Nuclear Experiments with Radioactive Isotope Beams II

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Radioactive isotope productions
and particle identification

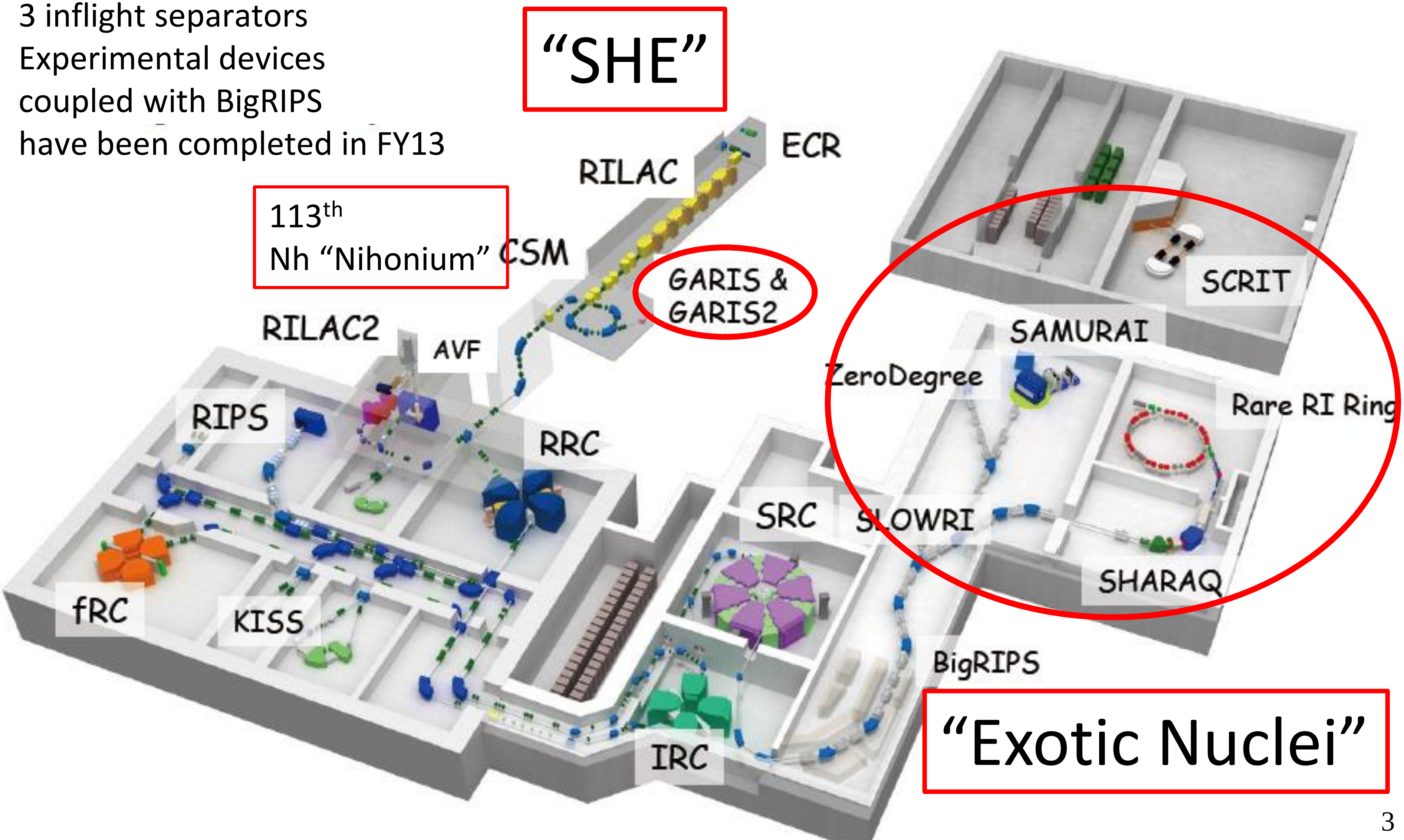
In-beam gamma spectroscopy
Decay spectroscopy

Mass spectroscopy

Invariant mass spectroscopy
Missing mass spectroscopy
Others

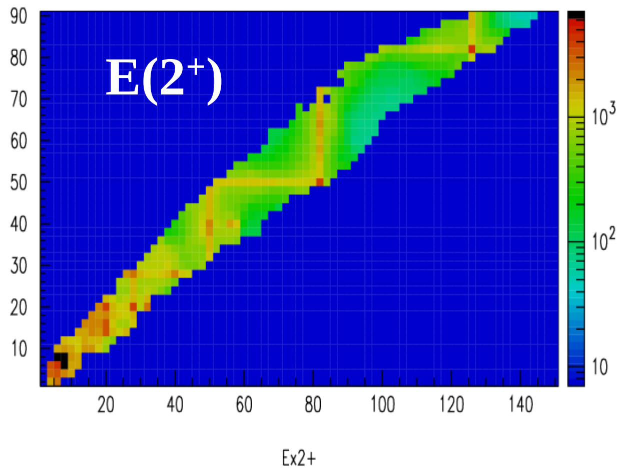
RI Beam Factory

5 cyclotrons + 2 linacs
3 inflight separators
Experimental devices
coupled with BigRIPS
have been completed in FY13

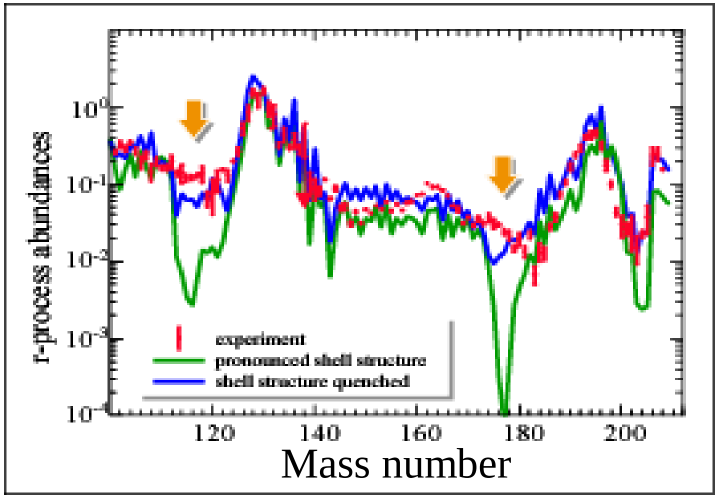


Physics with Exotic Nuclei

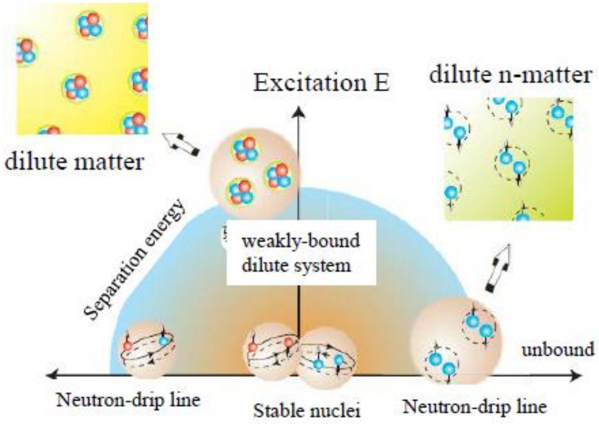
Shell Evolution : magicity loss and new magicity



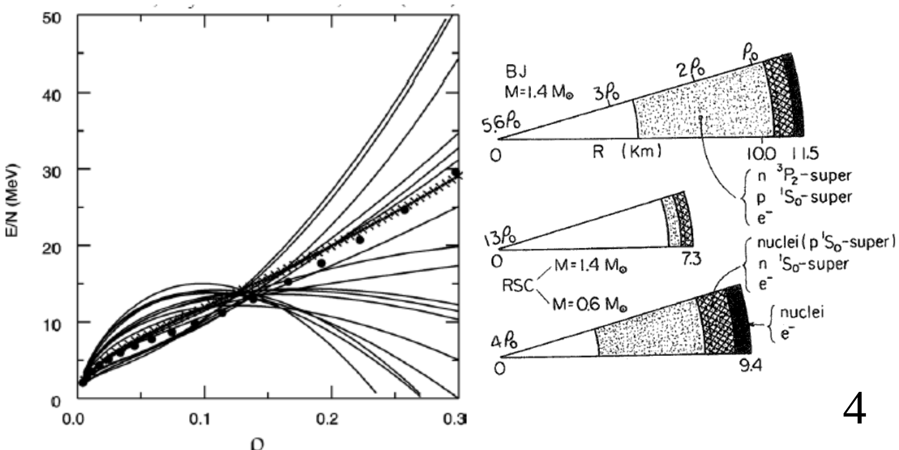
R-process path: Synthesis up to U



Neutron Correlation in the vicinity of the Drip-line



EOS: asymmetric nuclear matter
SN explosion, neutron-star, gravitational wave

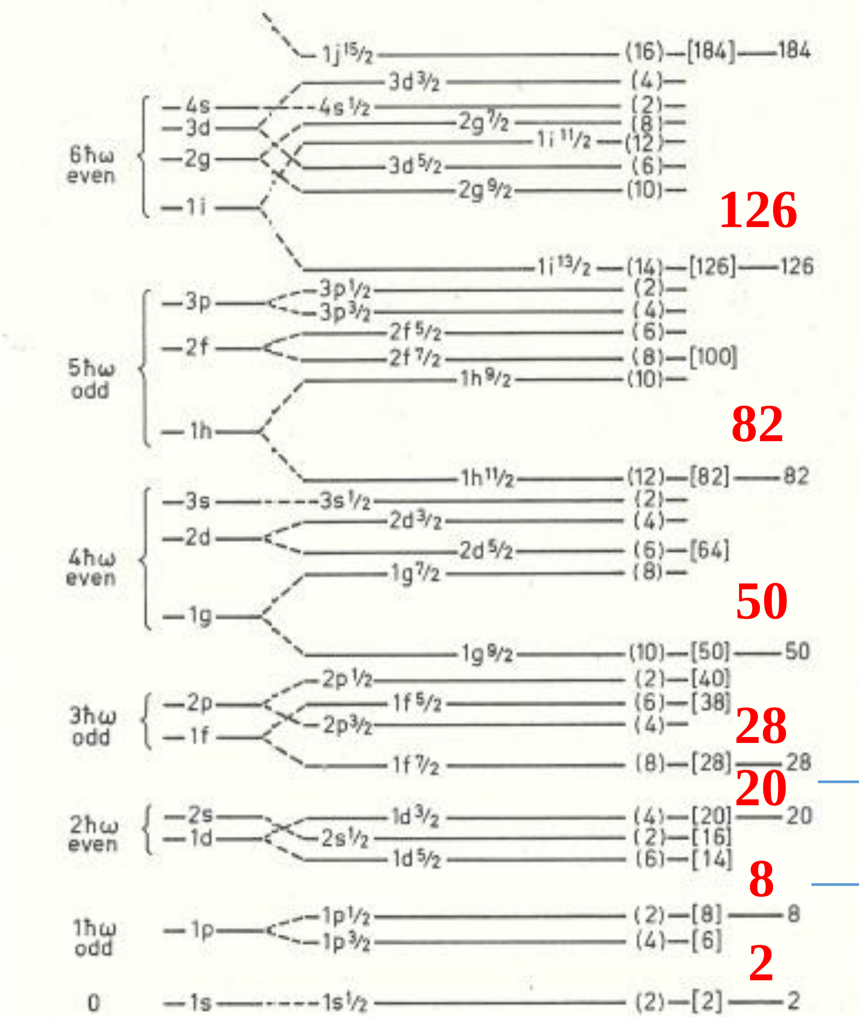


Nuclear Magic Numbers and Shell Evolution

Mayer & Jensen

Nobel Prize 1963

Stable nuclei | Neutron-rich nuclei



20 → loss

8 → loss

? ? ? ?

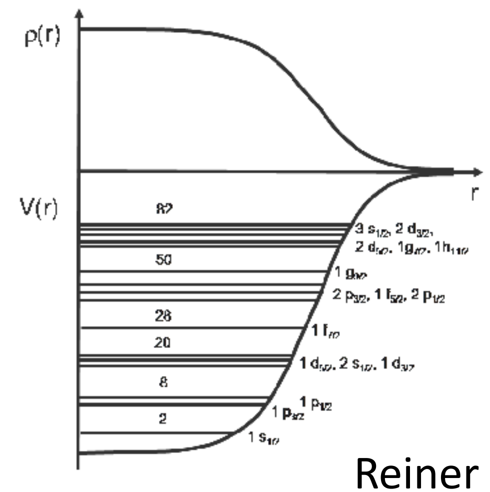
N=16

Shell Structure

One-body potential

Large LS term

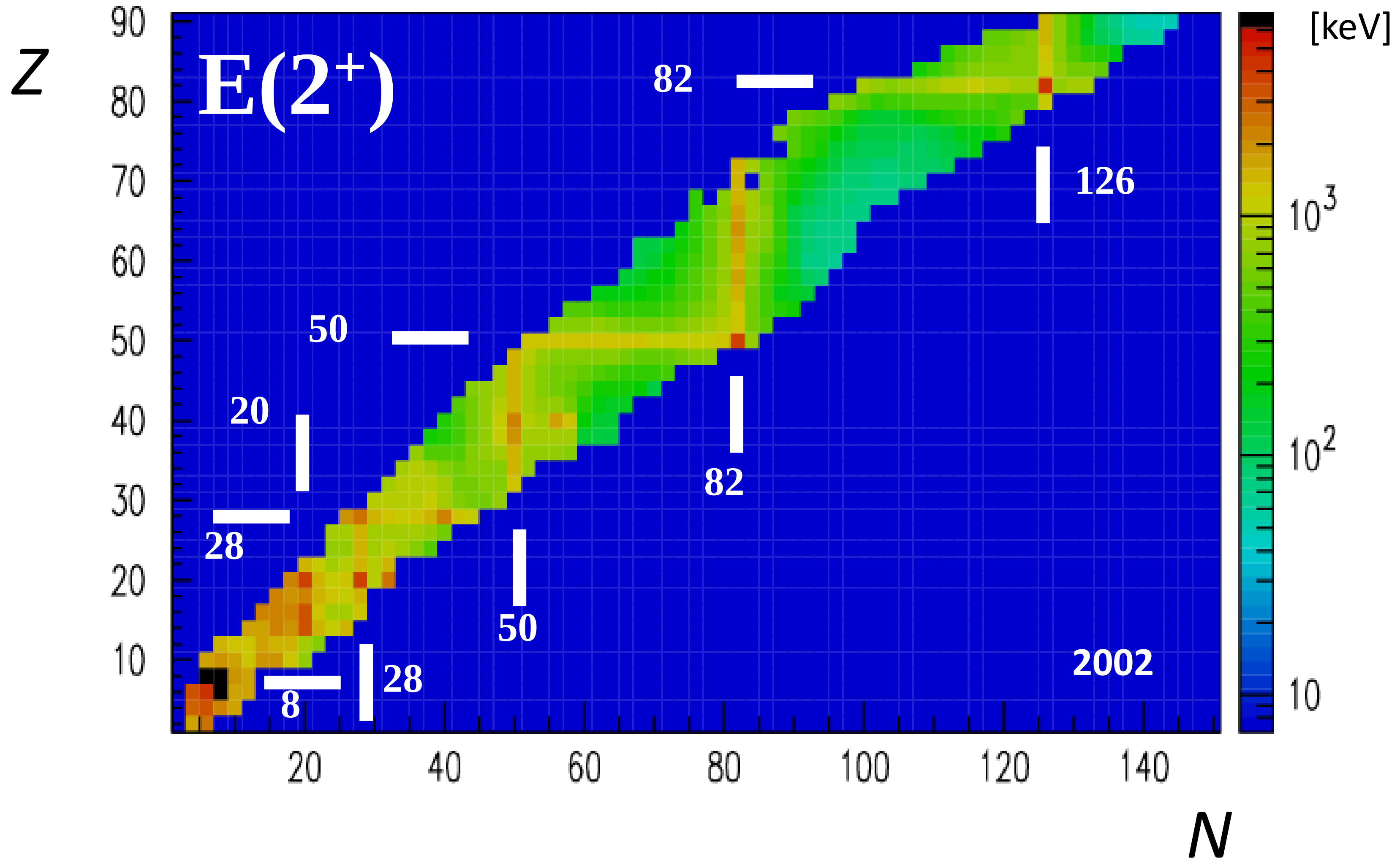
(surface contribution)



Magic numbers ->

2, 8, 20, 28, 50 …

Magicity and its loss through determining E(2⁺)



The 1st in-beam gamma experiment

1.E.1 :
3.A

Nuclear Physics **46** (1963) 210-224; © *North-Holland Publishing Co., Amsterdam*

GAMMA RAYS FOLLOWING (α, xn) REACTIONS

H. MORINAGA† and P.C. GUGELOT
Instituut voor Kernphysisch Onderzoek, Amsterdam, Netherlands

Received 14 January 1963

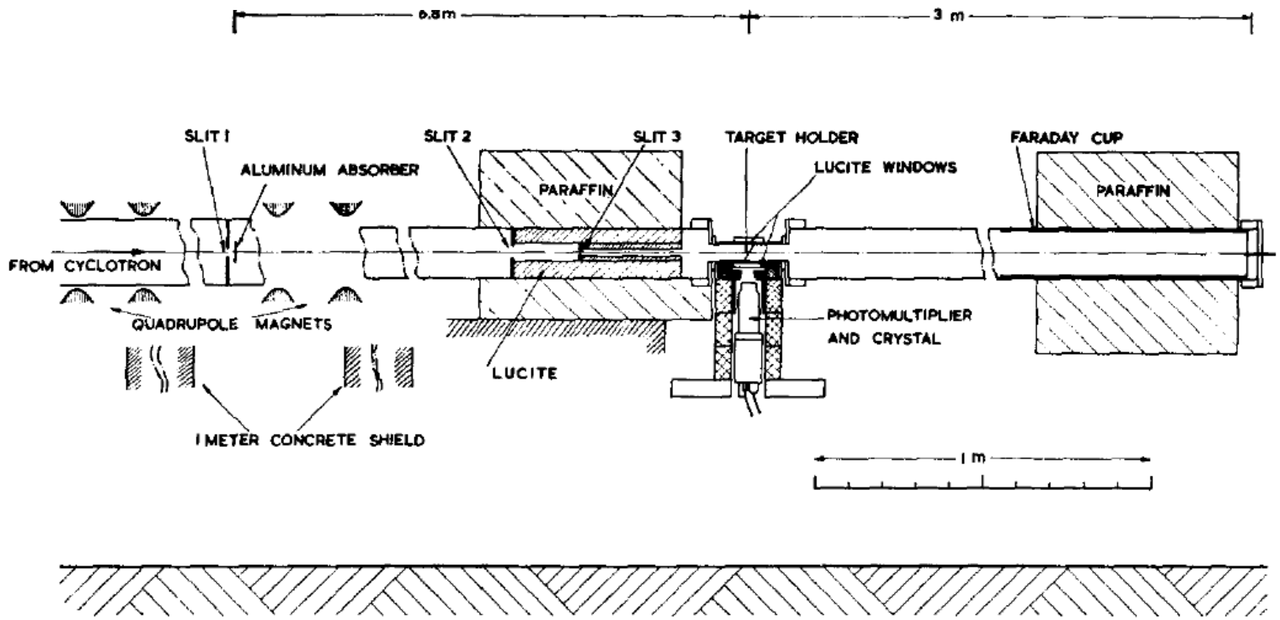


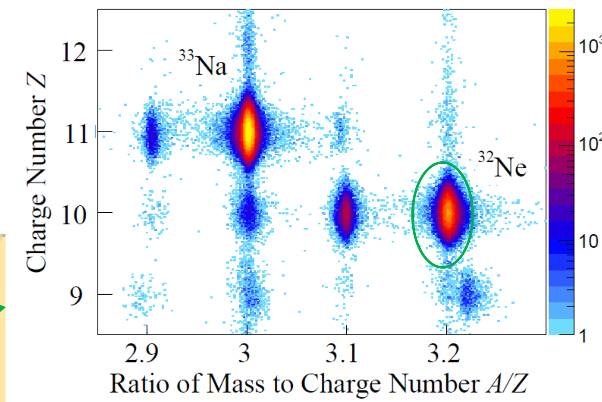
Fig. 2. Experimental set-up for the detection of gamma rays from thin targets bombarded by 27 to 52 MeV alpha particles.

Spectroscopy via reactions with in-beam gamma method

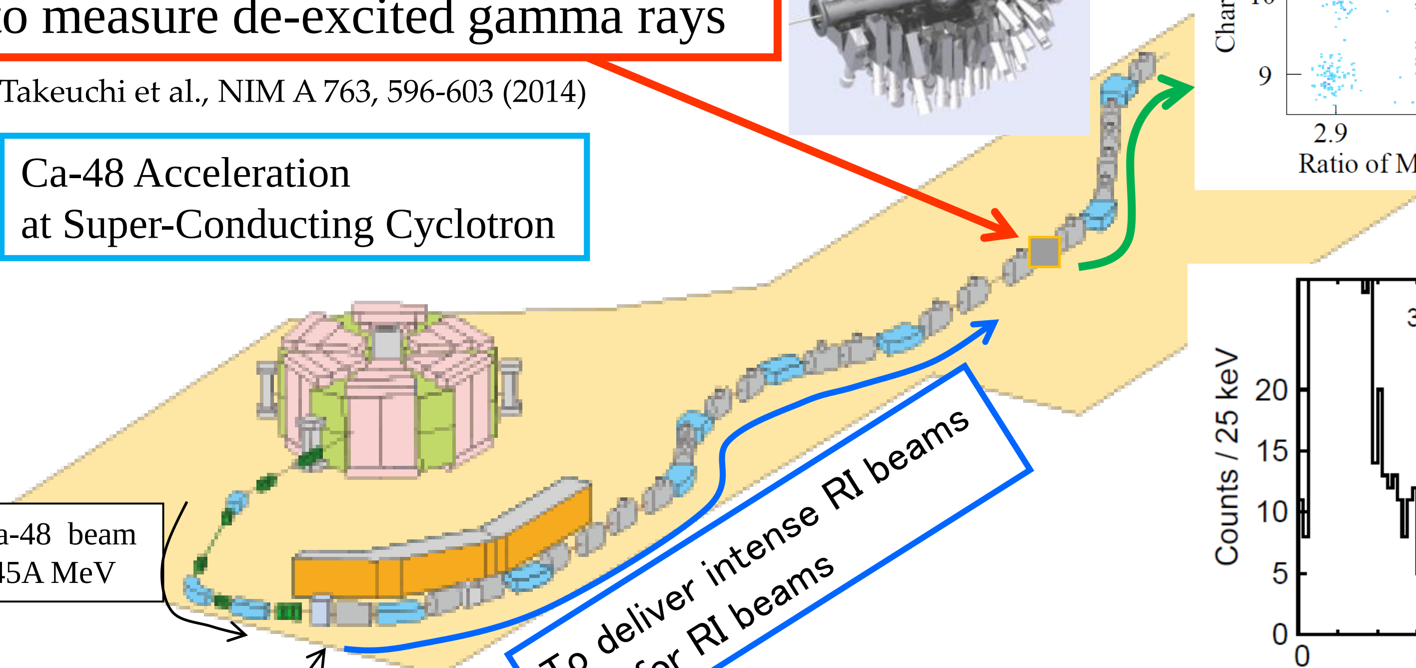
Secondary target: H_2, C, Pb….
Gamma-detectors : DALI2 NaI array to measure de-excited gamma rays

S.Takeuchi et al., NIM A 763, 596-603 (2014)

PID at ZeroDegree



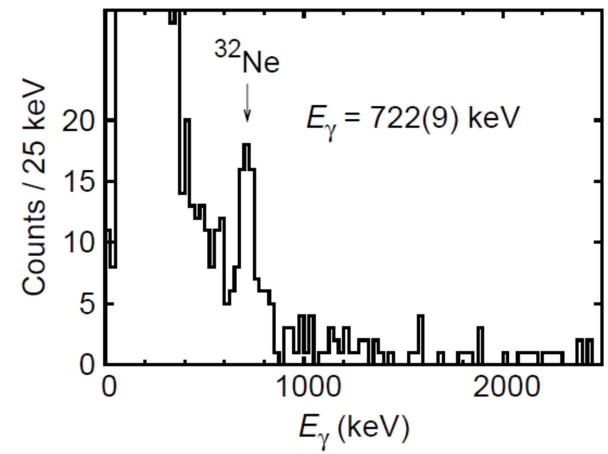
Ca-48 Acceleration
at Super-Conducting Cyclotron

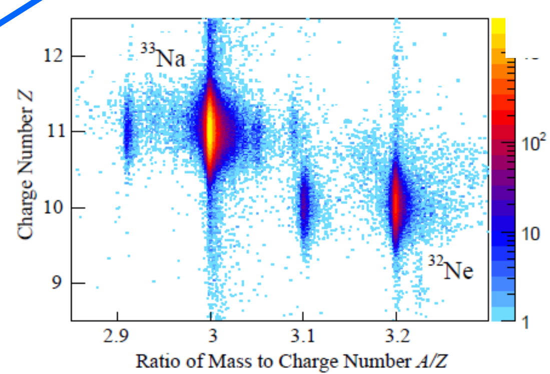


Ca-48 beam
345A MeV

Be production target
fragmentation

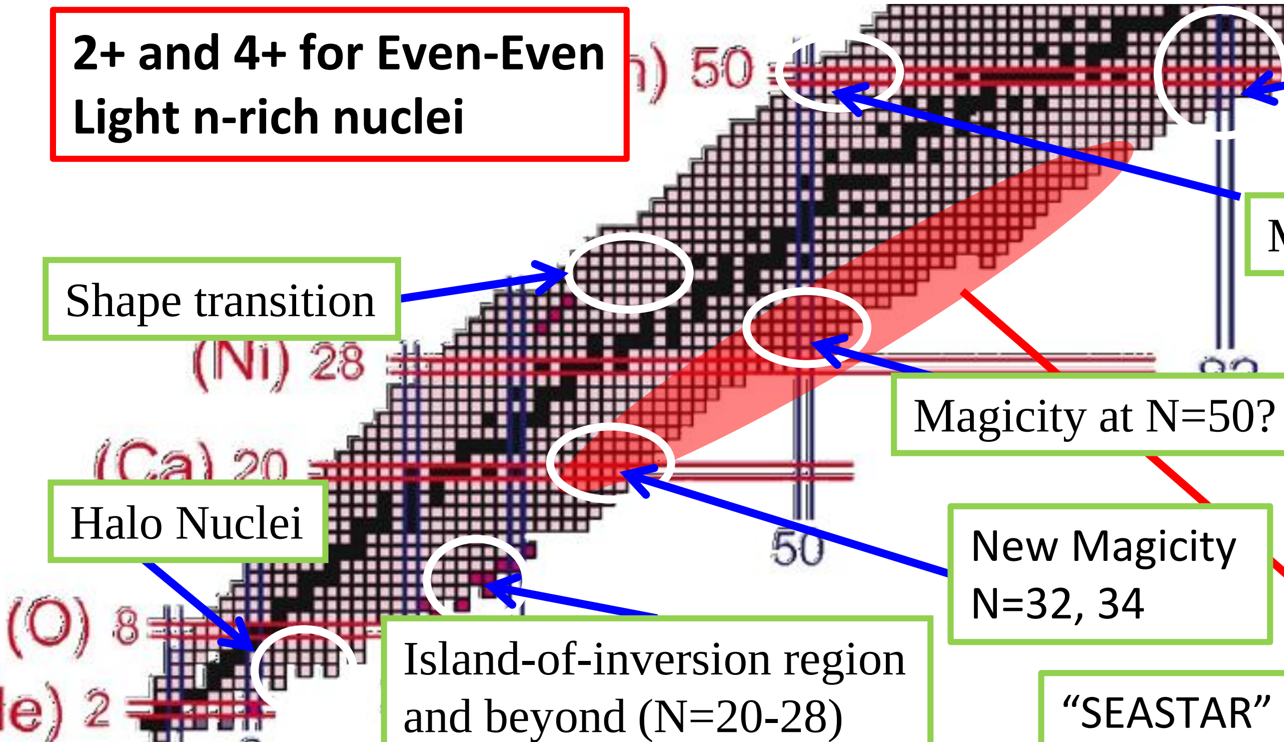
To deliver intense RI beams
PID for RI beams





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

Achievements with DALI2 at ZD



2+ and 4+ for Even-Even Light n-rich nuclei

Magicity at N=82 and Z=50?

