不安定核ビームを利用した核構造研究

東京大学・理学系研究科/
理化学研究所・仁科加速器研究センター

櫻井博儀

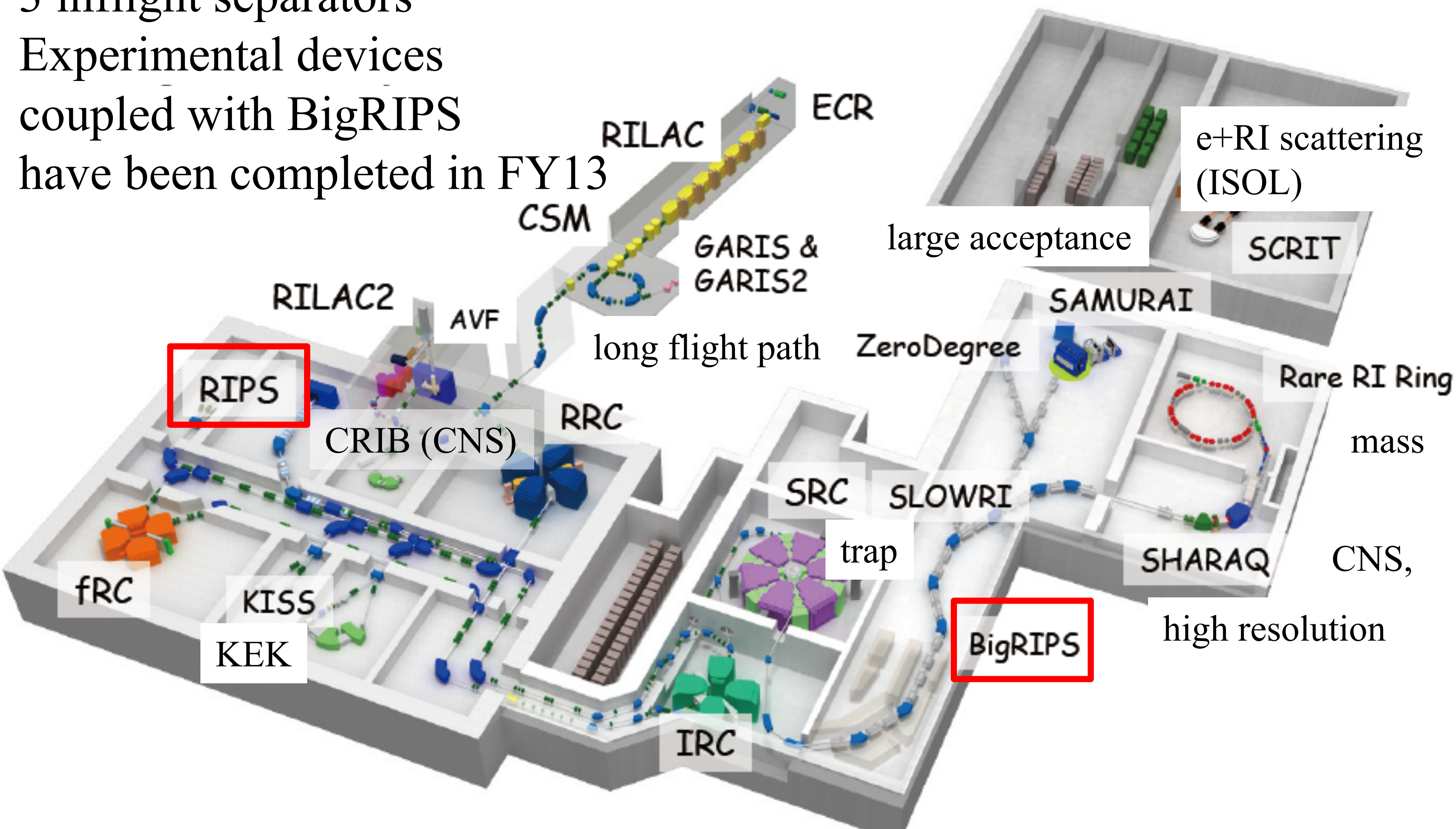
Exotic nuclei explored at in-flight separators

T. Nakamura, H. Sakurai, H. Watanabe
Prog. Part. and Nucl. Phys.

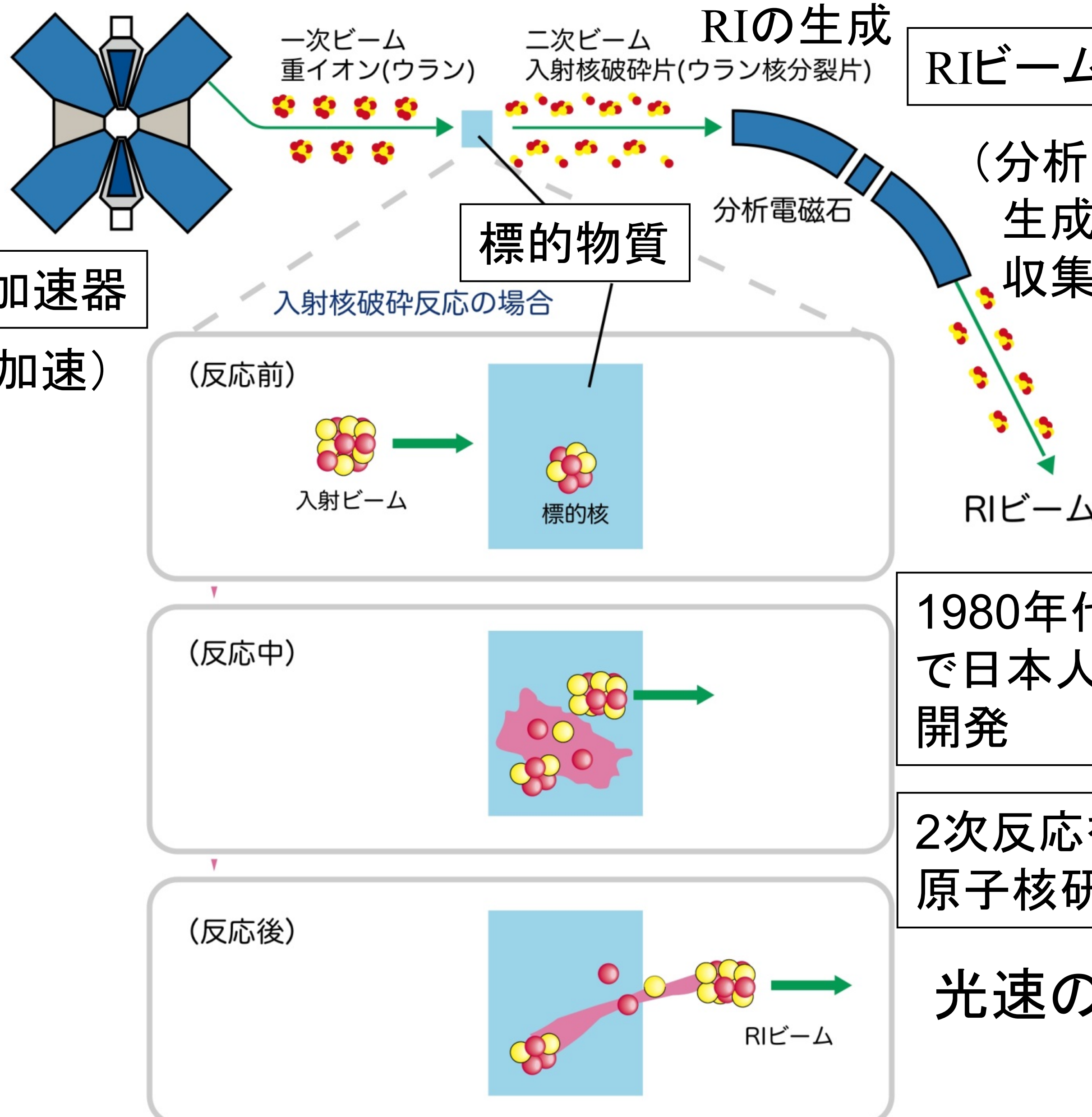
https://doi.org/10.1016/j.ppnp.2017.05.001

RI Beam Factory

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



RIビームの生成法



重イオン加速器

（原子核を加速）

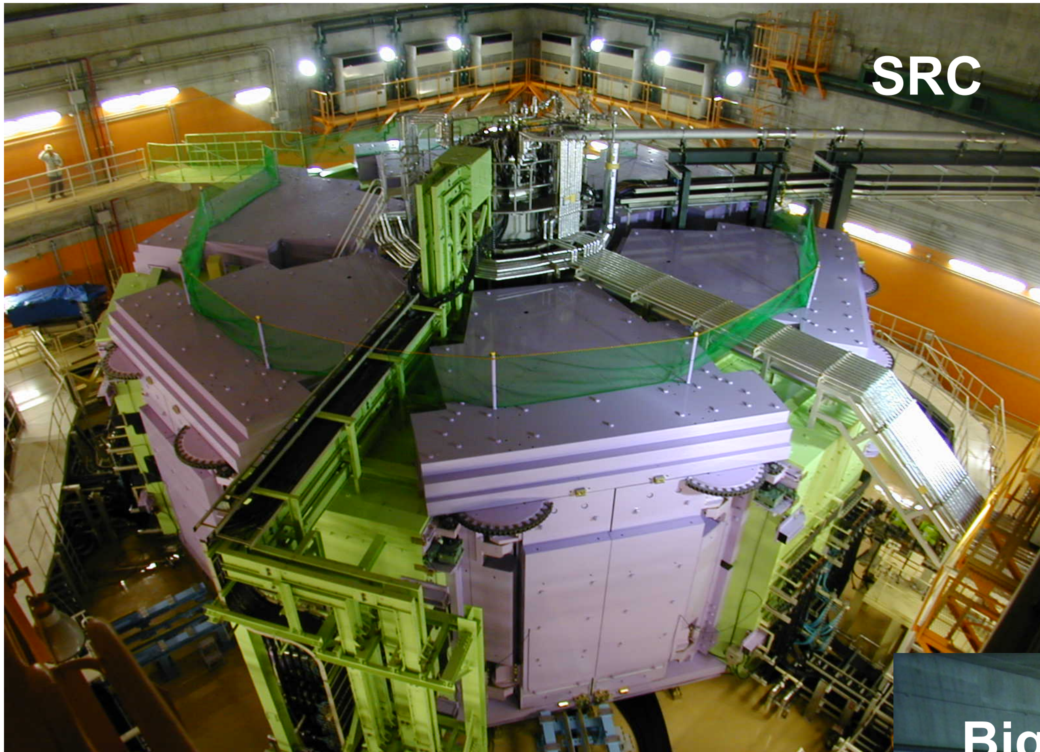
RIビーム収集分離装置

（分析電磁石で構成
生成されたRIを
収集・分離）

1980年代LBNL（米国）
で日本人研究者が
開発

2次反応を利用した
原子核研究

光速の約60%

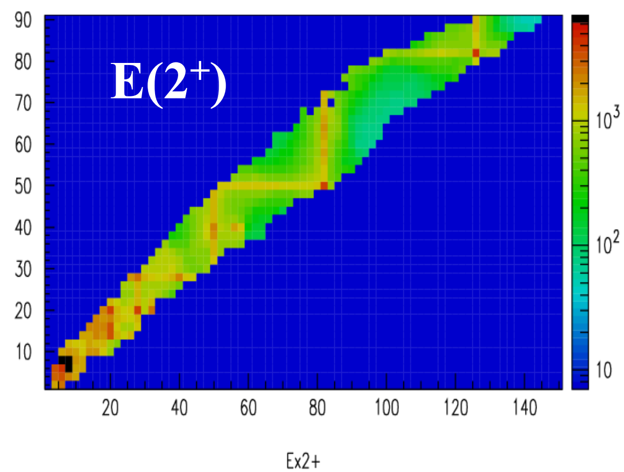


世界初、史上最強
K2600MeV (8,300tons)
超伝導リングサイクロトロン
(SRC)
水素からウランまでの元素を
光速の70%まで加速
ウランを目標エネルギーまで
加速に成功　2006年12月

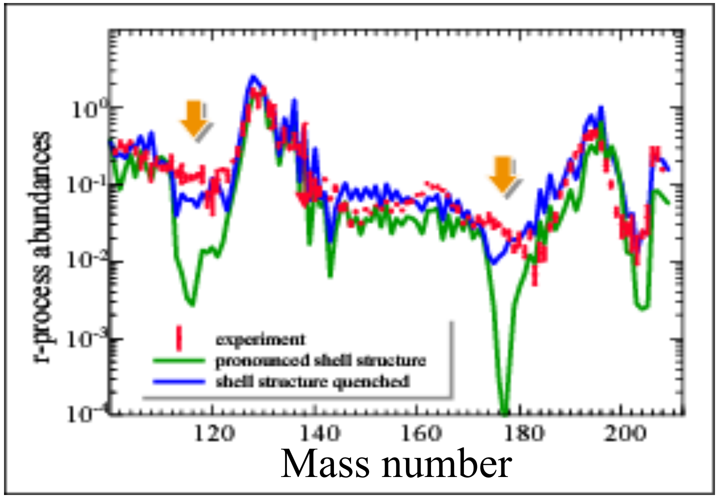
世界最大口径
9 Tm (77 m)
超伝導RIビーム収集分離装置
(BigRIPS)
核分裂片の約50%を収集
世界最高のRIビーム分解能
を達成　2007年5月

Physics with Exotic Nuclei

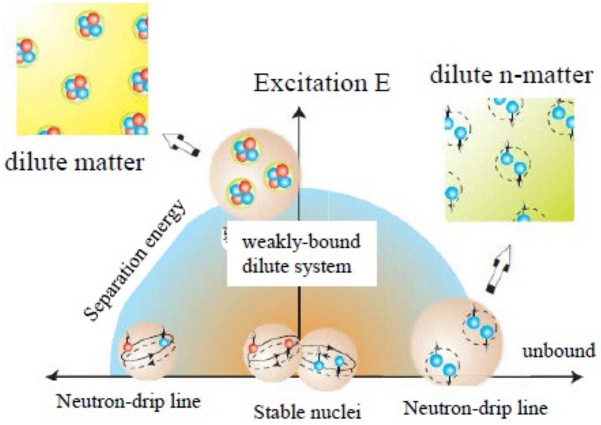
Shell Evolution :
magicity loss and new magicity



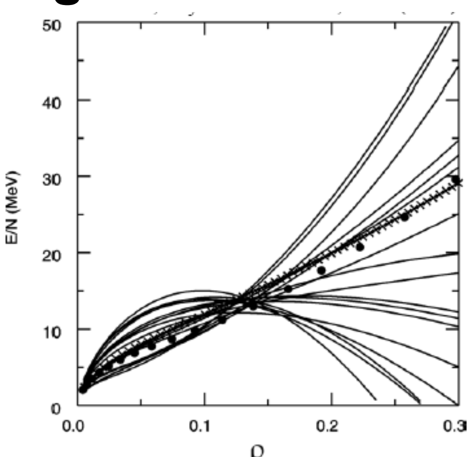
R-process path: Synthesis up to U

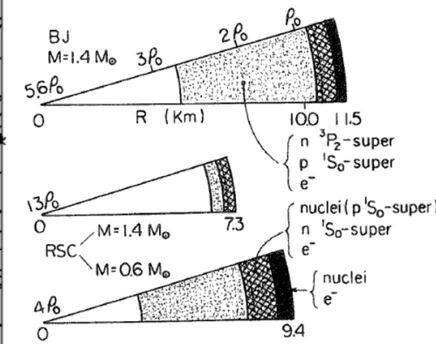


Neutron Correlation in the vicinity of the Drip-line



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

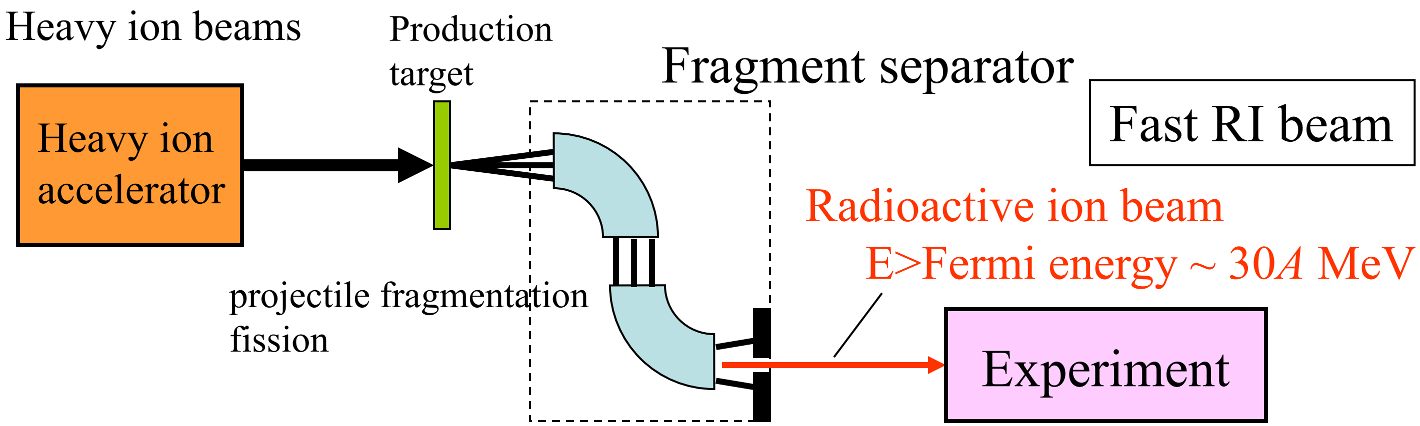




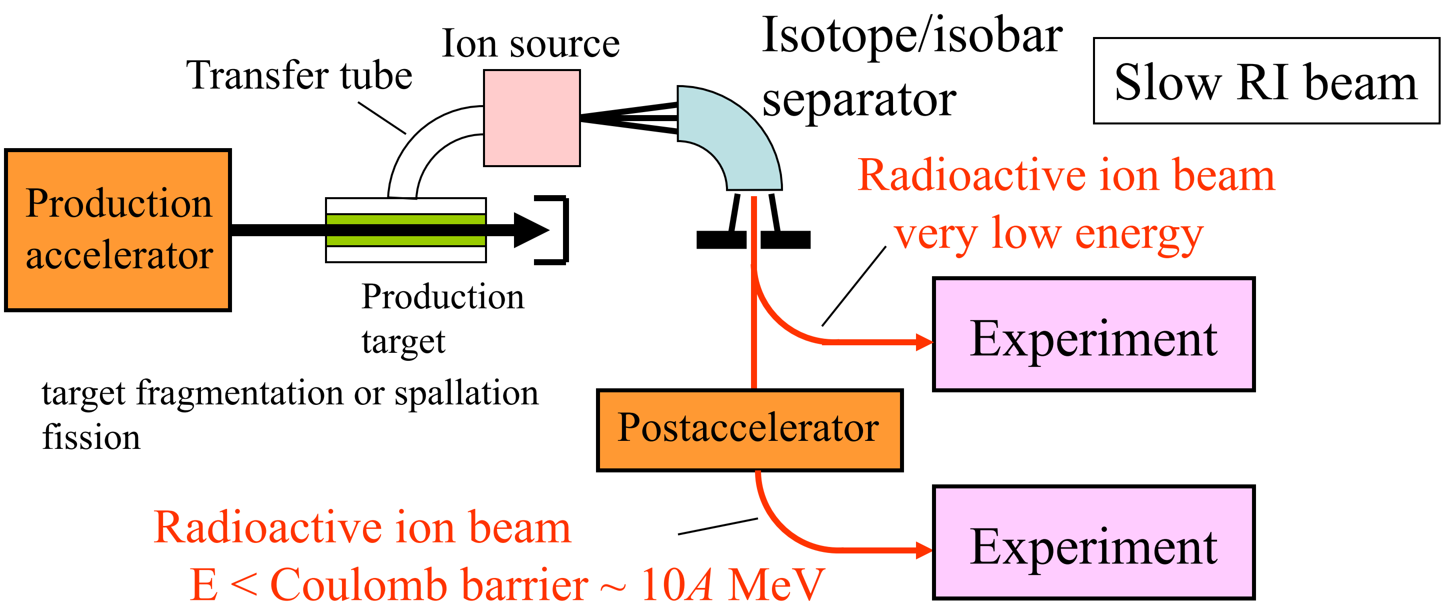
1. In-flight facility
2. Shell evolution
3. r-process path
4. EOS
5. Facility upgrade

In-flight and ISOL methods to produce radioactive ions

In-Flight Method

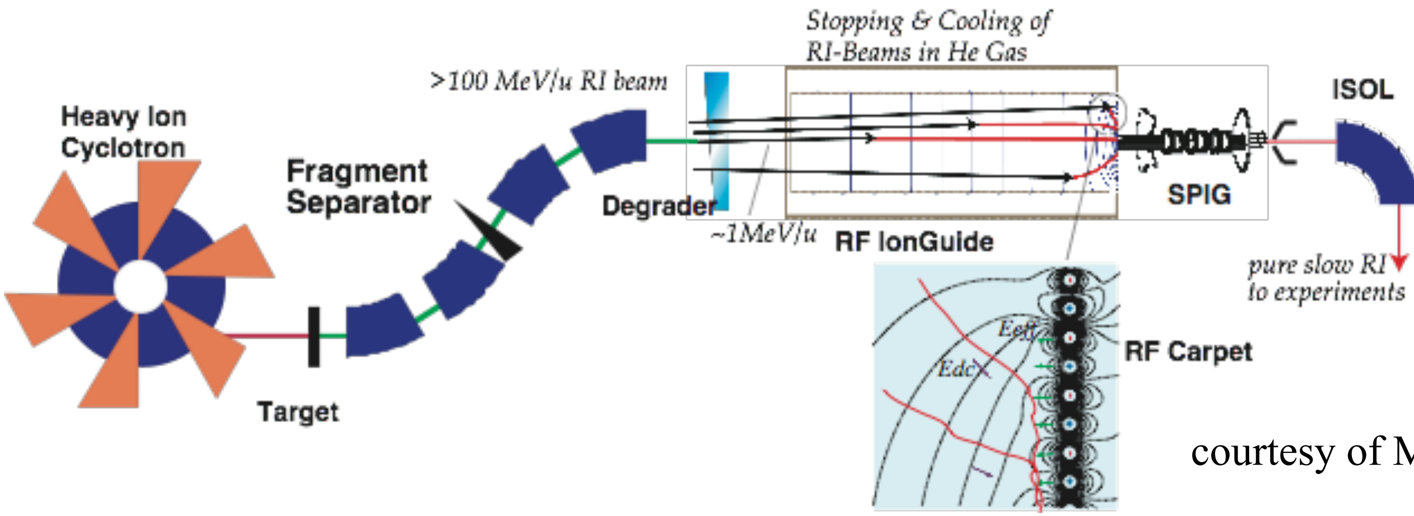


ISOL Method



New experimental techniques to have very slow RI beams

RIKEN, NSCL/MSU, ANL



courtesy of M.Wada

In-flight Method | Gas-catcher system | ISOL

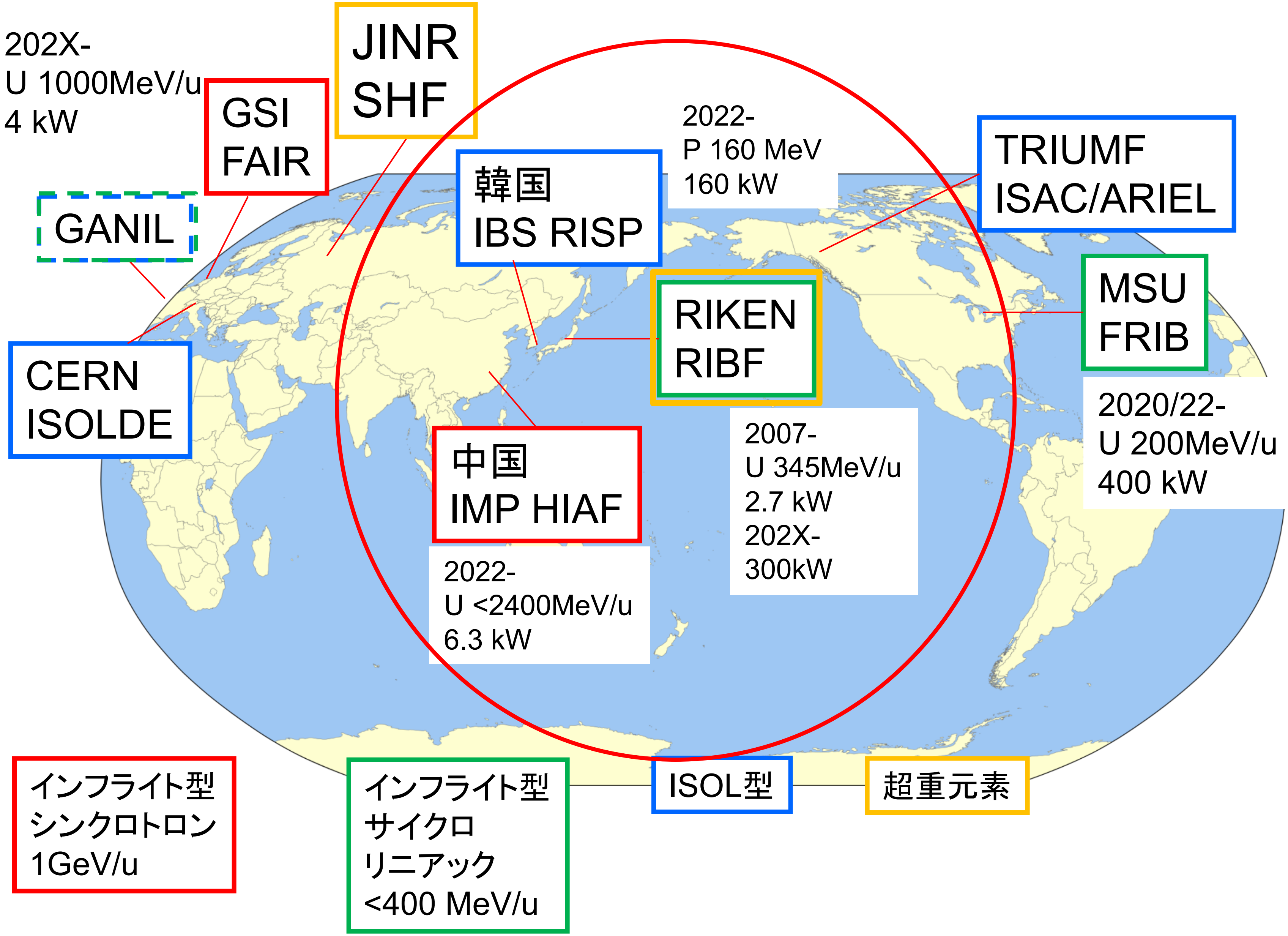
High energy, large variety of species,
Poor optical qualities

→

large variety of species,
good optical qualities,
nice purity

Wada

世界の主要研究所と動向　三極化とアジアの時代



History of In-flight Method

<u>0^{th} Generation (70's-80's) LBNL</u>

"Discovery" of Projectile Fragmentation

<u>1^{st} Generation (80's) GANIL/LISE</u> LISE was originally designed for atomic-physics

Establishment of Separation Technique Bρ-ΔE-Bρ Method

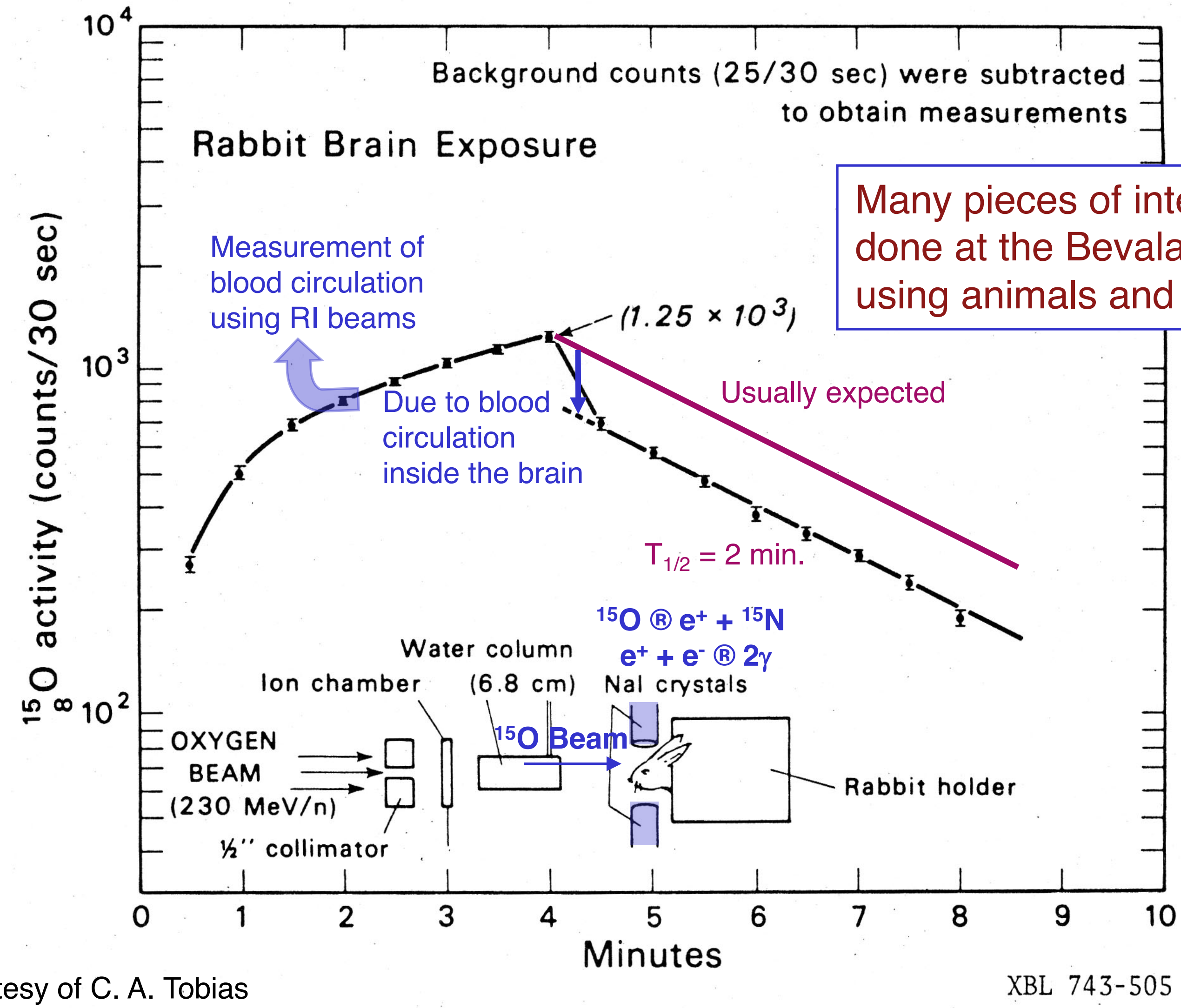
<u>2^{nd} Generation (90's) GSI/FRS, NSCL/A1200-1900, GANIL/SISSI, RIKEN/RIPS</u>

Large-Collection Technique	
Max. Bρ and Large Acceptances	RIKEN/RIPS
Emittance-transformation	GANIL/SISSI
Further Purification Methods	
ExB filter	GANIL/LISE
rf-deflector	RIKEN/RIPS
In-flight Fission for neutron-rich nuclei	GSI/FRS
Combination of separator	
+High-Res. Spectrometer	GANIL/SPEG, NSCL/S800,
+ storage ring	GSI/ESR

<u>3^{rd} Generation (00's-20's) RIKEN/RIBF, GSI/FAIR, MSU/FRIB</u>

High-Power Heavy-Ion Beams up to U

The First RI Beam Experiment (1974)

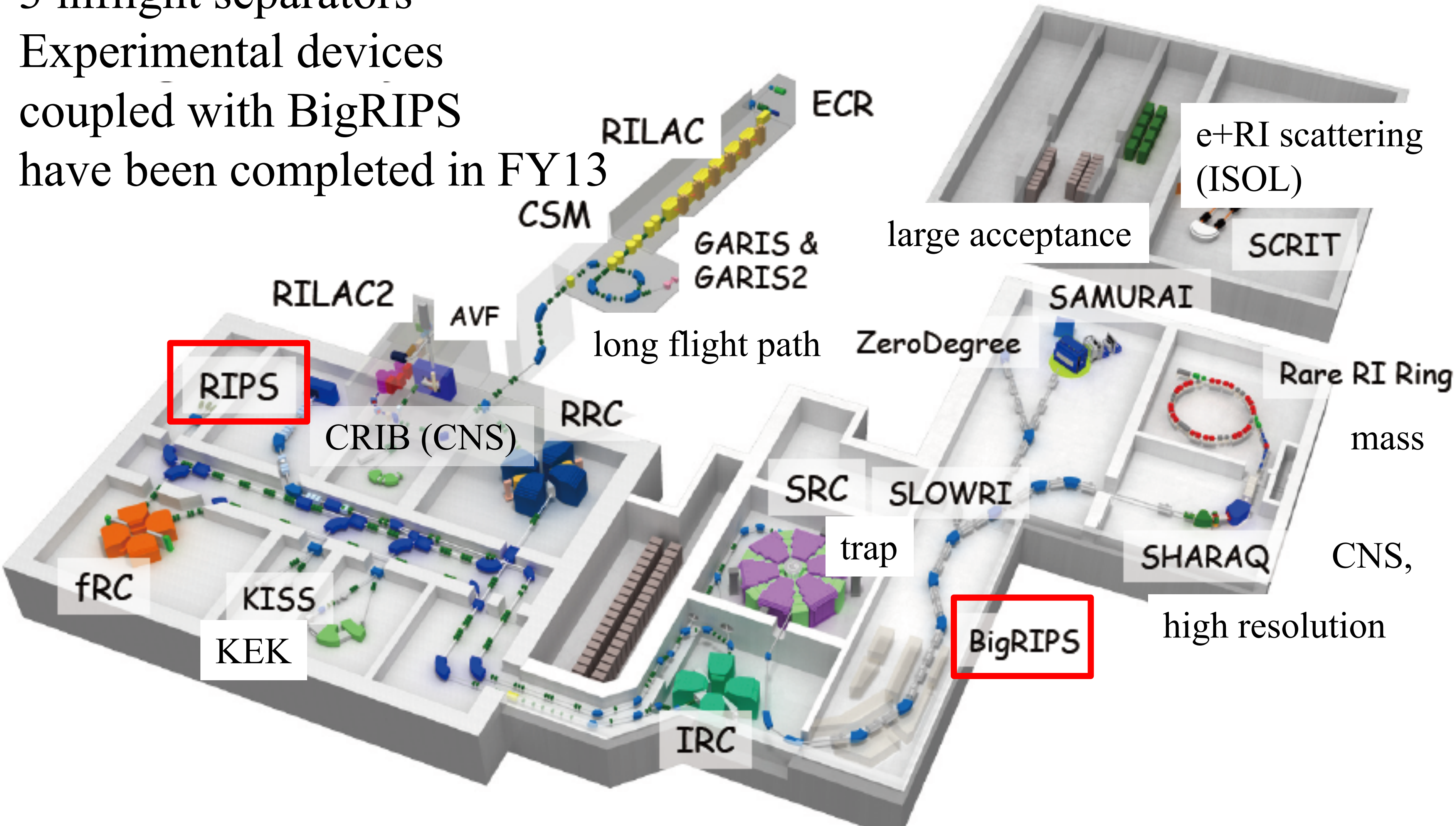


Many pieces of interesting work done at the Bevalac in biology using animals and plants

Courtesy of C. A. Tobias

RI Beam Factory

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

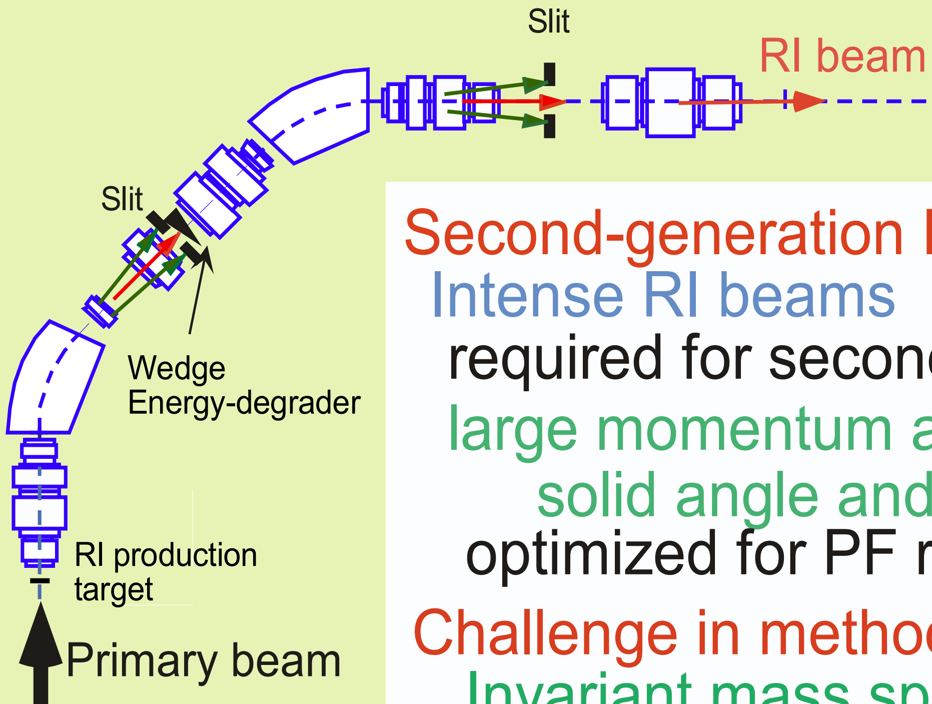


Progress of Research Opportunities with RI Beams

Construction of a dedicated facility for RI beam production via the projectile fragmentation

RIPS (RIKEN Projectile-fragment Separator)

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



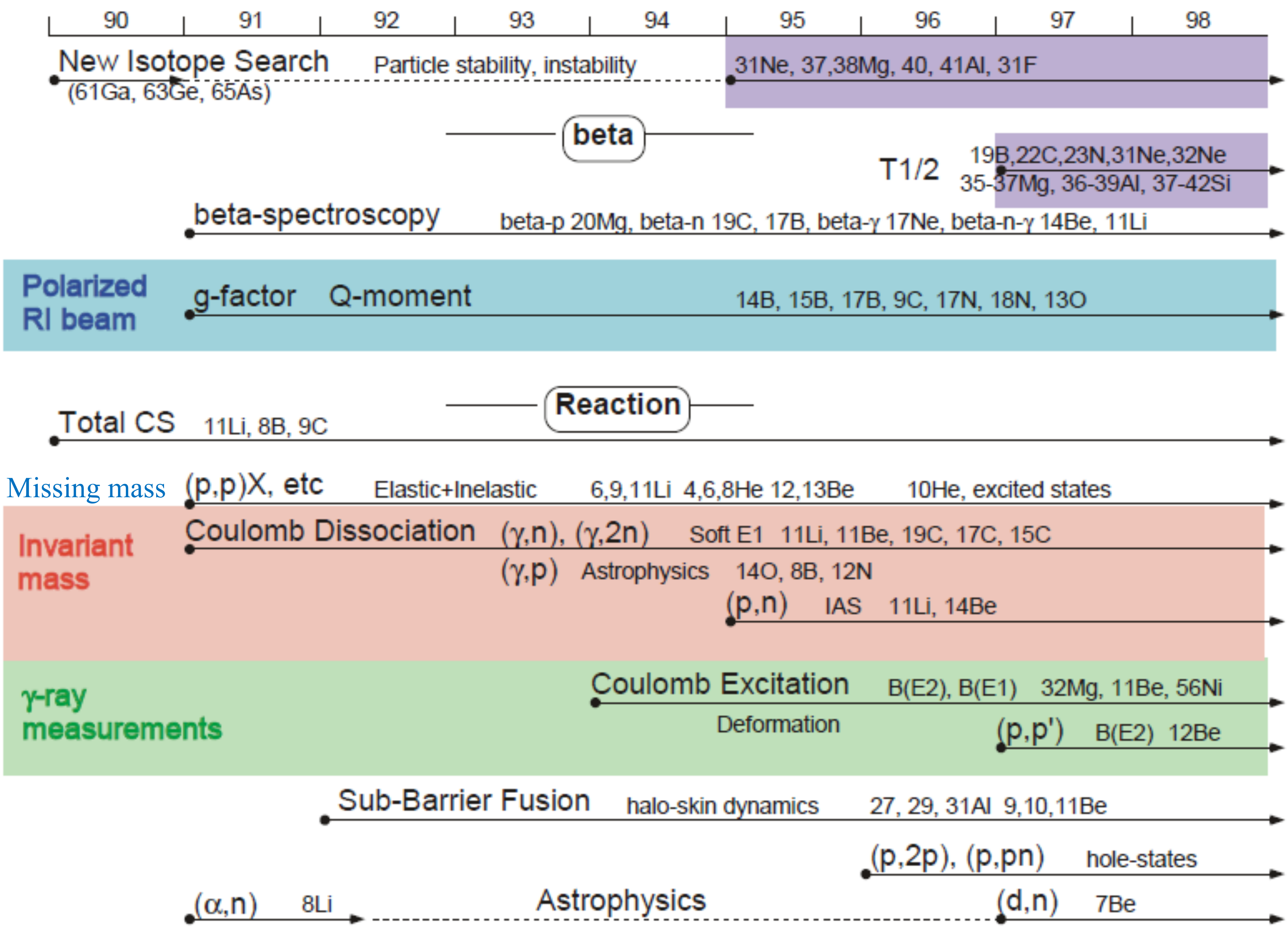
Second-generation PF separator

Intense RI beams
required for secondary nuclear reactions
large momentum acceptance,
solid angle and high magnetic rigidity
optimized for PF reaction

Challenge in methodology

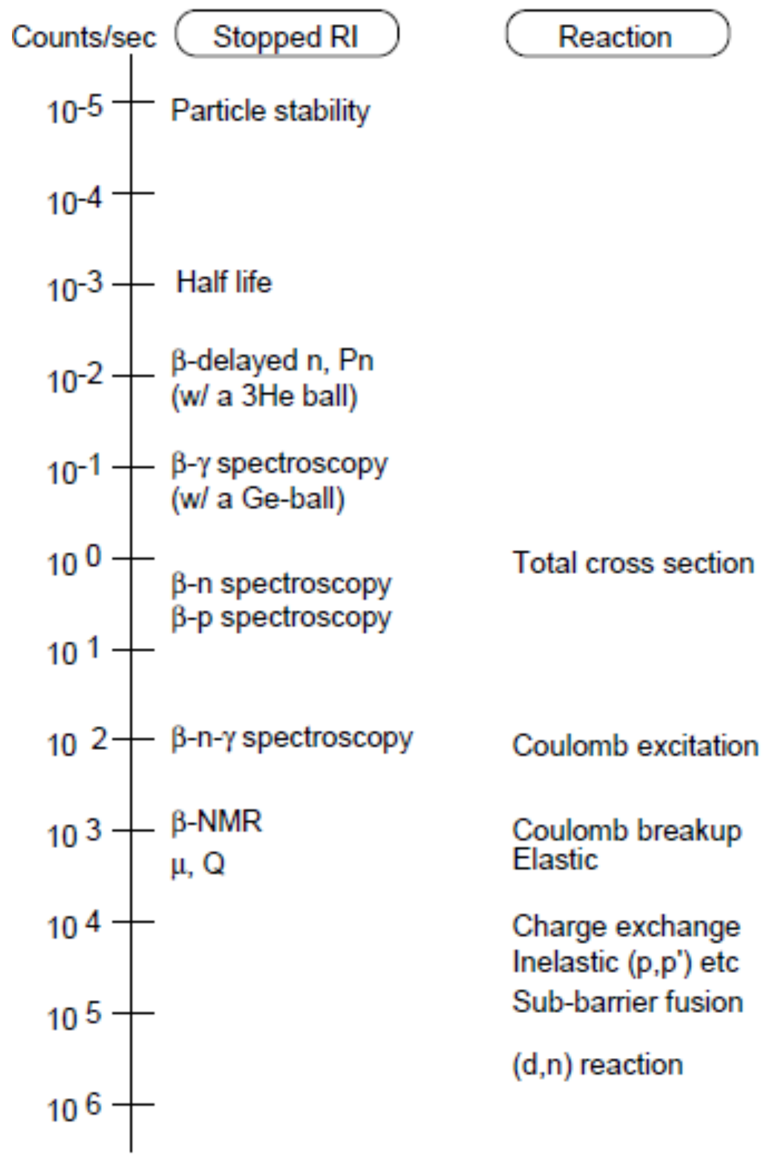
Invariant mass spectroscopy
for particle unbound states
Intermediate energy Coulomb excitation
for B(E2)
etc...

