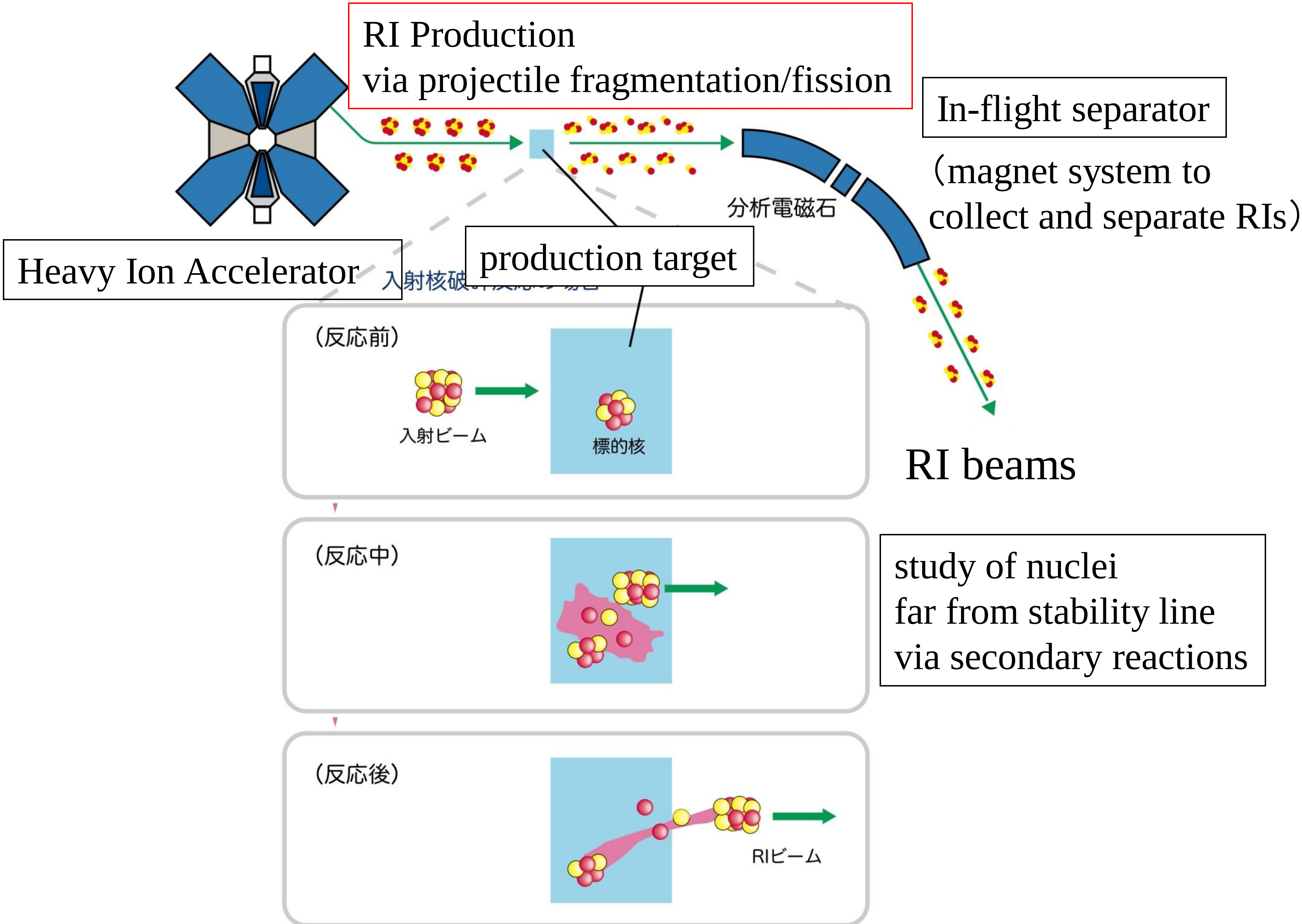
Nuclear Physics at RIBF

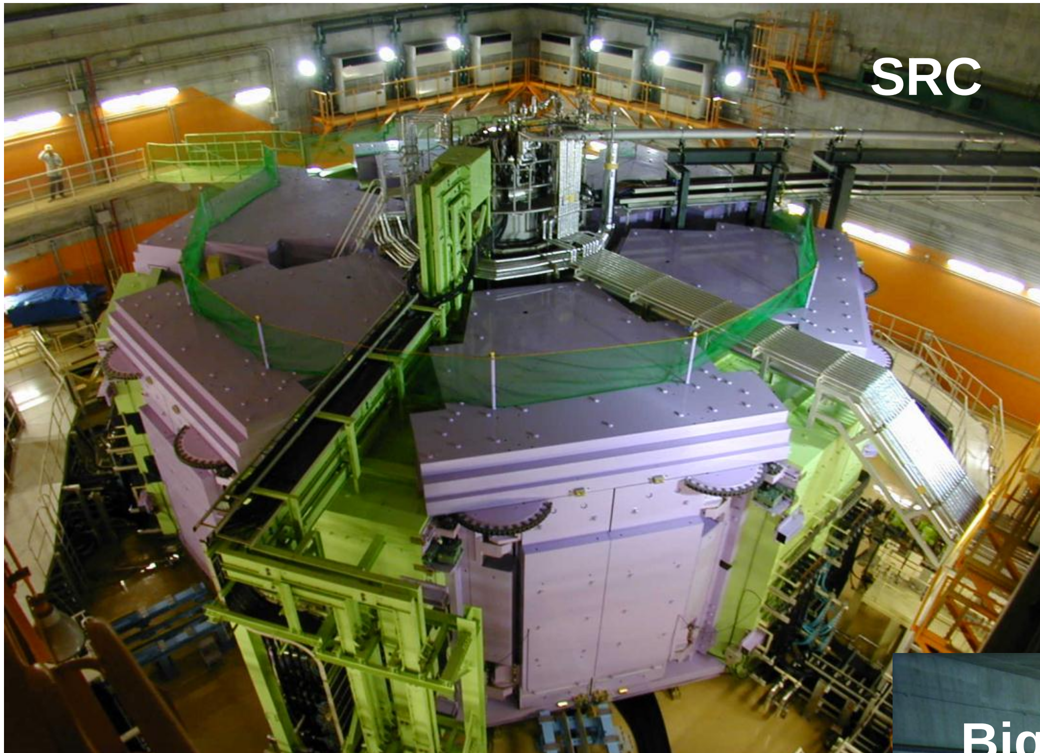
1. Facility Overview
2. Nuclear structure & astrophysics
   Highlights and on-going programs
3. Toward "Island-of-Stability"
4. Summary

H. Sakurai
RIKEN Nishina Center/Dept of Phys., Univ. of Tokyo

RI=Radioactive Isotope B=Beam F=Factory
Mass production of radioactive isotopes as secondary beams

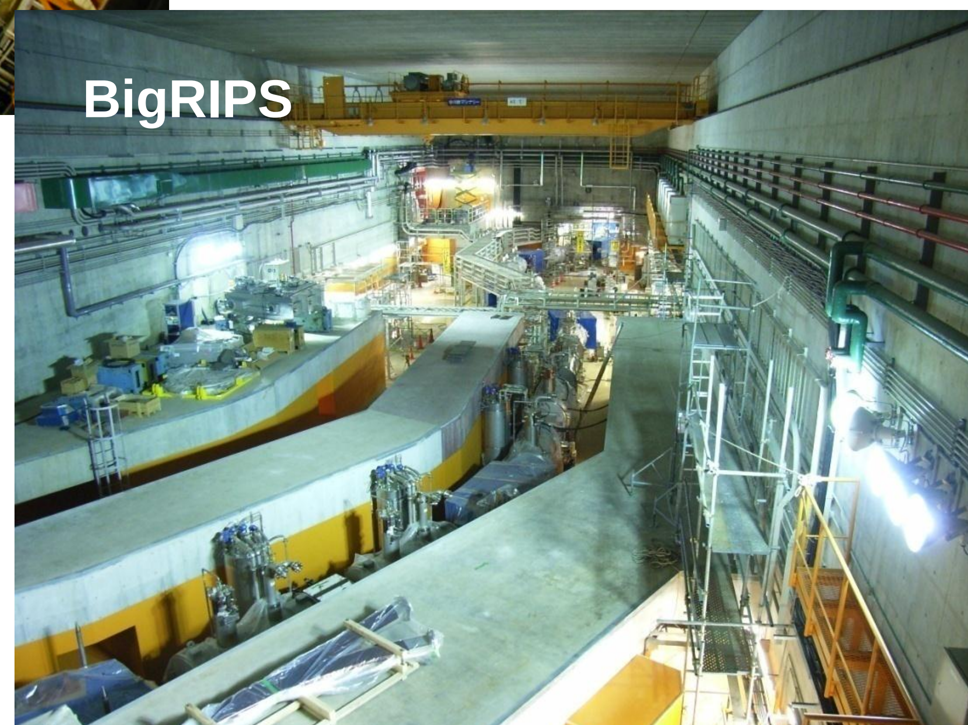
In-flight Production Method of RI beam





World's First and Strongest
K2600MeV
Superconducting Ring Cyclotron

400 MeV/u Light-ion beam
345 MeV/u Uranium beam



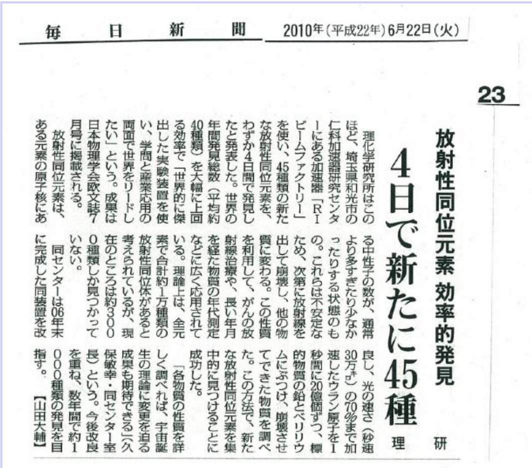
World's Largest Acceptance
9 Tm
Superconducting RI beam Separator

~250-300 MeV/nucleon RIB

Press-Conference on June 8th, 2010

June 8, 2010
RIKEN

Scientists discover 45 new radioisotopes in 4 days


毎日新聞 2010年（平成22年）6月22日（火） 23

放射性同位元素 効率的発見
4日で新たに45種
理研

理化学研究所はこのほど、埼玉県和光市の仁科加速器研究センターにある加速器「RIビームファクトリー」を使い、45種類の新たな放射性同位元素を、わずか4日間で発見したと発表した。世界の年間発見総数（平均約40種類）を大幅に上回る効率で「世界的に傑出した実験装置を使い、学問と産業応用の両面で世界をリードしたい」という。成果は日本物理学会欧文誌7月号に掲載される。

放射性同位元素は、ある元素の原子核にある中性子の数が、通常より多すぎたり少なかったりする状態のもの。これらは不安定なため、次第に放射線を出して崩壊し、他の物質に変わる。この性質を利用して、がんの放射線治療や、長い年月を経た物質の年代測定などに広く応用されている。理論上は、全元素で合計約1万種類の放射性同位体があると考えられているが、現在のところは約3000種類しか見つかっていない。

同センターは06年末に完成した同装置を改良し、光の速さ（秒速30万キロ）の70％まで加速したウラン原子を1秒間に20億個ずつ、標的物質の鉛とベリリウムにぶつけ、崩壊させてできた物質を調べた。この方法で、新たな放射性同位元素を集中的に見つけることに成功した。

「各物質の性質を詳しく調べれば、宇宙誕生の理論に変更を迫る成果も期待できる」（久保敏幸・同センター室長）という。今後改良を重ね、数年間で約1000種類の発見を目指す。【山田大輔】


東京新聞 2010年（平成22年）6月9日（水曜日） 3

同位元素45種 一度に発見
加速器施設 世界最高の性能

理化学研究所は八日、加速器施設「RIビームファクトリー」を使って四十五種の放射性同位元素（RI）を新たに見つけたと発表した。これほど多くの種類が一度の実験で発見されるのは初めて。物質の成り立ちを解明する手掛かりになると期待される。成果は来週にも日本物理学会誌の電子版に発表する。

理化学研究所

ウランの原子を光速の70％まで加速して金属板にぶつけると、ウランの原子核が砕けて何種ものRIが飛び出す。同施設の研究グループでは、これらを磁石の〝ふるい〟にかけて一種ずつ効率よく選別して捕らえることに成功した。

約四日間の実験でマンガンやバリウムなどのRIを計四十五種確認した。世界で発見されるRIは年間四十種ほど。これを超す数を数日で見つけて世界最高の性能を示した。

宇宙の歴史の中で、鉄より重い元素がどのように作られたかは、はっきり分かっていない。RIがその謎を解く鍵と考えられ、欧米でも研究が始まっている。

RIは一万種近くあると予想され、これまで確認されたのは約二千六百種。グループでは「施設の性能がフルに発揮できれば、あと一千種は見つけられる」と話す。

IOP A website from the Institute of Physics

physicsworld.com

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Radioisotopes galore at RIKEN

Jun 14, 2010

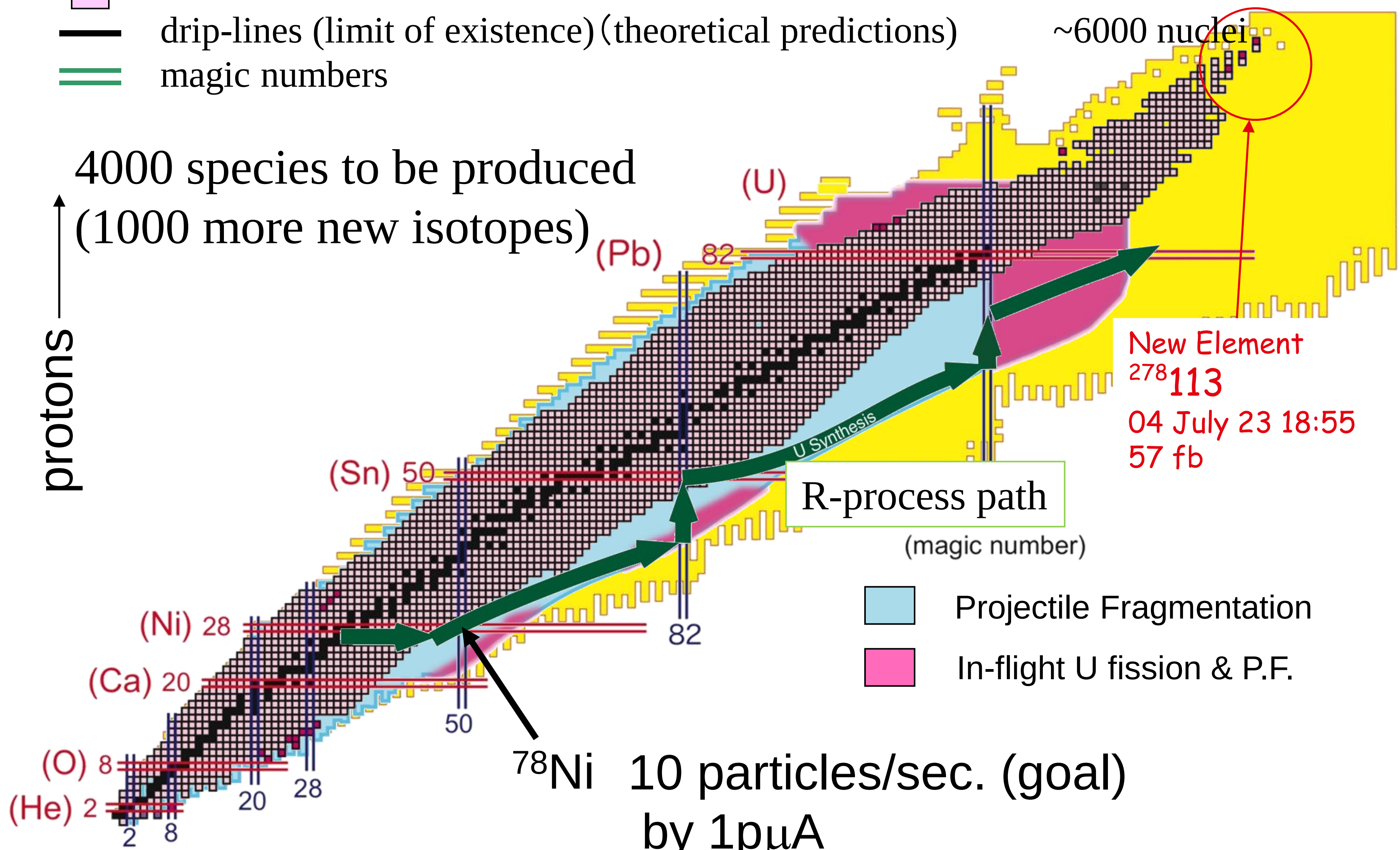
BigRIPS has found 45 new radioisotopes

The chart of the known nuclides has been extended significantly by physicists in Japan, who have discovered 45 new neutron-rich isotopes. The nuclei were spotted at the RIKEN laboratory by smashing a powerful beam of heavy ions into beryllium and lead targets.

