Production of High Nuclear Spin Alignment of Radioactive Ion Beams

UENO, Hideki

RIKEN Nishina Center

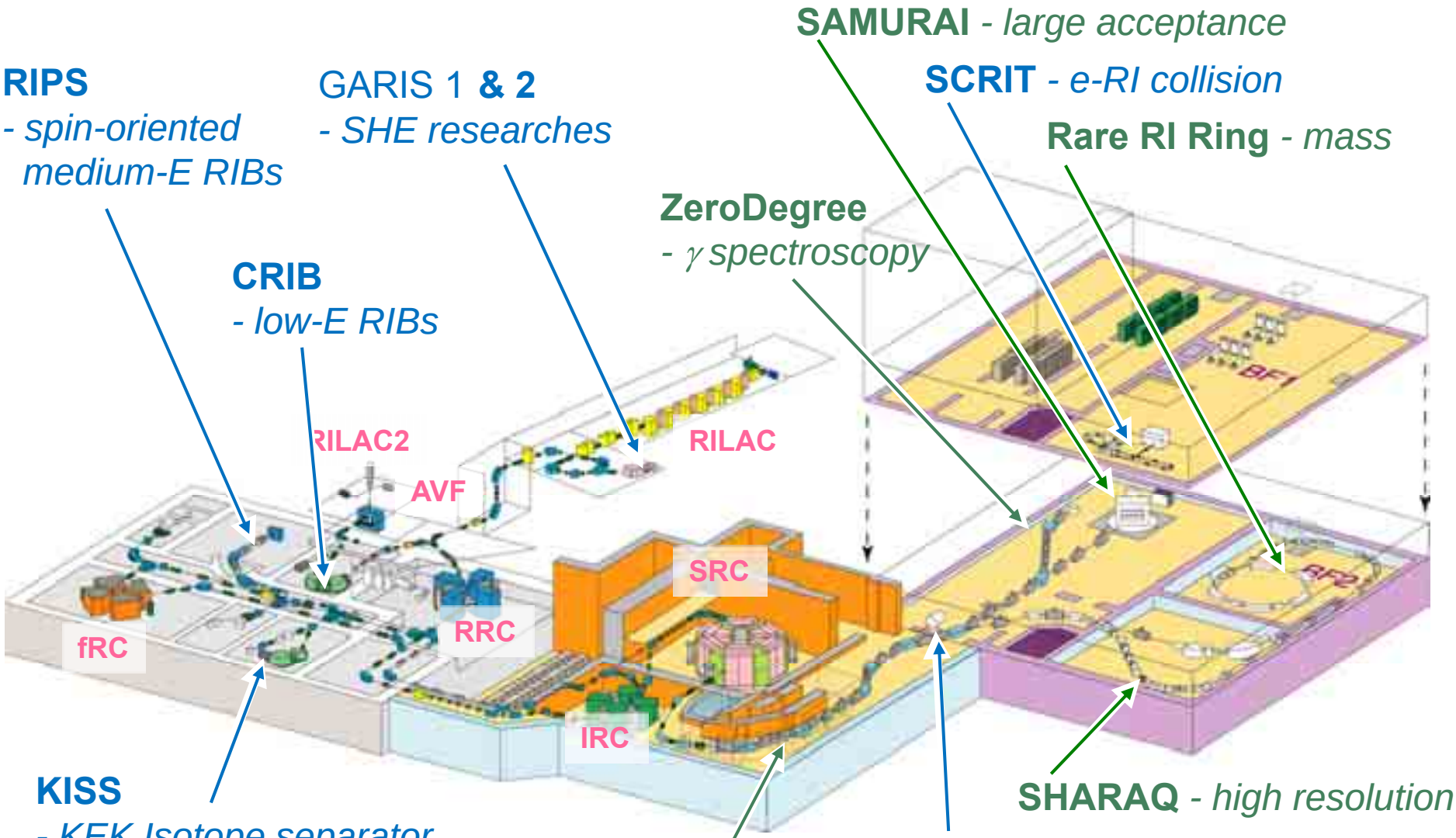
SPIN2014, Beijing, October 21-25, 2014

1. **RIBF recent progress**

2. **Spin-aligned RI beams**
   - Isomeric-state nuclear moments
   - Disp.-matching two-step fragmentation method

3. **Spin-polarized RI beams**
   - ① Ground-state nuclear moments
   - ② β-delayed γ & n spectroscopy

RIBF key experimental devices

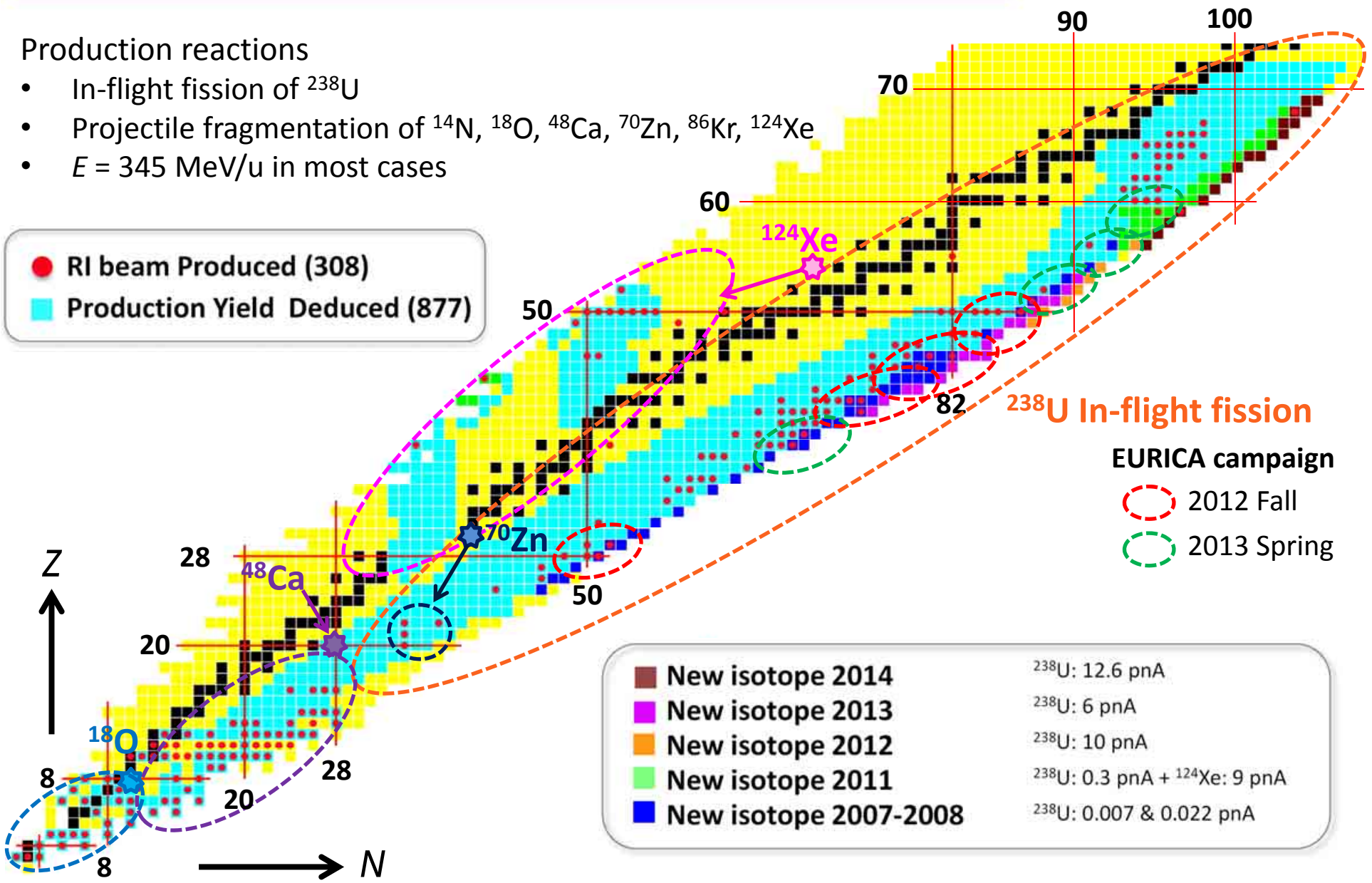


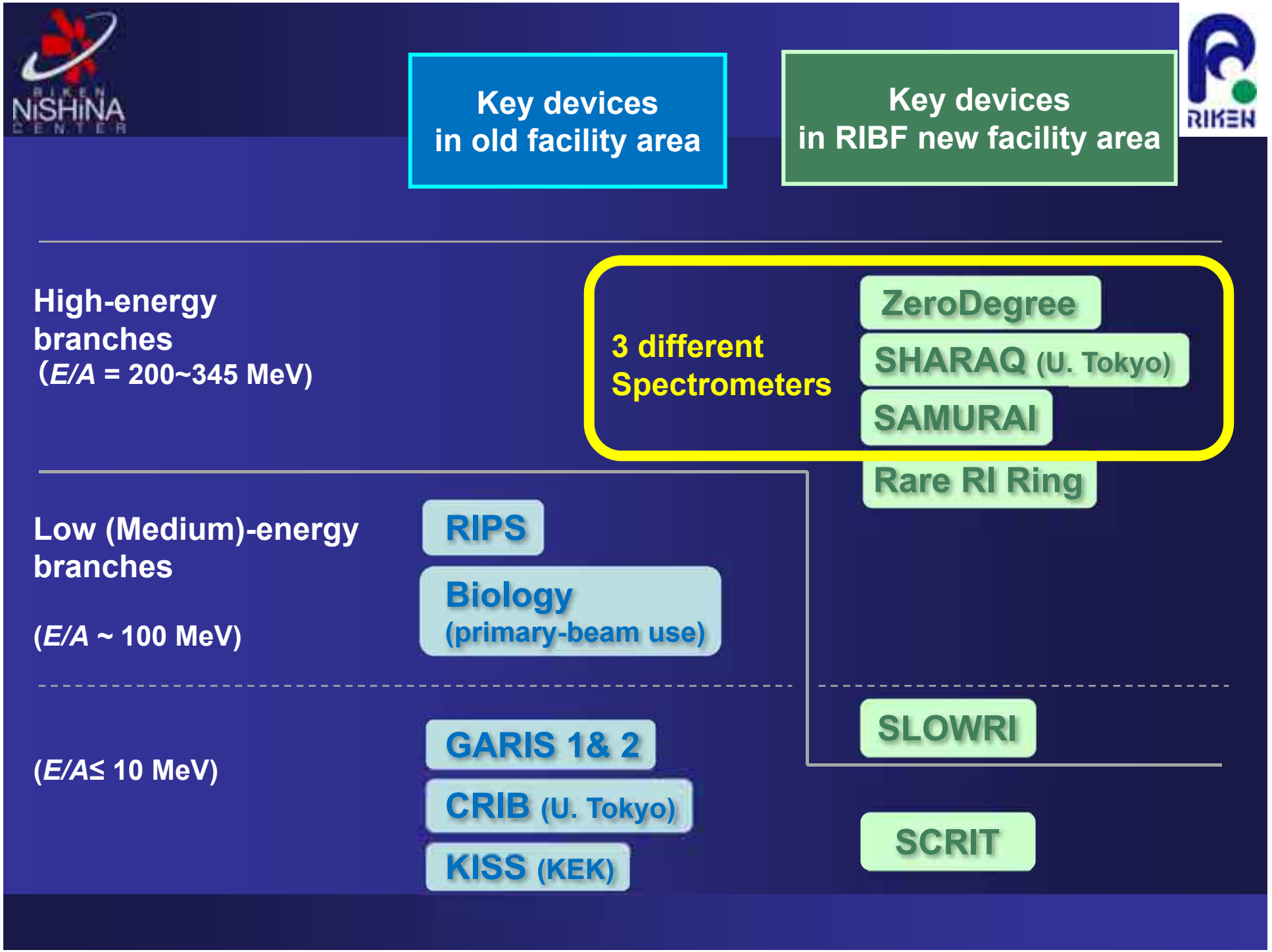
RI beams produced at BigRIPS (Mar 2007– April 2014)

From T. Kubo
2014/06/17

Production reactions

- In-flight fission of ^{238}U
- Projectile fragmentation of ^{14}N, ^{18}O, ^{48}Ca, ^{70}Zn, ^{86}Kr, ^{124}Xe
- E = 345 MeV/u in most cases

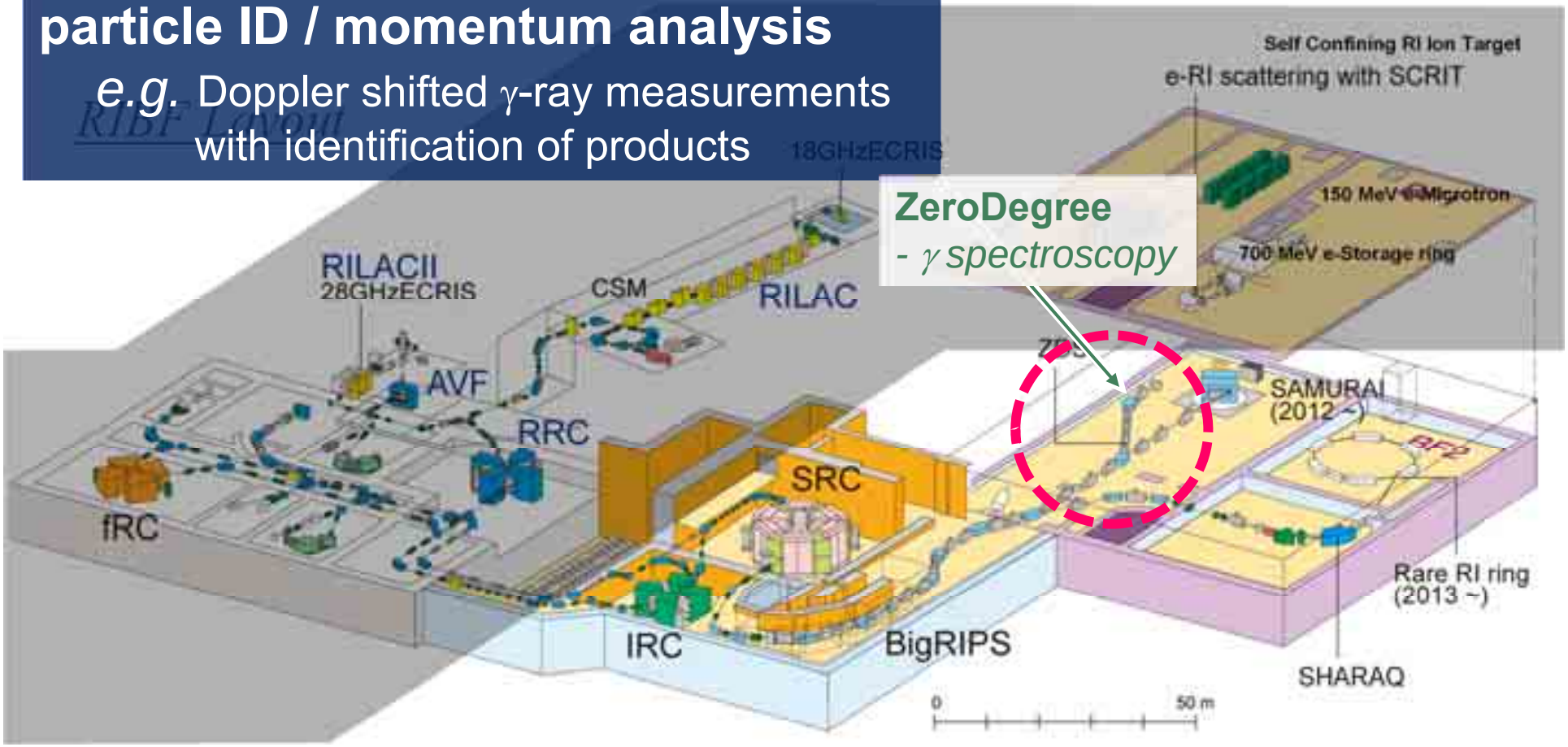



Key devices
in old facility area
Key devices
in RIBF new facility area
High-energy
branches
(E/A = 200~345 MeV)
3 different
Spectrometers
ZeroDegree
SHARAQ (U. Tokyo)
SAMURAI
Rare RI Ring
Low (Medium)-energy
branches
(E/A ~ 100 MeV)
RIPS
Biology
(primary-beam use)
SLOWRI
(E/A≤ 10 MeV)
GARIS 1& 2
CRIB (U. Tokyo)
KISS (KEK)
SCRIT

② BigRIPS + ZD (+DALI2)