Nuclear Physics Programs at RIPS '90-'98



Int. Summer School, Beijing
25-29th July, 1999

To overcome Intensity, Purity and Emittance of in-flight beams



Experimental Points

1. RI beam intensity → "Subjects" limited due to the intensity
   strong isospin-dependence

2. RI beam purity → Particle identifcation for beam species
   Fraction of RI of interest is NOT 100%!
   TOF, dE, Bρ, (E)
   dE, E, (TOF) → Z, A, (Q)

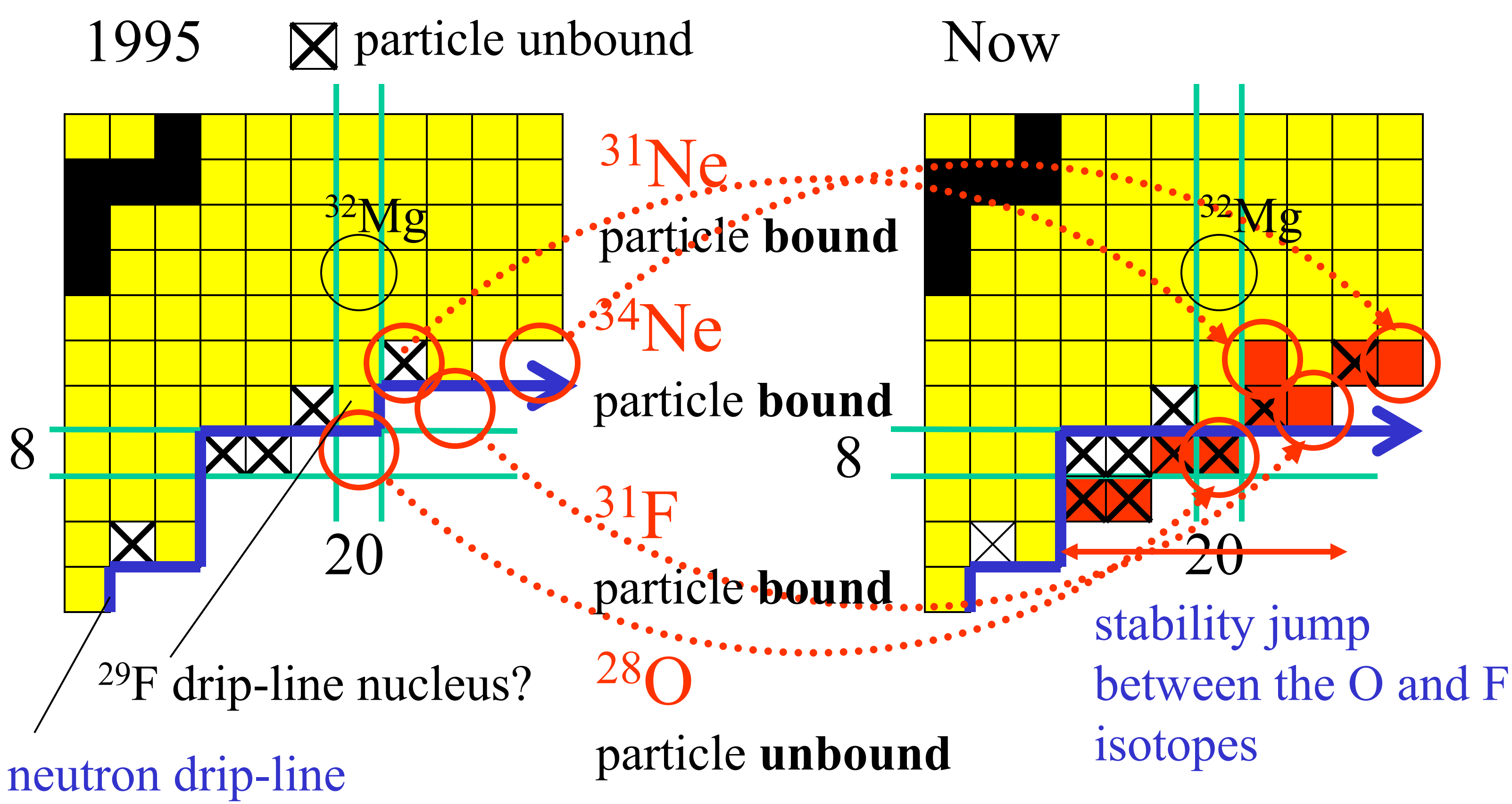
3. Large emittance and energy spread → To be measured if necessary
   $\varepsilon \sim$ a few 10 π mm.mrad
   $\Delta E/E \sim o(10)\%$
   Tracking, TOF or Bρ

2, 3-> Detectors
time response
pileup (cyclotron beams) → Maximum beam intensity

Int. Summer School, Beijing
25-29th July, 1999

Stability Enhancement in the neutron-rich F and Ne isotopes

Search for new neutron-rich nuclei at RIKEN-RIPS from 1996 to 2002

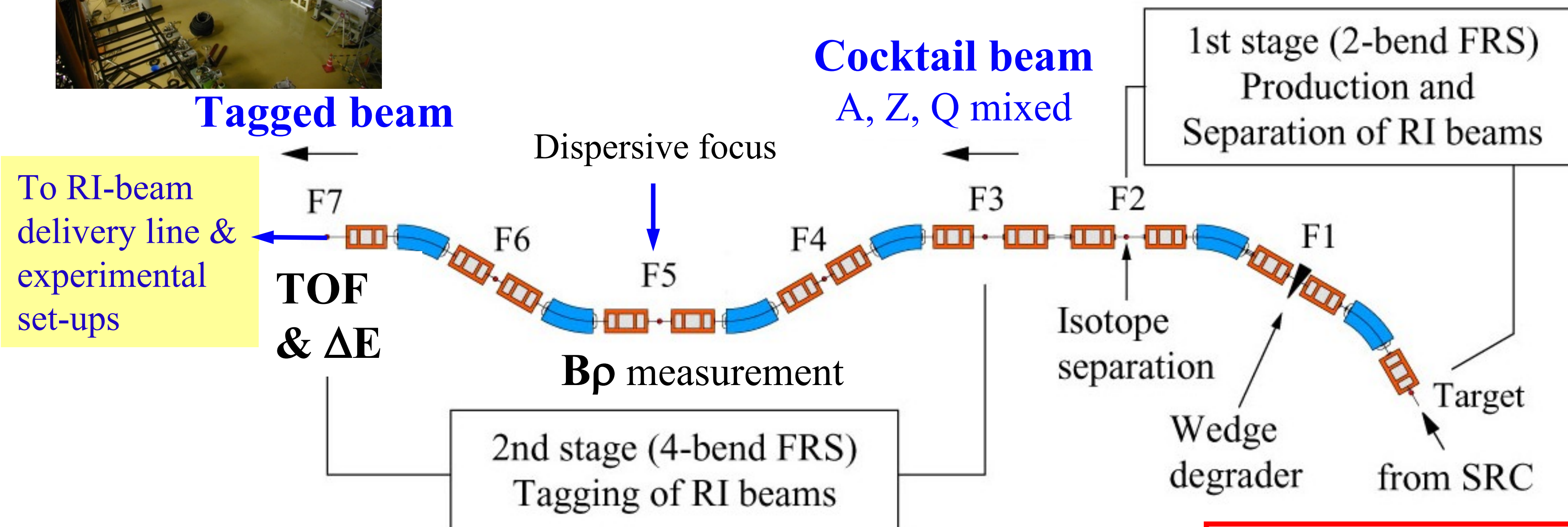


^{31}Ne, ^{37}Mg	H.Sakurai et al., Phys. Rev. C 54, R2802 (1996)
^{31}F, ^{28}O, ...	H.Sakurai et al., Phys. Lett. B 448, 180 (1999)
^{34}Ne, ^{37}Na, ^{43}Si, ...	M.Notani et al., Phys. Lett. B 542, 49 (2002)

Delivery of tagged RI-beam

Based on two-stage separator scheme

T. Kubo et al.



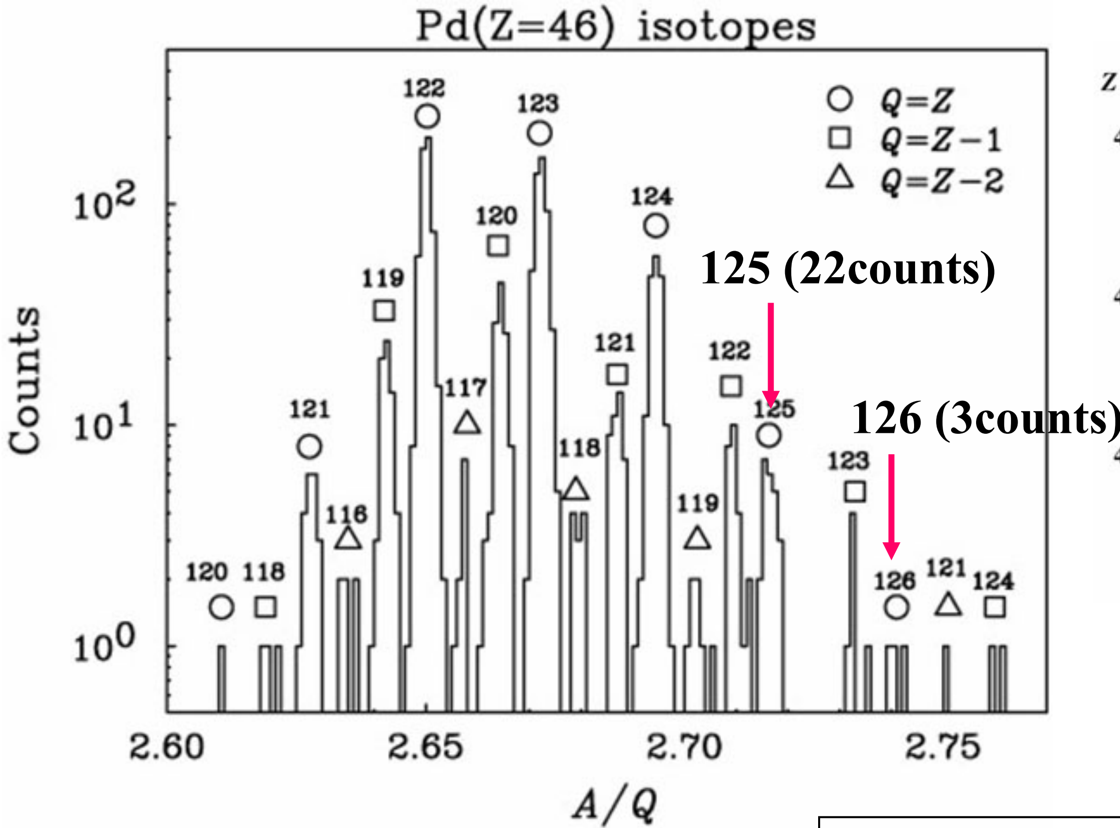
In-flight fission of ^{238}U at 350 MeV/u
$\Delta\theta \sim$ 100 mr
$\Delta p/p \sim$ 10 %

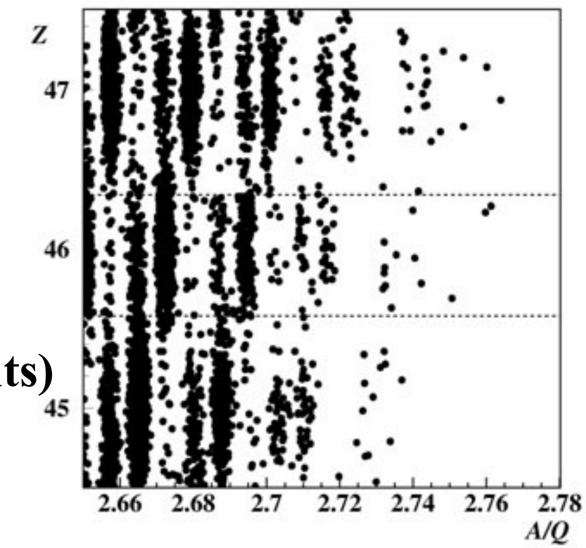
Identify RI-beam species Z, A/Q by measuring ΔE, Bρ, TOF in an event-by-event mode using beam-line detectors on the 2nd stage. Aim at tagging rate up to 1 x 10^6 pps.

Standard		New Scheme
Bρ-TOF-dE-**E**	→	Bρ-TOF-dE
Z, A, Q		Z, A/Q

Identification of new isotopes ^{125,126}Pd

T. Onishi et al, JPSJ 77 (08)083201.





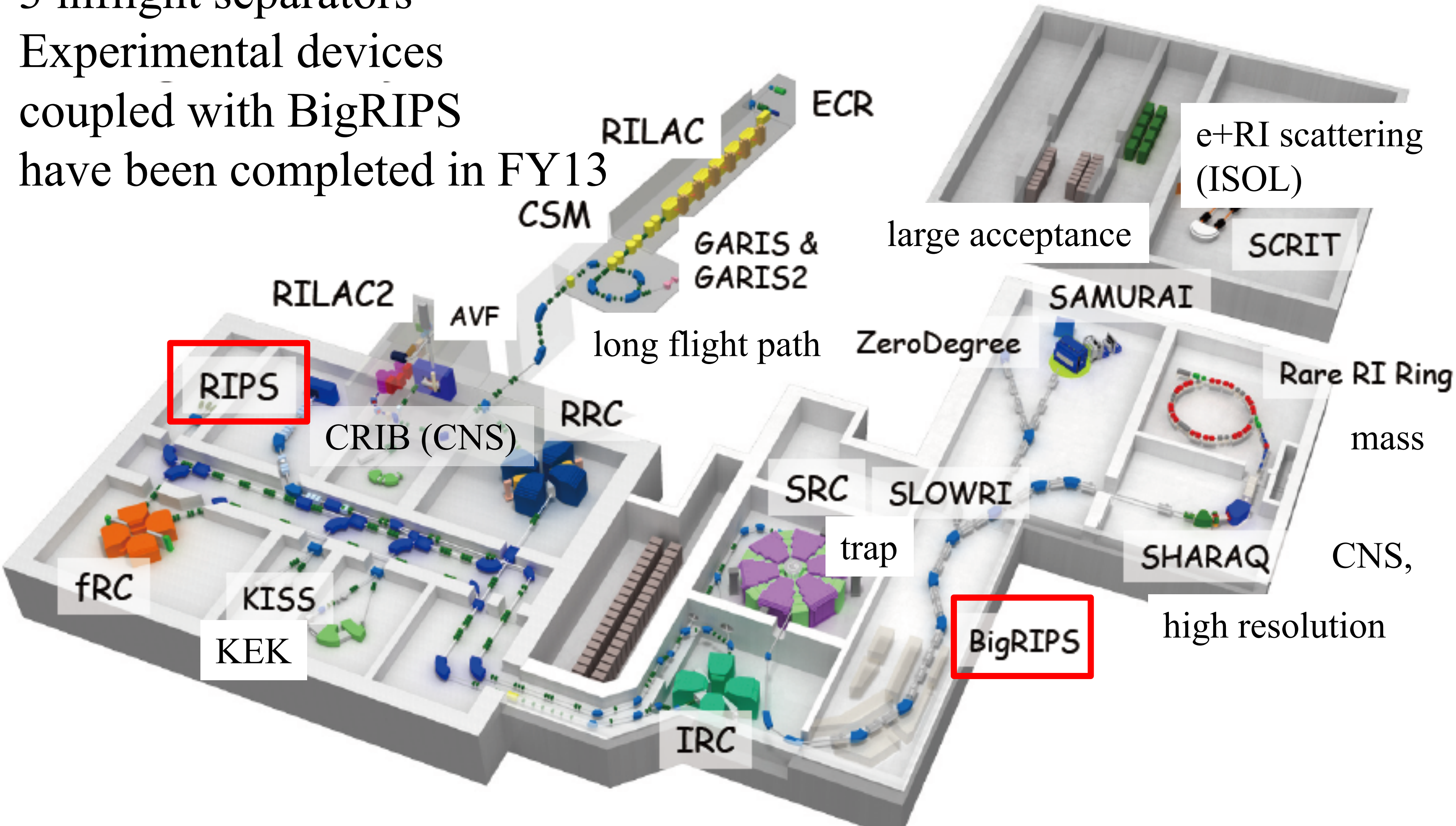
Total dose 3.6x10^{12} for 25 hrs
I ~0.01 pnA on average

A/Q resolution(r.m.s): 0.041% at Z=46
Bρ resolution (r.m.s): 0.02%
ΔT resolution (r.m.s.): 40 psec

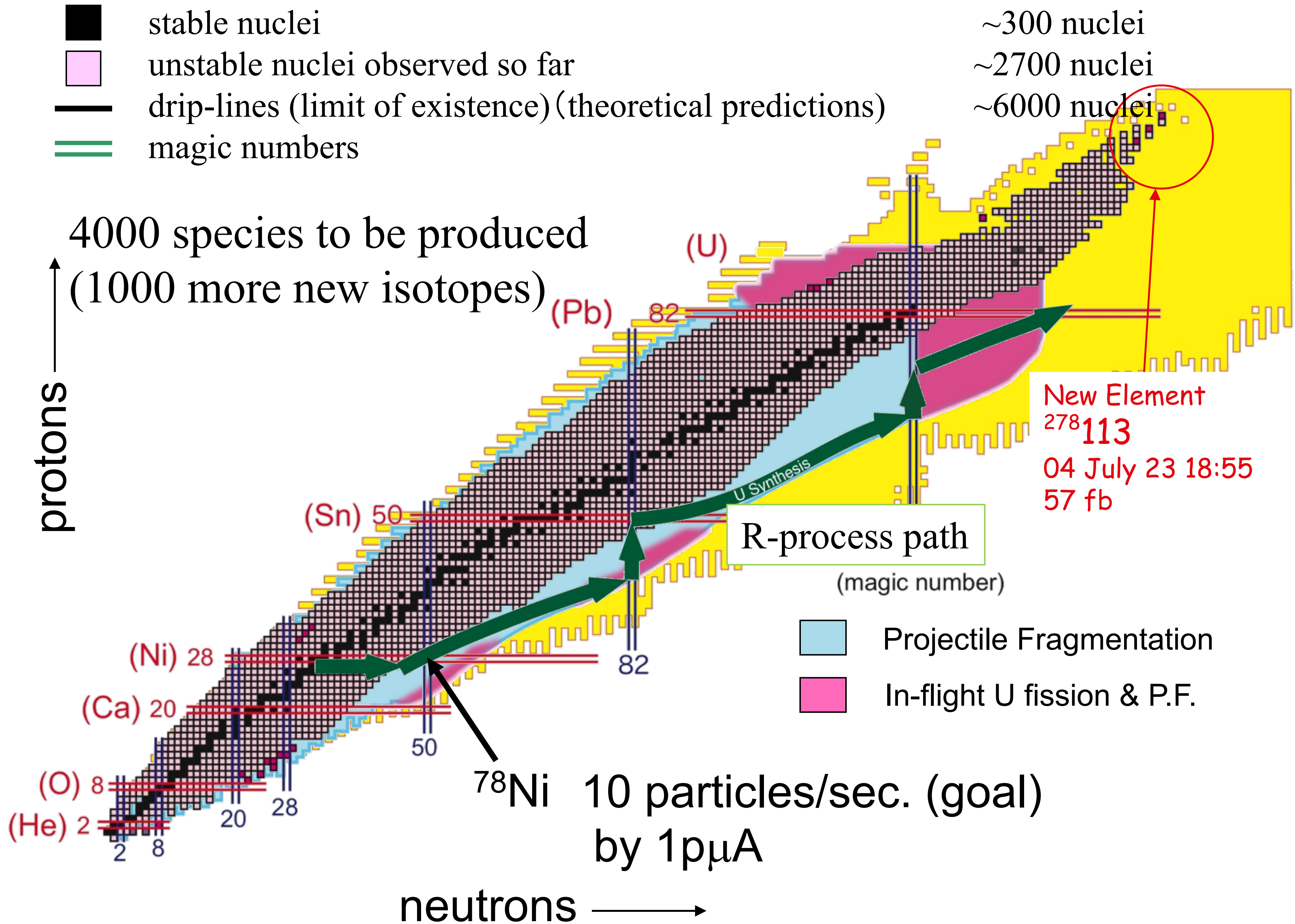
Cf. ^{124}Pd 19 counts, ^{125}Pd(cand.) 1count at GSI, 1997
PLB 415, 111 (97); total dose ~1x10^{12}

RI Beam Factory

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

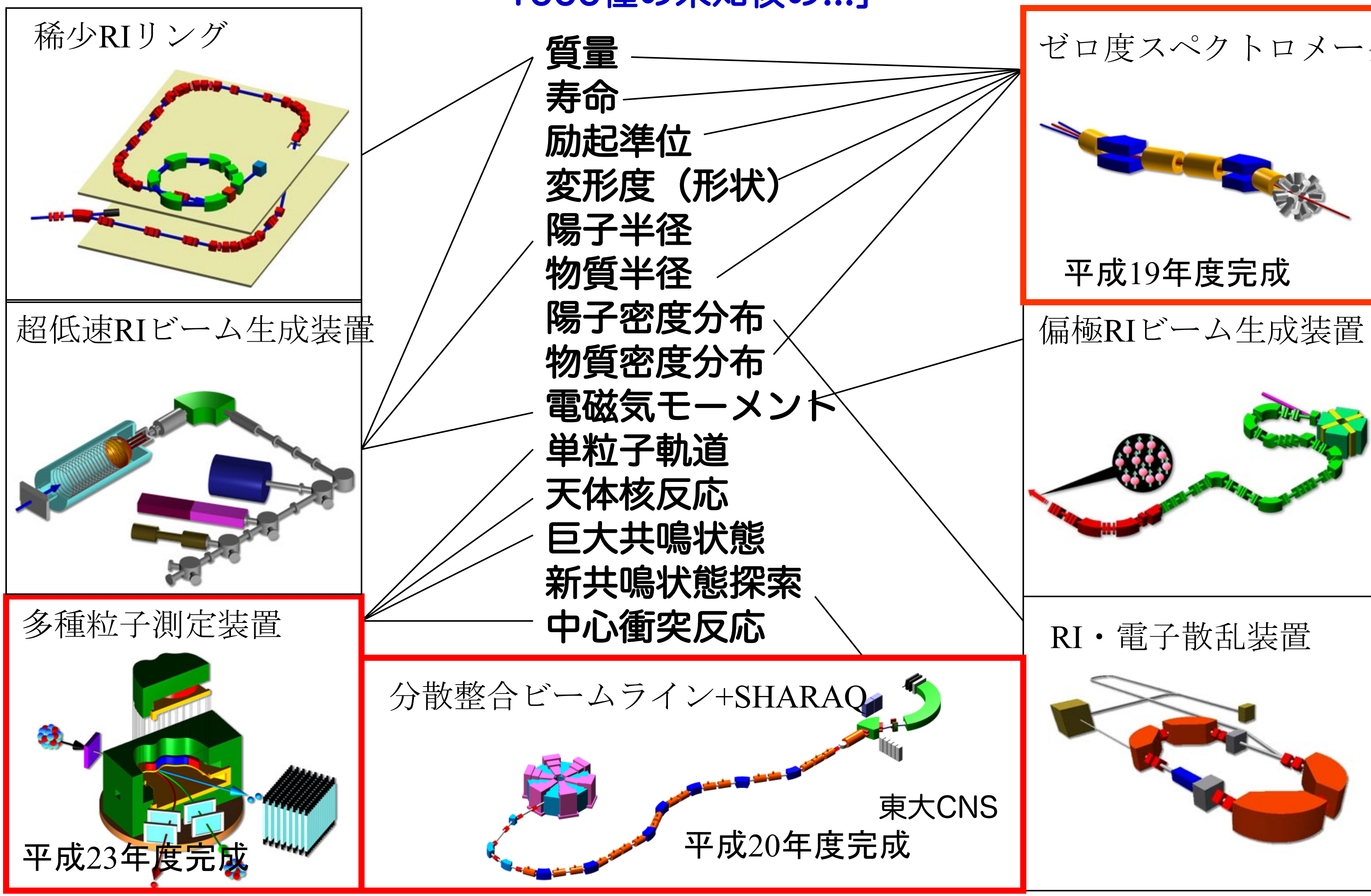


Exploration of the Limit of Existence



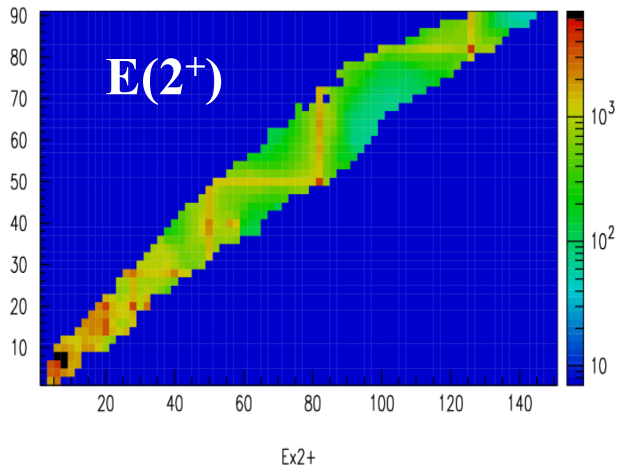
未知のエキゾチック核の諸性質を網羅的かつ系統的に測定

「1000種の未知核の…」

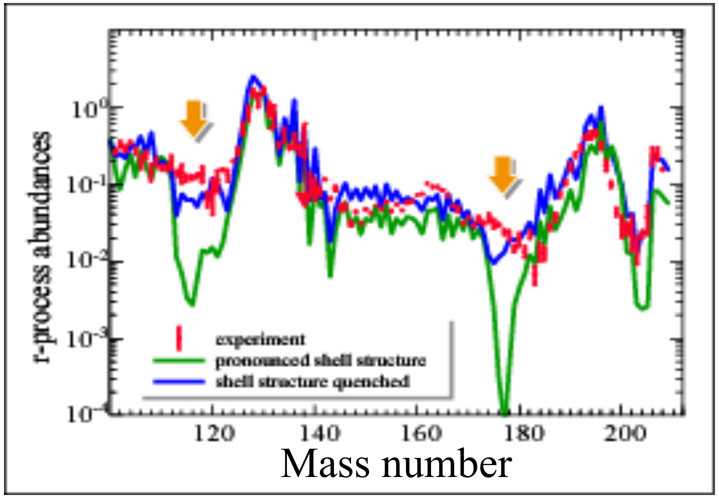


Physics with Exotic Nuclei

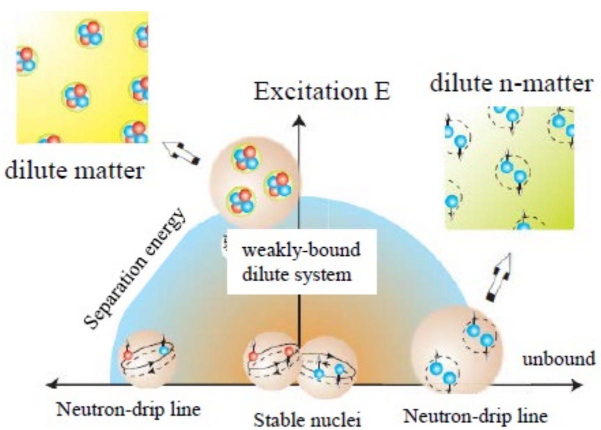
Shell Evolution : magicity loss and new magicity



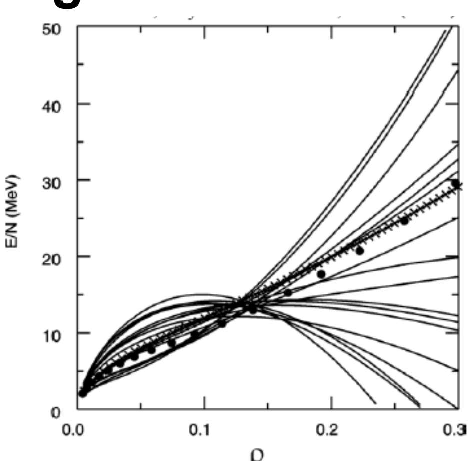
R-process path: Synthesis up to U

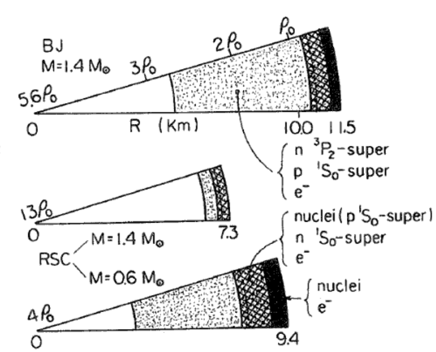


Neutron Correlation in the vicinity of the Drip-line



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





Shell evolution

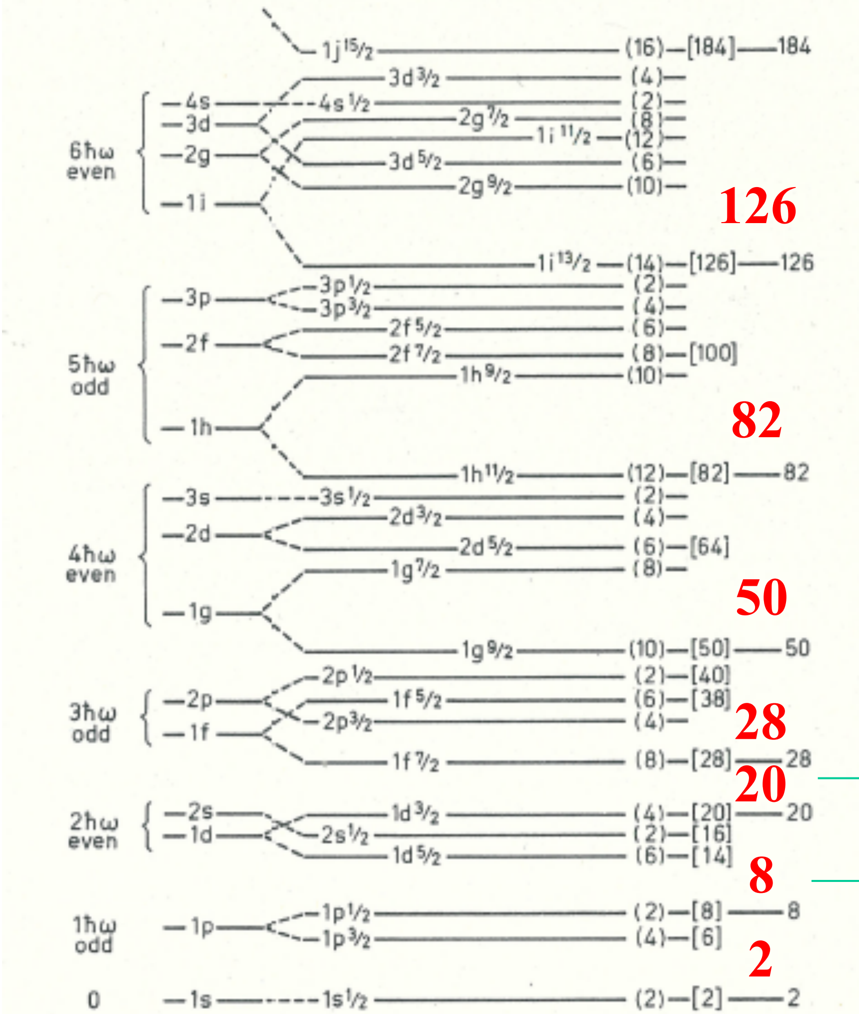
Nuclear Magic Numbers and Shell Evolution (1)

Stable nuclei

Neutron-rich nuclei

Mayer & Jensen

Nobel Prize 1963



loss

loss

?

?

?

?

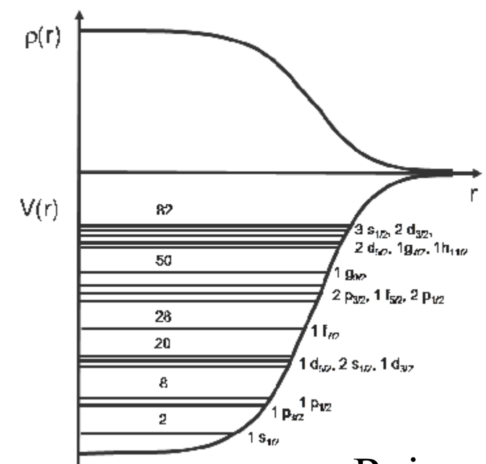
N=16

Shell Structure

One-body potential

Large LS term

(surface contribution)



Reiner K

Magic numbers ->

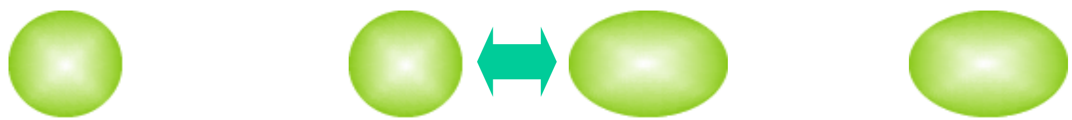
2, 8, 20, 28, 50 …

Nuclear Collective Motion

closed shell ⟷ open shell

at magic number

spherical nuclei — surface vibration — deformed nuclei



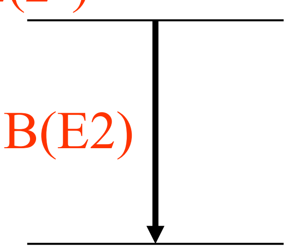
$|\beta| \sim 0$ ← **Quadrupole deformation parameter β** → $|\beta|$ large

degree of collectivity

Quantum Liquid Drop Model

Even-Even Nuclei

E(2$^+$)



2^+

B(E2)

0^+

ground state

Energy of the first excited state

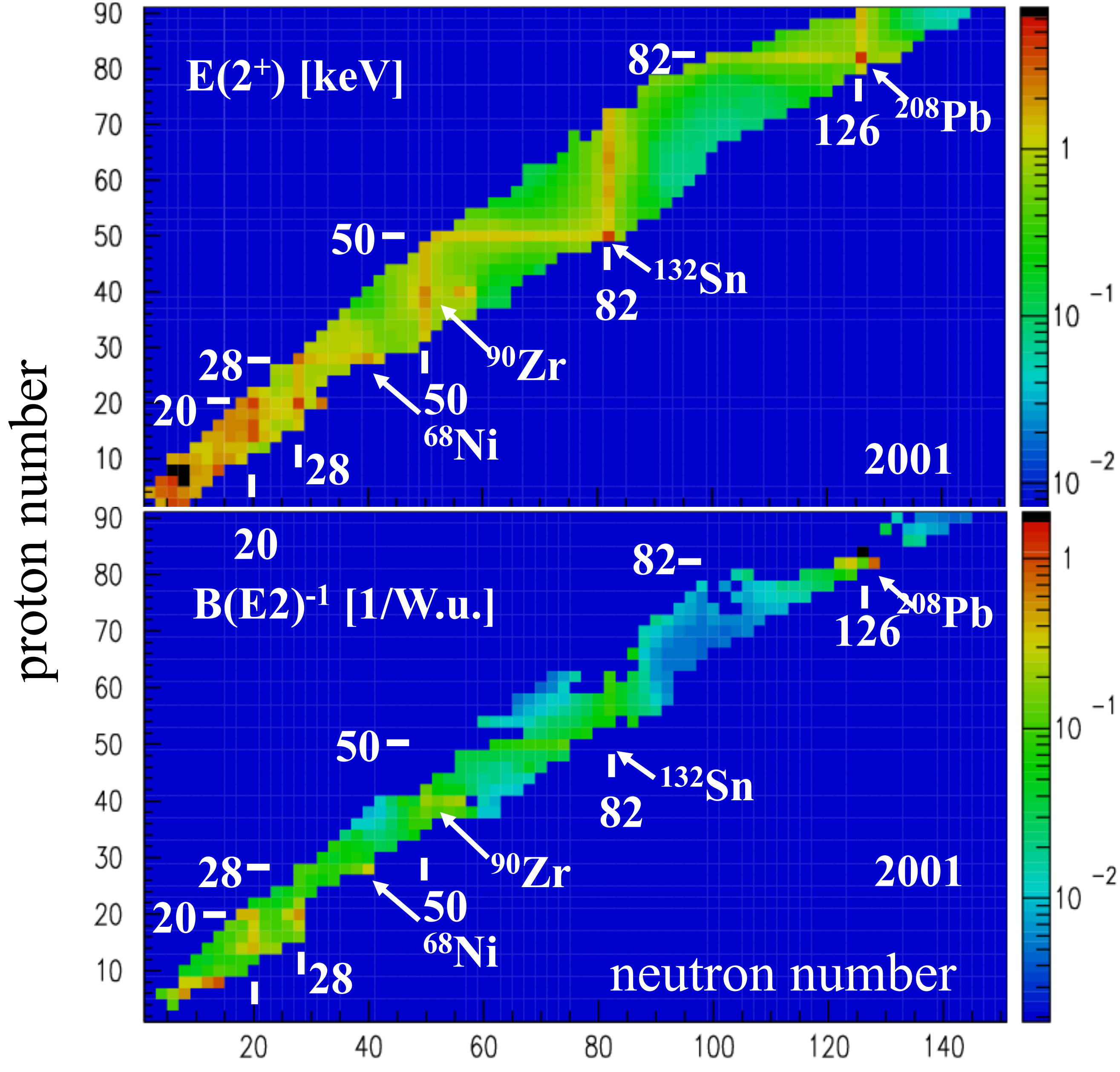
$$E(2^+) \propto 1/\beta^2$$

E2 transition probability between 2^+ and 0^+

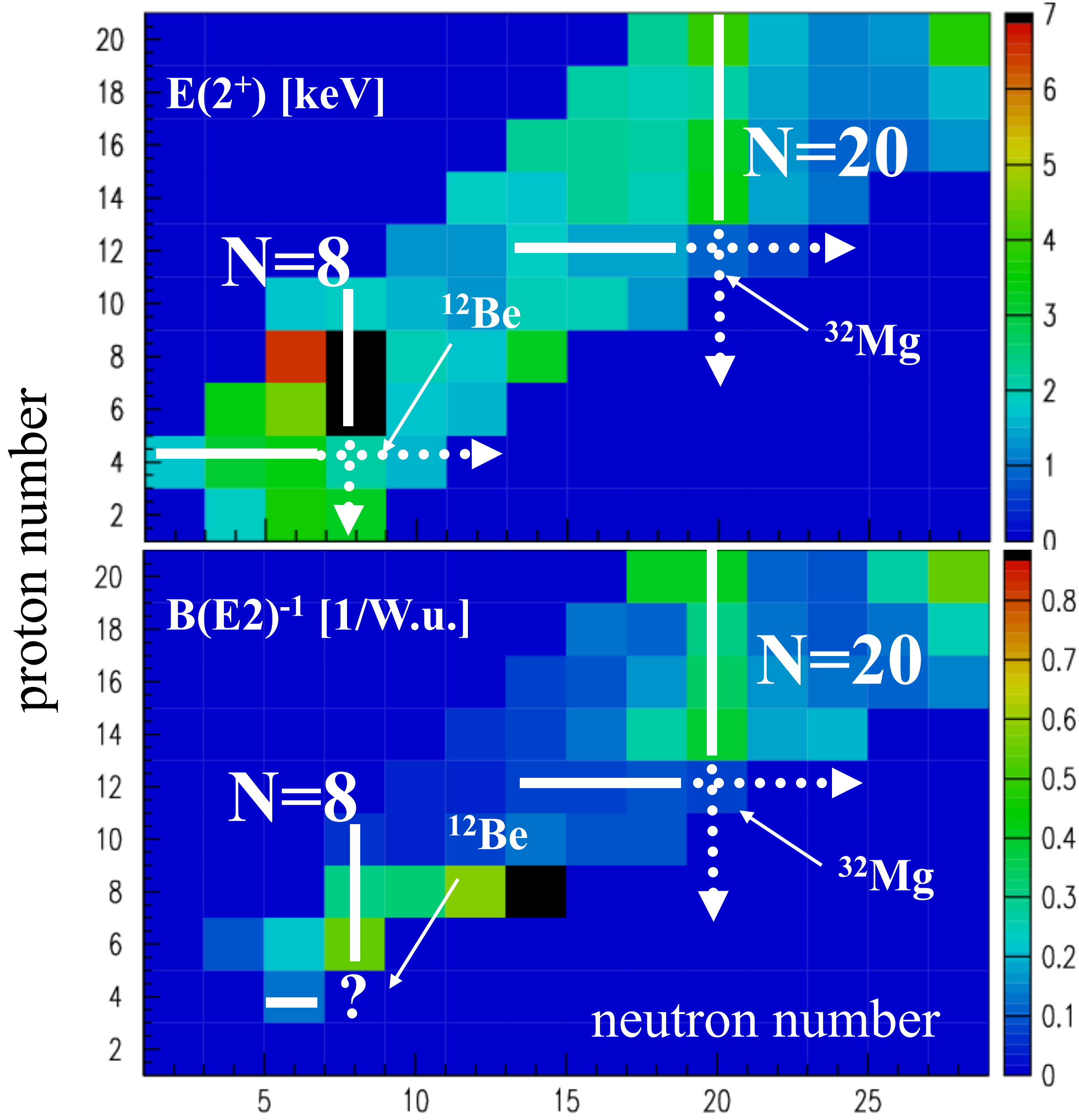
$$B(E2) \propto \beta^2$$

$$E(2^+) \propto B(E2)^{-1}$$

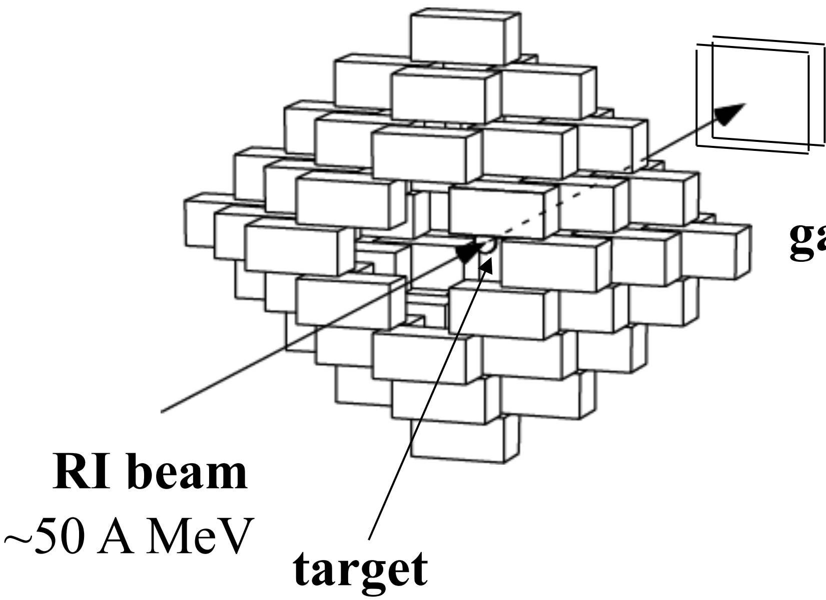
Magic number, E(2$^+$) and B(E2)



Magicity loss at N=8 and 20



Experimental setup for in-beam gamma spectroscopy with fast RI beams



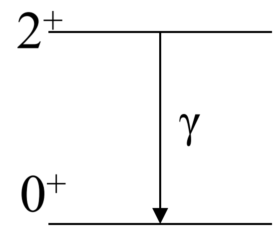
Charged particle detectors

particle identification for ejectiles

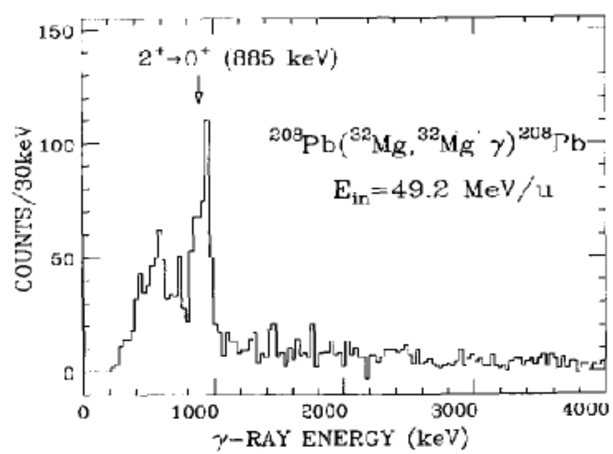
gamma-ray detector array

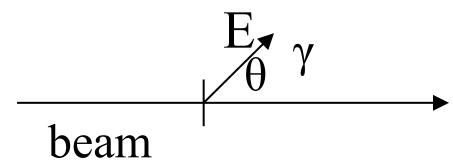
observation of de-excited γ rays

γ-ray energy and emission angle for Doppler correction



NaI detector





Doppler-shift corrected spectrum

inverse reaction

high energy beam -> thick target

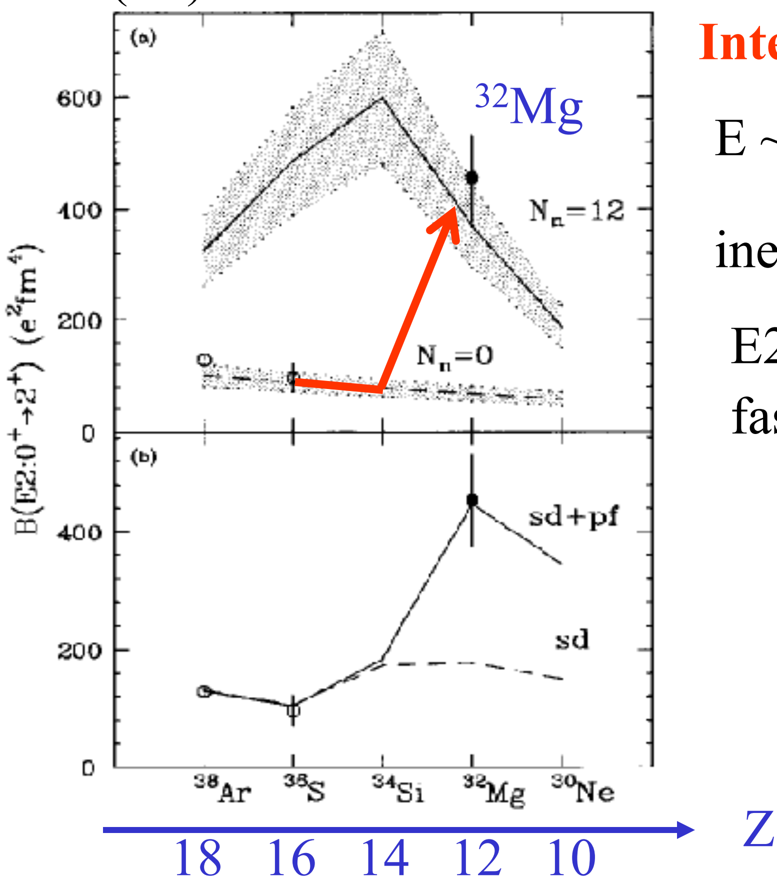
kinematical focusing -> high efficiency

Large B(E2) observed for ^{32}Mg

The dawn of in-beam γ spectroscopy with fast RI beams

T.Motobayashi, et al., PLB 346, 9 (1995)

B(E2) for the N=20 isotones



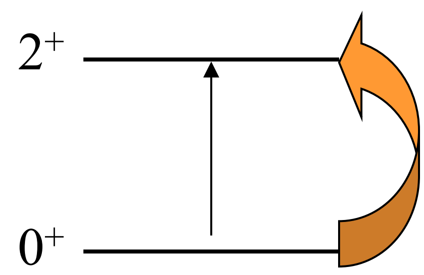
Intermediate energy Coulomb excitation

E ~ 50*A* MeV >> Coulomb barrier ~ 5*A* MeV

inelastic scattering on heavy target such as Pb

E2 excitation: Coulomb dominant if Z>10

fast interaction -> single step excitation



$\sigma \propto B(E2)$

Density distributions for the C isotopes

AMD calculation by Kanada-En’yo and Horiuchi

protons neutrons

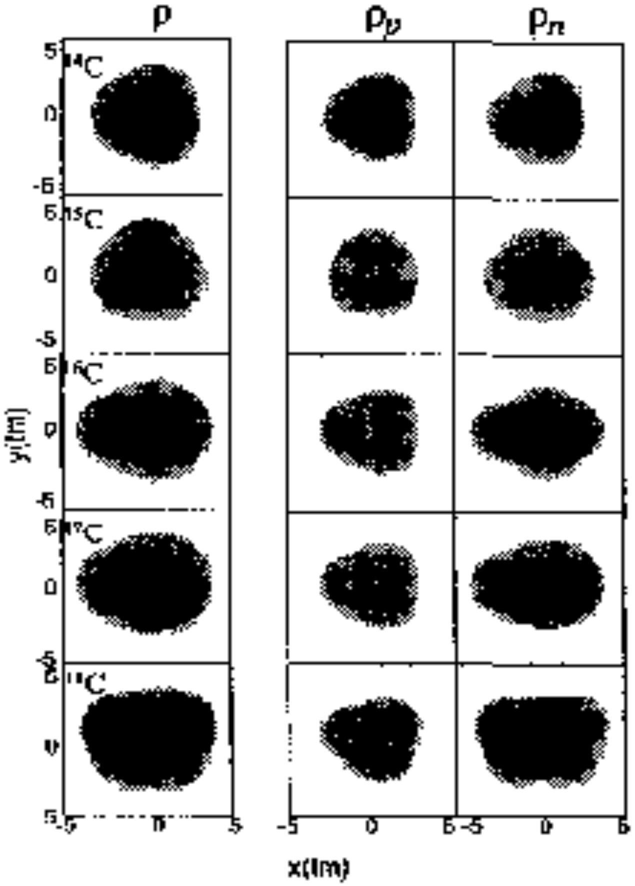
^{14}C

^{15}C

^{16}C

^{17}C

^{18}C

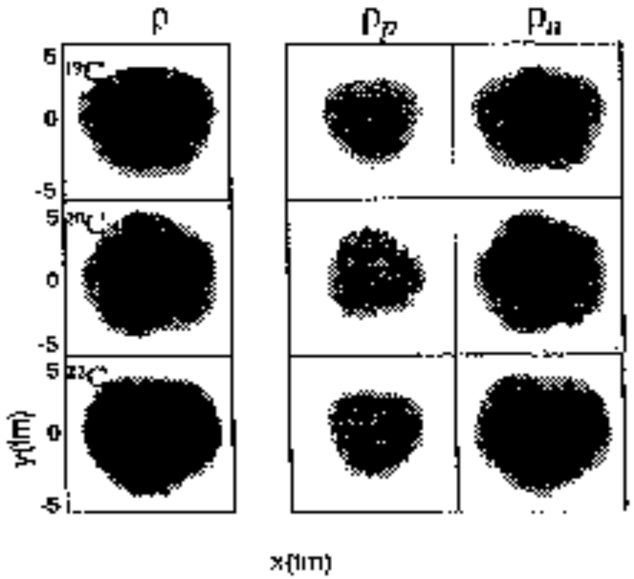


protons neutrons

^{19}C

^{20}C

^{21}C



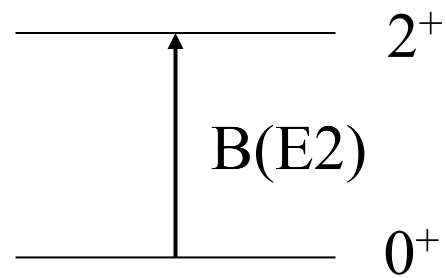
Degree of collectivity for proton- and neutron matters

$\beta \rightarrow \beta p$ proton matter

$\beta \rightarrow \beta n$ neutron matter

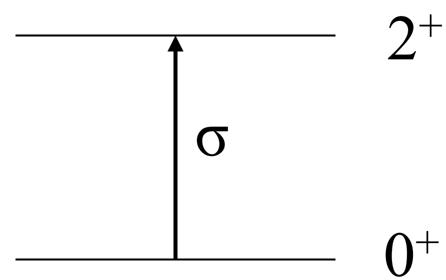
βp electromagnetic probe
e.g. Coulomb excitation

$B(E2) \propto \beta_p^2$



βn strong-interaction probe
e.g. proton inelastic scattering

$\sigma \propto \beta_n^2$

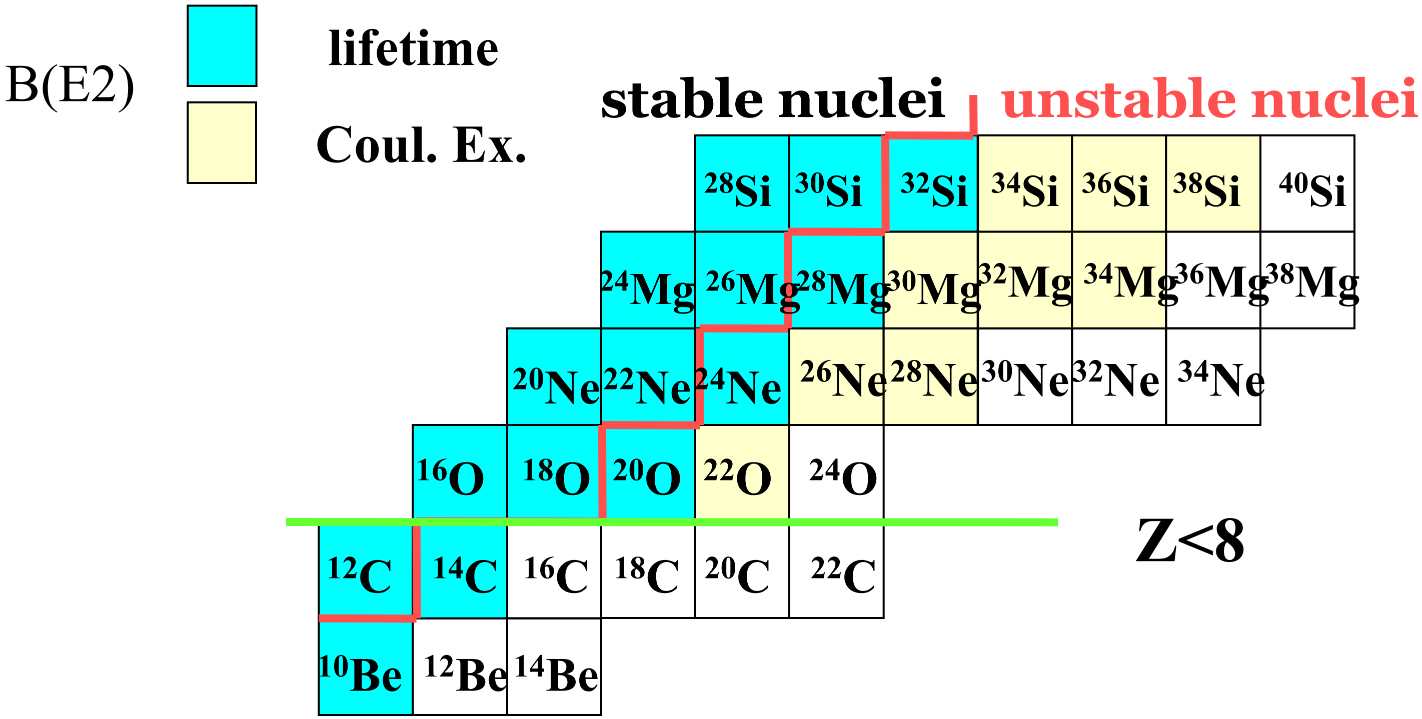


$\sigma(pn) \sim 2\, \sigma(pp)$

Since 1980's, large difference between β_n and β_p has been searched for,
but $|\beta_n|/|\beta_p| \sim 1$ for stable and unstable nuclei observed so far .

even for ^{32}Mg, too

B(E2) measurement for the light mass region

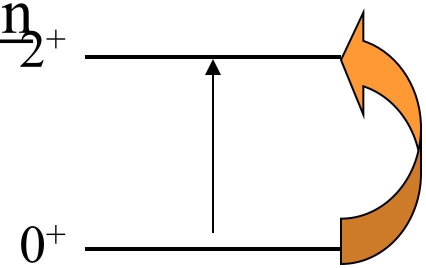


No data for the neutron-rich Be and C isotopes

How to measure B(E2)?