[126]Pd: Wang, PRC 88 054318 (2013)
[136]Sn: Wang, PTEP 023D02 (2014)

Magicity at Z=50 and N=50?

[104]Sn: Corsi, PLB 743, 451 (2015)
[104]Sn: Doornenbal, PRC90, 061302 (2014)

Shape transition

Magicity at N=50?

[80,82]Zn: Shiga, PRC 93, 024320 (2016)

Halo Nuclei

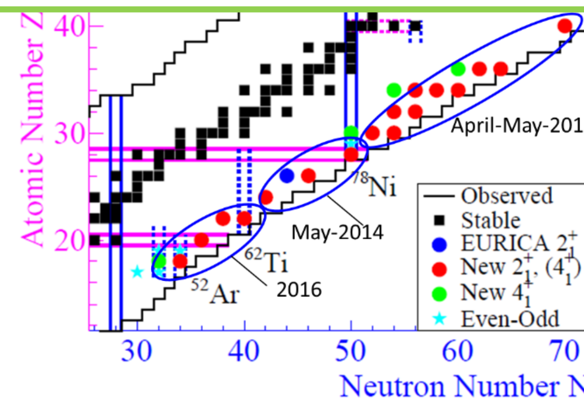
New Magicity N=32, 34

Steppenbeck, Nature 502, 207 (2013)
PRL 114, 252501 (2015)

Island-of-inversion region and beyond (N=20-28)

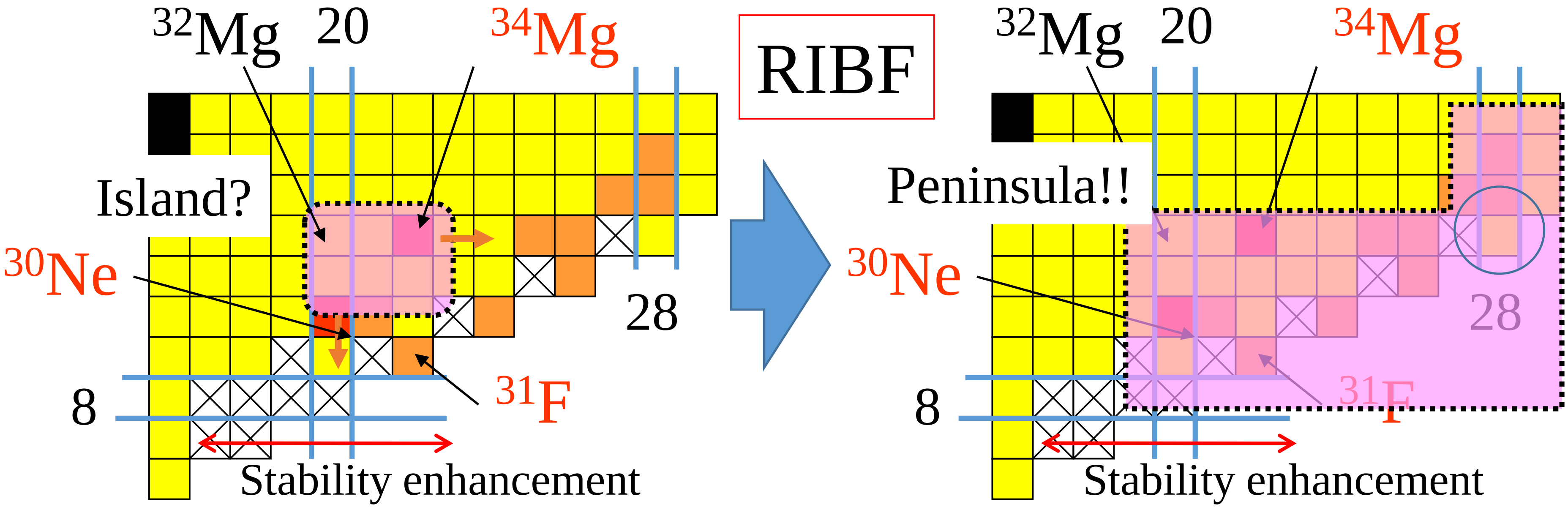
[29]Ne : Kobayashi, PRC 93, 014613 (2016)
[32]Ne:: Doornenbal, PRL 103, 032501 (2009)
[31,32,33]Na: Doornenbal, PRC 81, 041305R (2010)
[33,34,35]Na: Doornenbal, PTEP 2014, 053D01 (2014)
[36,38]Mg: Doornenbal, PRL111, 212502 (2013)
[32]Mg: Li, PRC 92, 014608 (2015)
[42]Si : Takeuchi PRL109, 182501 (2012)
[40]Mg : Crawford PRC 89, 041303 (2014)
[31]Ne: Nakamura, PRL 103, 262501 (2009), PRL, 112, 142501 (2014)
[37]Mg: Kobayashi PRL 112, 242501,(2014)

"SEASTAR" project (MINOS+DALI2)



[66]Cr, [72]Fe : Santamaria, PRL 115:192501 (2015)

Island-of-inversion and beyond



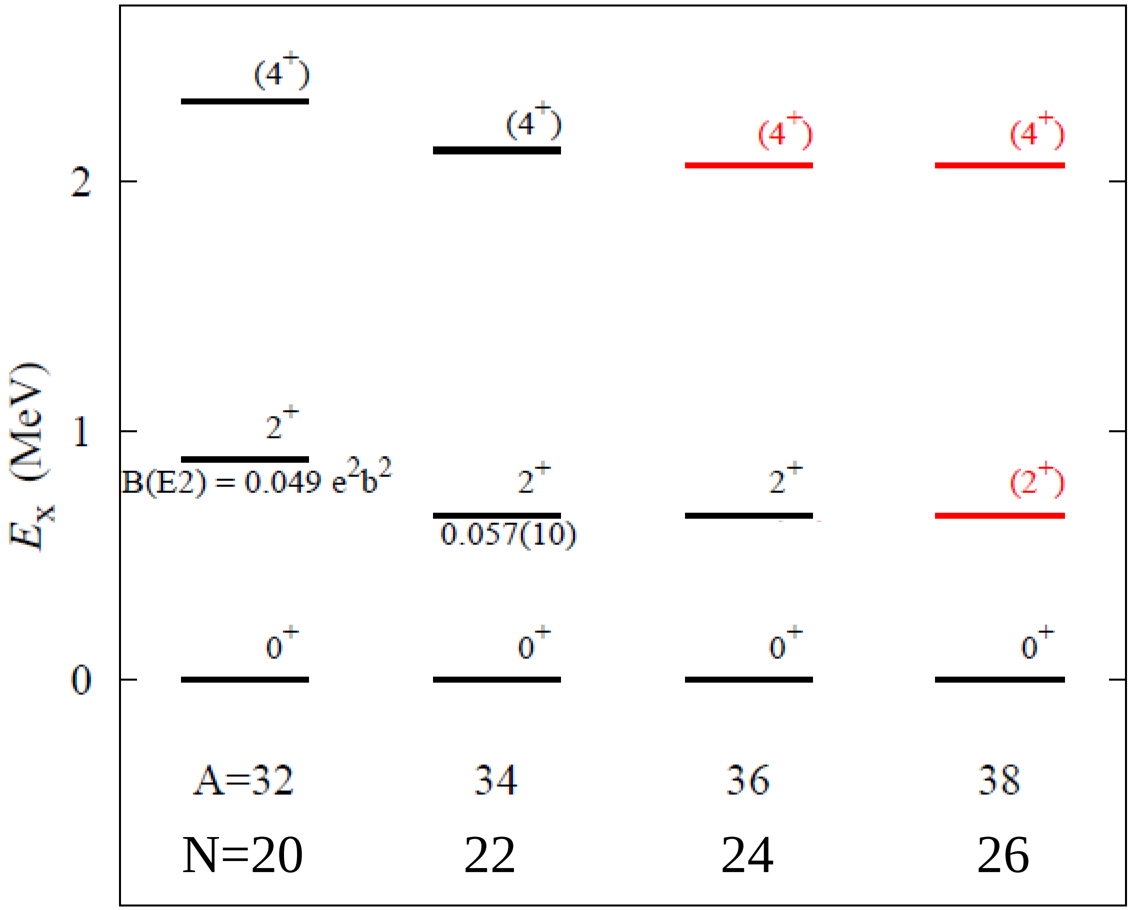
A large deformation at Z=10-12
in spite of N=20
A pilot-region for nuclear structure
Interplay of three ingredients:
Weakly-bound natures
Tensor forces
Pairing

<u>Doornenbal, Scheit, et al.</u>
Ne-32 1st excited states: PRL 103, 032501 (2009)
New states in ^{31,32,33}Na: PRC 81, 041305R (2010)
Mg-36,-38: PRL111, 212502 (2013)
F-29: in preparation
<u>Takeuchi et al.</u>
Si-42 : PRL109, 182501 (2012)
<u>P.Fallon et al.</u>
Mg-40 : PRC 89, 041303 (2014)

Collectivity of the neutron-rich Mg isotopes

P. Doornenbal, H. Scheit et al. PRL111 212502 (2013)

Excitation Energy of 2^+ and 4^+ in Mg



$^{A}Al + C \rightarrow {}^{A-1}Mg$

For A=34 to 38
$E(2^+)$~700 keV
$E(4^+)/E(2^+)$~3.1

At N=22, 24, 26 the nuclei are well deformed

No increase of $E(2^+)$ at N=26
N=28 for Mg is not magic?

B(E2)?
Mn/Mp?
$E(2^+)$, $E(4^+)$ in ^{40}Mg?
Energy of single particle states?

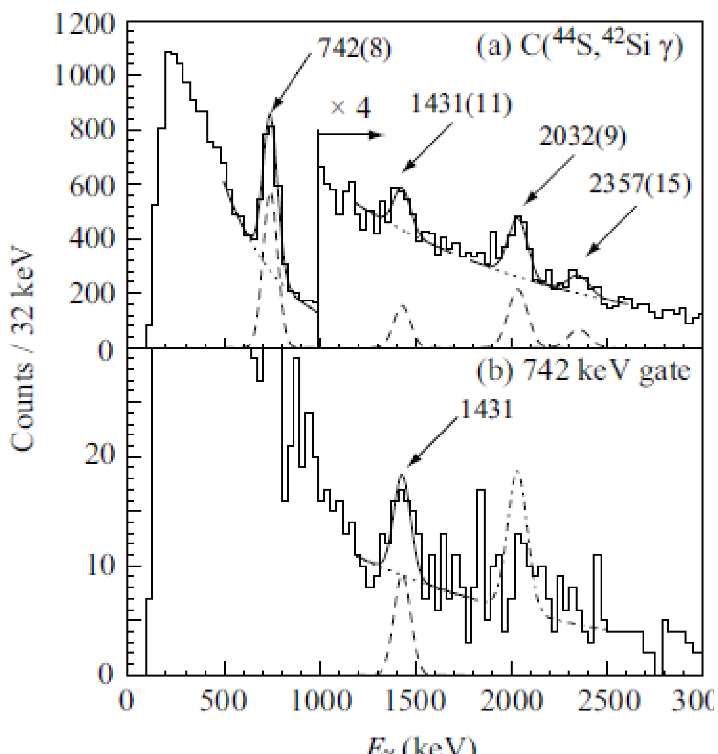
Well developed deformation of ^{42}Si

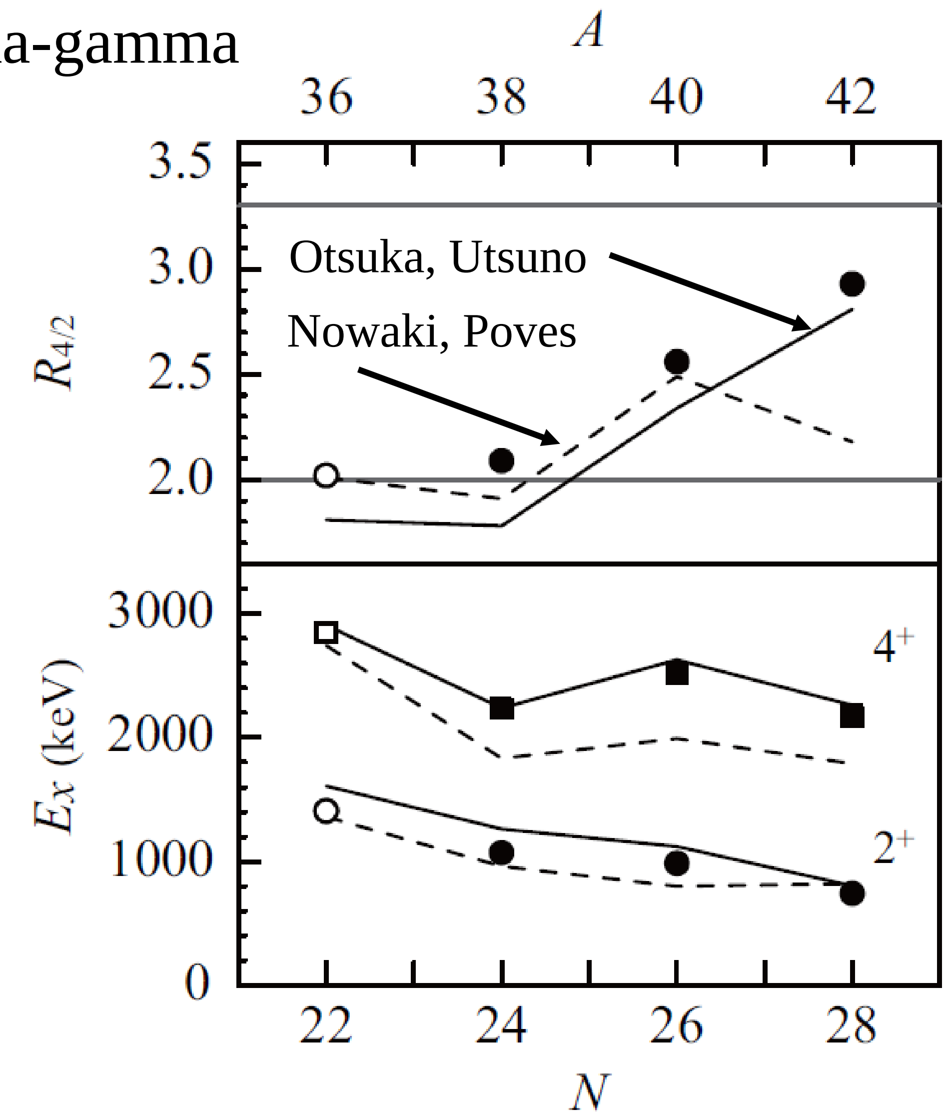
S. Takeuchi et al., PRL109, 182501 (2012)

Confirmation of 2+ energy observed at GANIL
High statistic data allows gamma-gamma Coincidence

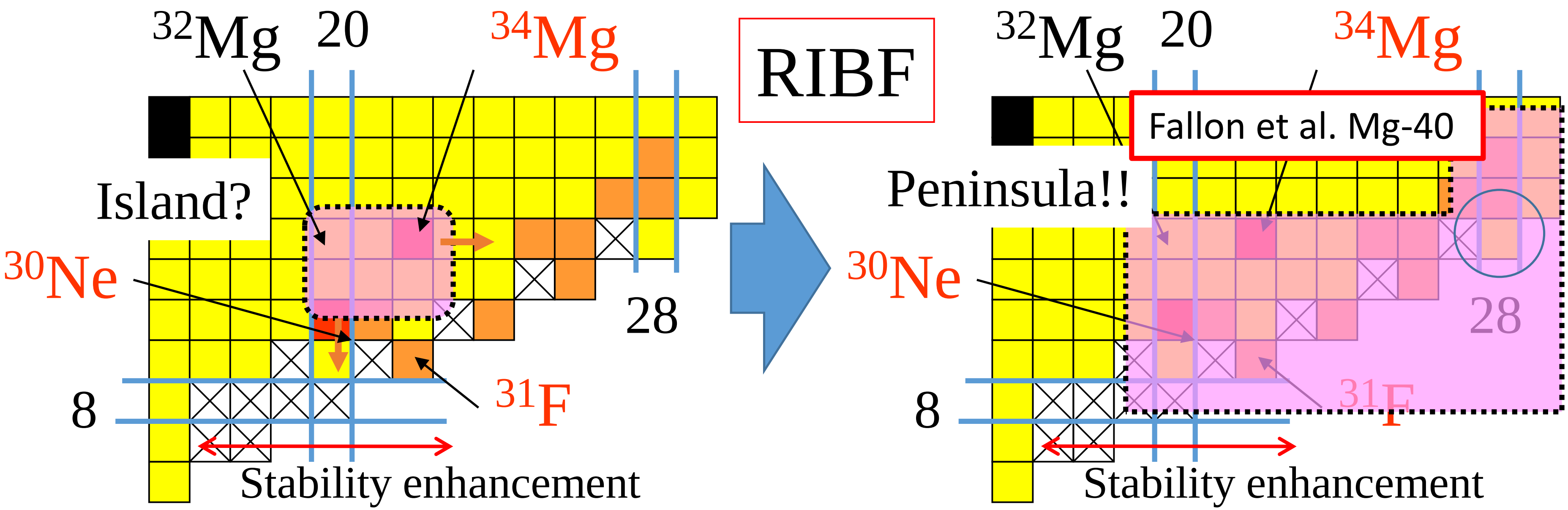
$$^{44}S + C \rightarrow {}^{42}Si + X$$

E(4+)/E(2+)~3 for Si-42





Island-of-inversion and beyond



A large deformation at Z=10-12 in spite of N=20
A pilot-region for nuclear structure
  Interplay of three ingredients:
    Weakly-bound natures
    Tensor forces
    Pairing

Do

What is the next “magic” ?

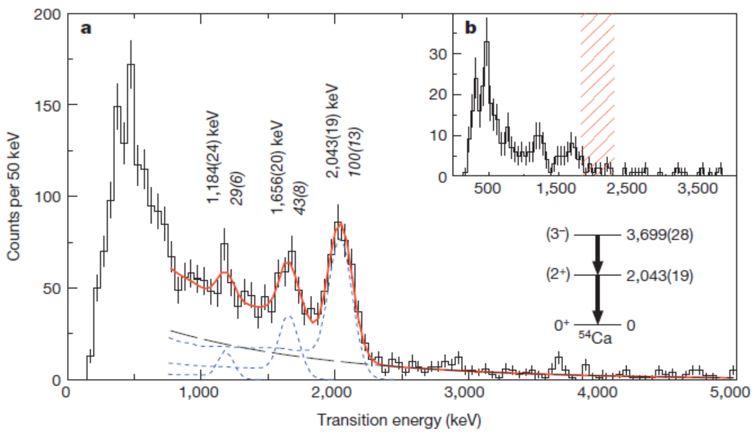
Ne-32 1st excited states: PRL 103, 032501 (2009)
New states in ^{31,32,33}Na: PRC 81, 041305R (2010)
Mg-36,-38: PRL111, 212502 (2013)
F-29: in preparation
Takeuchi et al.
Si-42 : PRL109, 182501 (2012)
P.Fallon et al.
Mg-40 : PRC 89, 041303 (2014)

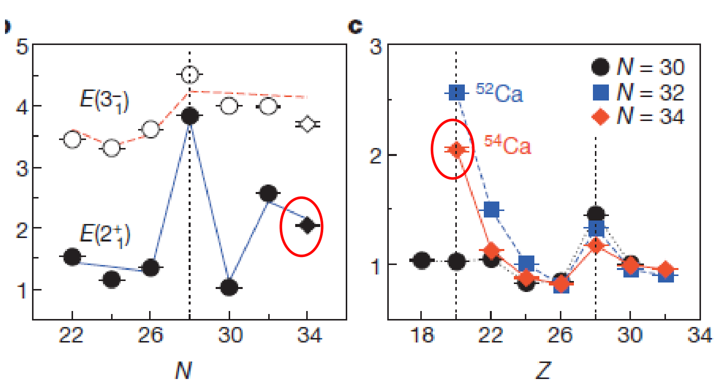
New “Magicity” of N=34 in the Ca isotopes

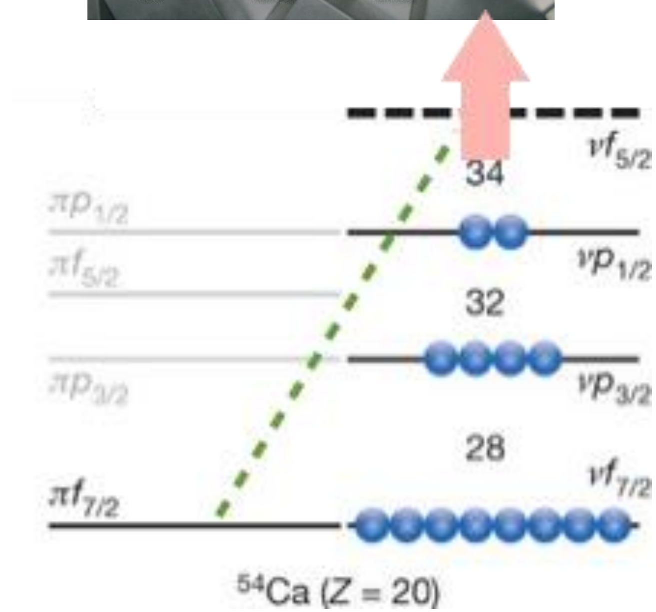
D. Steppenbeck et al., Nature 502

Zn-70 primary beam (100 pnA max)
Ti-56 120 pps/pnA, Sc-55 12 pps/pnA

Zn-70 -> Ti-56, Sc-55
Ti-56, Sc-55 + Be -> Ca-54 + X







“Magicity” in the Ar isotopes : Ar-50 (N=32)

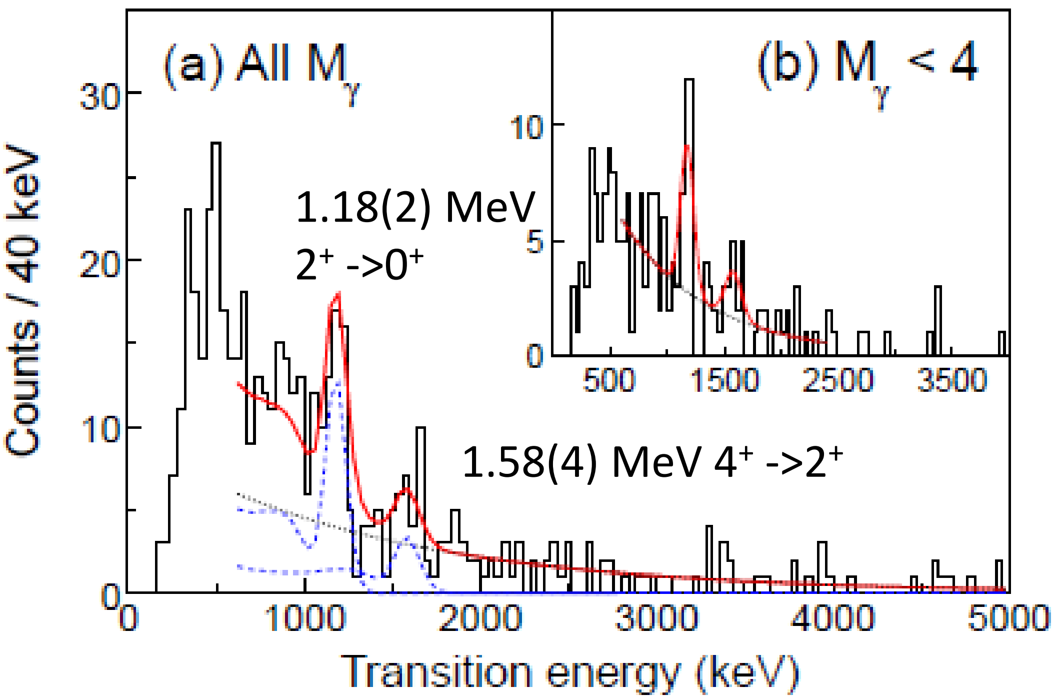
D. Steppenbeck et al., Phys. Rev. Lett. 114, 252501 (2015)

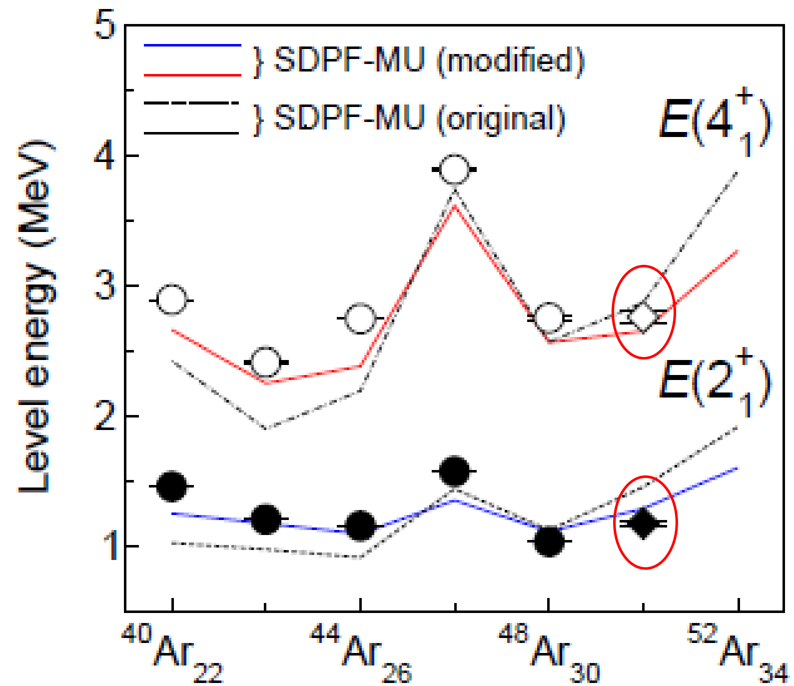
Sum of the reaction channels

$^{9}Be(^{54}Ca, ^{50}Ar+\gamma)X$

$^{9}Be(^{55}Sc, ^{50}Ar+\gamma)X$

$^{9}Be(^{56}Ti, ^{50}Ar+\gamma)X$





N=22 24 26 28 30 32 34

N=32 gap in Ar is similar at that in Ca and Ti…

How about Ar-52 (N=34)?

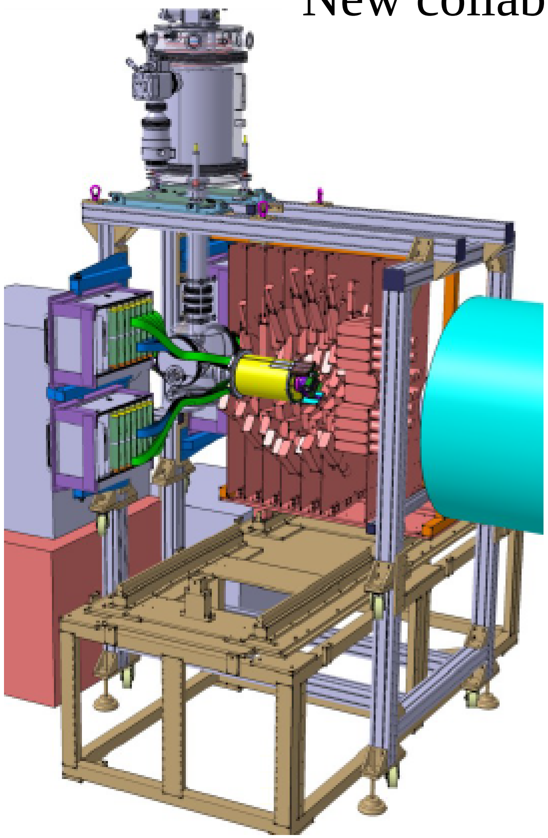
Ca-56 (N=36)?