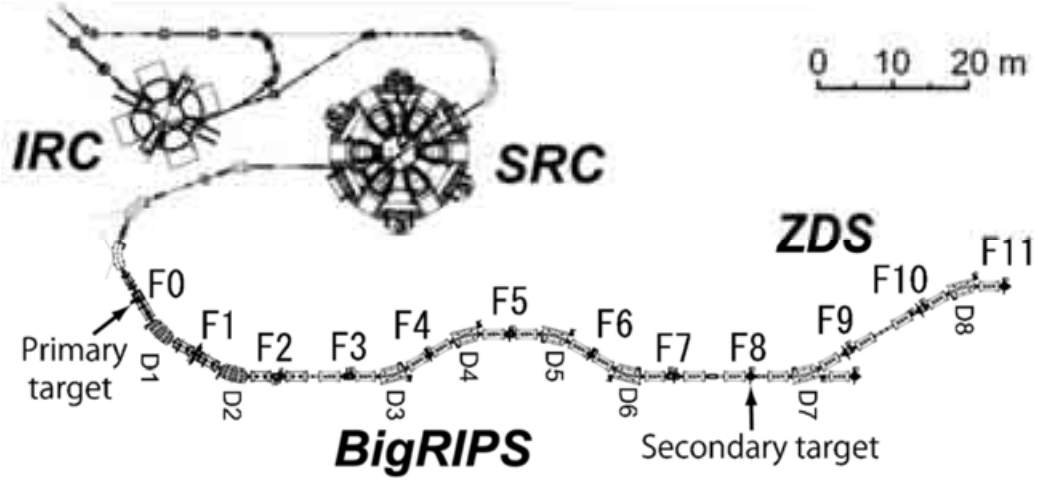
particle ID / momentum analysis

e.g. Doppler shifted γ-ray measurements with identification of products

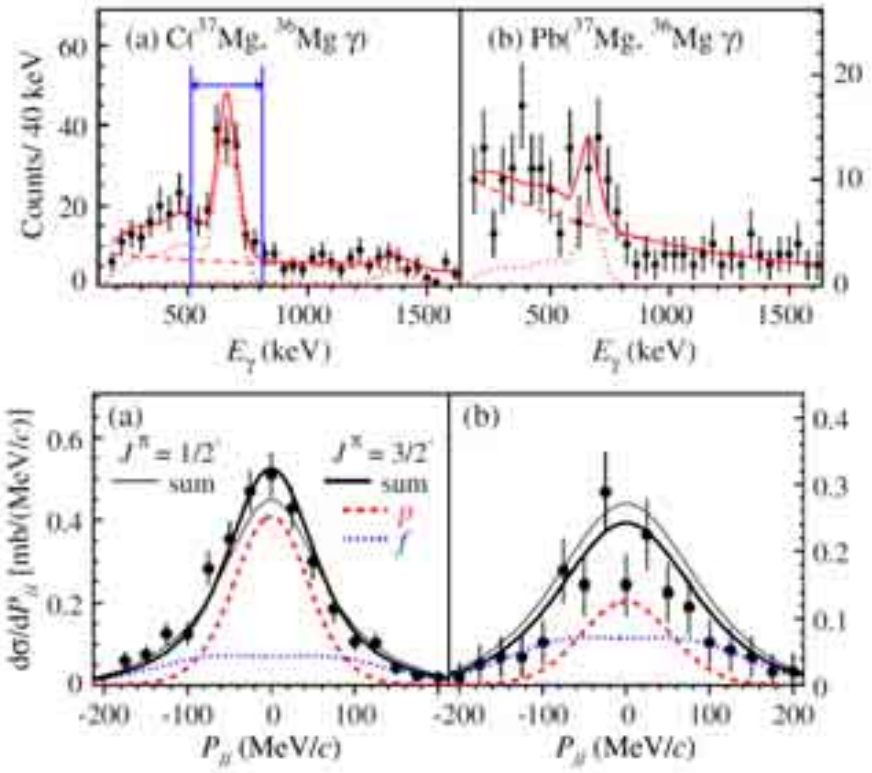


High-energy branches

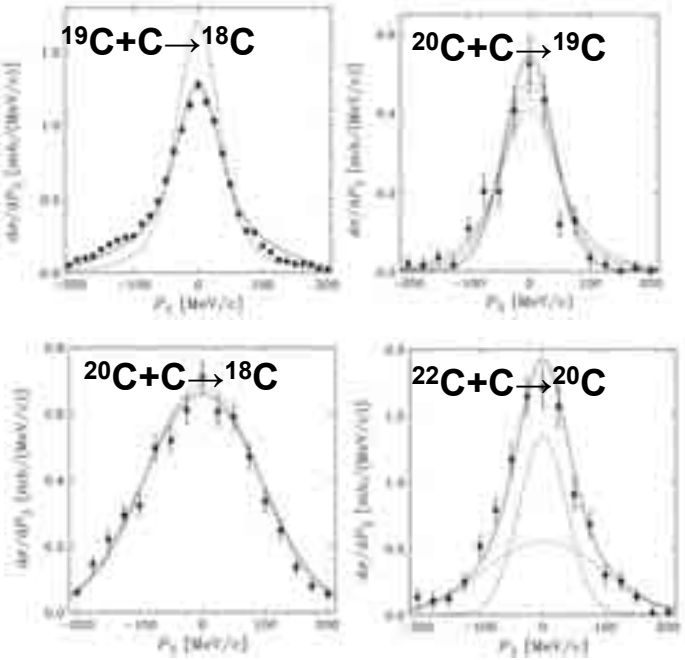
neutron removal reactions



p-wave neutron halo of ^{37}Mg

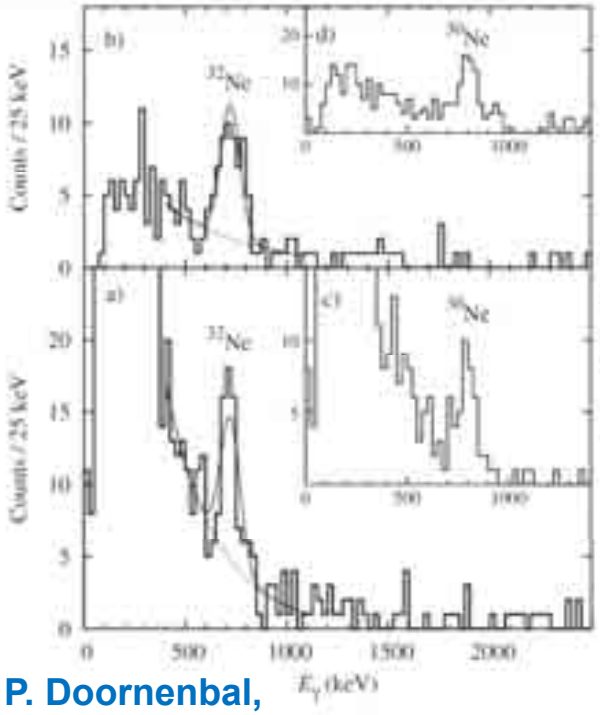


$\nu s_{1/2}$ ground-state properties of ^{20}C and ^{22}C

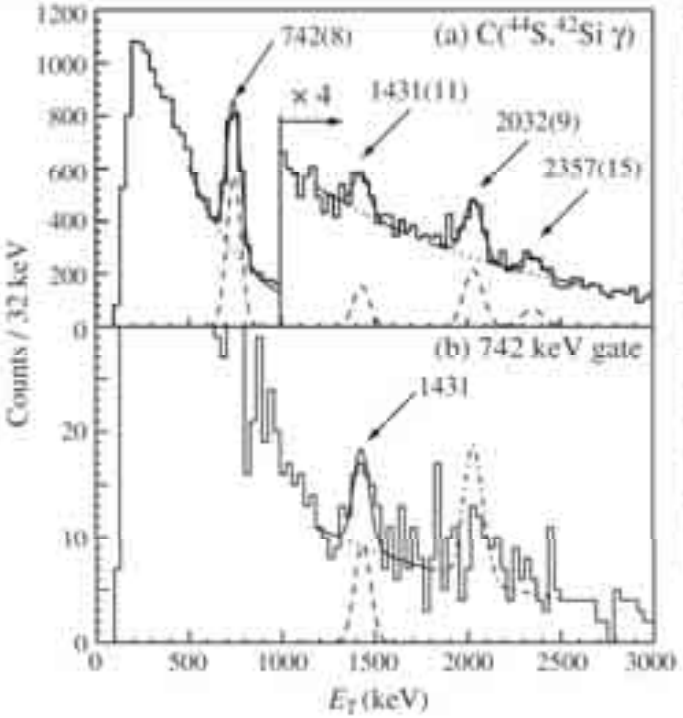


N. Kobayashi *et al.*, PRC 86, 054604 (2012) – ^{20,22}C
T. Nakamura *et al.*, PRL 112, 142501 (2014) – ^{31}Ne
Press release paper
N. Kobayashi *et al.*, PRL 112, 242501 (2014) – ^{37}Mg

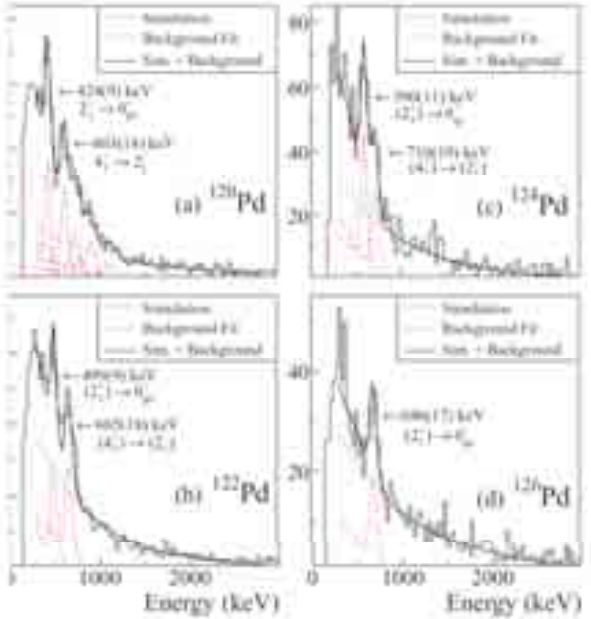
In-beam γ-ray spectroscopy



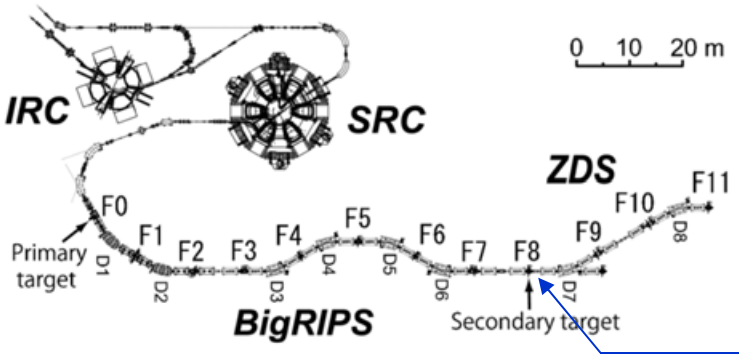
P. Doornenbal,
H. Scheit *et al.*,
PRL 103, 032501 (2009)



S. Takeuchi *et al.*,
PRL 109, 182501 (2012)



H. Wang, N. Aoi *et al.*,
PRC 88, 054318 (2013)



DALI2
NaI array

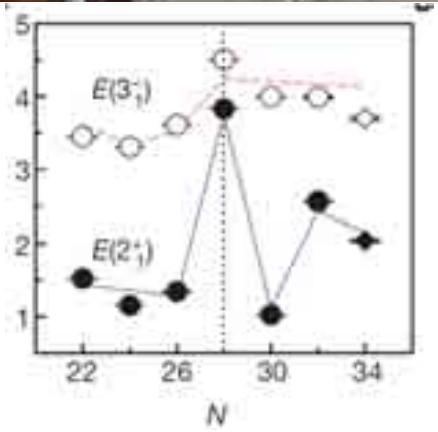
In-beam γ-ray spectroscopy

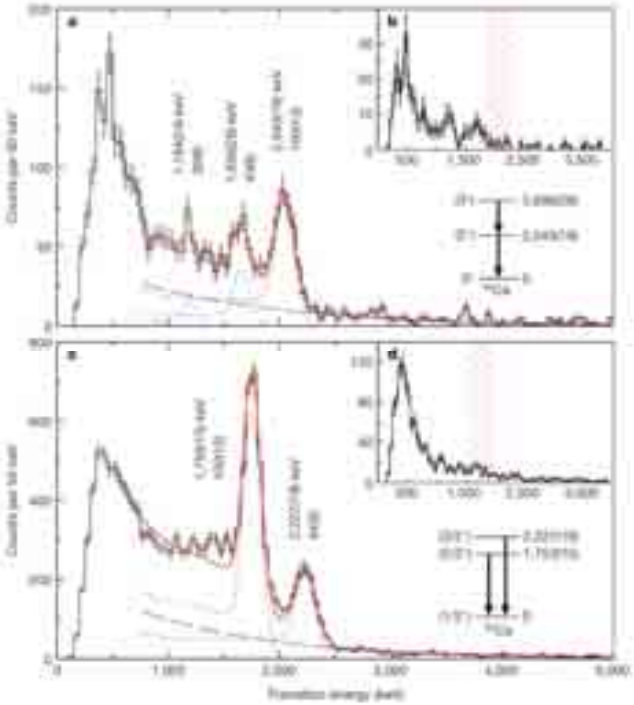
LETTER

doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[5], K. Matsui[3], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,3], H. Sakurai[2,3], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[3], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

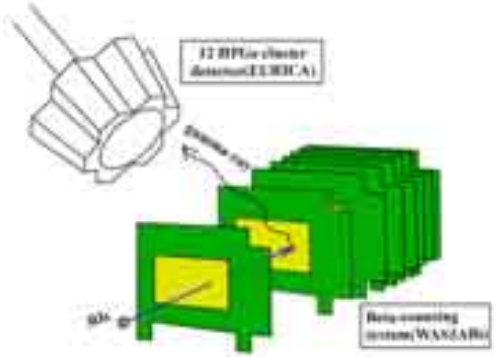


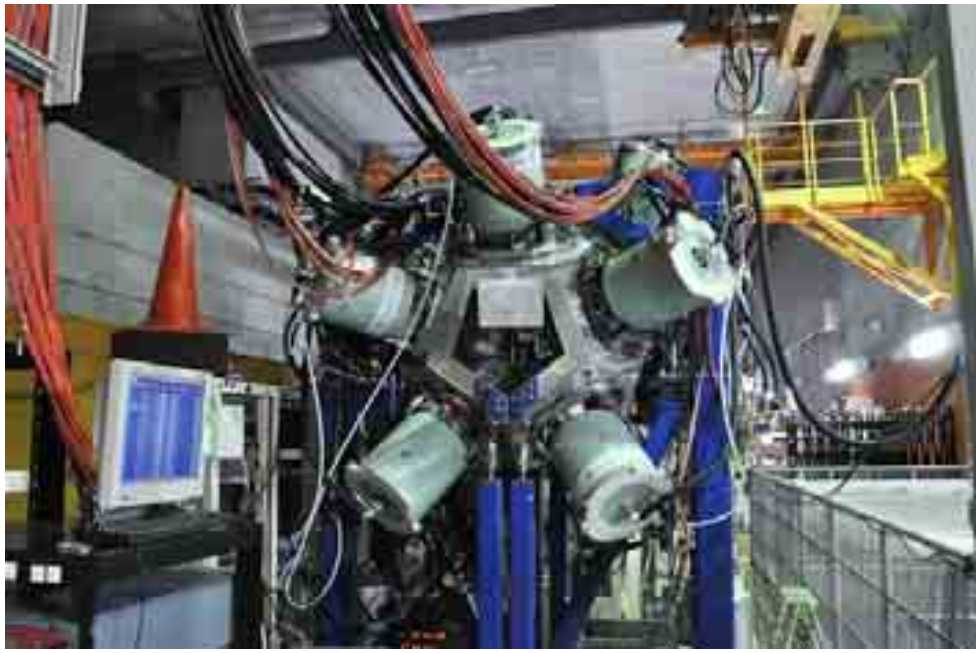


③ BigRIPS + ZD + EURICA

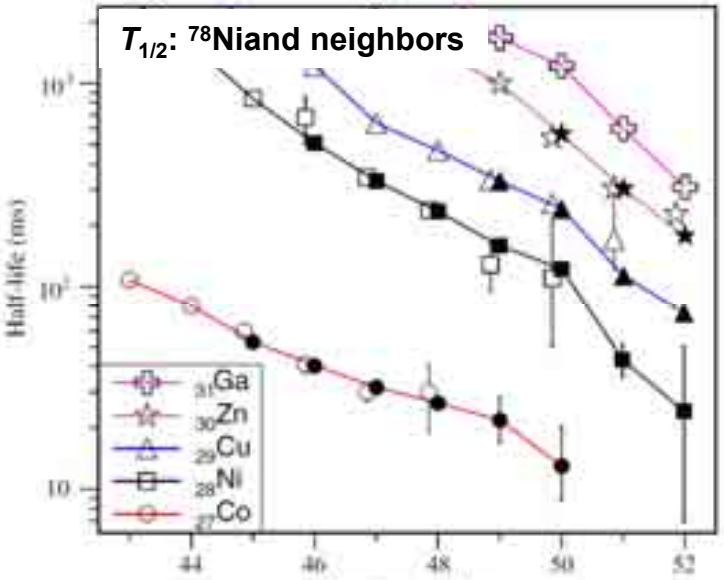
EUroball Riken Cluster Array (EURICA) project

- Commenced since 2012 spring
- Gamma-ray detector clusters
  - 84 high-purity germanium crystals in 12 clusters
  - High resolution (~ 2.5 keV @ 1.3 MeV)
  - High efficiency (~ 13% @ 1 MeV)
  - High granularity (84 crystals)
- Double-side-stripped-silicon-detector stack
  - 8 pieces of DSSD with 60 x 40 pixels

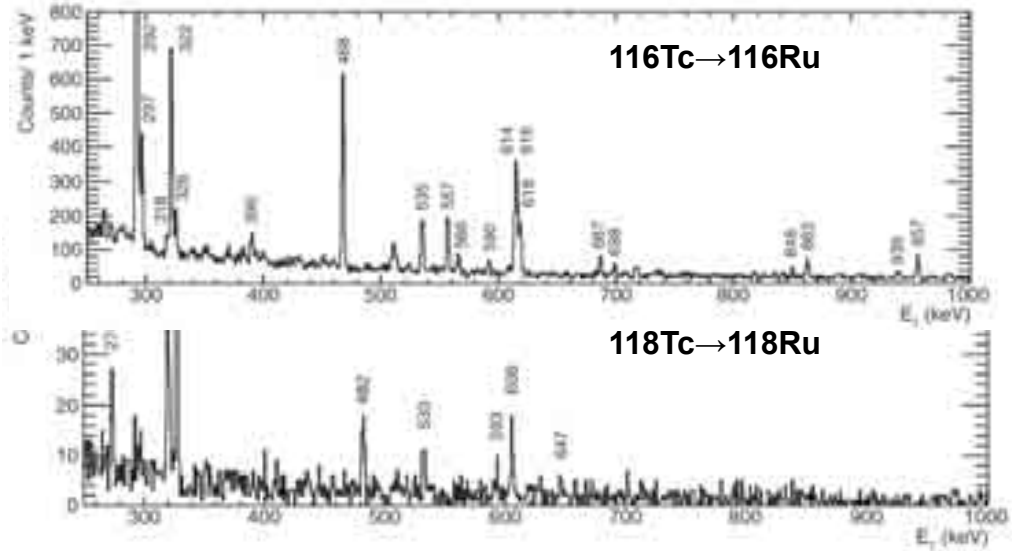




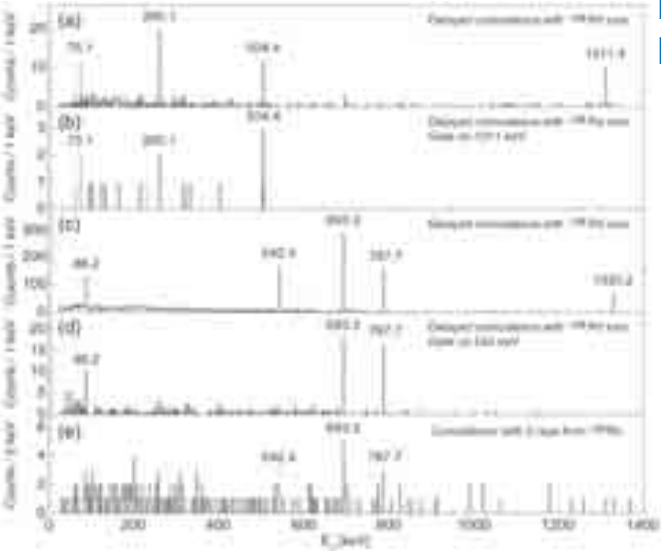
③ BigRIPS + ZD + EURICA



Z.Y. Xu, Nishimura *et al.*,
PRL 112, 132501 (2014)