Intermediate energy Coulomb excitation

for unstable nuclei
inelastic scattering on heavy target such as Pb
E2 excitation: Coulomb dominant if **Z>10**



$\sigma \propto B(E2)$

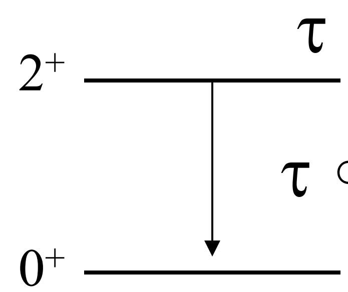
Z<8 Coulomb Ex. $\lesssim$ Nuclear Ex.

Lifetime measurement of 2^+ state

for stable nuclei or nuclei close to stability line

(p,p' γ), (t, pγ), and etc...
+
Doppler Shift Attenuation

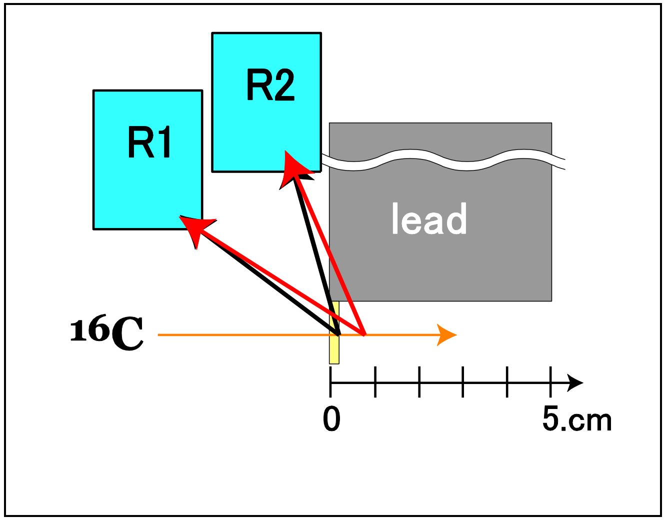
1970's

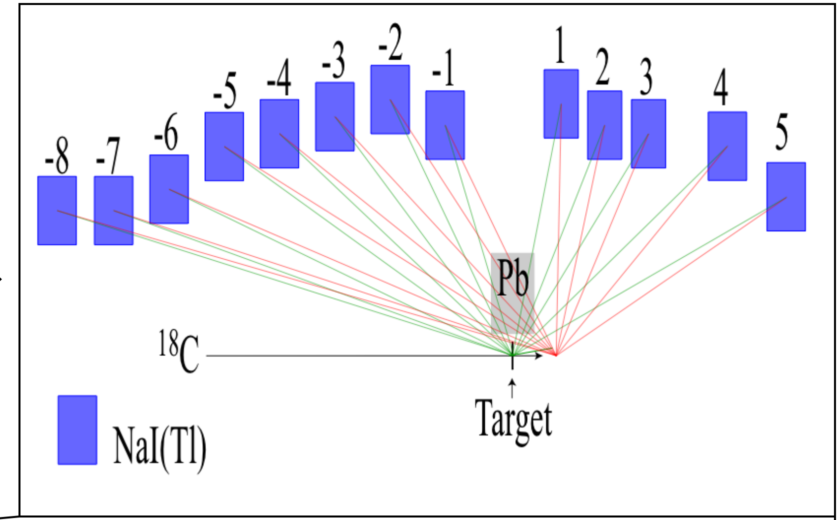


$\tau \propto 1/B(E2)$

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

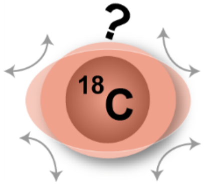
^{18}C: Ong et al. PRC in press. ^{17}C: Suzuki et al. PLB in press





- 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**



^{18}C B(E2)

H.J. Ong et al., PRC

- Lifetime measurement of 2^+ state in ^{18}C using an upgraded Recoil Shadow Method
- Mean lifetime:

$$\tau = 18.9 \pm 0.9(\mathrm{stat}) \pm 4.4(\mathrm{syst})\mathrm{ps}$$

$$B(E2) = 4.3 \pm 0.2(\mathrm{stat}) \pm 1.0(\mathrm{syst}) e^2 \mathrm{fm}^4$$

- Small *B(E2)* (hindered *E2* strength)

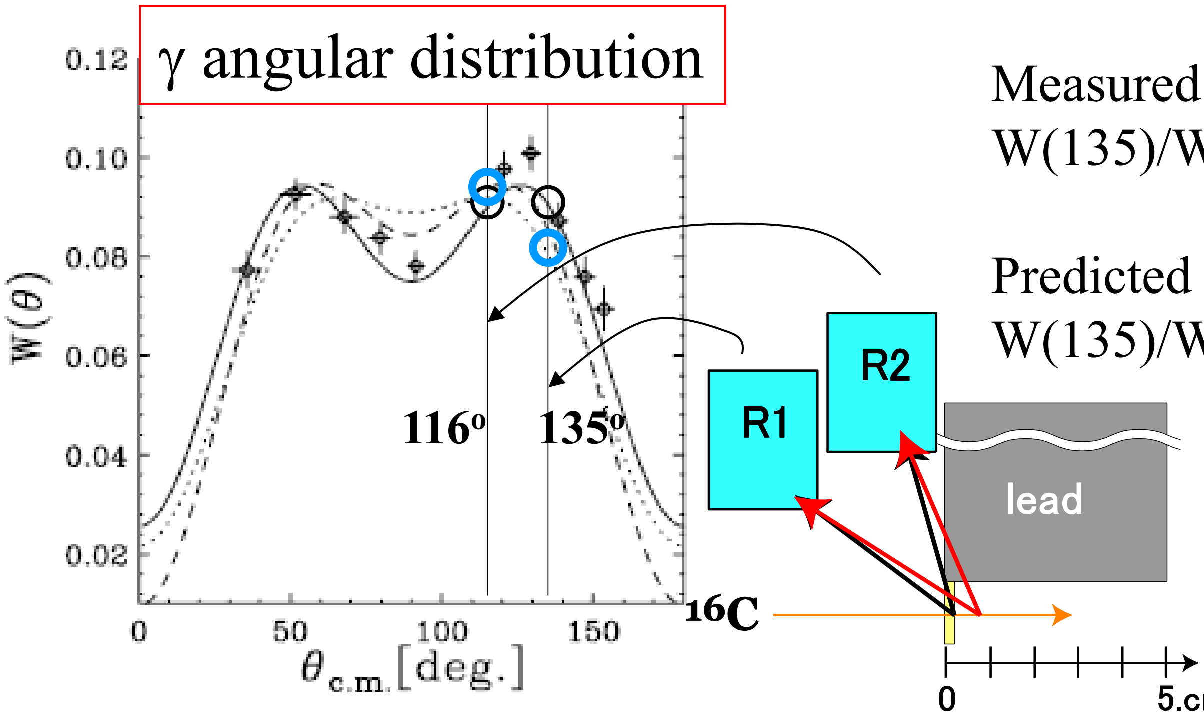
  ⇨ suppressed proton contribution to quadrupole collectivity in ^{18}C

Lifetime of 2_1^+ state in ^{16}C revisited

Ong et al.

τ= 18.0 +/- 1.6(stat.) +/- 4.7(syst.) psec
B(E2) = 2.6 +/- 0.2(stat.) +/- 0.7(syst.) e^2fm^4

72*A* MeV inelastic channel	17.7 +/- 1.6 +/- 4.6 ps
79*A* MeV break-up channel	19.5 +/- 7.7 +/- 4.5 ps
40*A* MeV inelastic channel	34 +/- 14 +/- 7 ps

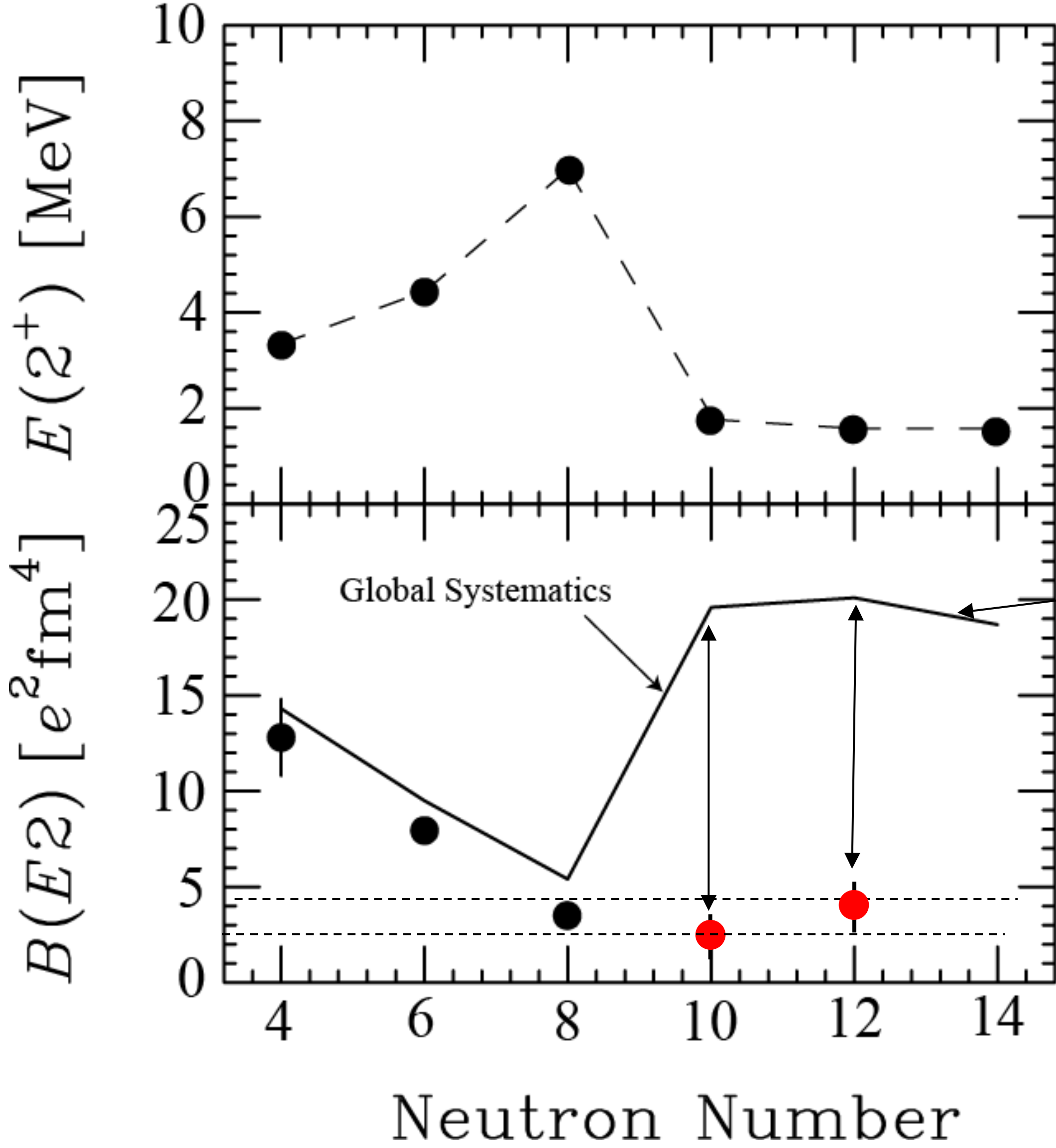


Measured
W(135)/W(116) =1.0

Predicted in the previous paper
W(135)/W(116) = 0.88 – 0.91

77 +/- 14 +/- 19 ps

Imai et al., PRL 92, 062501 (04)

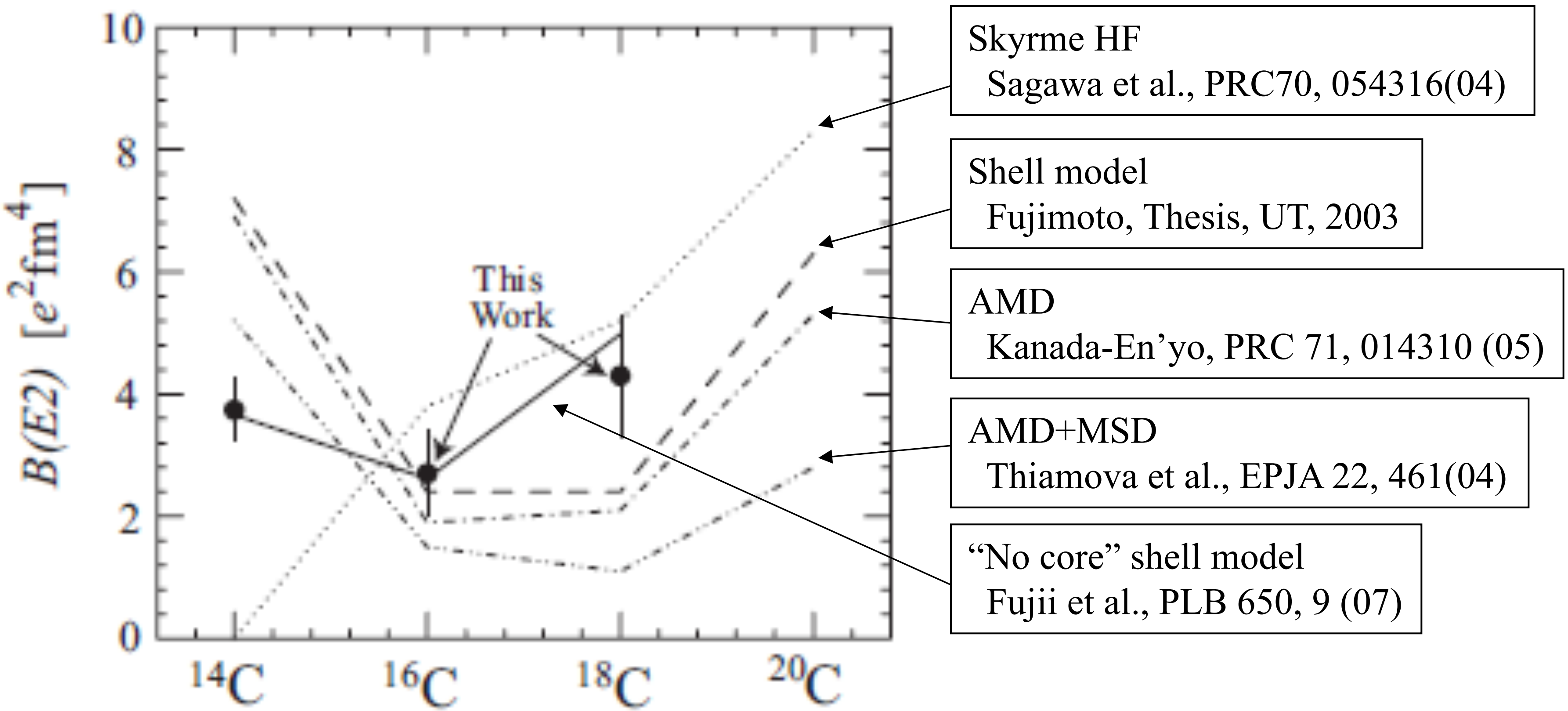


$B(E2)_{sys} = (5140 \pm 900) E^{-1} Z^2 A^{-2/3}$

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

significant discrepancy from Raman's systematics

Comparison with B(E2) values from microscopic models



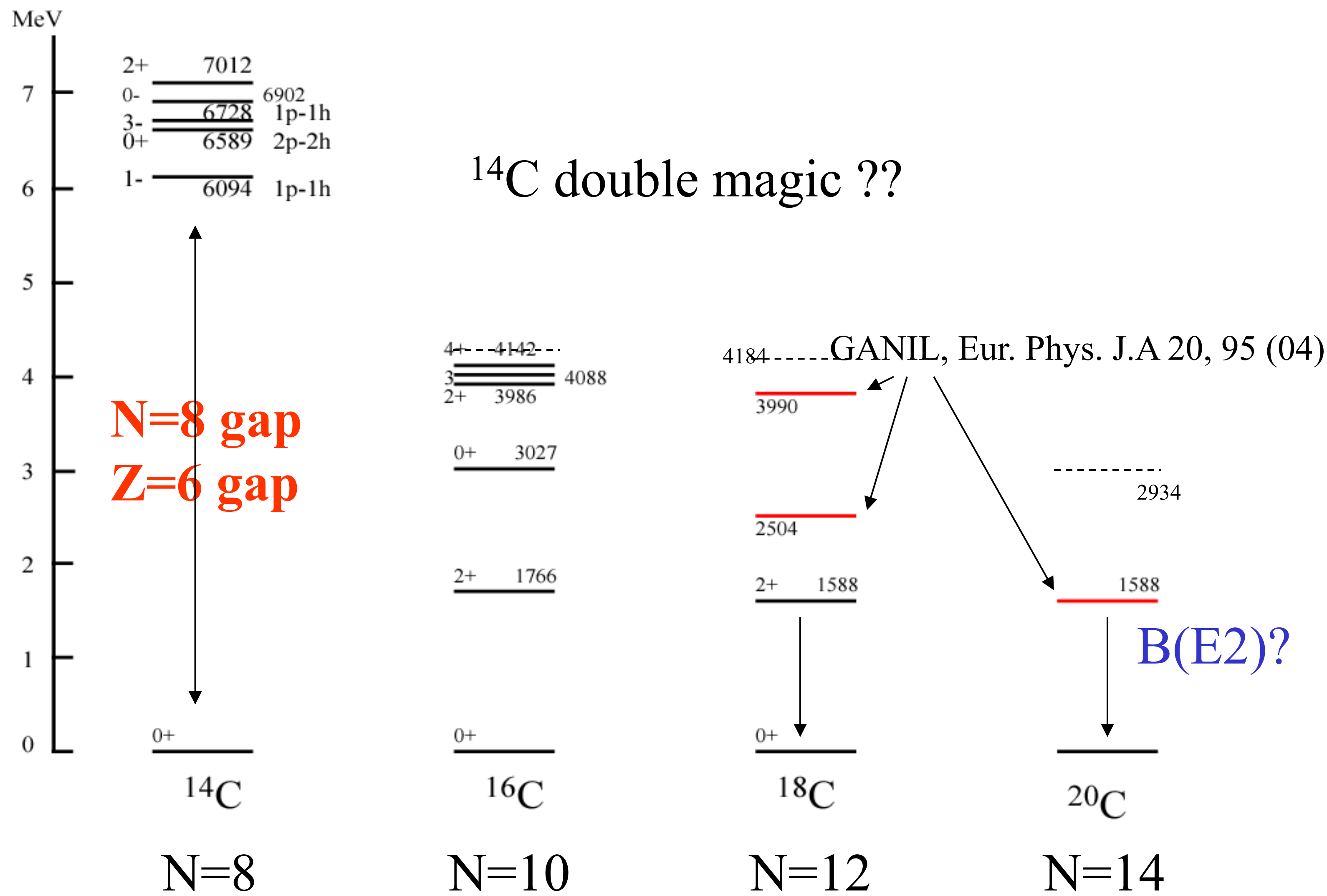
In the shell models,

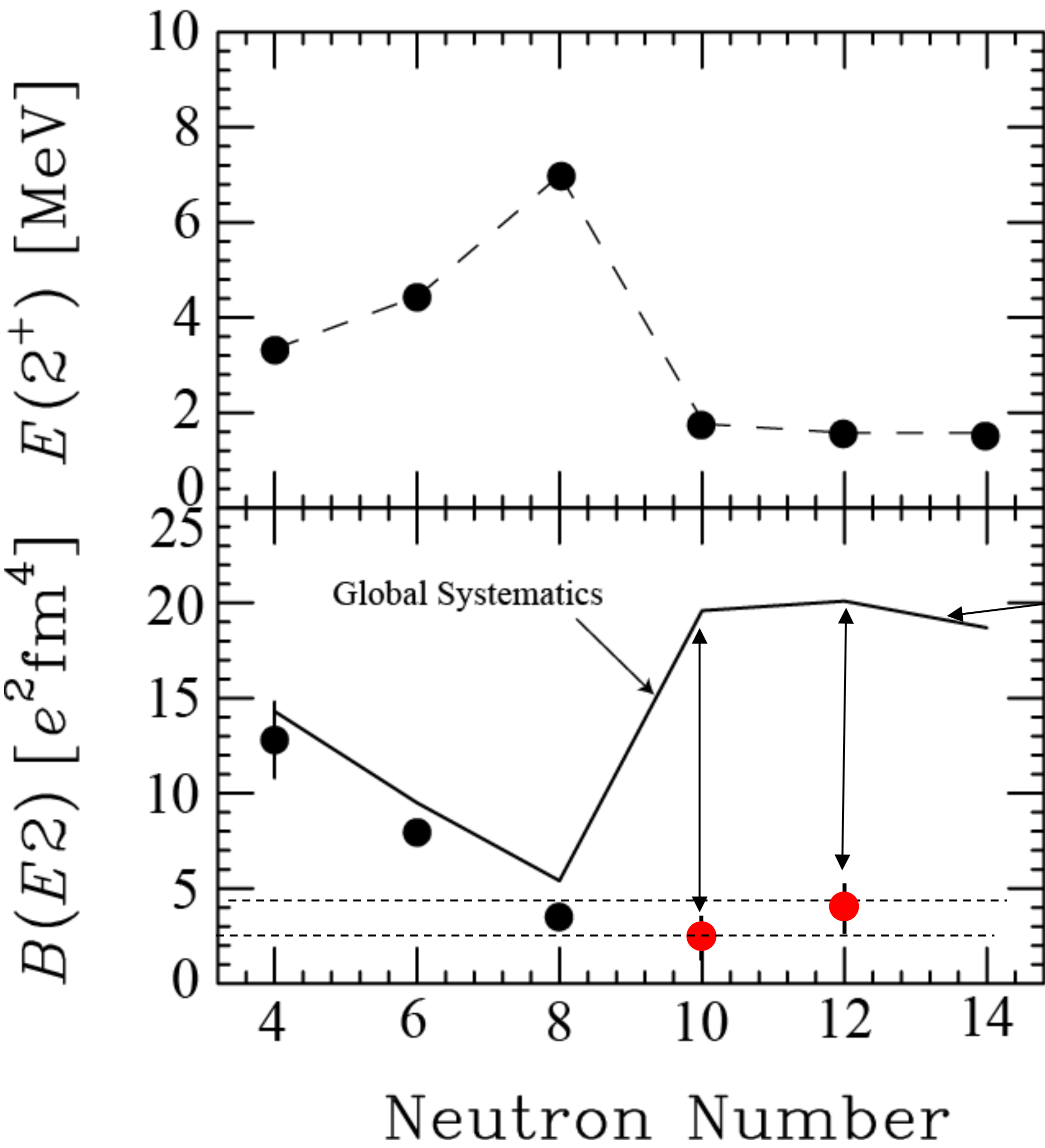
larger sub-shell gap for protons; 0p3/2 - 0p1/2

smaller effective charge $e_n \sim 0.2e$

due to s-wave dominance and week-bound neutrons

Excited states in even-even C isotopes





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

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

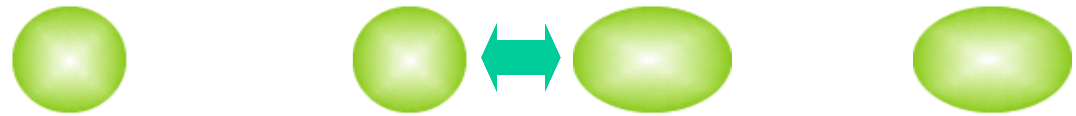
significant discrepancy
from
Raman's systematics

Nuclear Collective Motion

closed shell ⟷ open shell

at magic number

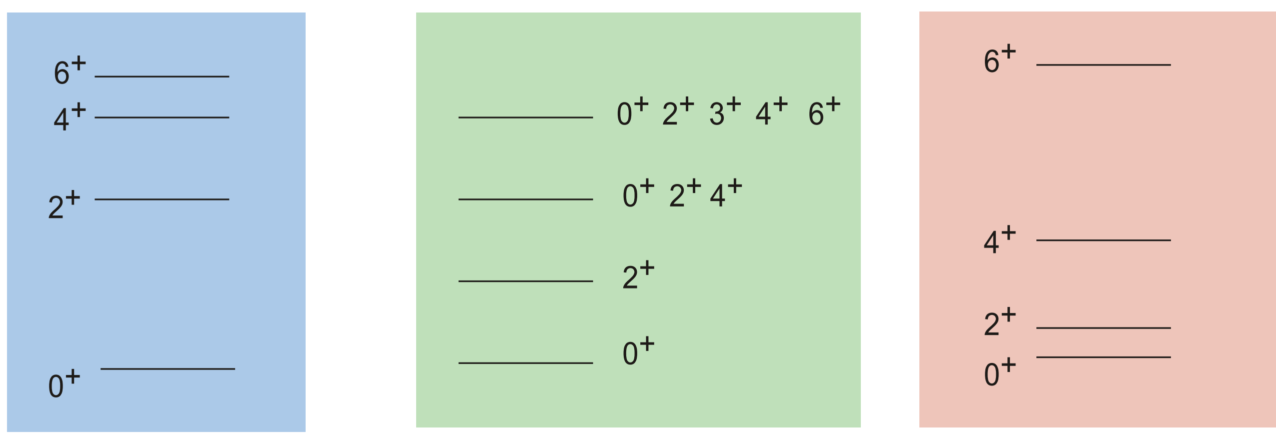
spherical nuclei | surface vibration | deformed nuclei



Quadrupole deformation parameter β

$|\beta| \sim 0$ ⟵ ⟶ $|\beta|$ large

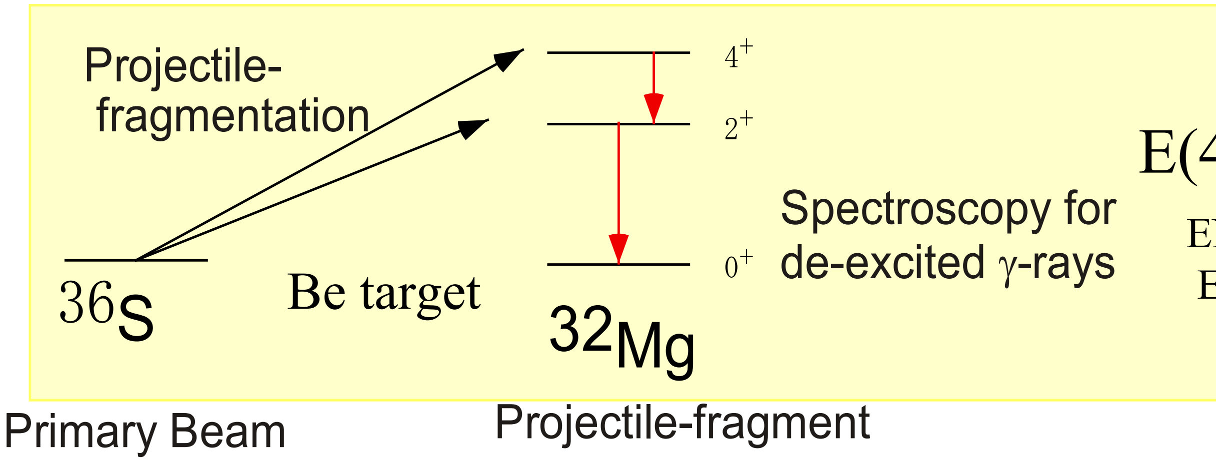
degree of collectivity



$E(4^+)/E(2^+)$	~ 1.8	~ 2.2	~ 3.3

In-beam γ-spectroscopy via projectile-fragmetation

^{32}Mg E(2$^+$) and E(4$^+$)?



E(4$^+$)/E(2$^+$) = 2.6

ENAM01
Eur.J.A. 15, 93(2002)

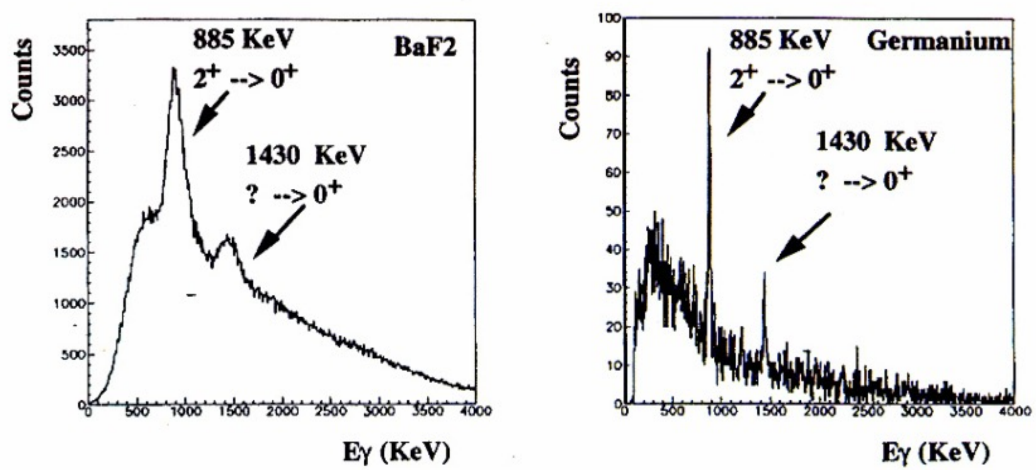


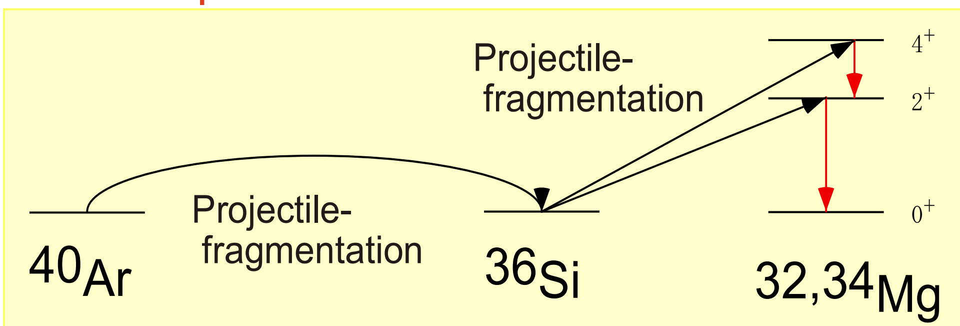
Fig. 4 : Gamma energy spectra of ^{32}Mg in the BaF$_2$ (left) and in the germanium (right).

XXXVII Int. Winter meeting on Nuclear Physics (Bormio, Italy, Jan. 99)

RI beam fragmentation method

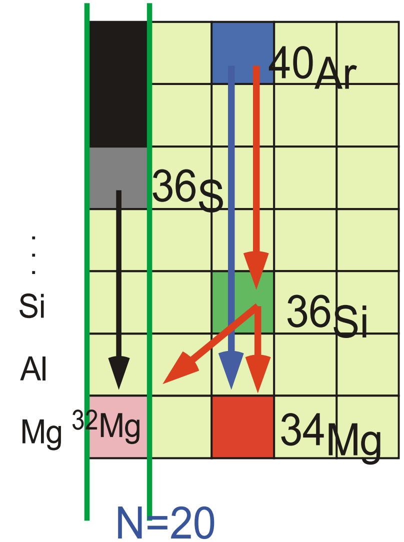
^{32,34}Mg E(2^+) and E(4^+)

Two-steps RIKEN(99)



Primary Beam

2ndary-beam



one step

^{40}Ar -> ^{34}Mg

^{40}Ar primary beam
high intensity

But...
limit of Intensity and target thickness

to avoid accidental coincidence

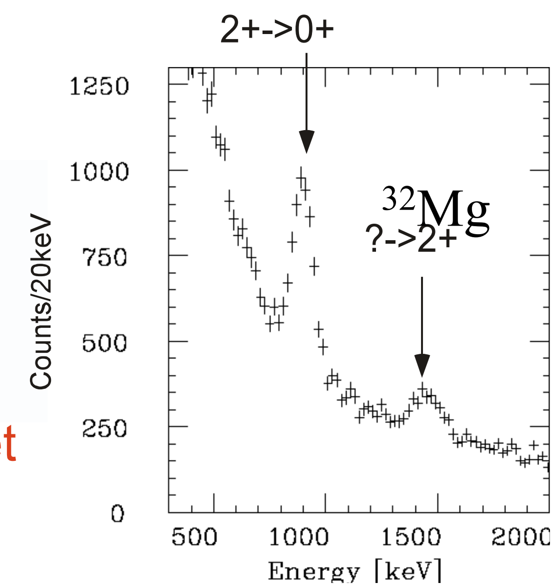
two steps

^{40}Ar -> ^{36}Si

^{36}Si -> ^{34}Mg

^{36}Si RI beam
low intensity

So...
thick production target

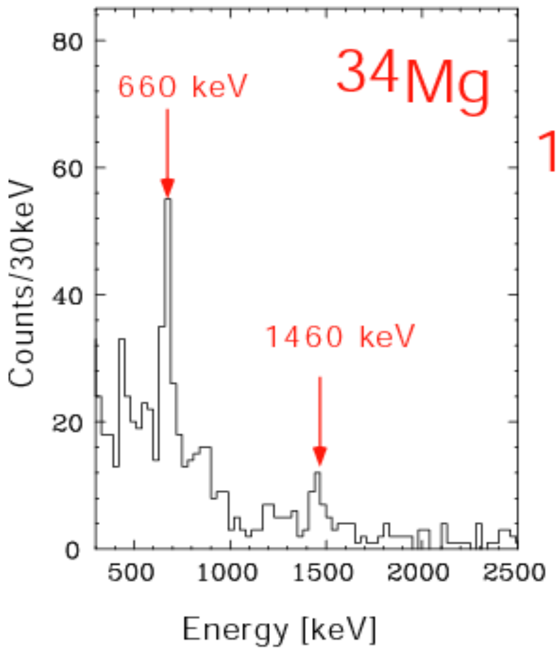


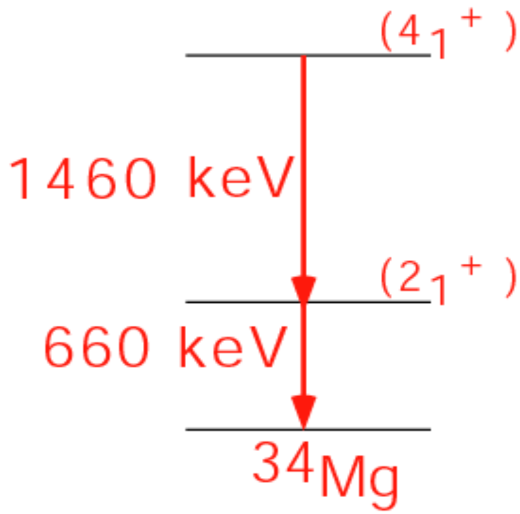
production cross sections o(1) nb o(0.1) mb

Yoneda et al., PLB499, 233(2001)

Spectroscopy on ^{34}Mg via RI beam fragmentation method

Yoneda et al., PLB499, 233(2001)





tentative Jp assignment

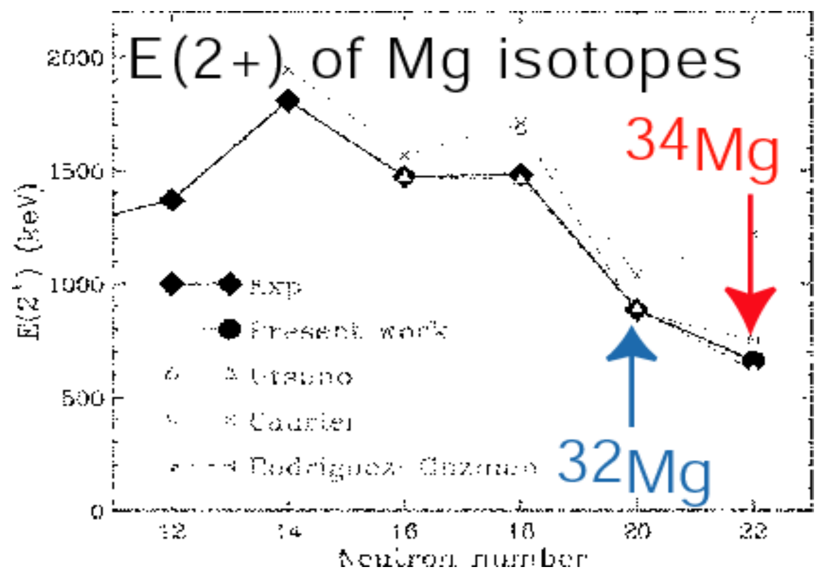
according to

relative g-ray strength

^{18,20}O, ^{22,24,26}Ne

^{26,28}Mg

population of excited states along the Yrast line

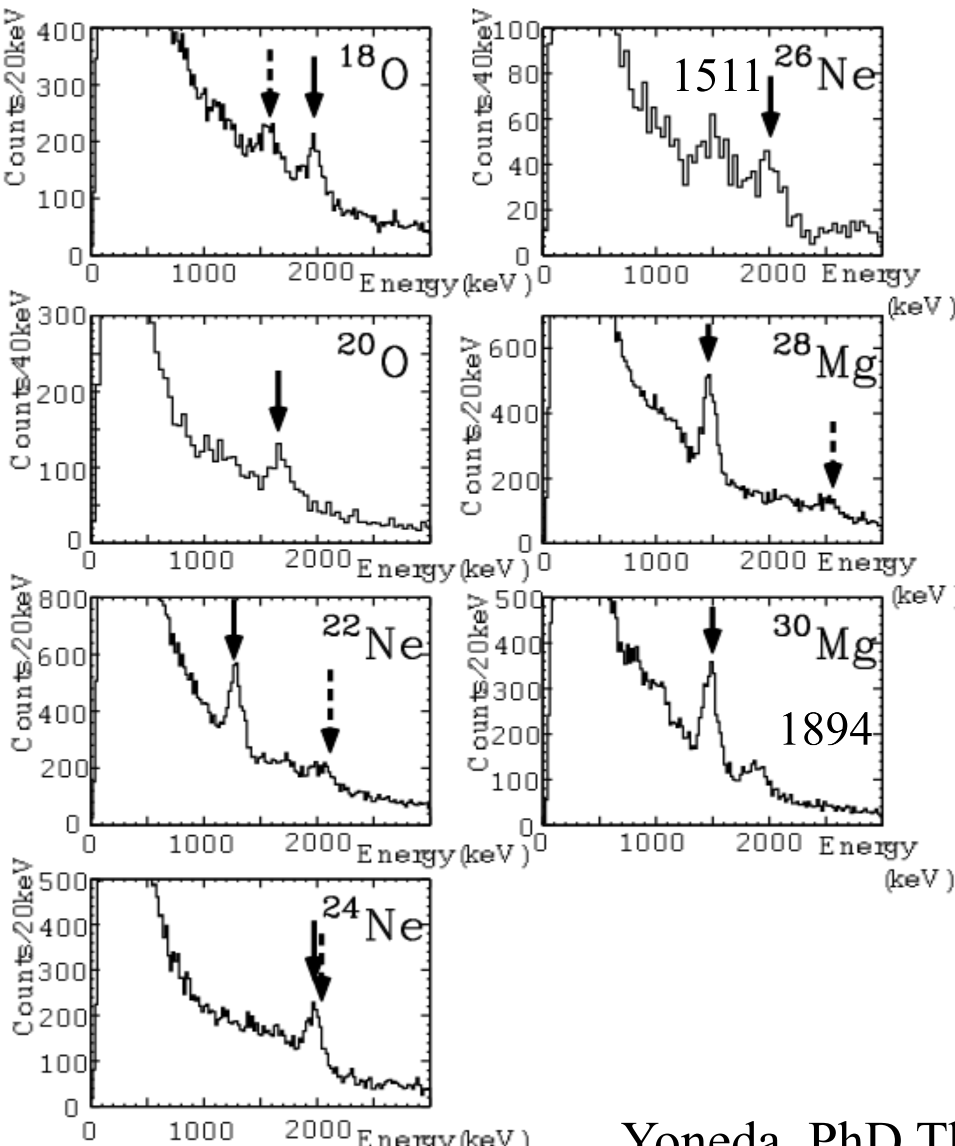


^{34}Mg $E(2_1^+)$ < ^{32}Mg $E(2_1^+)$

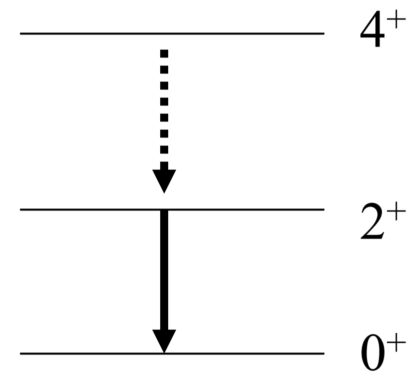
$E(4_1^+)/E(2_1^+) \sim 3.2$

^{34}Mg larger deformation than ^{32}Mg

Doppler-corrected g-ray energy spectra for the O, Ne, and Mg isotopes

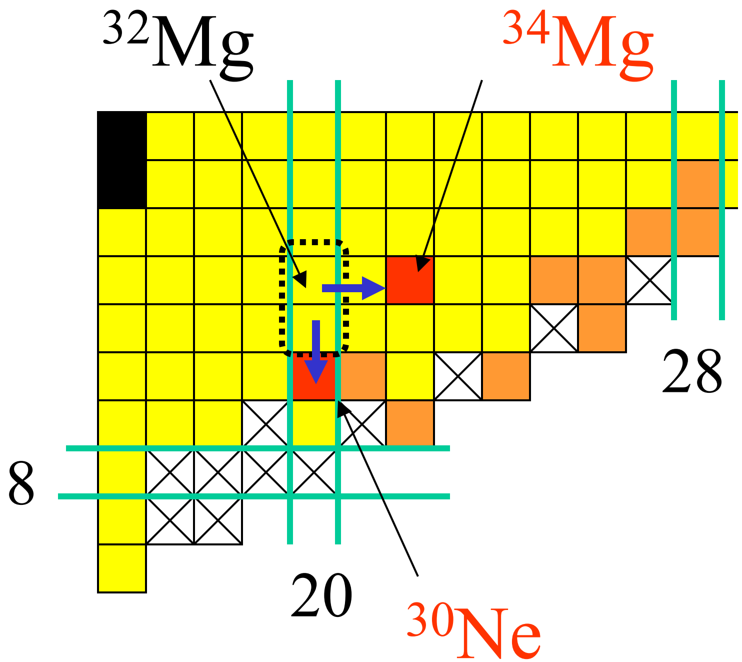


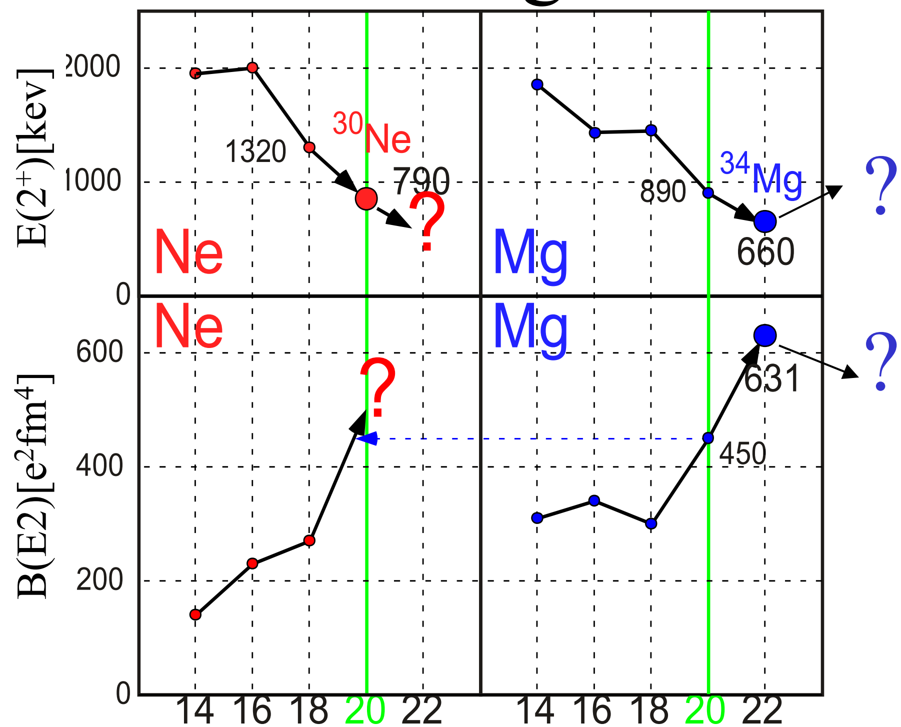
literature values

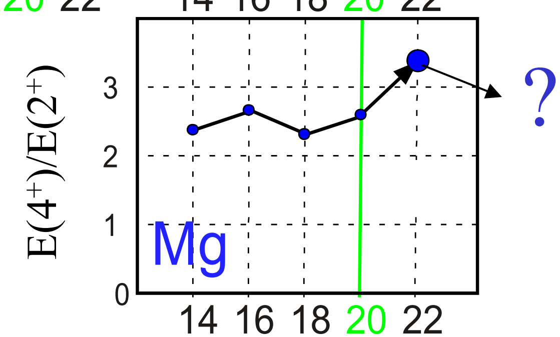


Yoneda, PhD Thesis, U. Tokyo (2003)

Spectroscopy on nuclei in the island-of-inversion region







The ^{30}Ne isotope has a larger collectivity than the ^{32}Mg isotope??