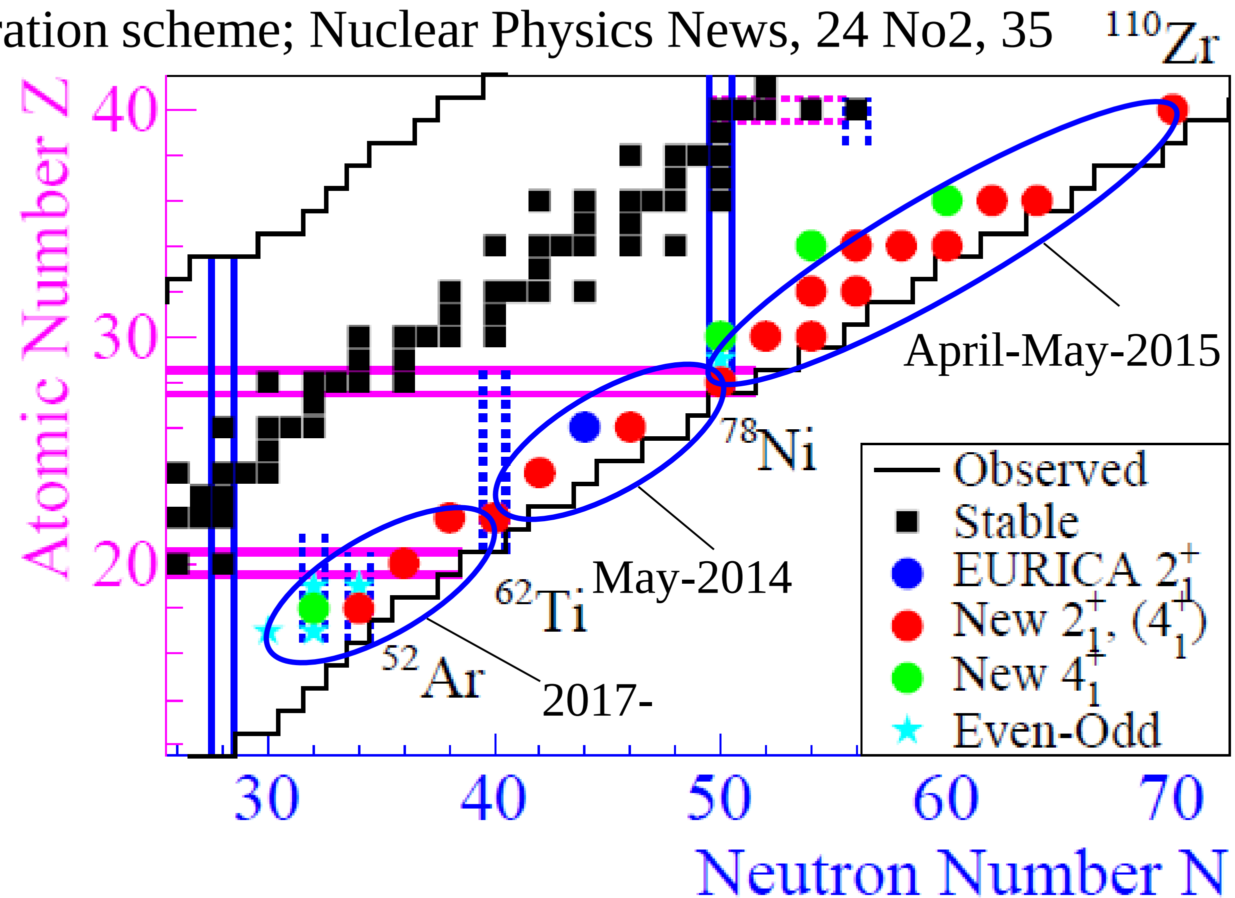
Robustness of N=34 ?

Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR) – a RIKEN Physics Program

Spokespersons: P. Doornenbal (RIKEN), A. Obertelli (CEA, RIKEN)

New collaboration scheme; Nuclear Physics News, 24 No2, 35





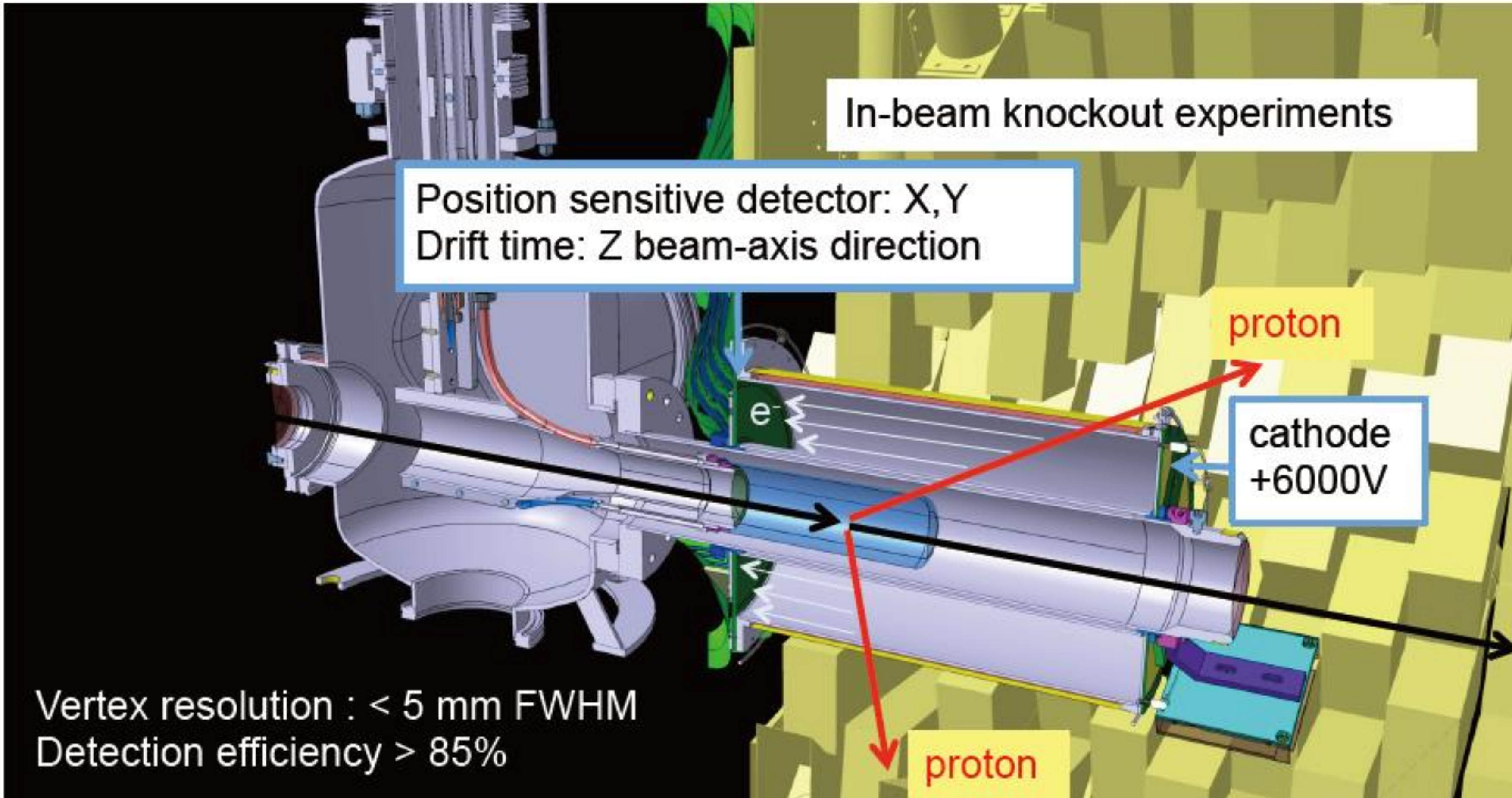
MINOS (100-mm thick Liq.H_2 target and TPC system, $\Delta\beta$ = 20%)

-> high luminosity and vertex position determination

DALI2 -> high efficiency

to access very neutron-rich nuclei

MINOS : Magic Numbers Off Stability



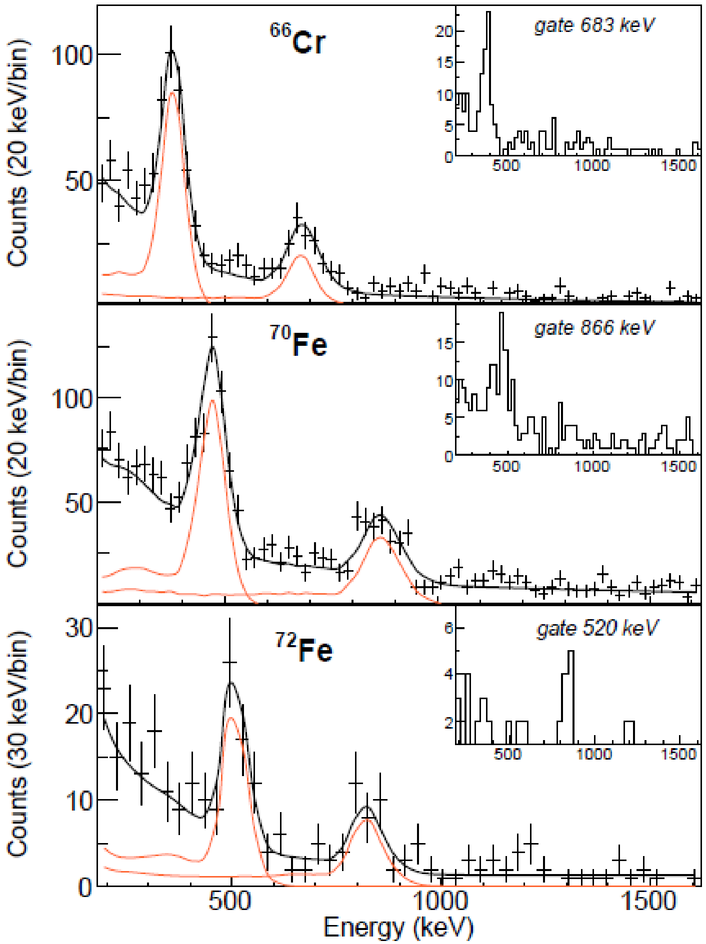
A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)
http://minos.cea.fr

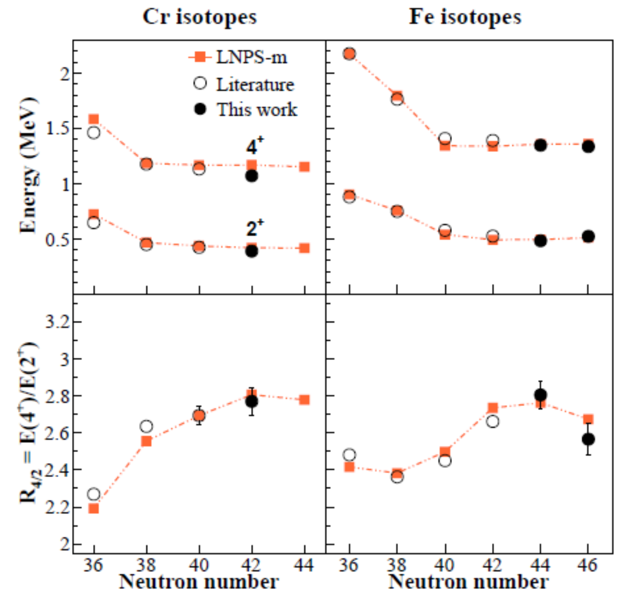
A. Obertelli

SEASTAR : The First Campaign May 2014

(1) Extension of the N=40 Island-of-Inversion towards N=50 Spectroscopy of ^{66}Cr, $^{70,72}Fe$

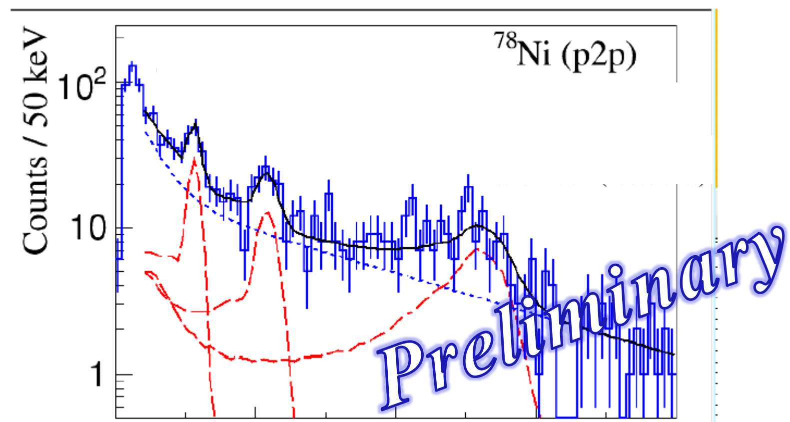
Santamaria, Louchart, Obertelli et al,
PRL 115, 192501 (2015)





(2) First spectroscopy of ^{78}Ni

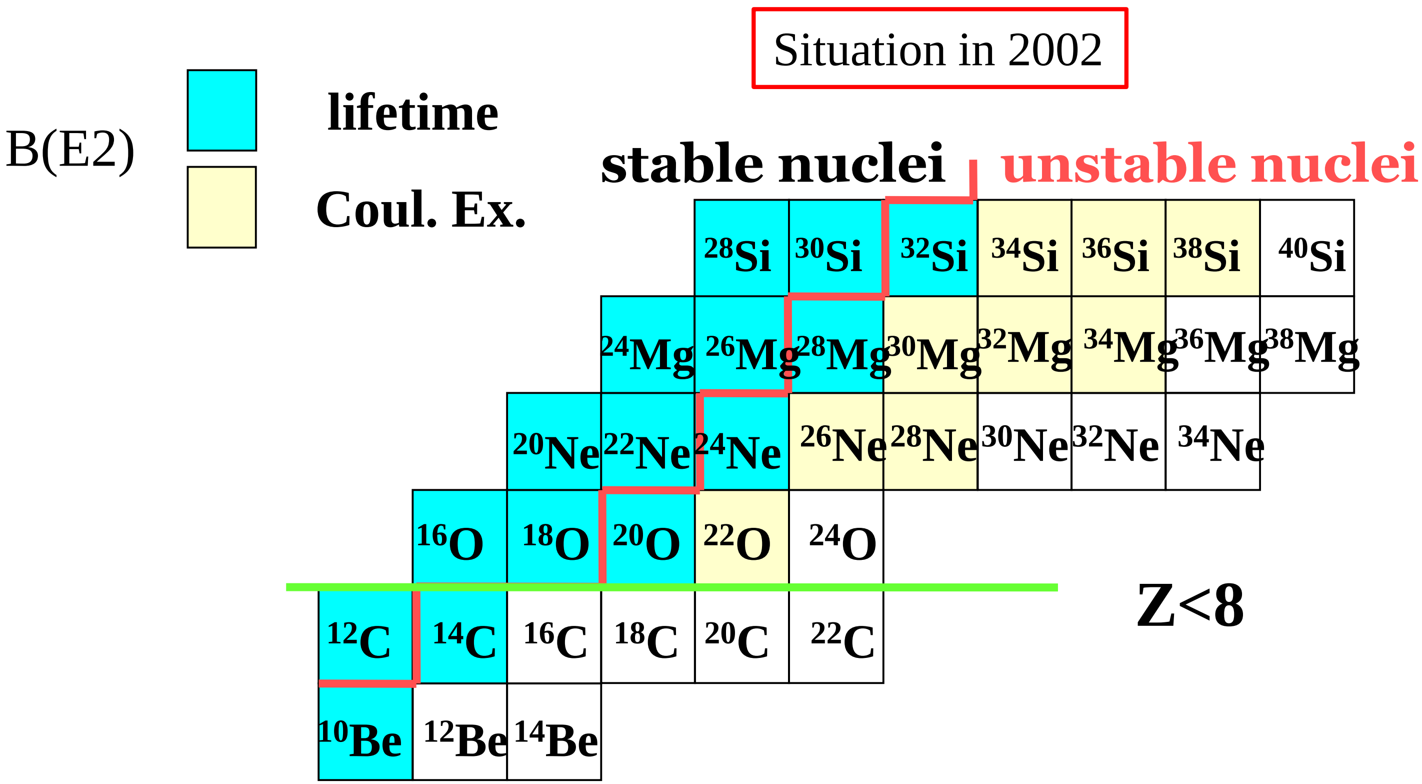
Taniuchi, Doornenbal, Yoneda et al., in preparation



Lifetime measurement for excited states

Introduction of several works at the old facility RIPS
Such lifetime measurement activities should be
re-encouraged/re-organized at the new facility RIBF

B(E2) measurement for the light mass region



No data for the neutron-rich Be and C isotopes

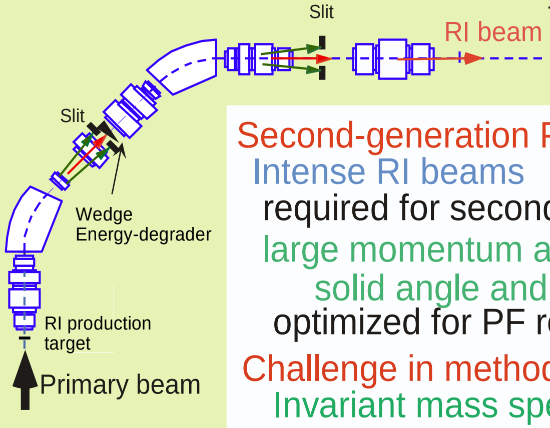
In-beam Gamma Spectroscopy at the RIPS facility

H.J. Ong et al., Phys. Rev. C 78, 014308 (2008)
  Lifetime measurements of first excited states in C-16 and C-18
H.J. Ong et al., Phys. Rev. C 73, 024610 (2006)
  Neutron-dominant quadrupole collective motion in C-16
D. Suzuki et al., Phys. Lett. B 666, 222(2008)
  Lifetime measurements of excited states in C-17
N. Imai et al., Phys. Lett. B 673, 179 (2009)
  First lifetime measurements of 2+ state in Be-12

Lifetime measurements developed
  Recoil Shadow Method
  Doppler Shift Attenuation Method
  Recoil Distance Method
to measure B(E2)
For light nuclei to which CEX is not applied.

RIPS (RIKEN Projectile-fragment Separator)

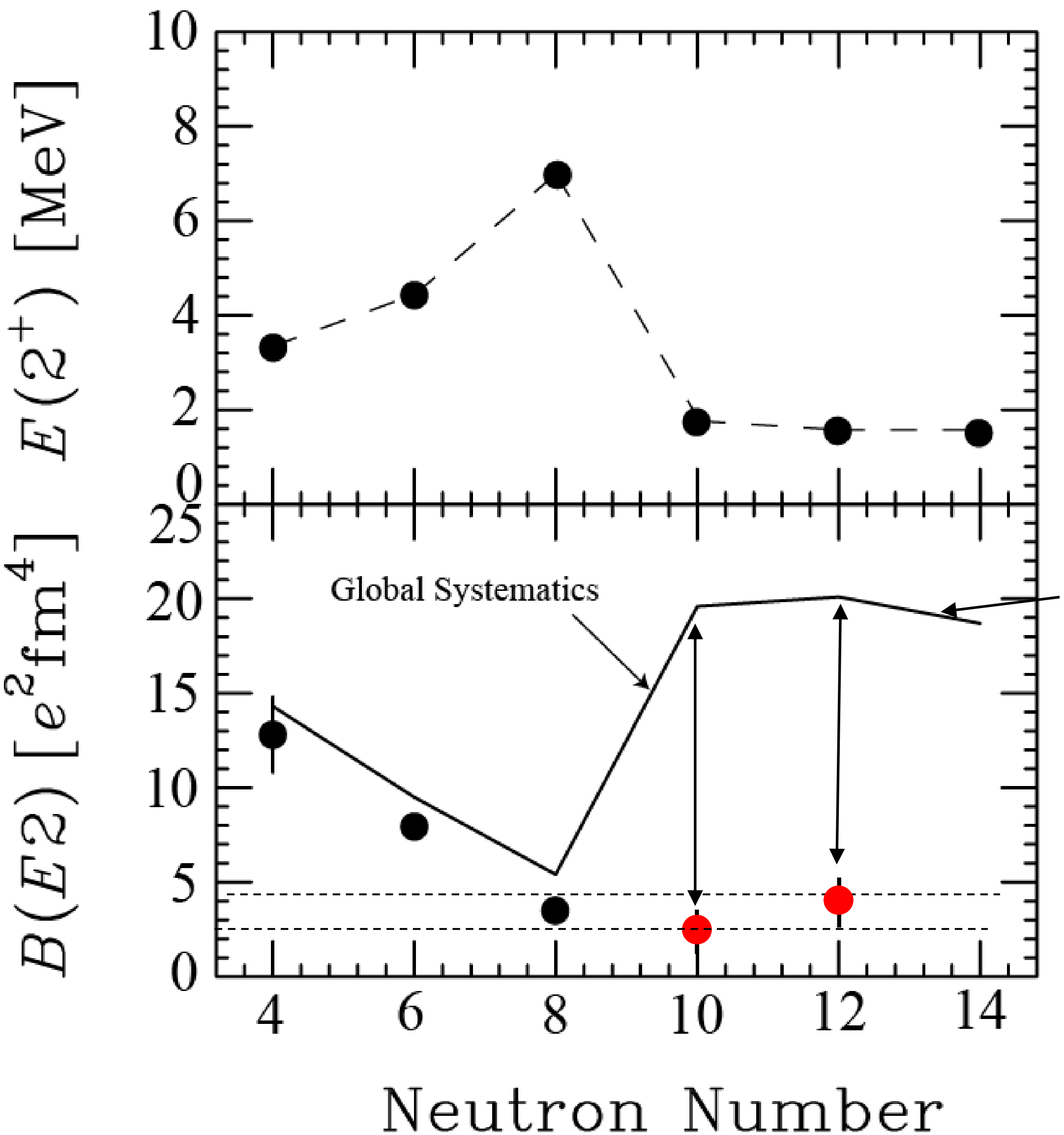
T.Kubo et al. NIMB70, 309(92)



Second-generation PF separator
 Intense RI beams
  required for secondary nuclear reactions
  large momentum acceptance,
    solid angle and high magnetic rigidity
  optimized for PF reaction
Challenge in methodology
  Invariant mass spectroscopy
    for particle unbound states
  Intermediate energy Coulomb excitation
    for B(E2)
  etc...

E(2+) and B(E2) systematics for Carbon isotopes

Ong, et al., Physical Review C 78 (2008) 014308

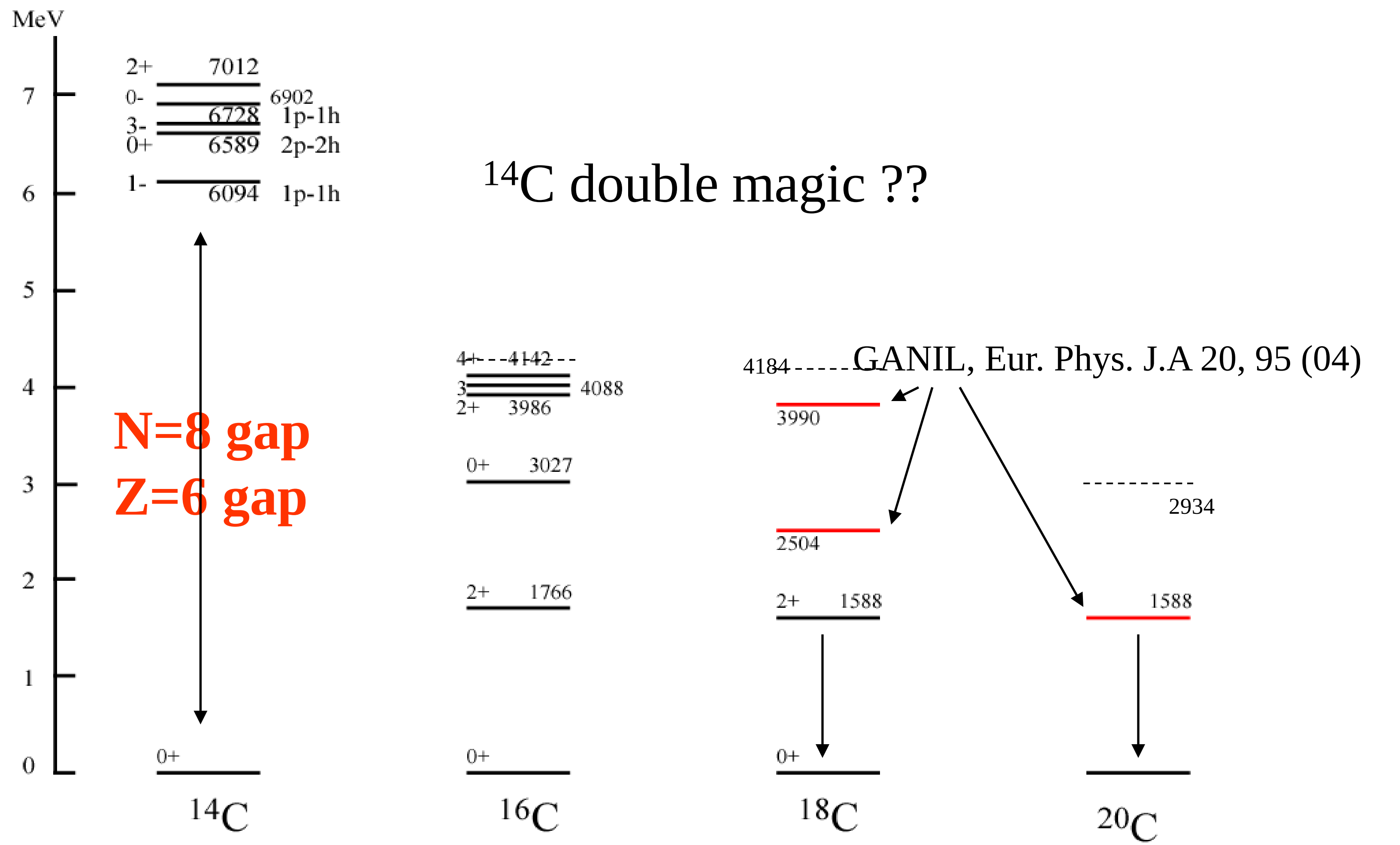


$B(E2)_{sys} = (5140 \pm 900) E^{-1} Z^2 A^{-2/3}$

S. Raman *et al*, ADNDT 78,1(2001)

significant discrepancy from Raman's systematics

Excited states in even-even C isotopes

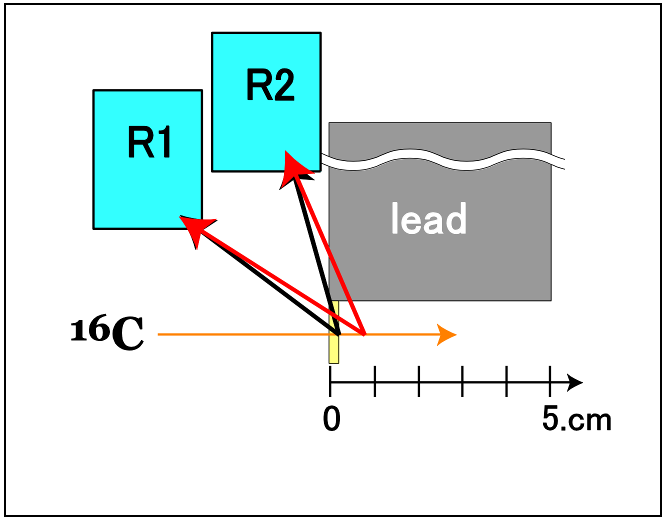


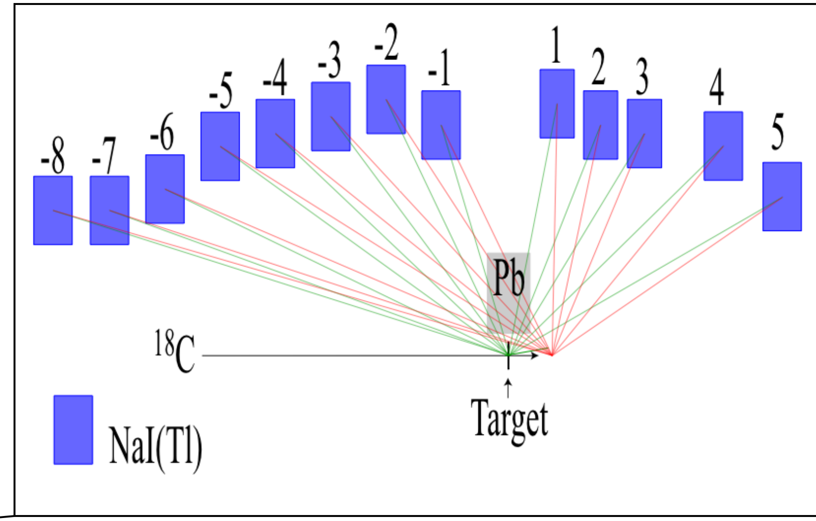
^{14}C double magic ??