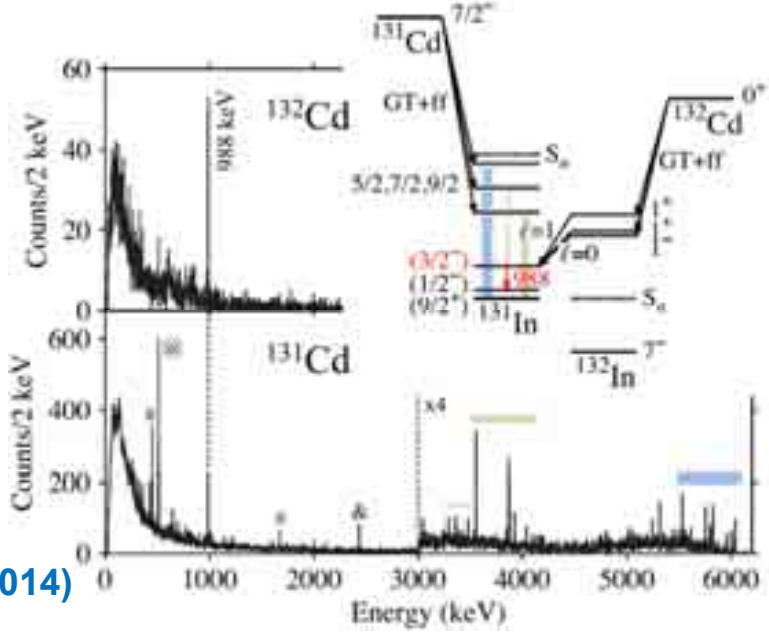


P-A. Söderström *et al.*, PRC 88, 024301 (2013)



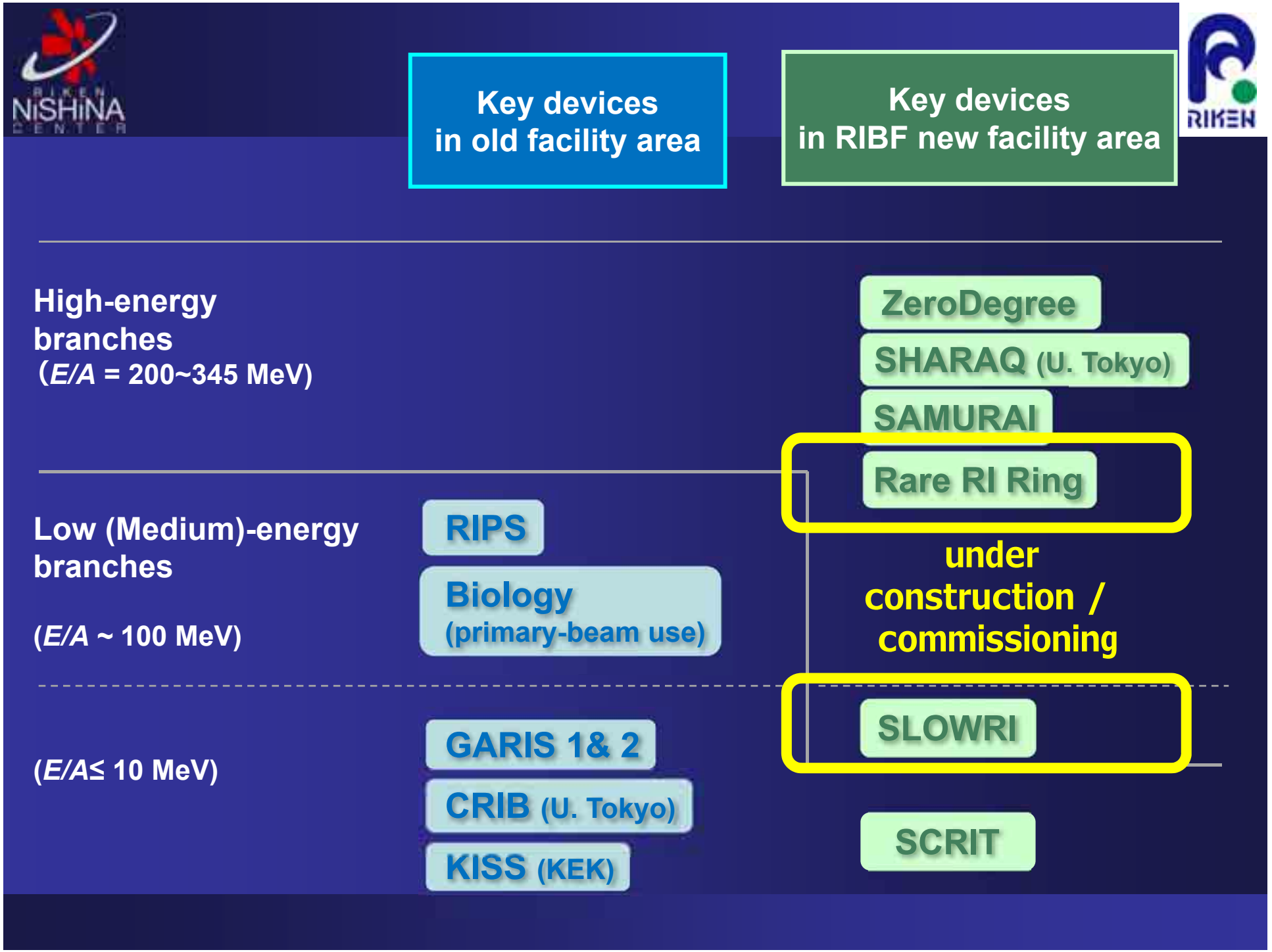
H. Watanabe *et al.*,
PRL 111, 152501 (2013)

$^{126, 128}$Pd isomers
(*N*=82 magicity)



$p_{3/2}$ hole state
(*N*=82 magicity)

J. Taprogge *et al.*,
PRL 112, 132501 (2014)


Key devices
in old facility area
Key devices
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(E/A = 200~345 MeV)
ZeroDegree
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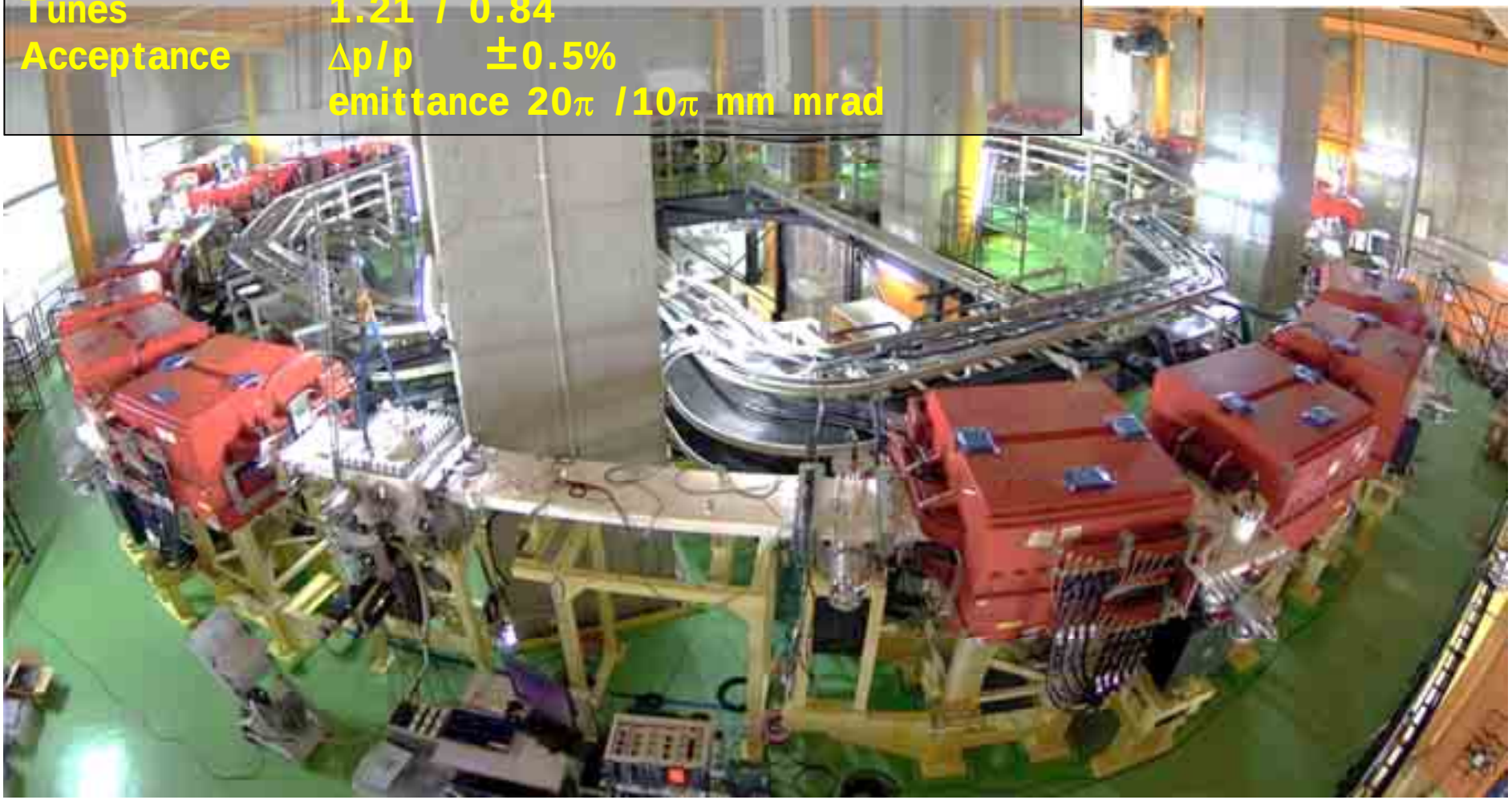
SAMURAI
Rare RI Ring
Low (Medium)-energy
branches
(E/A ~ 100 MeV)
RIPS
Biology
(primary-beam use)
under
construction /
commissioning
SLOWRI
(E/A≤ 10 MeV)
GARIS 1& 2
CRIB (U. Tokyo)
KISS (KEK)
SCRIT

Rare RI Ring (R3)

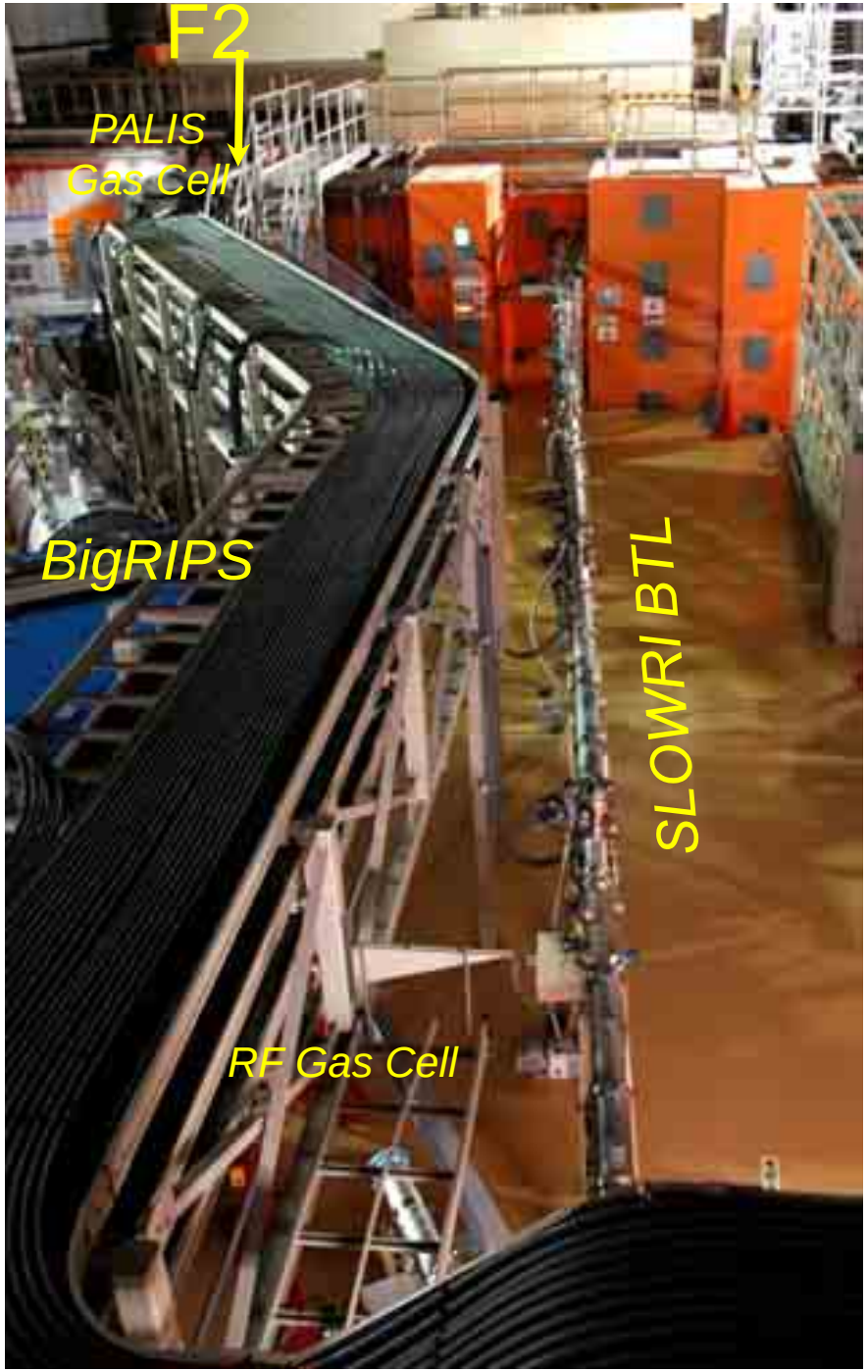
M. Wakasugi *et al.*

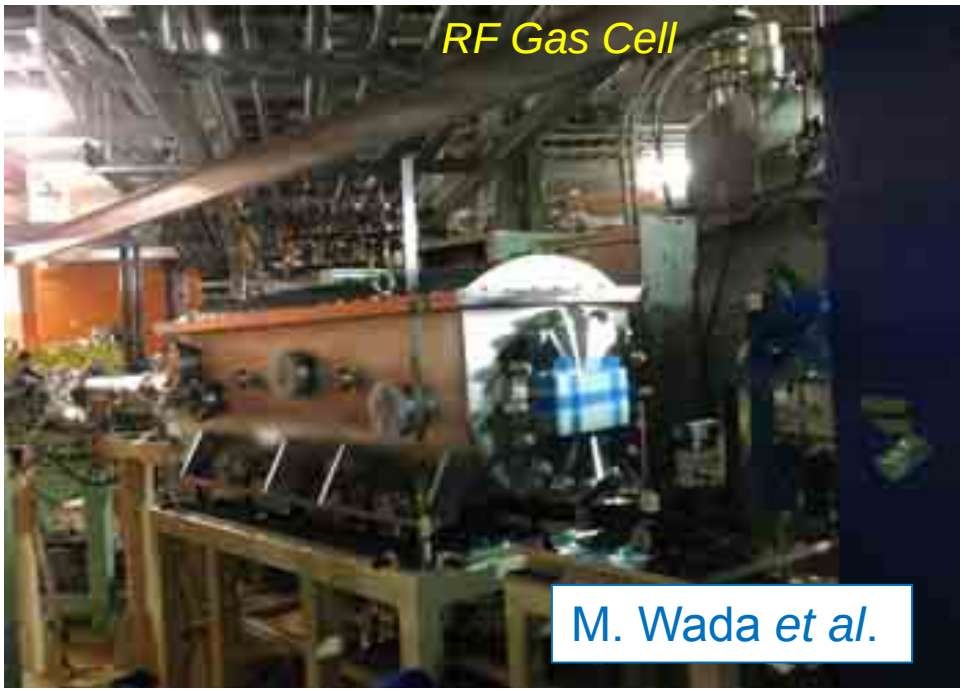
Hexagonal Symmetry Weak-Focusing Lattice Structure

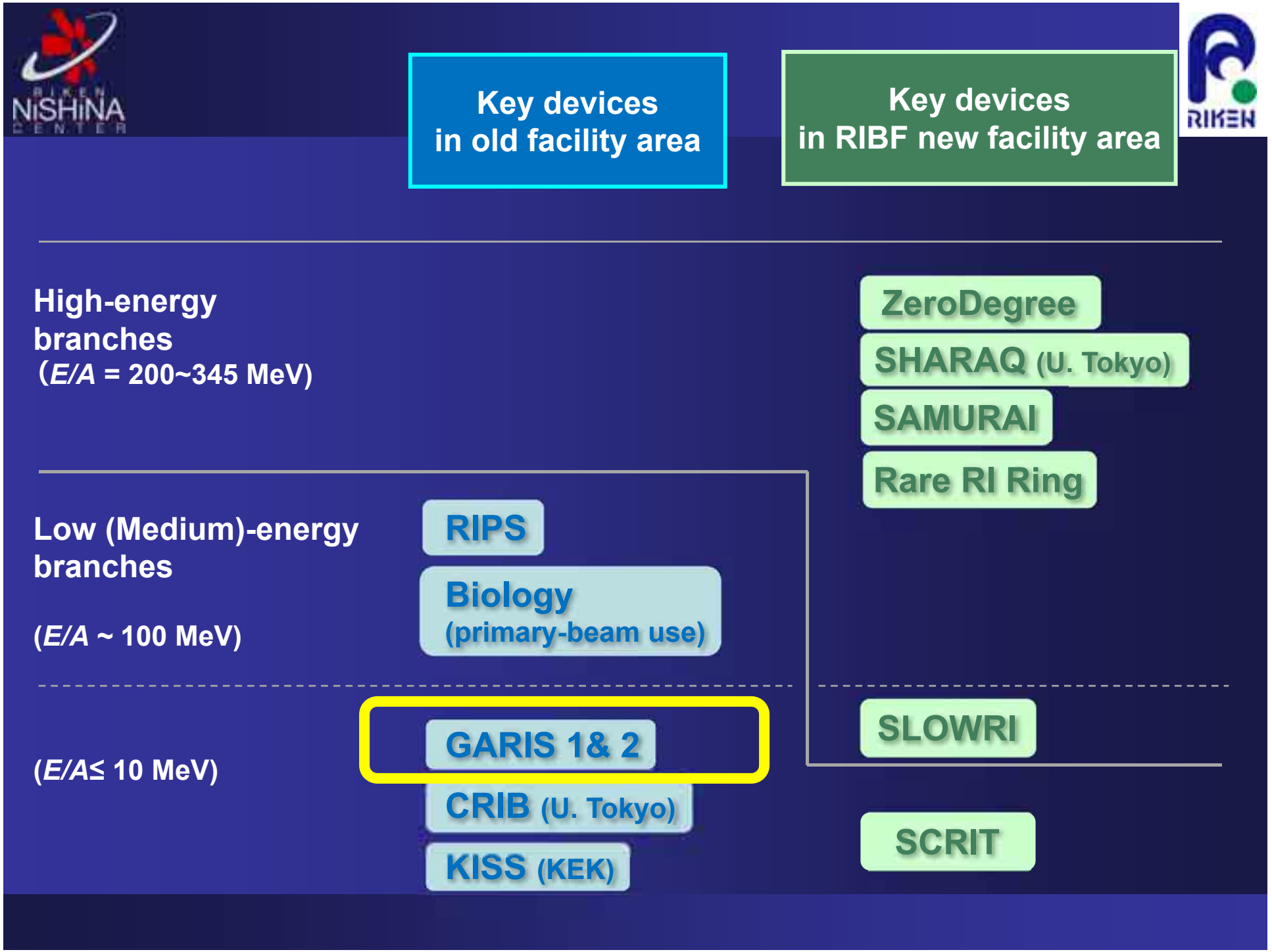
Energy	200 MeV/u
Circumference	60.3 m
Tunes	1.21 / 0.84
Acceptance	$\Delta p/p$ $\pm 0.5\%$
	emittance 20π / 10π mm mrad