T. Ohnishi et al., JPSJ 79, 073201 (2010)
D.Kameda et al., PRC 84 054319 (2012); 18 new isomers

Exploration of the Limit of Existence

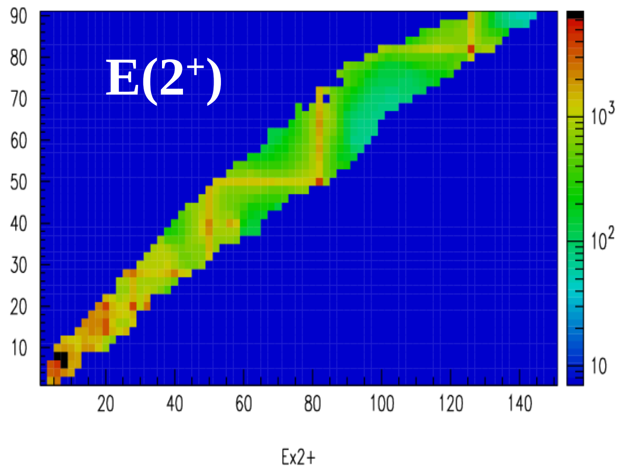
■	stable nuclei	~300 nuclei
□	unstable nuclei observed so far	~2700 nuclei
—	drip-lines (limit of existence)（theoretical predictions)	~6000 nuclei
=	magic numbers	



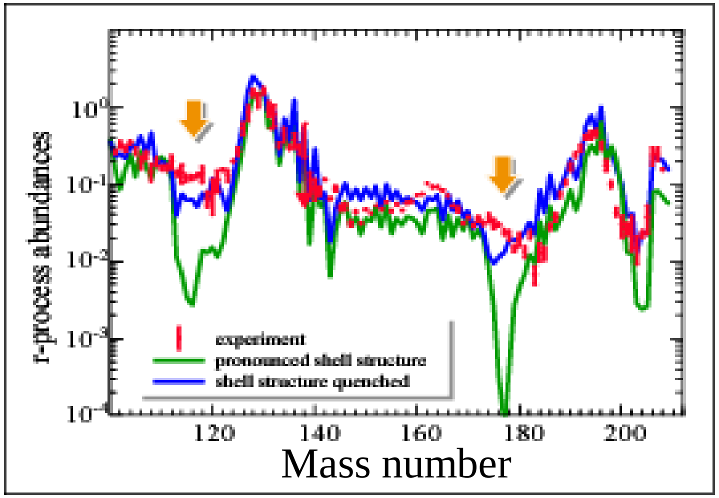
neutrons →

Challenges at the RIBF

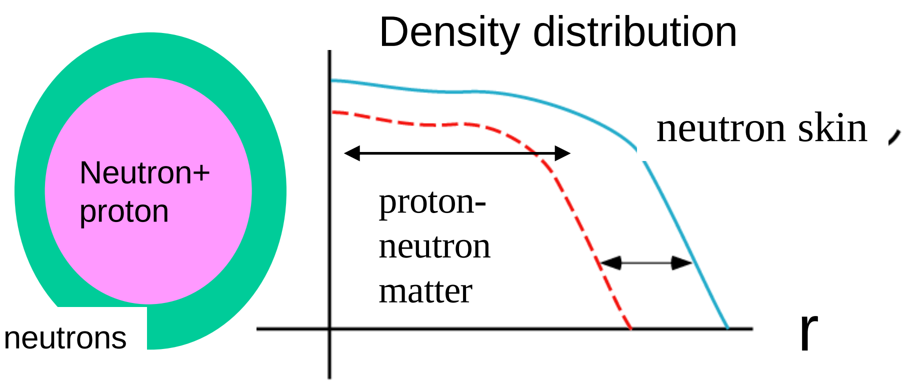
Shell Evolution :
magicity loss and new magicity



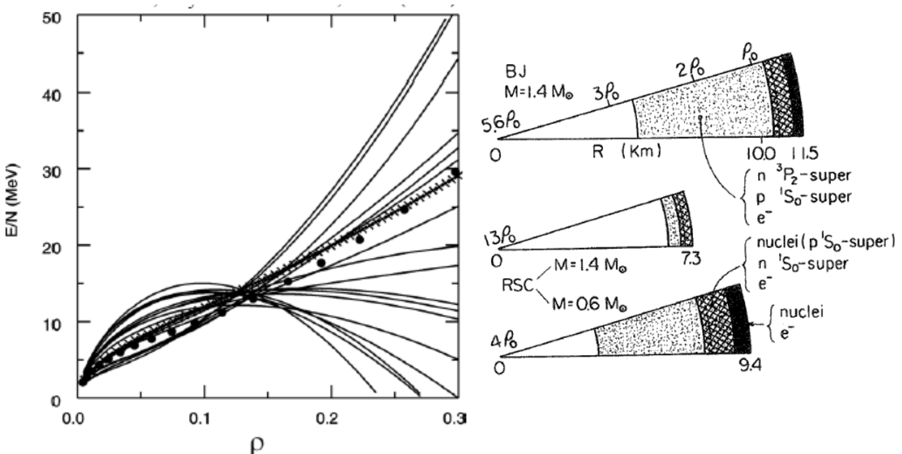
R-process path: Synthesis up to U



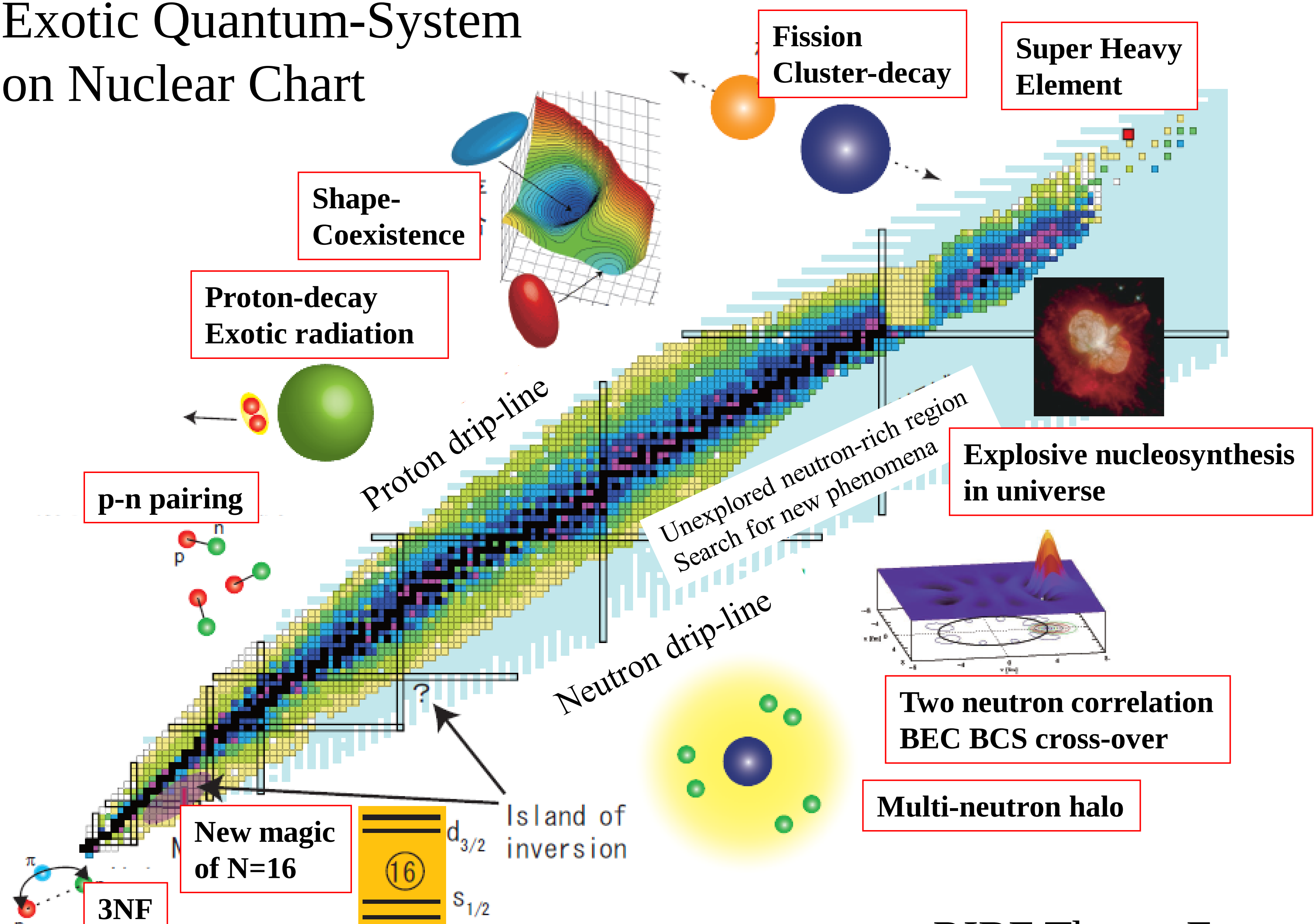
Dynamics of new "material" :
Neutron-skin（halo）



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



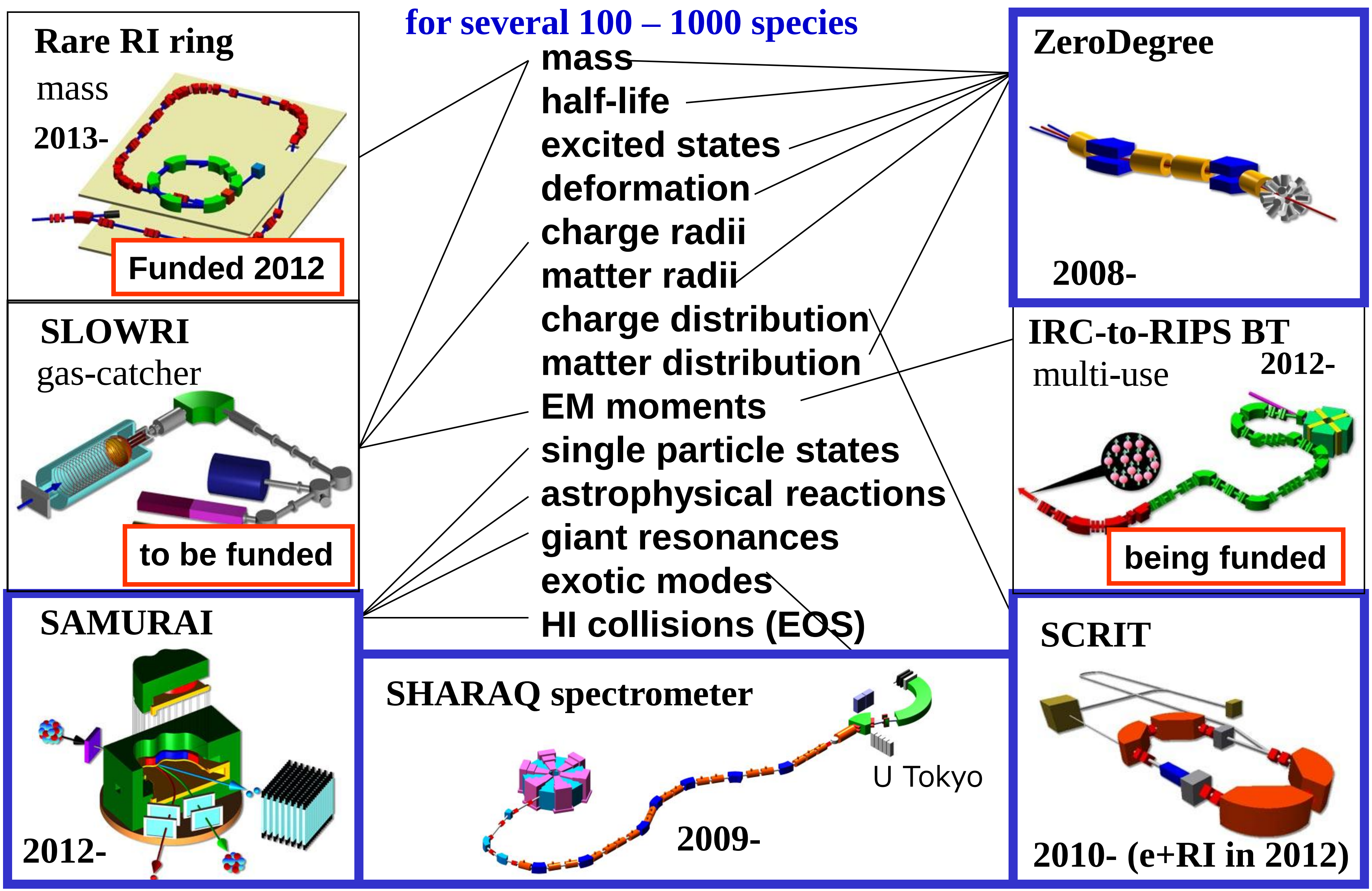
Exotic Quantum-System on Nuclear Chart



RIBF Theory Forum

New Experimental Devices of RIBF

To maximize the potentials of intense RI beams available at RIBF



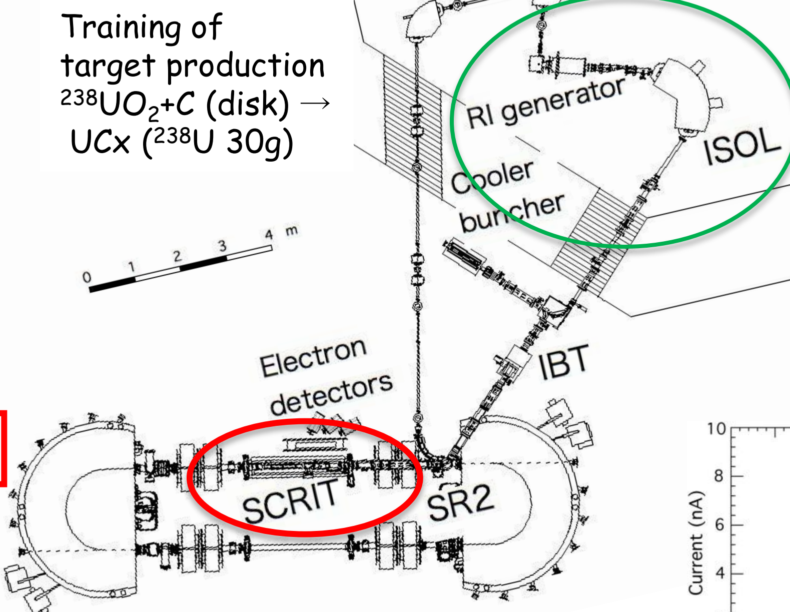
SCRIT Electron Scattering Facility

Wakasugi et al.