N=8 N=10 N=12 N=14

New data for transition strengths in ^{16,17,18}C based on an upgrade setup for recoil shadow method

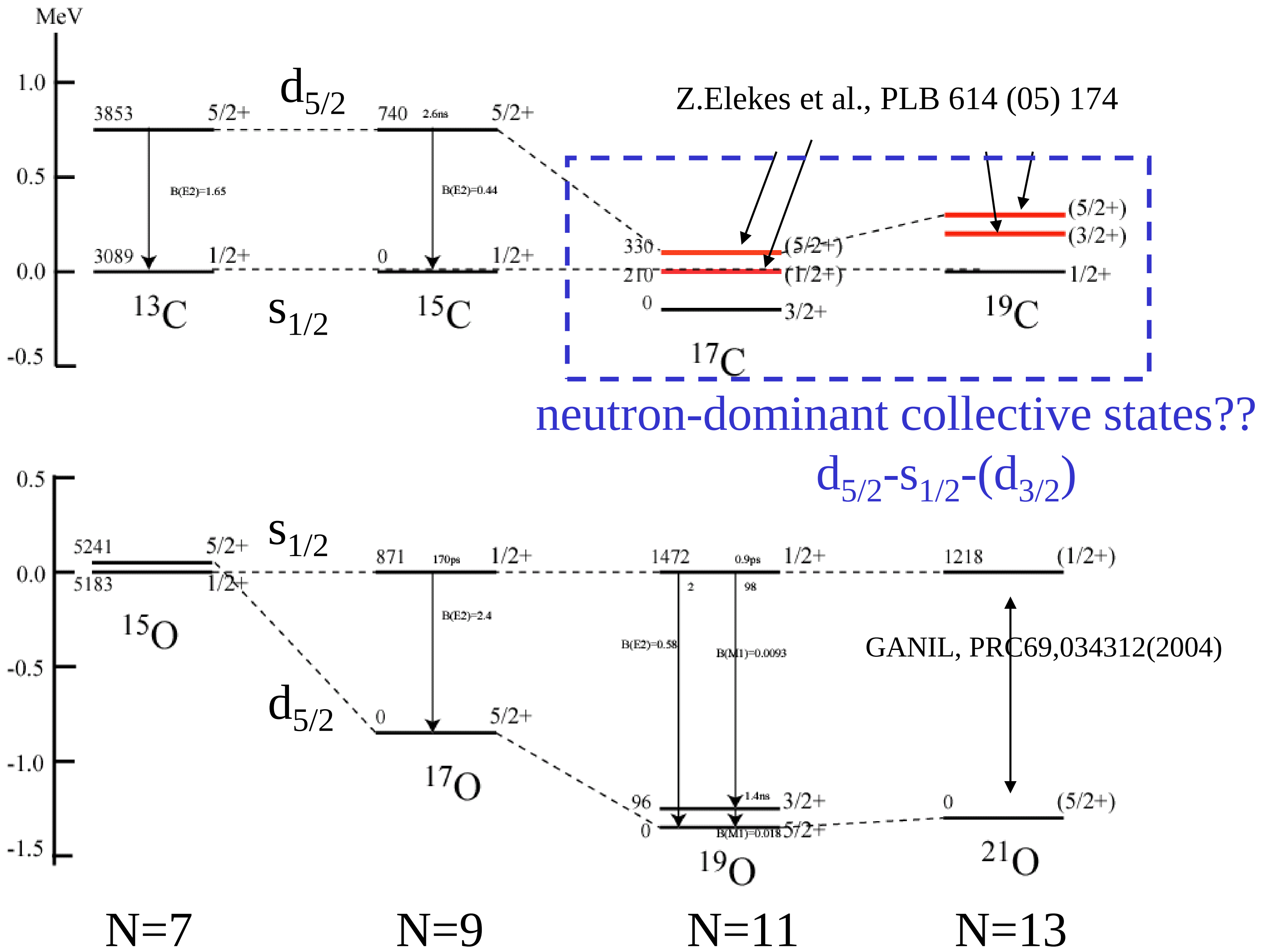
^{18}C: Ong et al. PRC ^{17}C: Suzuki et al. PLB





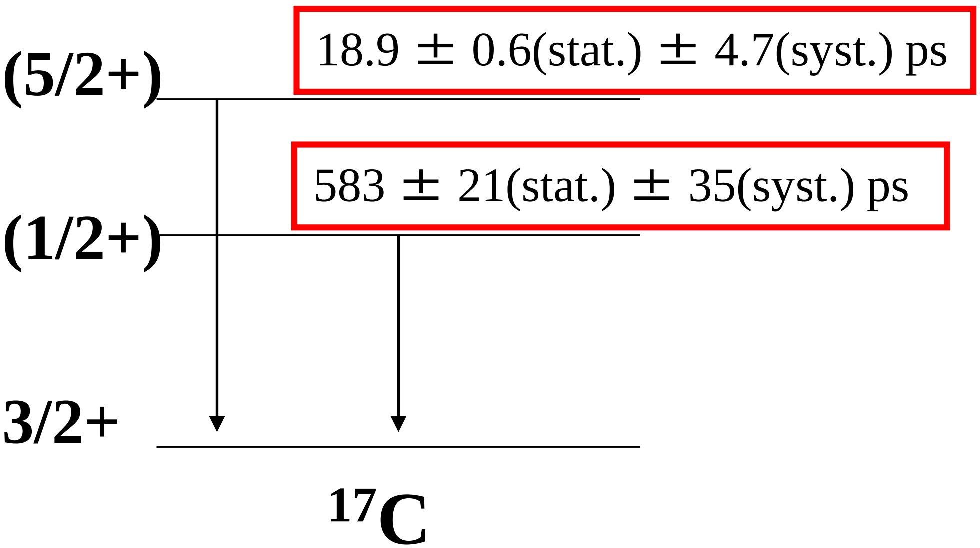
- Increased detectors
  - → **improved statistics**
- Various combinations
  - → **increased sensitivity towards lifetime**
- Measurement with/without lead shield
  - → R_{wPb}/R_{woPb}
  - → **NO uncertainty due to angular distribution of γ-ray**

Excited states in the odd C and O isotopes

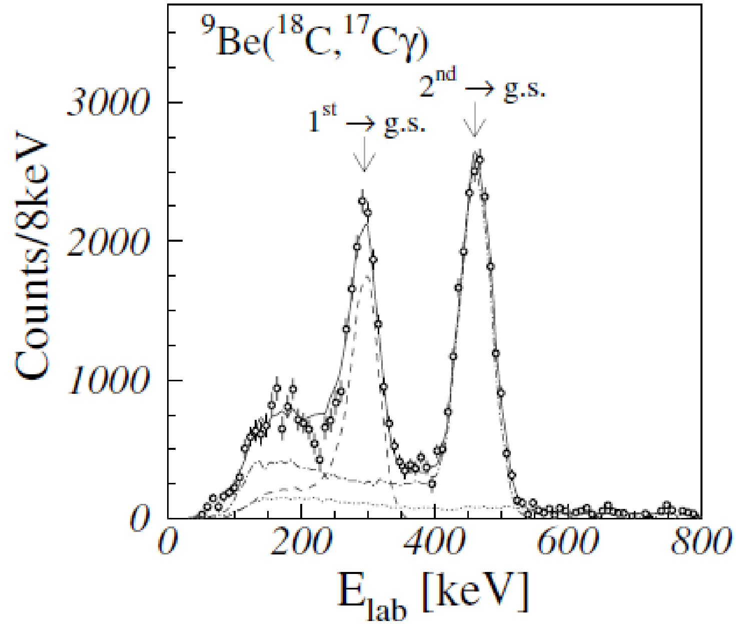


Life-time measurements of excited states in ^{17}C

D. Suzuki, et al., PLB



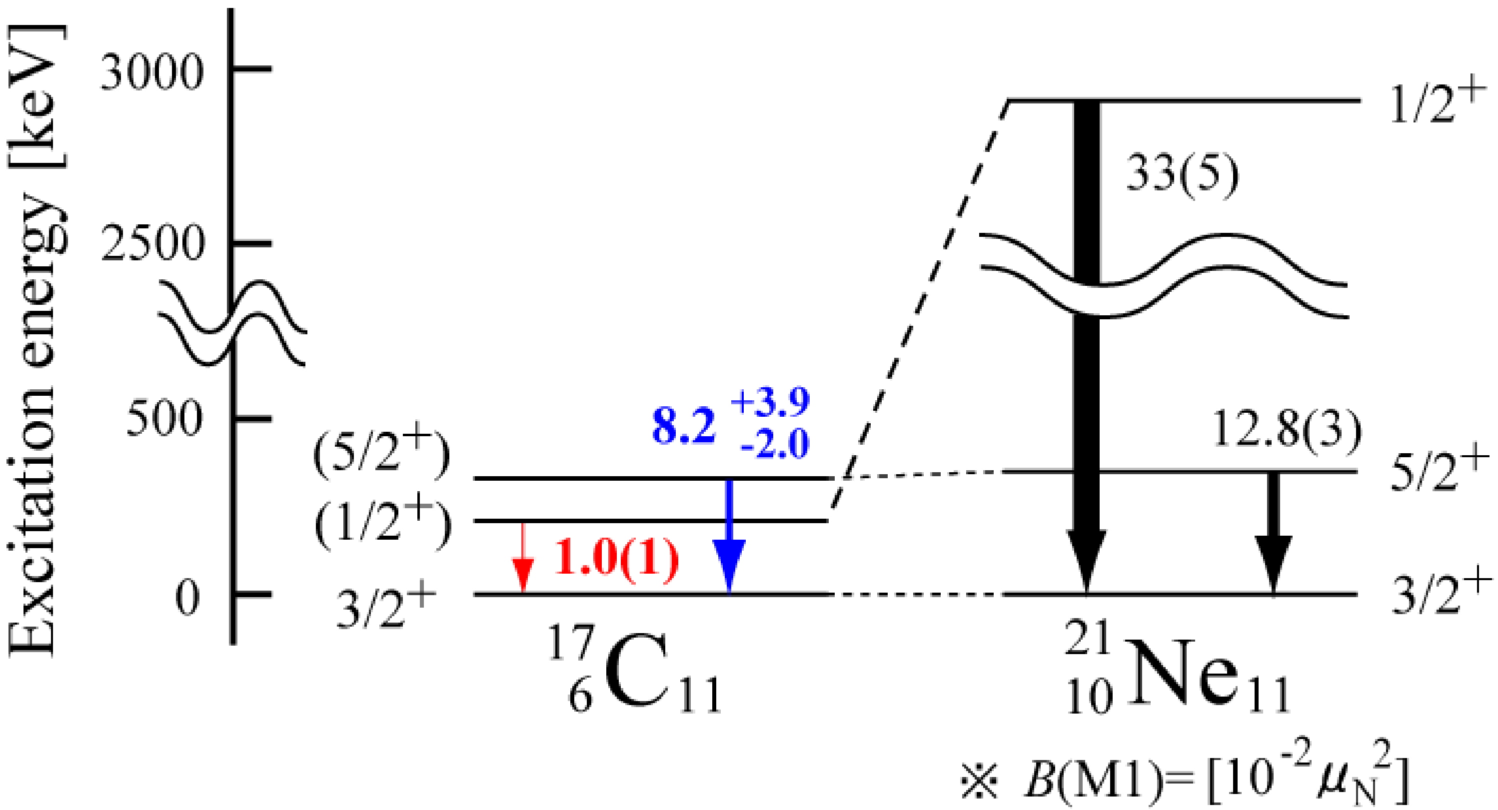
^{18}C+Be -> ^{17}C + X



$B(\mathrm{M1}; (1/2^{+}) \to 3/2^{+}) = (1.0 \pm 0.1) \times 10^{-2}\ [\mu_N^{2}]$

$B(\mathrm{M1}; (5/2^{+}) \to 3/2^{+}) = (8.2\ {+3.2}/{-1.8}) \times 10^{-2}\ [\mu_N^{2}]$

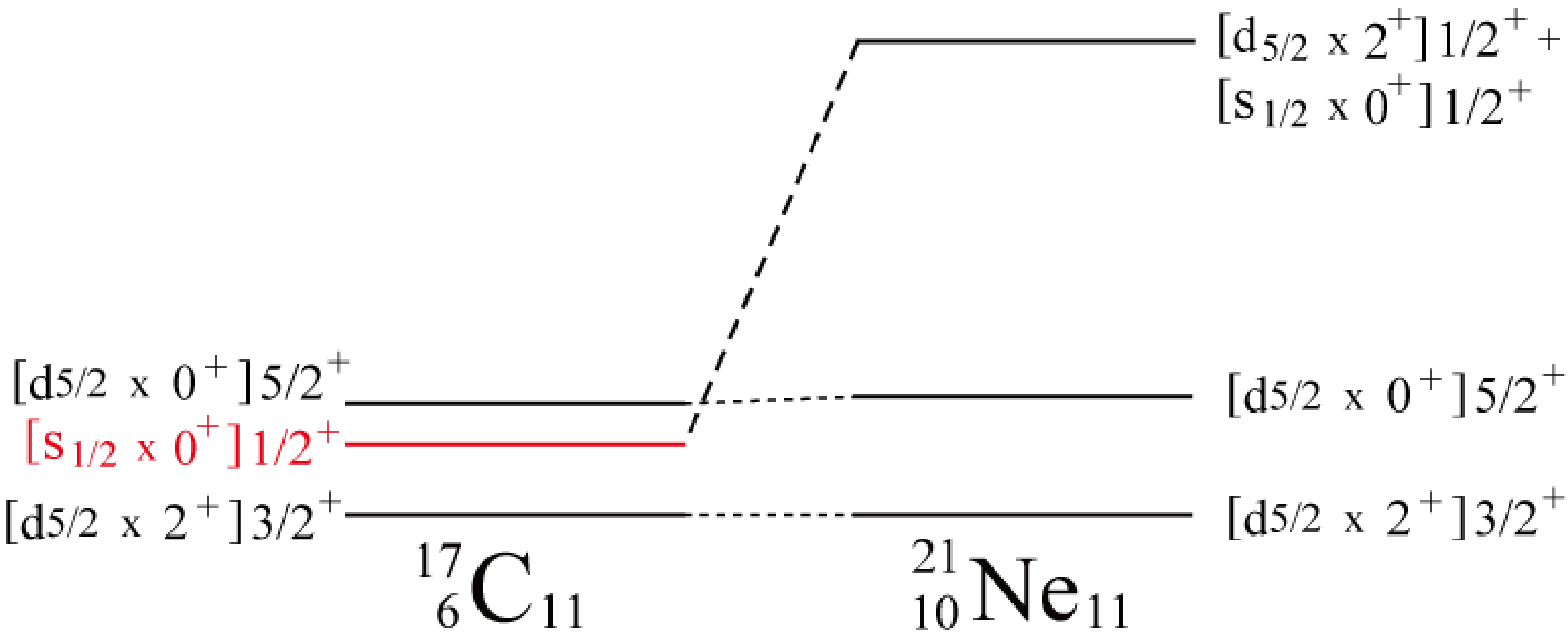
Comparison between ^{17}C and ^{21}Ne



- $(5/2^+)$; Almost identical excitation energy and M1 strength
- $(1/2^+)$; Low excitation energy and small M1 strength

⇒ Drastic change in the structure of the 1/2+ state

s-wave dominance in the $1/2^+$ state?

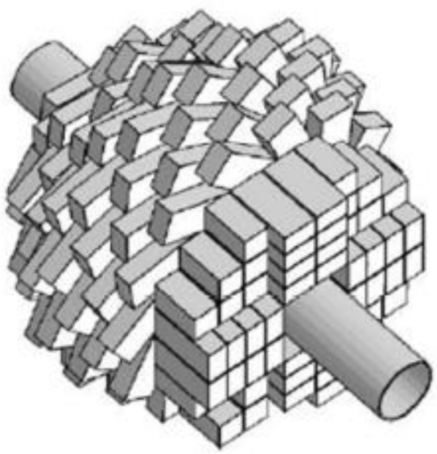


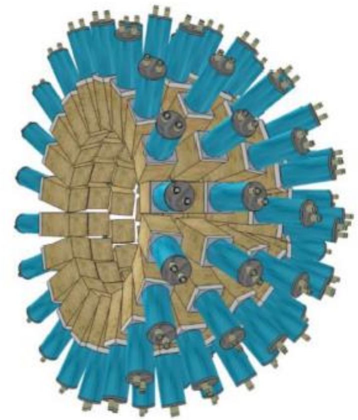
- $3/2^+$; the $[d_{5/2} \times 2^+]^{3/2+}$ configuration is dominant.

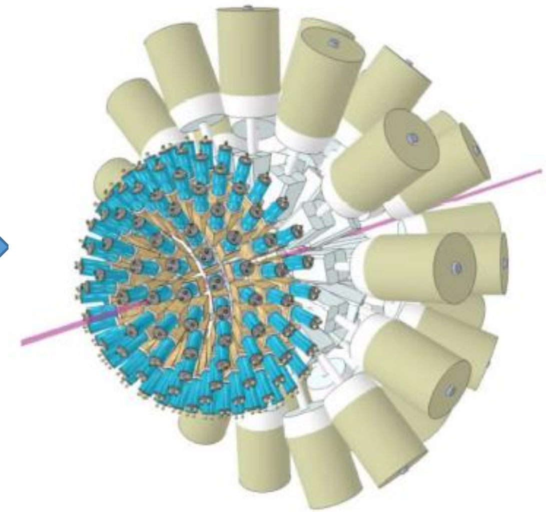
$\Rightarrow$ The $1/2^+$ state of ^{17}C may have a large amount of the $[s_{1/2} \times 0^+]^{1/2+}$ configuration since the M1 transition between the $s_{1/2}$ and $d_{5/2}$ orbitals is forbidden.

The $1/2^+$ state of ^{17}C may be a halo state ?.

Next Generation Gamma-ray Array







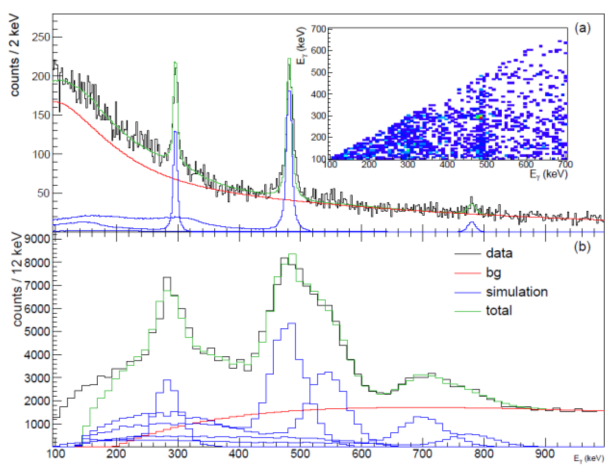
DALI2 (present)
NaI crystals

dE/E ~ 8%

SHOGUN (future)
LaBr3 crystals

dE/E ~ 2%

Asia-Ball (5-10 years)
Ge crystals
dE/E ~ 0.2%
+ SHOGUN

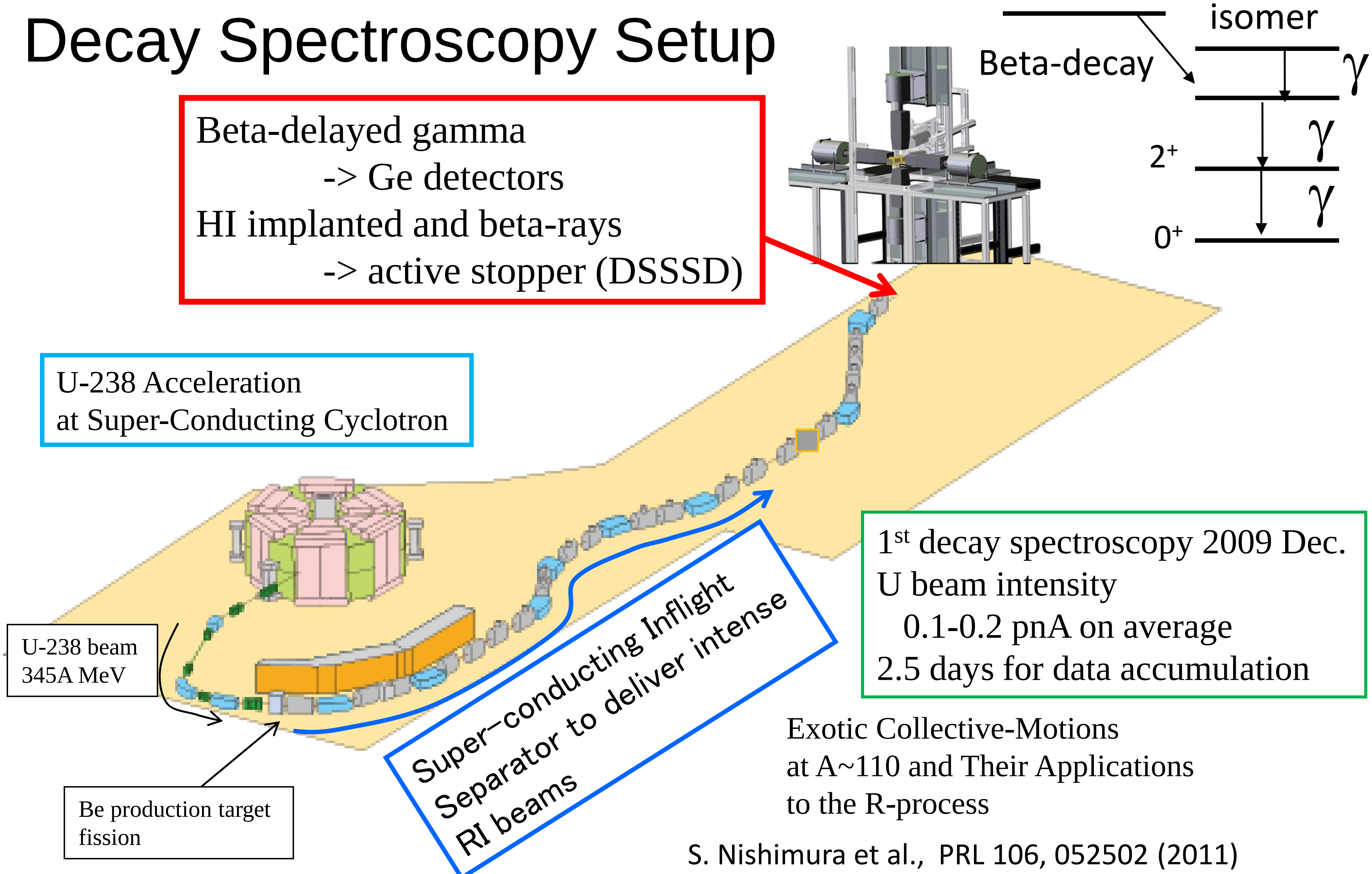


Doppler corrected gamma energy spectra of Mg-33 (real data)

Inelastic scattering with GRETINA at NSCL
(K. Wimmer)

Neutron knockout with DALI2 at RIBF
(D. Bazin)

Decay Spectroscopy Setup

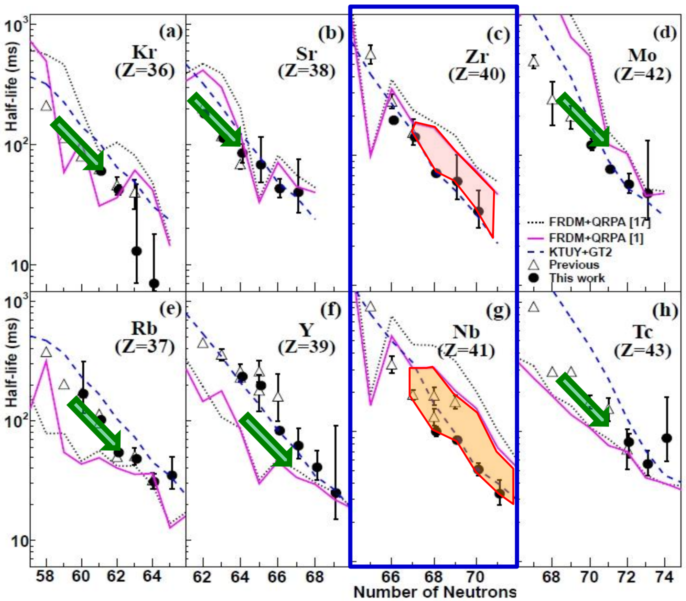


Particle Identification of RI beams

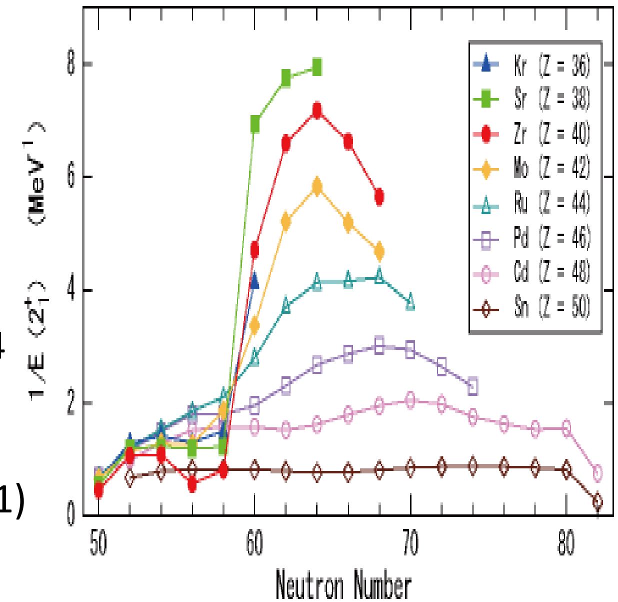
Exotic Collective-Motions
at A~110 and Their Applications
to the R-process

S. Nishimura et al., PRL 106, 052502 (2011)
T. Sumikama et al., PRL 106, 202501 (2011)
H. Watanabe et al., Phys.Lett.B 704,270-275(2011)
H. Watanabe et al., Phys. Lett. B 696, 186-190 (2011)

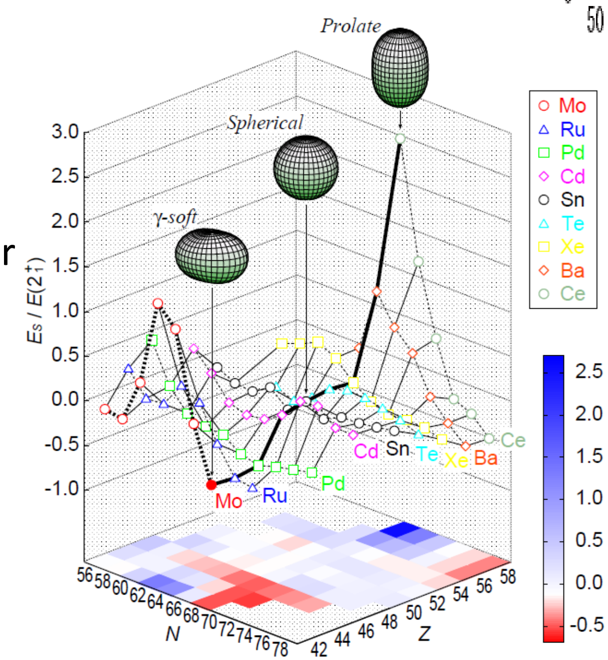
Exotic Collective-Motions at A~110 and Their Applications to the R-process Nucleosynthesis



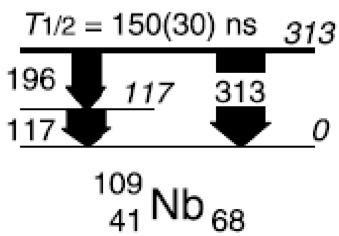
New Half-life data for
18 new isotopes
S. Nishimura et al.,
PRL 106, 052502 (2011)



Deformed magic N=64
in Zr isotopes
T. Sumikama et al.,
PRL 106, 202501 (2011)



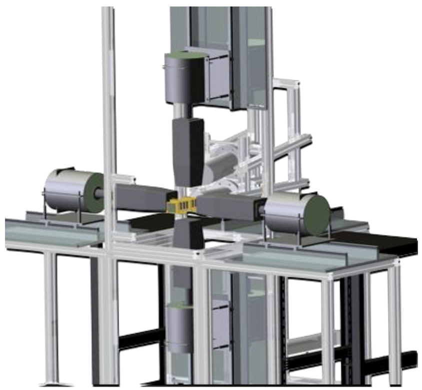
Low-lying level structure of Nb-109:
A possible oblate prolate shape isomer
H. Watanabe et al.,
Phys. Lett. B 696, 186-190 (2011)