SLOWRI @BigRIPS



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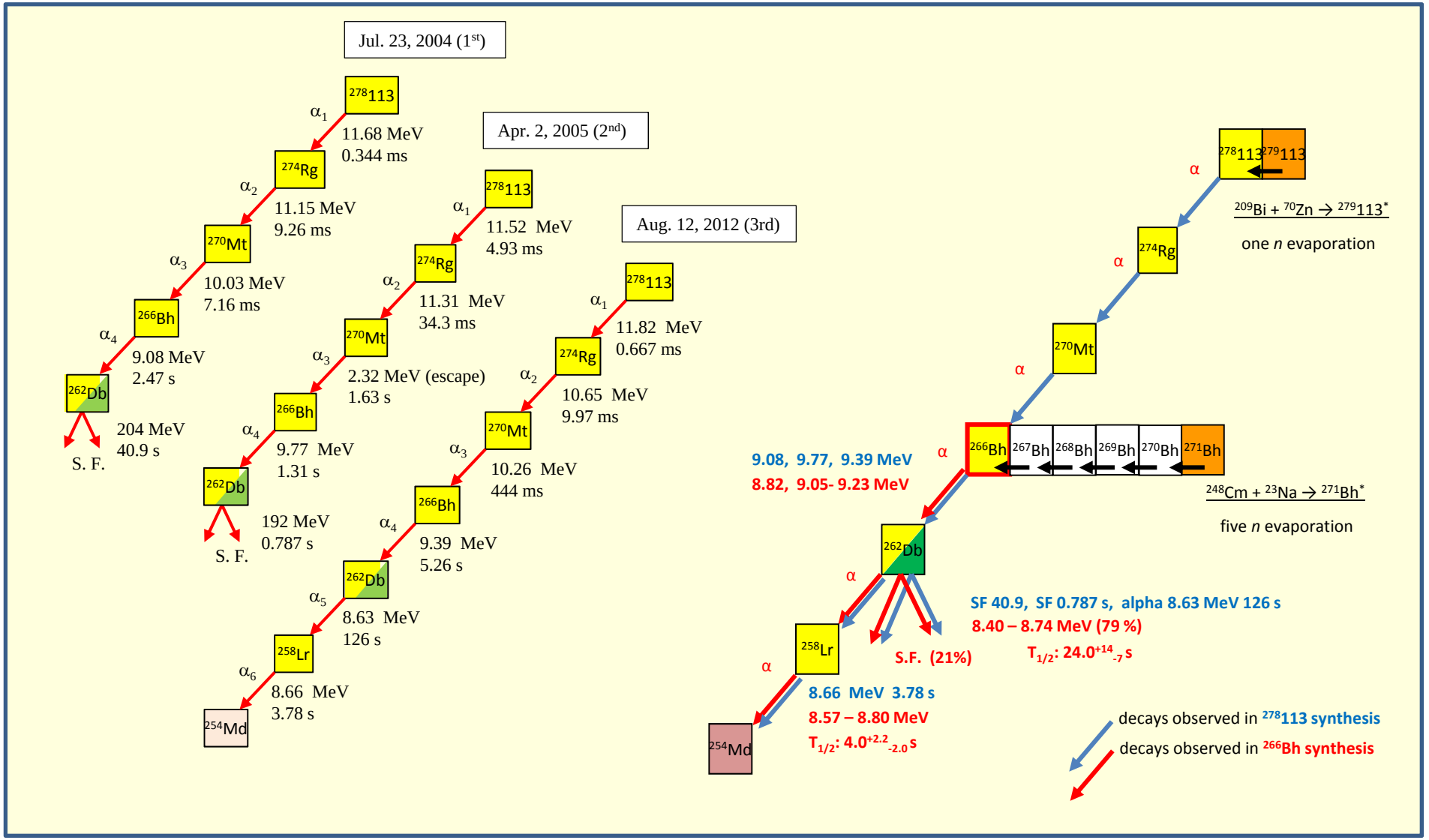
CRIB (U. Tokyo)
KISS (KEK)
SCRIT

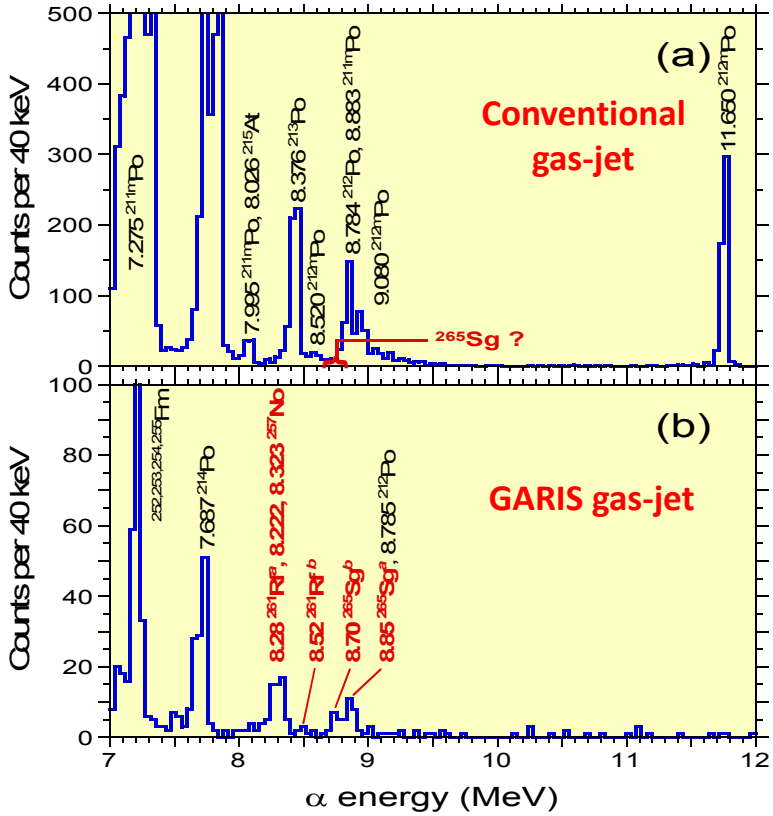
Summary for production and decay of $^{278}113$

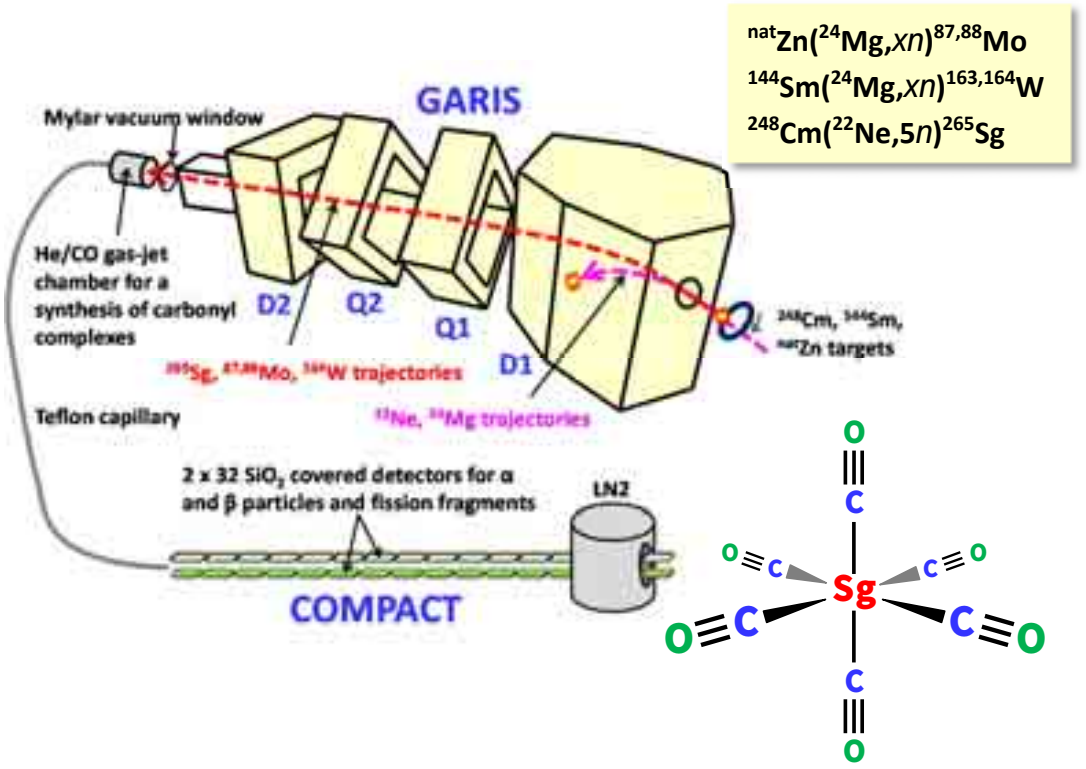
Morita *et al*



Chemistry Synthesis and detection of a seaborgium carbonyl complex

Helmholtz-Institut Mainz, GSI, Mainz Univ., RIKEN, JAEA, Bern Univ., PSI, IMP, Hirosima Univ., Kyushu Univ., Niigata Univ., UC Berkeley, LBNL, and Saitama Univ.





$^{nat}Zn(^{24}Mg,xn)^{87,88}Mo$
$^{144}Sm(^{24}Mg,xn)^{163,164}W$
$^{248}Cm(^{22}Ne,5n)^{265}Sg$

- Production and decay studies of ^{265}Sg for chemical studies using the GARIS gas-jet system
- Synthesis and detection of $Sg(CO)_6$
- First organometallic compound of SHEs: Sg(0) – C chemical bonding
- Adsorption enthalpy (ΔH_{ads}) on SiO_2 : $Sg(CO)_6 \approx W(CO)_6 \approx Mo(CO)_6$
- Sg: typical member of the group-6 element

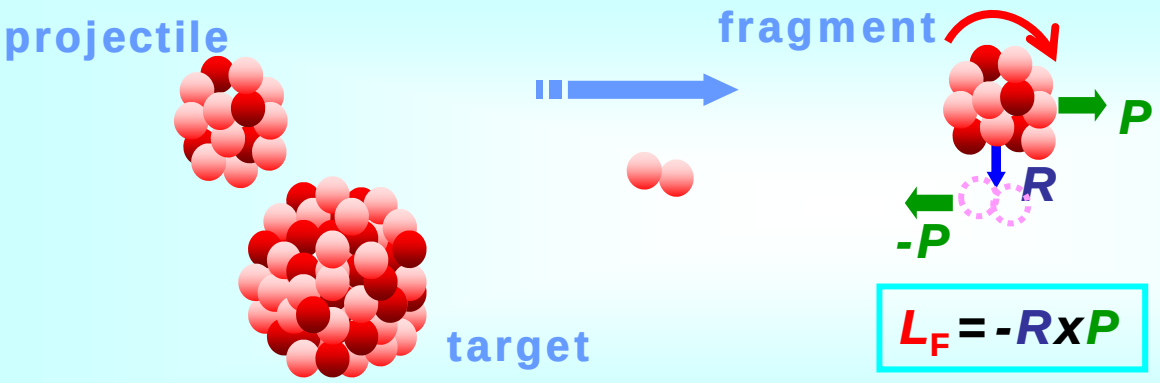
Haba *et al.*, PRC **85**, 024611 (2012).
Even *et al.*, Science **345**, 1491 (2014).

1. **RIBF recent progress**

2. **Spin-aligned RI beams**
   - Isomeric-state nuclear moments
   - Disp.-matching two-step fragmentation method

3. **Spin-polarized RI beams**
   - ① Ground-state nuclear moments
   - ② β-delayed γ & n spectroscopy

Fragment-induced spin orientation



Sum of the lost Fermi momenta

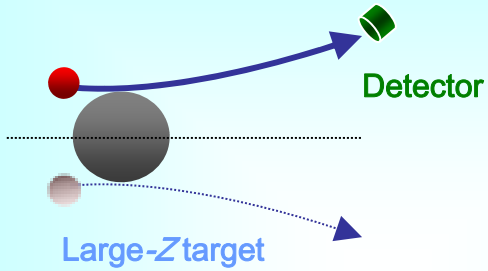
Position vector of the participant portion

$L_F = -R \times P$

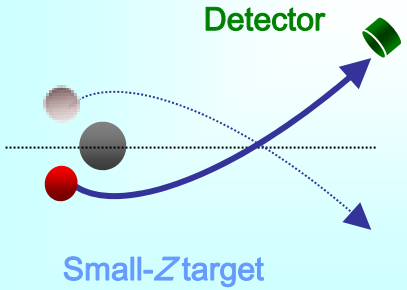
Angular momentum left in the fragment part

K.Asahi *et al.*, PLB 251, 499 (1990)

Spin polarization

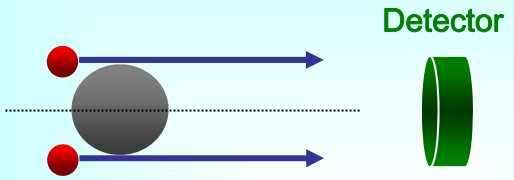


near-side trajectory



far-side trajectory

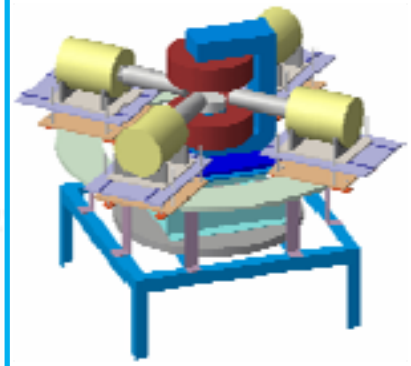
Spin alignment

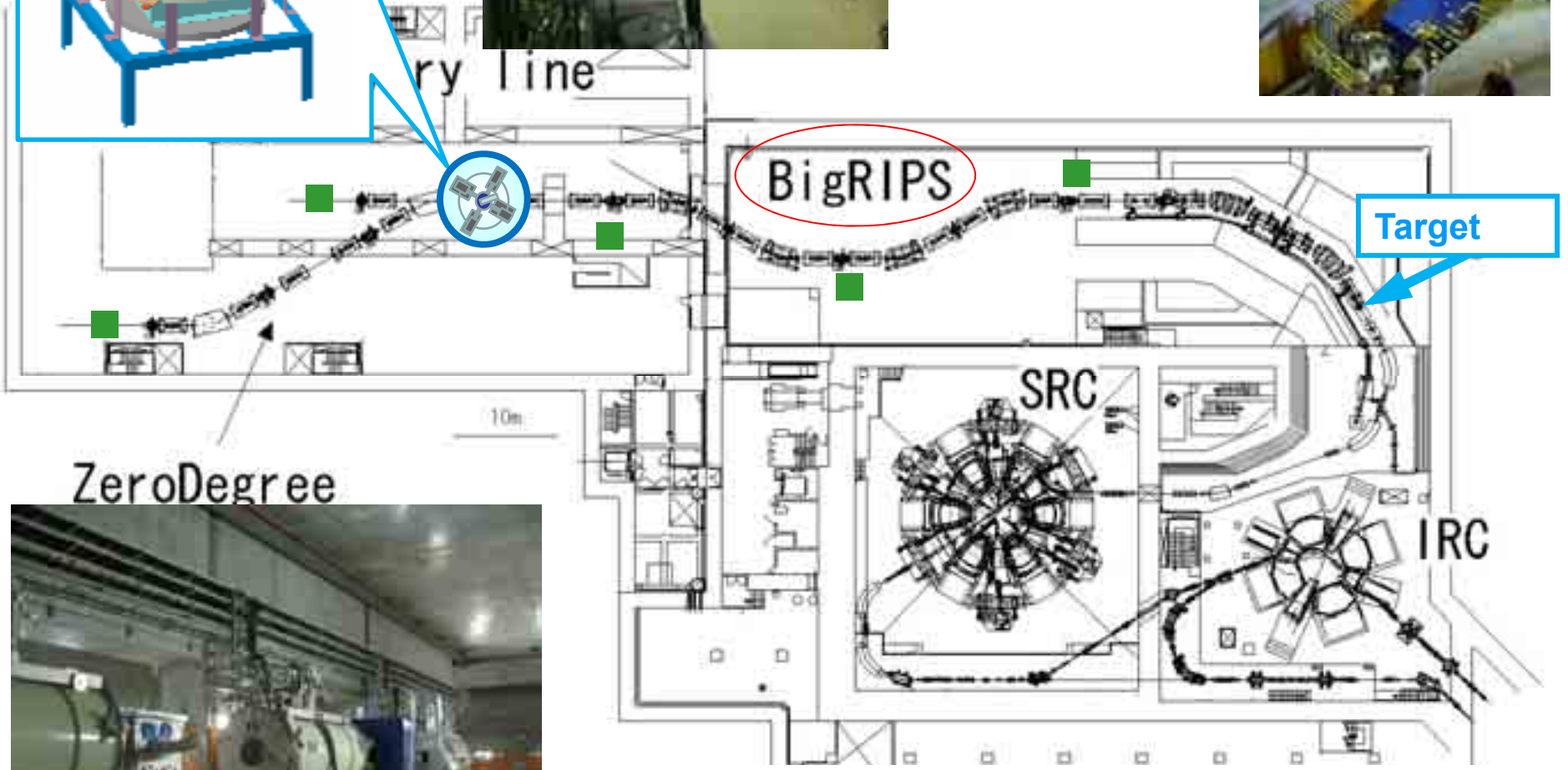


Fragments scattered at 0°
High energies are suitable because of
- production of RIBs
- population of isomeric states
- production of spin alignment

