The 3rd Nuclear physics School for Young Scientists (NUSYS2023)
August 6th-13th 2023

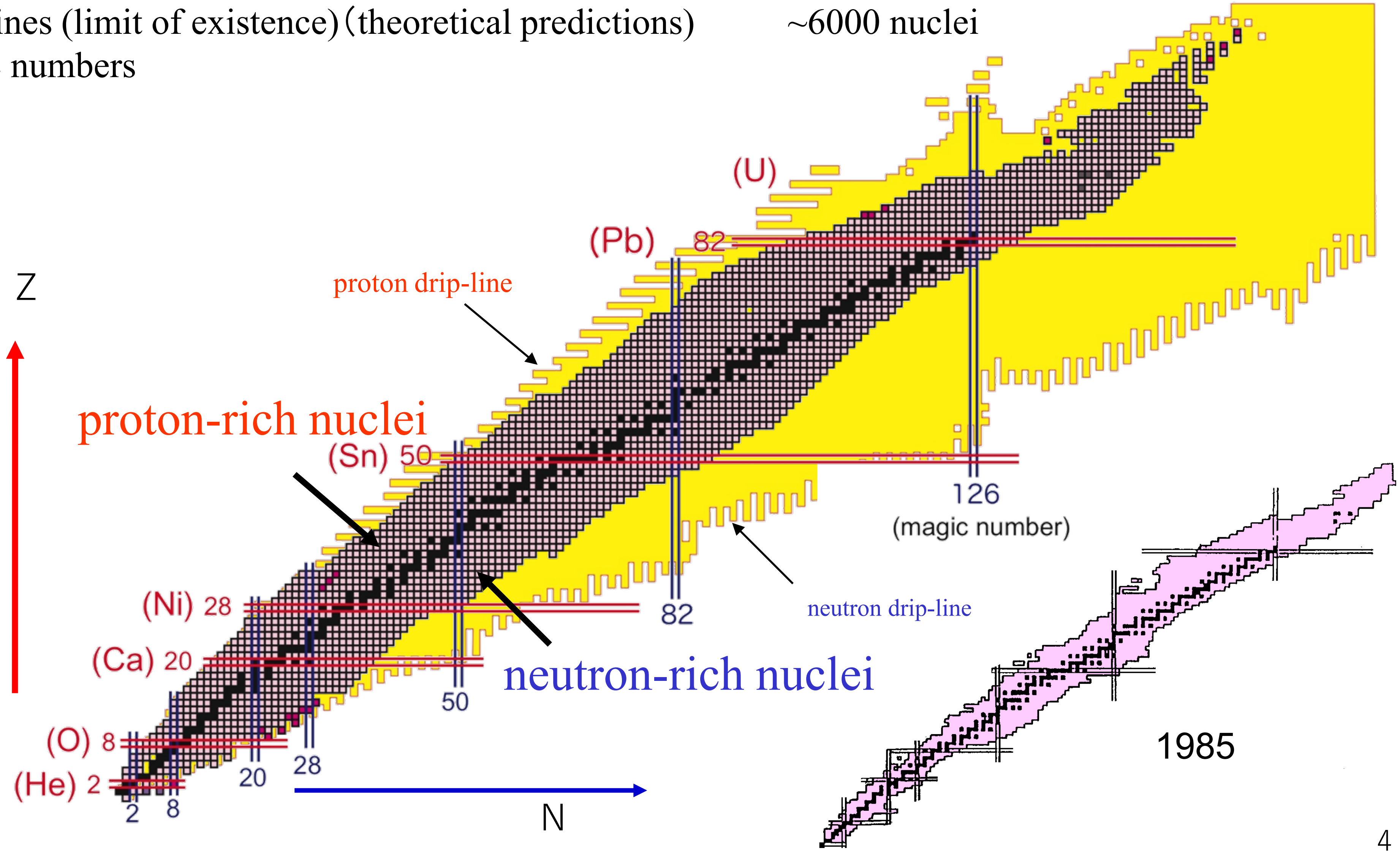
Physics with exotic nuclei

–its achievement and perspective-

Hiroyoshi Sakurai
RIKEN Nishina Center for Accelerator-Based Science

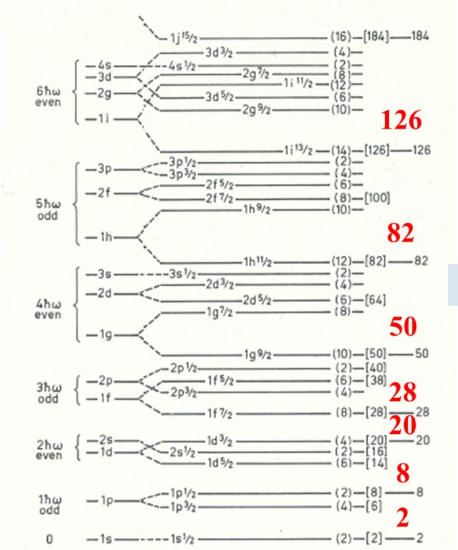
Exploration of the Limit of Existence

■	stable nuclei	~300 nuclei