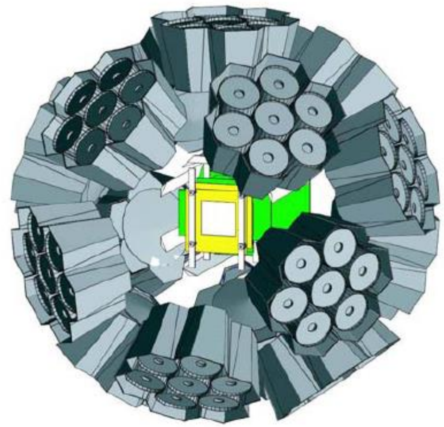
Development of axial
asymmetry in neutron-rich
nucleus Mo-110
H. Watanabe et al.,
Phys.Lett.B 704,270-275(2011)

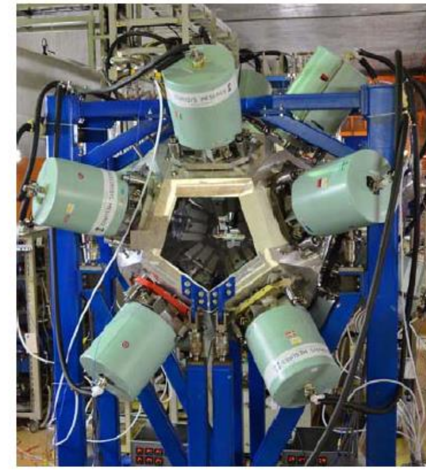
Decay Spectroscopy at RIBF

First decay spectroscopy in 2009



EURICA setup





EUroball-RIKEN Cluster Array

EURICA Collaboration

Si-strip: IBS-RIKEN

U-beam intensity ... <u>x 50 times</u>

- 0.2 pnA → 10 pnA

Gamma-ray efficiency ... <u>x 10 times</u>

- 4 Clover detectors (Det. Effi. ~1.5% at 0.662 MeV)

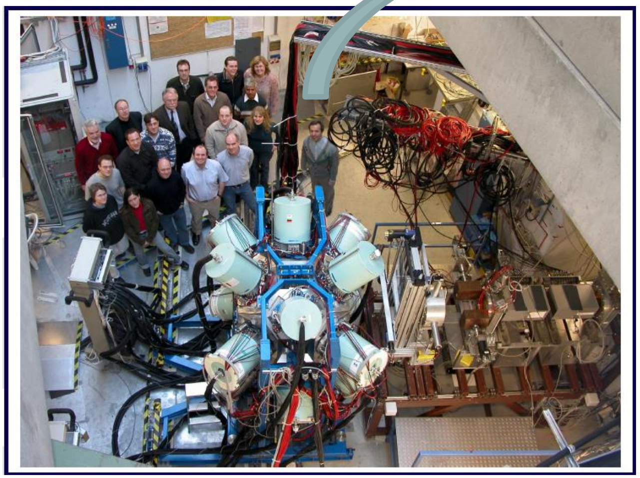
→ 12 Cluster detectors (Det. Eff. ~ 15 % at 0.662MeV)

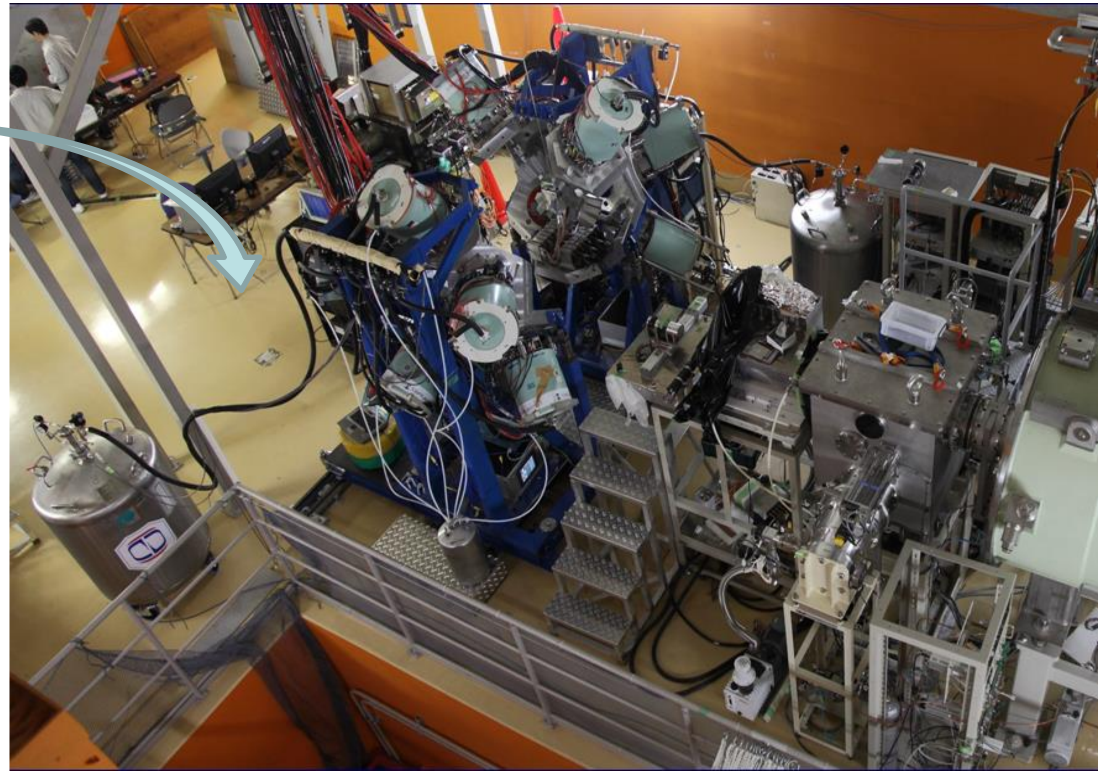
Beam time <u>x 40 times</u>

- 2.5 days (4 papers) → 100 days ... <u>(160 papers)</u>

EURICA Project at RIBF

EUROBALL-RIKEN Cluster Array (EURICA) 2012-16





Euroball Cluster detectors
Support structure
Readout electronics
used for GSI-RISING

2011 Nov.

RIKEN RIBF
(Japan)

EURICA Installation

Ivan Kojouharov

Nick Kurtz

Henning Schaffner

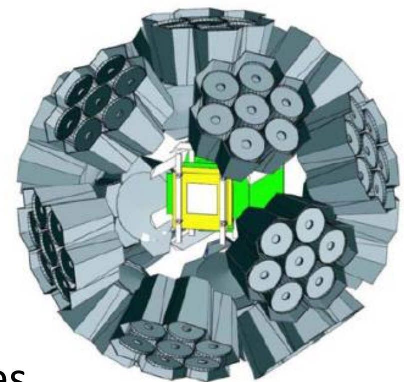
EURICA

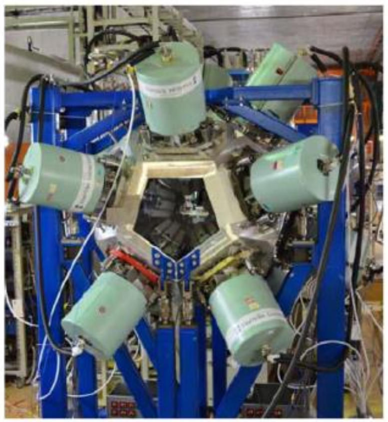
EUroball-RIKEN Cluster Array

2012-2016

Beta-delayed gamma / Isomer Spectroscopy

12 Euroball Cluster detectors
Support structure
Electronics used for RISING

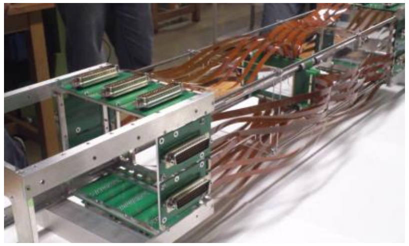




RIBF: decay station
Active stopper: DS-SSD (WAS3ABi)
Liq. N_2 system, other infrastructures

+Additional detectors ($LaBr_3$, Plastic …)

WAS3ABi

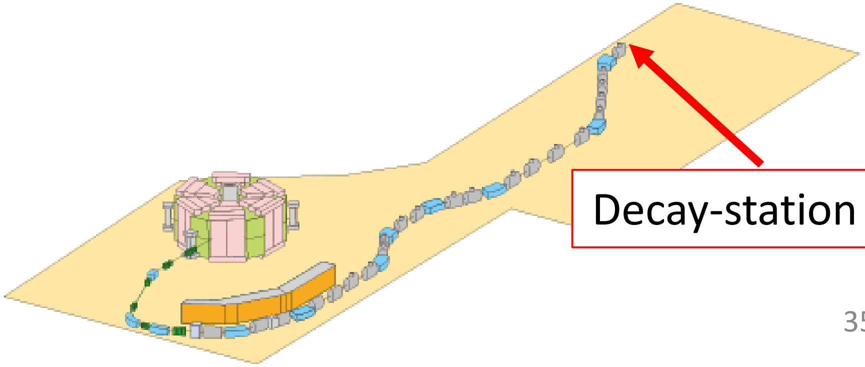


230 collaborators from 19 countries
About 100 days were approved for physics run

Commissioning	March 2012
Physics Run	June 2012 – June 2016

Publication at this time (August 2016)

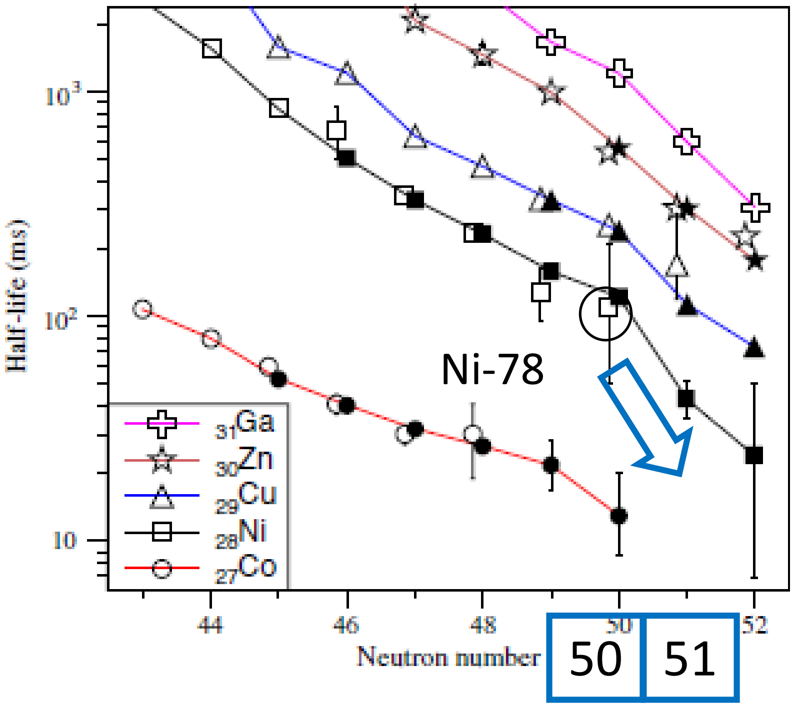
- 23 papers (8 PRL, 5 PLB, 3 PRC(R), 7 PRC)
  - 9 PhD Thesis + 1 Master Thesis
- 31 proceedings
  - 8 technical articles



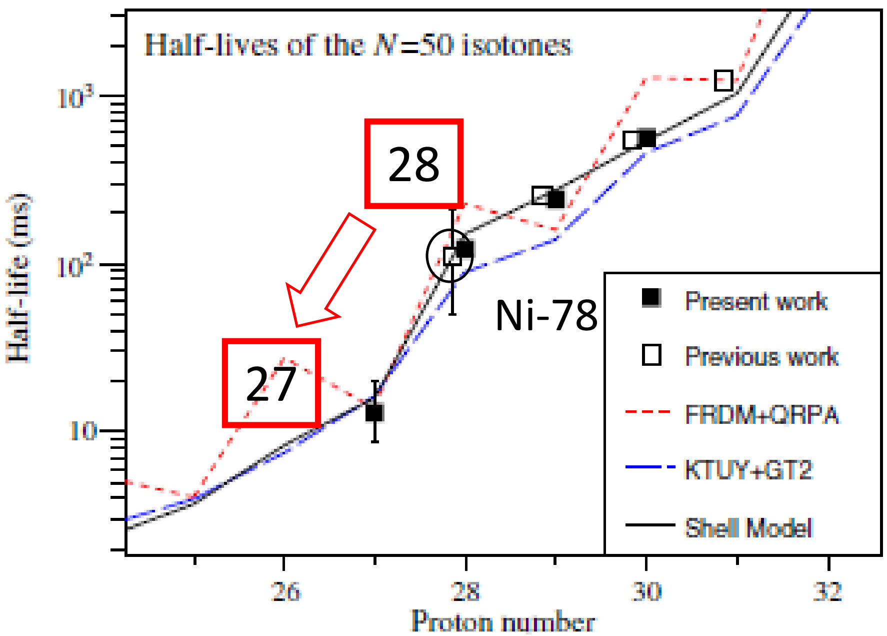
β-Decay Half-Lives of Co76,77, Ni79,80, and Cu81: Experimental Indication of a Doubly Magic Ni78
Xu and Nishimura et al., Phys. Rev. Lett. 113, 032505 (2014)

NP0702-RIBF10: S. Nishimura
Decay study for 75-78Co, 77-80Ni, 80-82Cu, and 82-83Zn near the N=50 shell closure

Isotope dependence of T1/2



Isotone dependence of T1/2



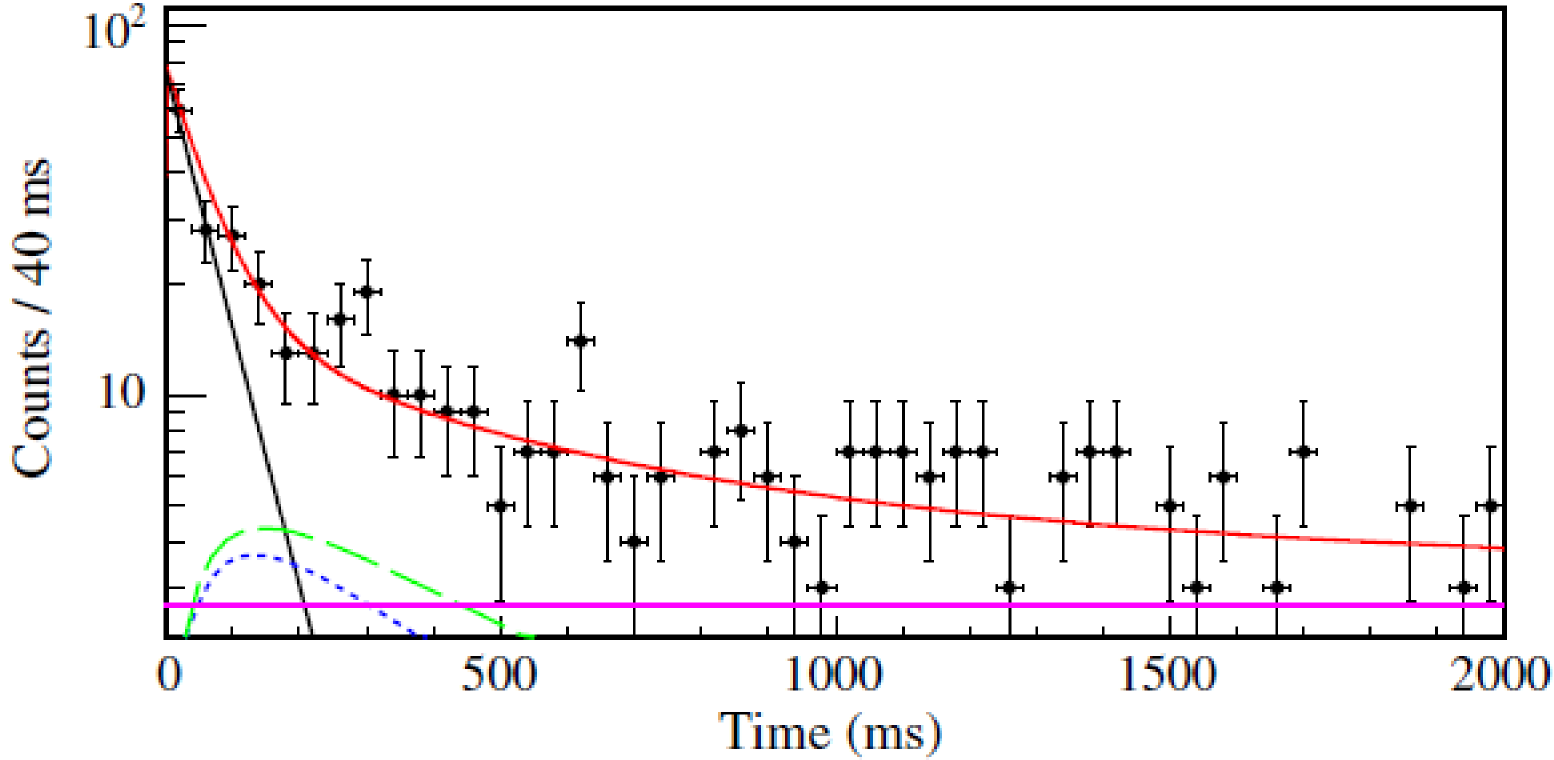
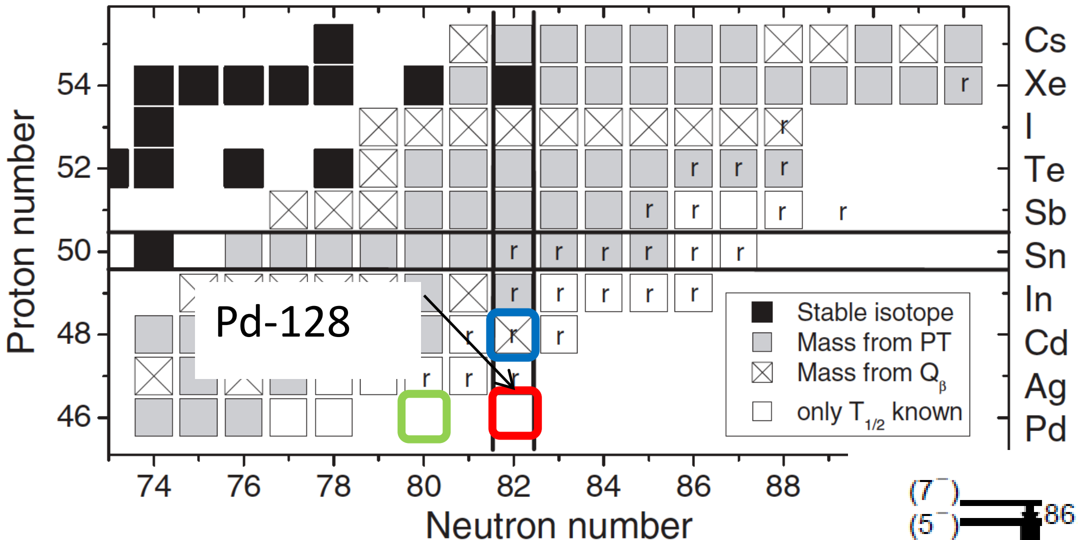


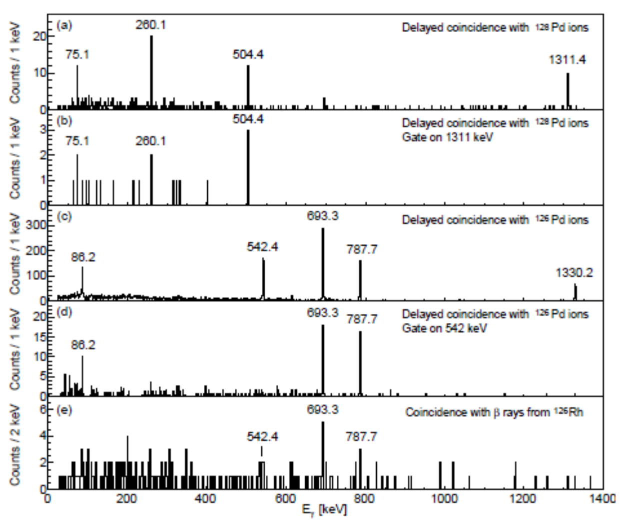
FIG. 2 (color online). Time distribution of the β-decay events correlated with implanted ^{79}Ni. The fitting function (solid red line) considers the activities of parent nuclei (dashed-dotted black line), β-decay daughter nuclei (fine-dashed blue line), βn-decay daughter nuclei (dashed green line), a constant background (solid pink line), and other decay products (granddaughter nuclei, etc.), which are not drawn in the figure.

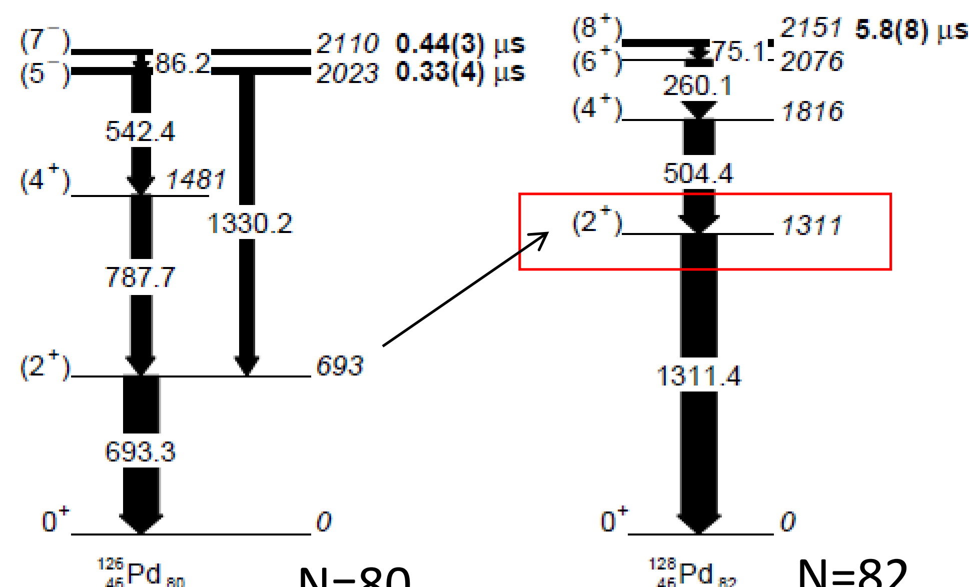
Isomers in 128Pd and 126Pd: Evidence for a Robust Shell Closure at the Neutron Magic Number 82 in Exotic Palladium Isotopes

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



Typical senority-isomer observed in Pd-128
→ No evidence of shell-quenching ....

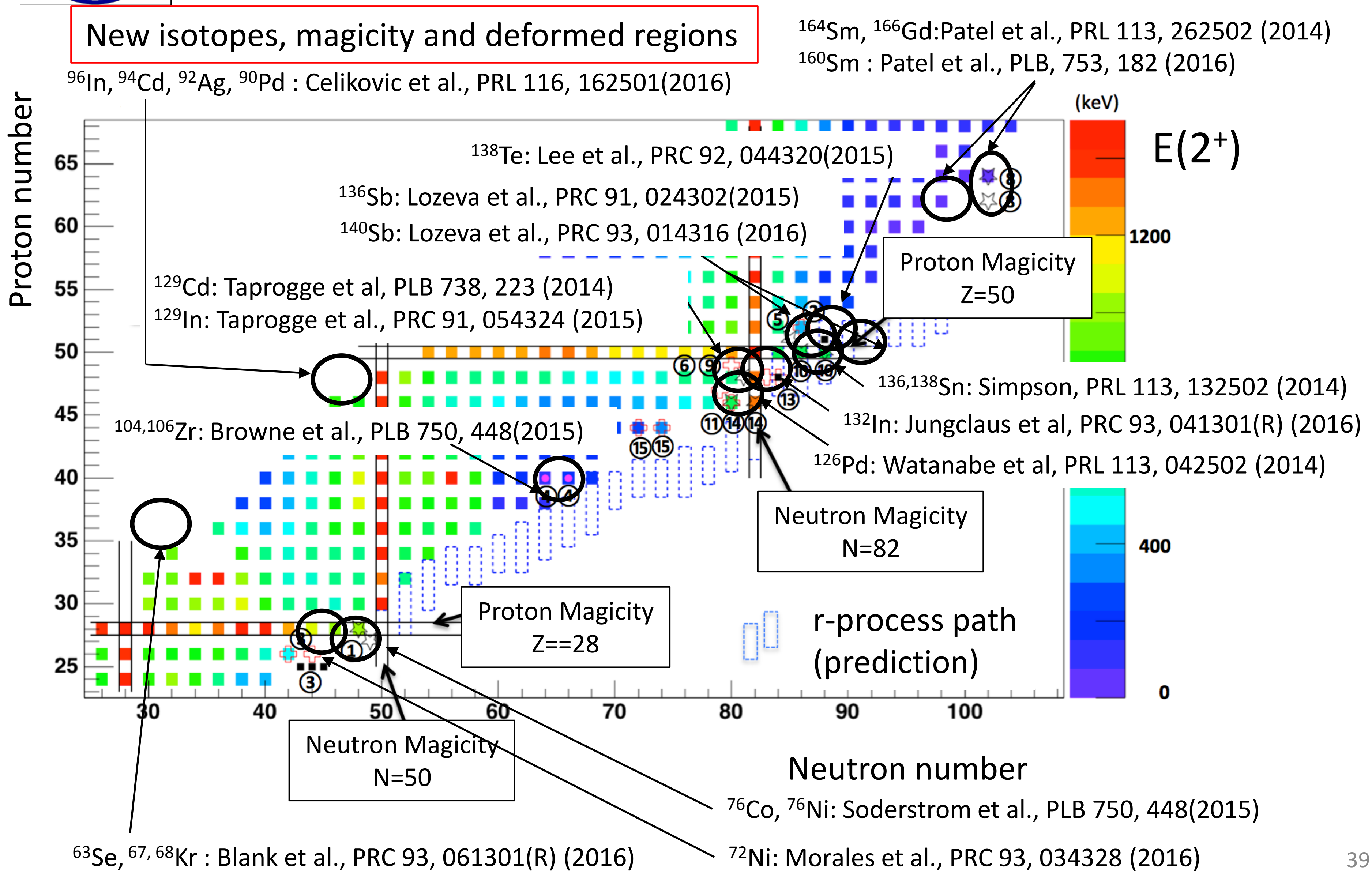




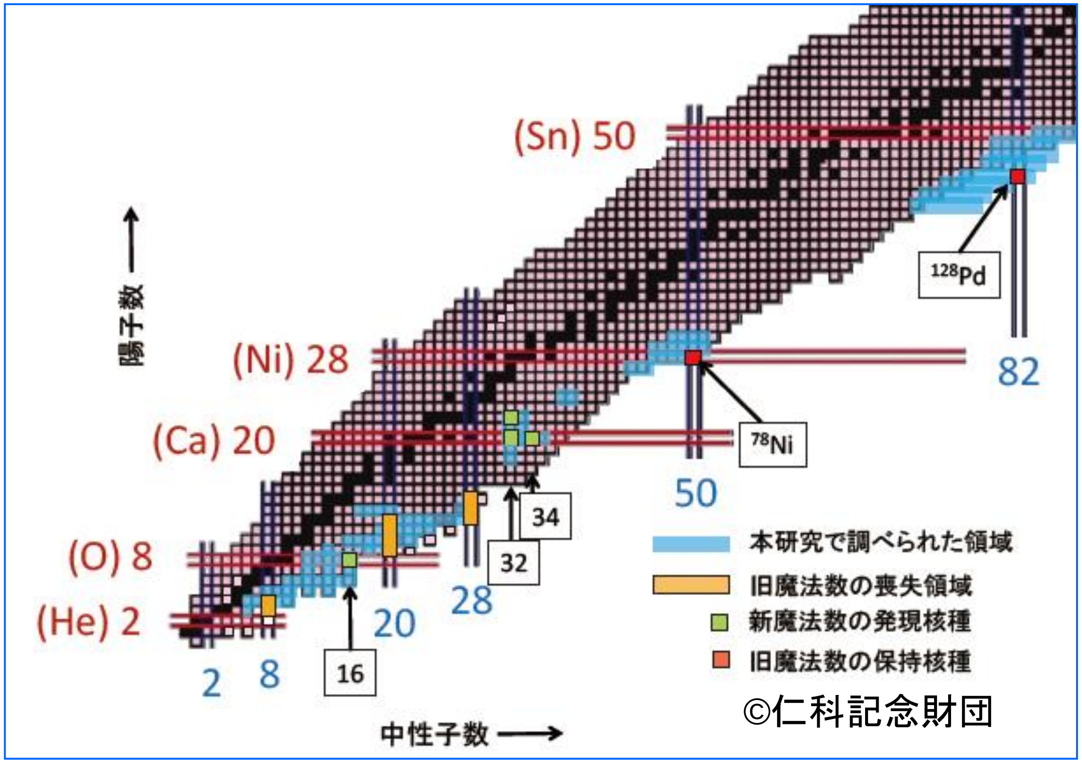
N=80

N=82

EURICA Achievements in 2014-2016 (July)
- New Isotopes/ Isomer/ Beta-delayed gamma