BigRIPS Layout for the present experiment

TDPAD apparatus

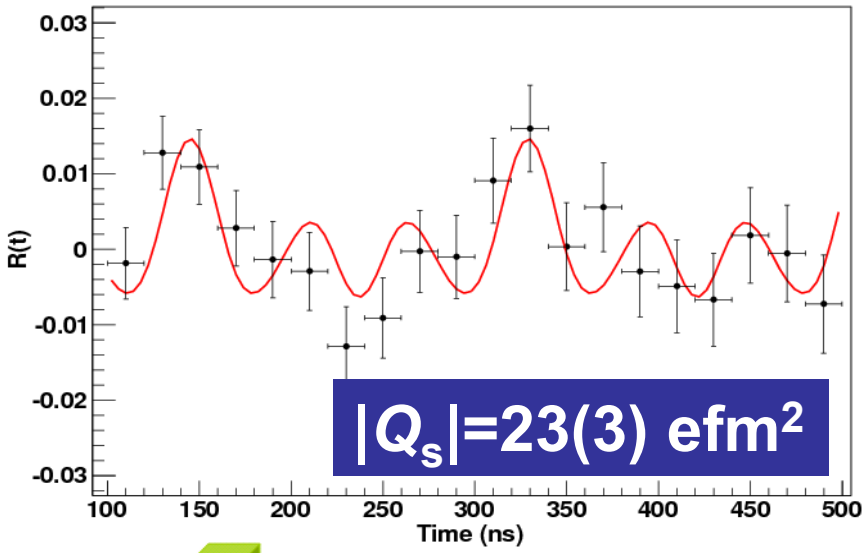




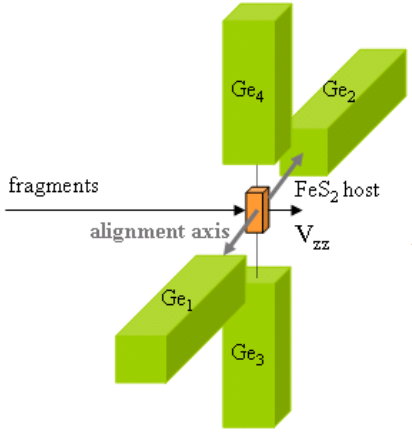
T. Kubo, Nucl. Instr. Meth. B204, 97 (2003).
T. Kubo *et al*., IEEE Transactions on Applied Superconductivity, 17, 1069 (2007)

$Q(^{43m}S)$ measurement @BigRIPS (Spokesperson: J.M. Daugas)

Fragmentation-induced spin-alignment
$^{48}Ca + ^{9}Be \rightarrow ^{43m}S + X$
(conventional single step fragmentation involving just 5-nucleon removal)



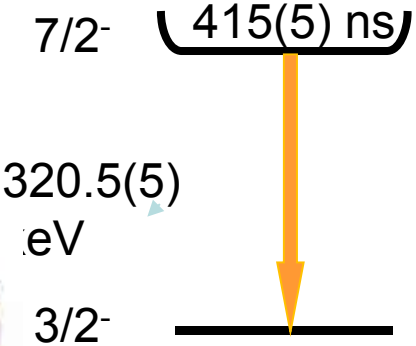
$|Q_s|$=23(3) efm²



crystal : pyrite FeS_2

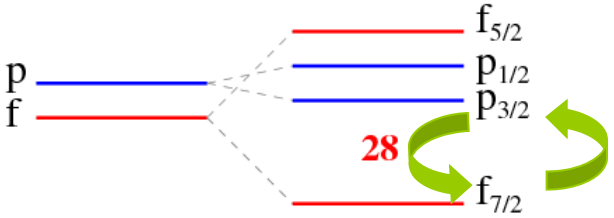
V_{zz}=14*10¹⁷ V/cm² (err. ~10%)
(solide state physics calculations)