□	unstable nuclei observed so far	~3300 nuclei
—	drip-lines (limit of existence)（theoretical predictions)	~6000 nuclei
=	magic numbers	

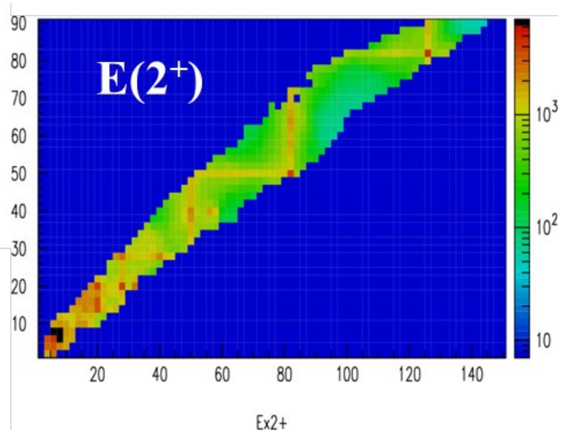


Why neutron-rich nuclei?: Large isospin-asymmetry

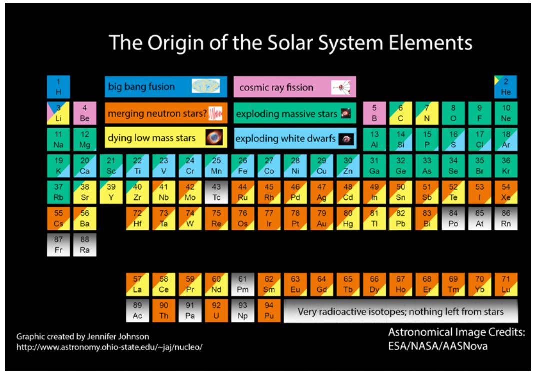
Shell-evolution: magicity loss and new magicity

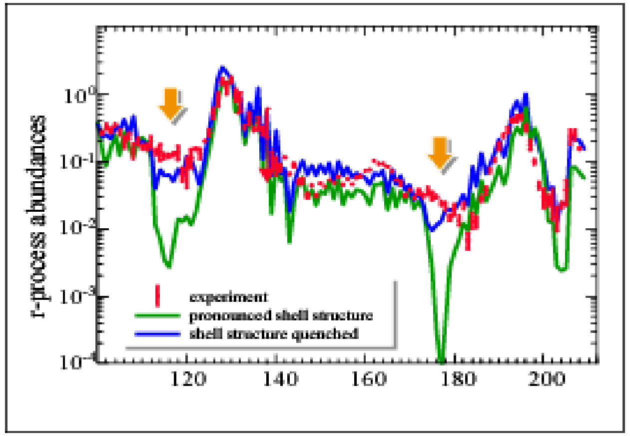


?