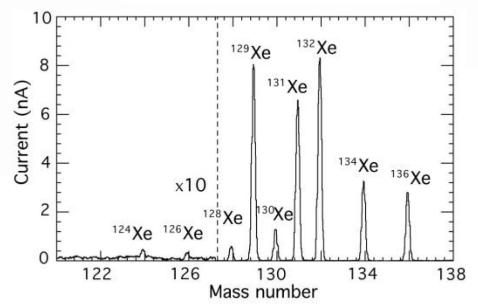
2009 Facility constructions
2010 Tuning of accelerators
Installation of SCRIT
2011 SCRIT performance test
ISOL commissioning
2012 Test of RI production
Tuning of ISOL
2013 Upgrade RTM
Construction e-Spectromete
Full-scale RI production
Start Experiments for RI's

Commissioning of ISOL and preparation of UCx target

Training of target production
$^{238}UO_2$+C (disk) → UCx (^{238}U 30g)

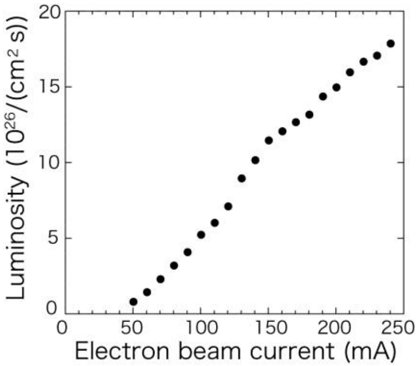


Test with stable Xe isotopes
Mass resolution M/ΔM 1660
Overall efficiency 21 %



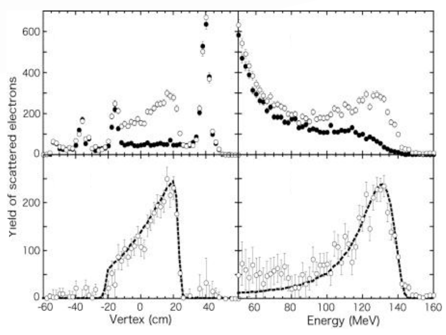
Test Experiments using Stable ^{133}Cs

Achieved luminosity 1.8×10^{27} /(cm²s)
Ion trapping efficiency 85 %
at 240 mA



Measurements of Electrons elastically scattered from trapped Cs ions in SCRIT

○ with Cs
● without Cs

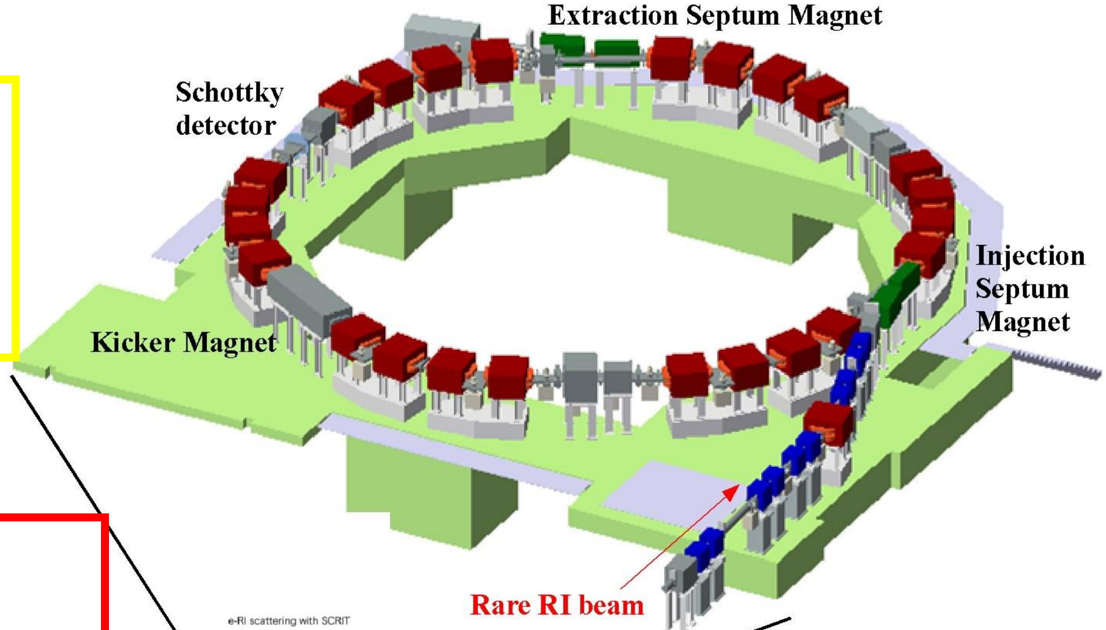


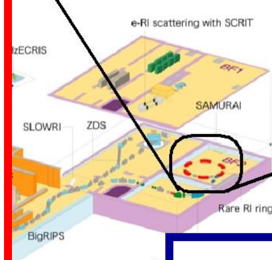
“Rare RI Ring” for mass measurement

RIKEN NISHINA CENTER

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

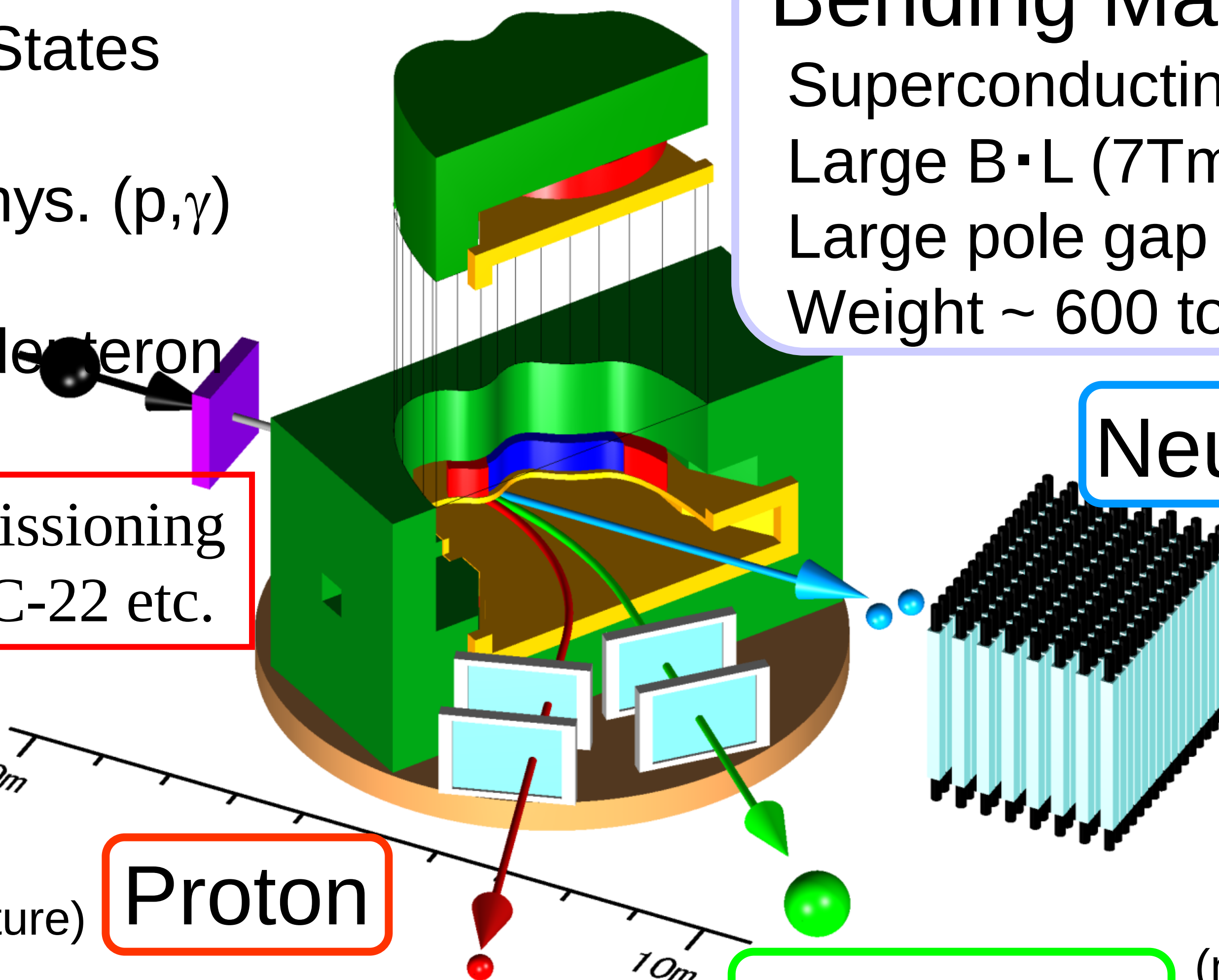
SAMURAI Spectrometer   Kobayashi et al   2012-

versatile spectrometer with a large superconducting magnet

Spectroscopy of
  Unbound States
 (p,2p)
Nucl. Astrophys. (p,γ)
Clustering
3NF w/ pol. deuteron
EoS in HIC

March Commissioning
May   B-19, C-22 etc.

Bending Magnet
- Superconducting
- Large B·L (7Tm)
- Large pole gap (80cm)
- Weight ~ 600 ton

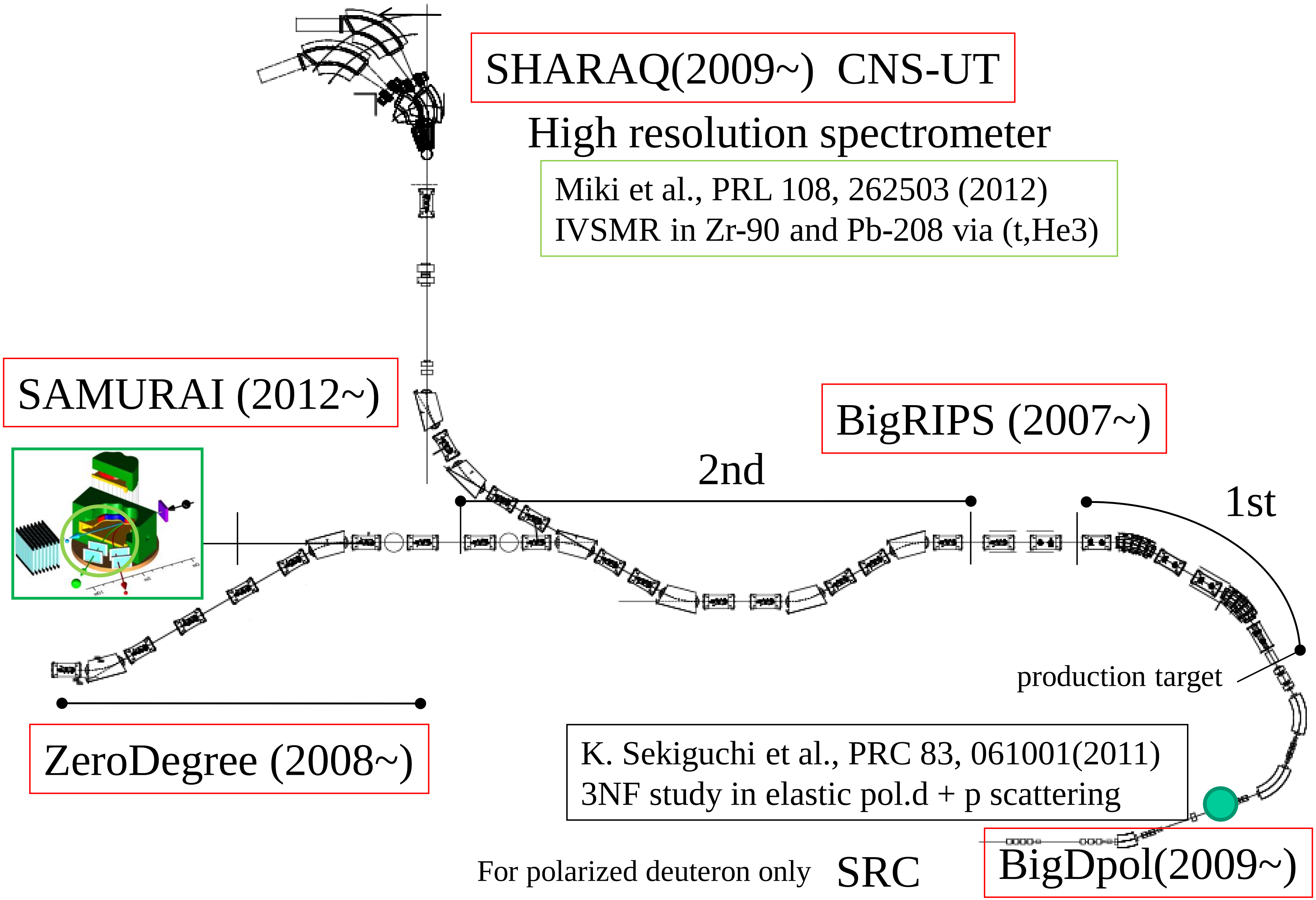


$\vec{d}$ setup
(not shown in picture)

TPC
(not shown in picture)

NSCL, Liverpool, TA&M joining this project

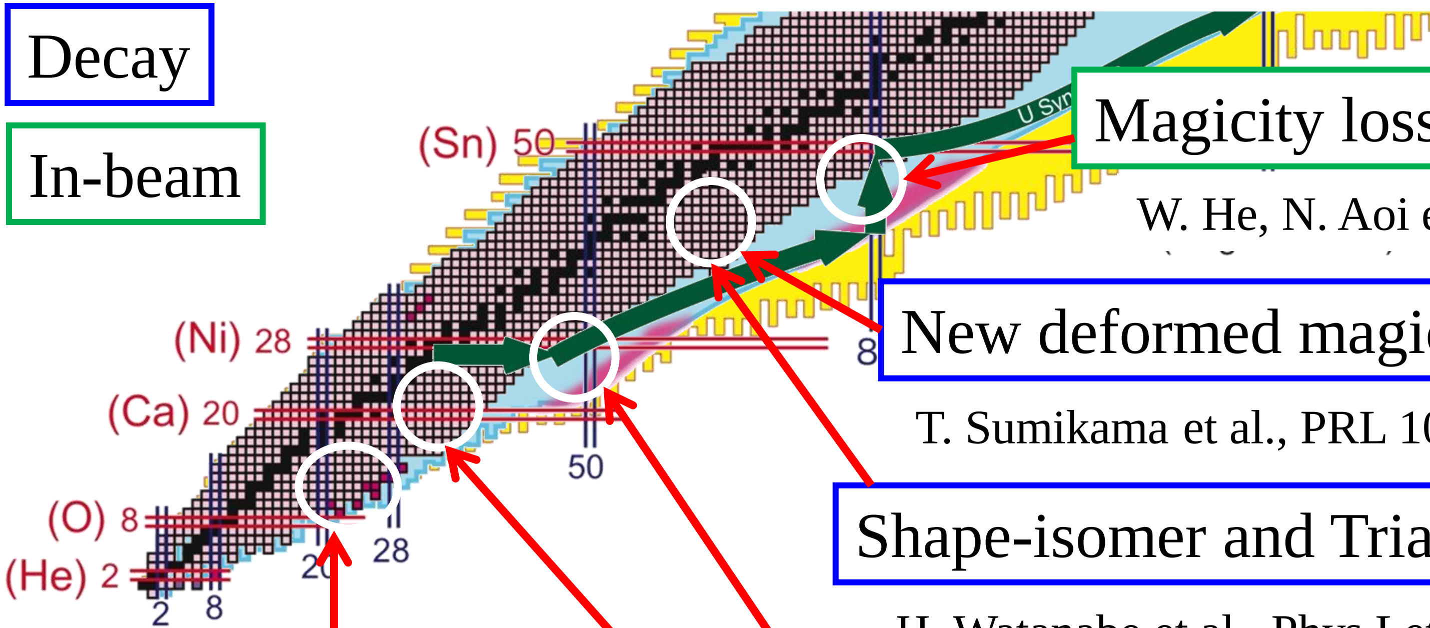
Experimental Devices available at the new facility



Shell Evolution : In-beam gamma and decay spectroscopy

Decay

In-beam



Magicity loss at N=82 ?