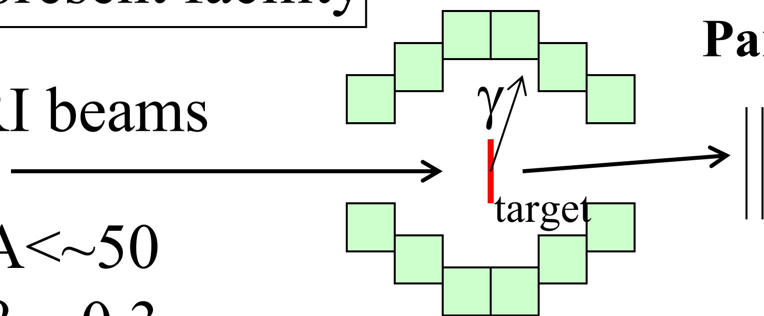
N=22 is the center of deformation??

→ Further investigation is necessary

Experiment at RIBF

At present facility

RI beams



A<~50

β ~ 0.3

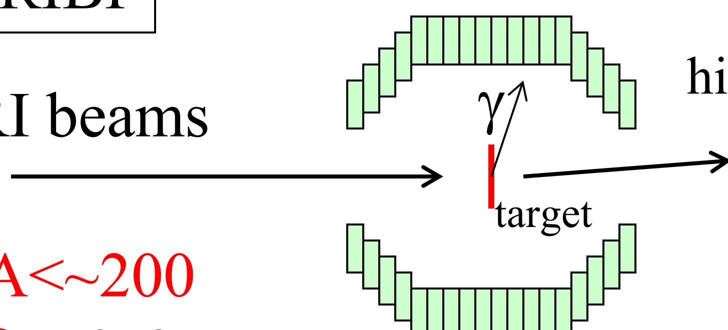
gamma-ray detectors

Particle Identification for Ejectiles

charged particle detectors

At RIBF

RI beams



A<~200

β ~ 0.6

high segmentation and/or
high resolution

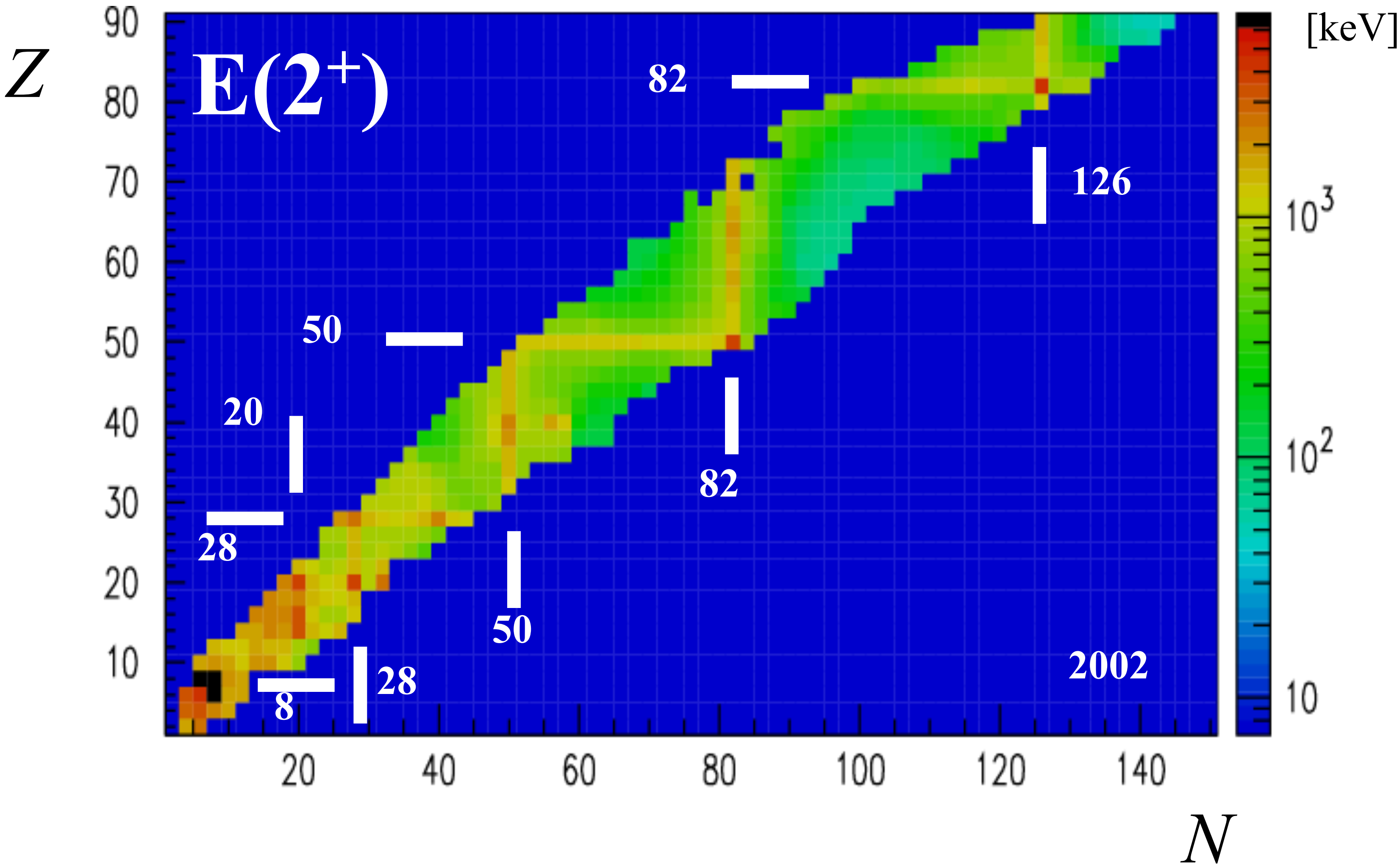
DALI2 (NaI)
CNS-GRAPE (Ge)

high resolving power for heavy mass region

Zero-degree forward spectrometer

To determine final channels
To achieve good S/N ratios
for low-intensity RI beams
→ Nice quality of data

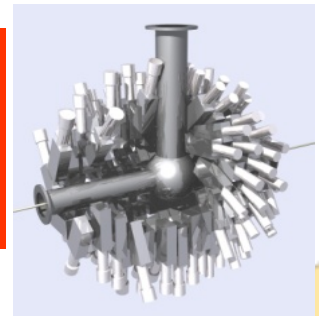
Magicity and its loss through determining E(2^+)



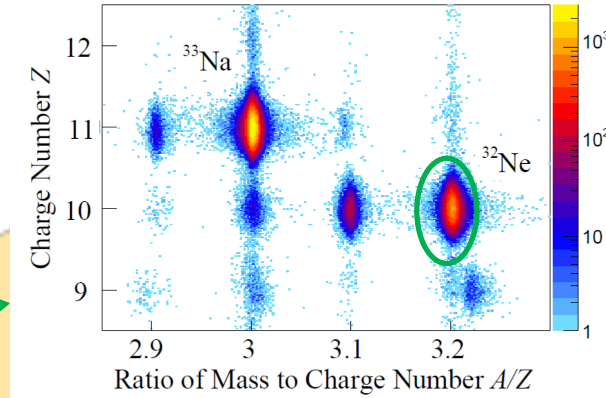
Spectroscopy via reactions with in-beam gamma method

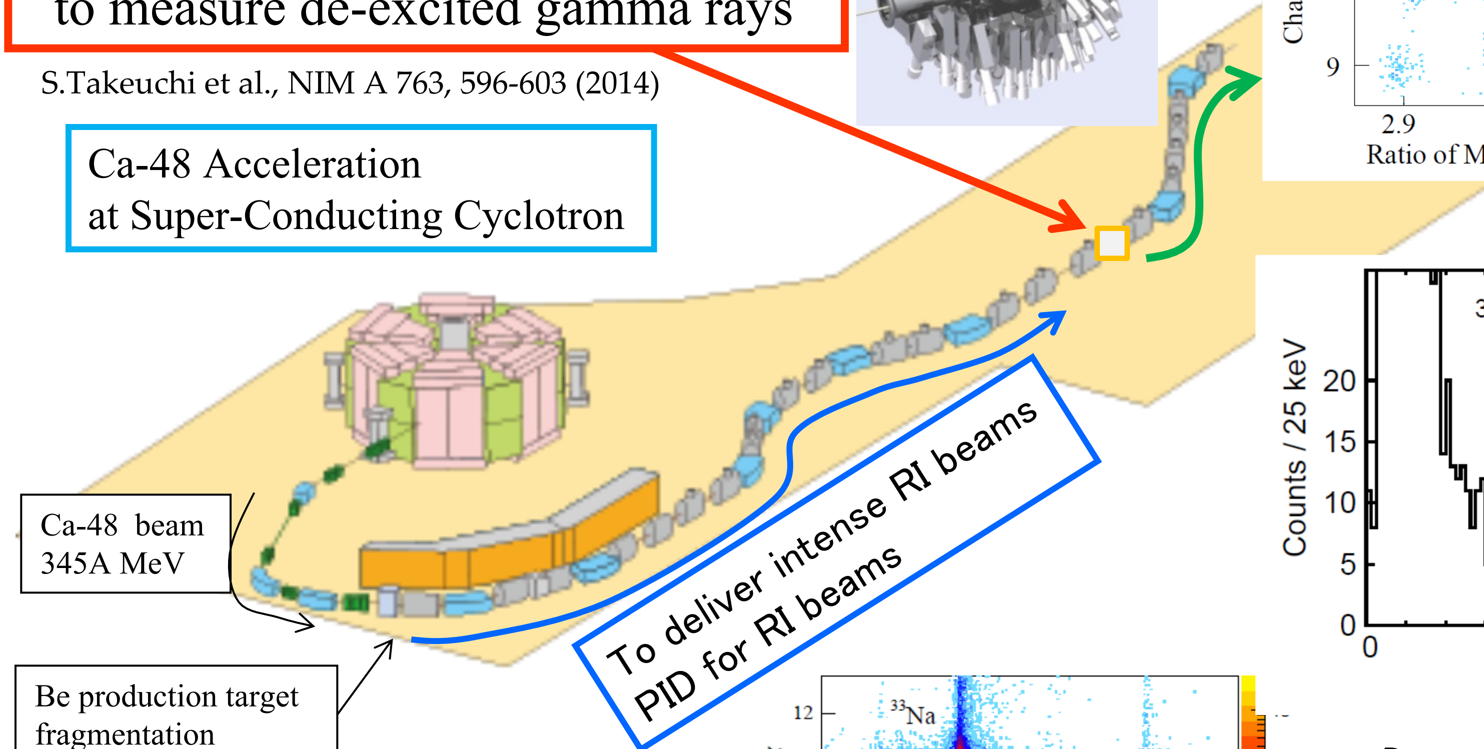
Secondary target: H_2, C, Pb….
Gamma-detectors : DALI2 NaI array to measure de-excited gamma rays

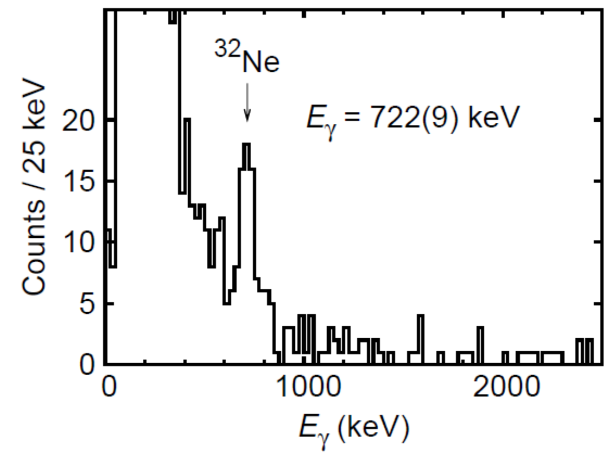
S.Takeuchi et al., NIM A 763, 596-603 (2014)

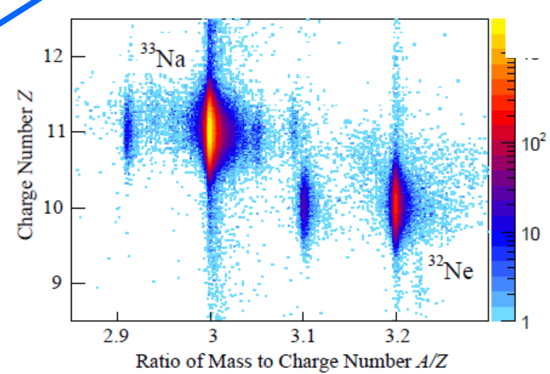


PID at ZeroDegree



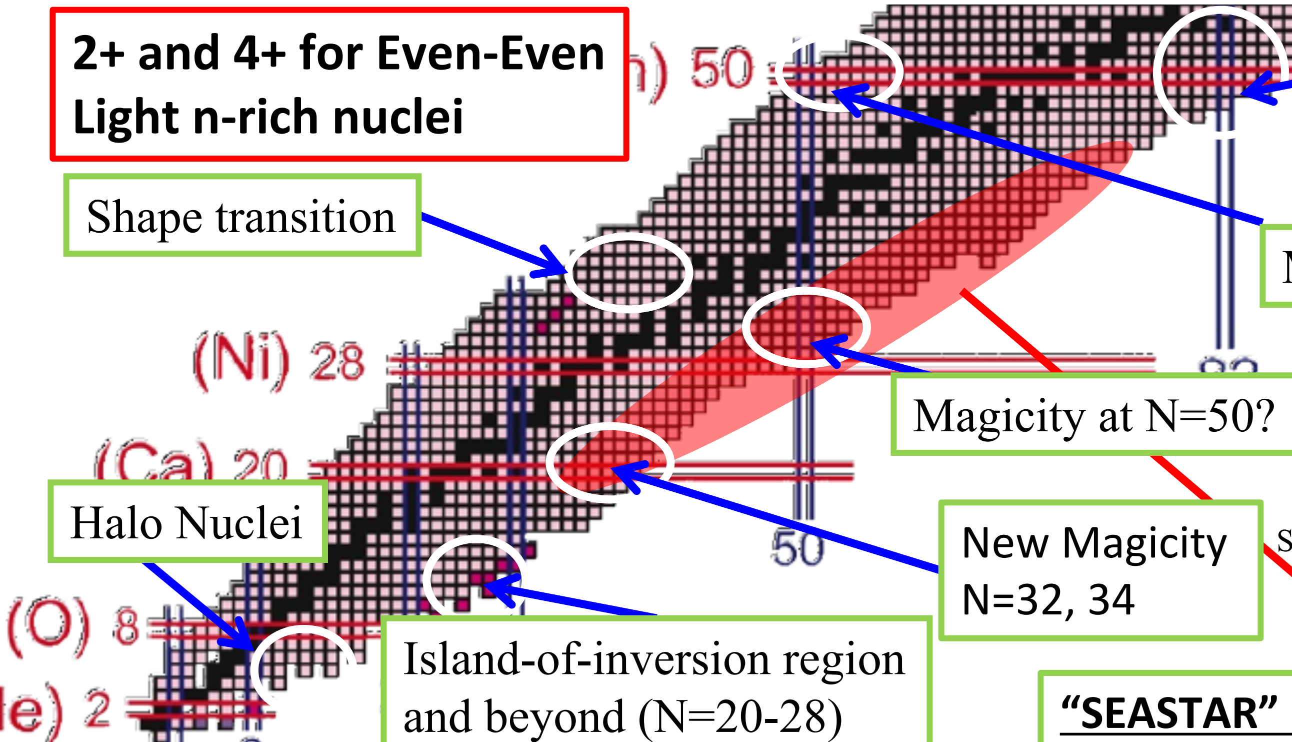






Doornenbal, Scheit et al.
PRL 103, 032501 (2009)

Achievements with DALI2 at ZD since 2009-



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

Shape transition

Halo Nuclei

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

New Magicity N=32, 34

Magicity at N=50?

Magicity at Z=50 and N=50?

Magicity at N=82 and Z=50?

^{126}Pd: Wang, PRC 88 054318 (2013)
^{136}Sn: Wang, PTEP 023D02 (2014)
^{126}Cd: Wang, PRC 94 051301 (2016)

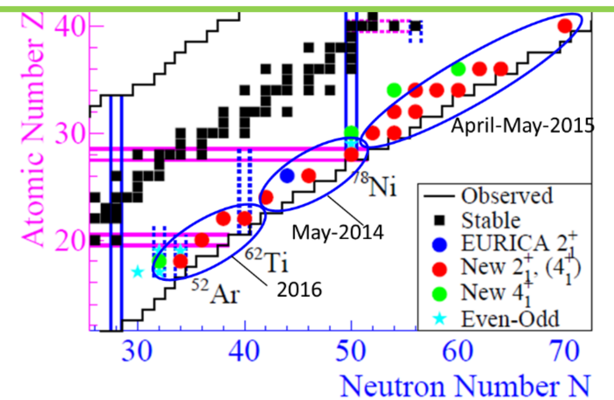
^{104}Sn: Corsi, PLB 743, 451 (2015)
^{104}Sn: Doornenbal, PRC90, 061302 (2014)

^{80,82}Zn: Shiga, PRC 93, 024320 (2016)

Steppenbeck, Nature 502, 207 (2013)
^{50}Ar PRL 114, 252501 (2015)

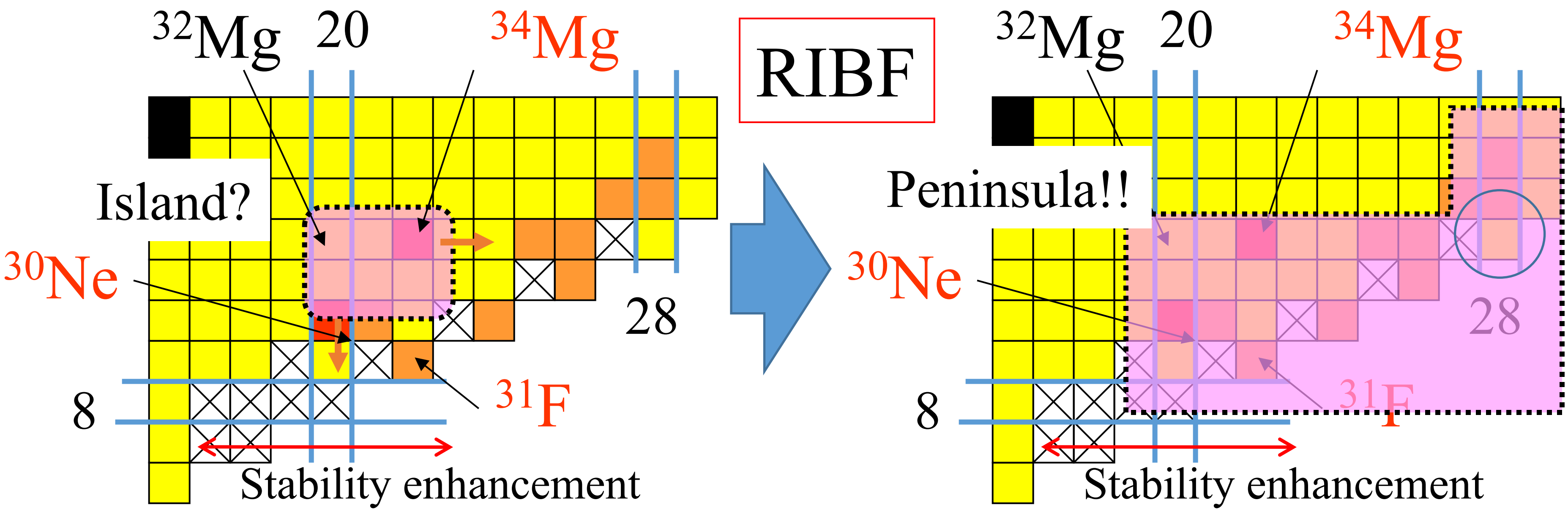
^{29}Ne : Kobayashi, PRC 93, 014613 (2016)
^{32}Ne:: Doornenbal, PRL 103, 032501 (2009)
^{31,32,33}Na: Doornenbal, PRC 81, 041305R (2010)
^{33,34,35}Na: Doornenbal, PTEP 2014, 053D01 (2014)
^{36,38}Mg: Doornenbal, PRL111, 212502 (2013)
^{32}Mg: Li, PRC 92, 014608 (2015)
^{42}Si : Takeuchi PRL109, 182501 (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)
^{30}Ne, ^{36}Mg B(E2): Doornenbal, PRC 93, 044306 (2016)

"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)

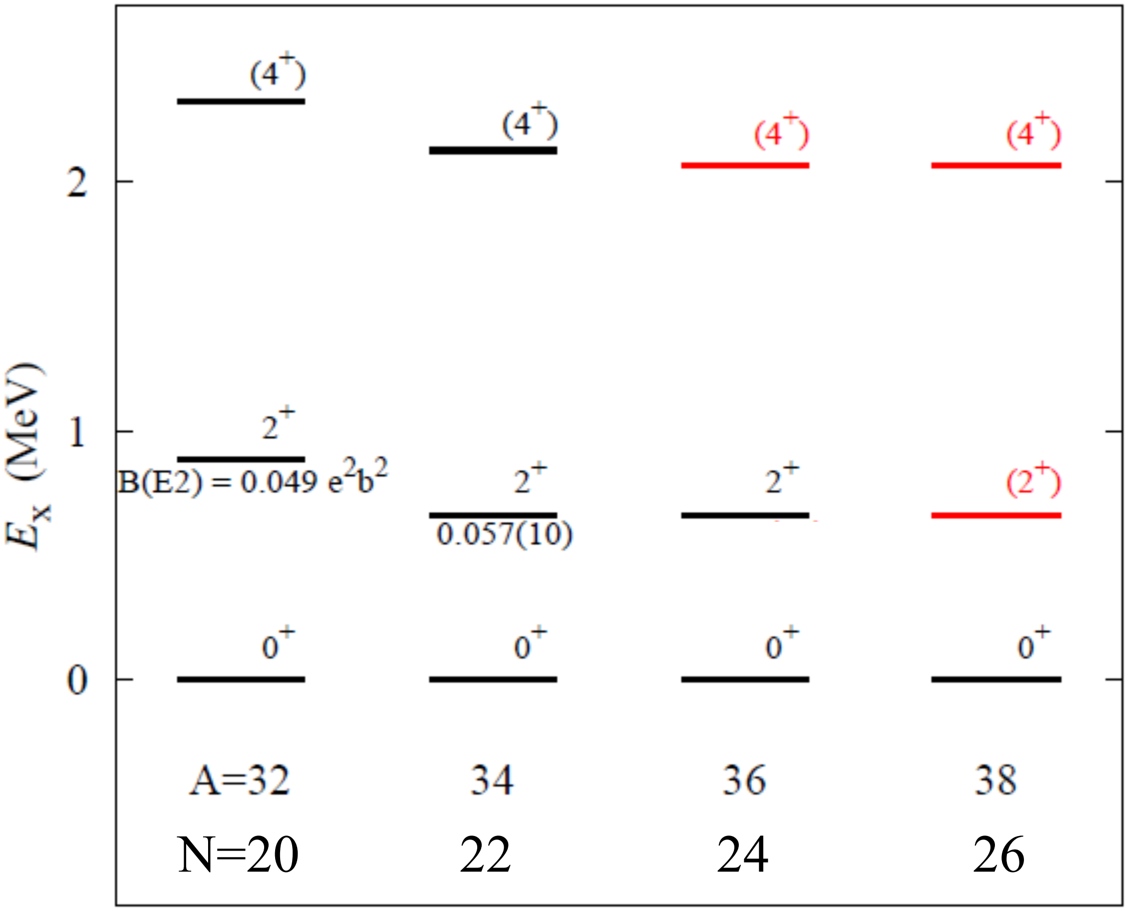
<u>P.Fallon et al.</u>

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?

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

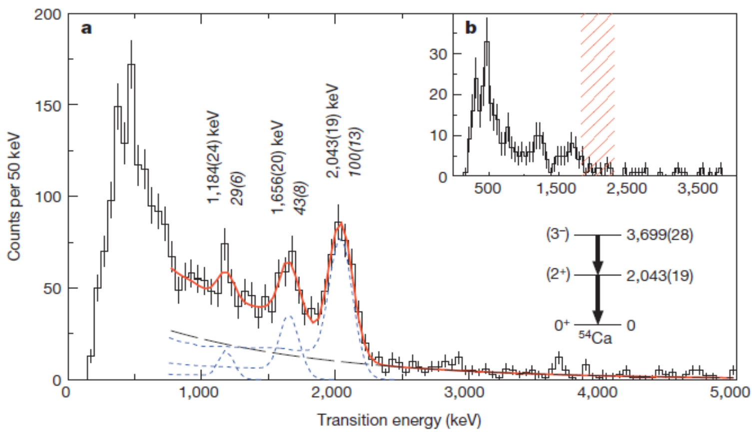
D. Steppenbeck et al., Nature 502

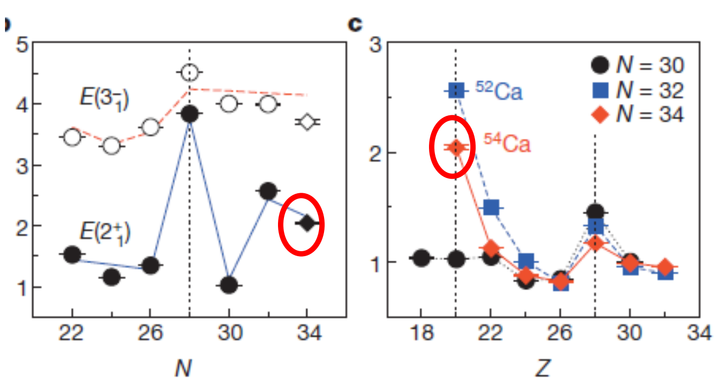
Zn-70 primary beam (100 pnA max)

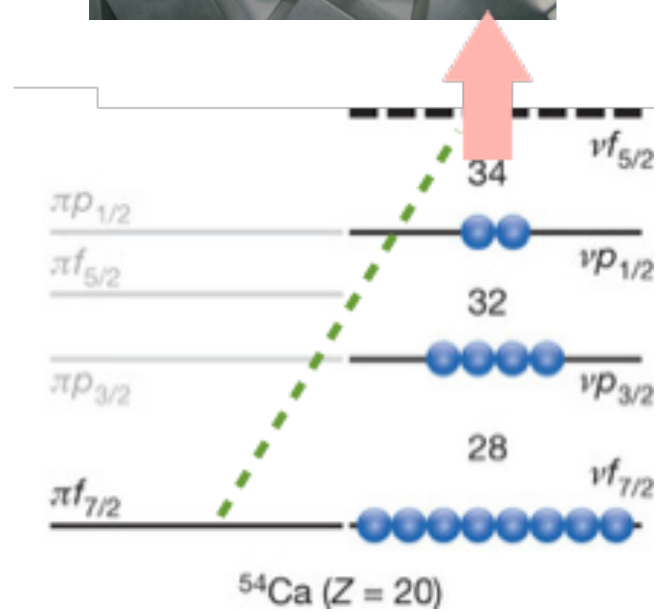
Ti-56 120 pps/pnA, Sc-55 12 pps/pnA

Zn-70 -> Ti-56, Sc-55

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







“Magicity” in the Ar isotopes : Ar-50 (N=32) 2012

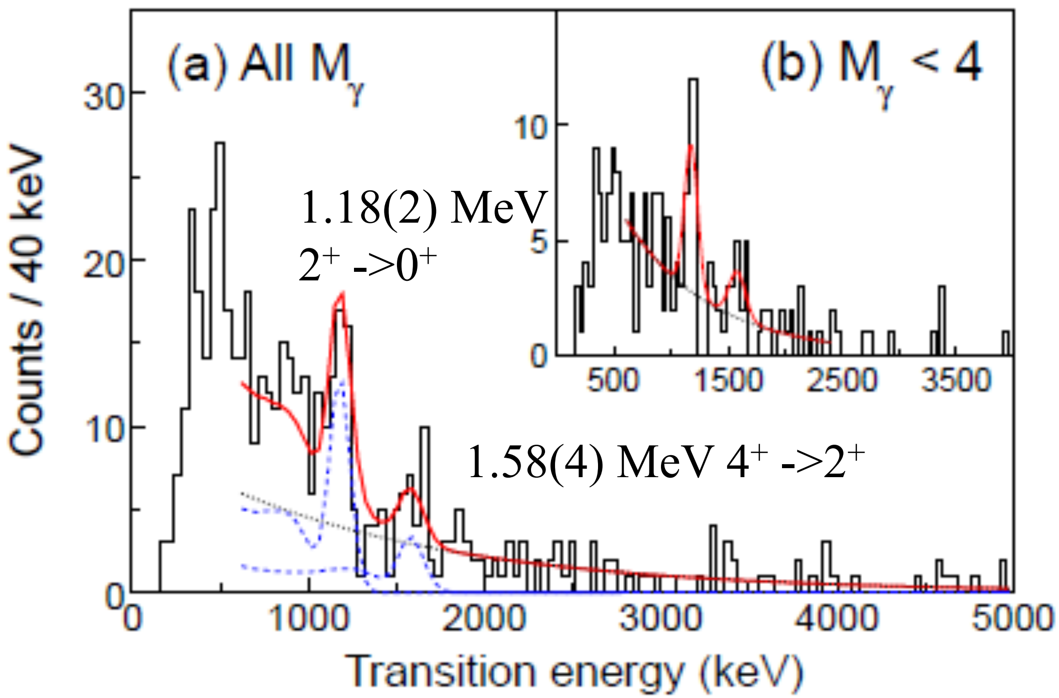
D. Steppenbeck et al., Phys. Rev. Lett. 114, 252501 (2015)

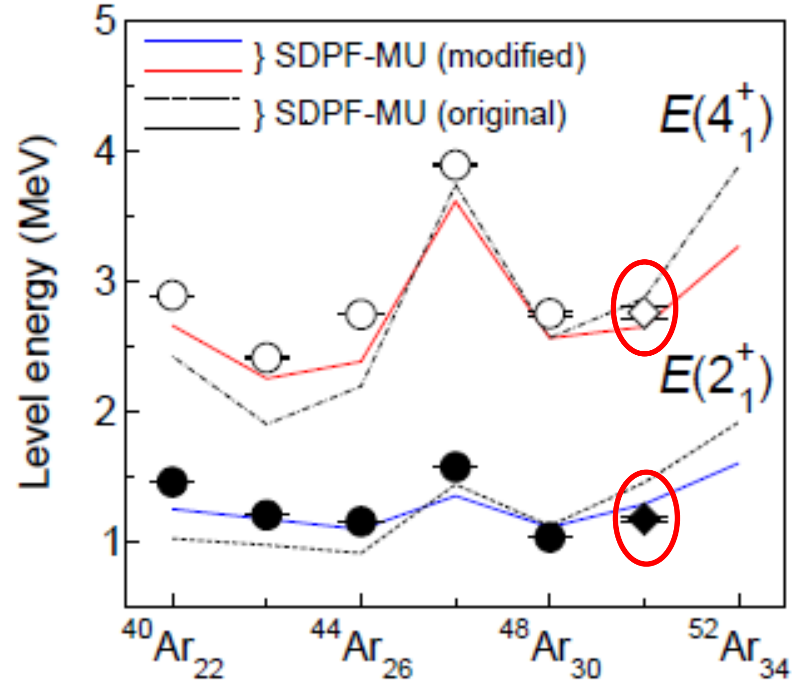
Sum of the reaction channels

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

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

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





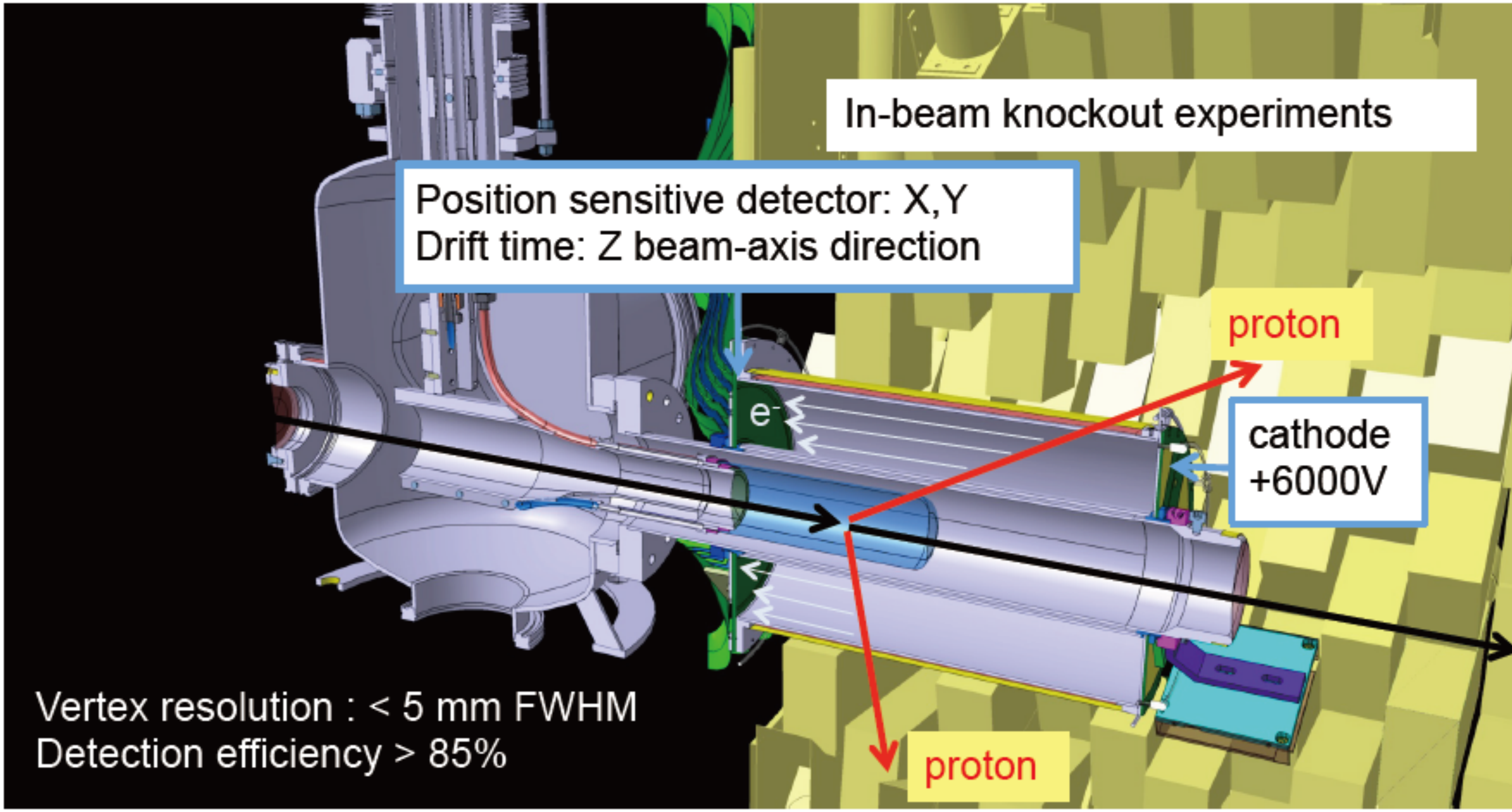
N=22 24 26 28 30 32 34

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

How about Ar-52 (N=34)?

Ca-56 (N=36)?

MINOS : Magic Numbers Off Stability



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

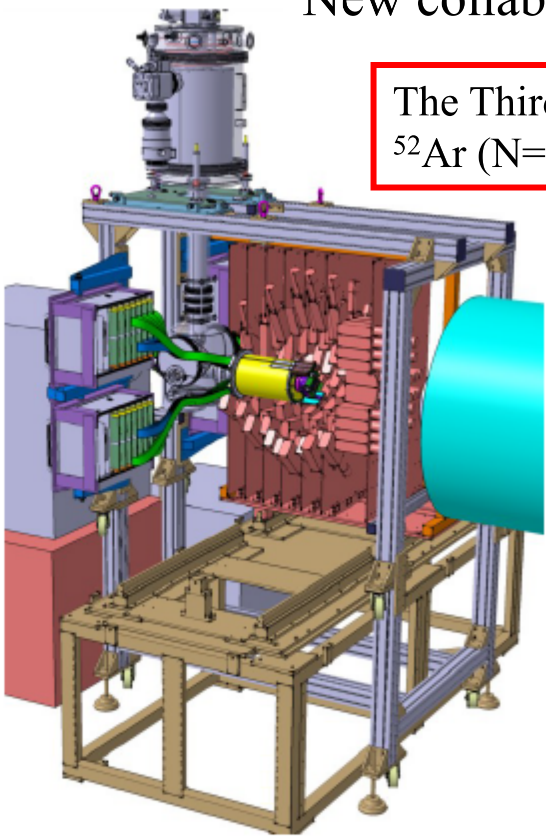
A. Obertelli

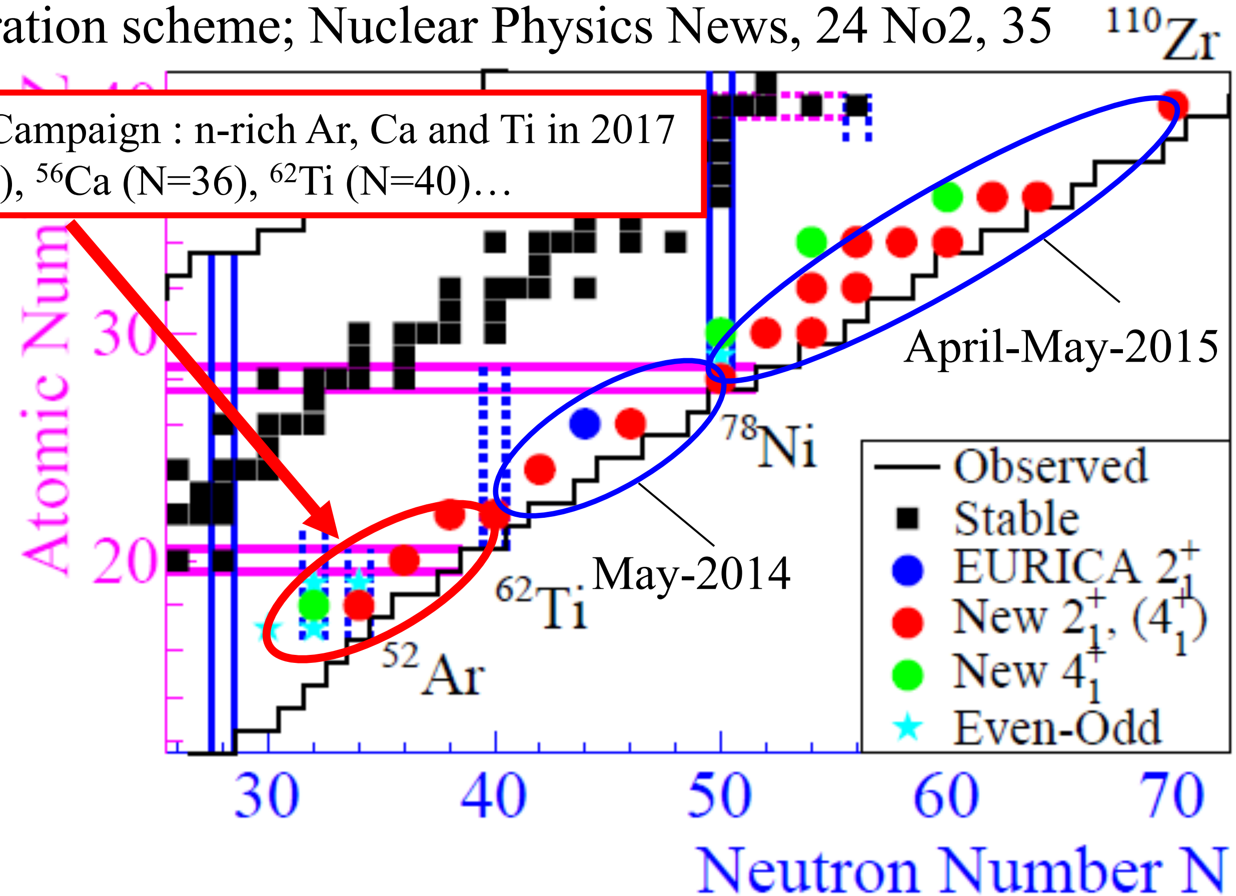
Shell Evolution And Search for Two-plus energies At the RIBF (SEASTAR) – a RIKEN Physics Program

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

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

The Third Campaign : n-rich Ar, Ca and Ti in 2017
^{52}Ar (N=34), ^{56}Ca (N=36), ^{62}Ti (N=40)…



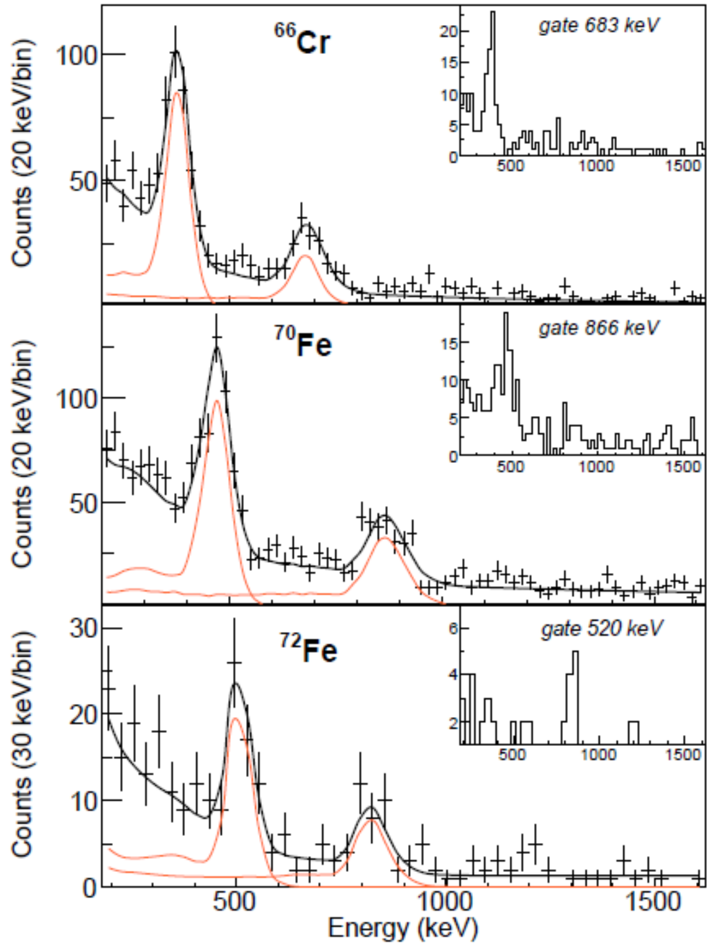


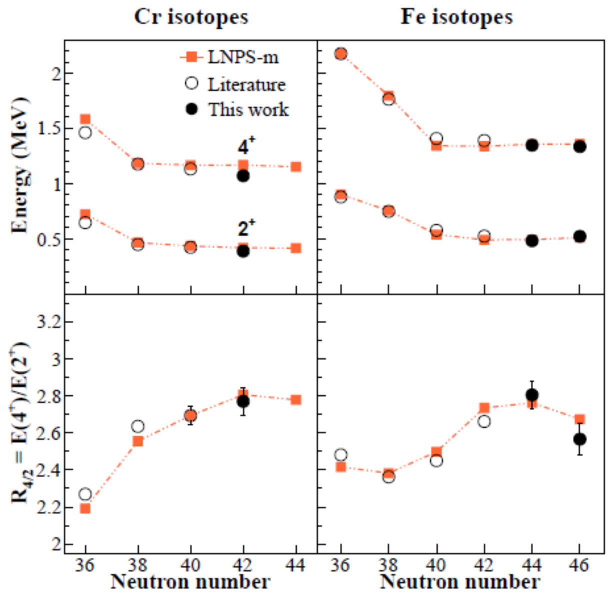
MINOS (100-mm thick Liq.H_2 target and TPC system, $\Delta\beta$ = 20%)
-> high luminosity and vertex position determination
DALI2 -> high efficiency
to access very neutron-rich nuclei

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

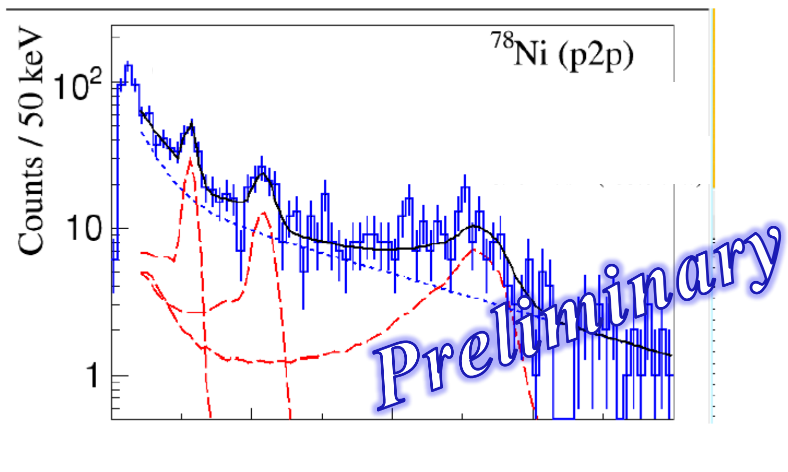
Santamaria, Louchart, Obertelli et al,
PRL 115, 192501 (2015)





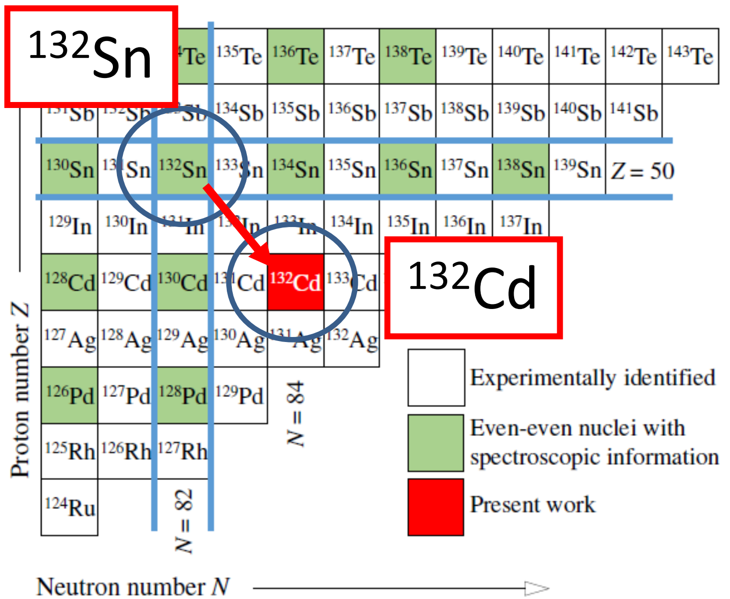
(2) First spectroscopy of ^{78}Ni

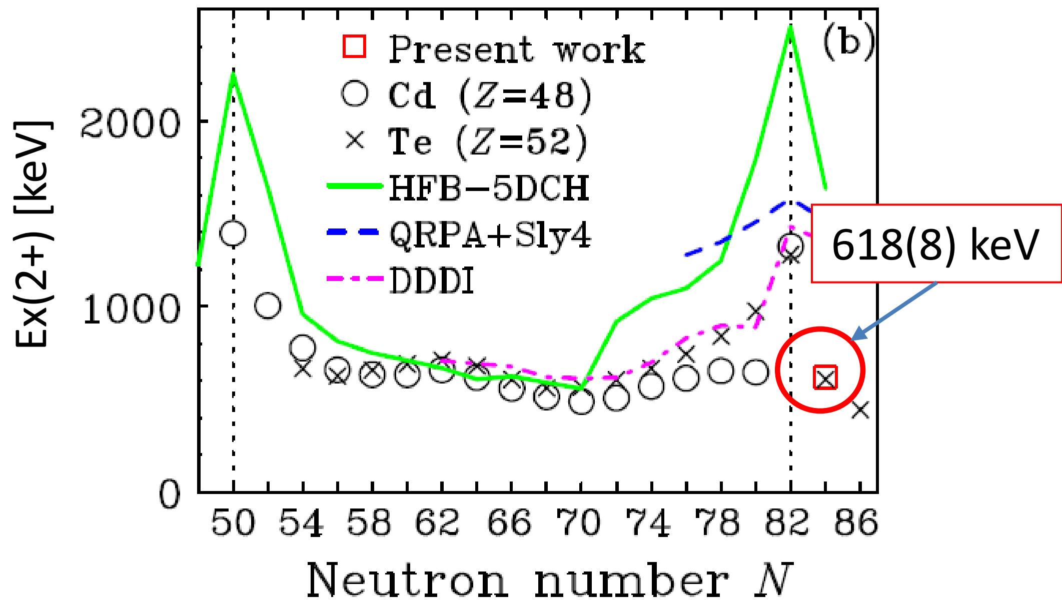
Taniuchi, Doornenbal, Yoneda et al., in preparation



First spectroscopic information on "Southeast" of ^{132}Sn; ^{132}Cd

Wang et al., PRC 94, 051301 (R), 2016





Neutron dominant excitation beyond N=82

N=84

$|2^+; {}^{132}\text{Cd}\rangle = (0.13)^{1/2}|\pi^{-2}\rangle +/- (0.87)^{1/2}|\nu^{2}\rangle$

$|2^+; {}^{136}\text{Te}\rangle = (0.15)^{1/2}|\pi^{2}\rangle +/- (0.85)^{1/2}|\nu^{2}\rangle$

Small B(E2) of 136Te
Radford et al., PRL88, 222501 (02)

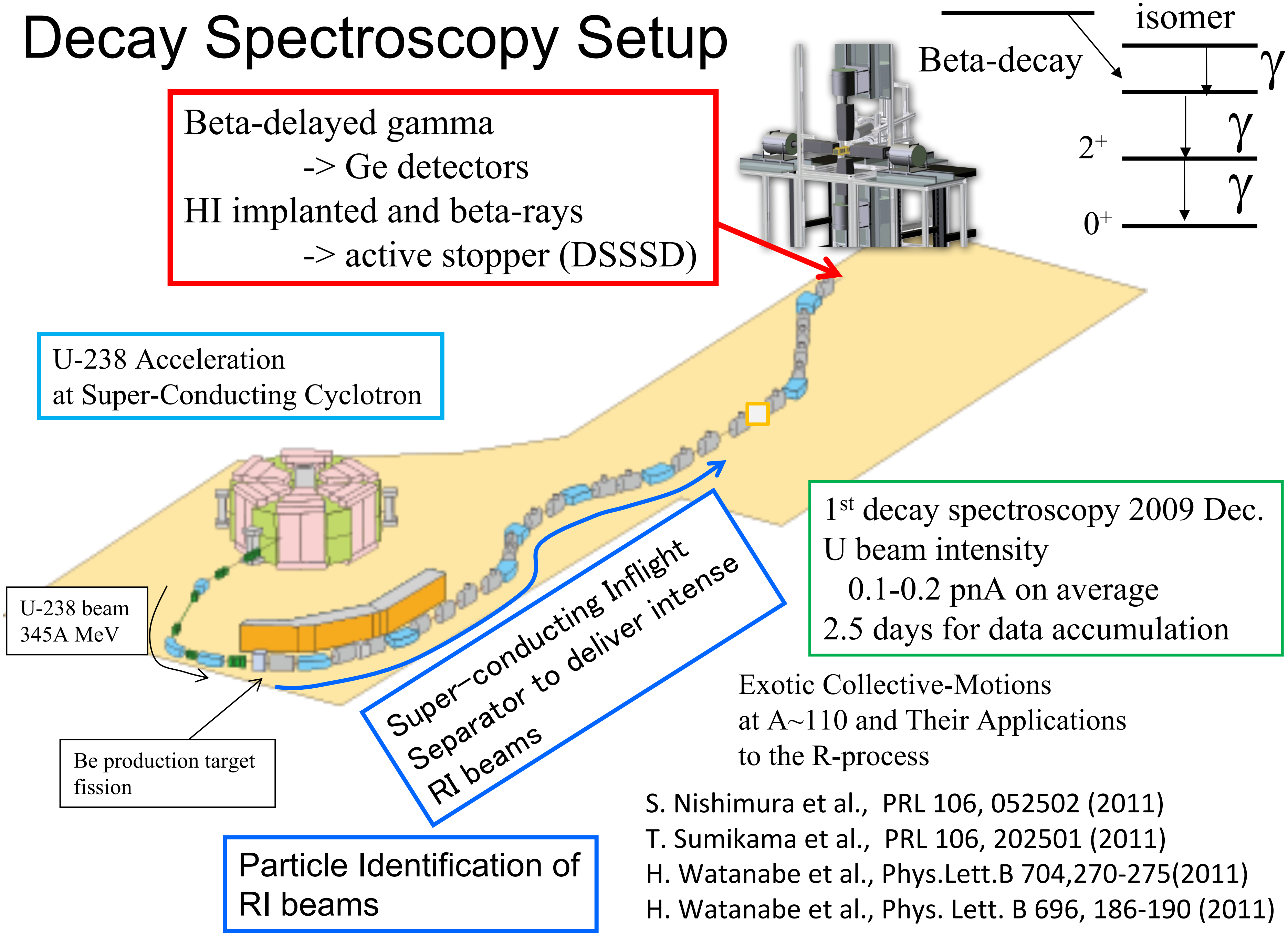
N=80

$|2^+; {}^{128}\text{Cd}\rangle = (0.46)^{1/2}|\pi^{-2}\rangle +/- (0.54)^{1/2}|\nu^{-2}\rangle$

$|2^+; {}^{132}\text{Te}\rangle = (0.45)^{1/2}|\pi^{2}\rangle +/- (0.55)^{1/2}|\nu^{-2}\rangle$

Precise mass measurement
Hakala et al., PRL 109, 032501 (12)
Neutron-pairing gap at Z=50
Is quenched beyond N=82…!?