Shell Evolution



New Magicity of N=34

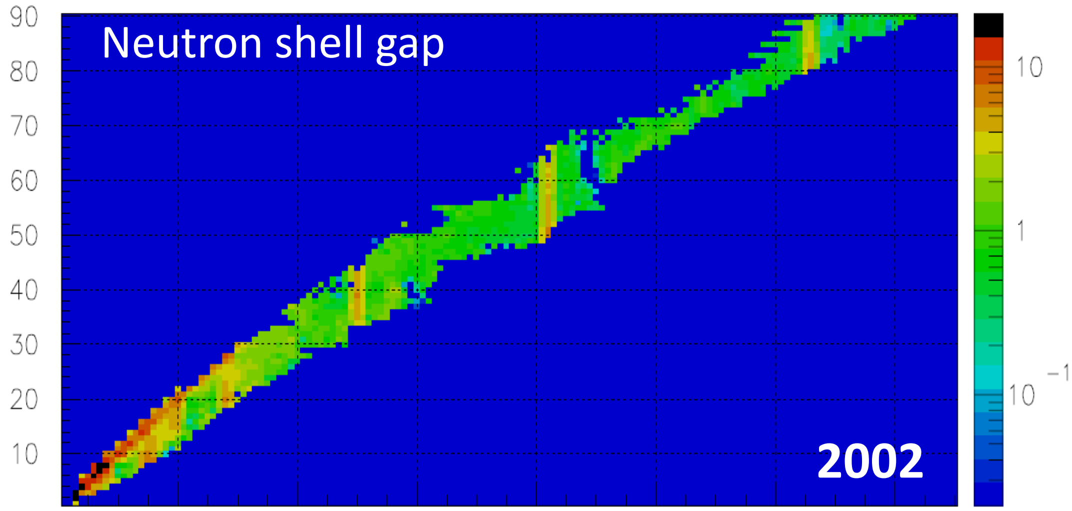
Magicity Loss at N=20、28
New magic number N=34
Double magicity of ^{78}Ni（Z=28, N=50）
Magicity at N=82 with Z>46…

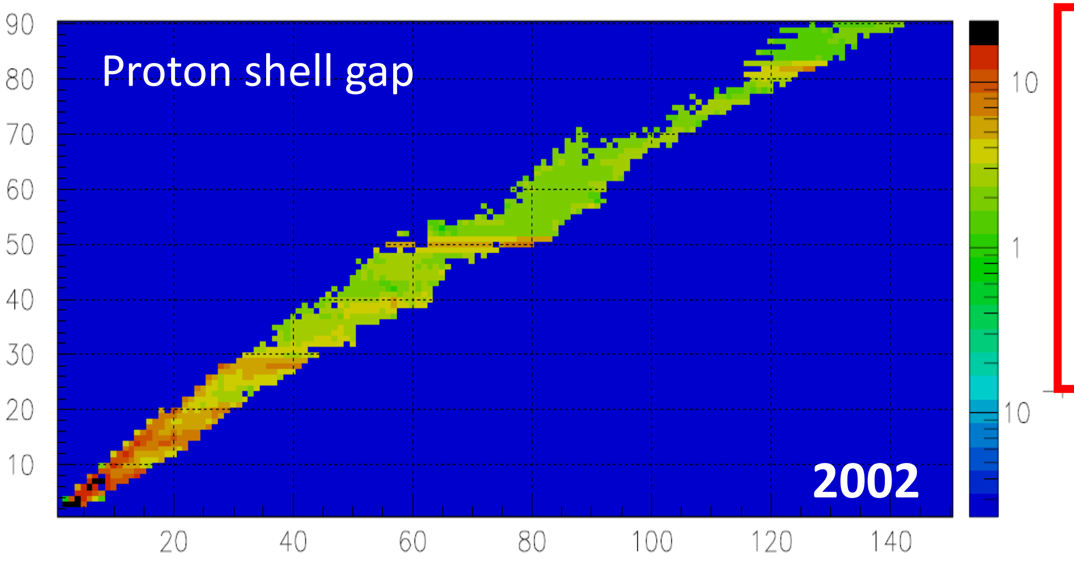
^{32}Ne:: Doornenbal, PRL 103, 032501 (2009)
^{31,32,33}Na: Doornenbal, PRC 81, 041305R (2010)
^{33,34,35}Na: Doornenbal, PTEP 2014, 053D01 (2014)
^{32}Mg: Li, PRC 92, 014608 (2015)
^{36,38}Mg: Doornenbal, PRL111, 212502 (2013)
^{42}Si : Takeuchi PRL109, 182501 (2012)
^{40}Mg : Crawford PRC 89, 041303 (2014)
^{54}Ca: Steppenbeck , Nature 502, 207 (2013)
^{50}Ar : Steppenbeck, PRL 114, 252501 (2015)
^{66}Cr, ^{72}Fe : Santamaria, PRL 115:192501 (2015)
^{126}Pd: Wang, PRC 88 054318 (2013)
^{136}Sn: Wang, PTEP 023D02 (2014)

^{106,108}Zr:: Sumikama, PRL 106, 202501 (2011)
^{126,128}Pd : Watanabe, PRL 111, 152501 (2013)
^{78}Ni: Xu, PRL 113, 032505 (2014)
^{136,138}Sn : Simpson, PRL113, 132502 (2014)

Mass measurements for shell evolution

Yamaguchi (Saitama U.), Wakasugi (RIKEN), Uesaka (RIKEN), Ozawa (Tsukuba U.), et al.





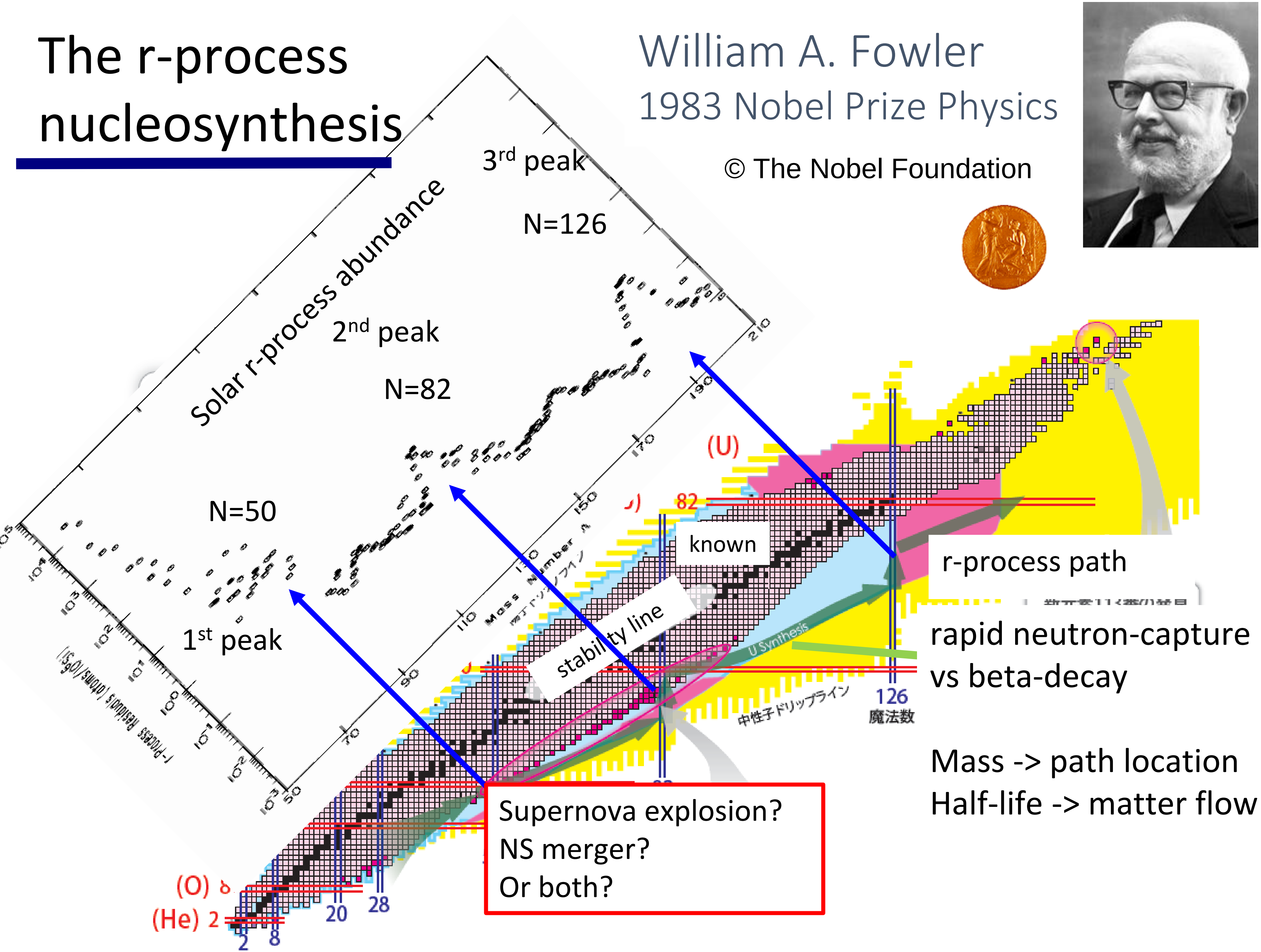
Key technologies:
- Isochronous ring
  - $\Delta T/T < 10^{-6}$ for $\delta p/p = \pm 0.5\%$
- Individual injection triggered by a detector at BigRIPS
  - efficiency ~ 100% even for a "cyclotron" beam

Schedule:
- **2015 Commissioning run**
- **2016~ Mass measurements of RI**

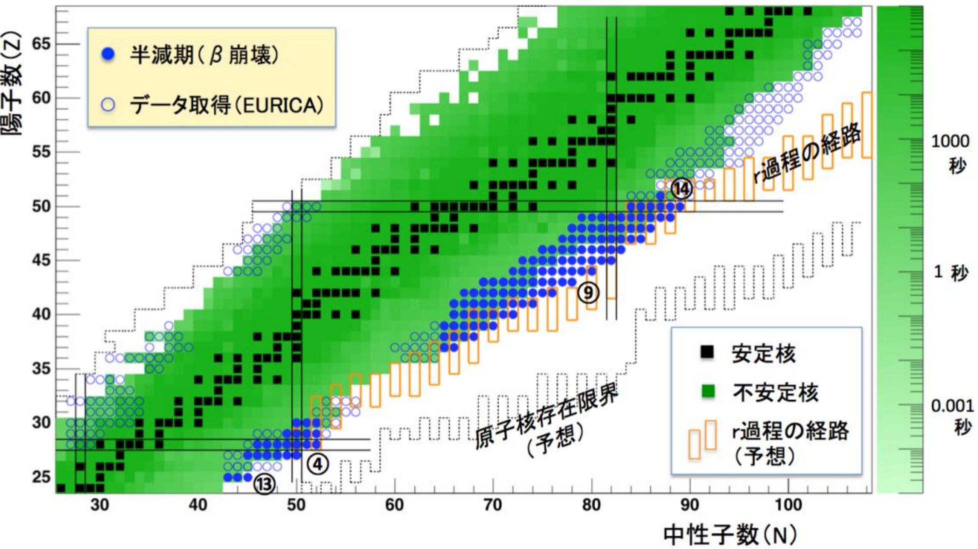
The r-process nucleosynthesis

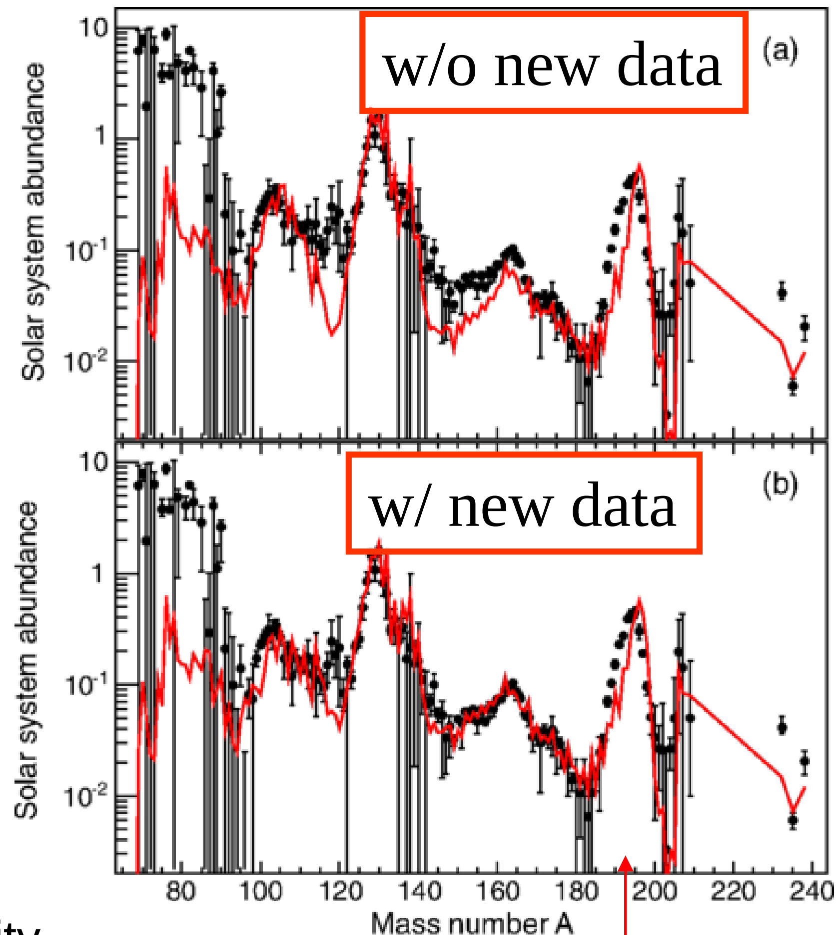
William A. Fowler

1983 Nobel Prize Physics



“Revolution” in the r-process research





G. Lorusso, S. Nishimura *et al. PRL*. 114, 192501 (2015)

Bunch of T1/2 data for A~100
A standard model assuming (n,gamma) equilibrium reproduces the r-abundance up to rare-earth region

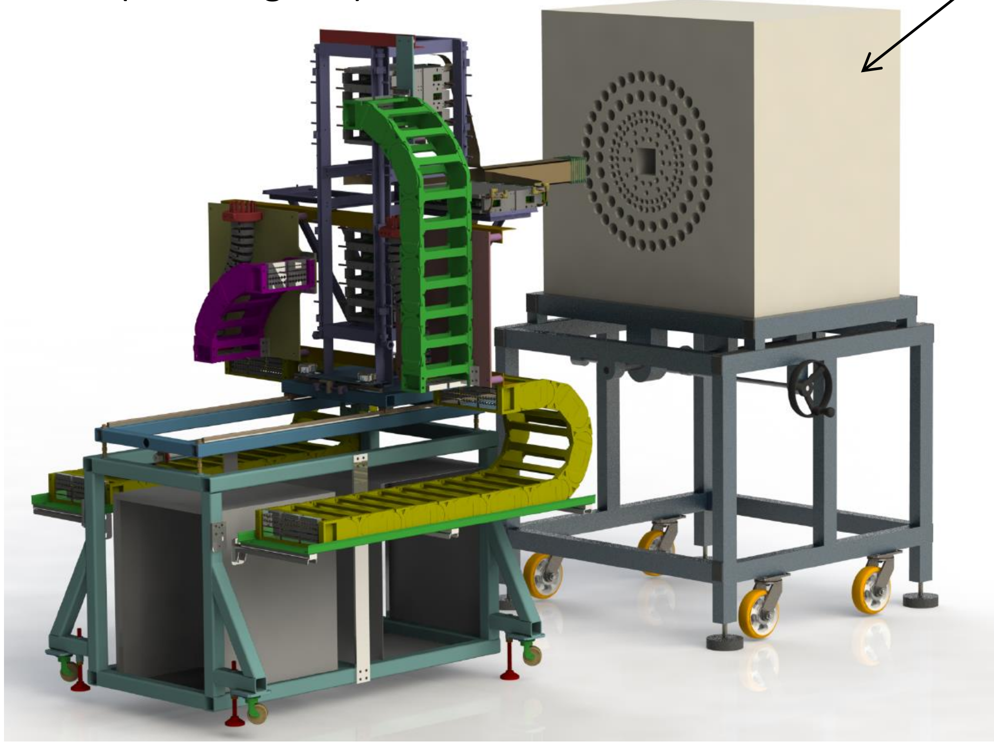
Mass, beta-delayed neutron emission probability measurement in future

Next step should be towards the 3rd peak

S. Nishimura et al., PRL. 106, 052502 (2011)
Z. Y. Xu, S. Nishimura *et al.*: PRL. 113, 032505 (2014)
G. Lorusso, S. Nishimura *et al.*: PRL. 114, 192501 (2015)
G. Benzoni, A.I. Morales, H. Watanabe *et al.*: PRC 92, 044320 (2015)
P. Lee, C.-B. Moon, C. S. Lee, A. Odahara *et al.*: PLB 751, 107 (2015)

BRIKEN: beta-delayed neutron detection (He-3)

AIDA (Edinburg, UK)

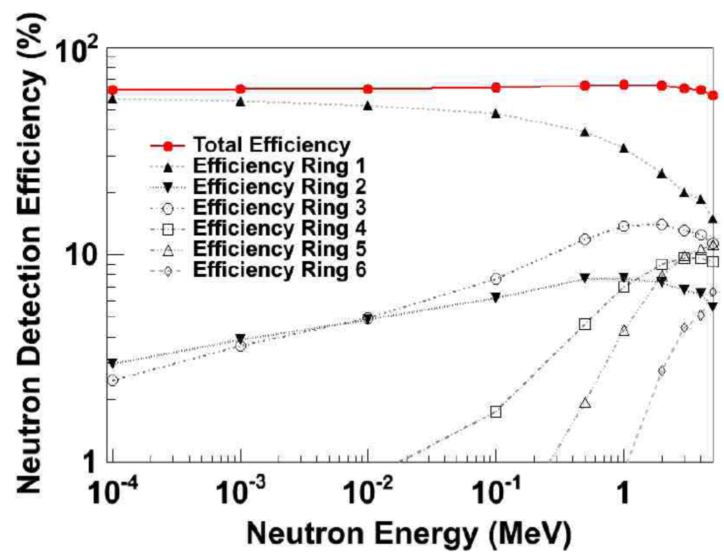


He-3 detector system

ORNL-JINR-GSI-UPC-RIKEN
182 counters

Table 1: ^{3}He tubes available within the BRIKEN Collaboration.

Owner	Pressure (atm)	Size: Diameter (inch/cm)	Size: Eff. Length (inch/mm)	Number of Counters
GSI	10	1 / 2.54	23.62 / 600	10
JINR	4	1.18 / 3.0	19.69/500	20
ORNL	10	2 / 5.08	24/609.6	67
ORNL	10	1 / 2.54	24/609.6	17
RIKEN	5.13	1 / 2.54	118.1/300	26
UPC	8	1 / 2.54	23.62/600	42
Total				182



Very high efficiency neutron detector → Survey of beta-delayed multi-neutron & T1/2
2016-

New Method for Spin Aligned RI-beam Production

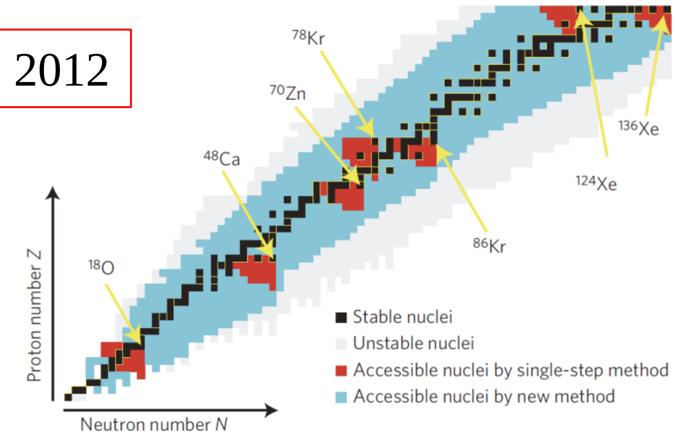
Nuclear Spectroscopy Lab.

nature physics | ARTICLES
PUBLISHED ONLINE: 21 OCTOBER 2012 | DOI: 10.1038/NPHYS2457

Oct. 2012

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]

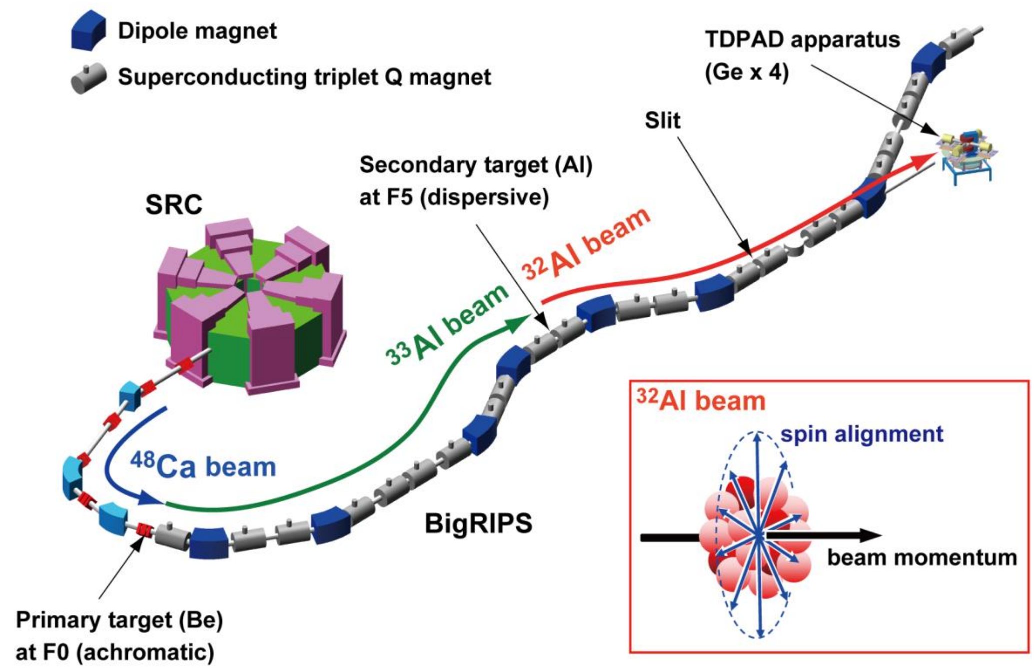


Key 1:

Two step PF
→ Maximize spin alignment

Key 2:

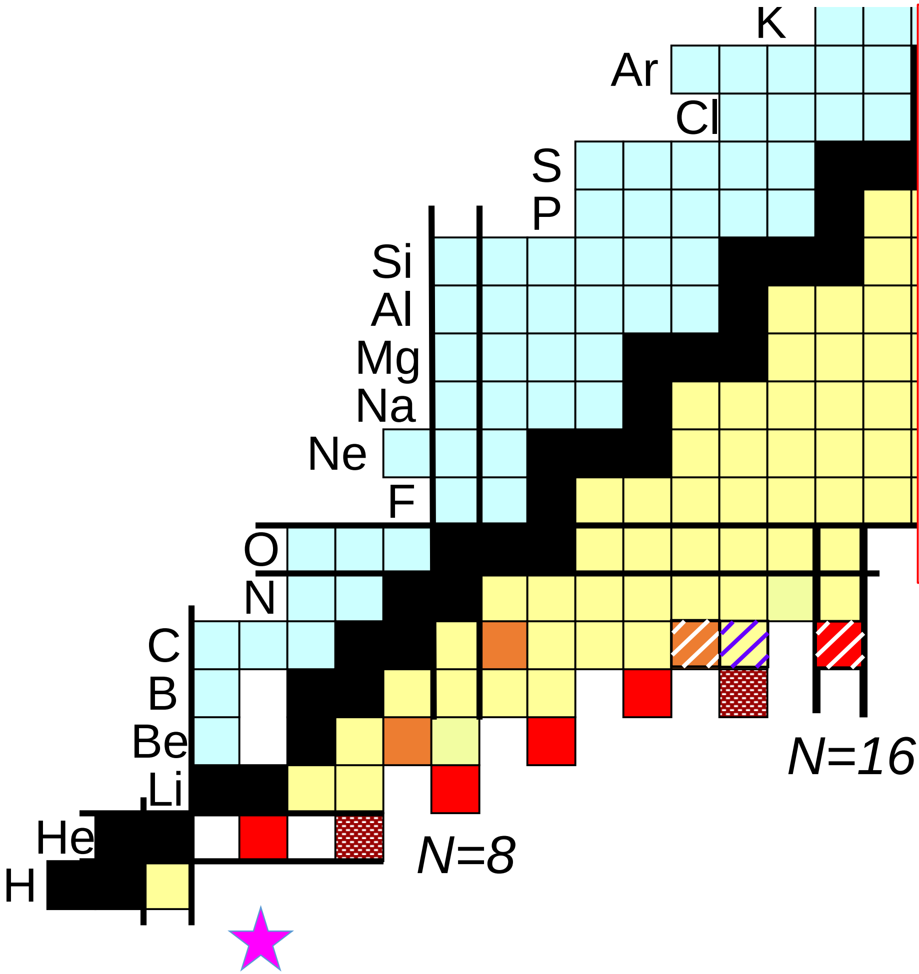
Dispersion matching
→ Maximize yield of two-step PF

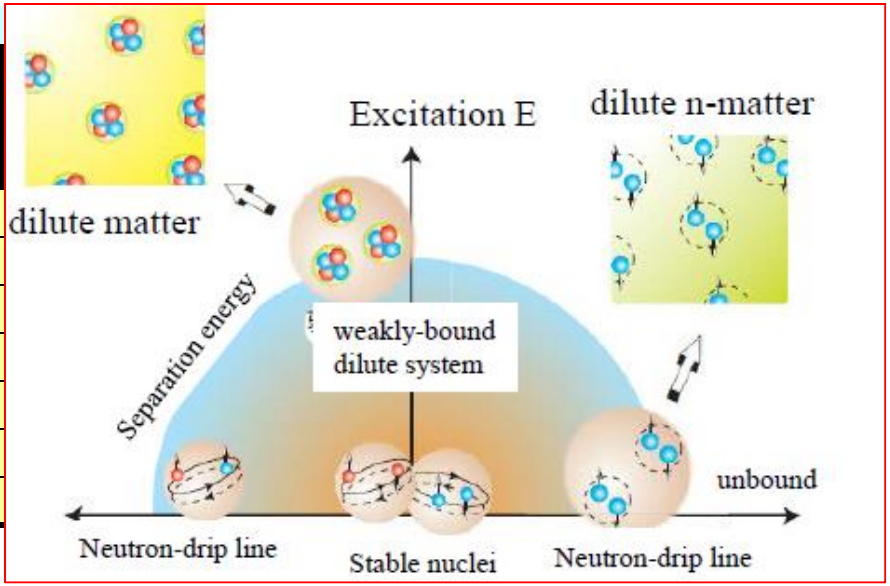


Neutron Correlation in the vicinity of the Drip-line

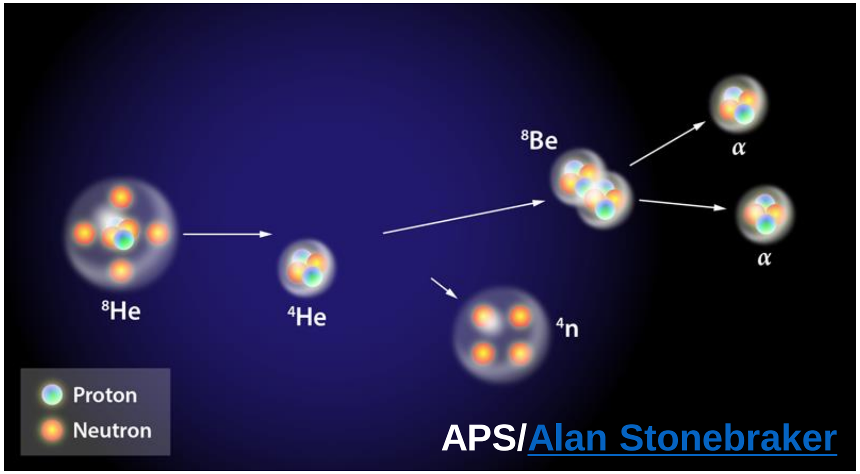
Halo: low density nuclear (neutron) matter in the lab.