W. He, N. Aoi et al

New deformed magic N=64 in Zr

T. Sumikama et al., PRL 106, 202501 (2011)

Shape-isomer and Triaxiality at A~100

H. Watanabe et al., Phys.Lett.B 704,270-275(2011)

H. Watanabe et al., Phys.Lett.B 696,186-190(2011)

Double-magicity of Ni-78?

K. Yoneda et al

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

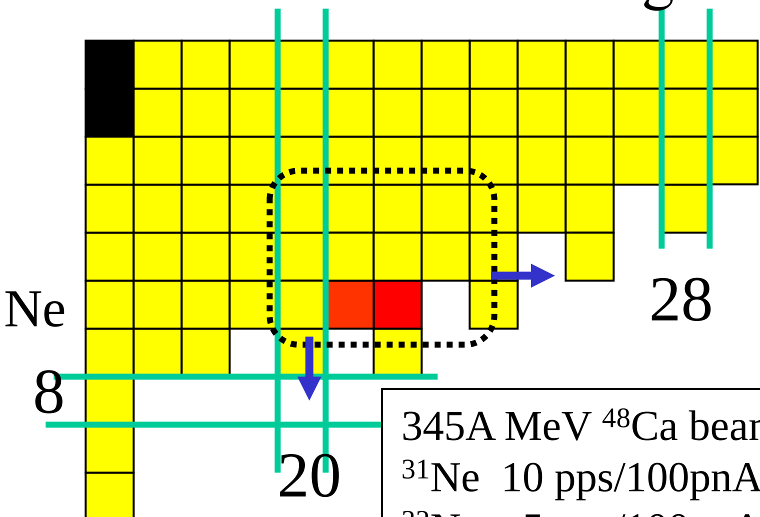
New magicity at N=34 in Ca?

D. Steppenbeck, S. Takeuchi et al.

Collectivity enhancement toward the drip line in Ne and Discovery of deformed halo nucleus ^{31}Ne

DayOne in 2008

“Island of inversion” region

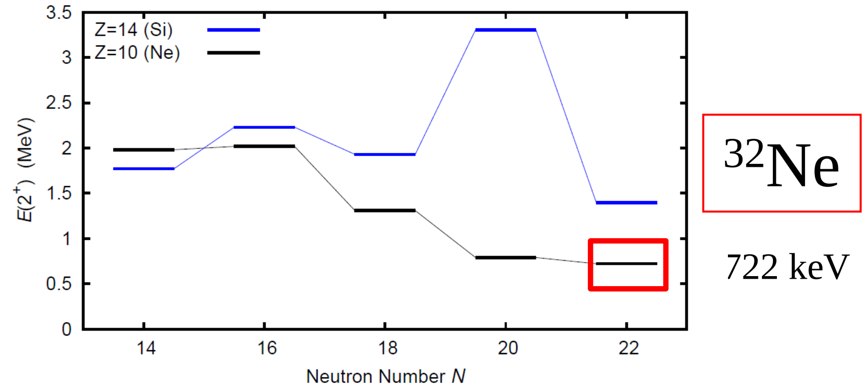


345A MeV ^{48}Ca beam
^{31}Ne 10 pps/100pnA
^{32}Ne 5 pps/100pnA

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

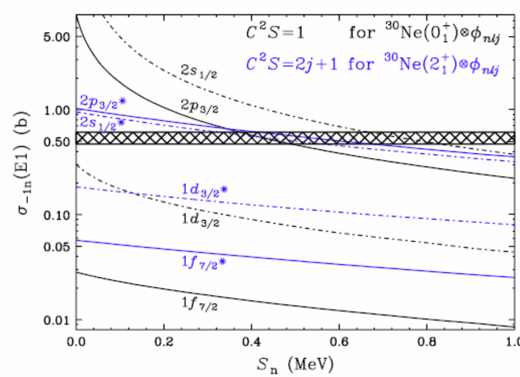
Collectivity enhancement toward the drip line?

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



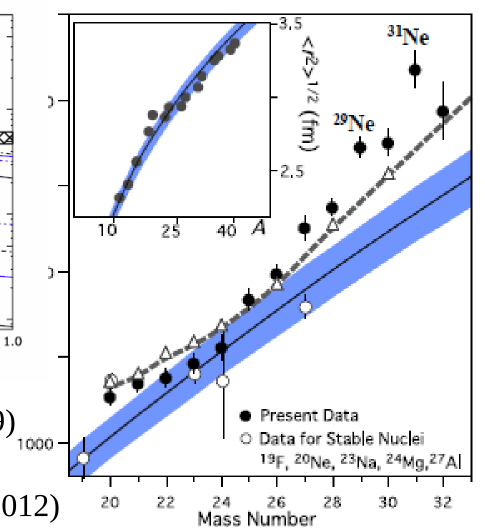
A new candidate of halo nuclei: ^{31}Ne

Large Coulomb breakup cross section



Nakamura et al., PRL 103, 262501(2009)

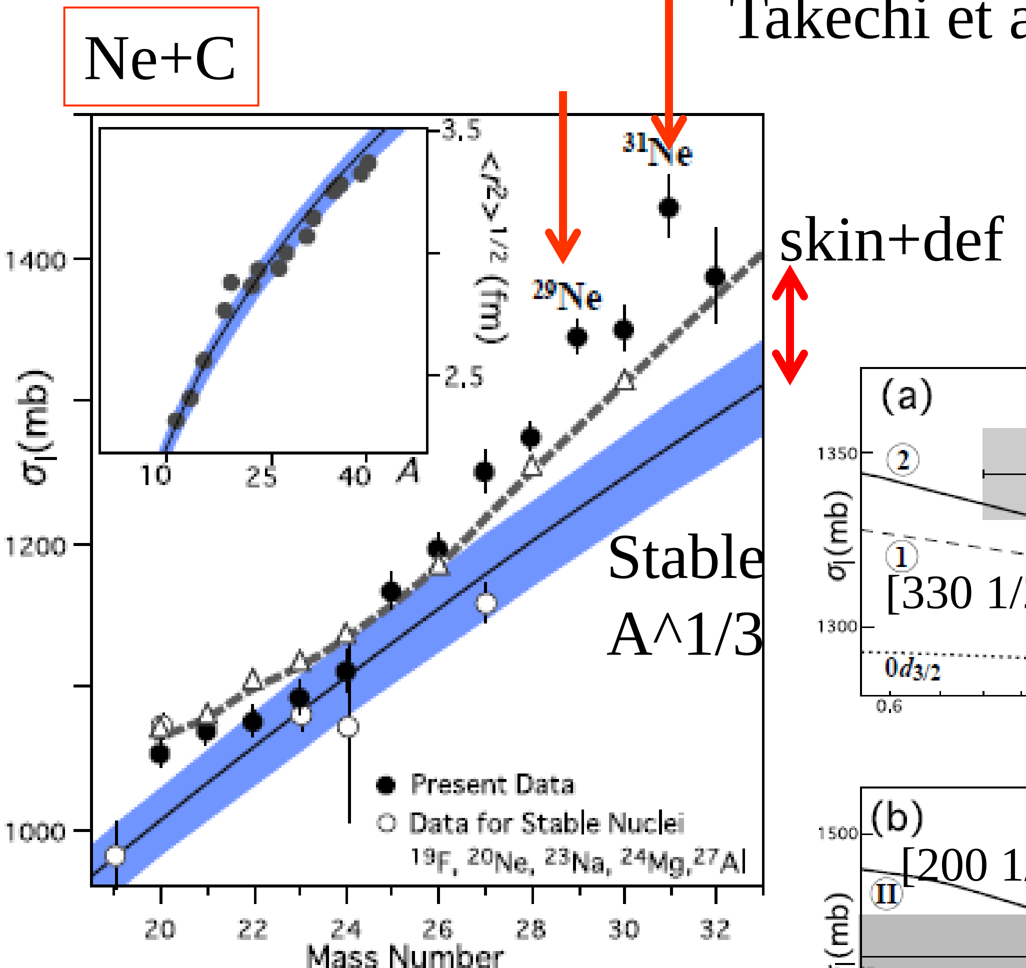
Total X-section Jump at ^{29,31}Ne

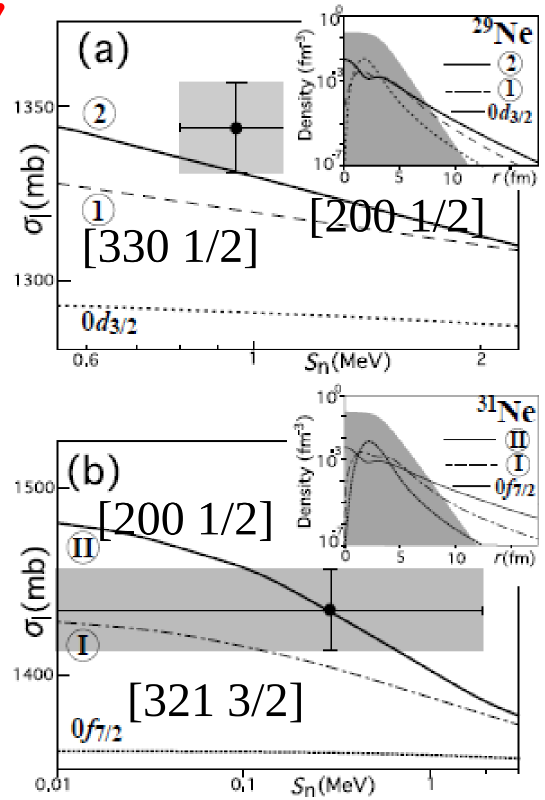


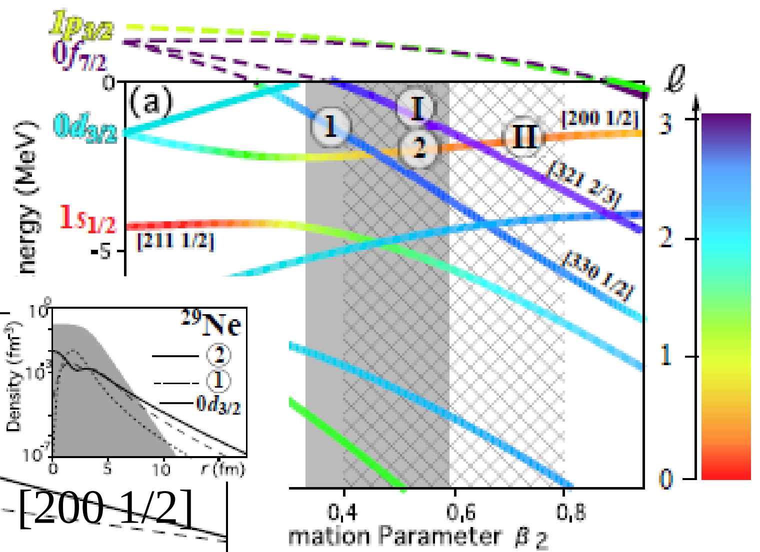
Takechi, Otsubo et al., PLB707, 357 (2012)

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

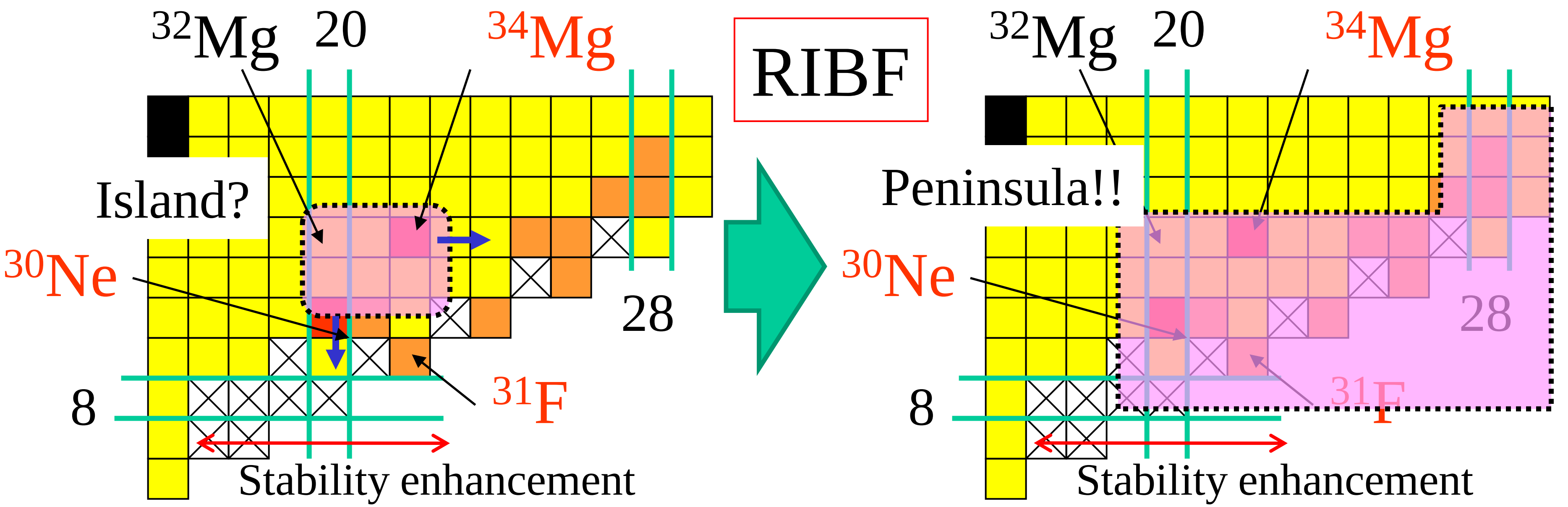
Takechi et al., Phys. Lett. B707, 357 (2012)







Extension of the deformation region up to the drip-line



<u>Doornenbal, Scheit, et al.</u>
Ne-32 1^{st} excited states: PRL 103, 032501 (2009)
New states in ^{31,32,33}Na: PRC 81, 041305R (2010)
Mg-36,-38: ARIS11; in preparation
F-29: in preparation
<u>Chevier, Ueno et al.,</u>
Intruder state in S-43: PRL 108, 162501 (2012)
<u>Takeuchi et al.</u>
Si-42 : PRL109, 182501 (2012)

