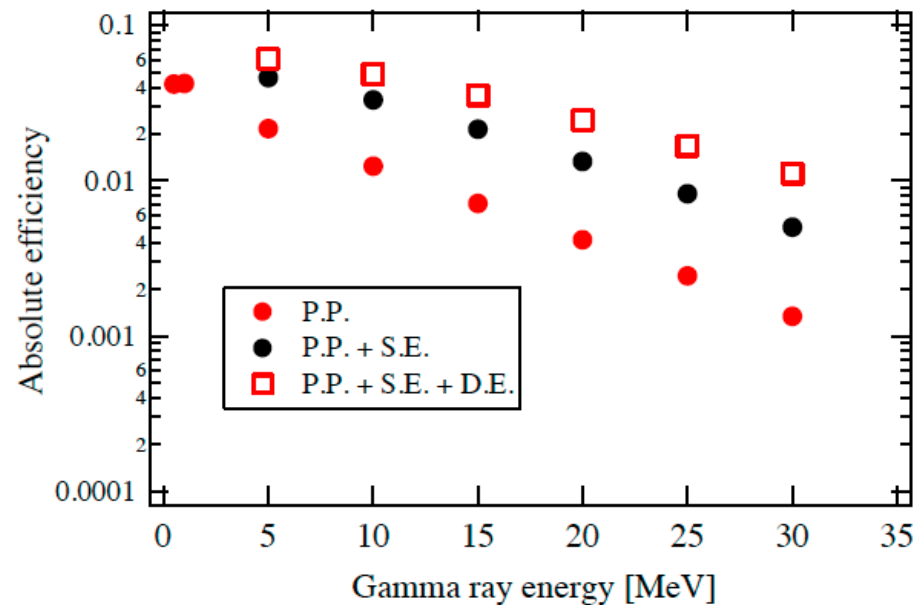
Achromatic mode: $\Delta E_x = \sim 100$ keV

Gamma ray detector array

Scylla

Plastic (2mm^t) for charged particle veto

Total Number of detectors	8
Detectors at 90'	4
Detectors at 135'	4
Distance from target	135 mm
Solid angle	20% of 4pi
Efficiency @ 15MeV	4% (PP+SE+DE)

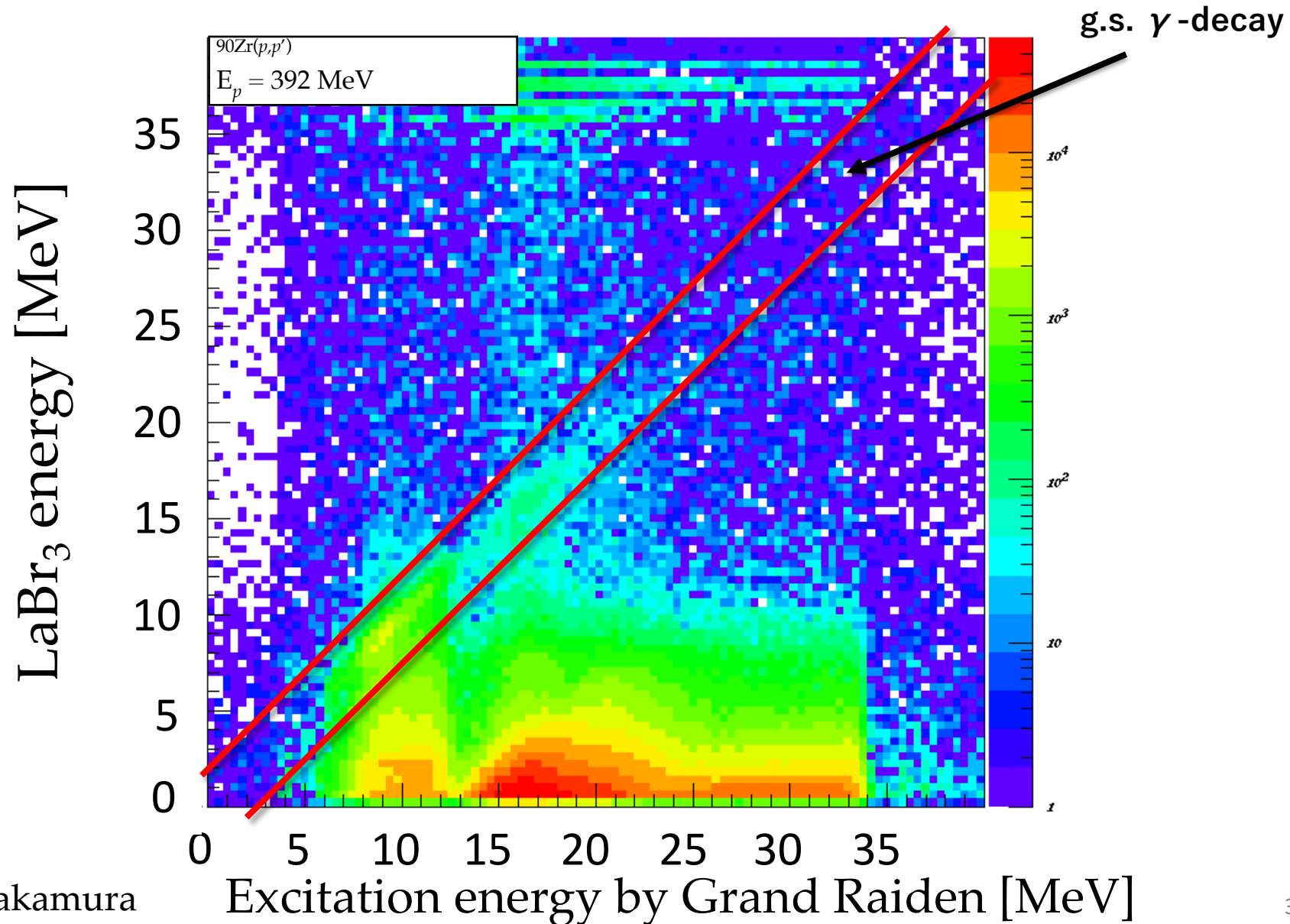


Pb(2mm^t) and Cu(4mm^t) absorber for low energy gammas

by S. Nakamura

Coincidence matrix of Grand Raiden and LaBr3

means the ground state gamma decay



Summary

- CAGRA project → gamma-ray spectroscopy at RCNP
 - International collaboration: RCNP-Tohoku-ANL-ARL-IMP-Milano...
 - CAGRA campaign experiments at EN and Grand Raiden
- CAGRA at JAEA
 - Gamma-ray spectroscopy of Actinoid
 - CAGRA including Gretina Quad detector available
- LaBr3 array at Grand Raiden: Scylla
 - Particle-gamma coincidence measurements