Rather spherical



F. Sarazin *et al.*, PRL 84, 5062 (2000)

Prolate deformed

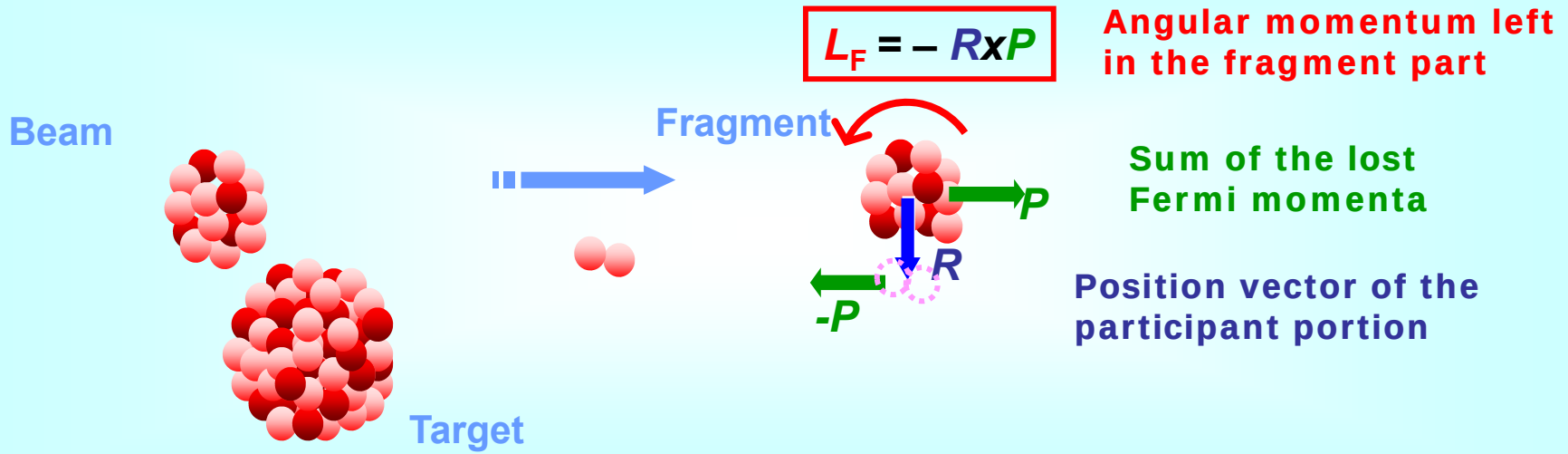


Configuration inversion between $\nu p_{3/2}$ and $\nu f_{7/2}$

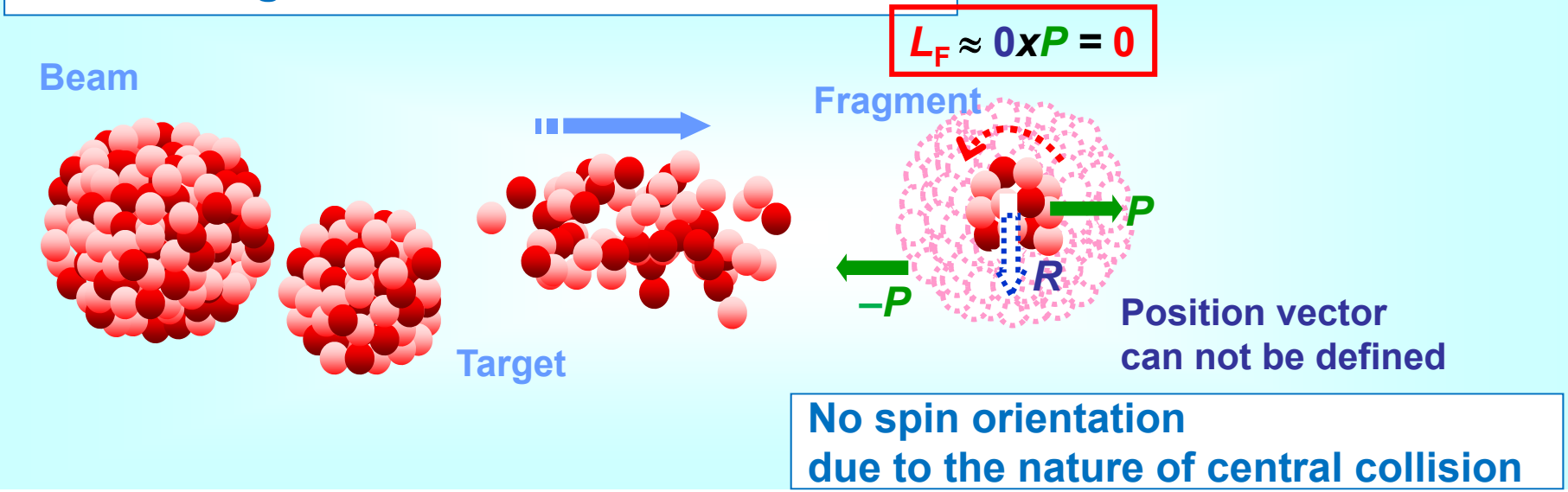
Shape coexistence

R. Chevrier *et al.*, Phys. Rev. Lett. **108**, 162501 (2012)

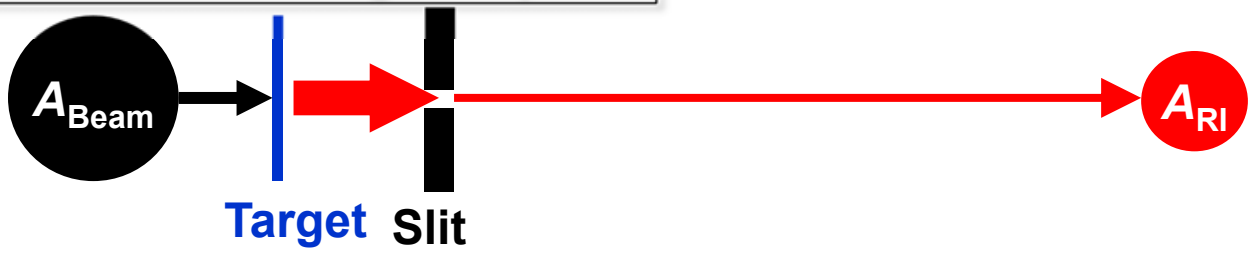
Problem

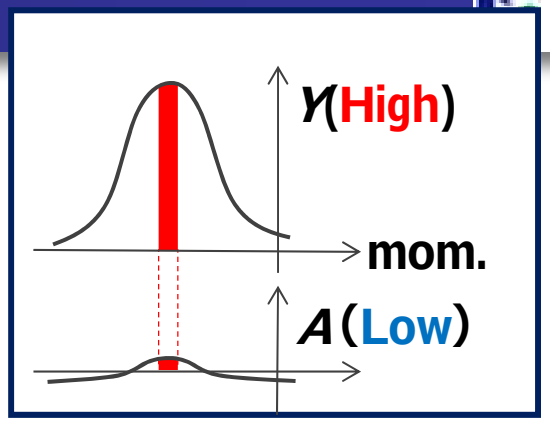


When a large nucleon removal is involved

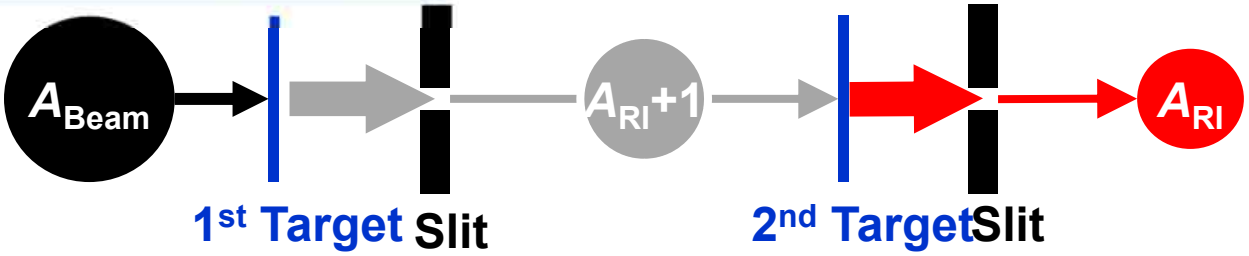


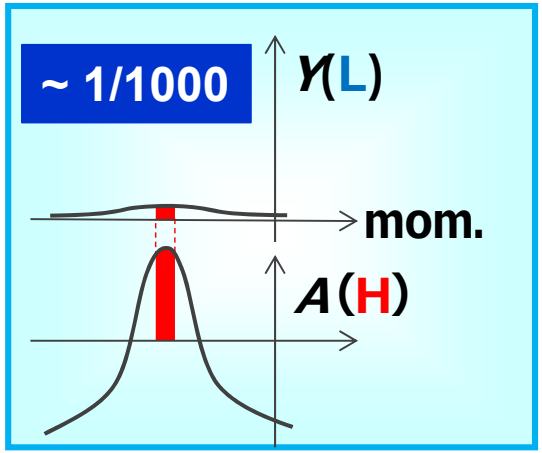
Conventional single step PF



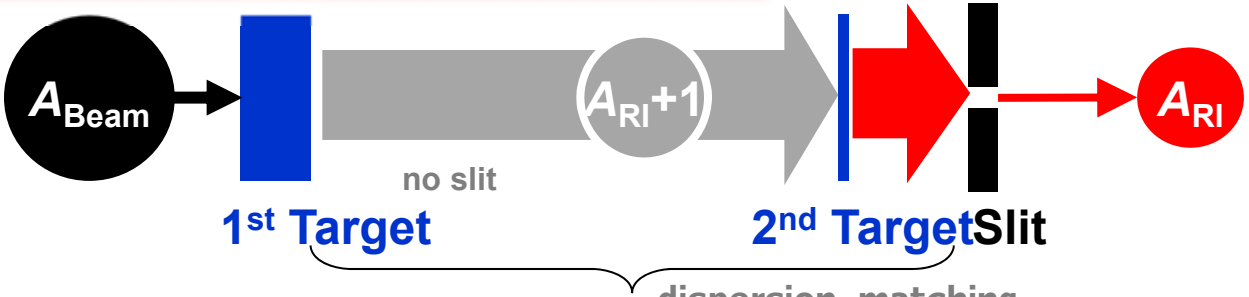


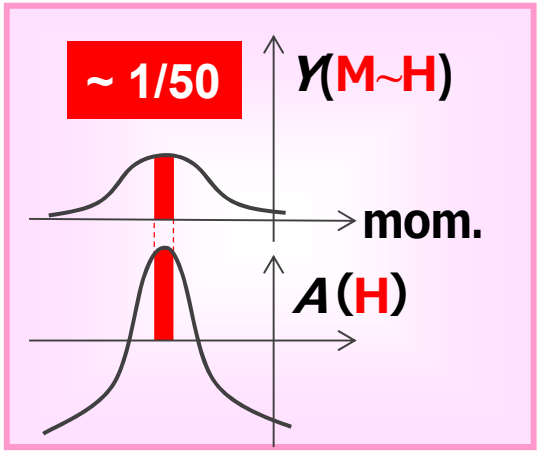
Simple two-step PF



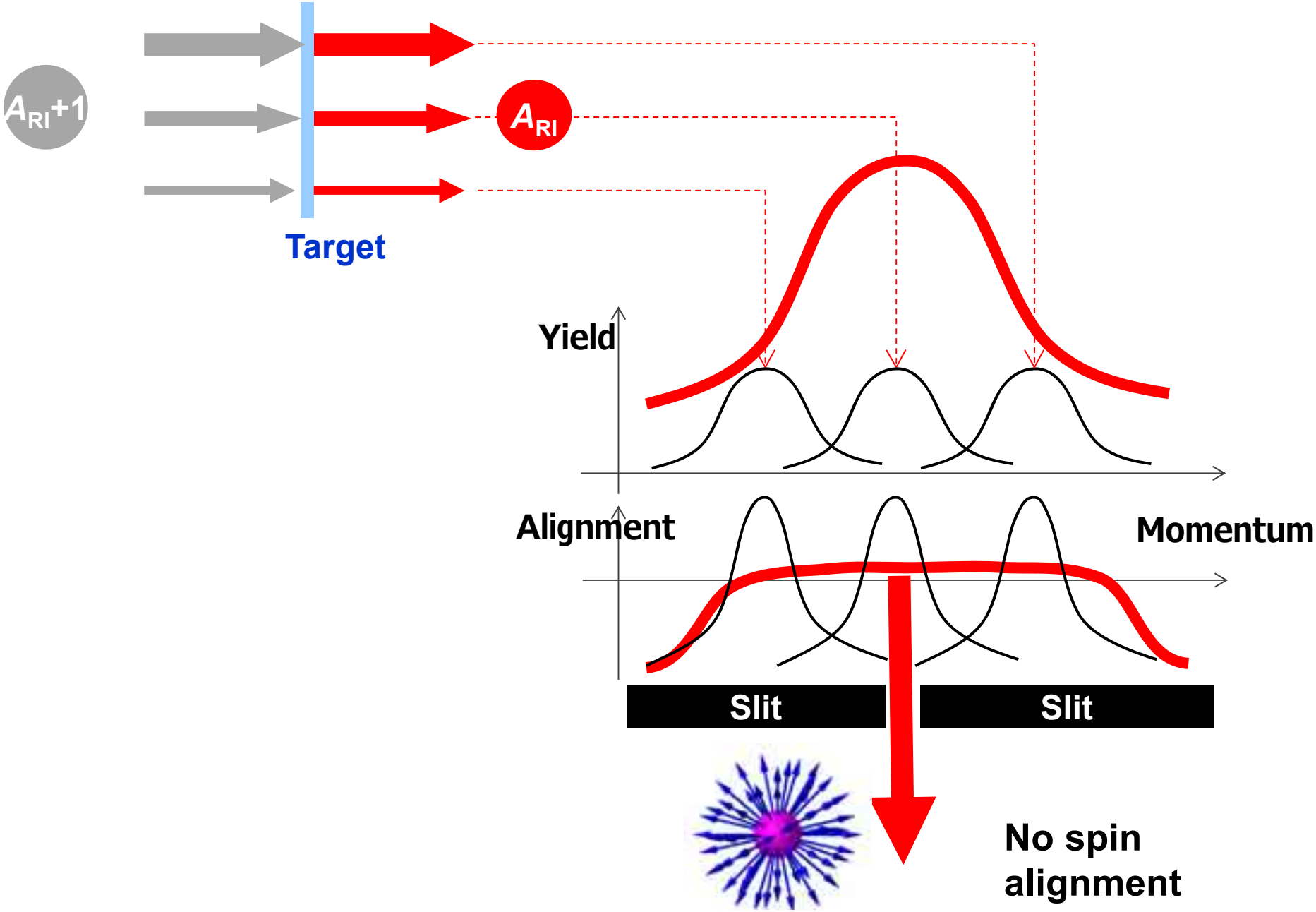


Dispersion-matching two-step PF

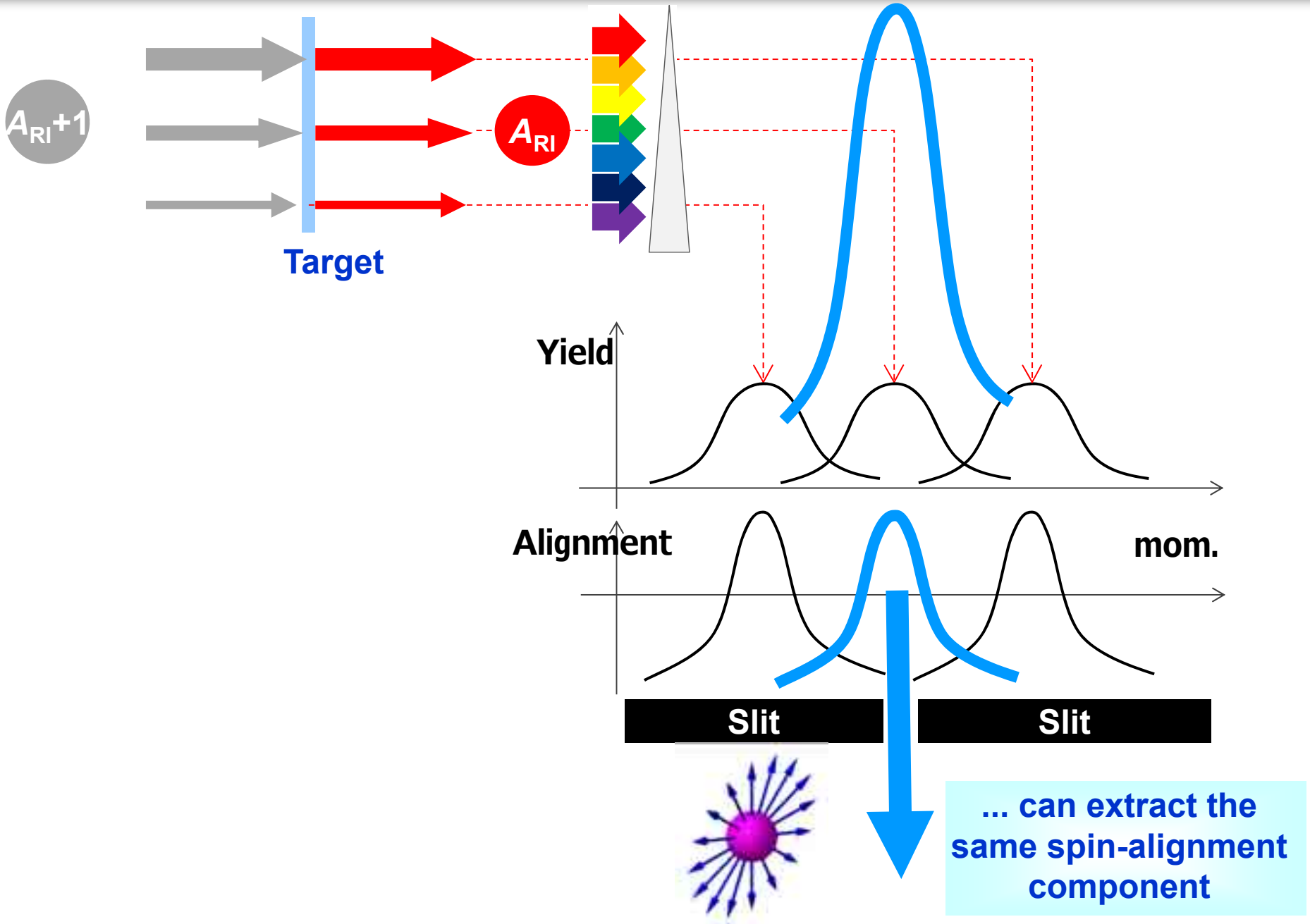




Smearing out of *A* due to target thickness



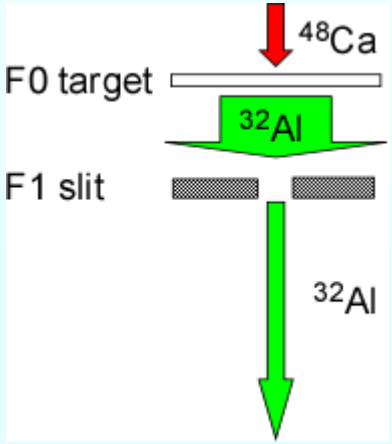
Dispersion matching for spin-aligned RIBs

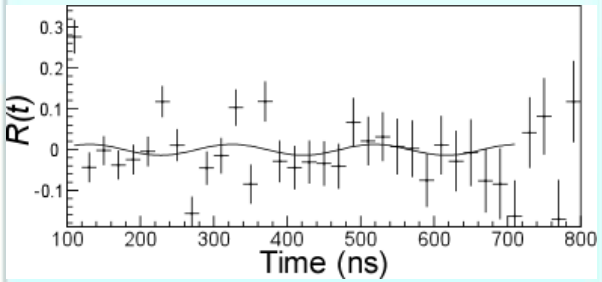


Result

Measurement 1

One-step PF



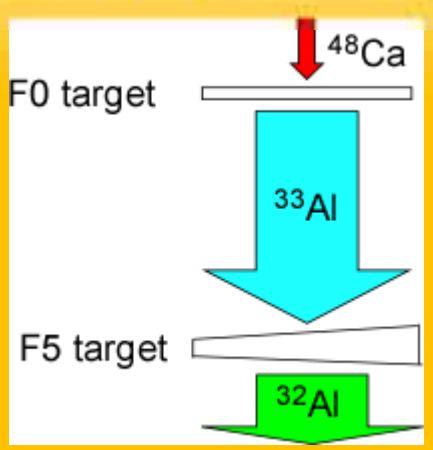


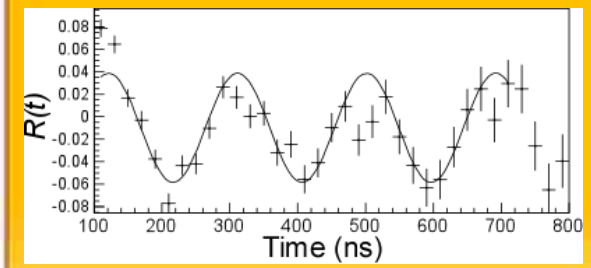
***A* < 0.8 %**

large *Y* but quite small *A*

Measurement 2

Two-step PF
w/ Disp. Matcing.



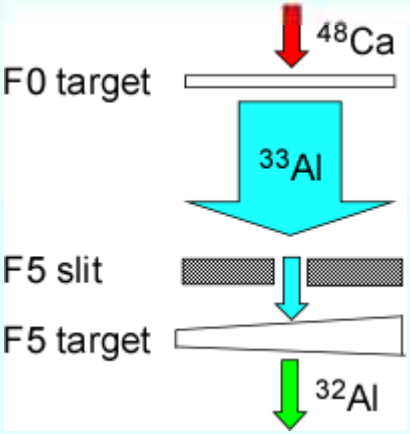


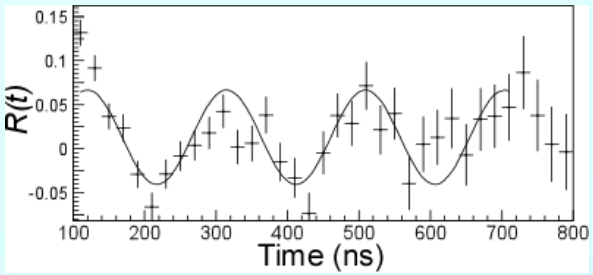
***A* = 8(1) %**
(~30% of theo. max.)

large *Y* and large *A*

Measurement 3

Two-step PF
w/o Disp. Matcing.





***A* = 9(2) %**

large *A* but quite small *Y*

nature physics
ARTICLES
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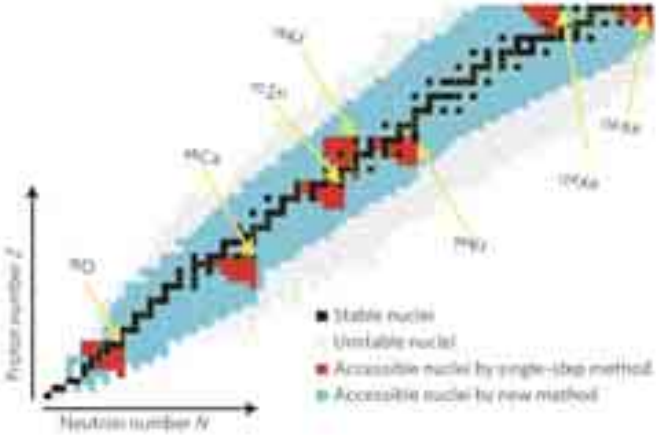
Production of spin-controlled rare isotope beams

Yuichi Ichikawa[1*†], Hideki Ueno[1], Yuji Ishii[2], Takeshi Furukawa[3], Akihiro Yoshimi[4], Daisuke Kameda[1], Hiroshi Watanabe[1], Nori Aoi[1], Koichiro Asahi[2], Dimiter L. Balabanski[5], Raphaël Chevrier[6], Jean-Michel Daugas[6], Naoki Fukuda[1], Georgi Georgiev[7], Hironori Hayashi[2], Hiroaki Iijima[2], Naoto Inabe[1], Takeshi Inoue[2], Masayasu Ishihara[1], Toshiyuki Kubo[1], Tsubasa Nanao[2], Tetsuya Ohnishi[1], Kunifumi Suzuki[2], Masato Tsuchiya[2], Hiroyuki Takeda[1] and Mustafa M. Rajabali[8]

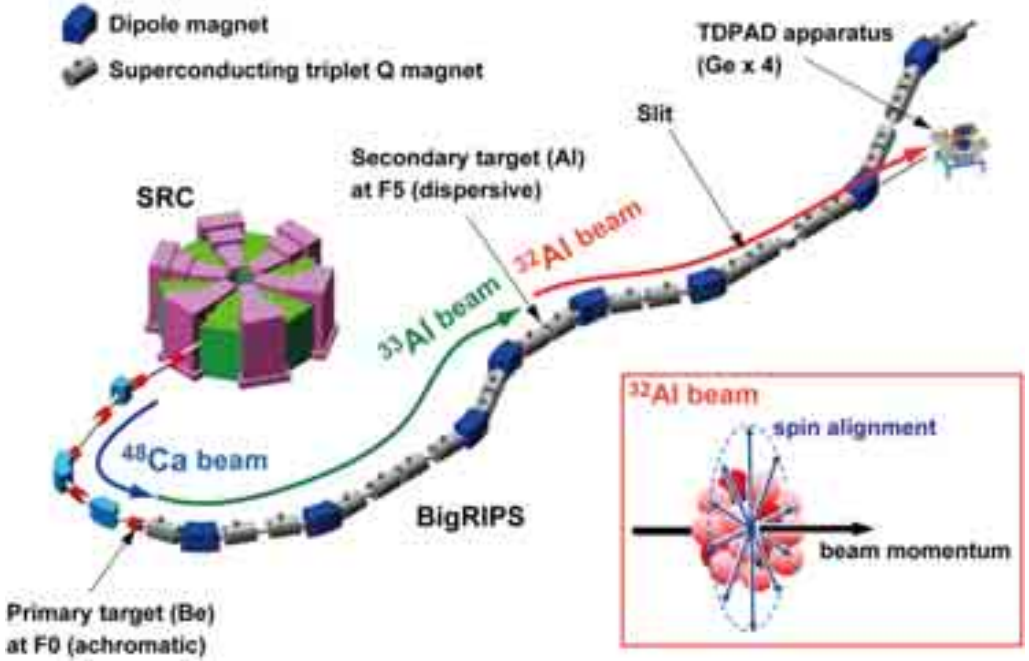


Key 1:

Two step PF
→ **Maximize spin alignment**

Key 2:

Dispersion matching
→ **Maximize yield of two-step PF**



1. **RIBF recent progress**

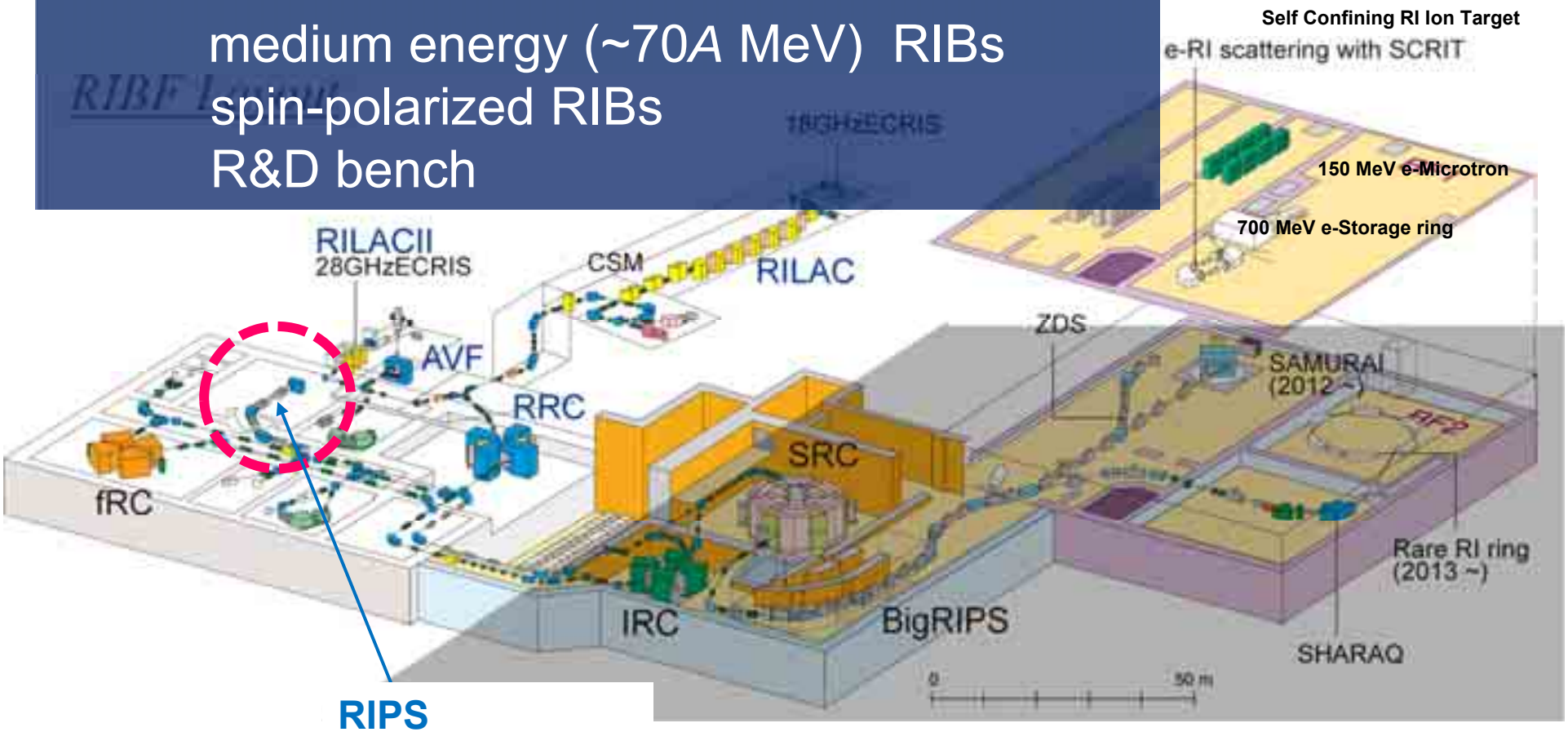
2. **Spin-aligned RI beams**
   - Isomeric-state nuclear moments
   - Disp.-matching two-step fragmentation method

3. **Spin-polarized RI beams**
   - ① Ground-state nuclear moments
   - ② β-delayed γ & n spectroscopy