Decay Spectroscopy Setup

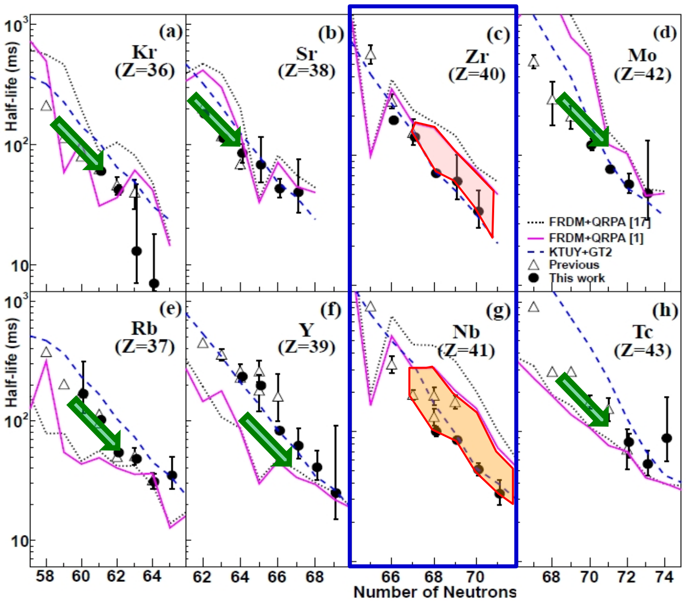


1st decay spectroscopy 2009 Dec.
U beam intensity
0.1-0.2 pnA on average
2.5 days for data accumulation

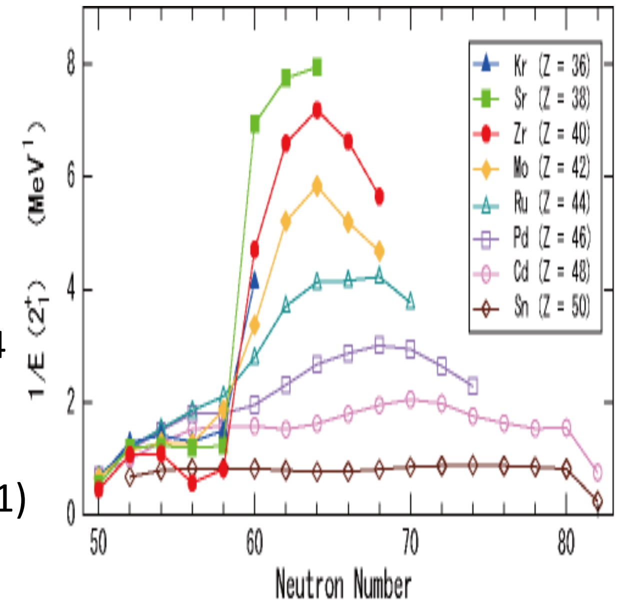
Exotic Collective-Motions
at A~110 and Their Applications
to the R-process

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

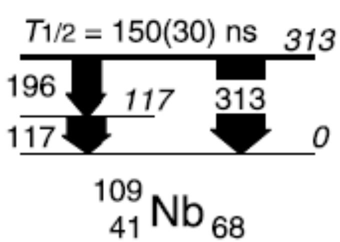


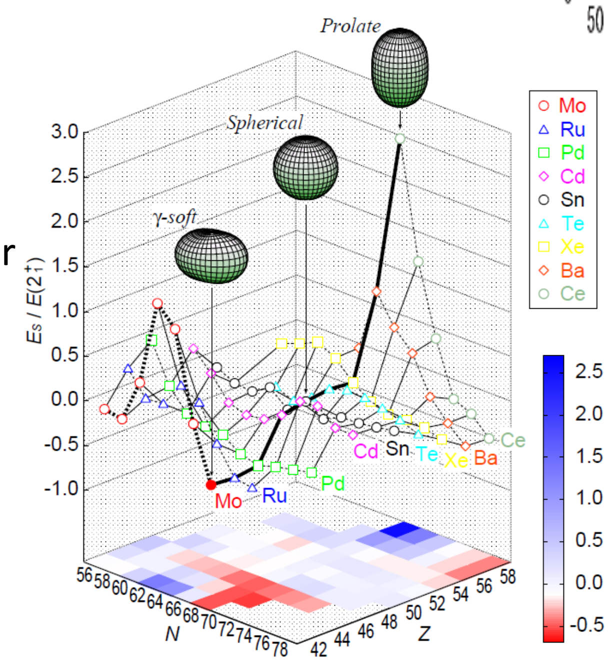
New Half-life data for 18 new isotopes
S. Nishimura et al.,
PRL 106, 052502 (2011)



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)

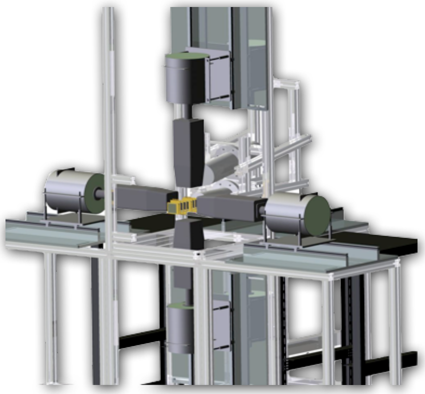




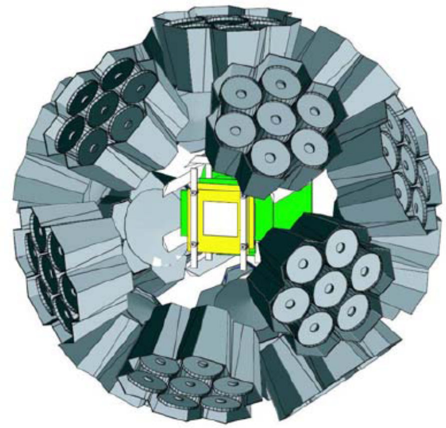
Development of axial asymmetry in neutron-rich nucleus Mo-110
H. Watanabe et al.,
Phys.Lett.B 704,270-275(2011)

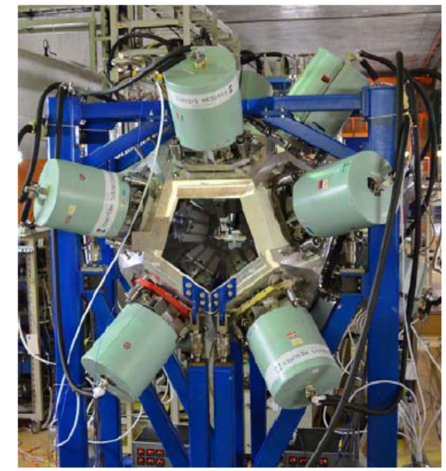
EURICA Invitation

First decay spectroscopy in 2009



EURICA setup





EUroball-RIKEN Cluster Array

U-beam intensity … x 50 times

- 0.2 pnA → 10 pnA

Gamma-ray efficiency … x 10 times

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

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

Beam time x 40 times

- 2.5 days (4 papers) → 100 days … (160 papers)

EURICA Installation

Ivan Kojouharov

Nick Kurtz

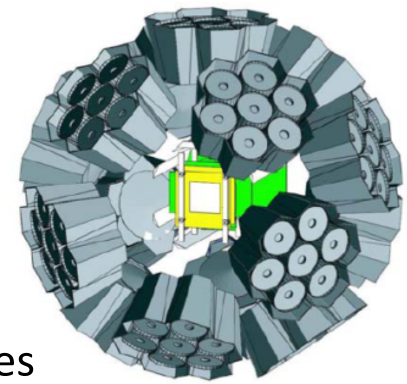
Henning Schaffner

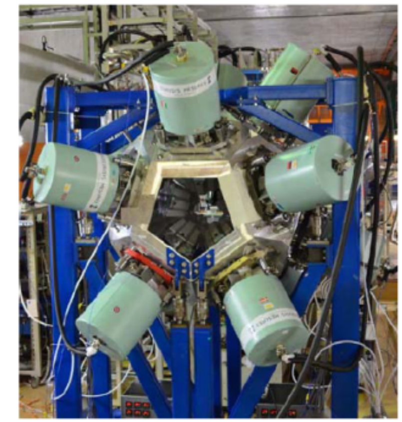
EURICA

EUroball-RIKEN Cluster Array 2012-2016

Beta-delayed gamma / Isomer Spectroscopy

12 Euroball Cluster detectors
Support structure
Electronics/daq used for RISING

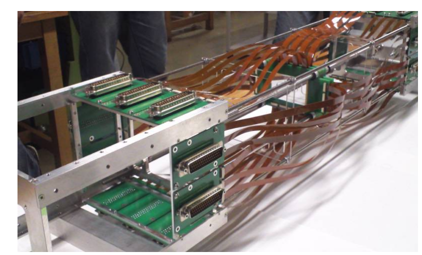




RIBF: decay station
Active stopper: DS-SSD (WAS3ABi)
Liq. N_2 system, other infrastructures

+Additional detectors ($LaBr_3$, Plastic …)

WAS3ABi

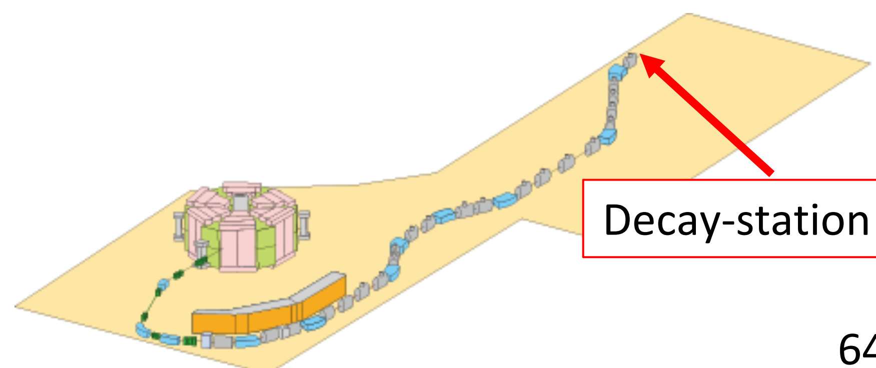


230 collaborators from 19 countries
About 100 days were approved for physics run

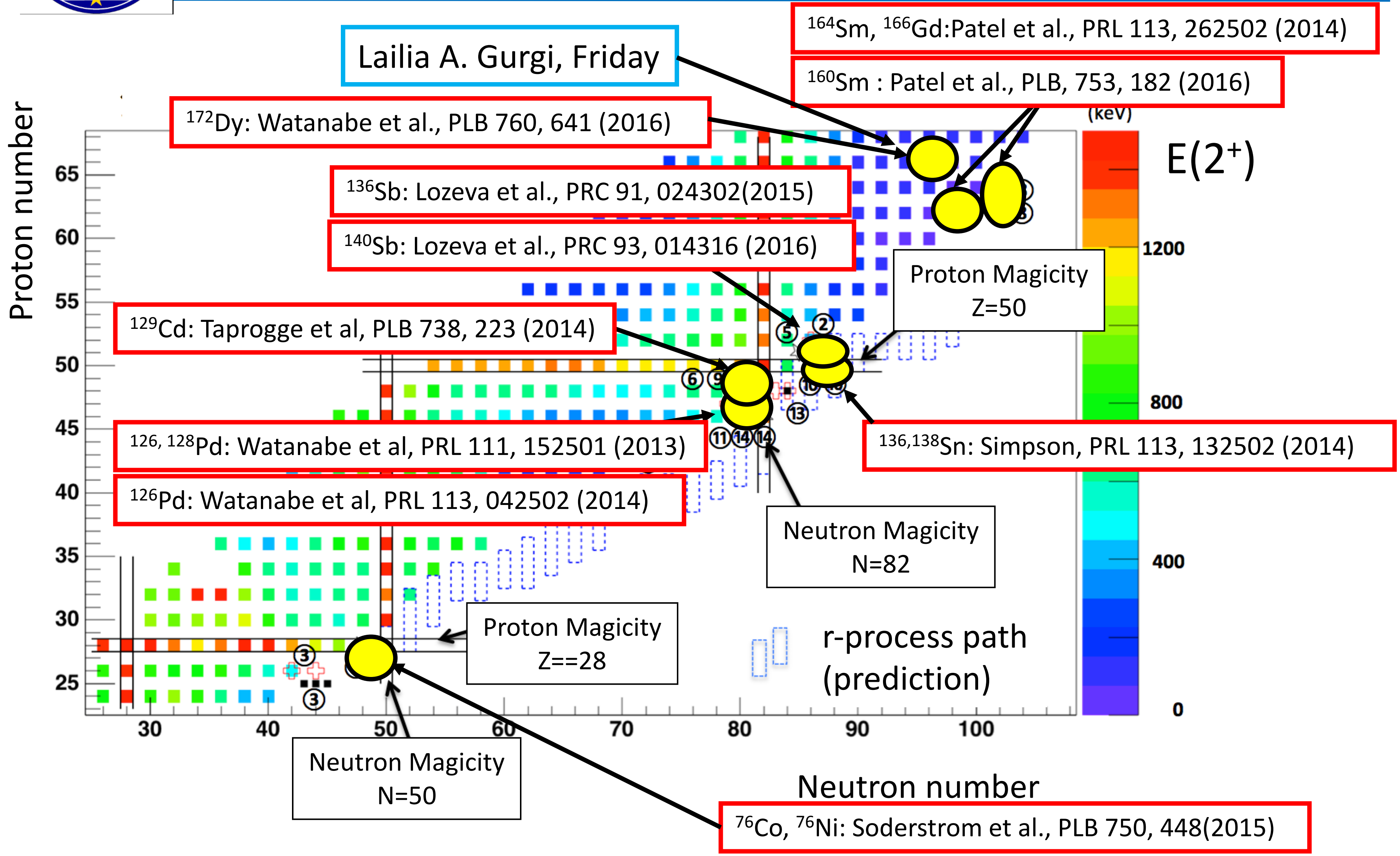
Commissioning	March 2012	NIM B 317, 649 (2013)
Physics Run	June 2012 – June 2016	

Publication at this time (September 2016)
- 23 papers (8xPRL, 5xPLB, 3xPRC(R), 7xPRC)
- 9 PhD Thesis + 1 Master Thesis
- 31 proceedings
- 8 technical articles

"End-of-Campaign WS Sept.6-7th, 2016

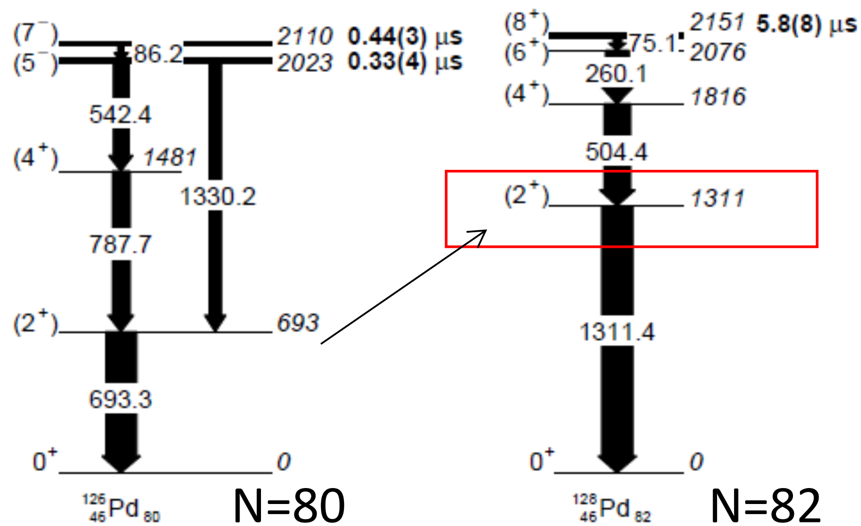


EURICA Achievements (2012-): isomers

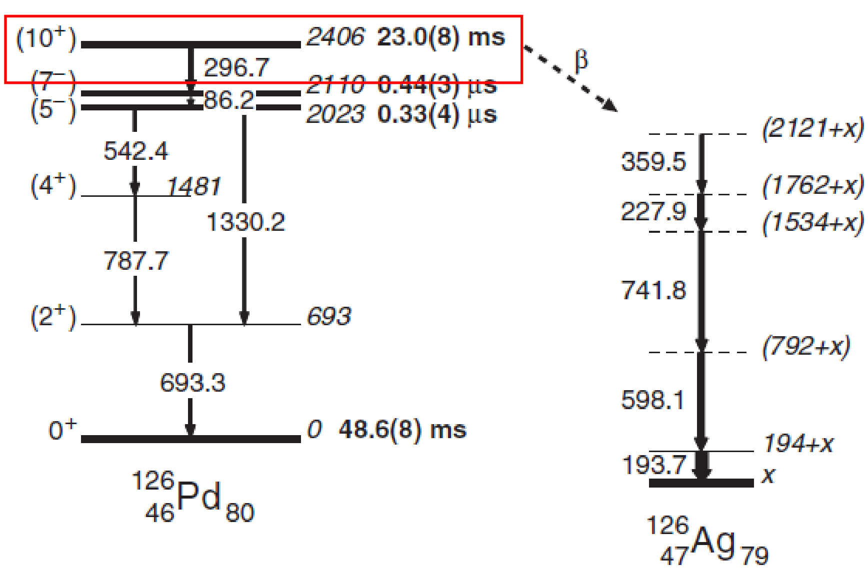


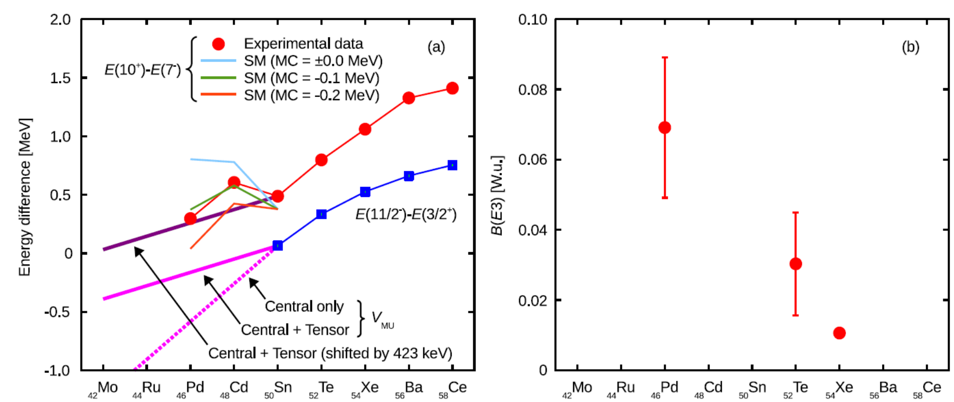
Isomers in ^{128}Pd and ^{126}Pd:

H. Watanabe et al., PRL 111, 152501 (2013)
H. Watanabe et al., PRL 113, 942502 (2014)



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



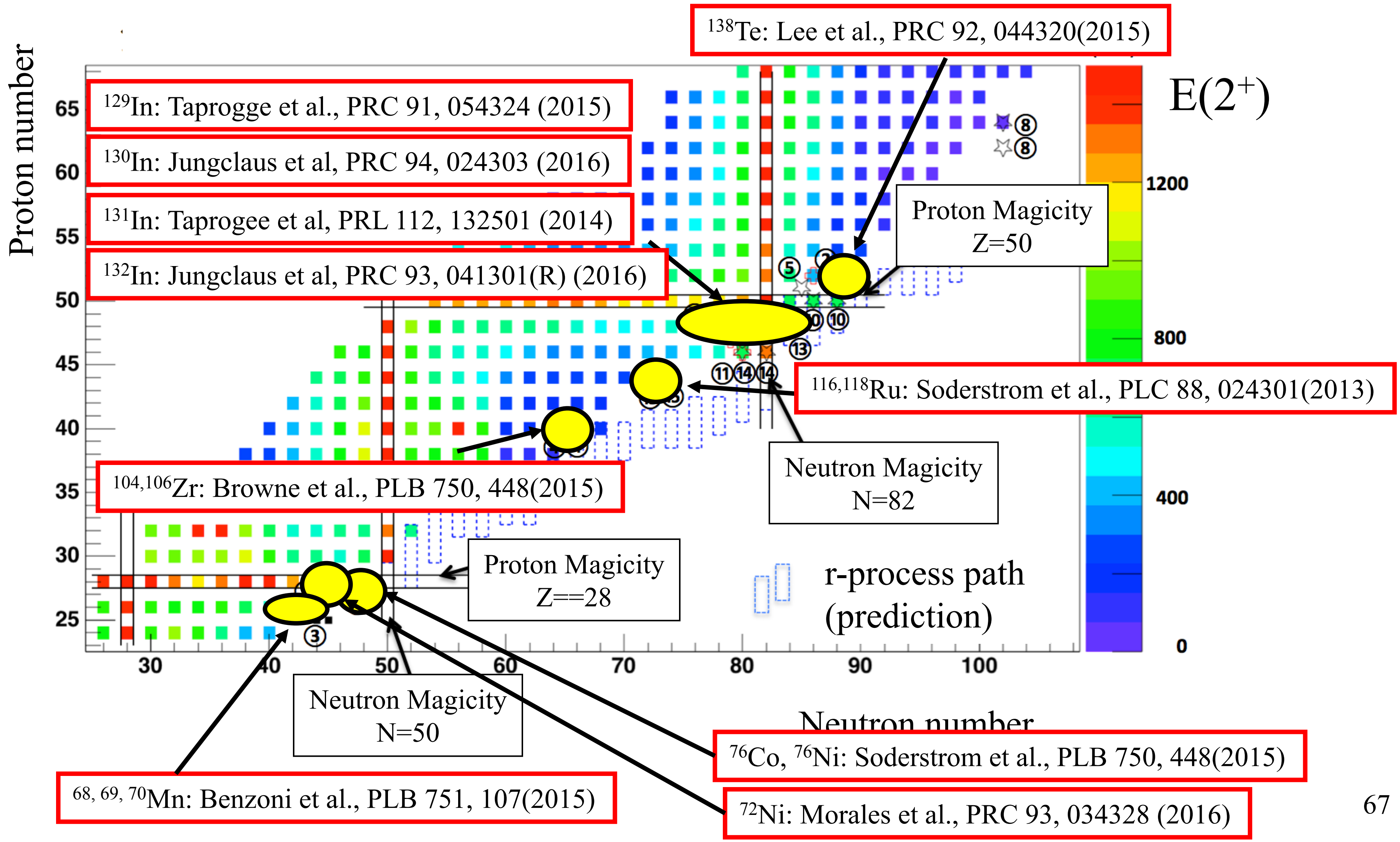


Small energy difference between (10^+) and (7^-)

$(\nu 1h_{11/2}^{-2})_{10^+} \quad (\nu 1h_{11/2}^{-1} 2d_{3/2}^{-1})_{7^-}$

Information for shell-model interactions

EURICA Achievements (2012-): Beta-gamma

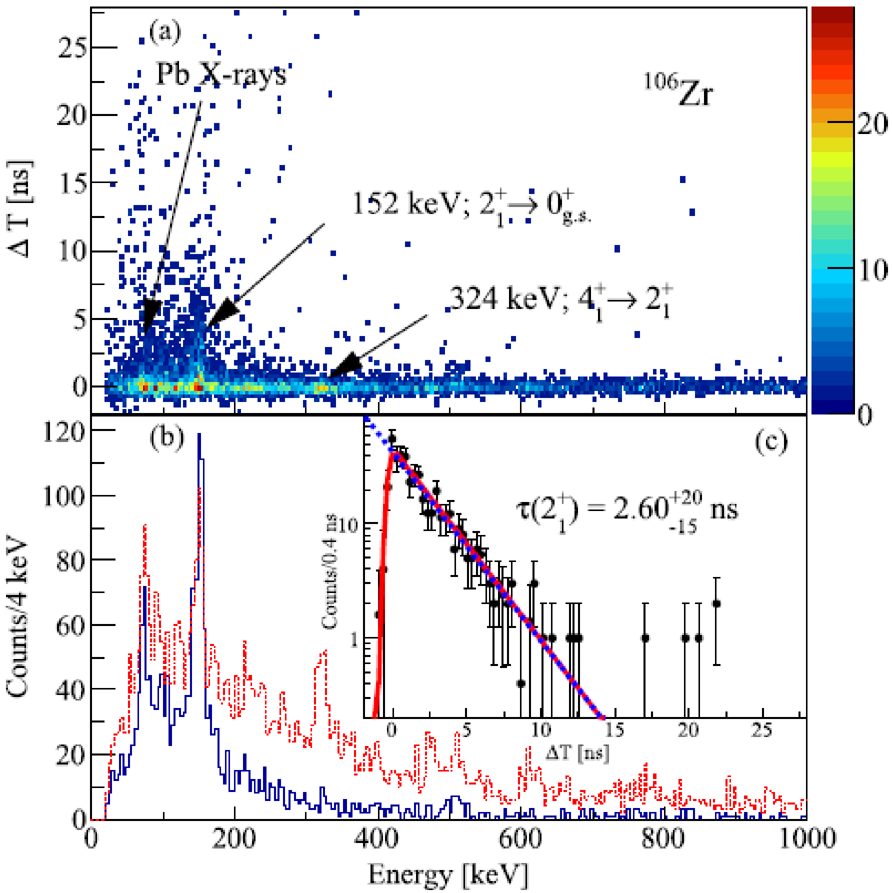


Lifetime of measurements of the first 2^+ states in ^{104,106}Zr: Evolution of ground-state deformations

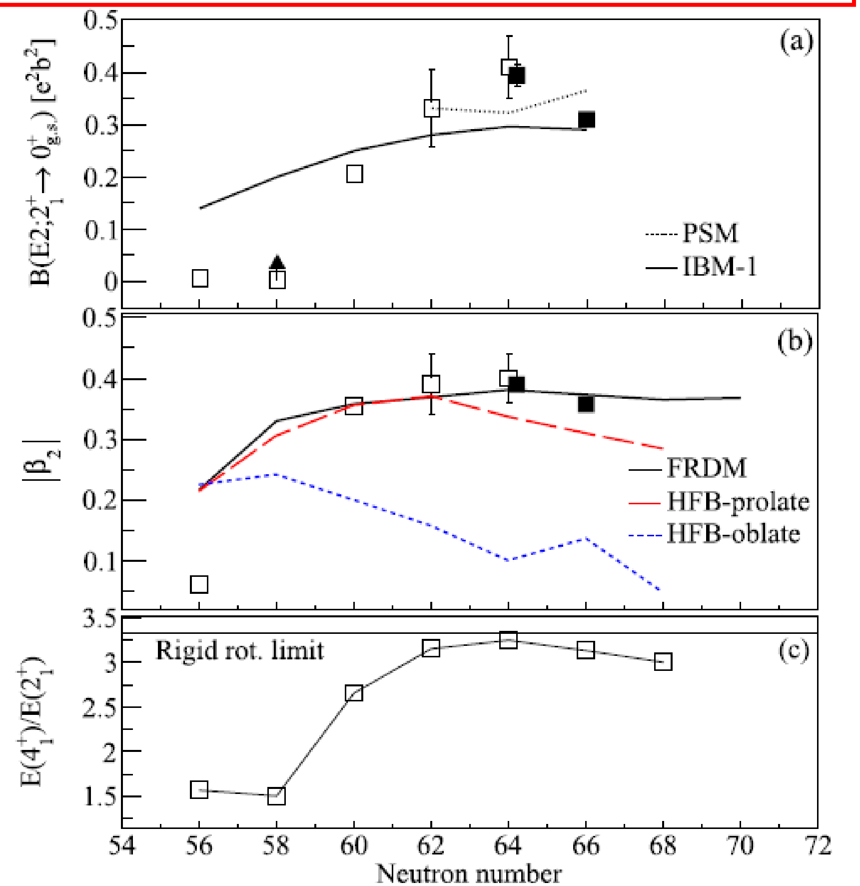
Browne et al., Phys. Lett. B 750 448-452 (2015)

$LaBr_3$(FATIMA) E and T resolution, 10% and 0.8 ns (FWHM), respectively for 150-170 keV gamma

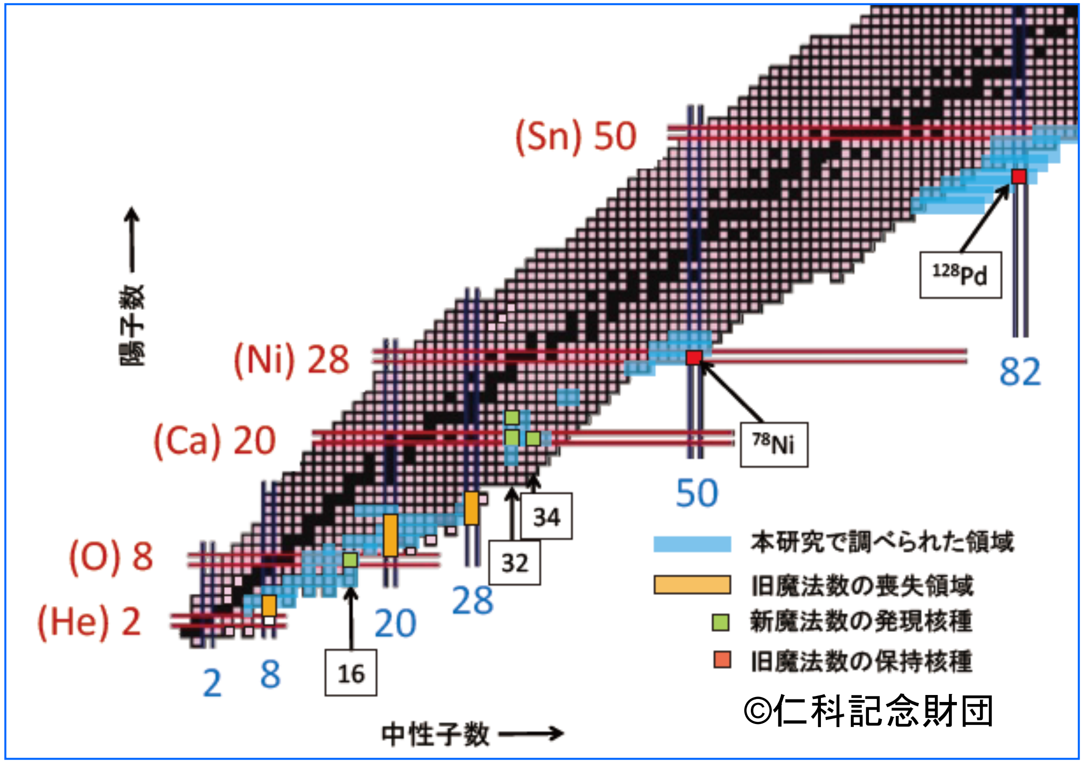
EURICA Feeding analysis 50% from 4^+, 20% from others



Confirmation of Deformed Magic of N=64



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）

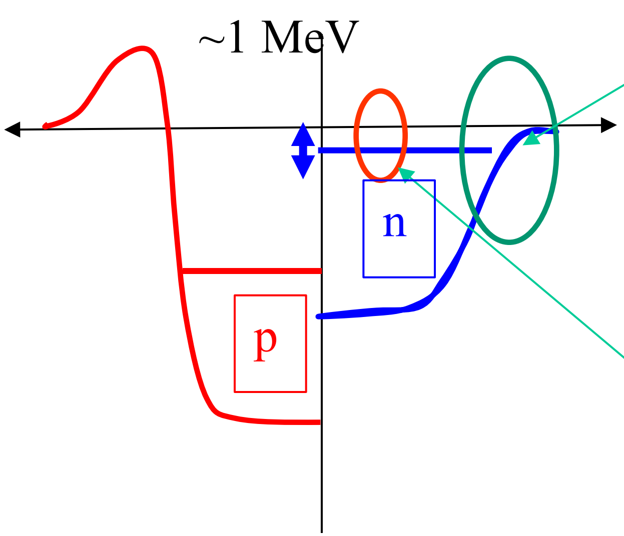
Magicity at N=82 with Z>46…

^{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)

Nuclear Magic Numbers and Shell Evolution

Neutron-rich nuclei

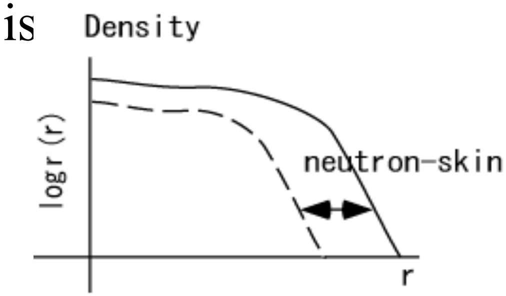


L dependence of single-particle energies

Lower L orbits are less sensitive to binding energies

LS term ?: proportional to dρ/dr

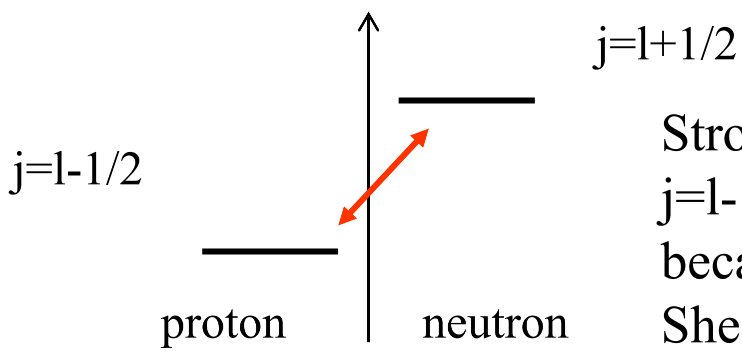
A typical skin thickness is order of 1fm.
High L orbits may have some effects



Coupling with continuum states?

Pairing effects might be changed
Dynamical properties become softer?

Residual interactions?



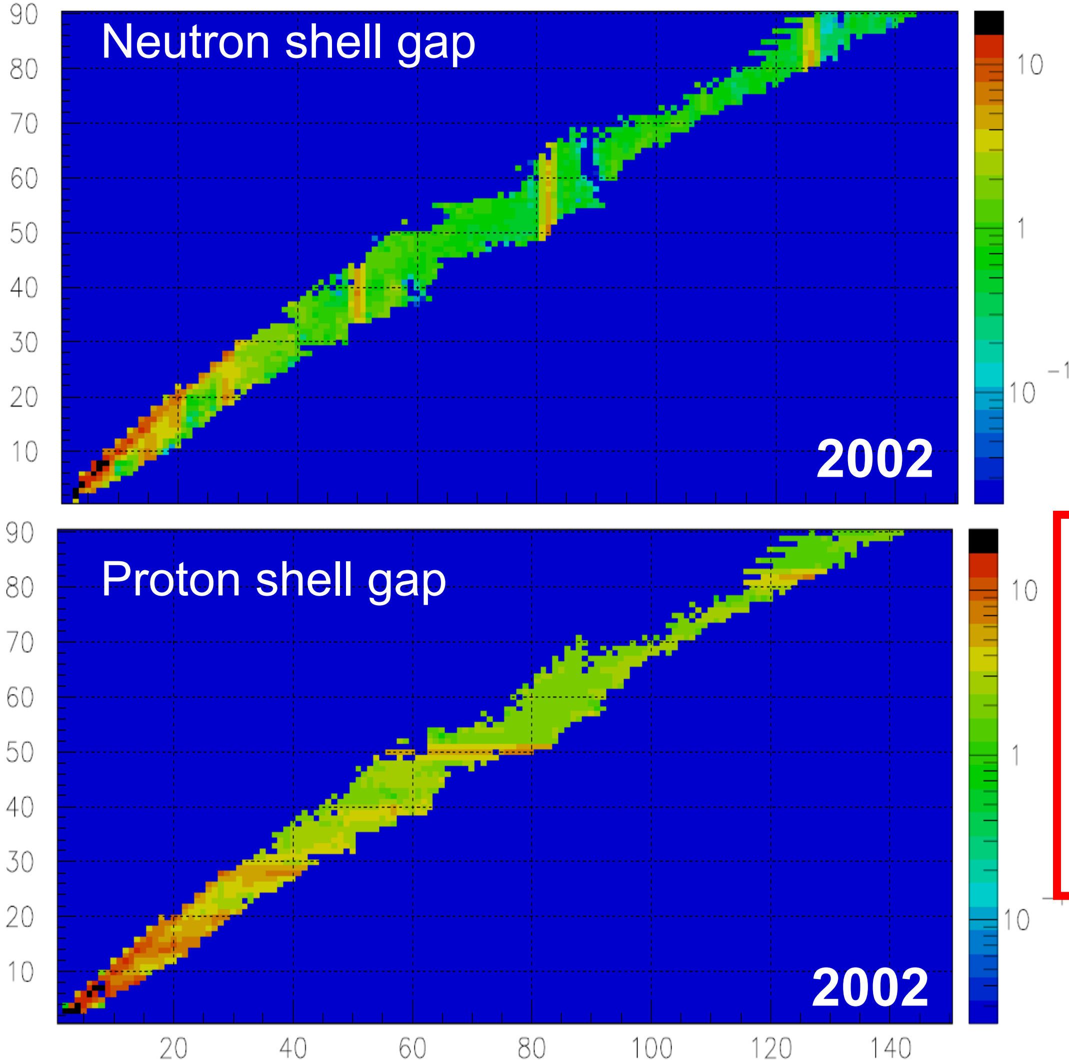
Strong p-n interactions between j=l-1/2 and j=l+1/2 orbits, because of tensor terms.
Shell gaps depend on number of nucleons in the orbits

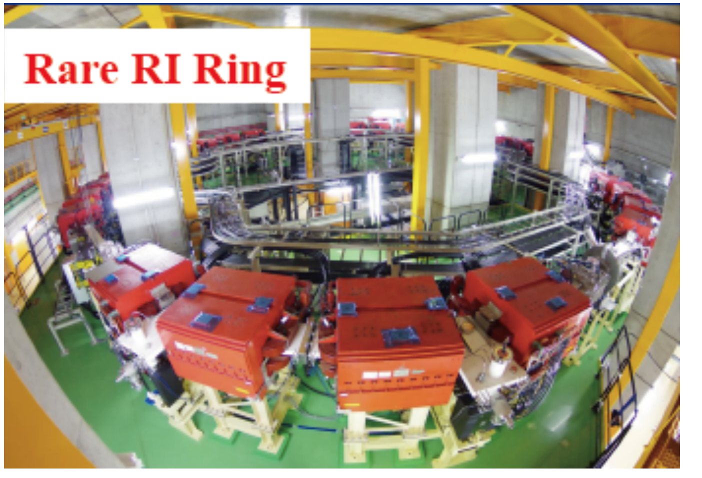
3NF?

ab-initio + chiral-perturbation

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**

“Asahi Shinbun” News Paper, 18th Aug., 2014

科学の扉

RI Beam Factory

ＲＩビームファクトリー

元素を加速して衝突させて分析する施設。円形や直線状の複数の加速器で構成され、約１万平方㍍の施設に加速器や原子核の大きさなどを調べる機器が据えられている。欧州などの大型加速器が電子など小さな粒子を加速させるのに対して、重い元素を加速できる特徴がある。不安定な原子核を作る能力は世界最大。

原子核

原子の中心。中性子と陽子で構成され、陽子の数で元素の種類が定まる。原子核は天然に約270存在し、実験などでできたものが約3000見つかっている。

元素の魔法数

Magic Numbers of Elements

万物誕生の謎 解明のカギ

身の回りには、ありふれた元素と少ししかない元素がある。星の中心で作り出され、その爆発で宇宙に散らばった主な元素。「魔法数」という不思議な数によって、元素が生み出される。その中心にある原子核を調べる研究が進み、元素が生まれる過程の謎が解き明かされつつある。

宇宙誕生のビッグバン直後に作られたのは、主に水素とヘリウムだった。だが、宇宙には、もっと多くの元素がある。人間の体にたくさん含まれる酸素や炭素、水素、骨のカルシウムや血液の鉄などの元素は、どうやってできたのか。

東京工業大の中村隆司教授（原子核物理学）は「私たちの体は、星屑でできていると言える」と話す。

太陽など恒星では水素が燃えてヘリウムを作り出す核融合反応が起きている。太陽より大きい恒星の中心部では、ヘリウム3個が集まって炭素が作られ、もう一つヘリウムが結合して酸素ができている。星が大きいほど作られる元素は増え、重い元素ほど中心に近い部分で作られる。いわば元素工場だ。

星が寿命を迎えると、超新星爆発で宇宙にばらまかれる。それが、再び集まって次世代の恒星や惑星を作り出している。

ただ、宇宙で元素ができる仕組みは謎もある。

恒星の核融合で作られる元素は、原子番号26の鉄まで。元素のなかで最も安定しており、そこで核融合が止まるためだ。

金や鉛のように、鉄より重い元素は、宇宙でどうやって合成されたのか。

重い元素は、鉄が中性子を吸収してできる。巨大な恒星の内部でゆっくりできるほか、太陽の8倍以上の恒星が超新星爆発を起こした時や、大きな星の最晩年の姿で主に中性子からできている中性子星同士が合体した時にできる説が有力だ。

原子核安定の数

宇宙に存在する元素の割合を比べてみると、重い元素ほど少ない。ビッグバン直後にできた水素やヘリウムは多く、その後にできた元素ほど少ない。

ただ、酸素やカルシウム、鉛などは重さが近い元素と比べて突出して多い。元素の原子核を作る中性子や、陽子の数が、原子核の安定とかかわる「魔法数」だからだ。

原子核の構造は、陽子や中性子が一つのボールのようにかたまっているのではなく、それぞれが何重もの殻の構造を持つと考えられている。「殻模型」と呼ばれる理論で、原子核を回る電子のように、特定の軌道を運動する。

一つの殻には一定の数の陽子や中性子しか存在できない「定員」があるため、内側から殻を埋めていく。最も外側の殻が「定員」ちょうどで埋まると安定する。安定になる陽子や中性子の数が魔法数だ。

魔法数は定説では、2、8、20、28、50、82、126の計七つ。ヘリウム（中性子と陽子が各2個）や酸素（同8個）など、陽子も中性子も魔法数のときは、特に安定する。安定な元素は、宇宙に存在する割合が多い。

変化する「定員」

元素ができる仕組みを解き明かすカギは、不安定な原子核だ。

重い原子を分析する装置が開発され、1990年代から中性子が陽子よりも多く不安定な元素の研究が進み、不安定な原子核には新しい魔法数があることがわかった。

「新しい魔法数34を見つけた」。昨年10月、埼玉県和光市にある理化学研究所の最先端加速器施設「放射性同位元素（RI）ビームファクトリー」で実験を続けてきた武内聡・協力研究員らのチームが発表した。