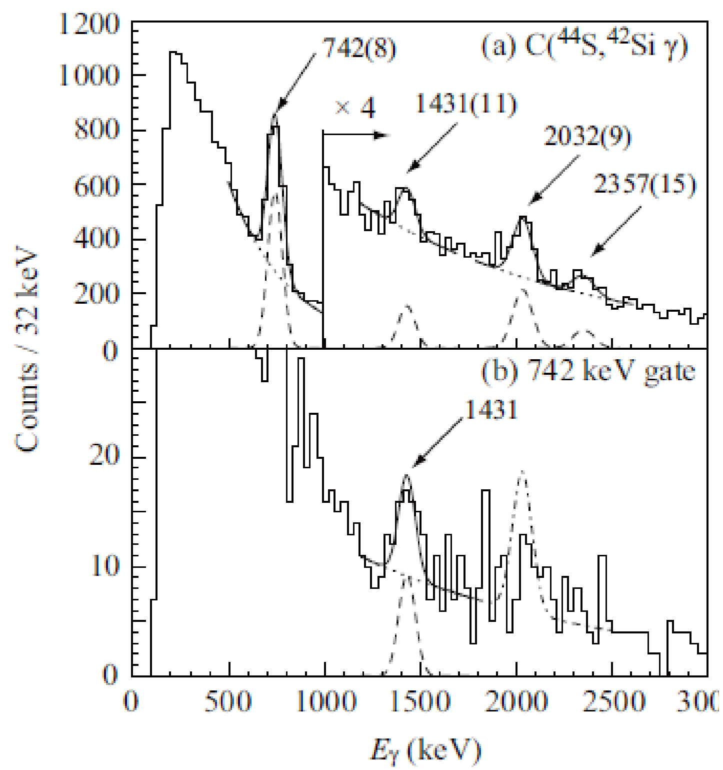
Well developed deformation of ^{42}Si

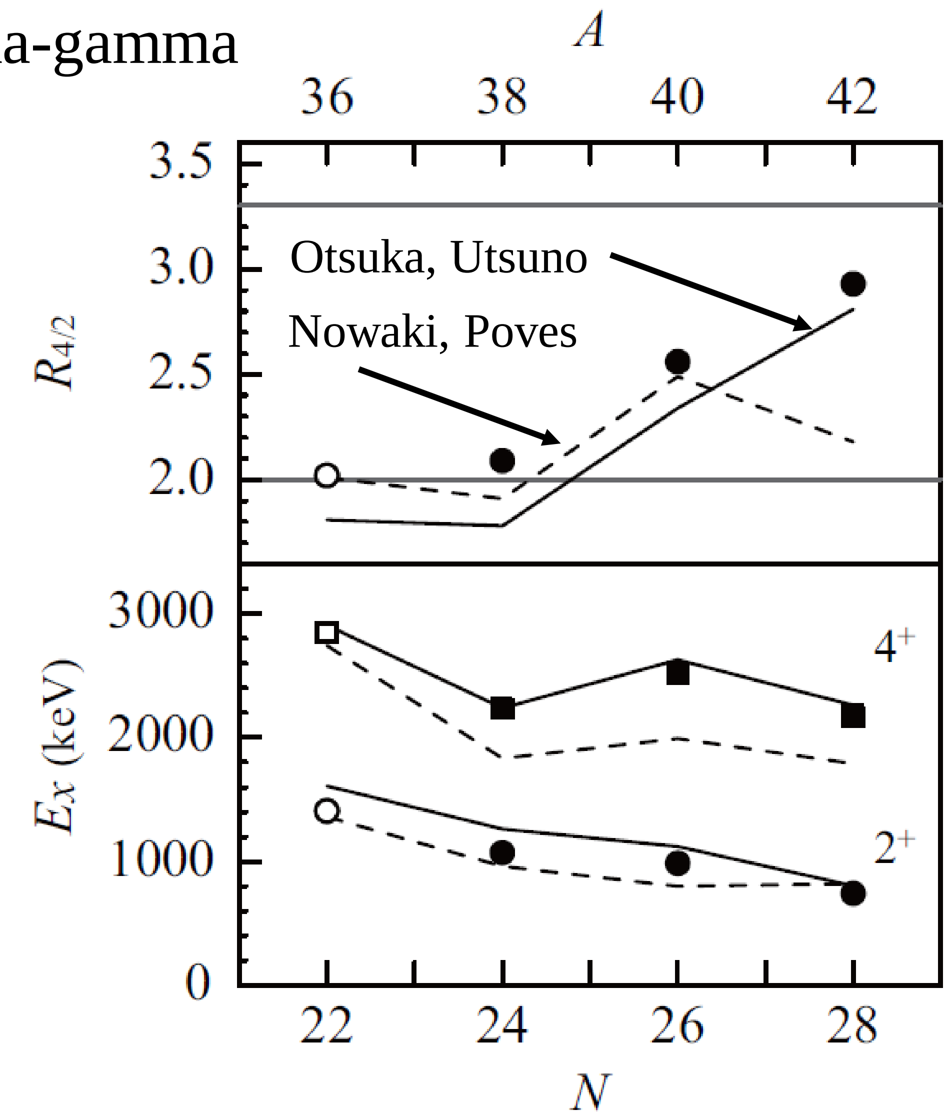
S. Takeuchi et al., PRL109, 182501 (2012)

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

^{44}S + C -> ^{42}Si +X

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

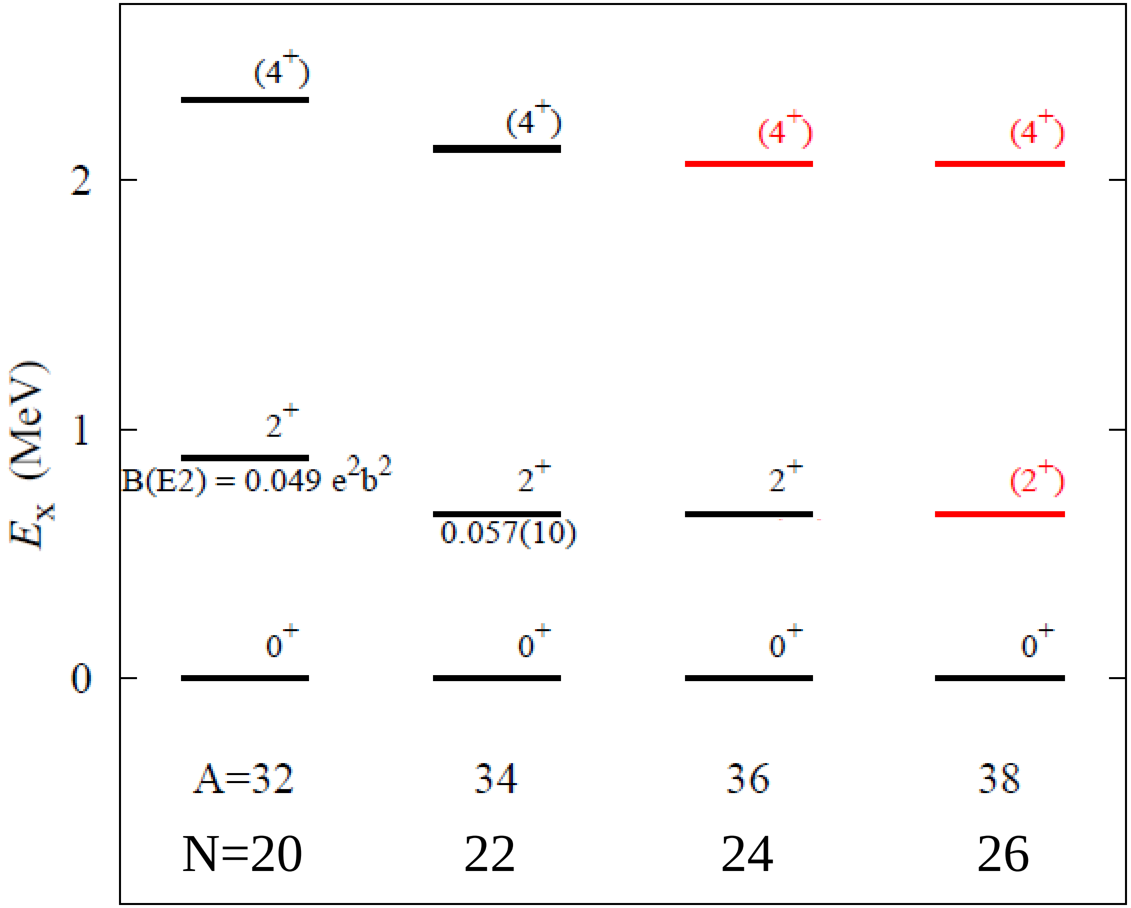




Collectivity of the neutron-rich Mg isotopes

P. Doornenbal, et al. in preparation

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



^{A}Al -> $^{A-1}$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?

The First Decay Spectroscopy at RIBF

2009 Dec.

U beam to access A~110 region

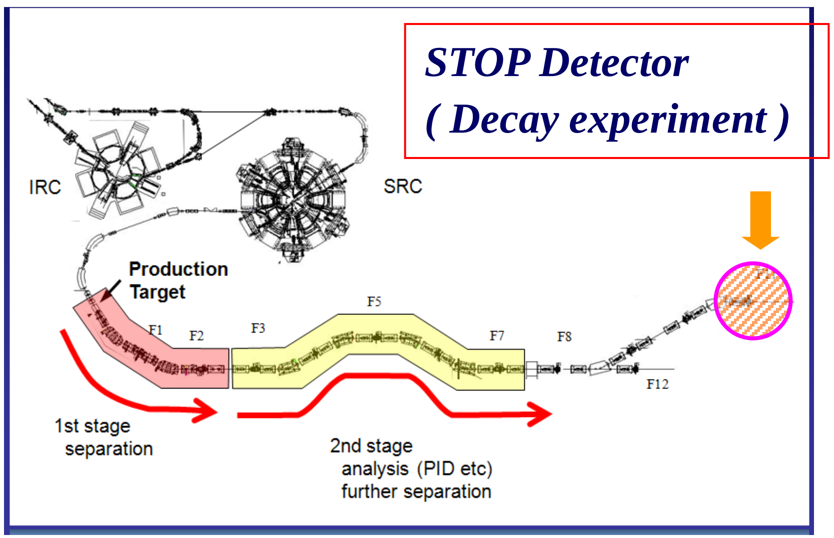
Collectivity

triaxiality, shape-coexistence, etc

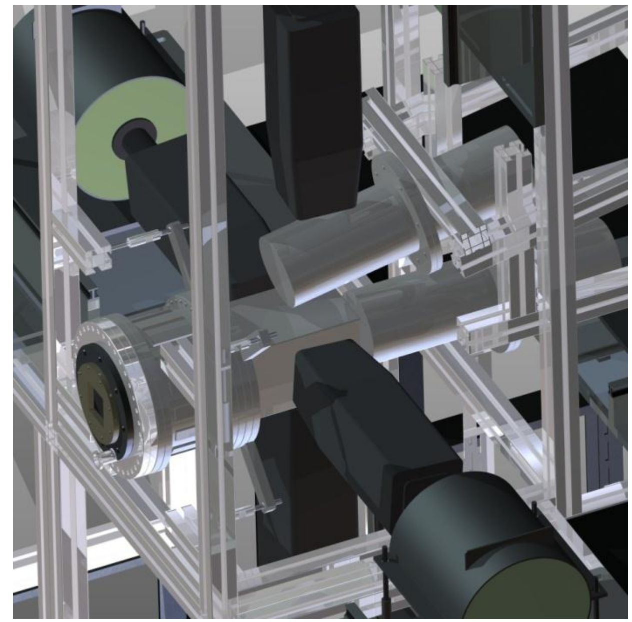
Intensity 0.8 pnA max.

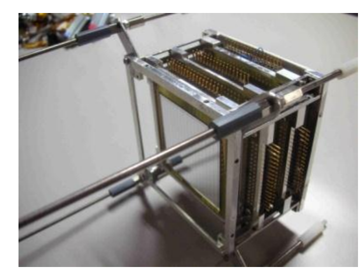
0.1-0.2 pnA on average

2.5 days for data accumulation



Sumikama, Nishimura, et al.



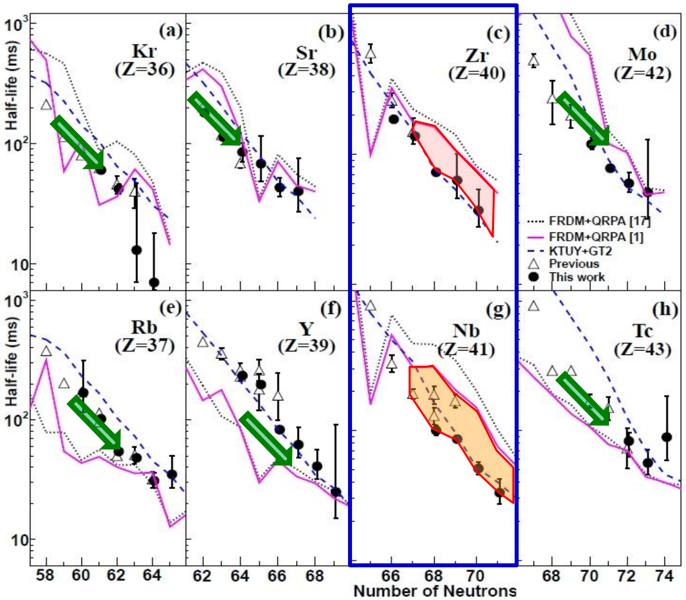


Clovers (RIKEN)

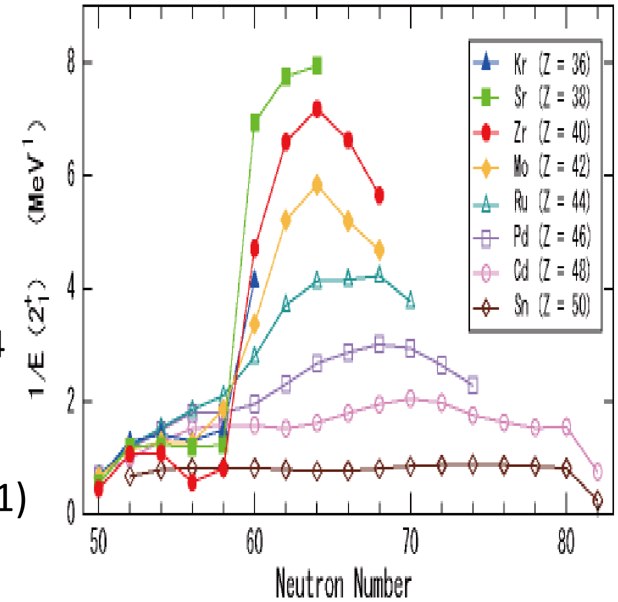
$LaBr_3$ (Milano)

9 layers of DSSD (RIKEN, TUS)