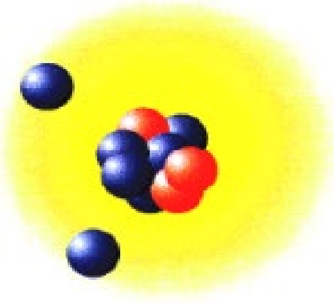
r-process path : nucleo-synthesis up to U



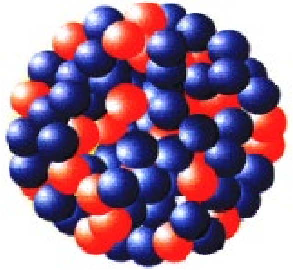


Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

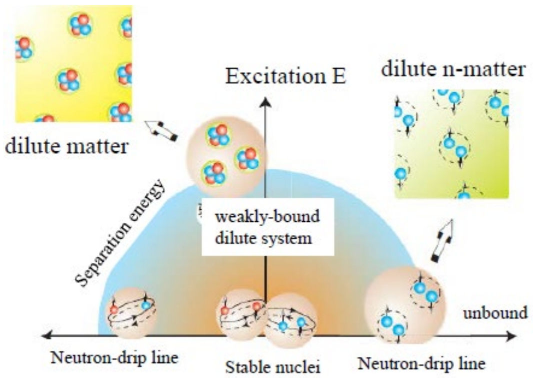
Neutron-neutron correlation in the vicinity of the dripline



^{11}Li
(two neutron halo)