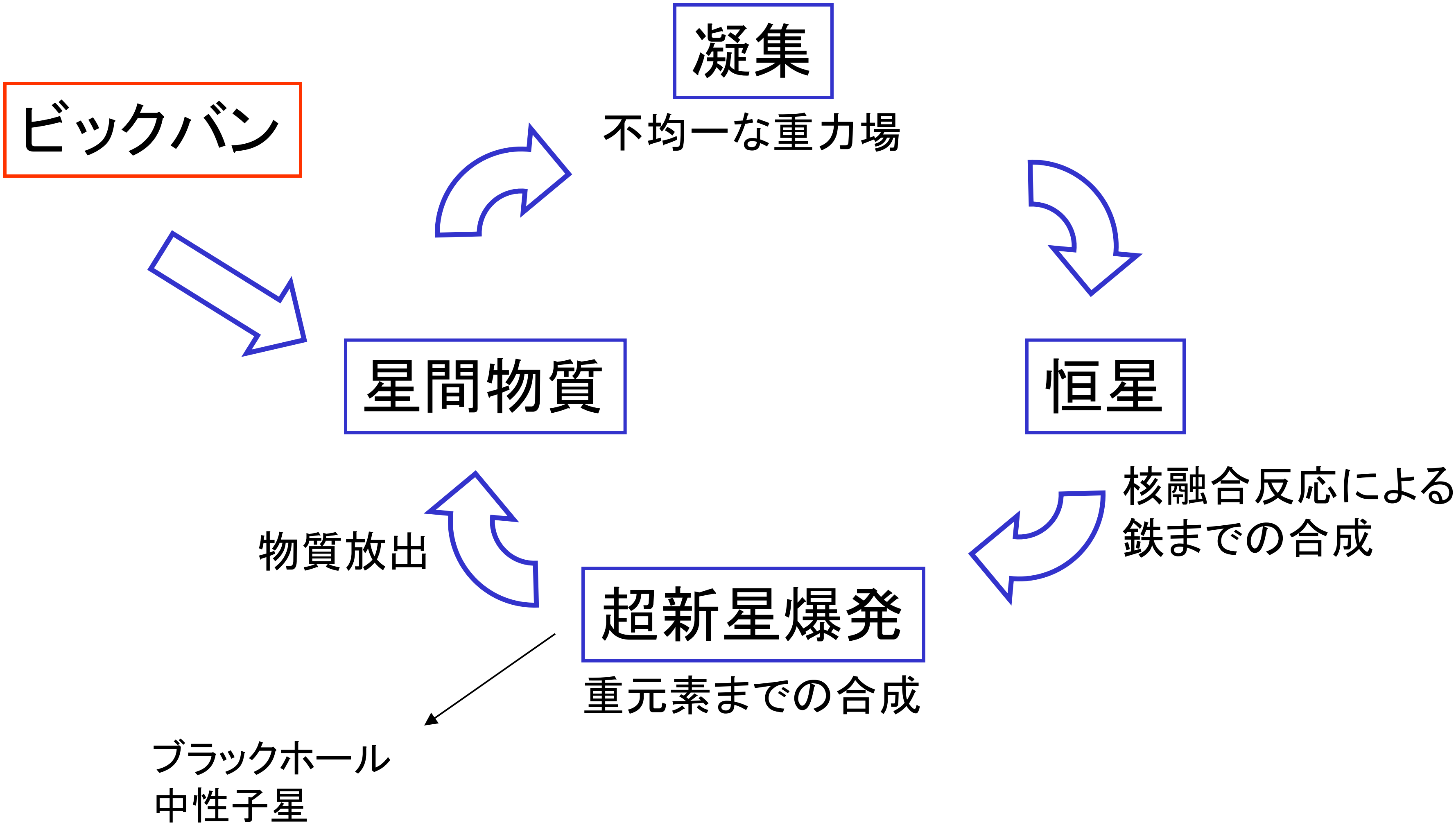
人工的に不安定な原子核を持つチタンなどを作り、陽子をはぎ取って中性子が34個と、陽子が20個のカルシウムを作った。そのときに放出されたエネルギーの大きさから原子核の状態を推定して、34が魔法数だとわかった。

魔法数は1949年に米独の研究者が提唱、長く不変とされてきた。しかし、理研のチームが2000年、定説を覆し、新たに16も魔法数だと発表。その後、中性子が多い不安定な原子核では、8、20、28は魔法数でなくなり、6、16、32が魔法数になることが分かった。殻の構造が変化し、「定員」が変わるためと考えられている。

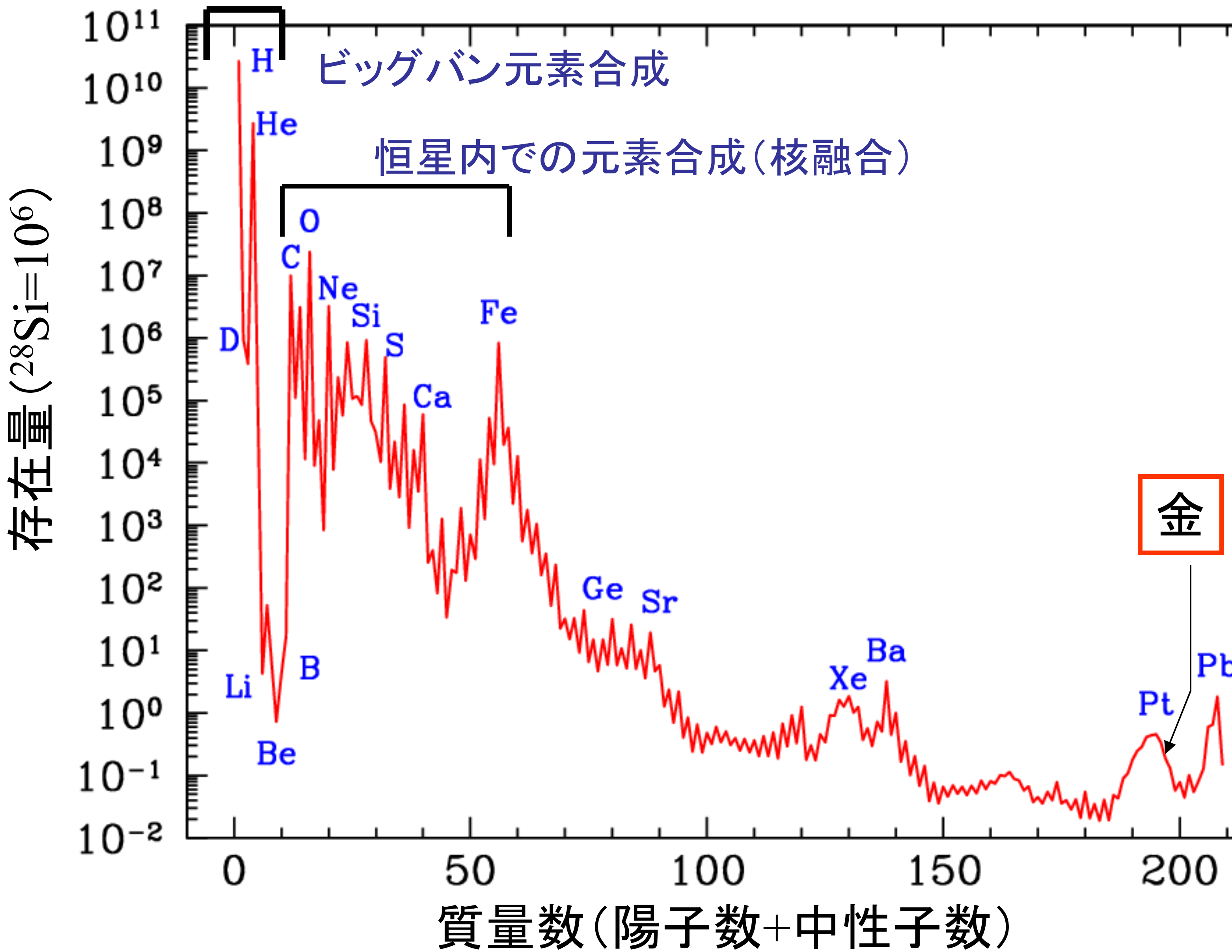
理研主任研究員を兼務する桜井博儀東京大教授は「元素生成過程は、鉄より重い元素がどのように作られたかなど謎が多い。不安定な原子核の研究を進めれば、原子核の構造や宇宙での元素合成過程の解明につながる」としている。（西川迅）

r-process path

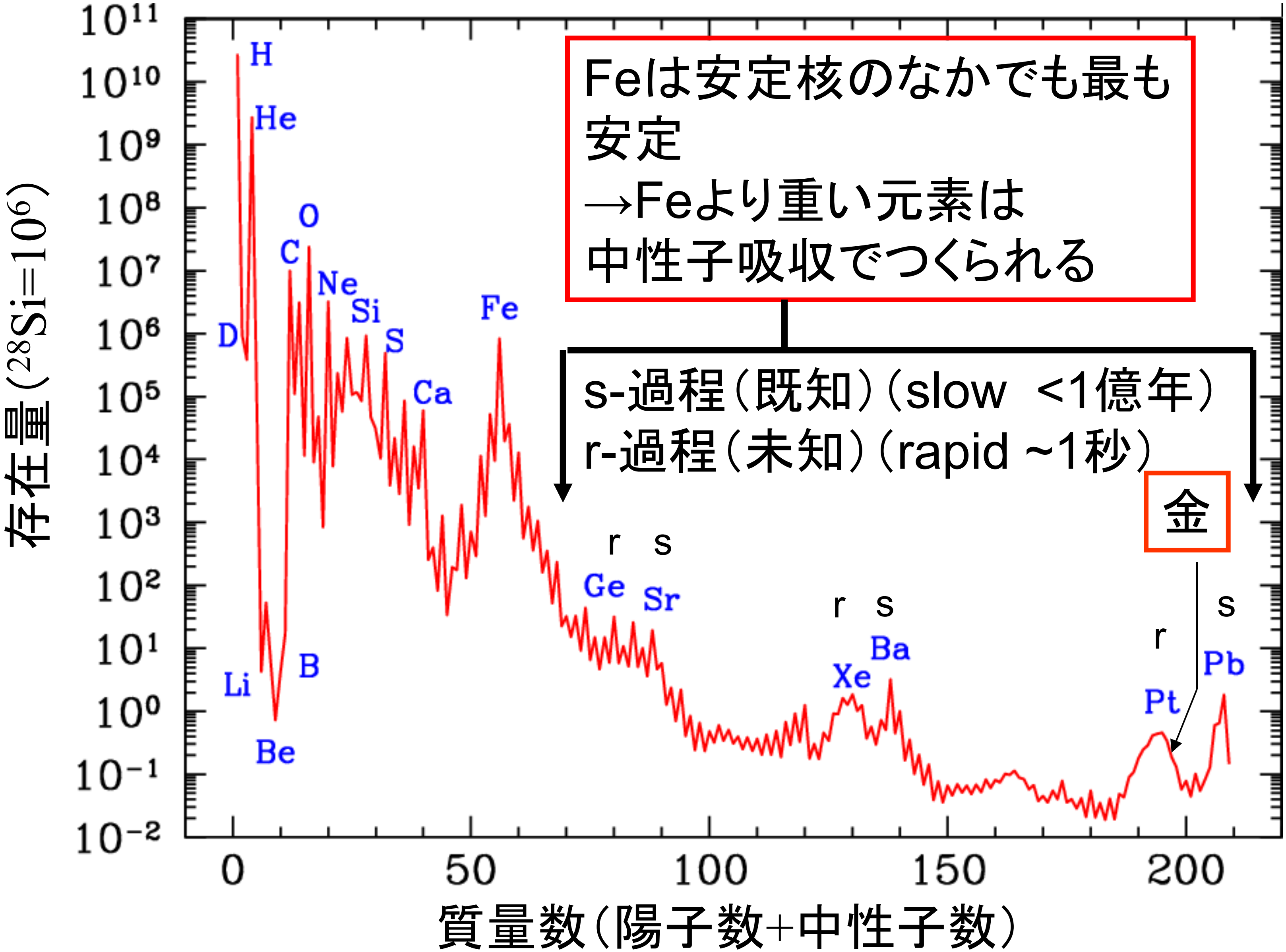
宇宙での元素合成サイクル



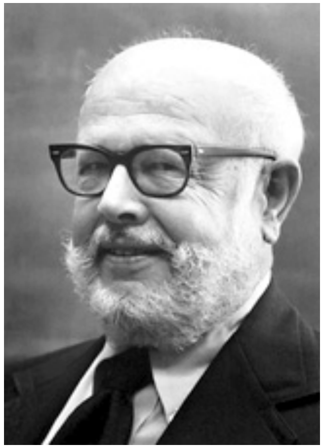
太陽系(~宇宙)の元素組成(存在比)



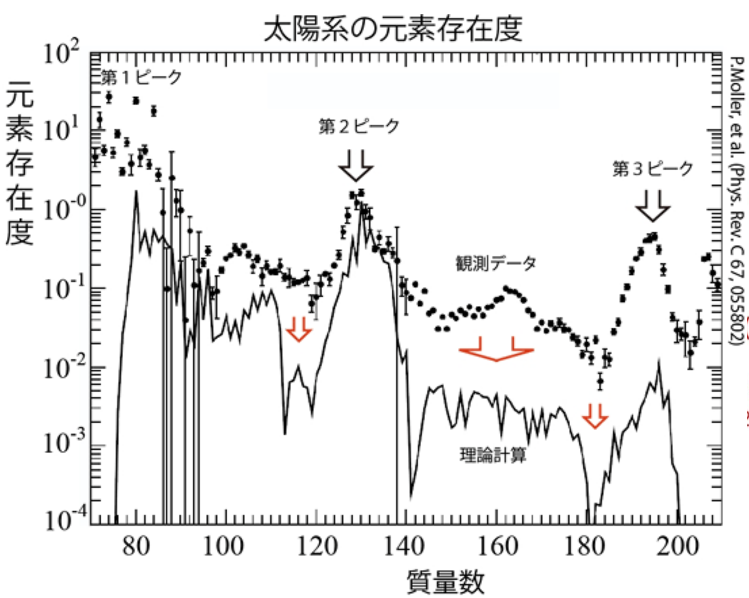
太陽系(~宇宙)の元素組成(存在比)

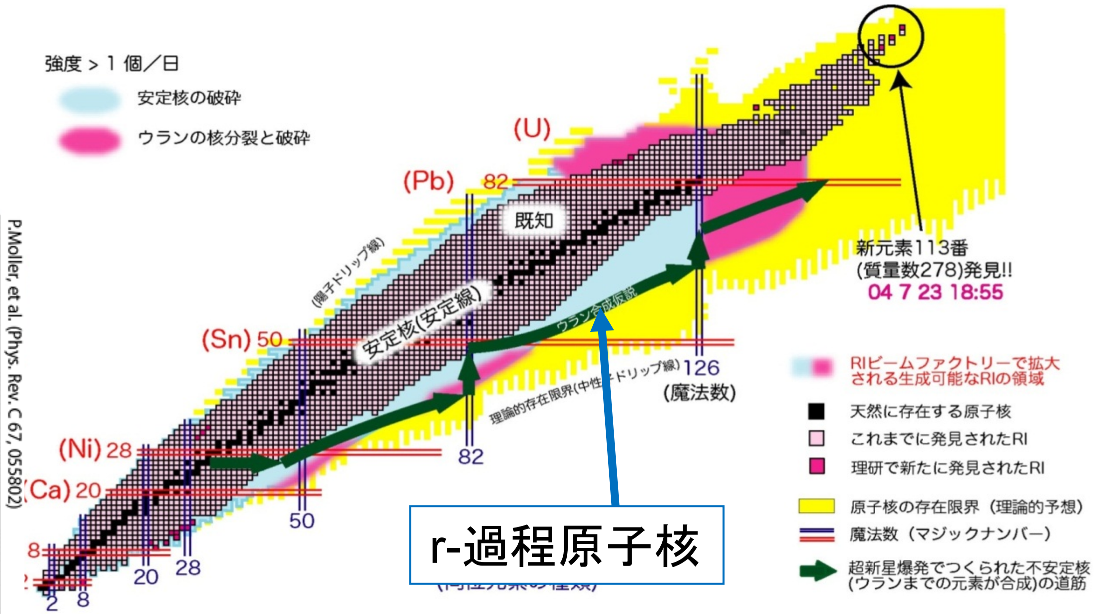


ウイリアム ファウラー
1983年 「宇宙での原子核反応による元素合成研究」でノーベル物理学賞受賞



**超新星爆発にともなう
ウランにいたる鉄より重い元素合成
仮説を提唱 (1957年) （r-過程）**

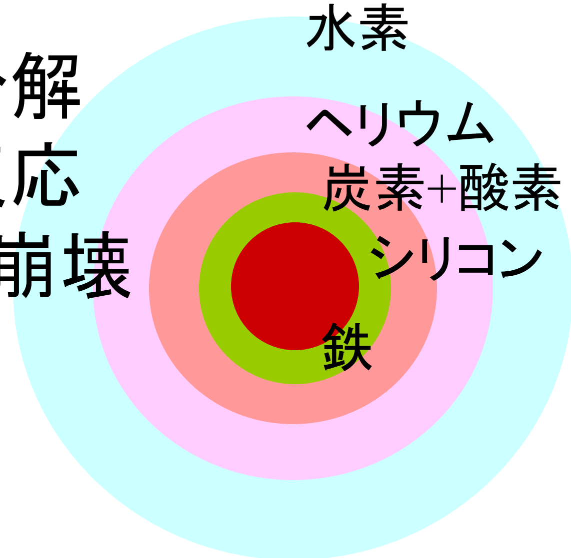




超新星爆発

重い星（太陽質量の約8倍以上）の最期

鉄核の光分解
電子捕獲反応
による重力崩壊



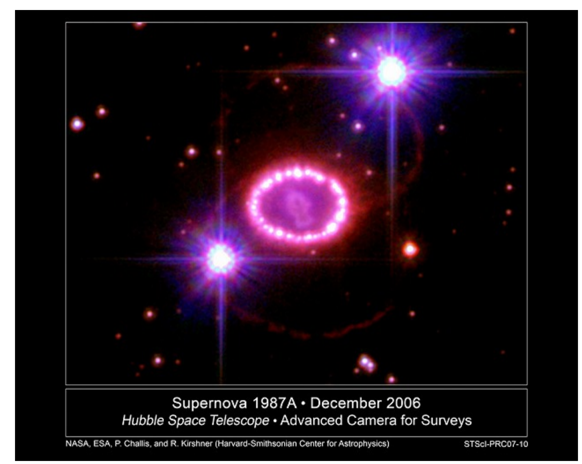
大量の中性子とニュートリノの放出

鉄からウランまでの元素の工場？

1987A　1987年

D.F.Malin, Anglo-Australian Telescope Board, 1987

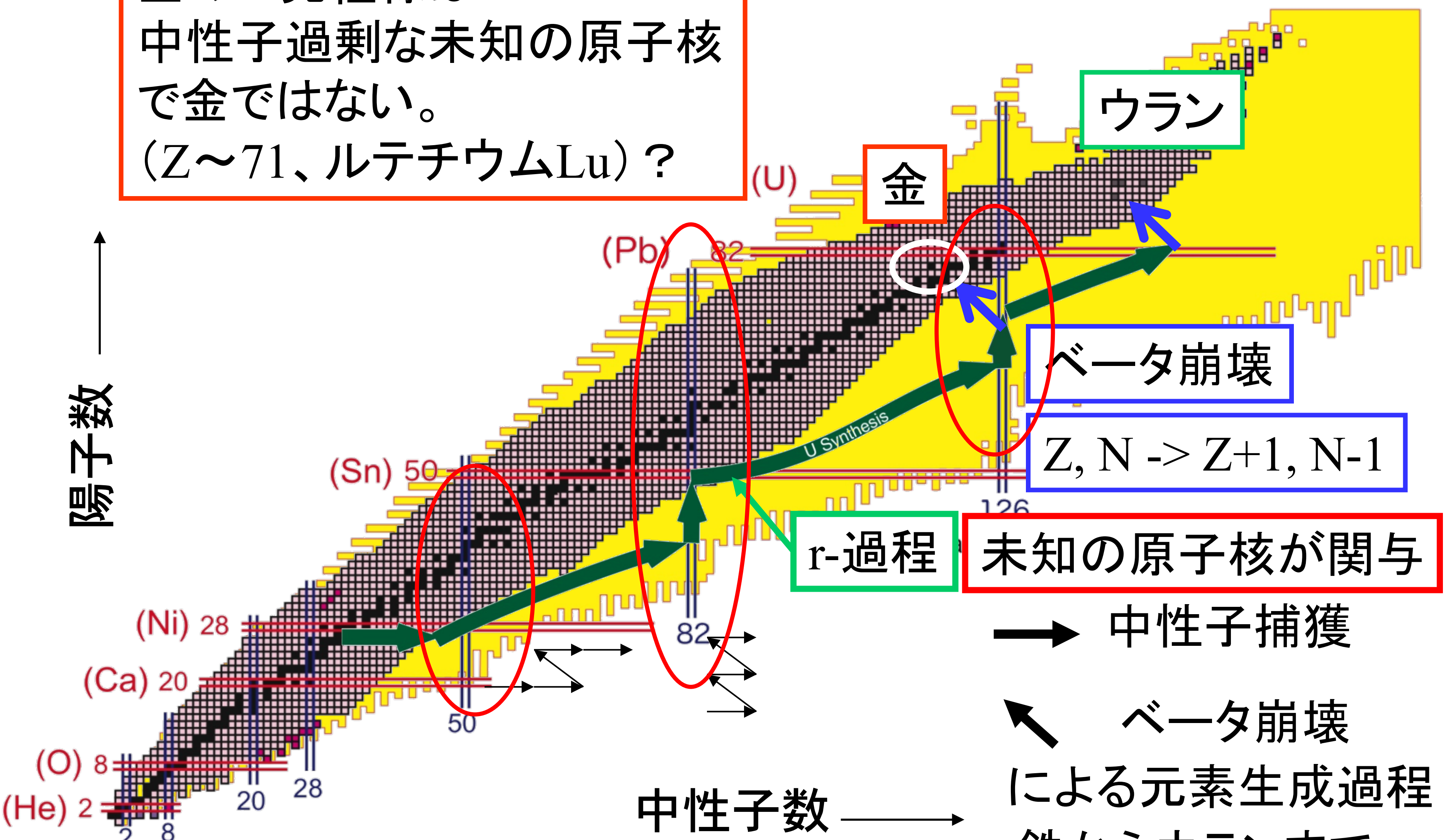
2006年末



ハッブル望遠鏡

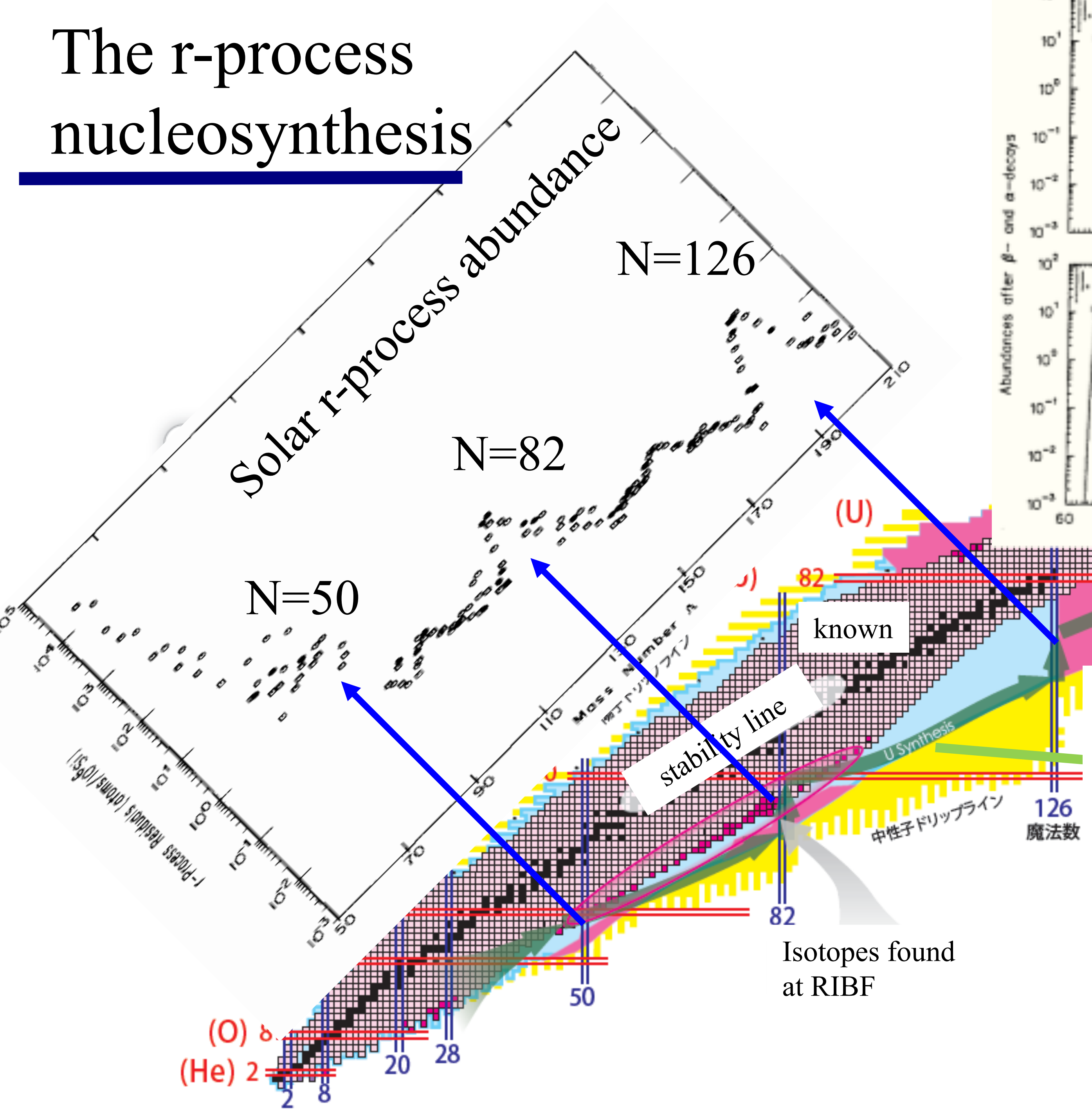
r-過程（仮説）

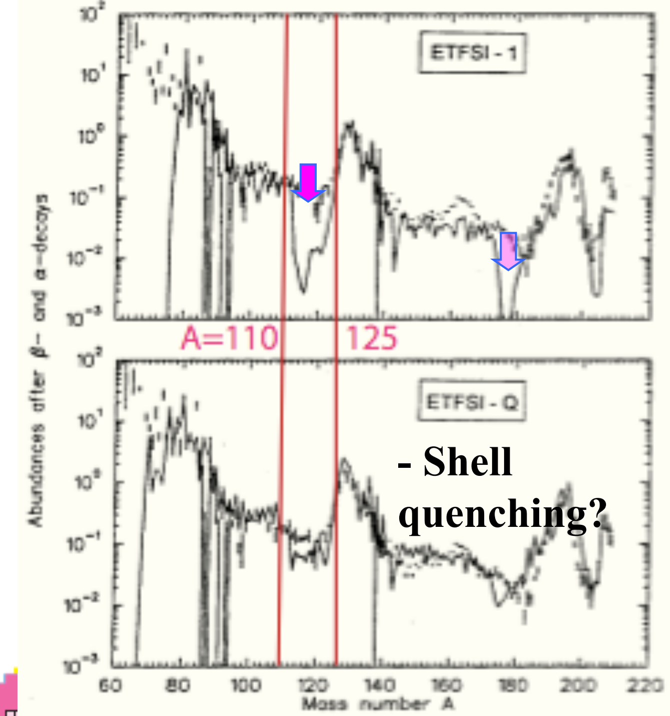
金のご先祖様は
中性子過剰な未知の原子核
で金ではない。
（Z〜71、ルテチウムLu）？



どこでどのように？は謎

The r-process nucleosynthesis





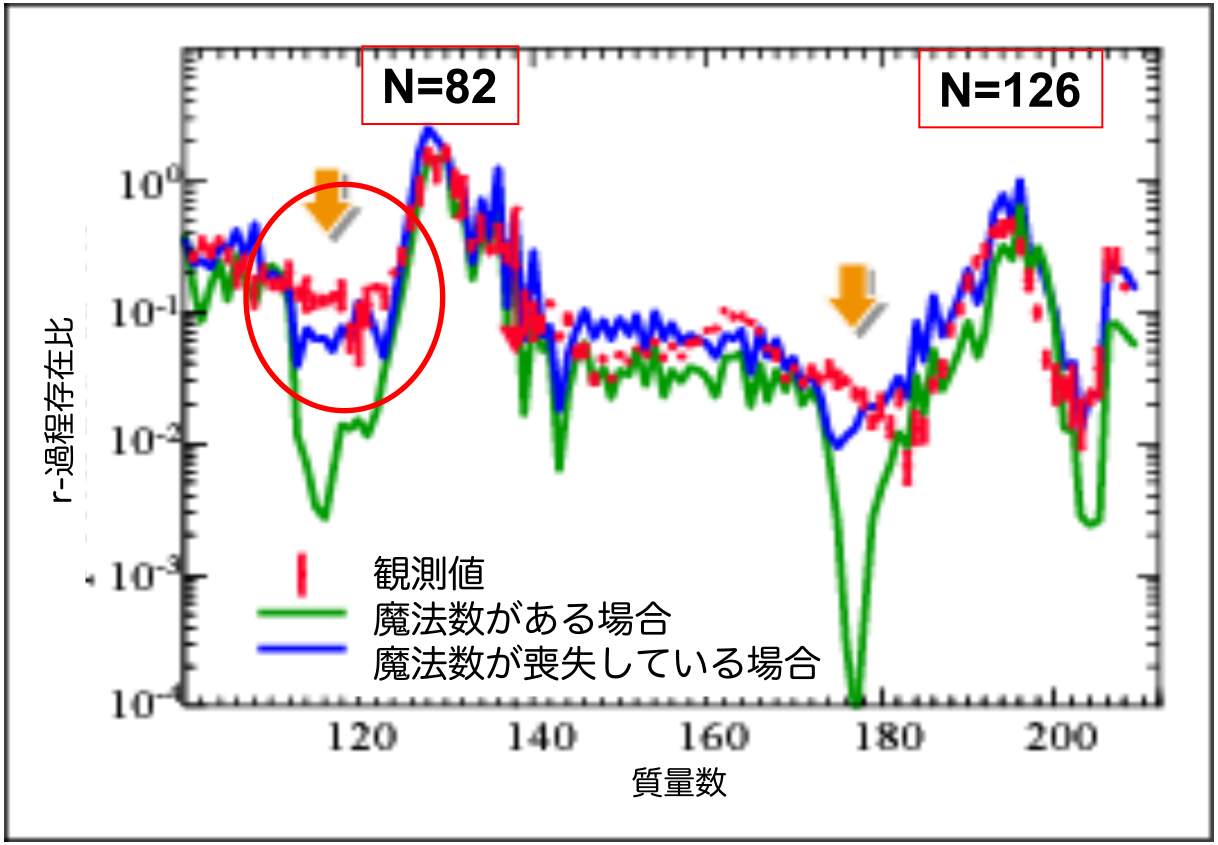
B.Pfeiffer et al. Z. Phys. A357 (1997)

r-process path

Supernova explosion?
rapid neutron-capture
vs beta-decay

Mass -> path location
Half-life -> matter flow

r-過程でつくられた元素の存在比　観測vs理論予想



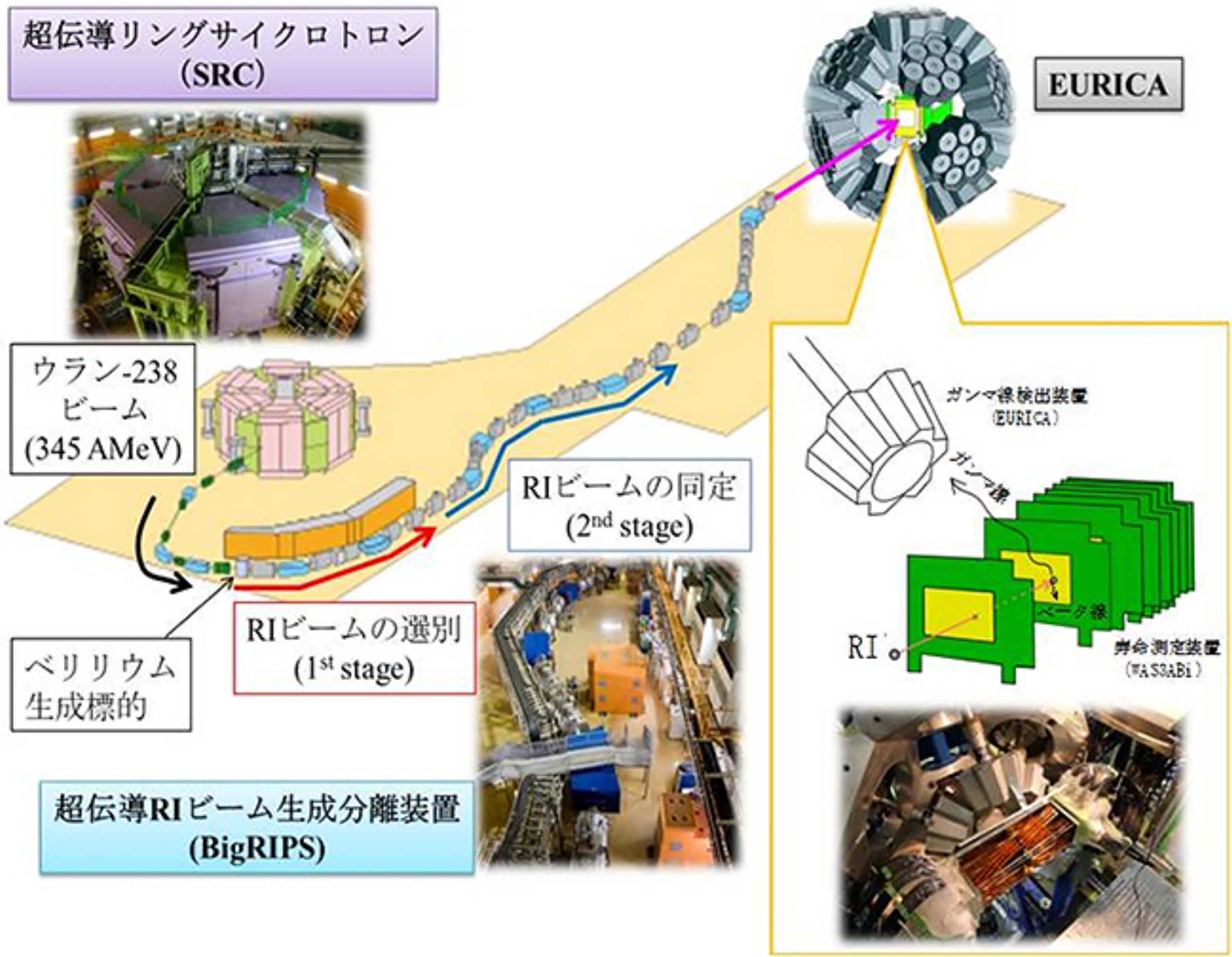
未知核の性質を測定する必要

寿命　⇒　進行速度

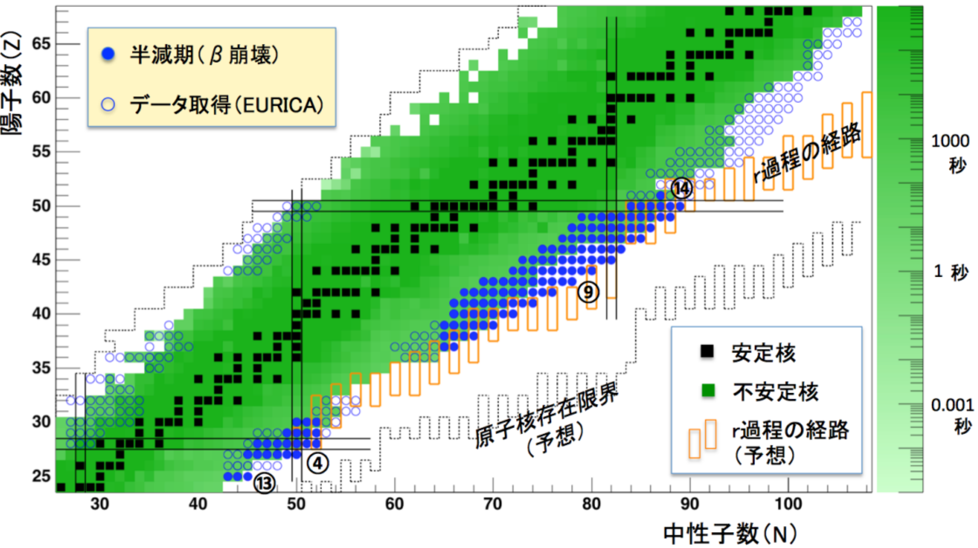
質量　⇒　経路

核分裂　⇒　終結点

寿命測定法

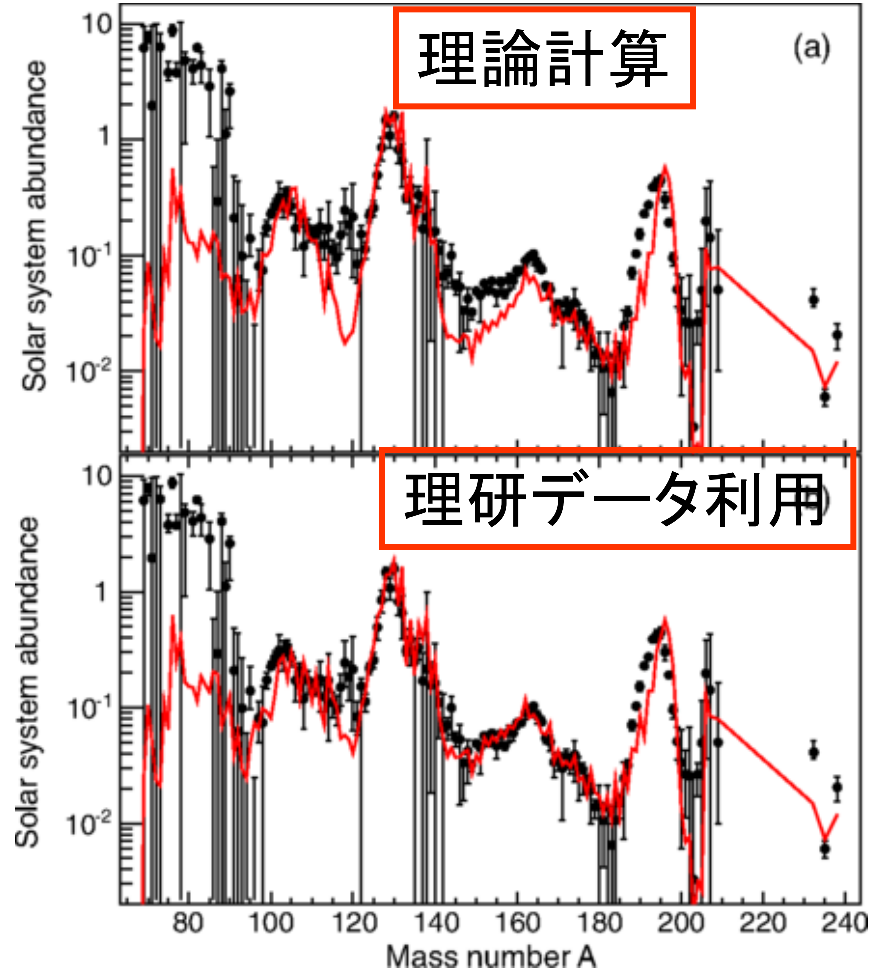

超伝導リングサイクロトロン
(SRC)
EURICA
ウラン-238
ビーム
(345 AMeV)
RIビームの同定
(2nd stage)
ベリリウム
生成標的
RIビームの選別
(1st stage)
超伝導RIビーム生成分離装置
(BigRIPS)
ガンマ線検出装置
(EURICA)
ガンマ線
ベータ線
RI
寿命測定装置
(WAS3ABi)

r-過程研究：理論、観測から地上実験の時代へ



大量の半減期データ
第2ピーク、希土類領域まで
超新星爆発モデル
と矛盾なし

質量、中性子放出確率測定へ
2017年から本格測定！

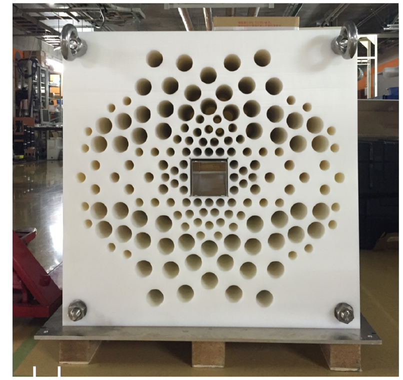


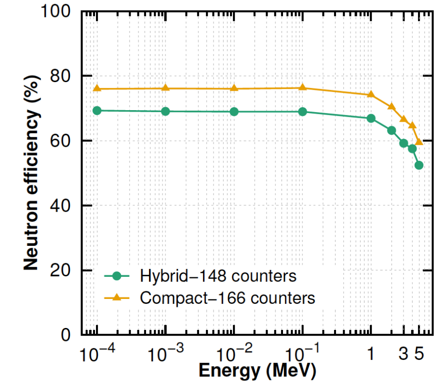
G. Lorusso, S. Nishimura *et al. PRL*. 114, 192501 (2015)

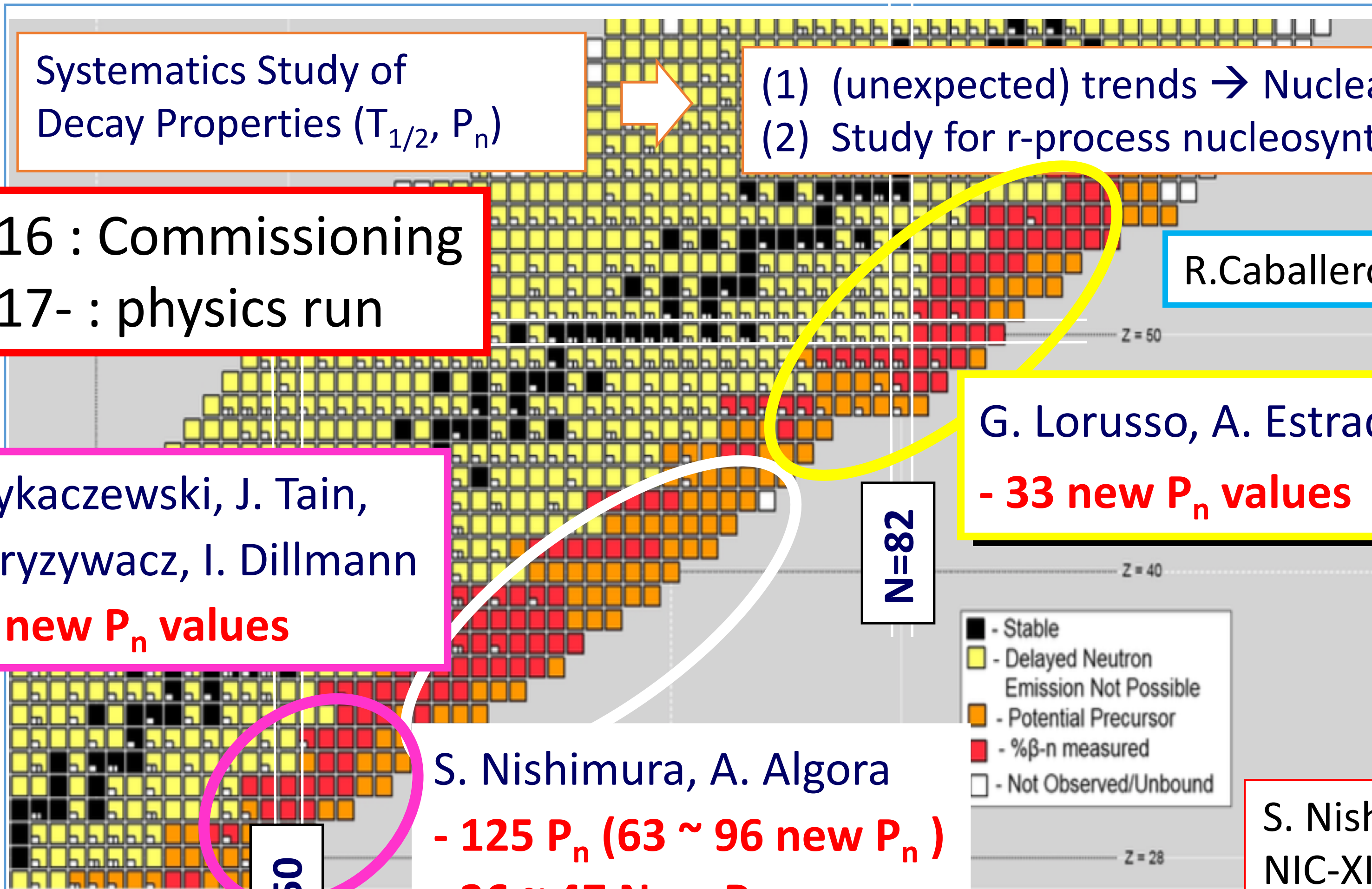
RIBF高度化：第三ピークへ

Future: BRIKEN
β-Delayed Neutron Study

166 He-3 tubes
ORNL-JINR-GSI-UPC-RIKEN







Systematics Study of Decay Properties ($T_{1/2}$, P_n)

(1) (unexpected) trends → Nuclear structure
(2) Study for r-process nucleosynthesis

2016 : Commissioning
2017- : physics run

R.Caballero-Folch, Wed.