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

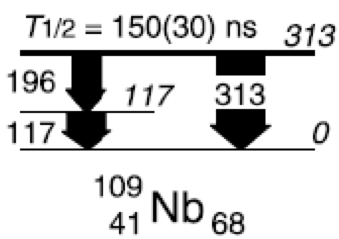


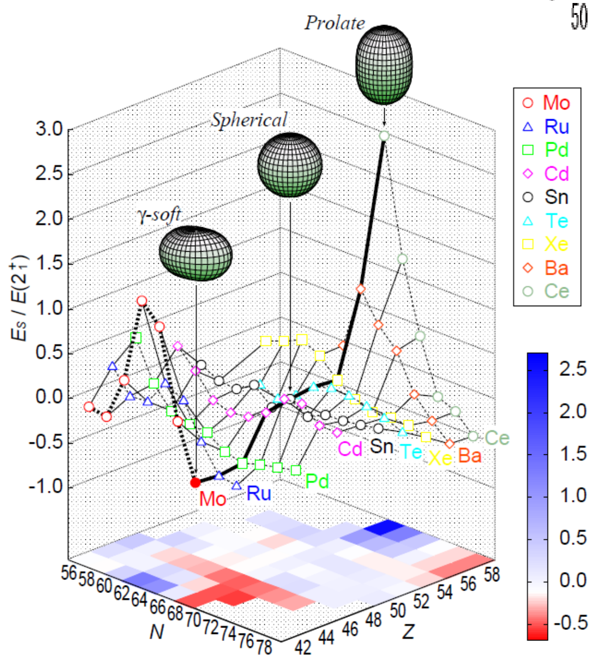
New Half-life data for 18 new isotopes
S. Nishimura et al.,
PRL 106, 052502 (2011)



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)





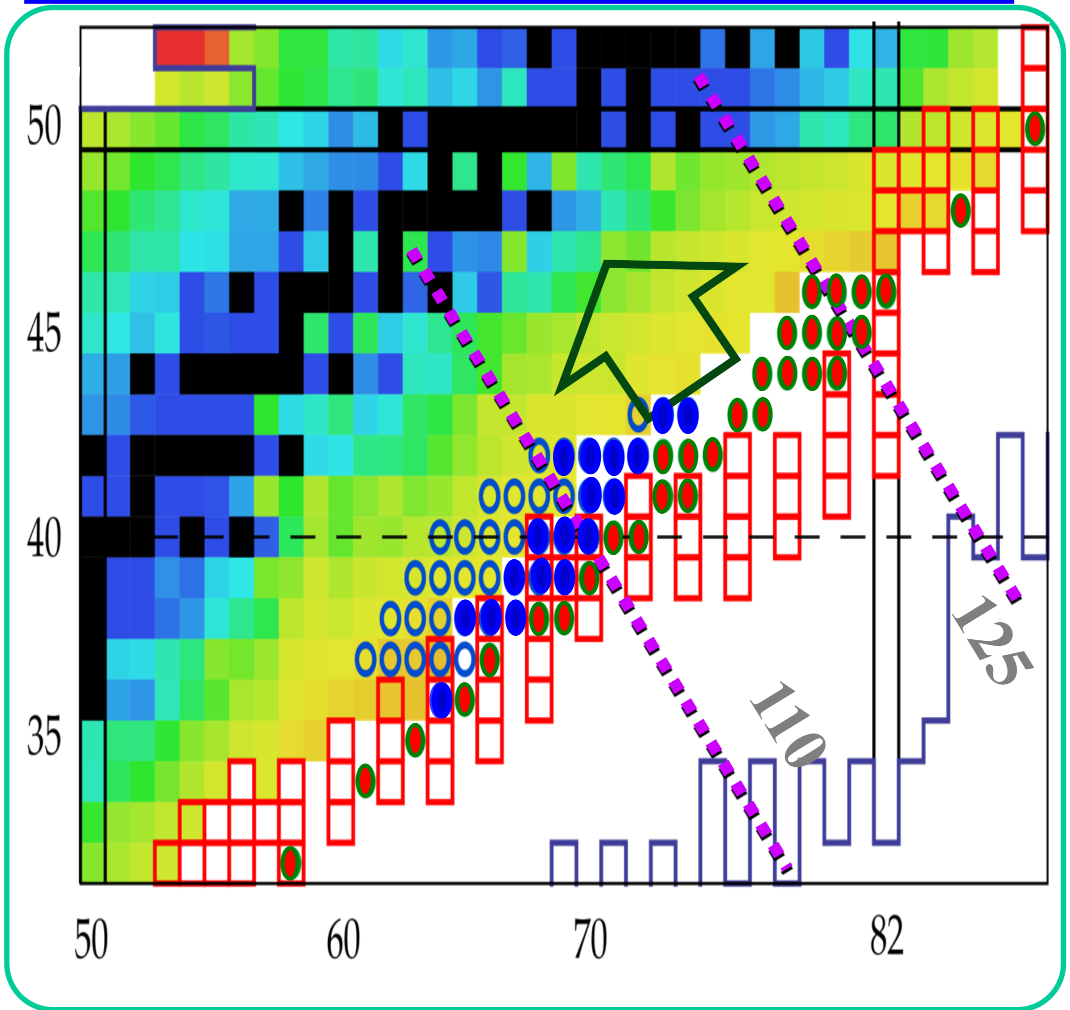
Development of axial asymmetry in neutron-rich nucleus Mo-110
H. Watanabe et al.,
Phys.Lett.B 704,270-275(2011)

First "touch" for the r-process nuclei

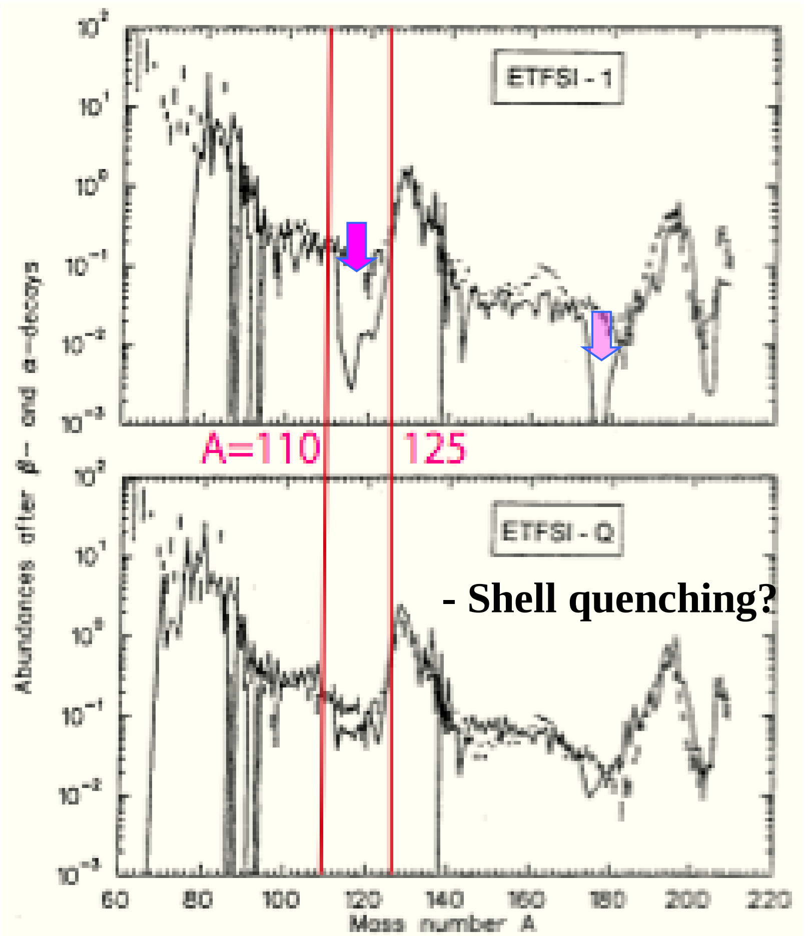
S. Nishimura et al.

T.Ohnishi, JPSJ 79 (2010).. 45 new isotopes

New half-lives (18 nuclei) are measured !

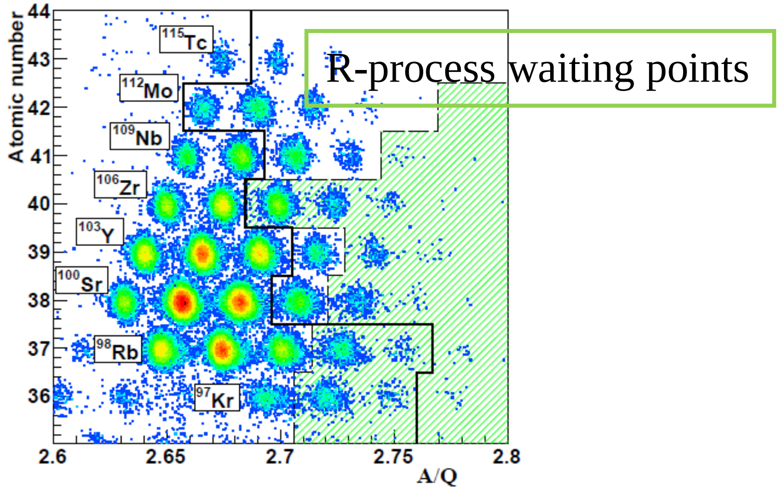


B.Pfeiffer et al. Z. Phys. A357 (1997)



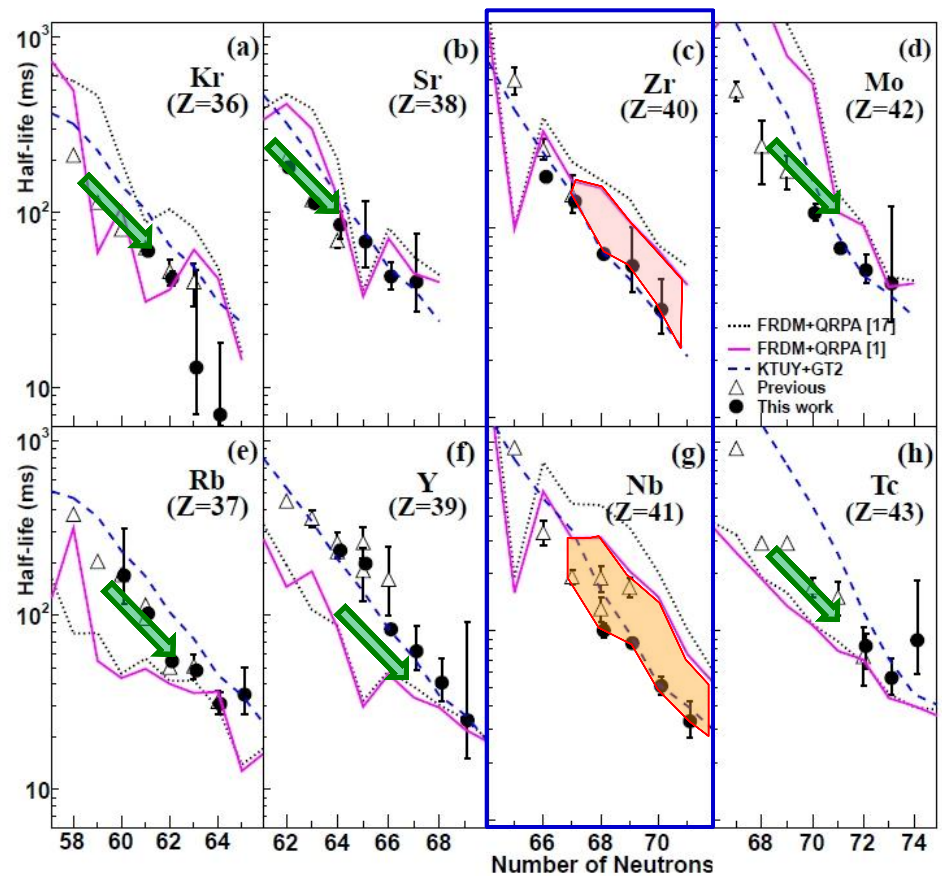
Brand-new half-life data for 18 isotopes

T1/2 unknown



S. Nishimura et al., PRL 106 (11) 052502

1/3 ~ 1/2 Shorter Half-lives of
Zr and Nb (A~110)

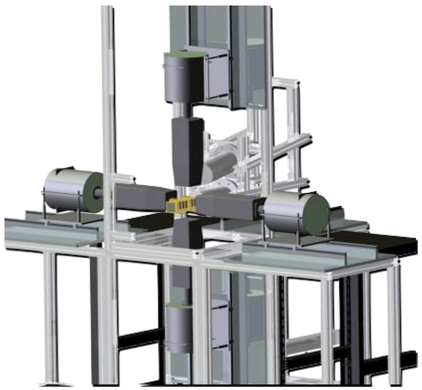


8 hour data acquisition
T1/2 data of 38 isotopes including
first data for 18 isotopes
FRDM may underestimate Q-value
for Zr and Nb by 1 MeV at A~110
More rapid flow in the rapid
neutron-capture process
than expected

EURICA

EUROBALL-RIKEN Cluster Array (EURICA) 2012-14

First decay spectroscopy in 2009

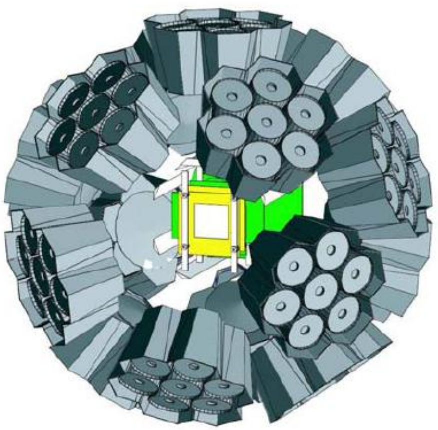


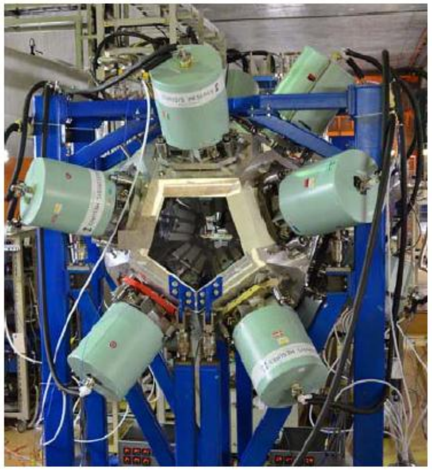
4 clovers

U beam ~0.1pnA

2.5 days MT

4 papers





Total gain factor for gamma-ray statistics
at EURICA campaign in 2012-14 x1000
gamma efficiency x10
primary beam intensity x100