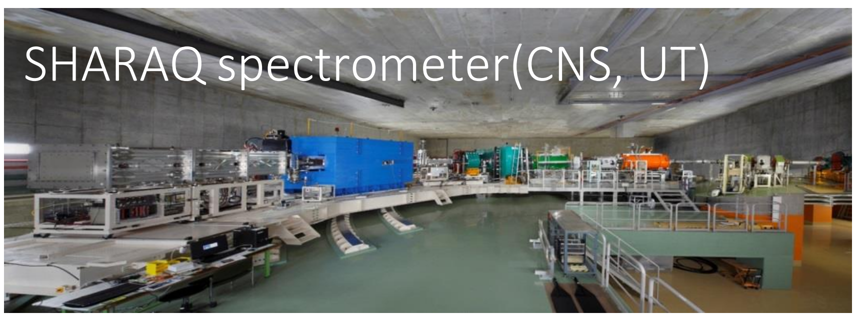
Multi-neutron correlation on and beyond the drip-line?





Element Number Zero: Tetra-neutron system



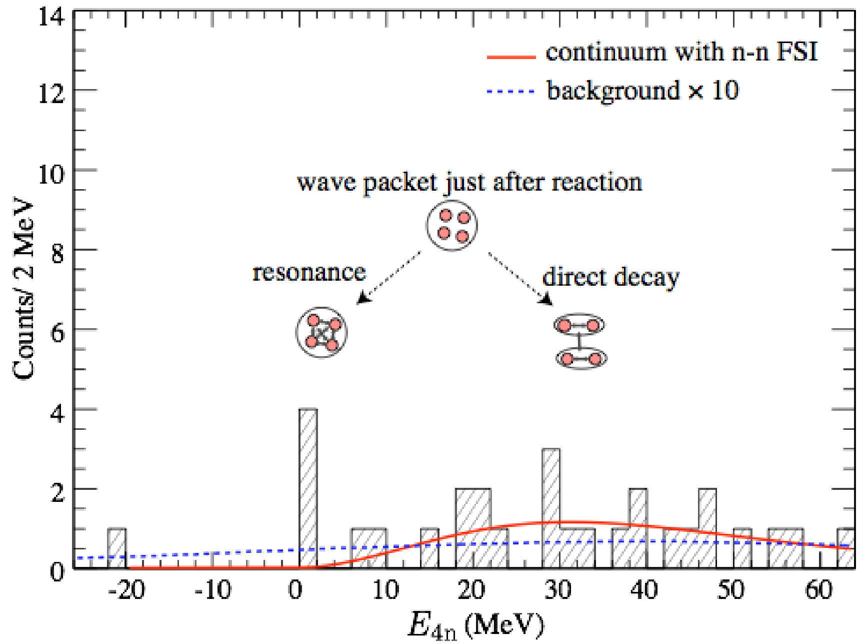


"Nucleus made only of neutrons"

- **Benchmark for ab initio calculations**
  - **NN, NNN, NNNN… interactions**
  - **high T interactions**
- **Multi-body resonances**

A high statistics experiment was conducted June 2016.

Kisamori, Shimoura et al., PRL 116, 052501 (2016)



Clear strength with 4.9σ significance level

E_{4n} = 0.83 ± 0.65 (stat.) ± 1.25 (syst.) MeV

Upper limit of Γ = 2.6 MeV (FWHM)

Cross section: 3.8 nb

(integrated up to θ_{CM} < 5.4 degree)

Energy resolution: 1.2 MeV

Uncertainty of calibration: ± 1.3 MeV

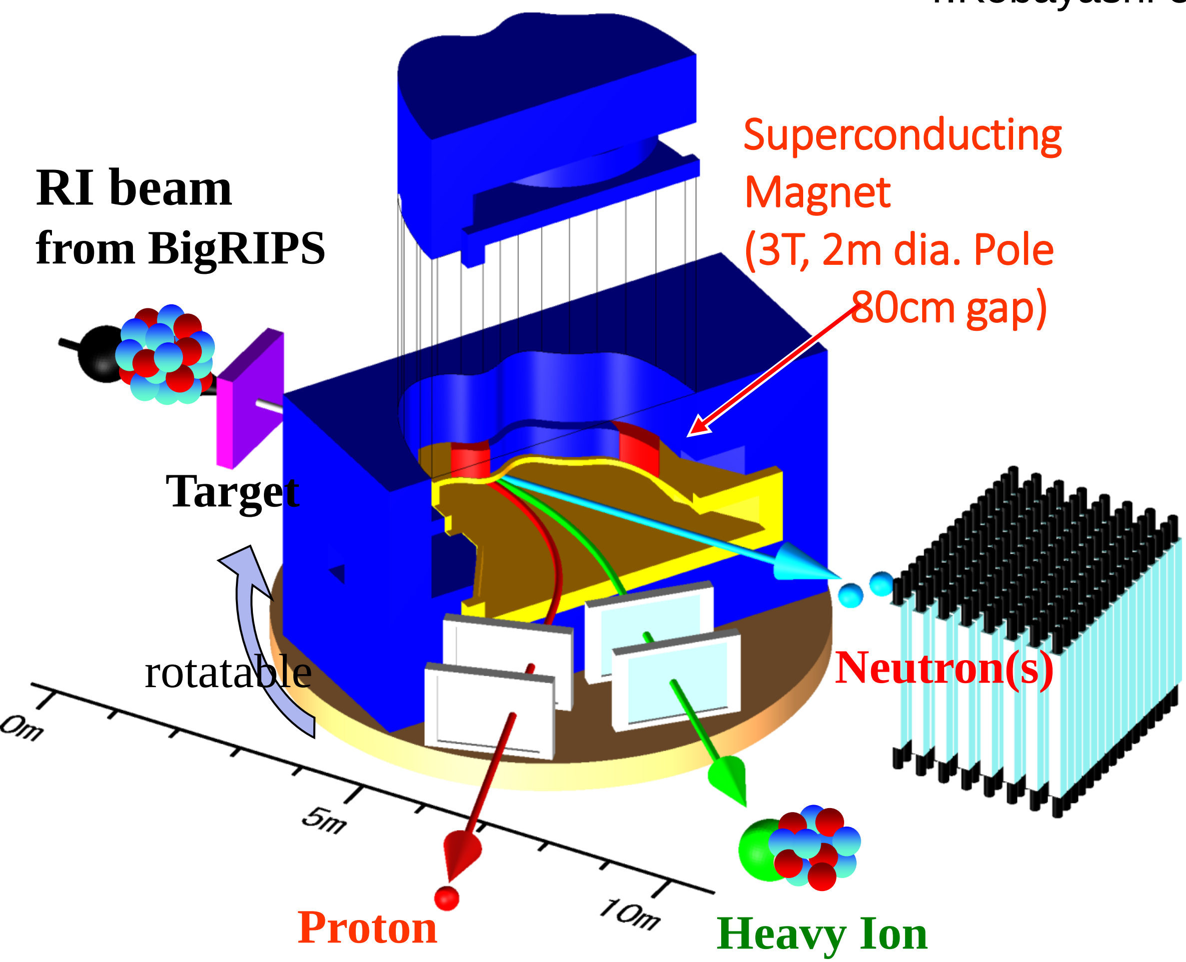
Background : 0.02 events/2MeV

SAMURAI

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam

Kinematically Complete measurements by detecting multiple particles in coincidence

T.Kobayashi et al., NIM B 317, 294 (2013).



Large momentum acceptance

$B\rho_{max} / B\rho_{min} \sim 2 - 3$

Good Momentum Resolution

$\Delta p/p \sim 1/700$ (designed value)

(5σ separation for A=100)

Large angular acceptance for *n*

20 deg (H) x 10 deg(V)

(~100% coverage < E_{rel} ~ 2MeV,

~ 30% coverage at E_{rel} ~ 10 MeV)

Stage: Rotatable (-5 -- 95 degrees)

Versatile Usage

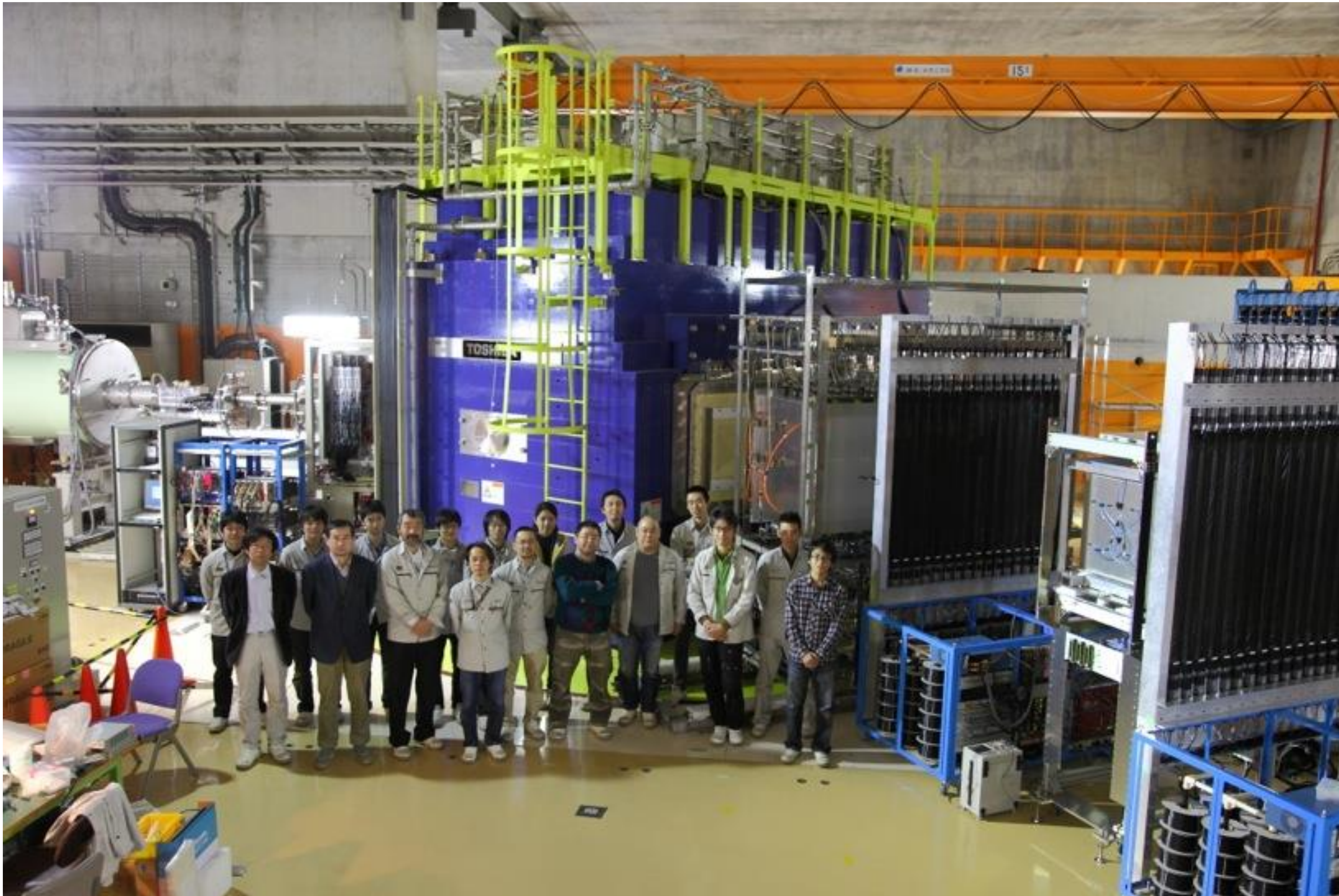
Invariant mass for n+HI

Invariant mass for p+HI

(p,n),(p,p'),(p,pn)(p,pp) etc.

Heavy Ion Collision

polarized deuteron, etc.

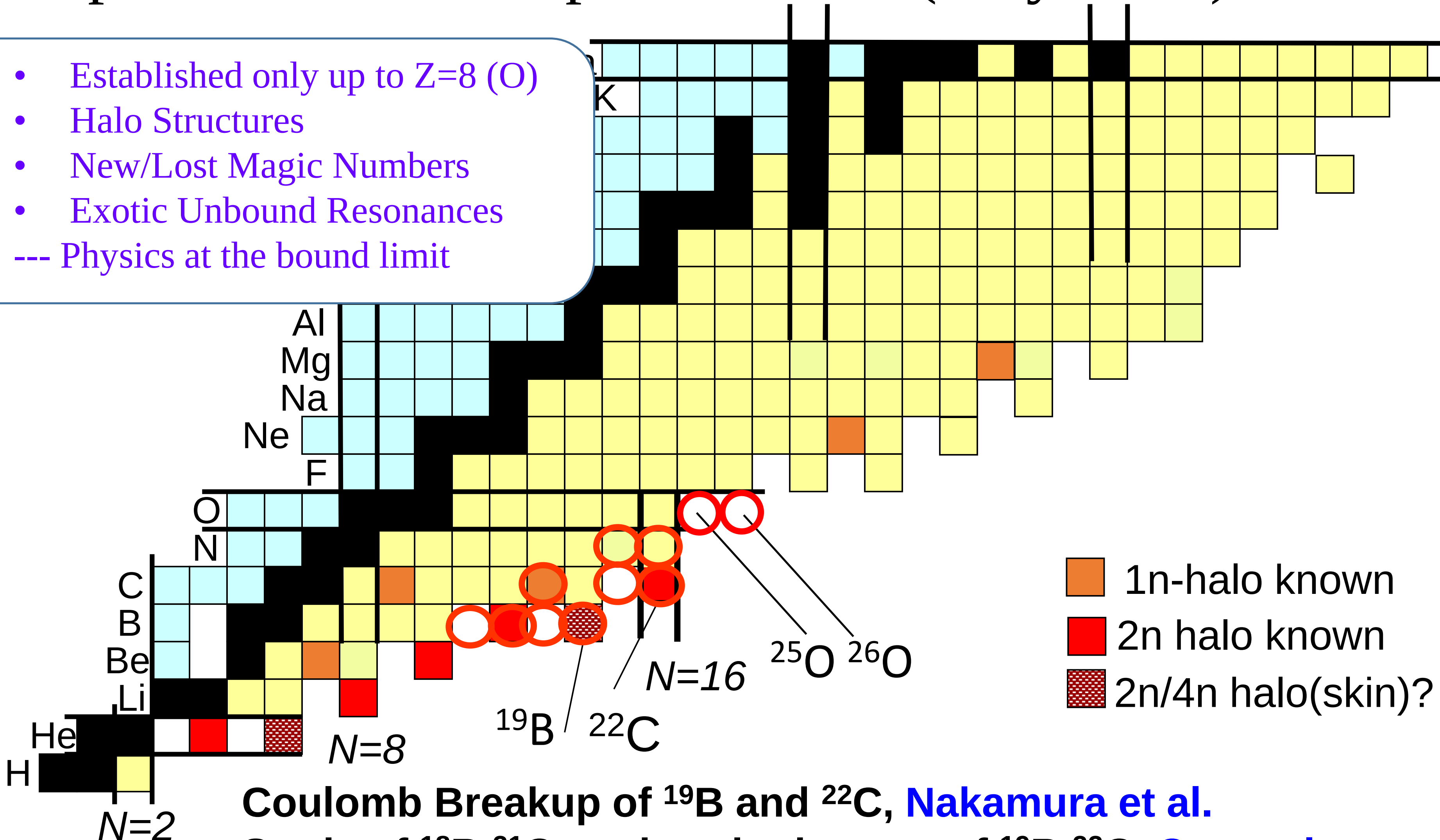


Commissioning Experiment March 2012

Day-One Campaign Experiments at SAMURAI: Explore Neutron Drip Line (May 2012)

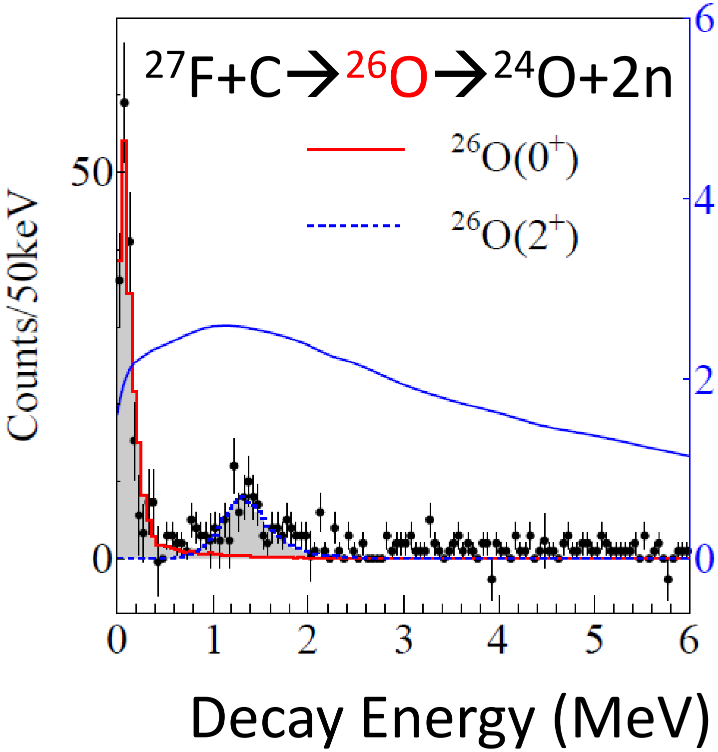
- Established only up to Z=8 (O)
- Halo Structures
- New/Lost Magic Numbers
- Exotic Unbound Resonances

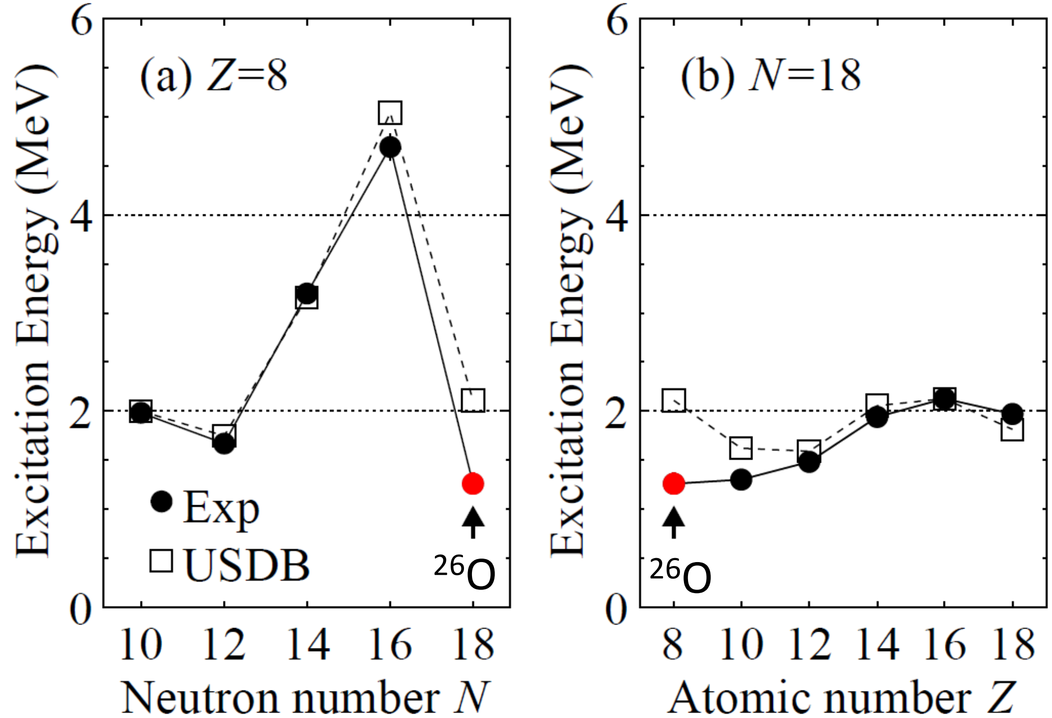
--- Physics at the bound limit



Coulomb Breakup of ^{19}B and ^{22}C, Nakamura et al.
Study of ^{18}B,^{21}C, and excited states of ^{19}B,^{22}C, Orr et al.
Structure of Unbound Oxygen Isotopes ^{25}O,^{26}O, Kondo et al.

^{26}O : barely unbound





Ground state

5 times higher statistics than previous study

E_{decay} = 18 ± 3(stat) ± 4(syst) keV

Finite value is determined for the first time

2^+ excited state

$E_{decay} = 1.28^{+0.11}_{-0.08}$ MeV

Observed for the first time

N=16 shell closure is confirmed

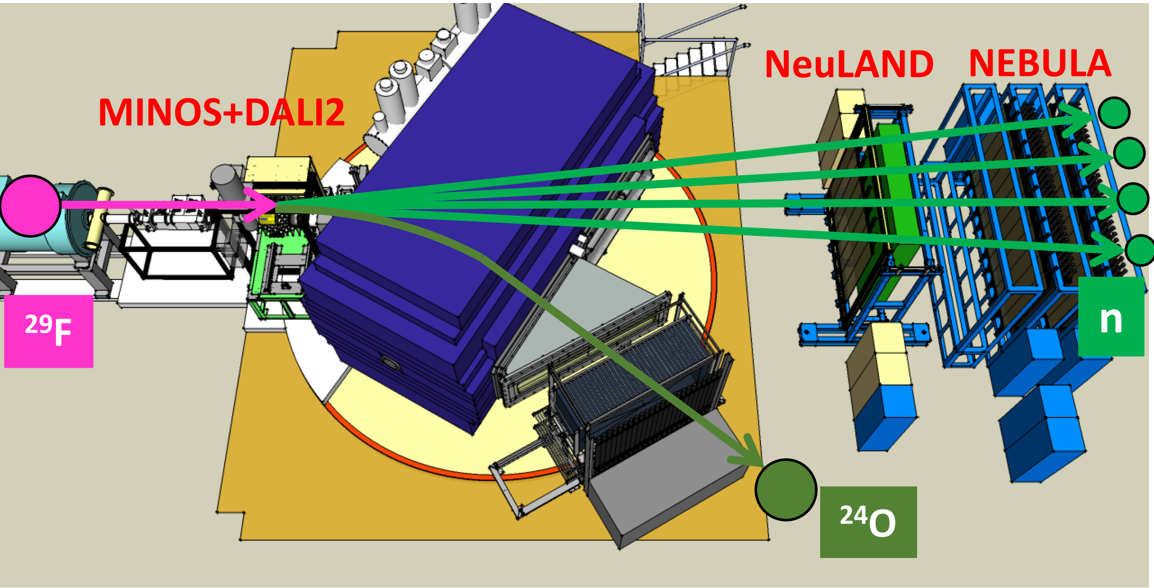
USDB cannot describe 2^+ energy at ^{26}O

→effect of pf shell? and/or continuum? Or other effects? (such as 3N forces, 2n correlation)

Y. Kondo et al., PRL 116, 102503 (2016)

Go much beyond the dripline: Extension to ^{28}O

(SAMURAI21 (Y. Kondo) in Nov-Dec 2015)



Successfully done with SAMURAI

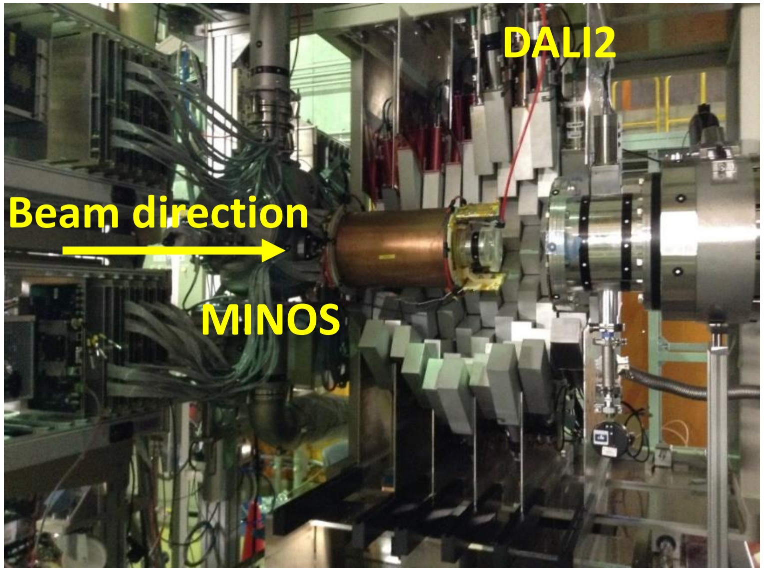
+MINOS

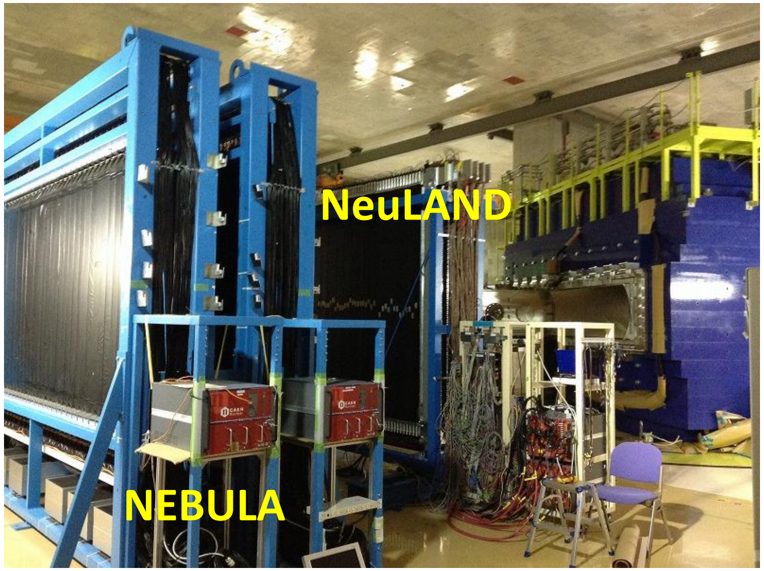
+NeuLAND

+DALI2

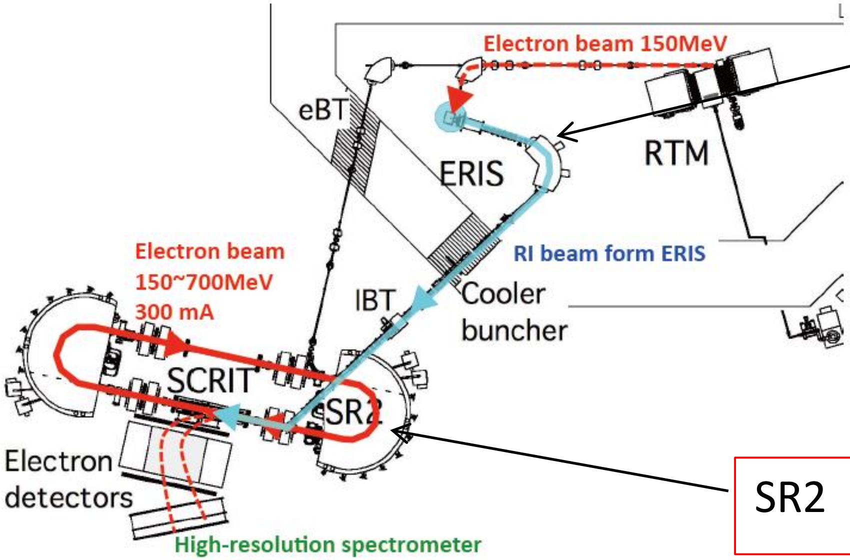
high intense beam (^{29}F: ~100 pps)