⑨ RIPS

RIPS

medium energy (~70*A* MeV) RIBs
spin-polarized RIBs
R&D bench

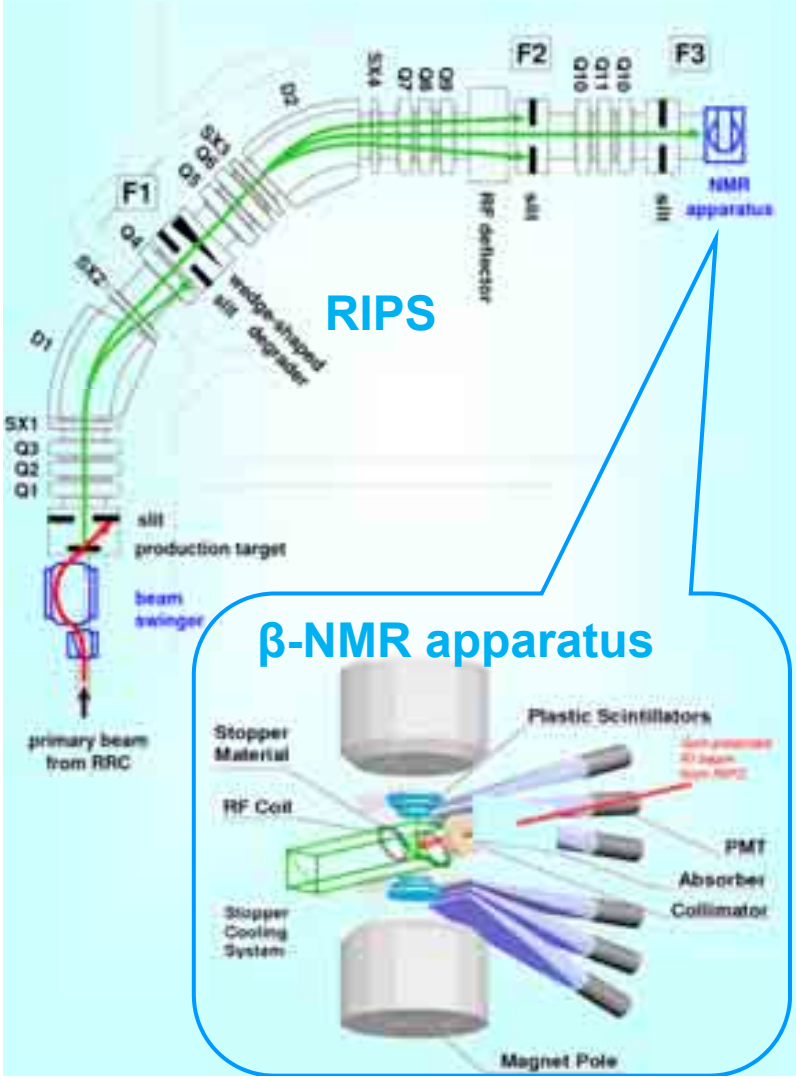


RIPS
- spin-oriented medium-E RIBs

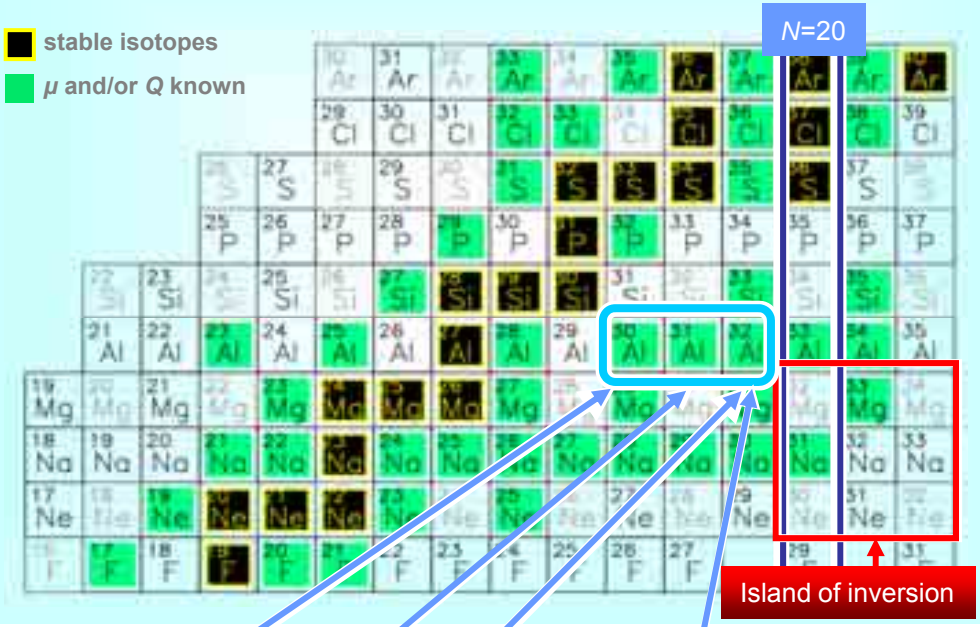
Low (Medium)-energy branches

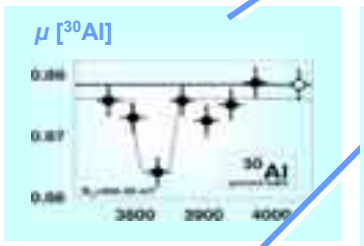
μ &Q ($Al_{G.S.}$) measurements @RIKEN

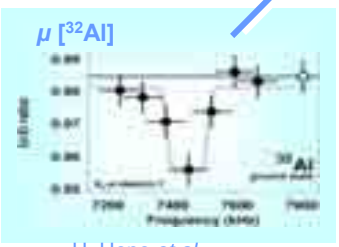
Method:
Polarized RI beam
+ β-NMR spectroscopy



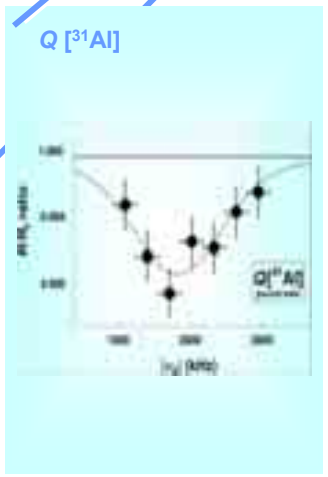
Measured:



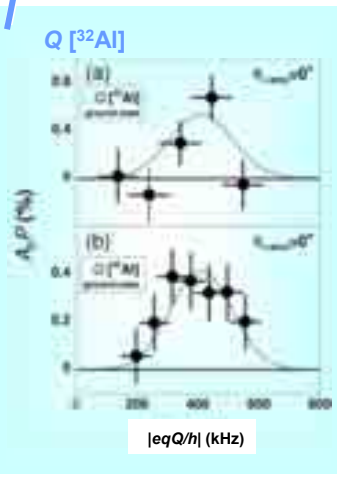




H. Ueno *et al.*,
PLB 615, 186 (2005)



D. Nagae *et al.*,
PRC 79 027301 (2009).

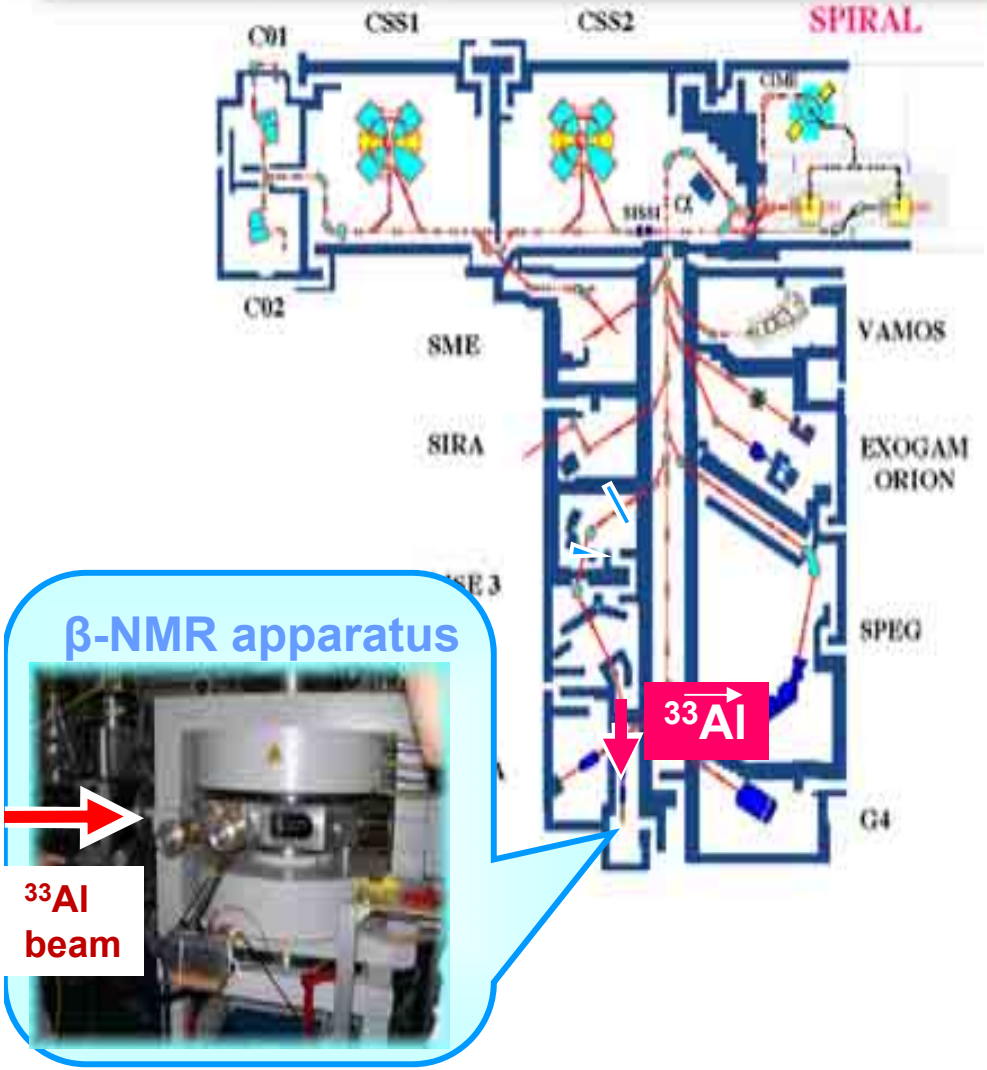


D. Kameda *et al.*,
PLB 647, 93 (2007)

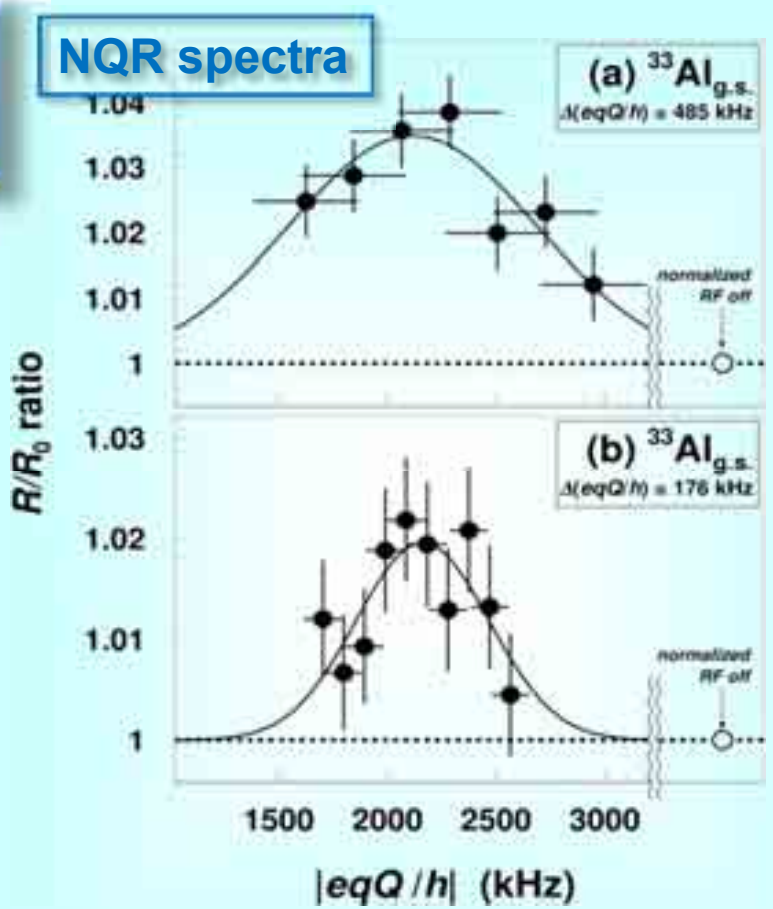
Q (^{33}Al) measurement @GANIL

Reaction:

$^{36}S^{16+}$ (E=77.5A MeV, I ~ 130pnA) +Be (224mg/cm^2)
→ ^{33}Al (θ_{Lab}=2±1°, p=(1.026-1.041)·p_{beam}, purity 83%, I [^{33}Al] ~ 1.4k pps)



NQR spectra



$|Q_{exp}(^{33}Al)|$ = 132 (18) e mb

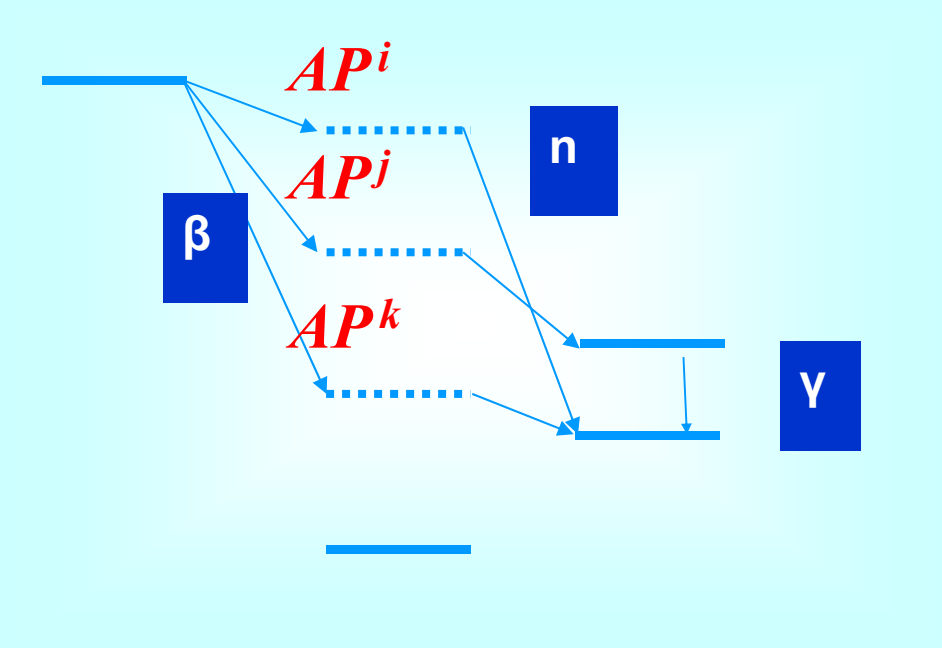
K. Shimada et al., Phys. Lett. ***B714****, 246-250 (2012)*

precision $|Q_{exp}|$ measurement

M. De Rydt al., to be submitted soon

Beta-delayed γ & n spectroscopy with stopped pol. RI

- **Beta-delayed neutron spectroscopy for the study of neutron-rich nuclei**
  - **R. Harkewicz *et al.*, PRC 44, 2365 (1991)**
  - **J.L. Lou *et al.*, PRC 75, 057302 (2007) and references therein.**
  - **^{17}B: G. Raimann et al., PR C 53, 453 (1996)**



β-ray asymmetry

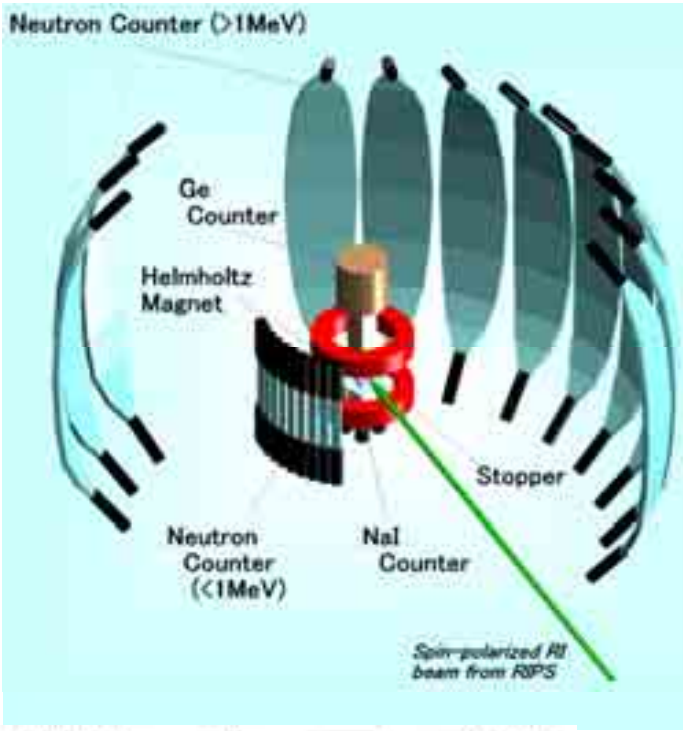
$$R \equiv U / D$$

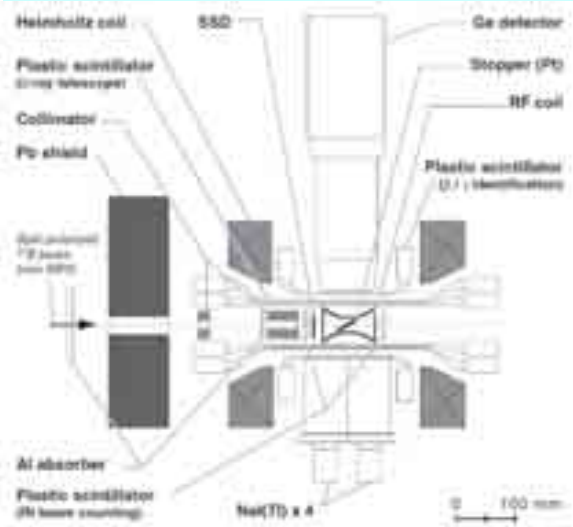
$$R / R_0 = \frac{1 - AP}{1 + AP} \cong 1 - 4AP$$

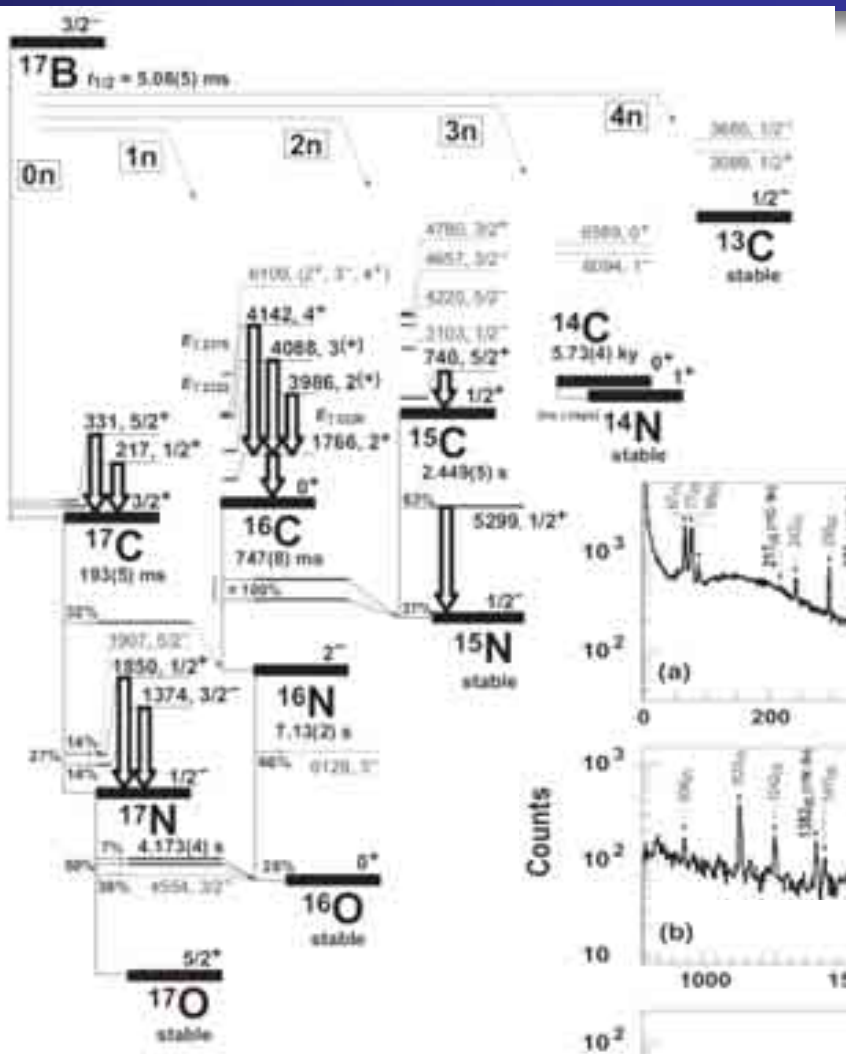
$$A = \begin{cases} \mp 1 & (\Delta I = -1) \\ \mp 1/(I_i + 1) & (\Delta I = 0) \\ \pm I_i/(I_i + 1) & (\Delta I = +1) \end{cases}$$