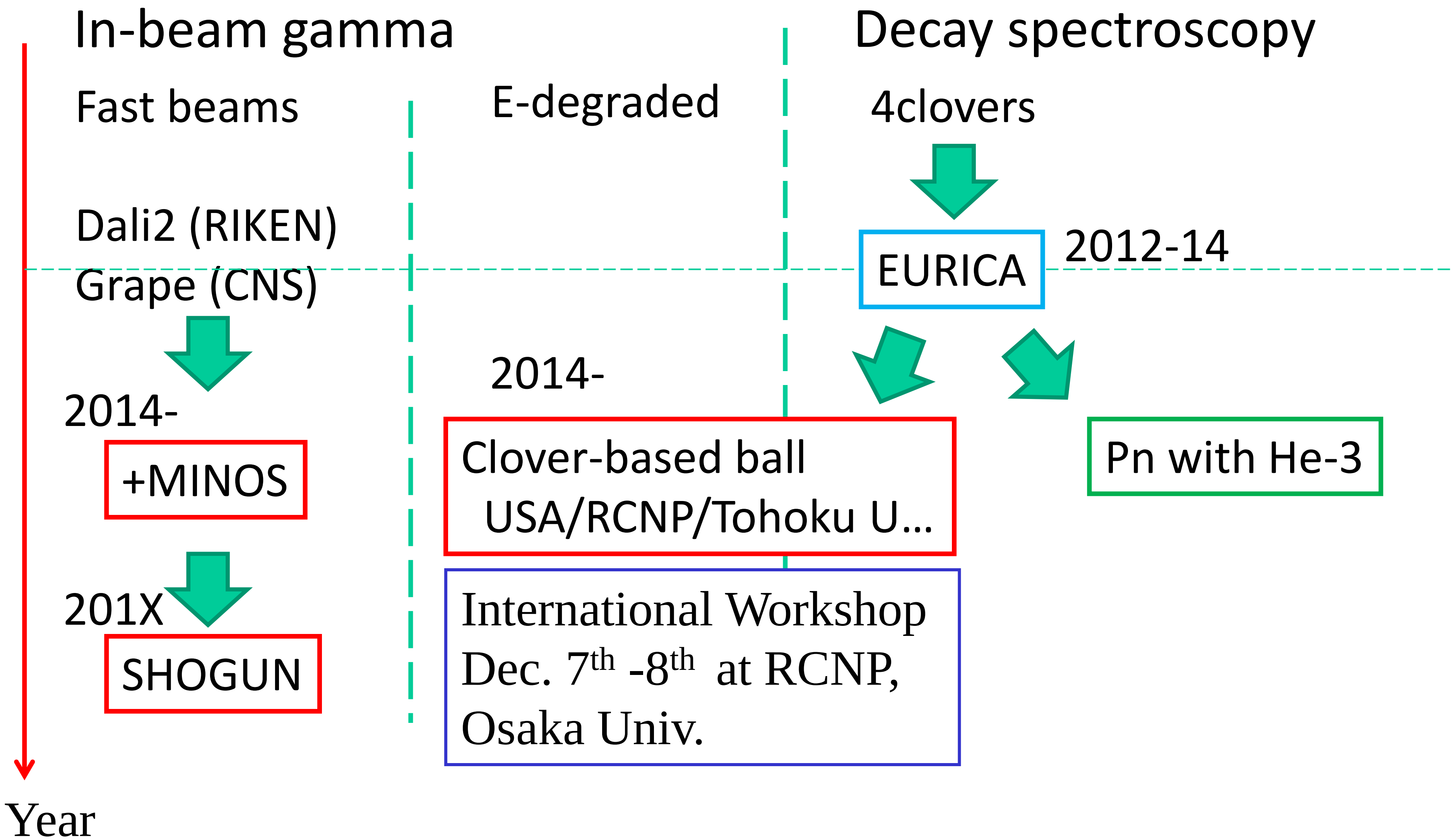
Approved MT 100 days

Estimation for number of papers expected
~100 days * 4 papers/2.5 days= ~160

Cf. RHIC PHENIX ~100 papers/10years

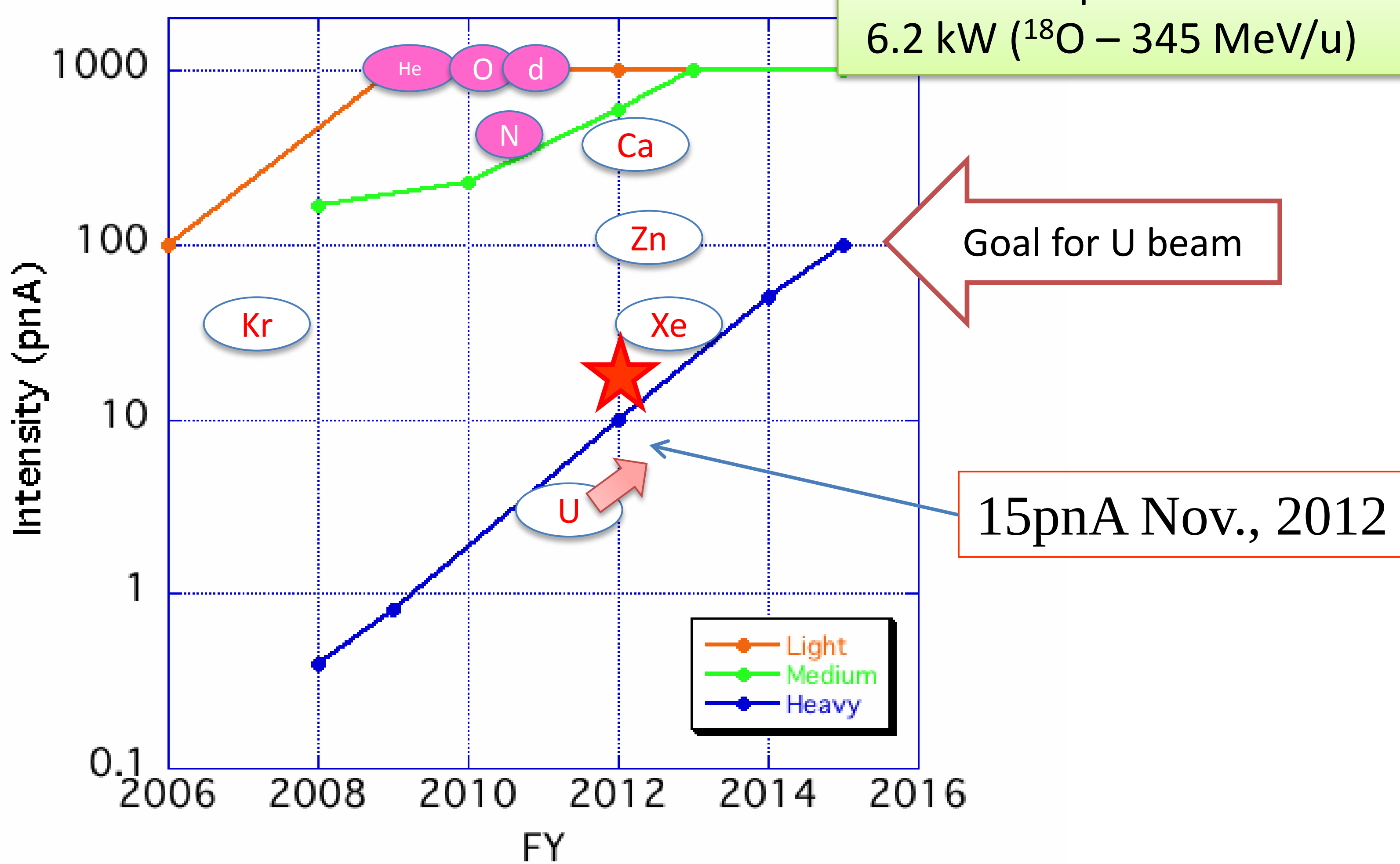
2012 March Commissioning
June N=Z decay experiment

Perspectives of gamma-spectroscopy for next 5 years



Intensity records and outlook

Max. beam power:
6.2 kW (^{18}O – 345 MeV/u)



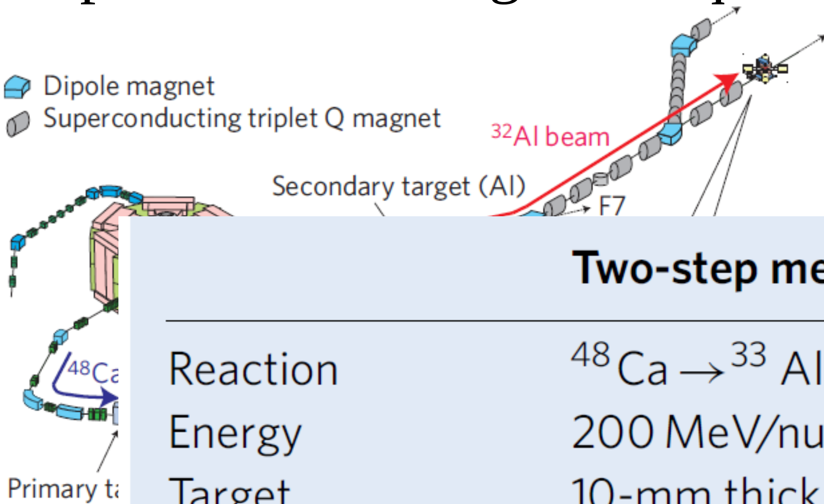
	^{48}Ca	^{70}Zn	Kr	^{124}Xe	^{238}U
FY2012 plan	150 pnA	-	30 pnA	10 pnA	5 pnA
achieved (maximum)	415 pnA ! (Jun. 2012)	100 pnA ! (Jul. 2012)	'30 pnA' (Nov. 2007)	27 pnA! (Jul. 2012)	3.8 pnA (Dec. 2011)

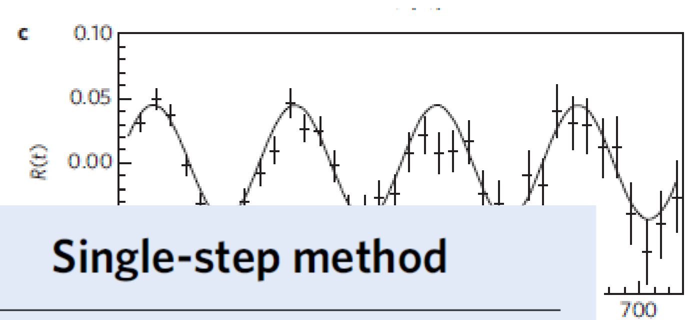
Kamigaito et al.

Two-step production of Spin-Aligned Rare Isotope Beams

Y.Ichikawa, H.Ueno et al., Nature Physics, on-line

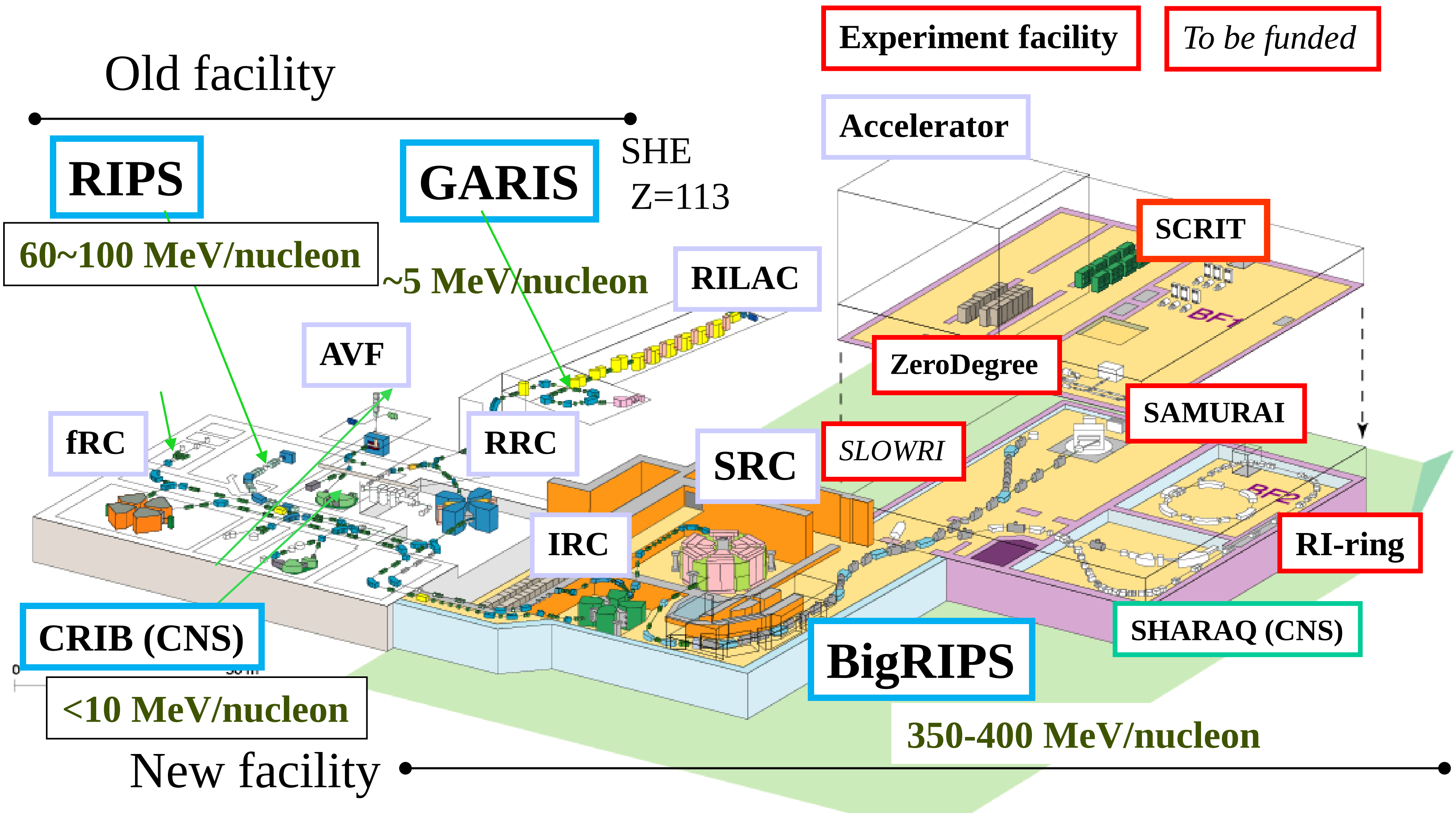
Dispersion matching technique





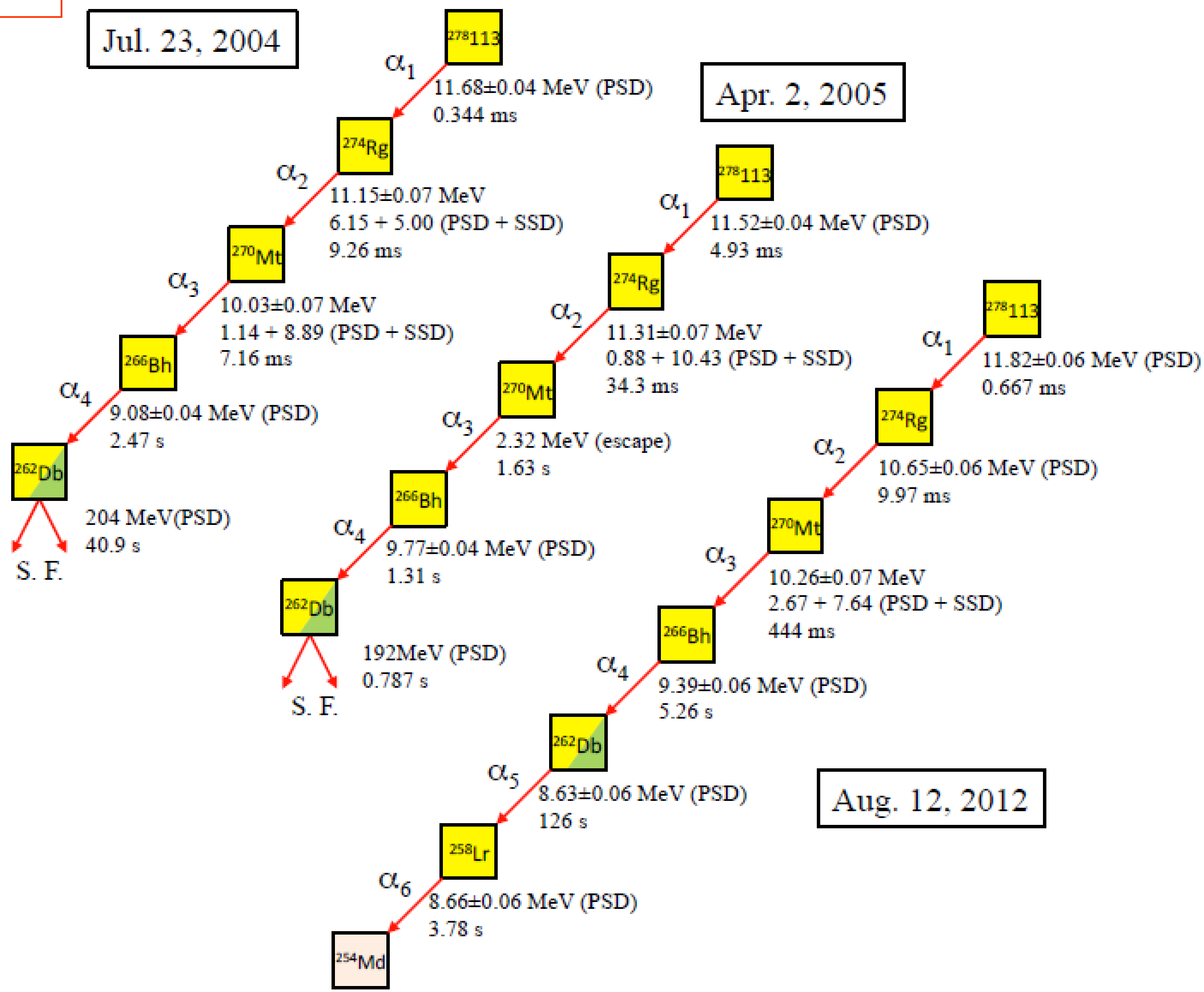
	Two-step method	Single-step method
Reaction	$^{48}Ca \rightarrow ^{33}Al \rightarrow ^{32}Al$	$^{48}Ca \rightarrow ^{32}Al$
Energy	200 MeV/nucleon	345 MeV/nucleon
Target	10-mm thick Be	4-mm thick Be
σ	0.4%	2.0%
$\Delta p/p$	$\pm$0.15%	$\pm$0.5%
p(^{32}Al)	39(3)%	85(3)%
Y(^{32}Al)	2.3(2) kcps	8.6(3) kcps (1/100 Att.)
Y(^{32m}Al)	0.54(5) kcps	0.87(6) kcps (1/100 Att.)
r	50(6)%	59(5)%
A	8(1)%	$<$0.8% (2σ)
FOM	1	$<$0.02
Meas. duration	11.9 h	9.3 h