88 participants from 25 institutes





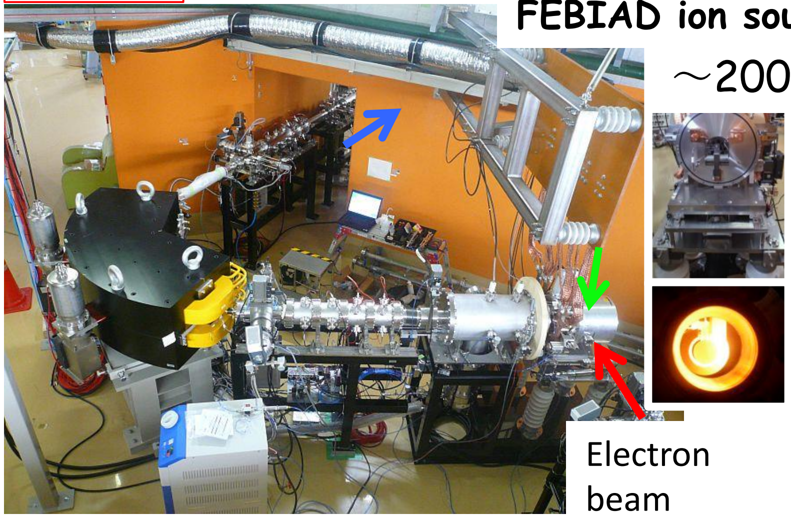
SCRIT Facility for e+RI scattering



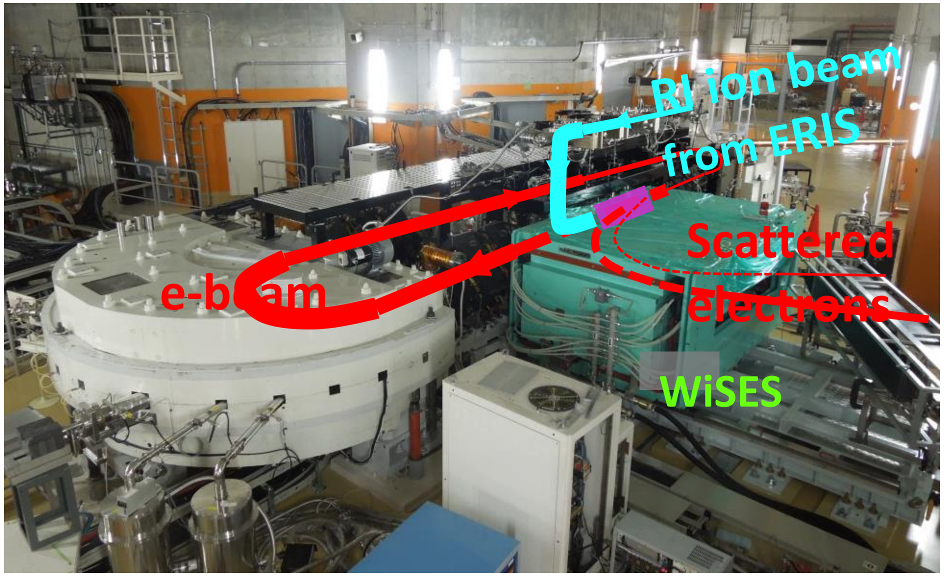
ERIS

SR2

UCx Target in
FEBIAD ion source
～2000℃



Electron
beam



SR2 (SCRIT-equipped RIKEN Storage Ring)

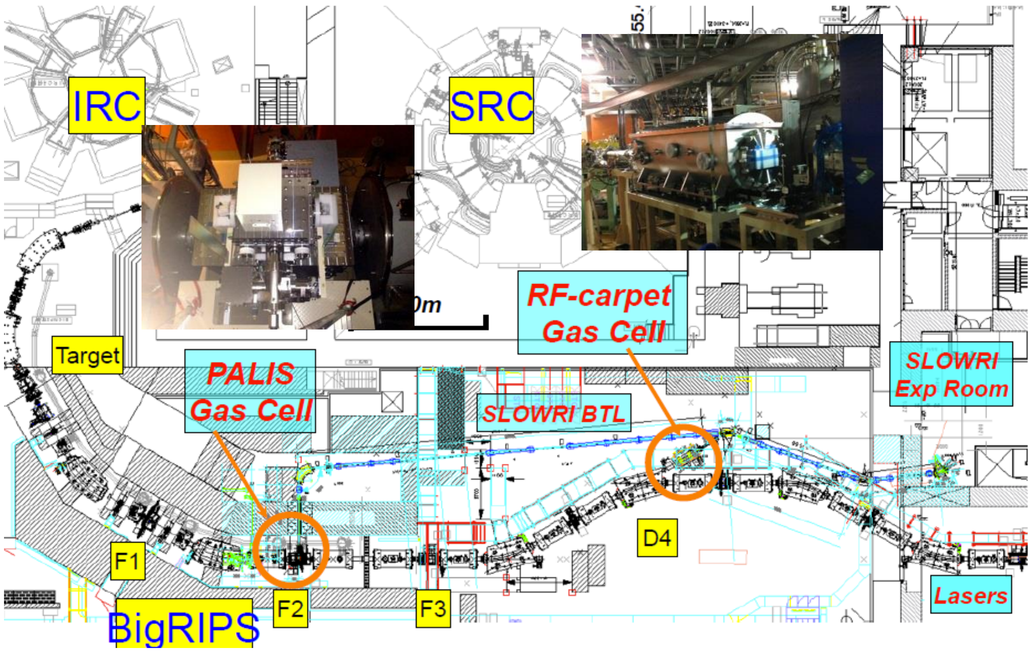
Energy	100 – 700 MeV
Stored current	300 mA (current operation)
Lifetime	~ 1 AH
Circumference	21.946 m
Tunes	1.62 / 1.58
β-max	10.36 / 4.09 m

Luminosity of $10^{27}/(cm^2 s)$ was achieved at the e-beam current of 250mA.

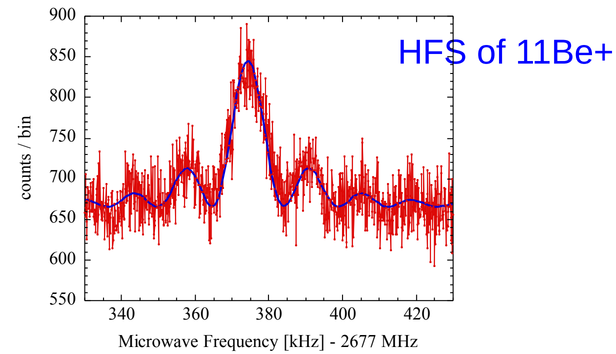
Efficiency improvement
More high power beam 10W->1kW
-> $10^{29}/cm^2/s$

SLOWRI Device for Trap Experiments

Wada, Sonoda et al.

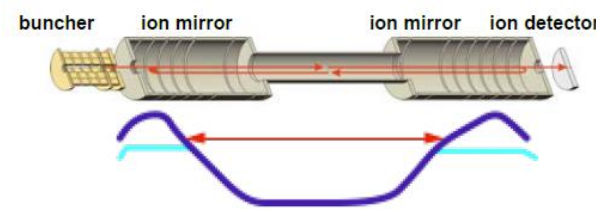


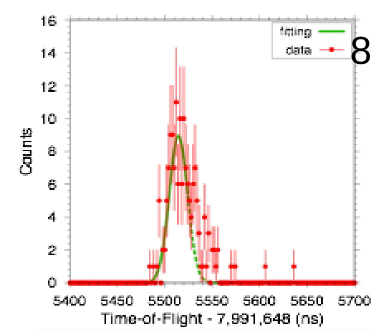
1)Optical spectroscopy



Takamine et al, PRL 112(2014)162502

2)Mass measurements of short-lived nuclei





^{8}Li ToF spectrum

ToF = 7,994,989.2(8) ns
R_m ~ 173,000

Ito, Schury et al, PRC 88(2013)011306R

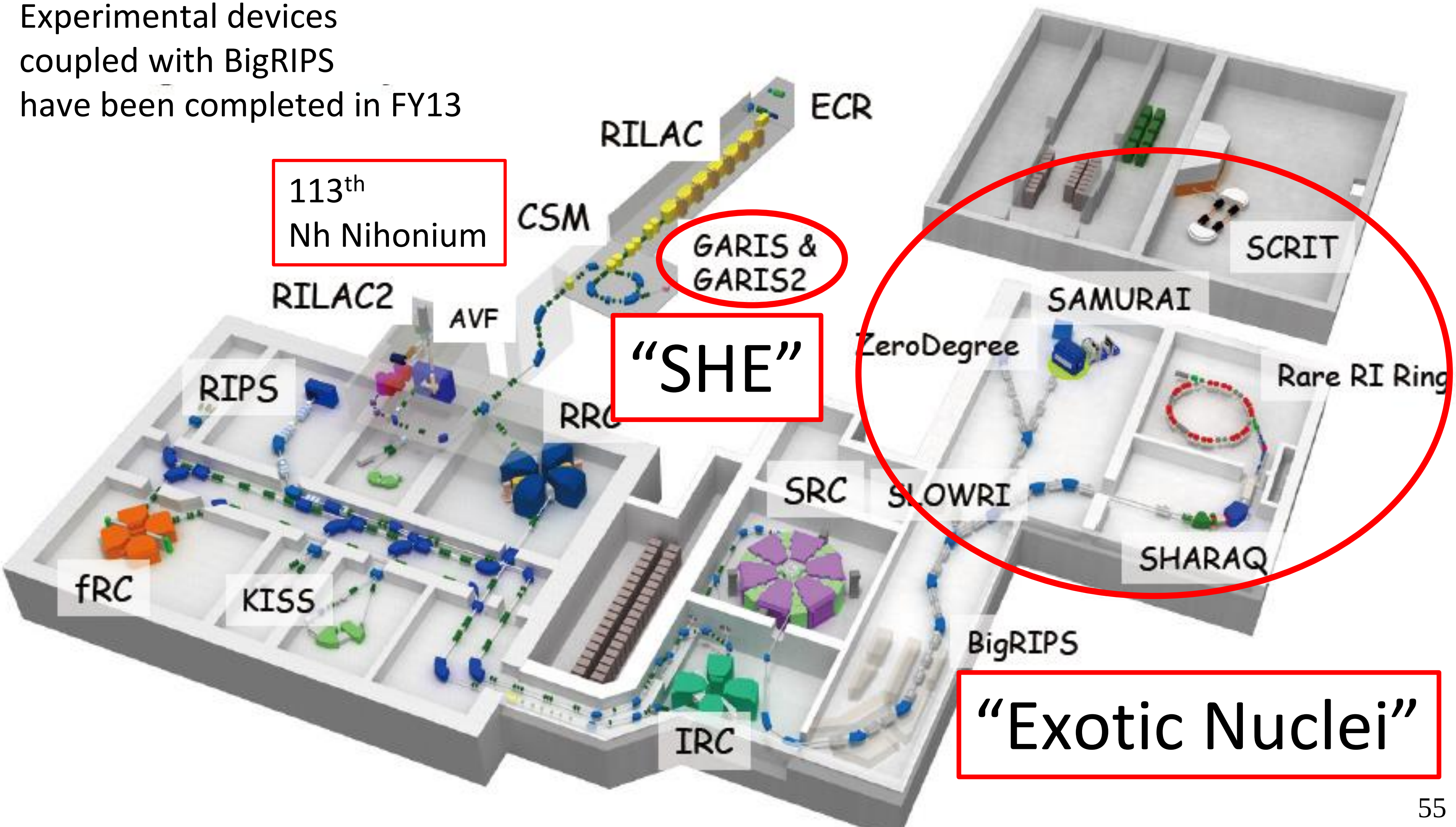
3)Resonance Ionization Spectroscopy

Parasitic RI beam production, spin, moments, radii..

RI Beam Factory

5 cyclotrons + 2 linacs
3 inflight separators
Experimental devices
coupled with BigRIPS
have been completed in FY13

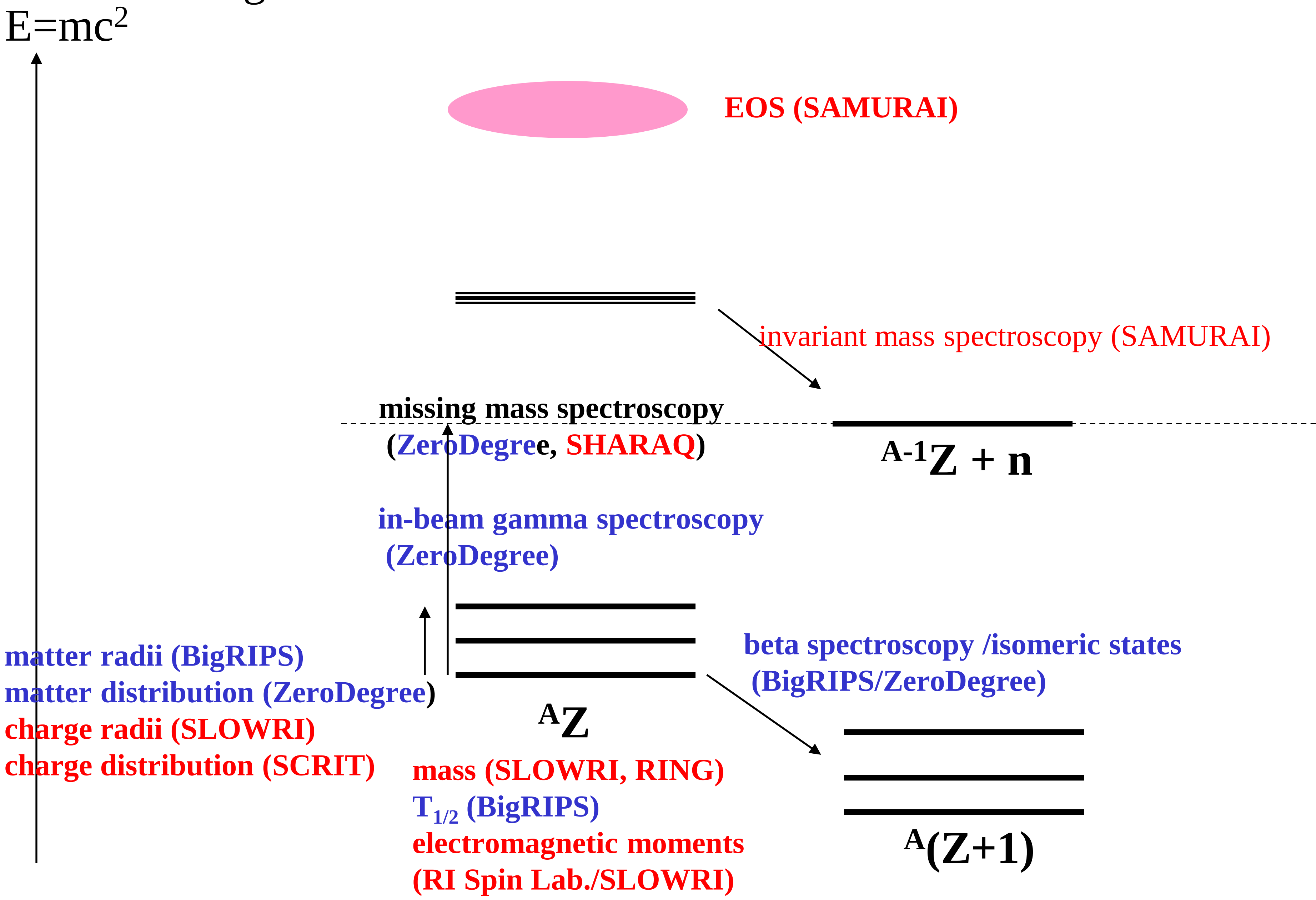
113th
Nh Nihonium



"SHE"

"Exotic Nuclei"

Program for nuclear structure and matter at RIBF

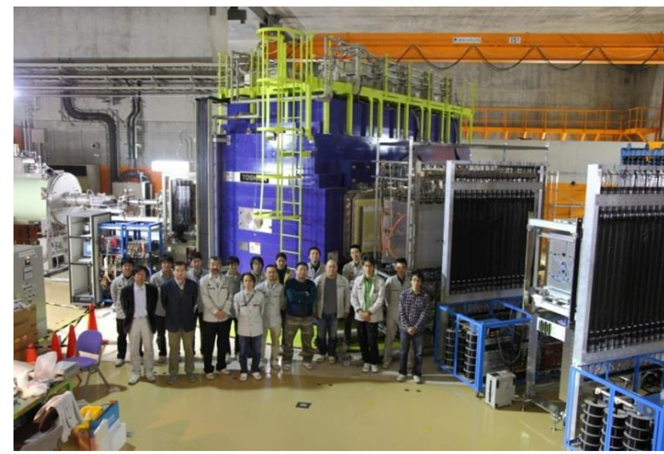


Experimental Devices (1) : spectrometer

ZeroDegree (2008-)

Beam line spectrometer
low-p (E) transfer reactions
$p/\Delta p \sim 2000$-4000
PID for ejectiles with A<200
In-beam gamma spectroscopy for bound excited states
missing mass with detectors for target recoiling

SAMURAI (2012-)



Versatile spectrometer with a super. dipole magnet
high-p (E) transfer reactions
$p/\Delta p \sim 700$ at $Z \sim 8$
Invariant mass spectroscopy for unbound states
Neutron corr. in halo, O-26, GDR, alpha-cluster,
EOS in HIC (2015-), 3NF…

SHARAQ (2009-)

high-resolution spectrometer
$p/\Delta p \sim 15000$
missing mass spectroscopy with RI beams
Exotic modes such as IVSMR, DGTR

Experimental Devices (2) : unique device

SCRIT (2012-)

e- + RI scattering for charge density distribution

U-238 photo-fission by 150-MeV e-beam (10W->1kW)

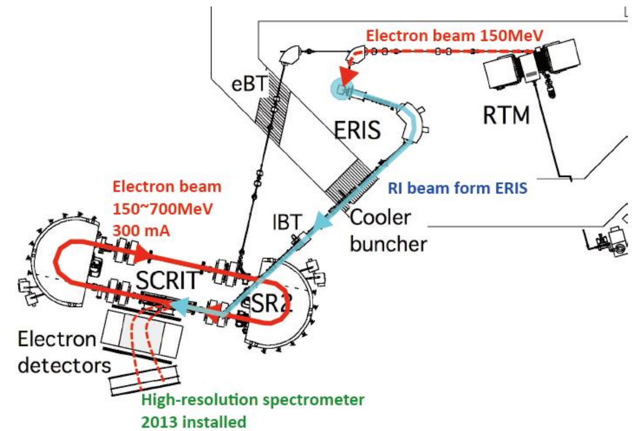
Electron beam 150-700 MeV 300mA

high-res. Spectrometer

Luminosity ~ 10^27 /cm2/s for stable isotopes

2015- data production

skin-thickness via p-elastic and e-elastic



Rare-RI Ring (2013-)

Isochronous mass measurement ~ O(1) ppm

C=60.3m, p/Δp = +/- 0.5%

Trans. Emittance 20pi/10pi mm mrad

2013- Commissioning

2016- data production

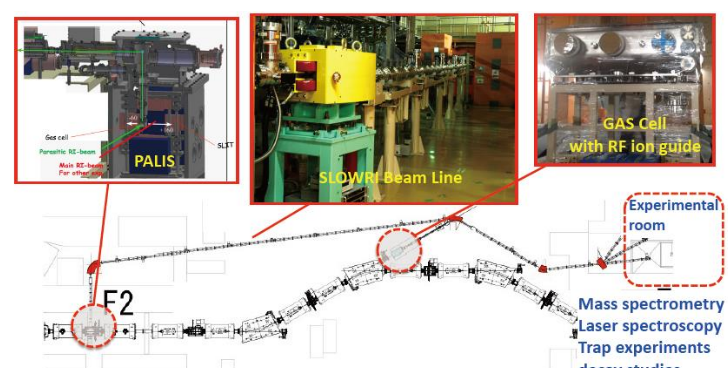
SLOWRI (2014-)

Gas-catcher system to slow down RI beams

mass, laser spec., decay studies

2014 commissioning

2015 day-one exp.



Transmutation for LLFP : Motivation

Nuclear transmutation facility dedicated for nuclear waste of FP?

FP is dominant in nuclear waste

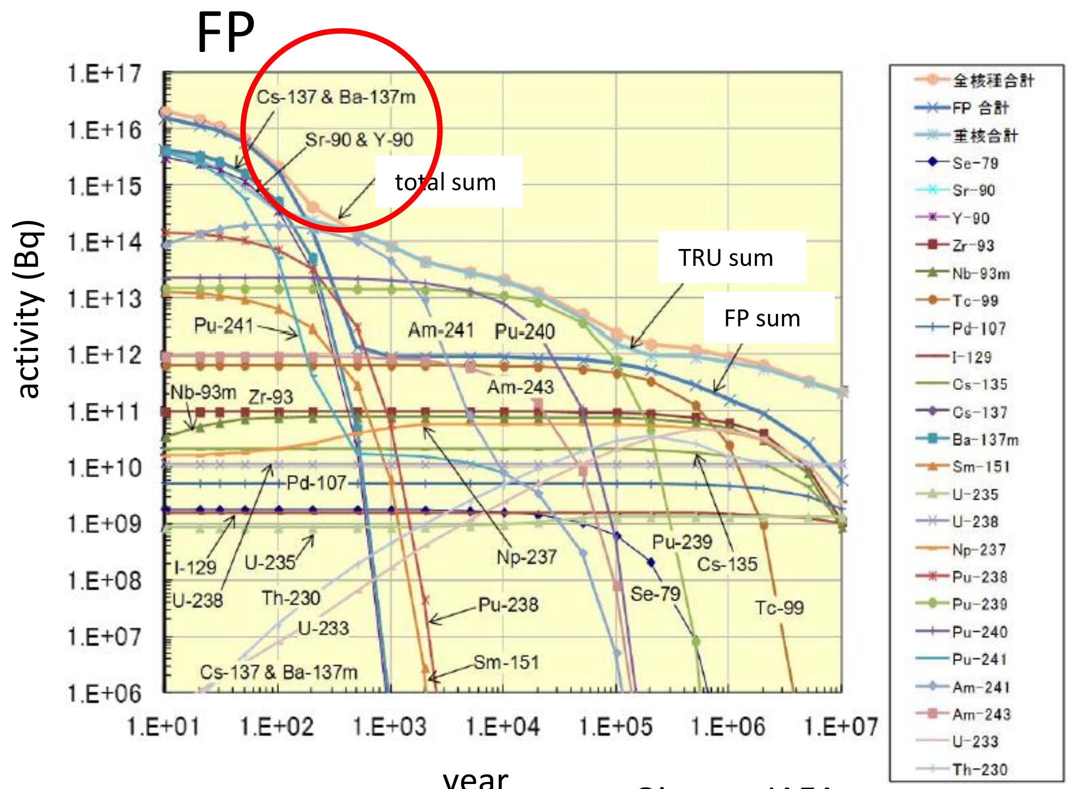
Partitioning technique + deep geological disposal are being considered…

MA -> ADS

FP -> ??

Possible FP transmutation? to minimize FP activities neutron induced transmutation with an accelerator system or others?

-> almost no reaction data…



Oigawa, JAEA

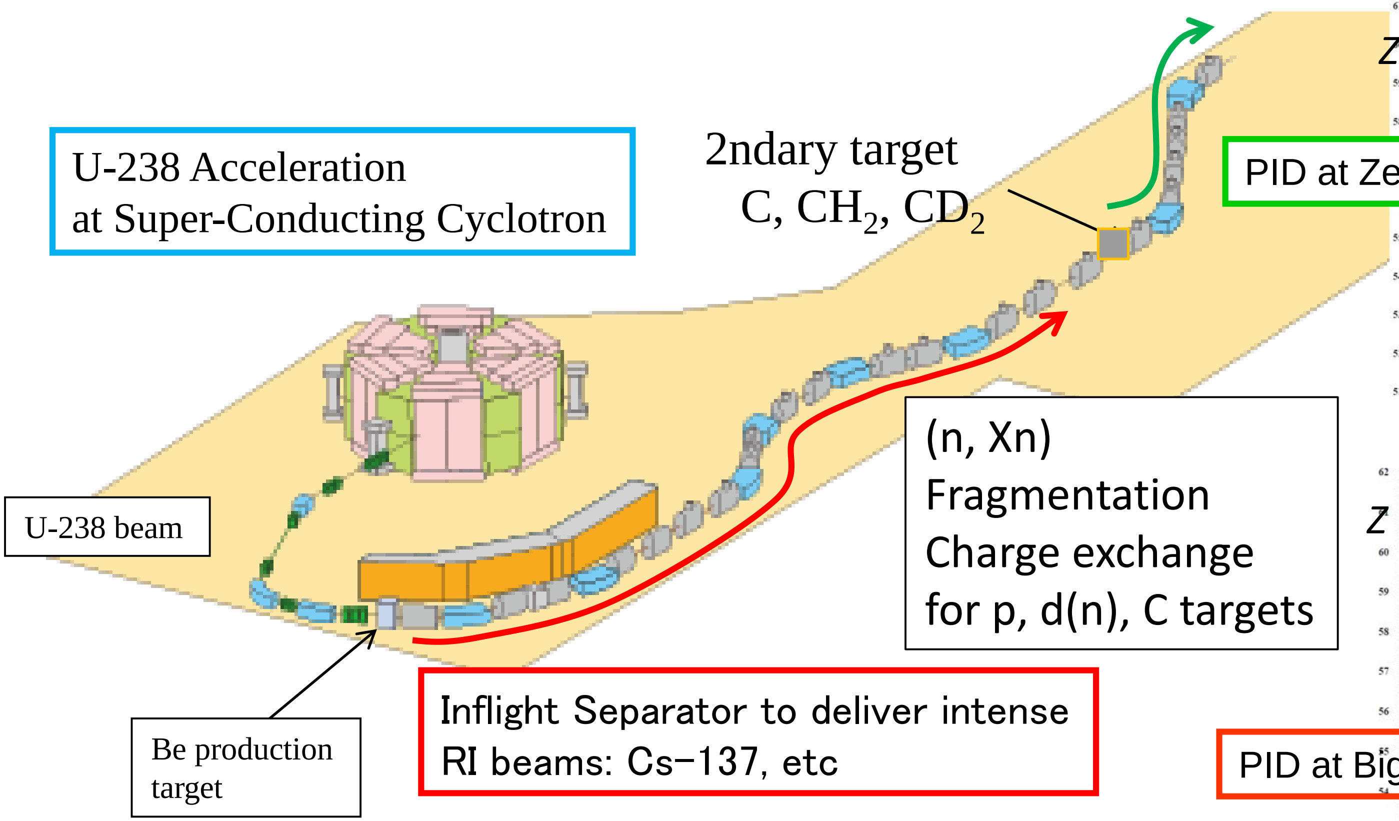
Transmutation for LLFP : The First Challenge

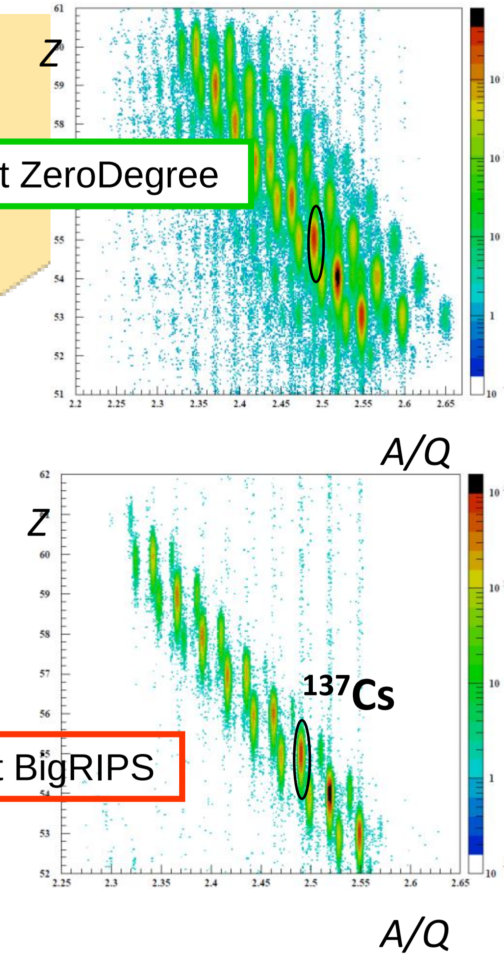
April, 2014

Beam species	Beam energy [MeV/u]	Intensity [/s/10pnA]	Purity [%]
137Cs	186	1200	14
90Sr	187	7100	28

ZeroDegree Spectrometer

PID for reaction products to determine reaction channels.





RIKEN, UT, Miyazaki, Kyushu …