G. Lorusso, A. Estrade, F. Montes
- 33 new P_n values

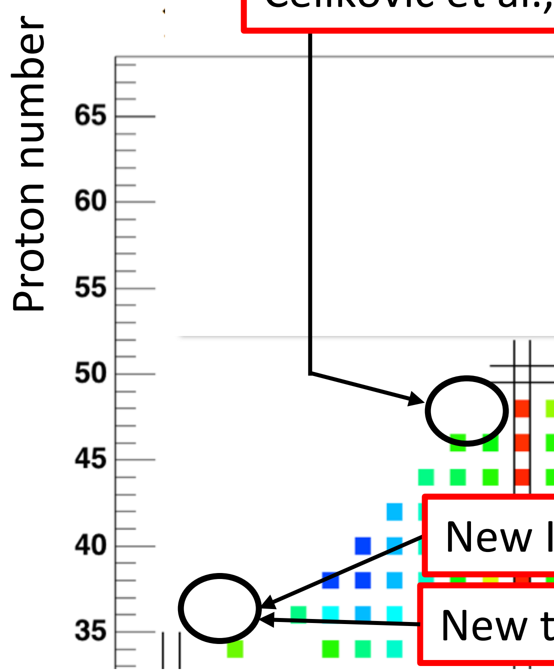
K. Rykaczewski, J. Tain, R. Gryzywacz, I. Dillmann
- 20 new P_n values

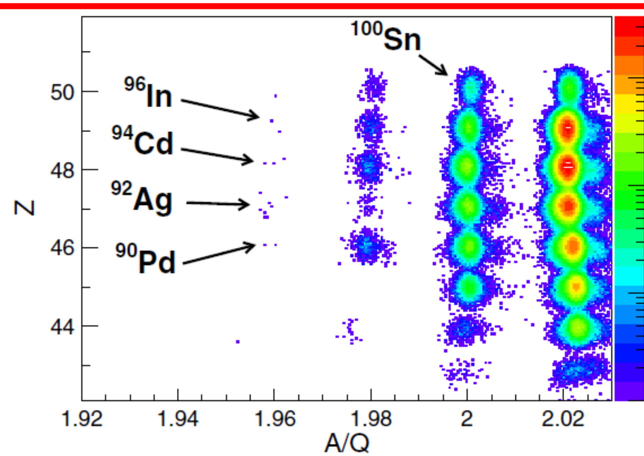
S. Nishimura, A. Algora
- 125 P_n (63 ~ 96 new P_n)
- 36 ~ 47 New P_{2n}

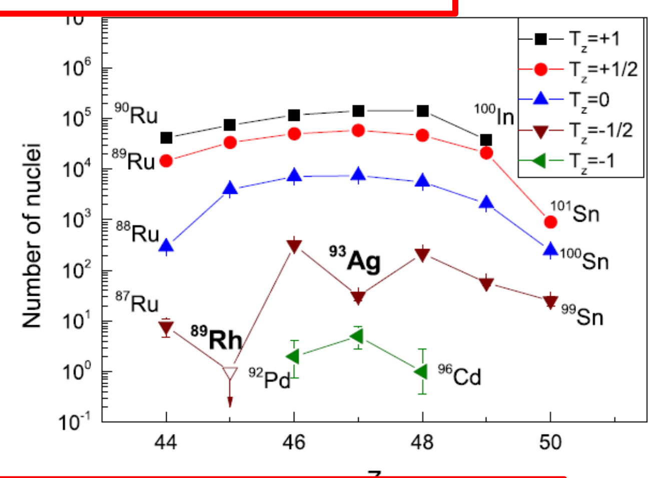
S. Nishimura
NIC-XIV June, 2016

EURICA Achievements (2012-) new isotopes and proton emitters

New Isotopes: ^{96}In, ^{94}Cd, ^{92}Ag, ^{90}Pd, New proton emitters: ^{89}Rh, ^{93}Ag
Celikovic et al., PRL 116, 162501(2016)

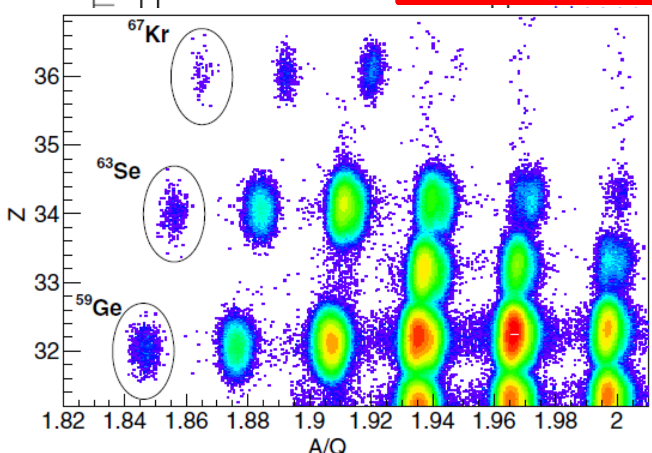


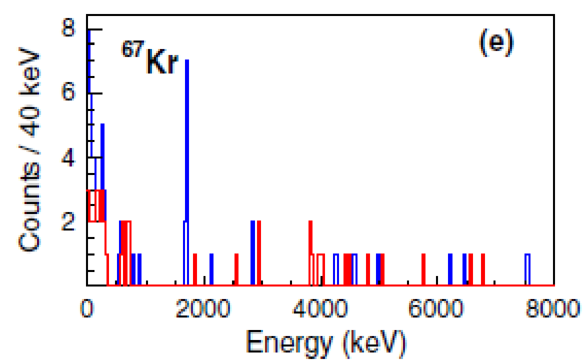


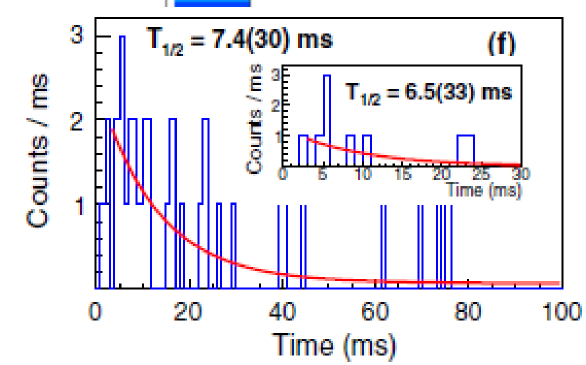


New Isotopes : ^{63}Se, $^{67,\,68}$Kr, Blank et al., PRC 93, 061301(R) (2016)

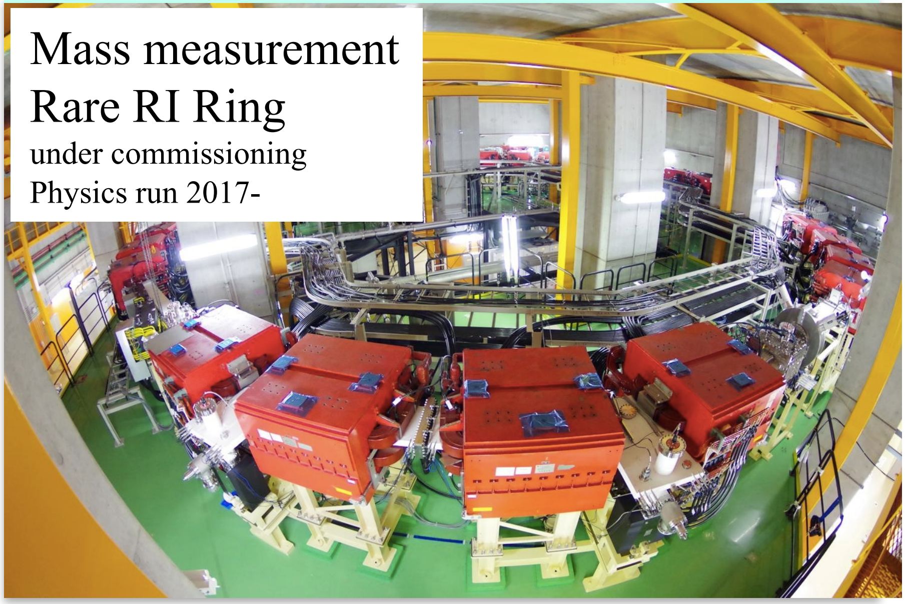
New two proton emitter ^{67}Kr, Goigoux et al., PRL 117, 162501 (2016)





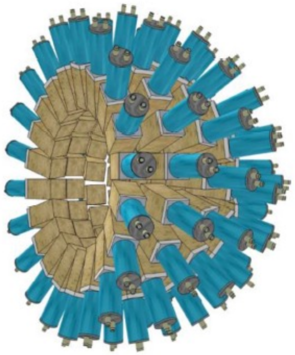


Plans for shell evolution

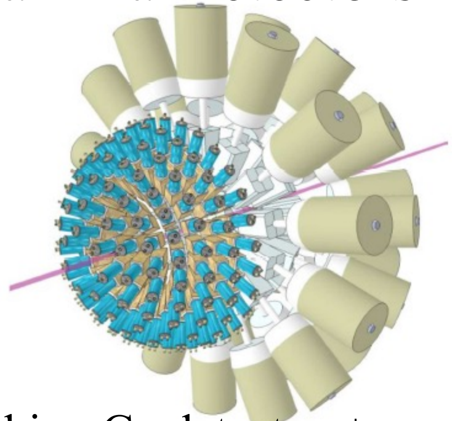


Mass measurement
Rare RI Ring
under commissioning
Physics run 2017-

Next Generation Gamma Detectors



SHOGUN ($LaBr_3$)
(less than 5 years)



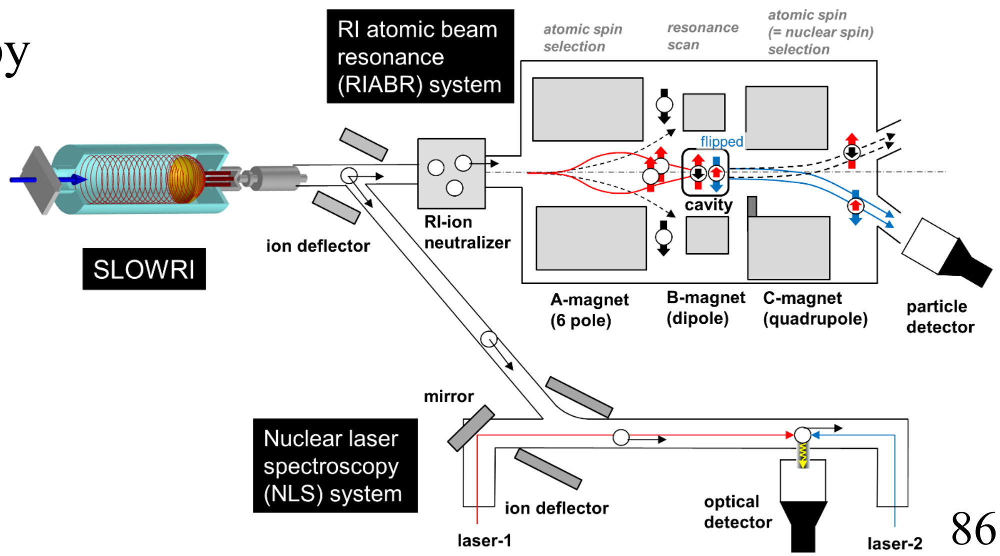
Tracking Ge detectors+
SHOGUN (within 5-10 years)

under discussion with RCNP-HKU-IMP…
(CAGRA clover array at RCNP -> RIBF 2018-)

RI Atomic Beam Resonance Spectroscopy
5-10 years project

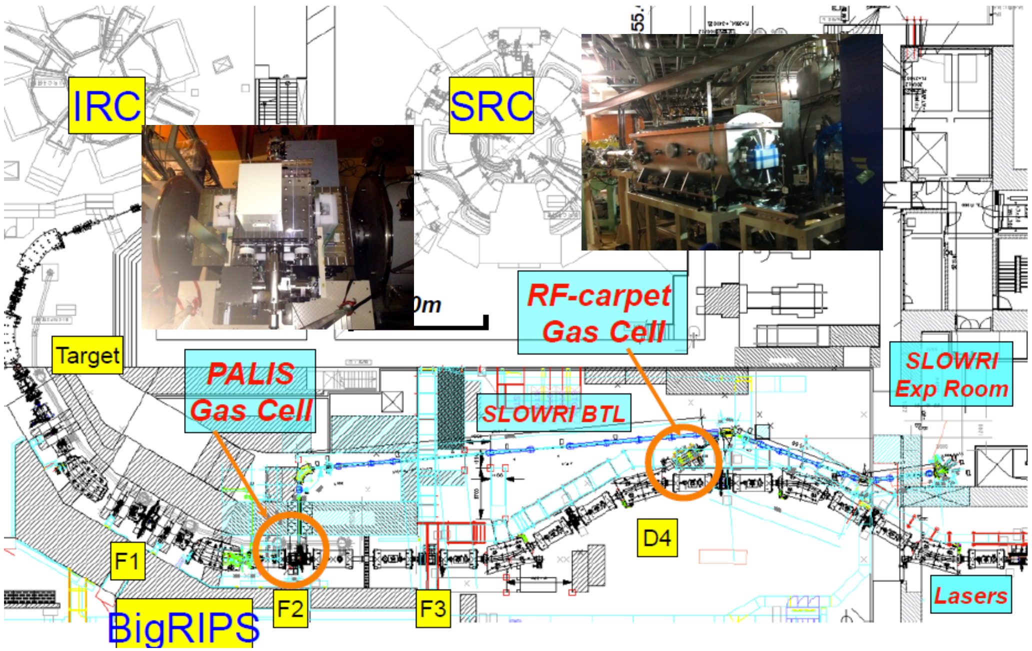
reaction-free and element-free measurement of moments coupled with SLOWRI

Design work has been finished.
RI-ion neutralizer section
\+ Atomic beam method section

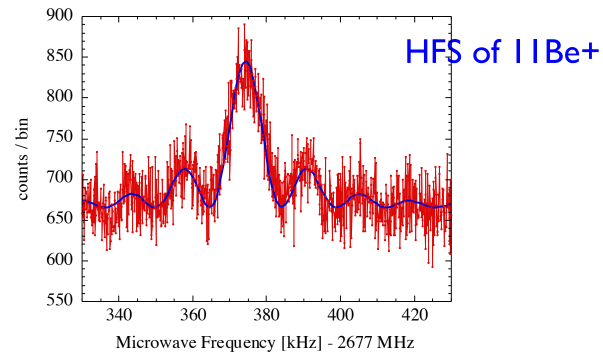


SLOWRI Device for Trap Experiments

Wada, Sonoda et al.

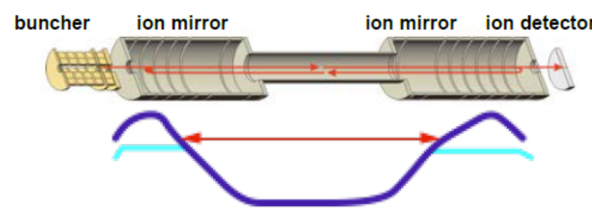


1)Optical spectroscopy



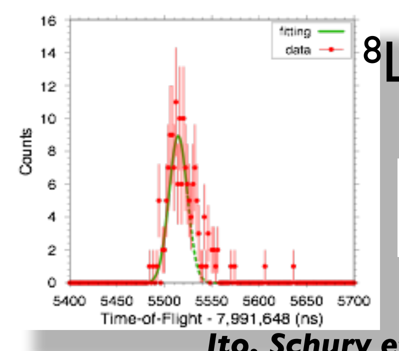
Takamine et al, PRL 112(2014)162502

2)Mass measurements of short-lived nuclei



3)Resonance Ionization Spectroscopy

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



^{8}Li ToF spectrum

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

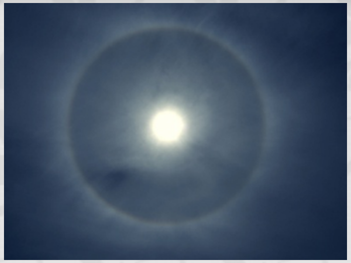
Ito, Schury et al, PRC 88(2013)011306R

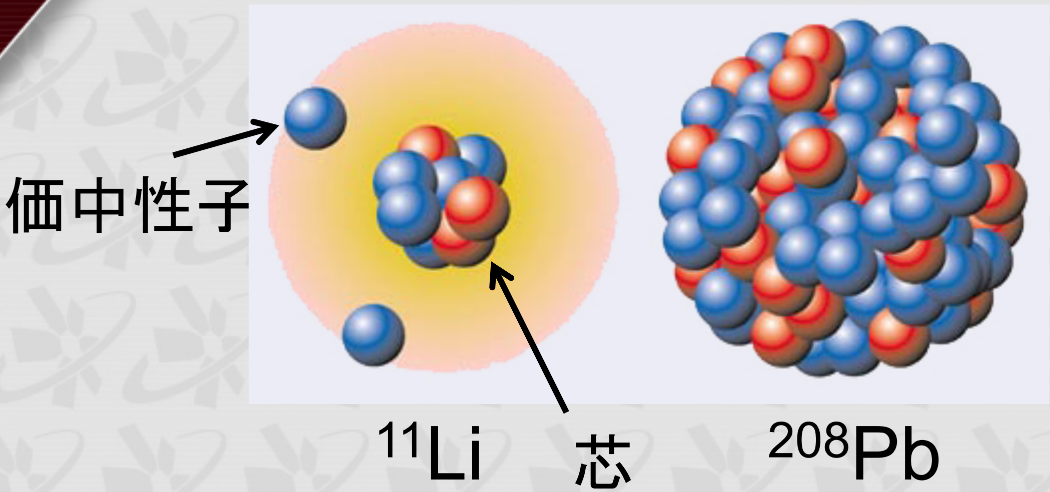
ハロー核

これ！

Hello [həlóʊ]　こんにちは!

Halo [héɪloʊ]　後光, (太陽・月の)暈

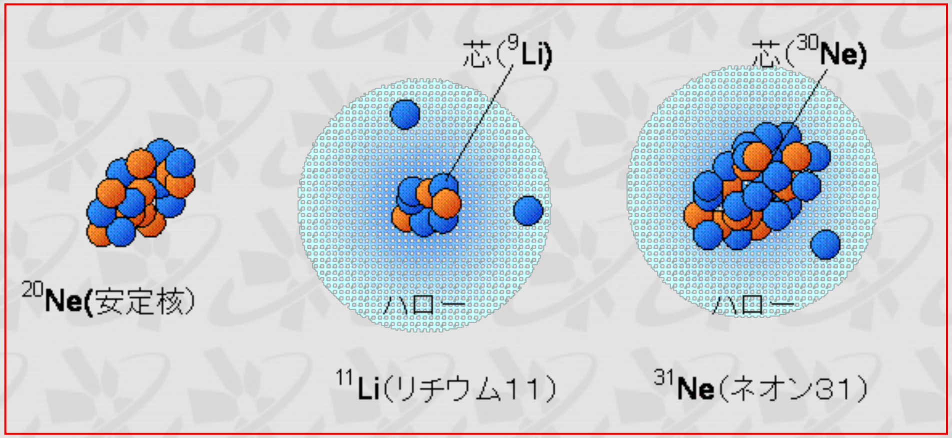




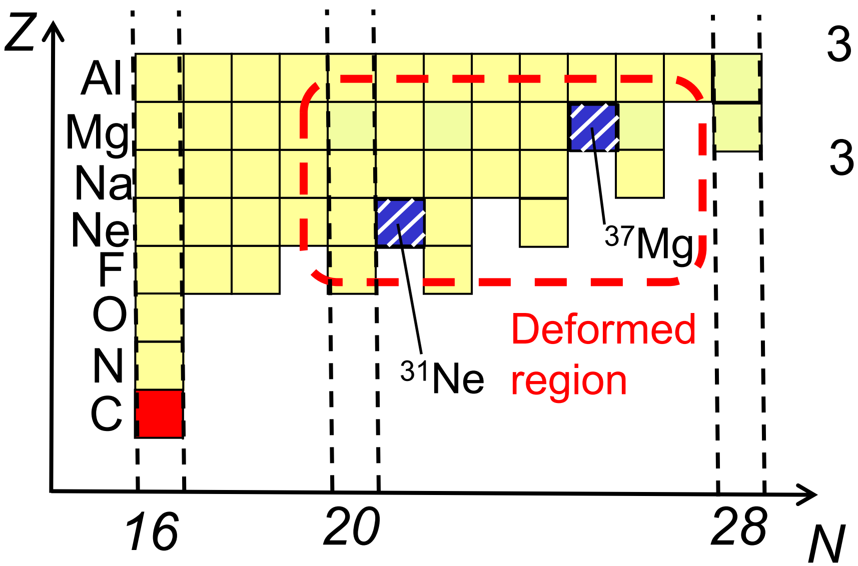
「ハロー核とは後光のある原子核」
芯の周りに、ゆるく束縛された
中性子が薄く広くひろがっている。
通常の原子核は陽子・中性子が
肉団子のように固まっていて、
ハロー核は通常の原子核とは異なる
特別な構造をもっている。

RIBFのハロー核研究

Ne-31, Mg-37のハロー核の発見！
芯が球状でなく変形しているのが特徴。
今後、従来の予想よりハロー核が多数
見つかる可能性がある。

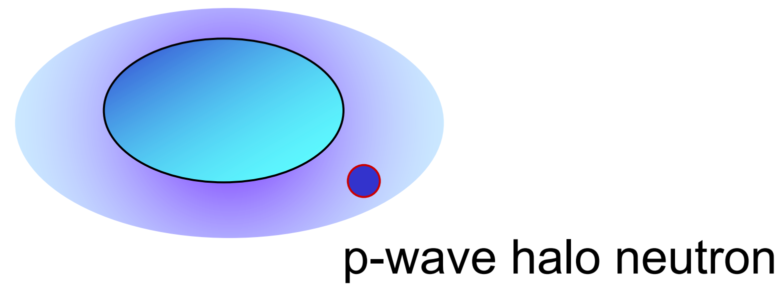


Deformed Halo Nuclei, Ne-31 and Mg-37, found at RIBF



^{31}Ne

^{37}Mg



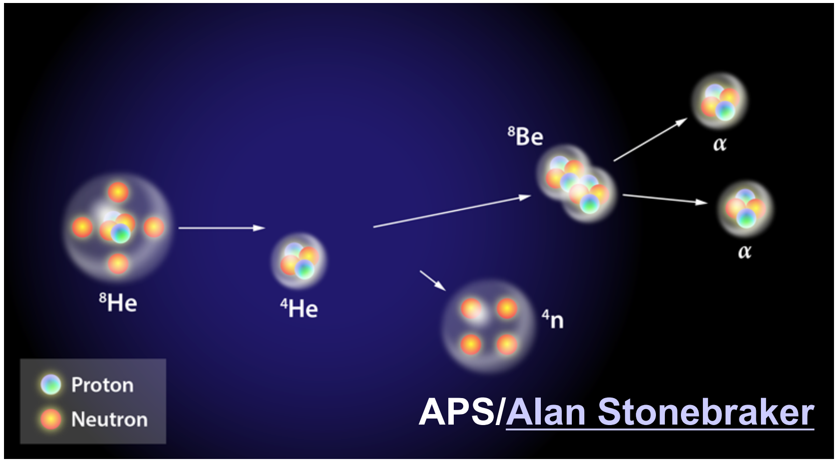
Inclusive Coulomb and Nuclear Breakup at

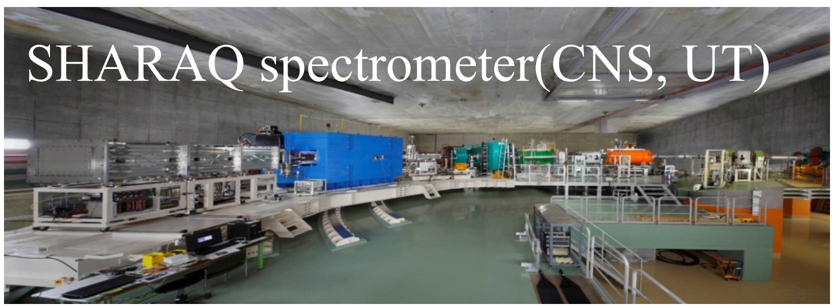
ZDS T.Nakamura et al., Phys.Rev.Lett.**103**,262501 (2009).
N.Kobayashi et al., PRC **86**, 054604 (2012)
T.Nakamura,et al., Phys.Rev.Lett.**112**,142501 (2014).
N.Kobayashi et al., Phys. Rev. Lett. **112**, 242501 (2014)

Total Interaction Cross Section at BigRIPS

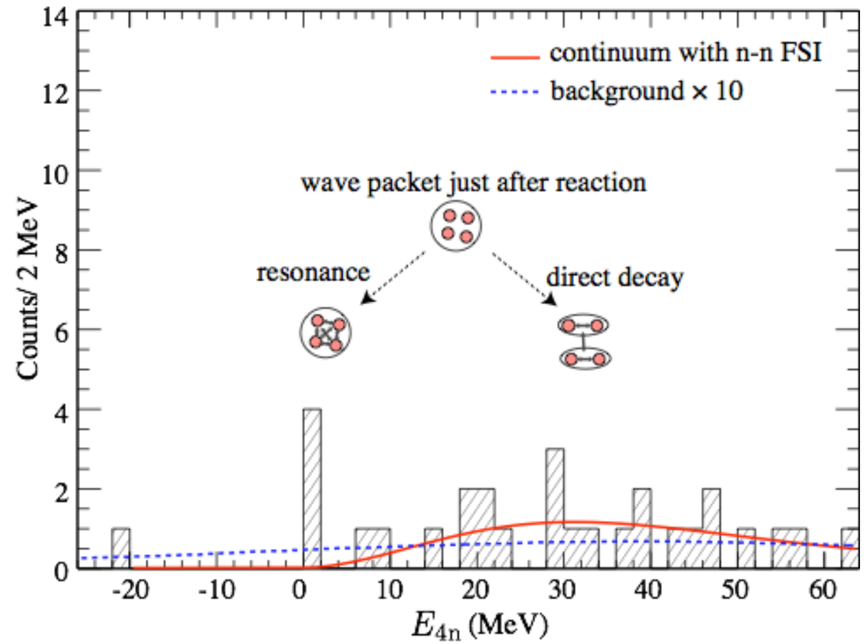
M. Takechi et al., Phys. Lett. B 707, 357 (2012)
M. Takechi et al., Phys. Rev. C 90, 061305(R) (2014)

Element Number Zero: Tetra-neutron system





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



"Nucleus made only of neutrons"

Benchmark for ab initio calculations

NN, NNN, NNNN… interactions

T=3/2, 2 interactions ??

T=1/2 d+p

K. Sekiguchi et al., Phys.Rev. C 83, 06100 (2011); Phys. Rev. C89, 064007 (2014)

A high statistics experiment was conducted June 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

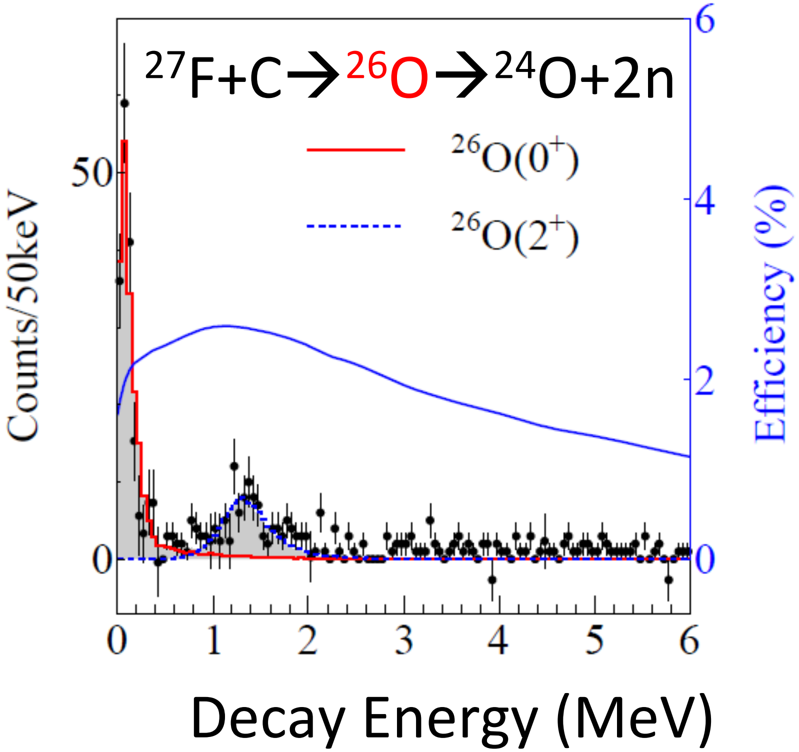
(integrated up to $\theta_{CM} < 5.4$ degree)

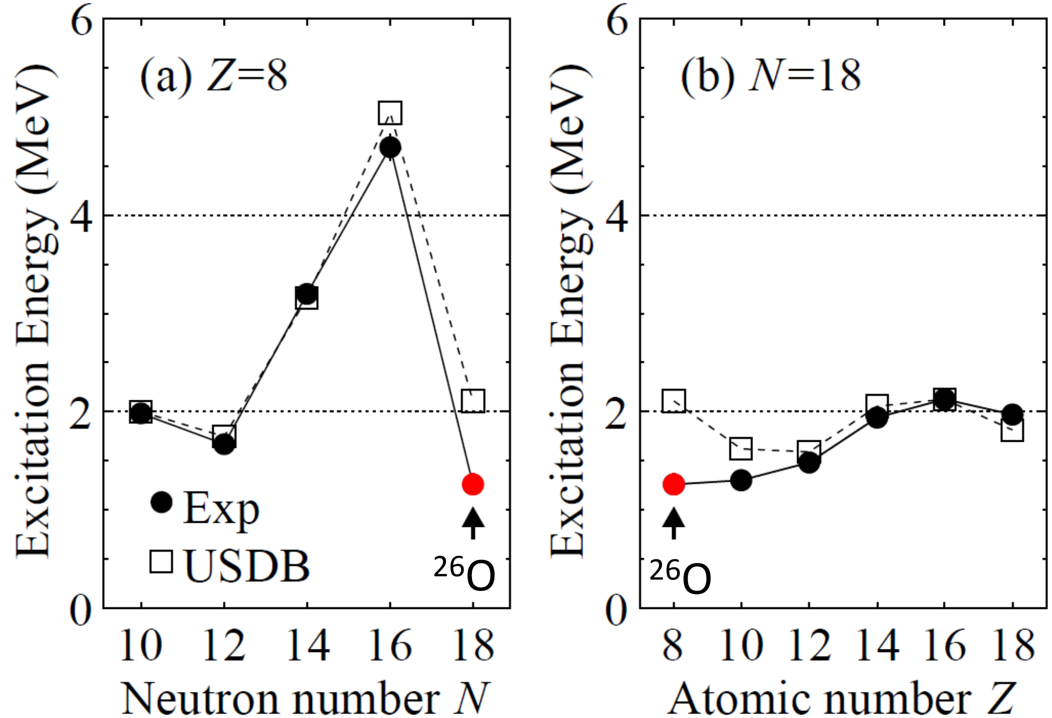
Energy resolution: 1.2 MeV

Uncertainty of calibration: ± 1.3 MeV

Background : 0.02 events/2MeV

^{26}O : barely unbound nucleus





Ground state

5 times higher statistics than previous study

$E_{decay} = 18 \pm 3(stat) \pm 4(syst)$ 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)

EOS

EOS for Asymmetric Nuclear Matter

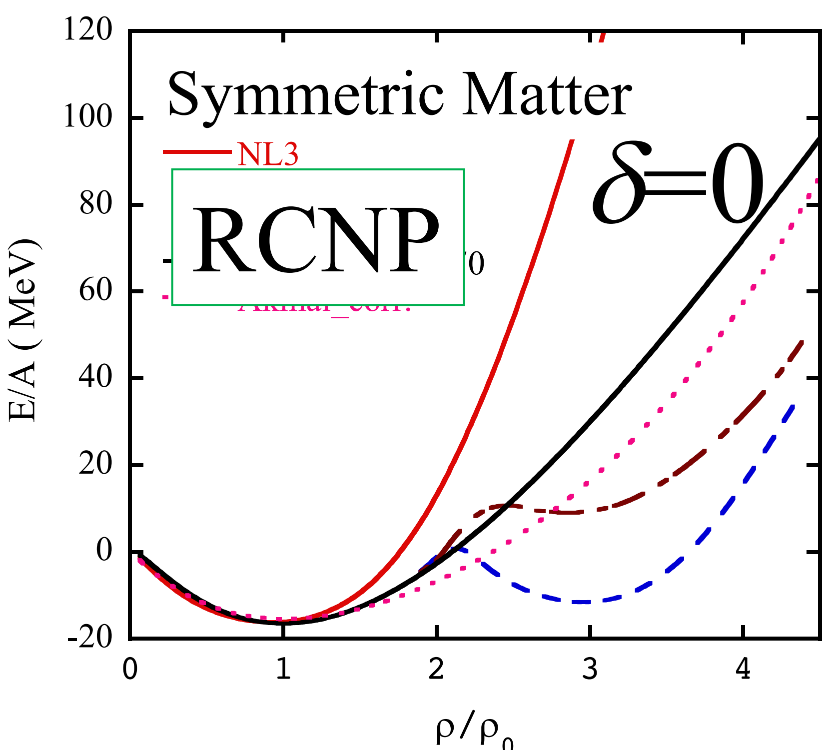
$$E(\rho, T=0, \delta) = \varepsilon(\rho, \delta=0) + E_{sym}\,\delta^2$$

Nuclear equation of state

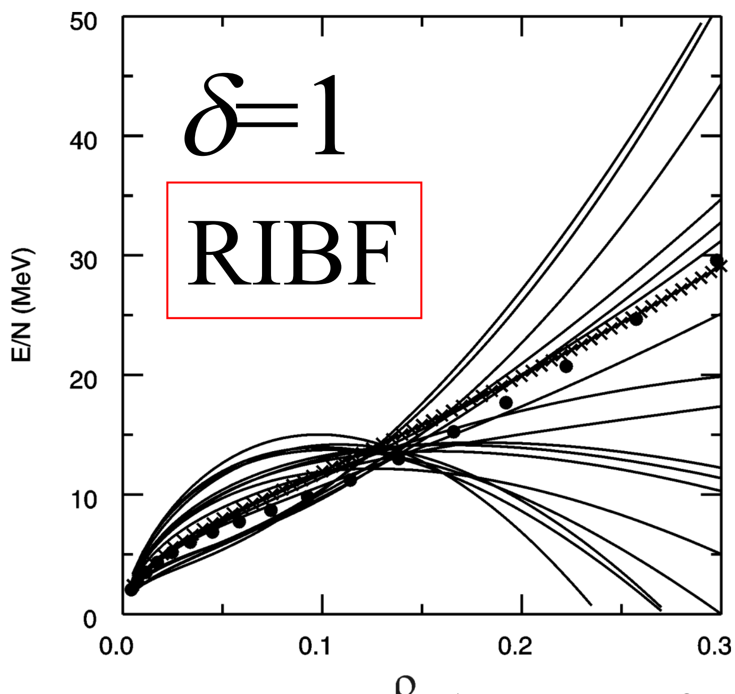
N=Z term: well known at $\rho \sim \rho_0$

N≠Z term
Asymmetry Energy

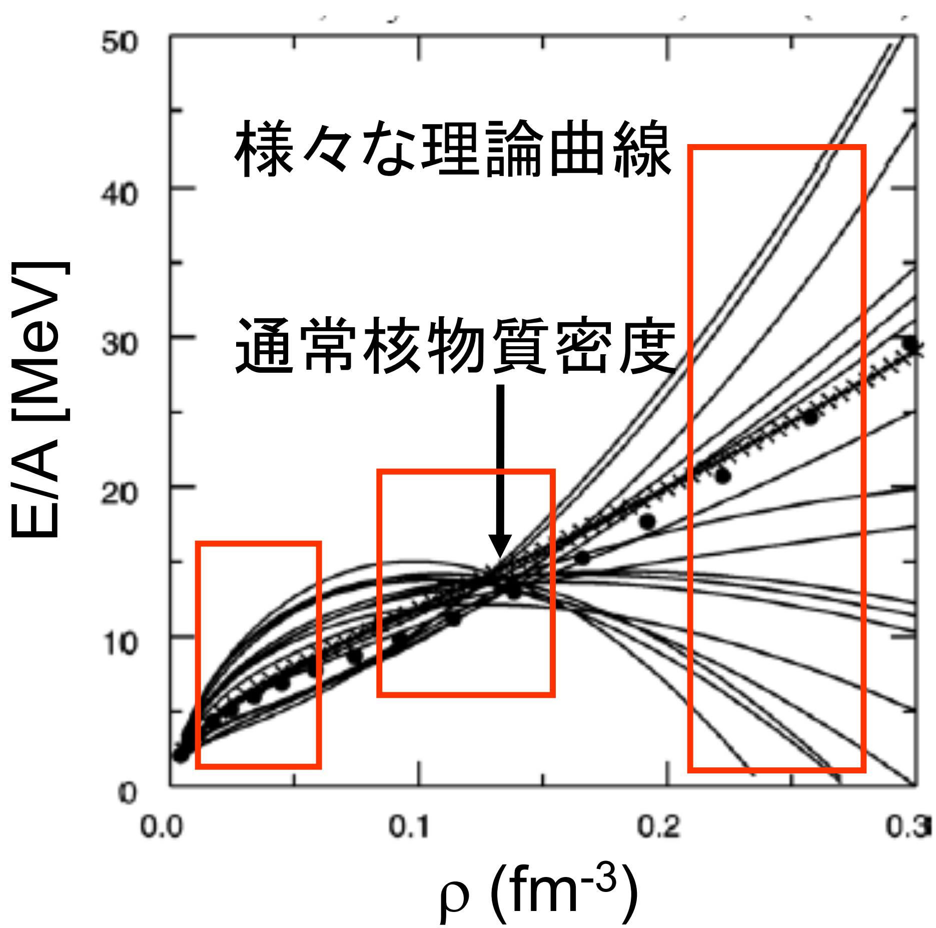
$$\delta = (N - Z)/A$$



Neutron Matter

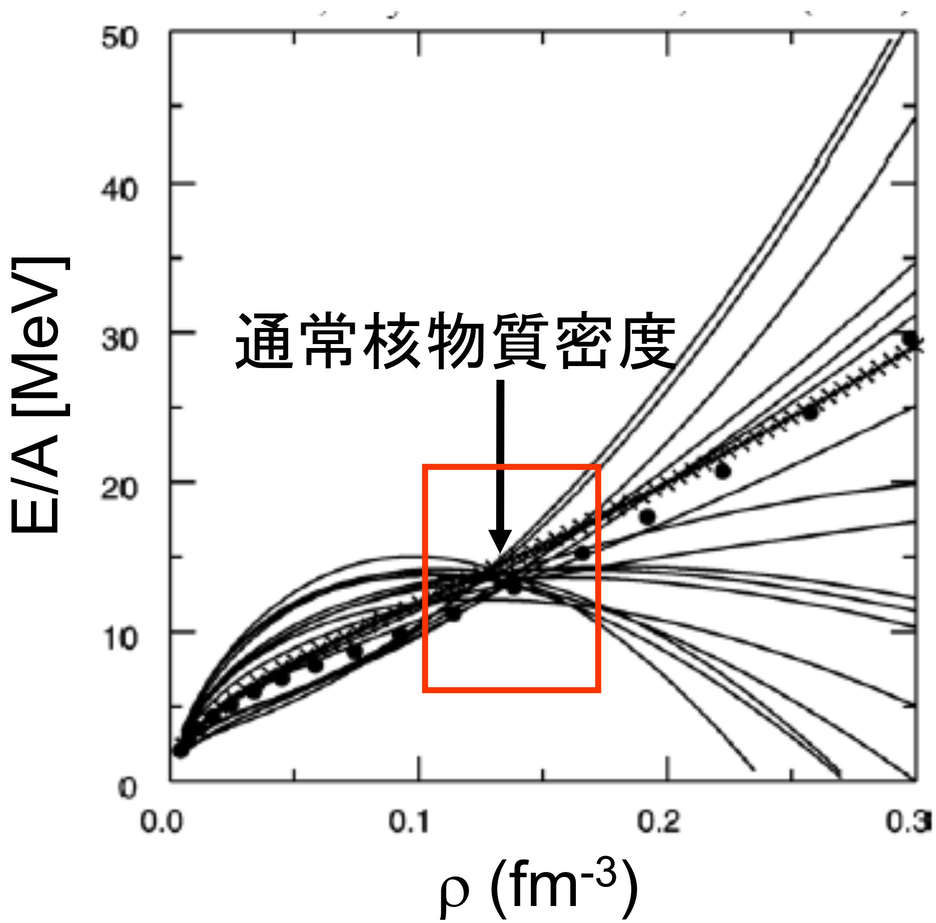


B.A.Brown, PRL 85, 5296(01),



1. $\rho \sim \rho_0$
2. $\rho > \rho_0$
3. $\rho \sim 0.1\rho_0$

1. $\rho \sim \rho_0$



核構造研究からの情報

質量測定

スキン厚測定

PDR

Fission

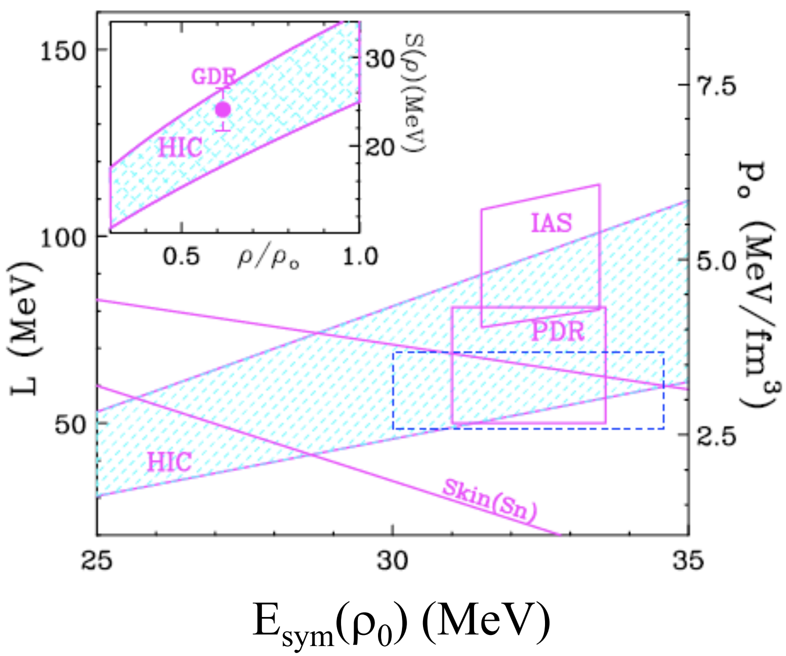
More precise determination of slope parameter L

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

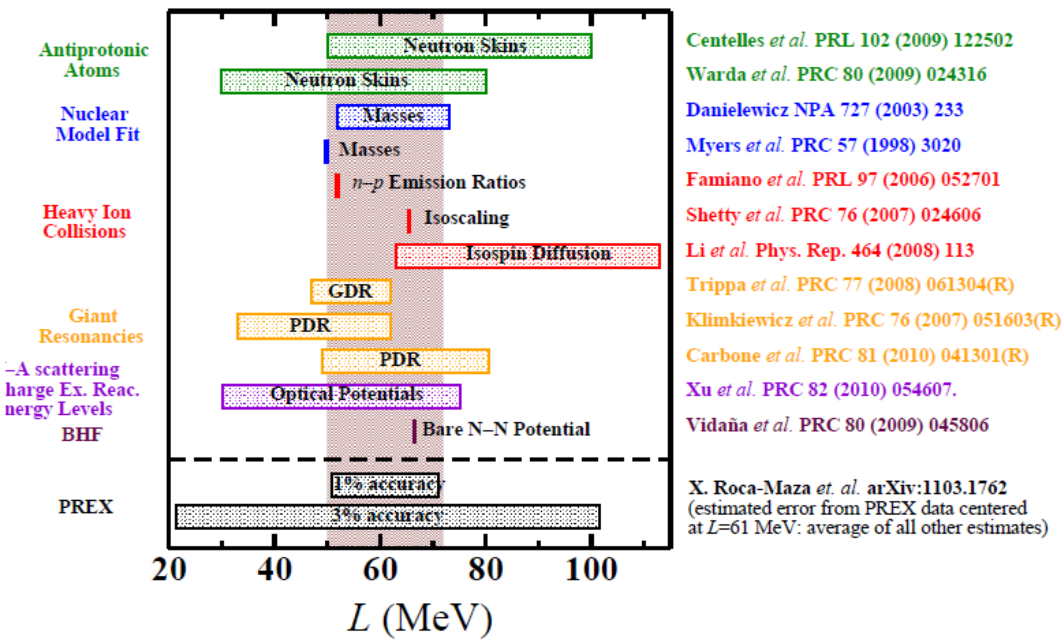
$E_{sym}(\rho_0) \approx$ **31-34 MeV**

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho=\rho_0}$$

30-110 MeV



Tsang et al., PRL 102, 122701 (09)

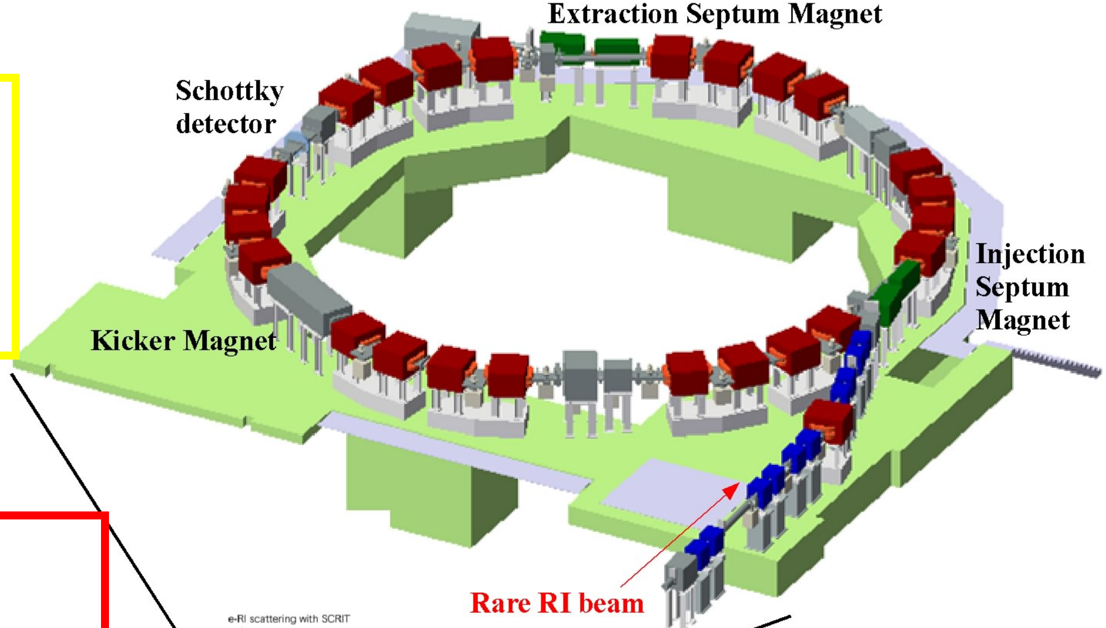


Xavier Roca-Maza, NuSYM11

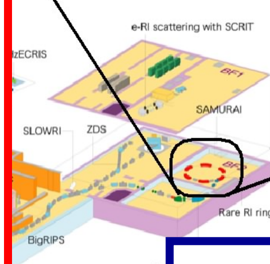
"Rare RI Ring" for mass measurement

Construction started in April 2012!
Ozawa, Wakasugi, Uesaka et al.

Specialized to mass measurements
  of r-process nuclei
   Low production rate (~1/day)
   Short life time (<50ms)



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

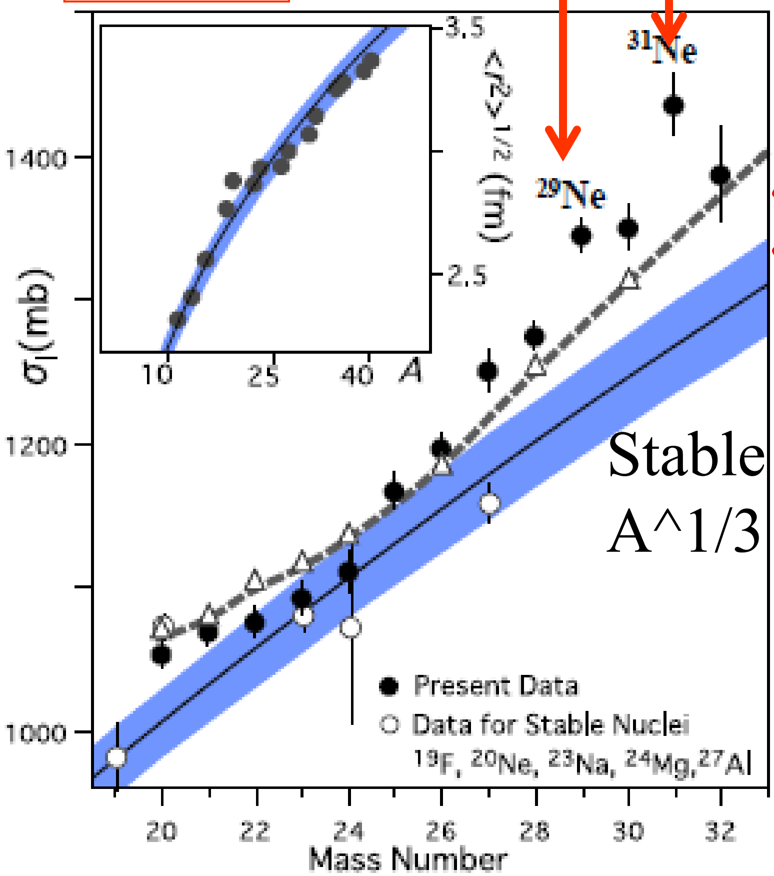


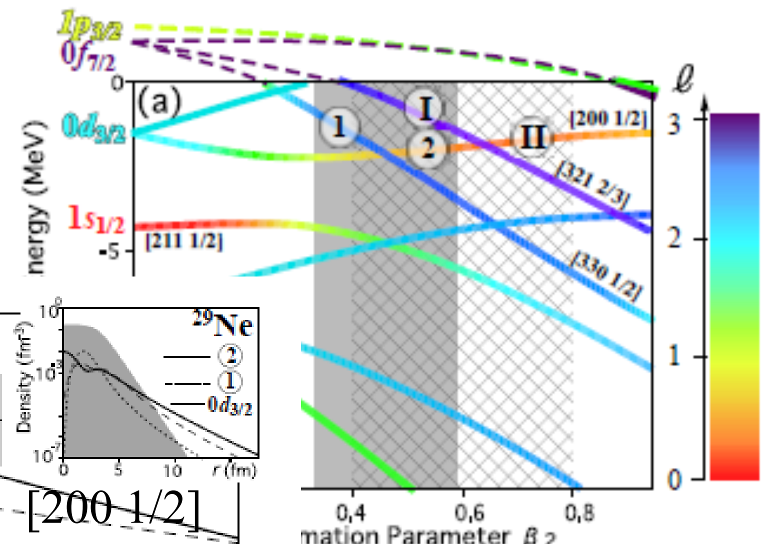
Schedule:
 2014 Commissioning run
 2015~ Mass measurements of RI

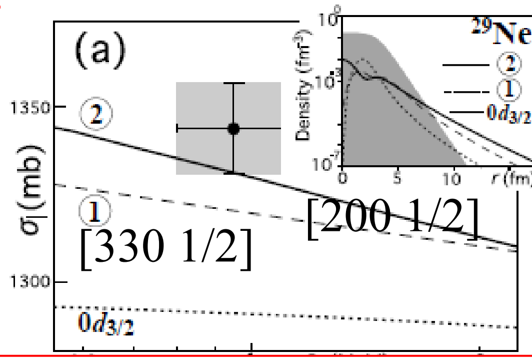
Halo Structures of ^{29}Ne and ^{31}Ne

Takechi et al., Phys. Lett. B707, 357 (2012)

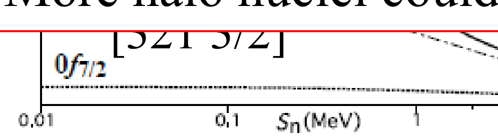
^{X}Ne+C







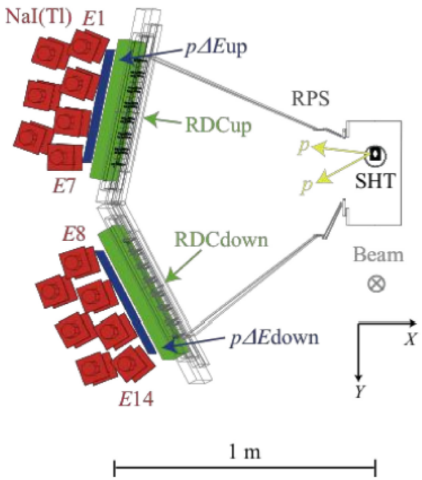
A weakly-bound valence neutron
coupled with a well deformed core.
The weak binding leads to a low-l dominance,
to form a halo system.
More halo nuclei could be discovered??