RIKEN RI Beam Factory (RIBF)



Intense (80 kW max.) H.I. beams (up to U) of 345*A*MeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
Operation since 2007

Element 113



K. Morita et al., J. Phys. Soc. Jpn. 81 (2012) 103201

Best Inventions of the Year 2012 | Element 113 | TIME.com

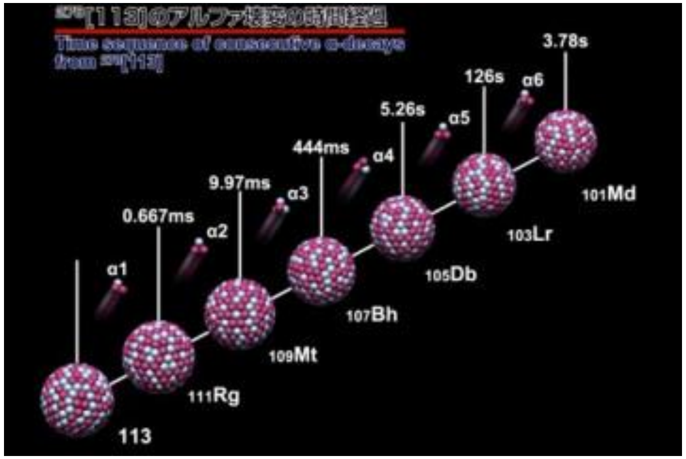
$1 million - $2.5 billion

Element 113

Price: $3 million

By TIME Staff

Nov. 01, 2012



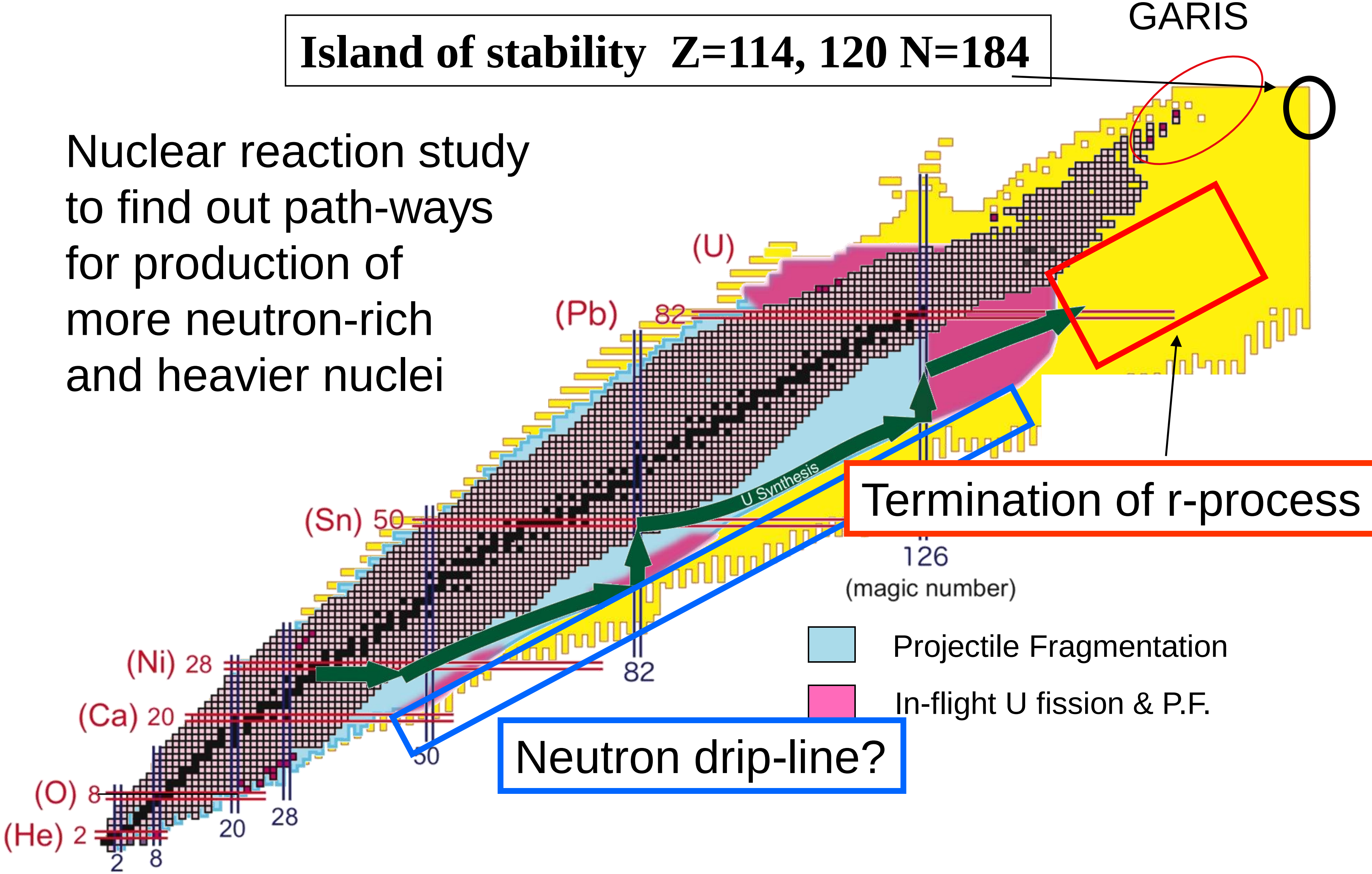
nishina.riken.jp

A time sequence of consecutive α-decays from element 113

After nine years of work,
a team led by Kosuke Morita at the RIKEN Nishina Center for Accelerator-Based Science in Japan has created three atoms of the highly unstable superheavy element 113.
As yet nameless, it has an enormous nucleus containing 113 protons and 165 neutrons.

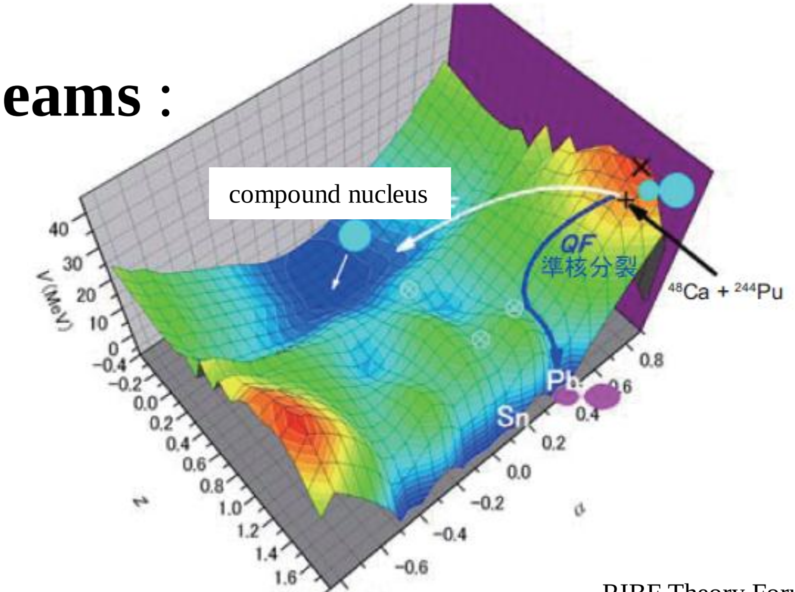
Challenge for the limit of existence

Nuclear reaction study to find out path-ways for production of more neutron-rich and heavier nuclei



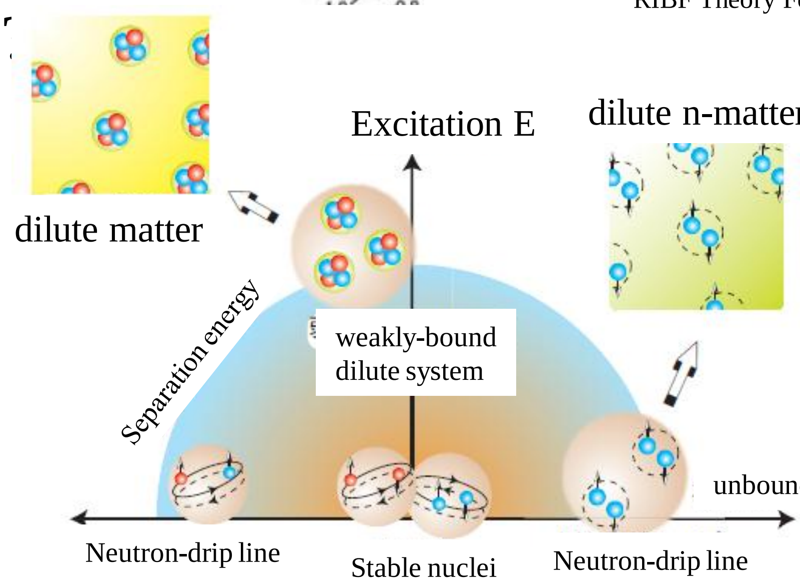
How to Create More N-rich and Heavier Nuclei ?

Low-E HI reactions with n-rich RI beams :
Deep in-elastic collisions?
Fusion/Fission Processes?
Combination of projectile and target?



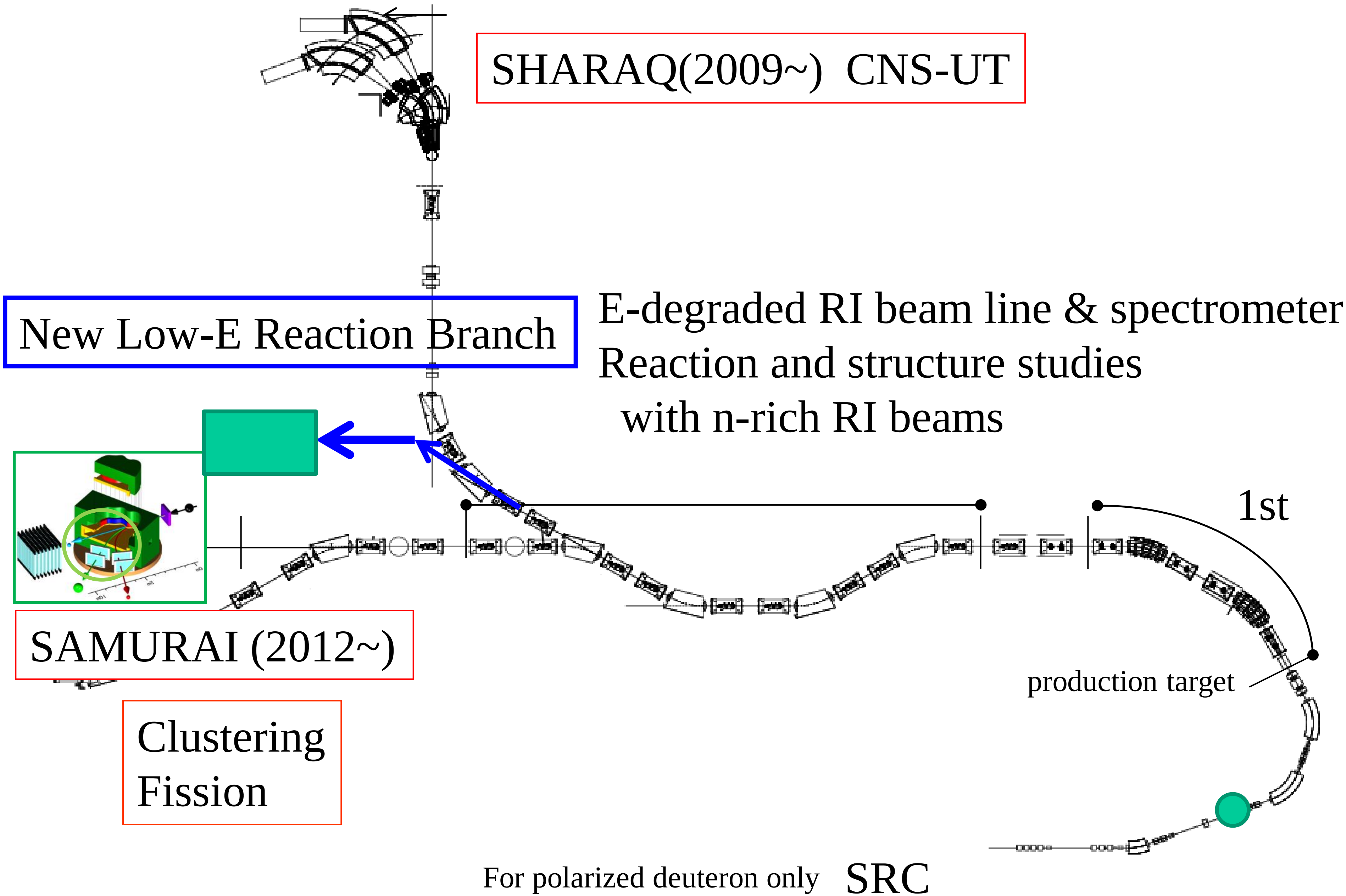
RIBF Theory Forum

Structure/Dynamics
in finite T and dilute system:
Role of neutrons in reactions/Fissions?
Clustering/Fission mechanism?
Isospin dependence of Fission?
Shell structure in hot nuclei?



RIBF Theory Forum

New Projects toward the island-of-stability



Summary

RIBF has started in operation since 2007.

Mass and charge-distribution measurements are being prepared.

Bunch of data for shell evolution and nuclear astrophysics
are being produced via in-beam gamma spectroscopy
and decay spectroscopy

Spin-aligned beams will give big opportunities for
electro-magnetic moment and new types of reaction studies.

Primary beam intensity is increased year by year
to expand our play ground.

Toward the island-of-stability, new programs are being considered.