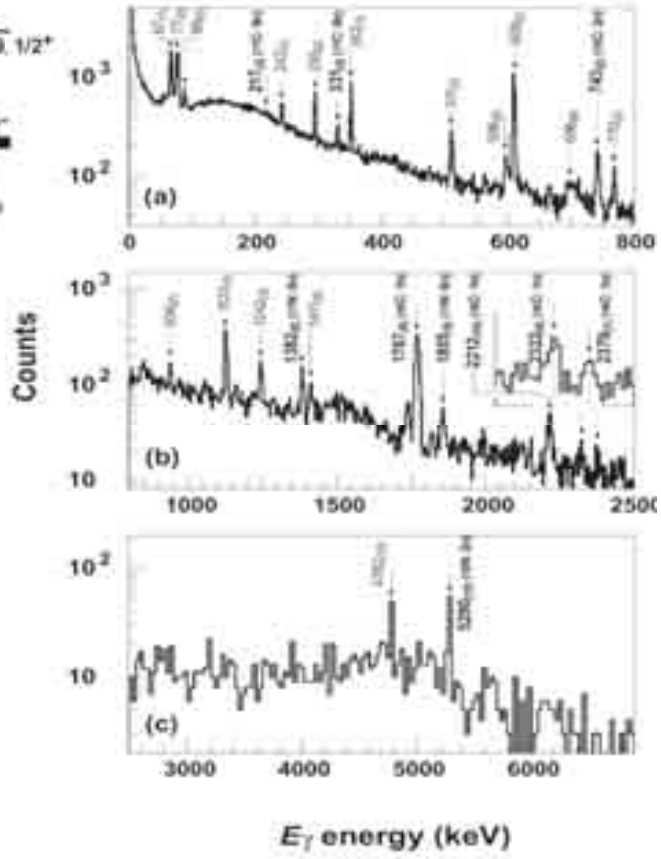
- **Beta-delayed neutron spectroscopy from spin-polarized RI**
  - ^{15}B↑: H. Miyatake *et al.*, PRC 67, 014306 (2003) …RIPS
  - ^{11}Li↑: Y. Hirayama *et al.*, PL B611, 239 (2005) …TRIUMF
  - ^{17}B↑: present

β-neutron-γ spectroscopy with ^{17}B↑

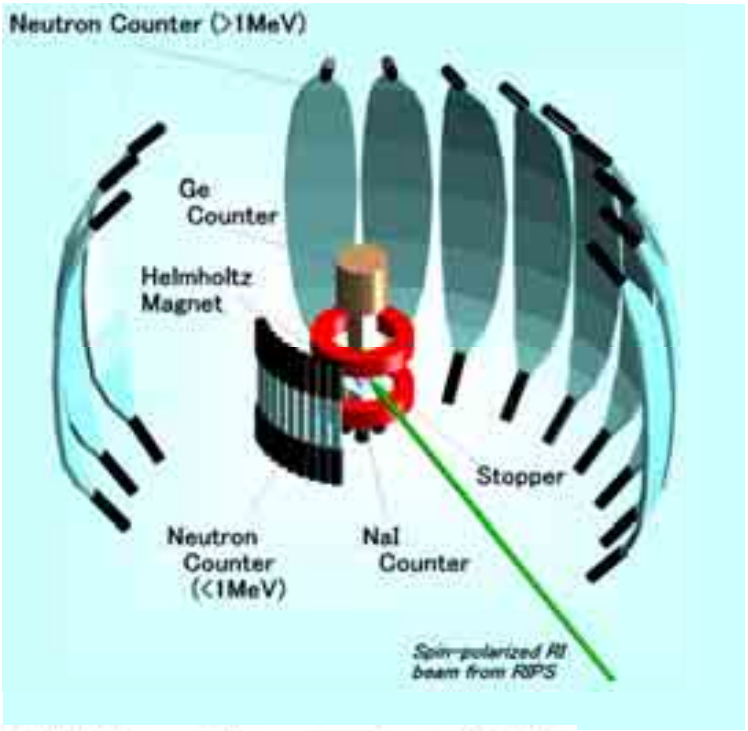


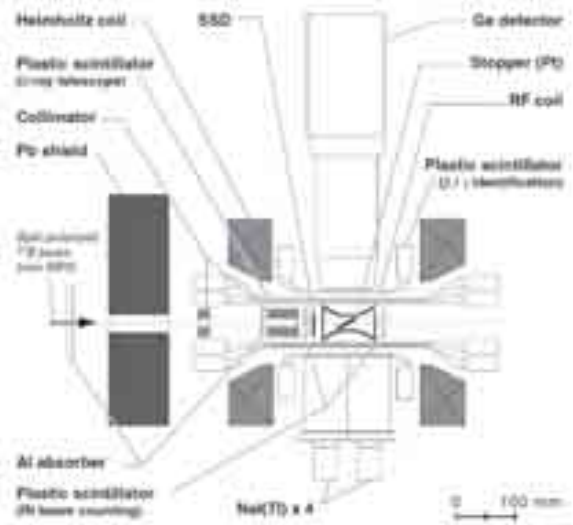


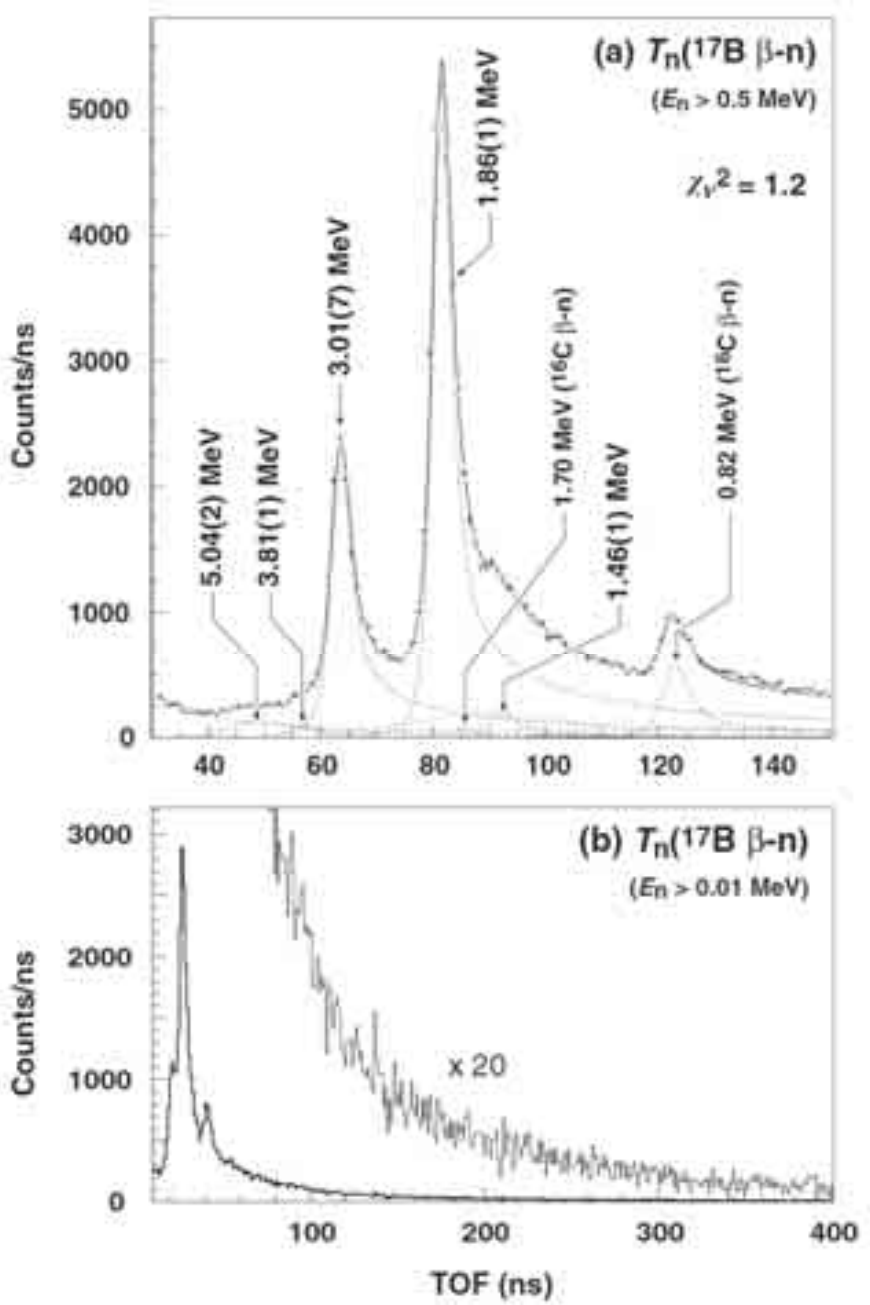




β-neutron-γ spectroscopy with ^{17}B↑







I^π assignment of the ^{17}C levels

E_n (MeV)	E_x (MeV)	I_β (%)	log ft	$A_\beta P$(%)	$2I^\pi$ (χ^2_ν Analysis)	$2I^\pi$ (End result)
{ 5.04(2)	6.08(3)	4(1)	5.3(1)			}
{ 3.81(1)	4.78(2)	0.9(1)	6.1(1)			}
1.46(1)	4.05(2)	1.5(2)	6.0(1)	+6(23)	$(1^-, 3^-, 5^-)$	(5^-)
3.01(1)	3.93(2)	20(3)	4.9(1)	−0.1(15)	$(3^-, 5^-)$	3^-
1.86(1)	2.71(2)	33(4)	4.8(1)	+1.6(8)	1^-	1^-

- **No reference I^π_f is known**
- **all possible combinations of I^π_f =1/2$^-$, 3/2$^-$, and 5/2$^-$ were examined (3 x 3 x 3 = 27 set)**
  → **calculated reduced χ^2 (≡ consistency check)**

$$A = \begin{cases} \mp 1 & (\Delta I = -1) \\ \mp 1/(I_i + 1) & (\Delta I = 0) \\ \pm I_i/(I_i + 1) & (\Delta I = +1) \end{cases}$$

$$\chi^2_\nu(\bar{P}_i) = \frac{1}{\nu}\sum_j (P_j - \bar{P}_i)^2 w_j \quad (i = 1, 2, \ldots$$

$$\bar{P}_i = \frac{\sum_j P_j w_j}{\sum_j w_j} p, \quad w_j = \frac{A_{\beta j}^2}{\sigma^2_{(A_\beta P)_j}},$$

$A(^{17}\mathrm{B} \rightarrow {}^{17}\mathrm{C})$

$$= \begin{cases} -1 & \text{for } ^{17}\mathrm{C}(1/2^-) \\ -0.4 & \text{for } ^{17}\mathrm{C}(3/2^-) \\ +0.6 & \text{for } ^{17}\mathrm{C}(5/2^-) \end{cases}$$

I^π assignment of the ^{17}C levels

E_n (MeV)	E_x (MeV)	I_β (%)	log ft	$A_\beta P$(%)	$2I^\pi$ (χ^2_ν Analysis)	$2I^\pi$ (End result)
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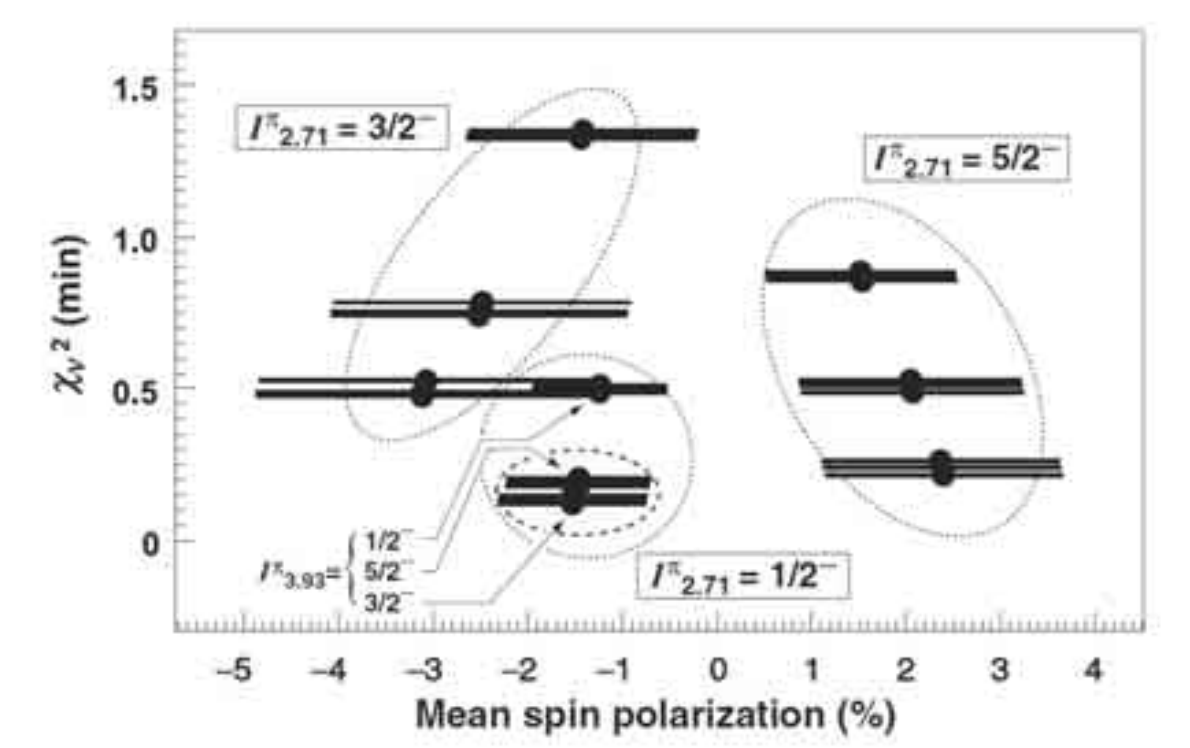
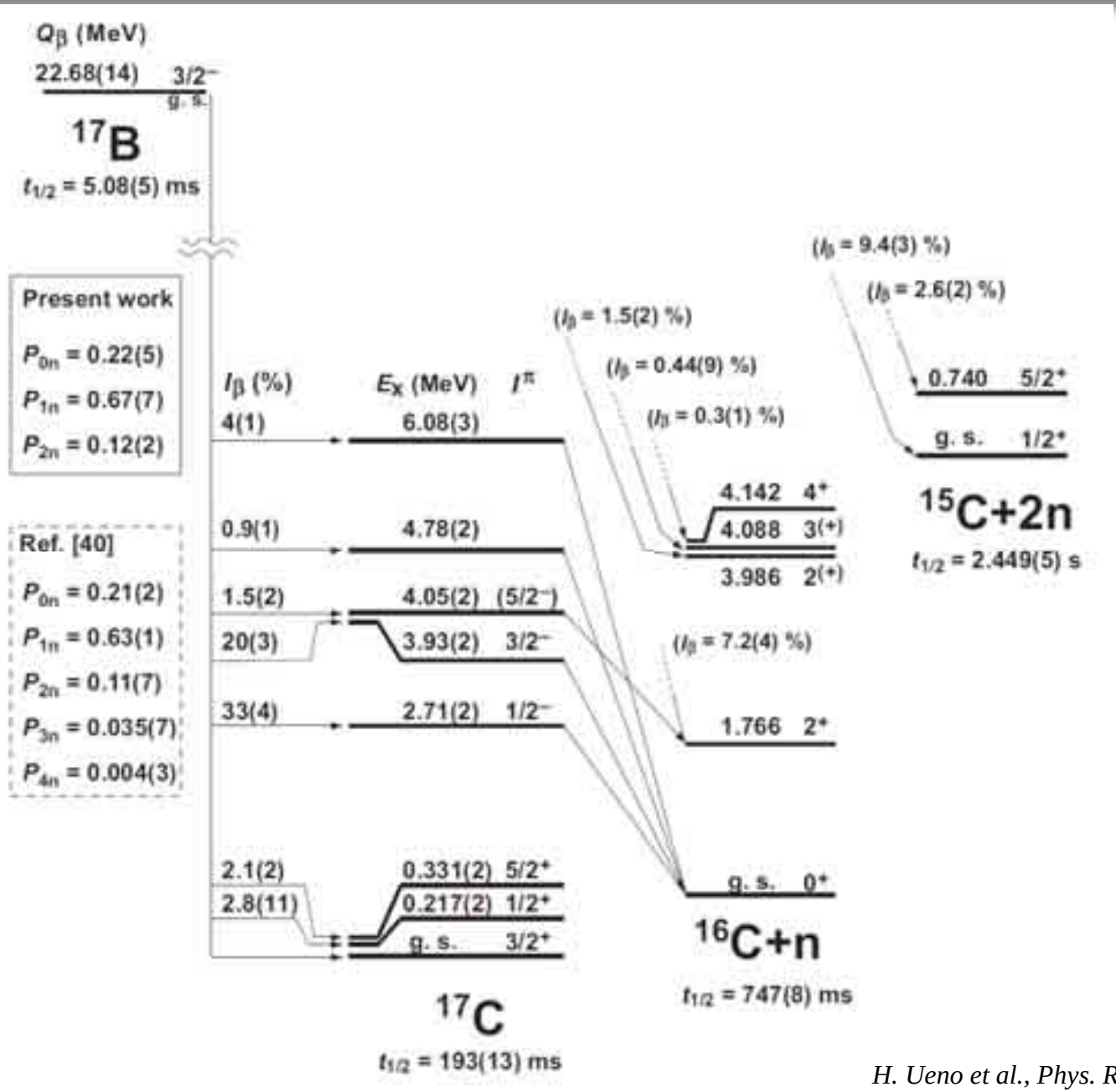


Decay scheme of 17B



*H. Ueno et al., Phys. Rev. C **87**, 034316 (2013)*

Summary

RIBF recent progress

- Cyclotron complex → p ~ ^{238}U beam at E/A up to 345 MeV
- RIBs at quite high currents delivered from BigRIPS
- RIBF experimental key devices: BigRIPS, ZD, SAMURAI, …
- BigRIPS-based experiments: 314 days conducted since 2007

Activities of spin-oriented RI beams at RIBF

1. Spin-aligned RI beams – BigRIPS
   - Excited (isomeric) -states nuclear moments: $Q(^{43m}\mathrm{S})$
   - A new scheme to produce *surely* spin-aligned RIBs
     → *Two-step PF combined with disp. matching*
2. Spin-polarized RI beams: Ground states – RIPS
   - Ground-state nuclear moments: $^{41\text{-}45}\mathrm{S}$
   - Application to β-delayed particle spectroscopy
   - Laser spectroscopy (SLOWRI, OROCHI)