Elastic scattering study for Exotic Nuclei with ESPRI

Terashima, Zenihiro, Sakaguchi et al.

Recoil Proton Spectrometer (RPS)



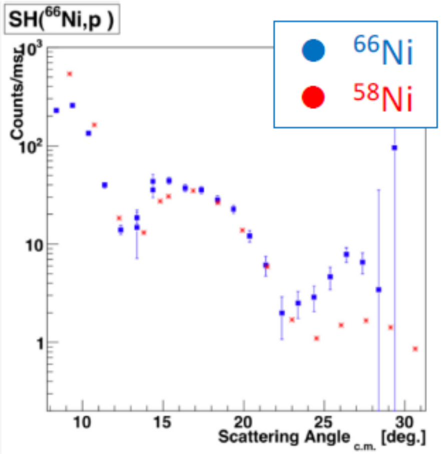
	Solid H_2 (SHT)	RDC	$p\Delta E$	E
material	Para H_2	Ar+C_2H_6	Plastic	NaI(Tl)
effective area	φ 30 mm	436 x 436 mm^2	440 x 440 mm^2	431.8 x 45.72 mm^2
thickness	1 mm	69.4 mm	2.53 / 3.09 mm	50.8 mm
Resolution		500 μm	TOF : 0.1 nsec	0.3 %(80 MeV)

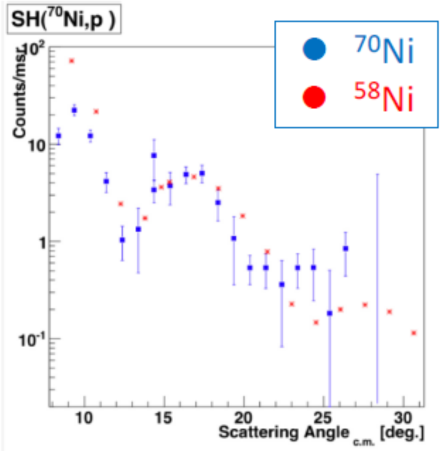
In 2006-2008

Experiments for C- and O-isotopes at HIMAC
9-11C, 20O at 300 MeV/u, 10^5 /s

In 2009-2010

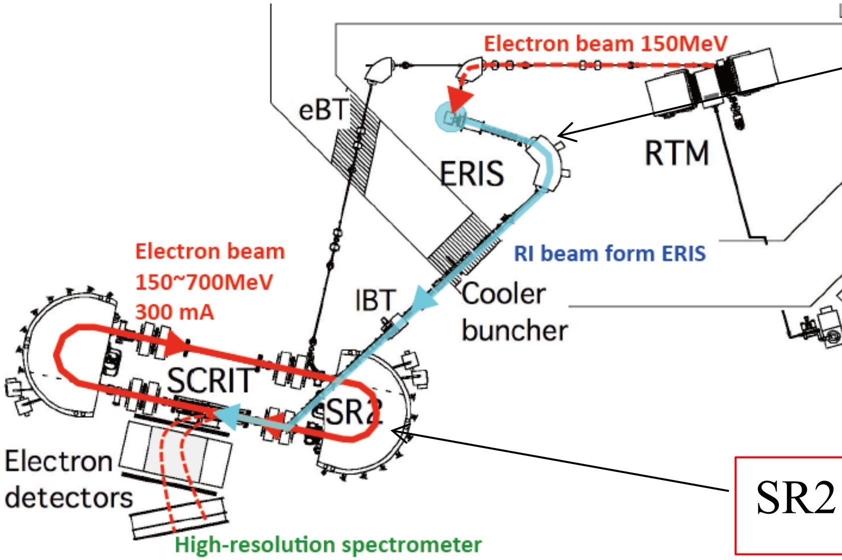
Experiment for n-rich Ni isotopes at GSI



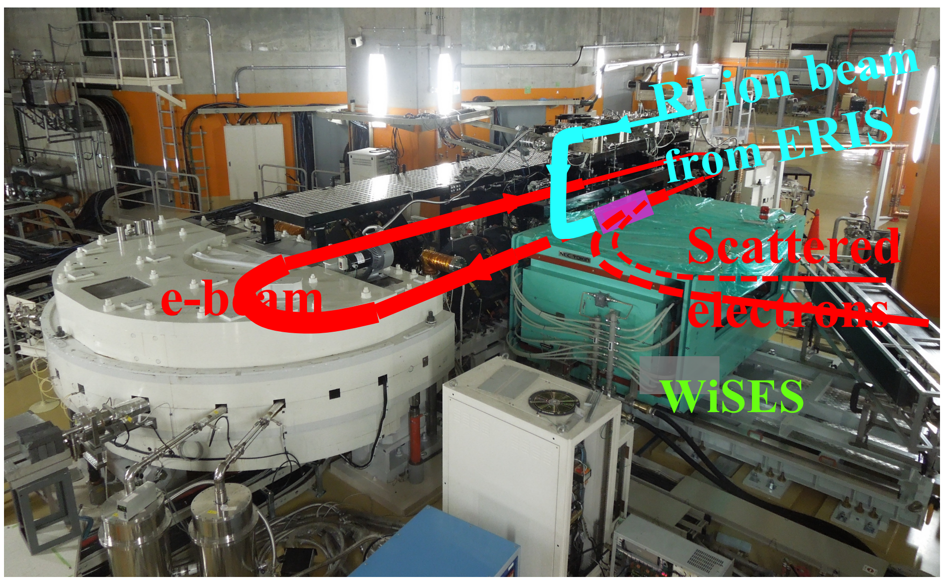


C-16 and Sn-132 at RIBF

SCRIT Facility for e+RI scattering



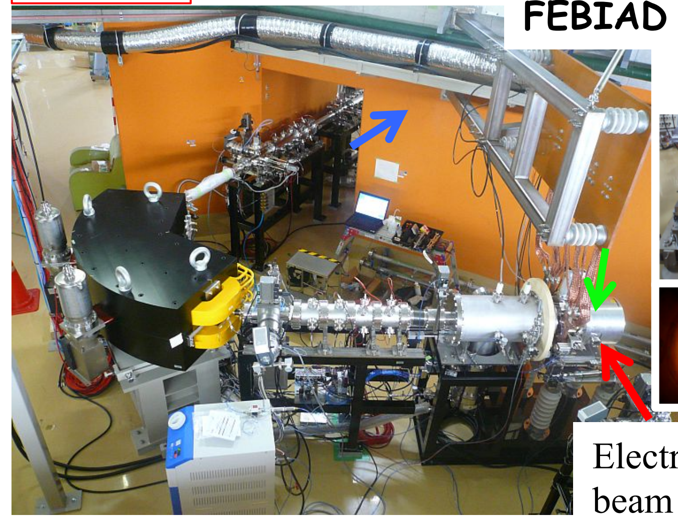
SR2

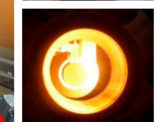


ERIS

UCx Target in
FEBIAD ion source

～2000℃





Electron
beam

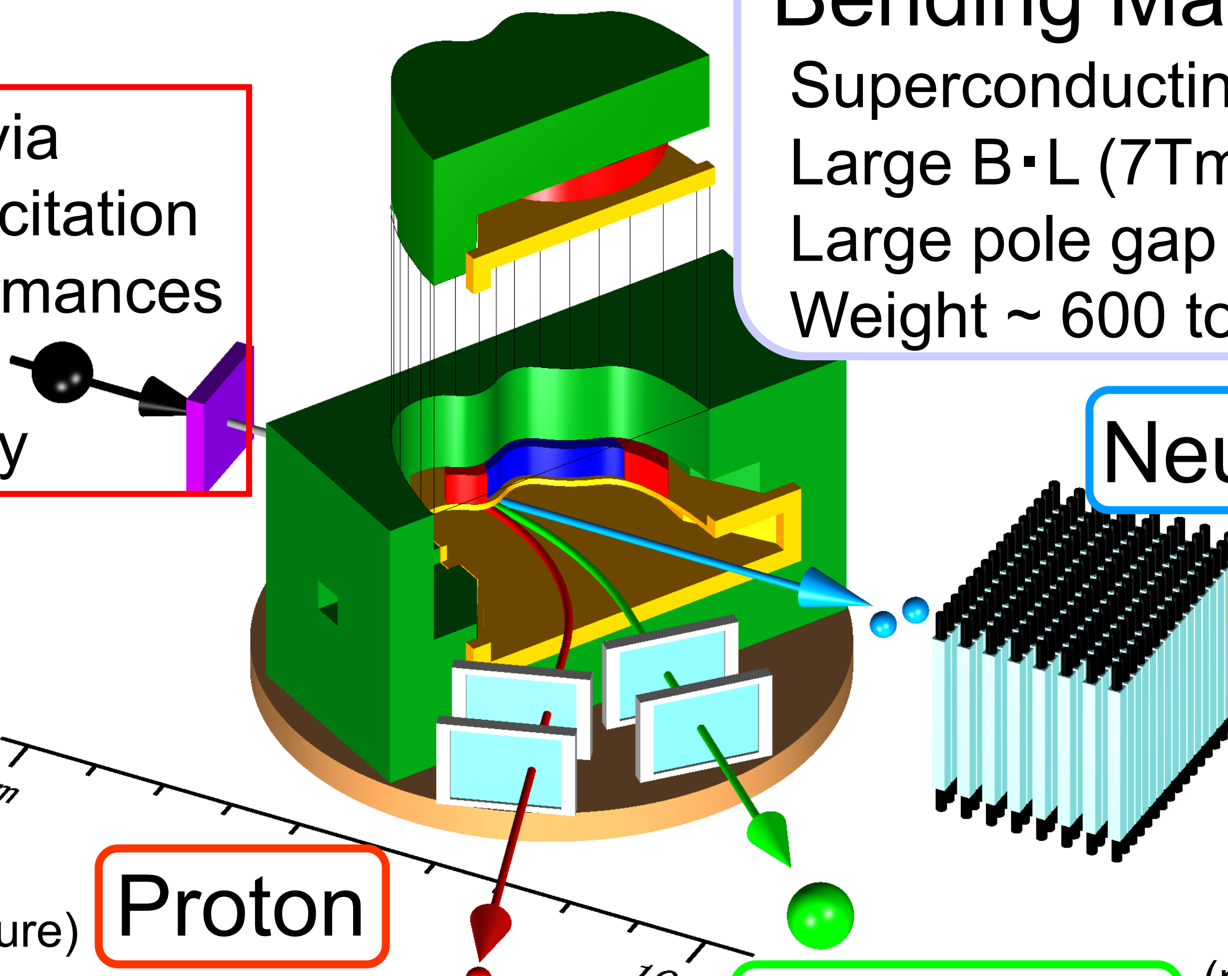
SR2 (SCRIT-equipped RIKEN Storage Ring)	
Energy	100 – 700 MeV
Stored current	300 mA (current operation)
Lifetime	~ 1 AH
Circumference	21.946 m
Tunes	1.62 / 1.58
β-max	10.36 / 4.09 m

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

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

SAMURAI Spectrometer **Kobayashi et al 2012-**

versatile spectrometer with a large superconducting magnet

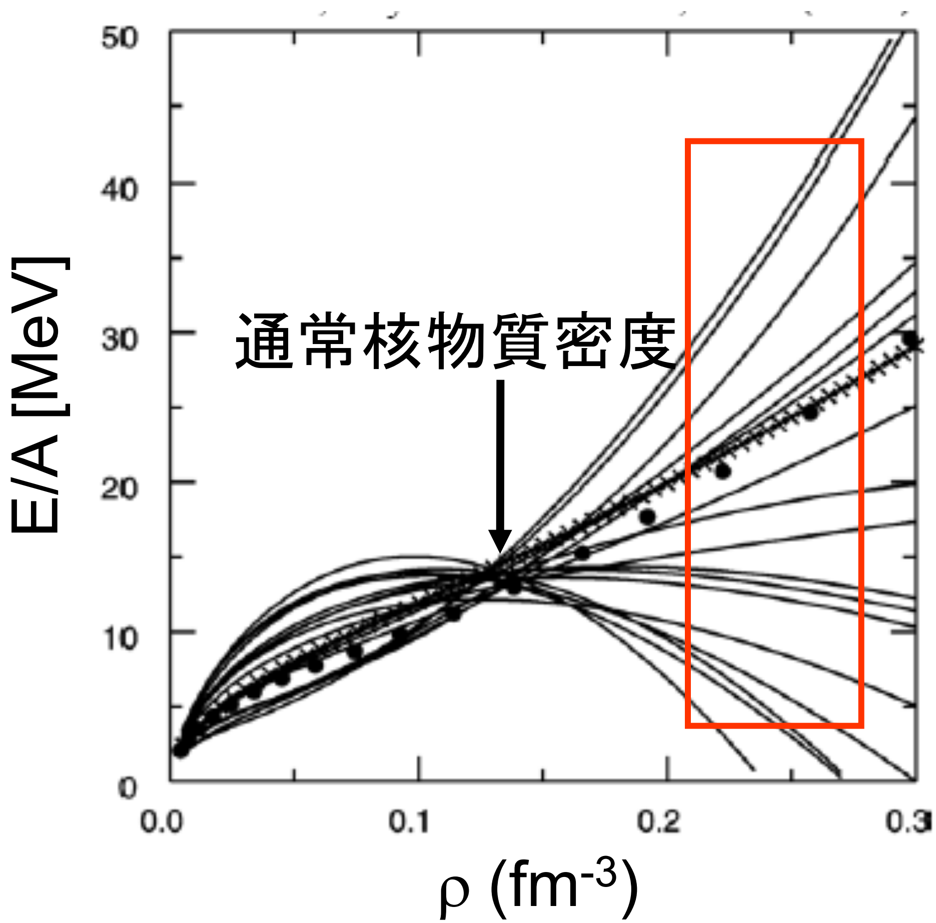


$\vec{d}$ setup
(not shown in picture)

TPC
(not shown in picture)

NSCL, Liverpool, TA&M joining this project

2. $\rho > \rho_0$



三体力…

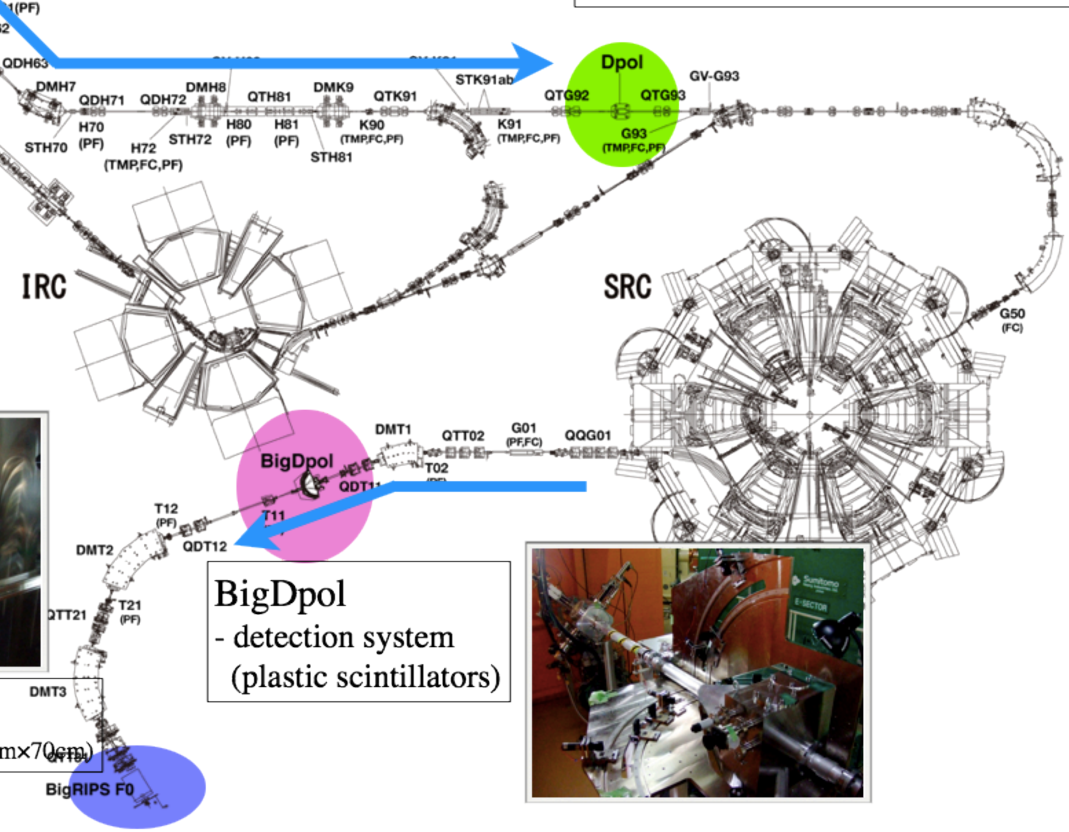
重イオン衝突

dp Elastic Scattering at RIBF and 3NF

K. Sekiguchi et al., Phys.Rev. C 83, 061001(2011)

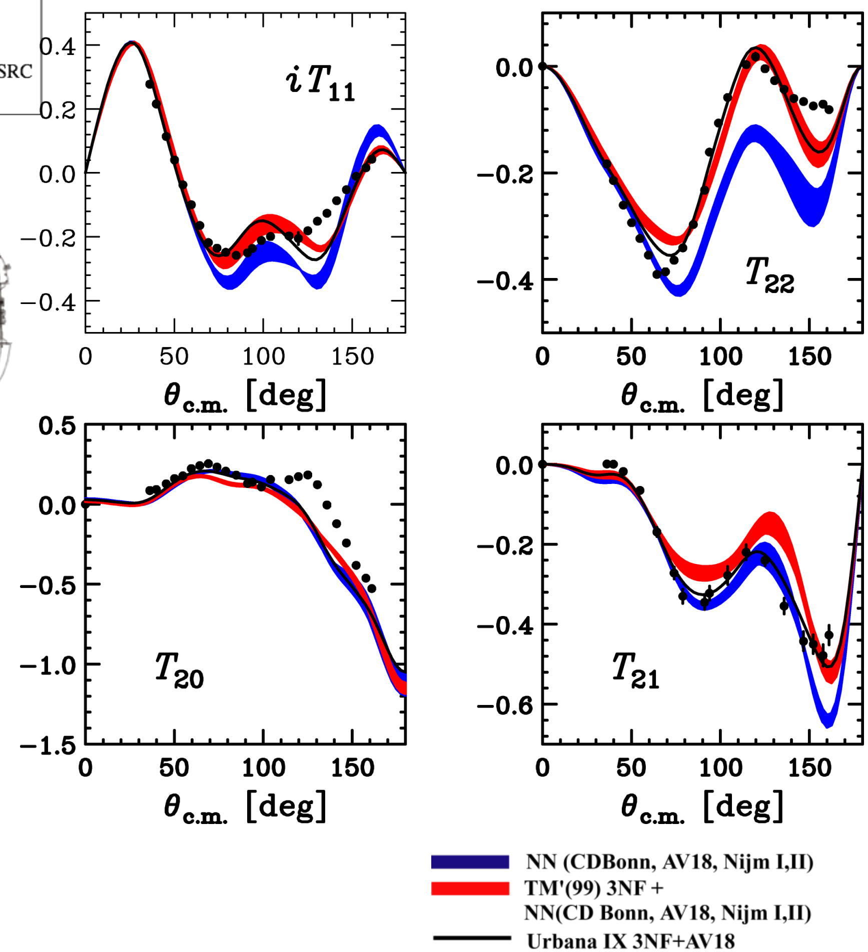
IRC bypass beam transport line
- beam line for AVF-RRC-SRC acceleration mode
- used for pol.*d* as well as light ions

Dpol
- beam line polarimeter
- measurement of beam polarization prior to acceleration by SRC
- reaction : *d-p* elastic scattering at 90 MeV/nucleon



BigDpol
- detection system (plastic scintillators)

dp @ 250 MeV/nucleon



New data at 294 MeV/nucleon, Wada and Sekiguchi, JPS, Spring 2013

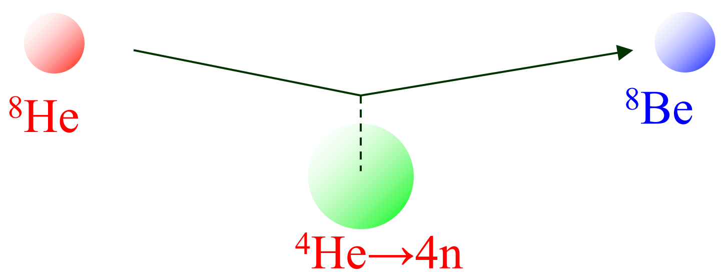
4n system study via double-charge exchange

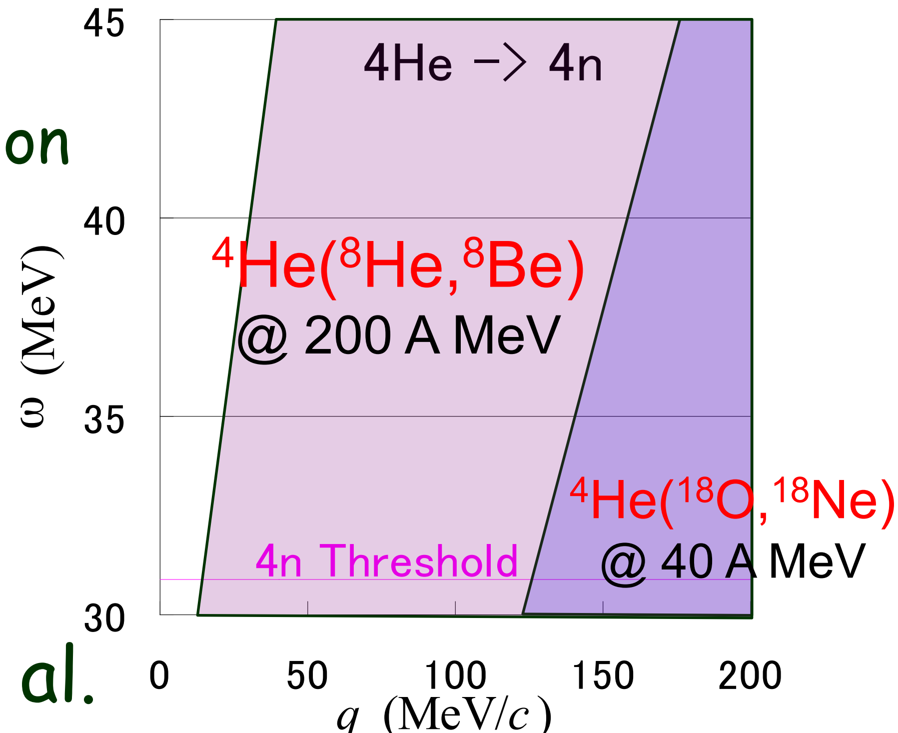
^{4}n production with ^{4}He(^{8}He,^{8}Be)

Small q <- exothermic reaction

Double-Charge ~200nb/sr

^{8}He :2x10^6/s at 190A MeV





Shimoura et al.

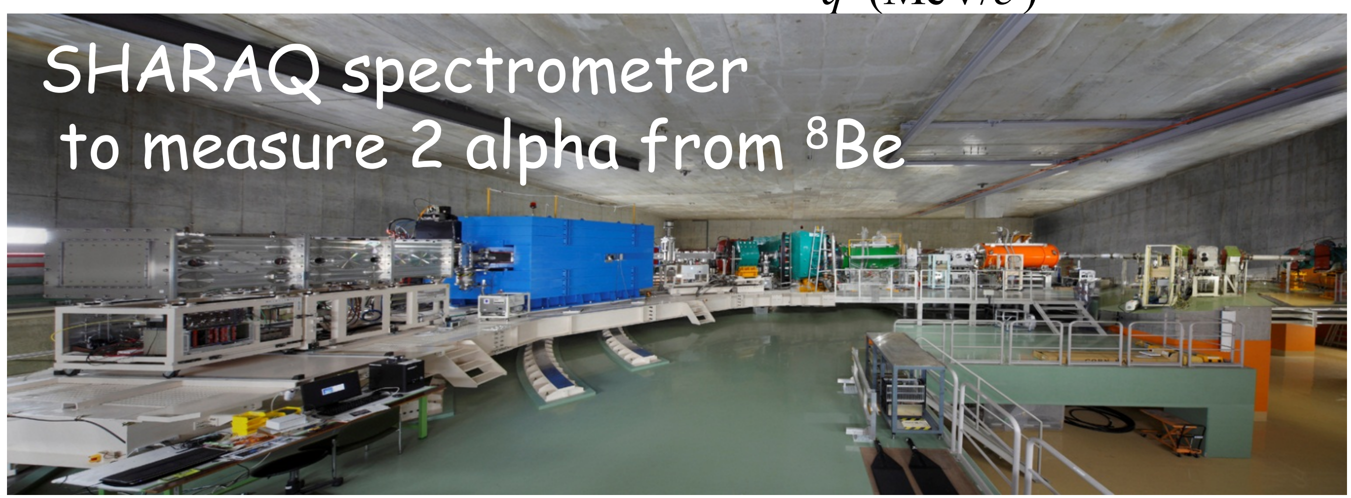
T. Uesaka et al.,
NIMB B **266** (2008) 4218.

Momentum resolution

dp/p = 1/14700

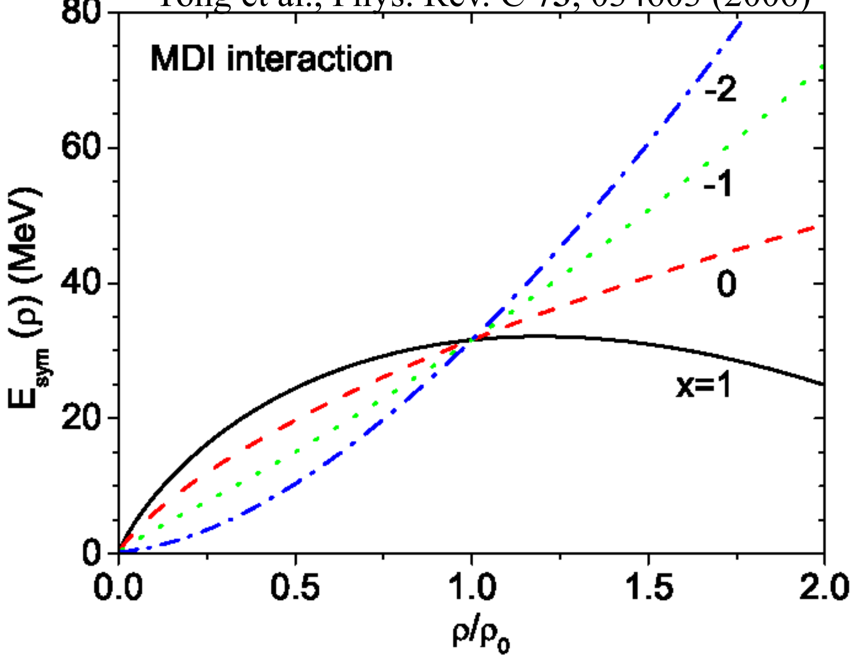
Angular resolution

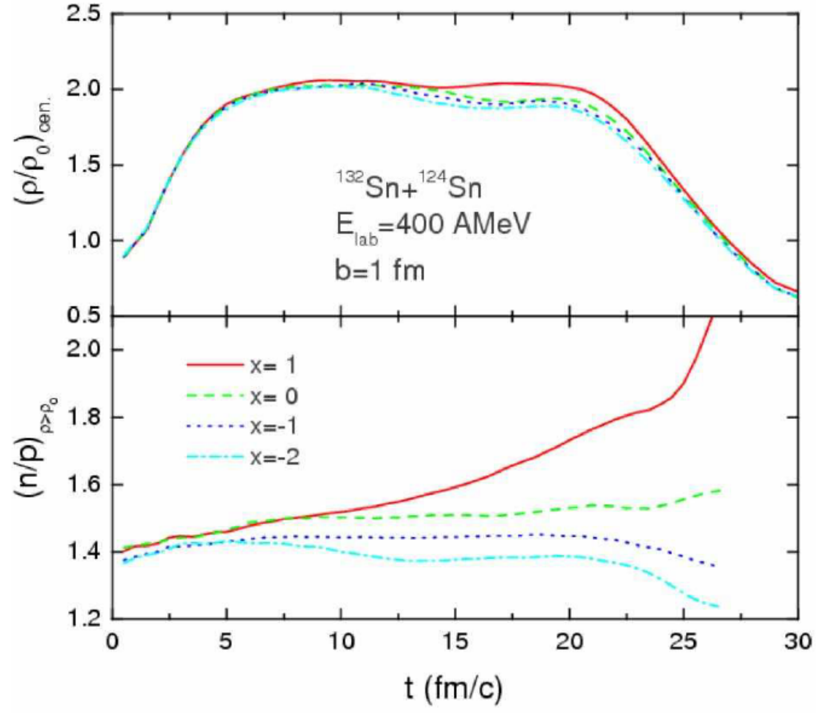
~ 1 mrad



Density profile in HIC collisions at 400A MeV

Yong et al., Phys. Rev. C **73**, 034603 (2006)



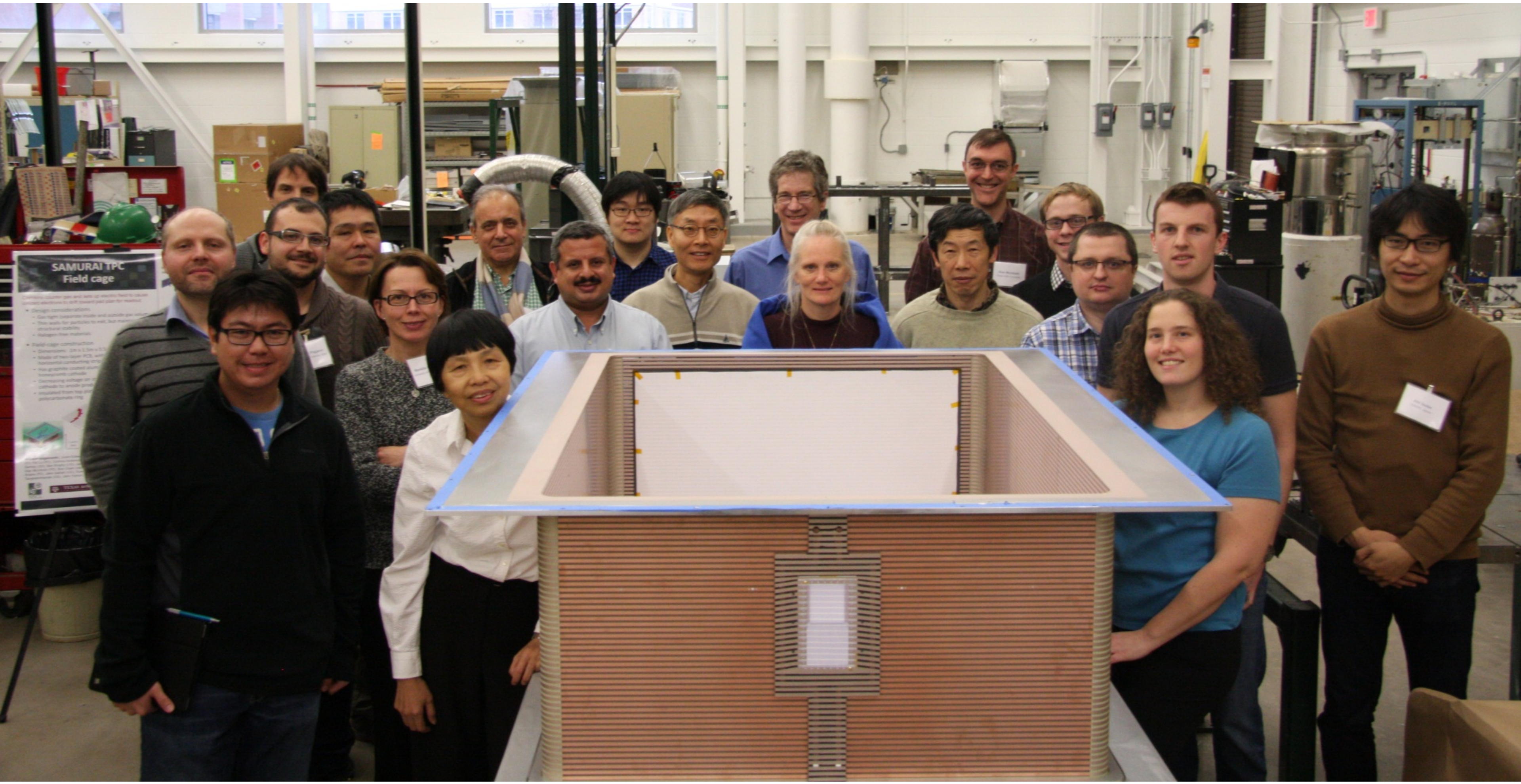


Symmetry energy dependence of density in HIC is not so large

$$\rho \sim 2\rho_0$$

n/p ratios beyond normal density depends on symmetry energy

International collaboration towards the study of nuclear symmetry energy
First RI collision experiment at RIBF at 2014



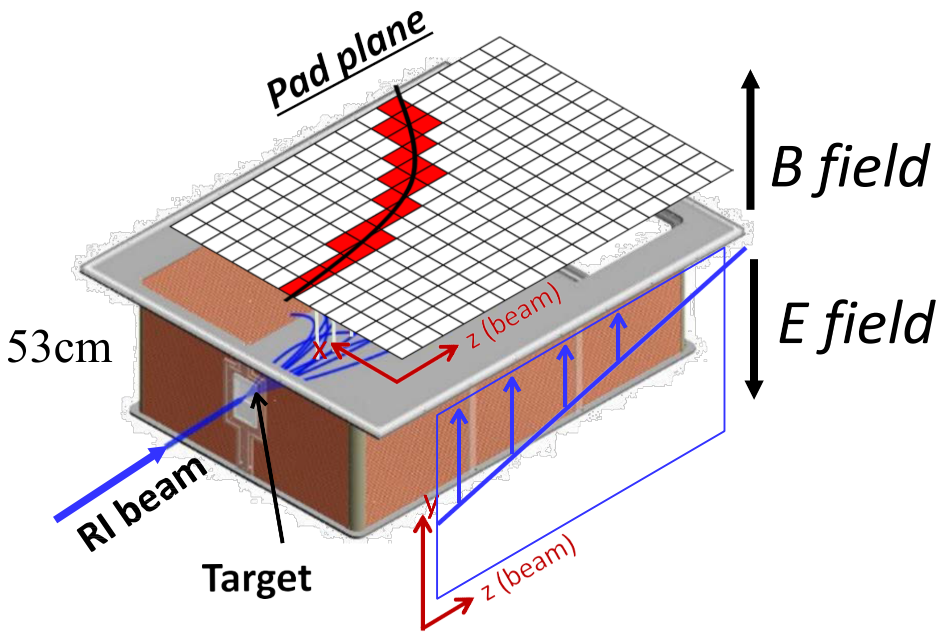
SπRIT Collaboration

MSU, RIKEN, Kyoto Univ, Texas A&M, Korea Univ, RISP, INP, TITech, CEA, Tsinghua Univ., Rikkyo Univ., Tohoku Univ.

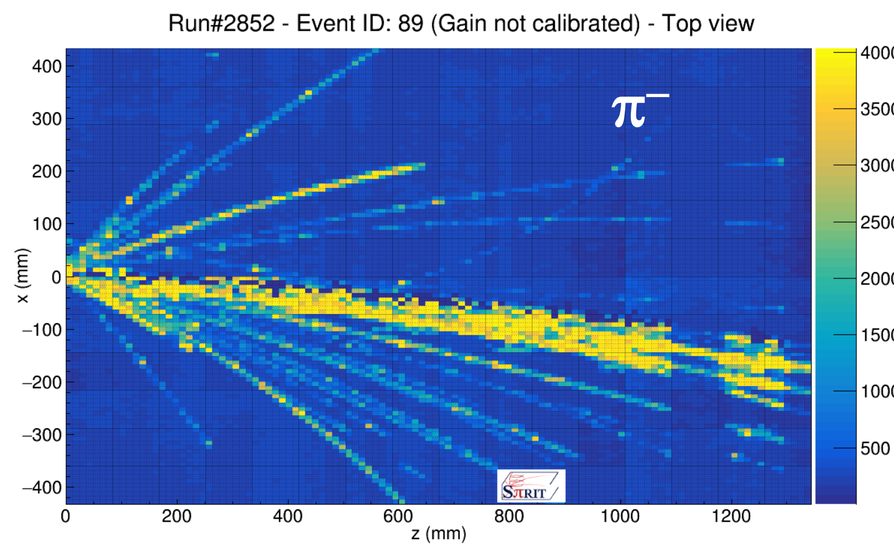
SAMURAI Pion Reconstruction and Ion Tracker

NIMA 784 (2015) 513

SπRIT-Time Projection Chamber



^{132}Sn + ^{124}Sn @E/A=300MeV TPC Top view



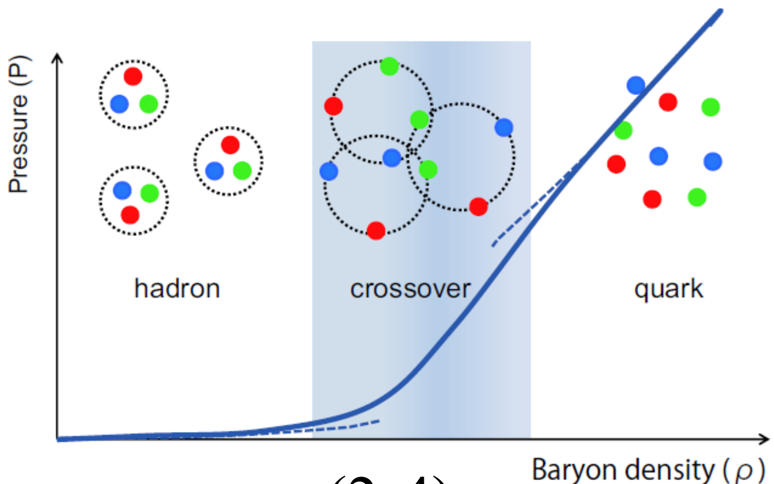
U.S. DEPARTMENT OF ENERGY Office of Science

文部科学省 MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

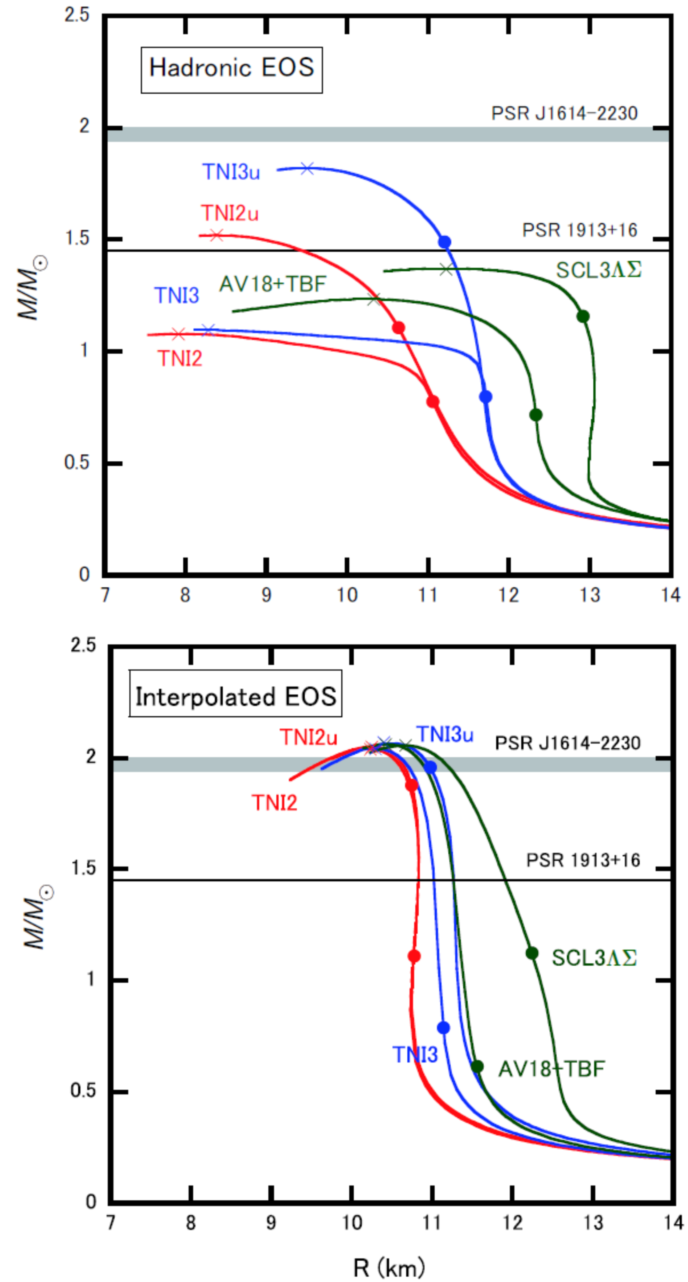
The first campaign with fast RI beams !
April-June 2016

Hadron-Quark Crossover and Massive Hybrid Stars

Masuda, Hatsuda, Takatsuka
Prog. Theor. Exp. Phys 2012
Astro. Phys. J. 764, 12 (2013)



$(2\text{-}4)\rho_0$

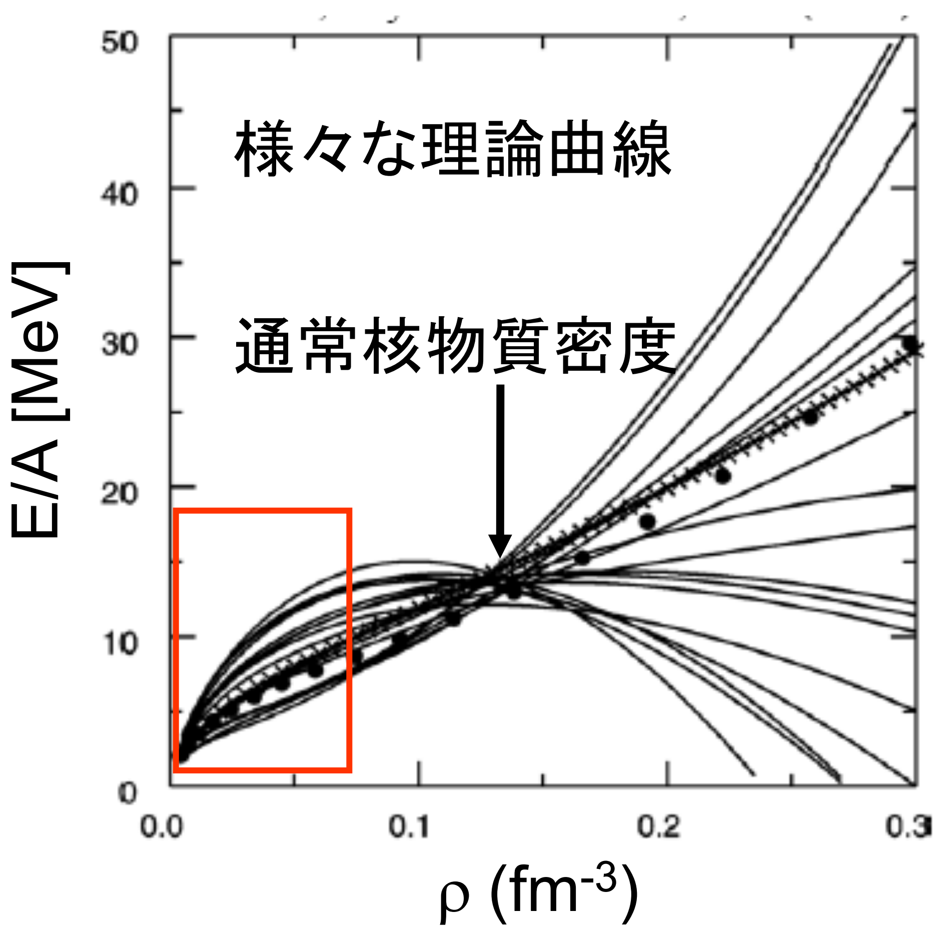


Stiff matter in the cross-over region

Any phenomena associated with crossover region??

highest density achieved at RIBF $\sim 2\rho_0$

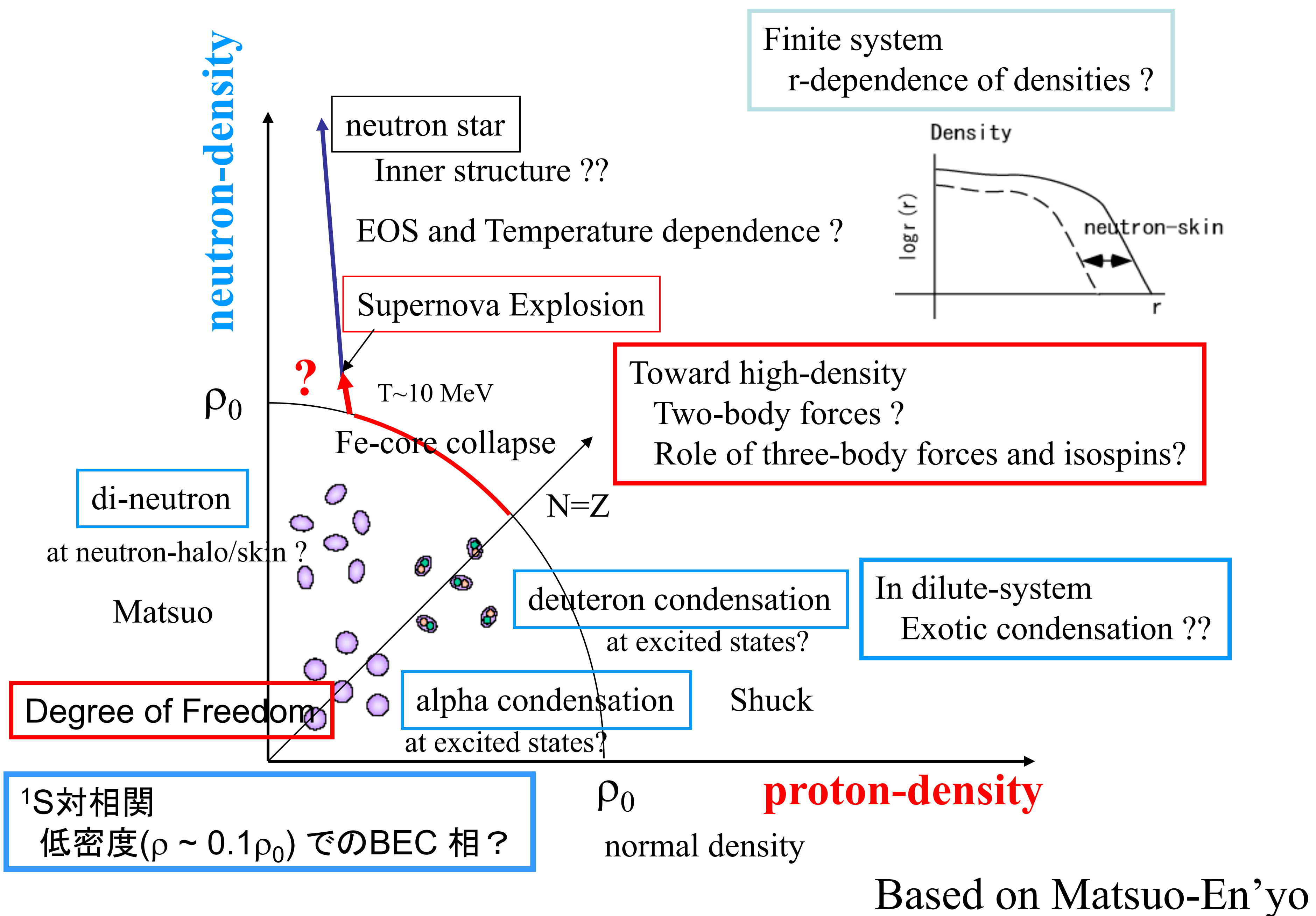
3. $\rho \sim 0.1\rho_0$



多粒子凝縮

重イオン衝突

“Phase diagram” in proton- and neutron-densities



Related activities at RIKEN

Old facility (RIPS)
Two neutron correlation in He-6(Lee, Nakamura)
  Analysis for old data on He-6 breakup reaction

New facility SAMURAI
n-n correlation (Kondo, Nakamura)
n-p correlation (Lee)
  exclusive C-12 breakup measurement
  $^{12}C \rightarrow {}^{10}B$ (-*np*), ^{10}C (-2*n*), ^{10}Be (-2*p*) @ 250 A MeV
cluster states in C-16 (Otsu)

RIBF高度化：戦略１　核図表の拡大