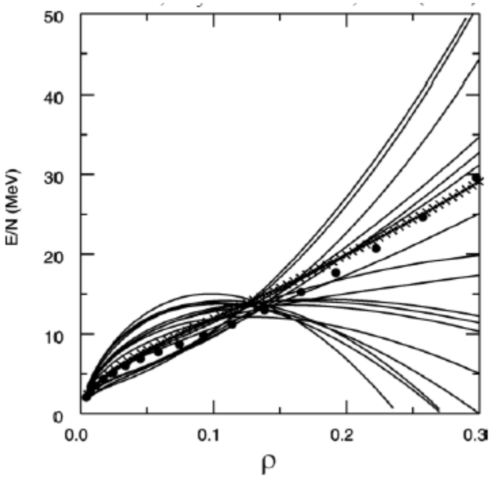


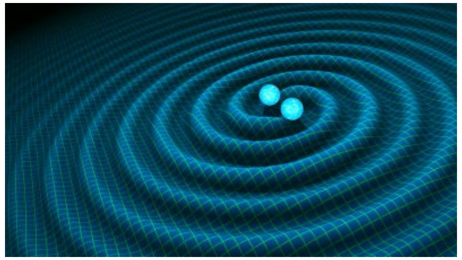
^{208}Pb



Equation-of-State in asymmetric nuclear matter

SN explosion, neutron-star, gravitational wave

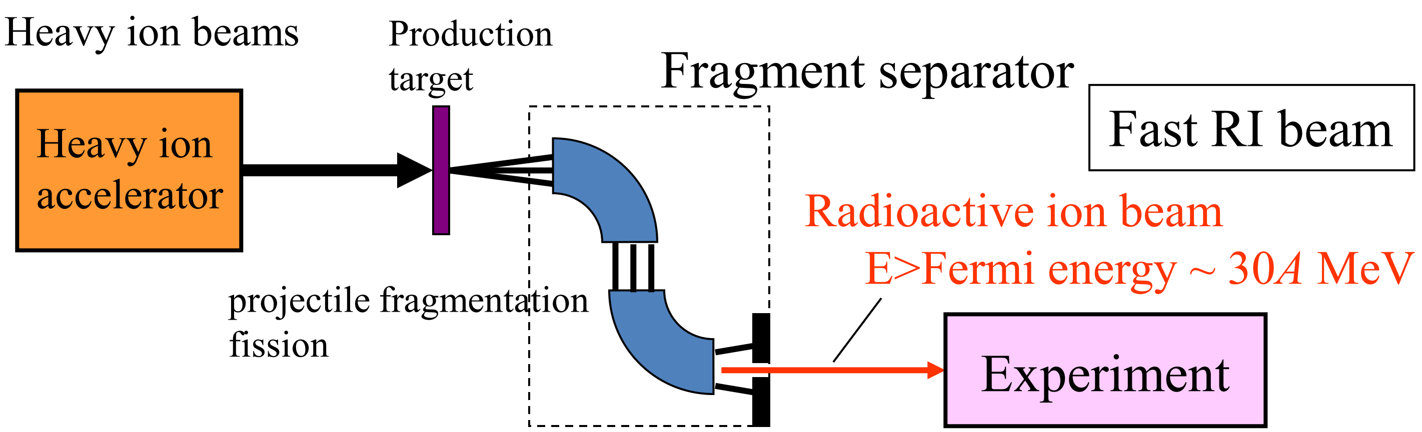




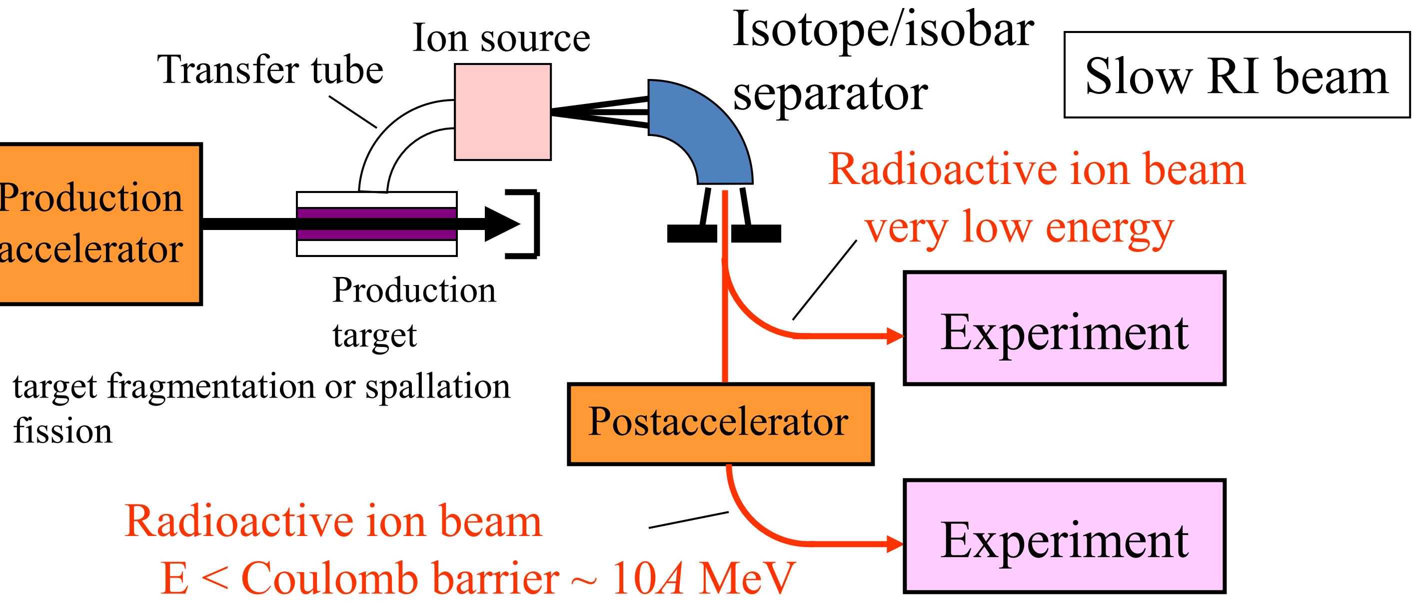
gravitation wave
from neutron-star mergers
Space.com

In-flight and ISOL methods to produce radioactive isotopes

In-Flight Method

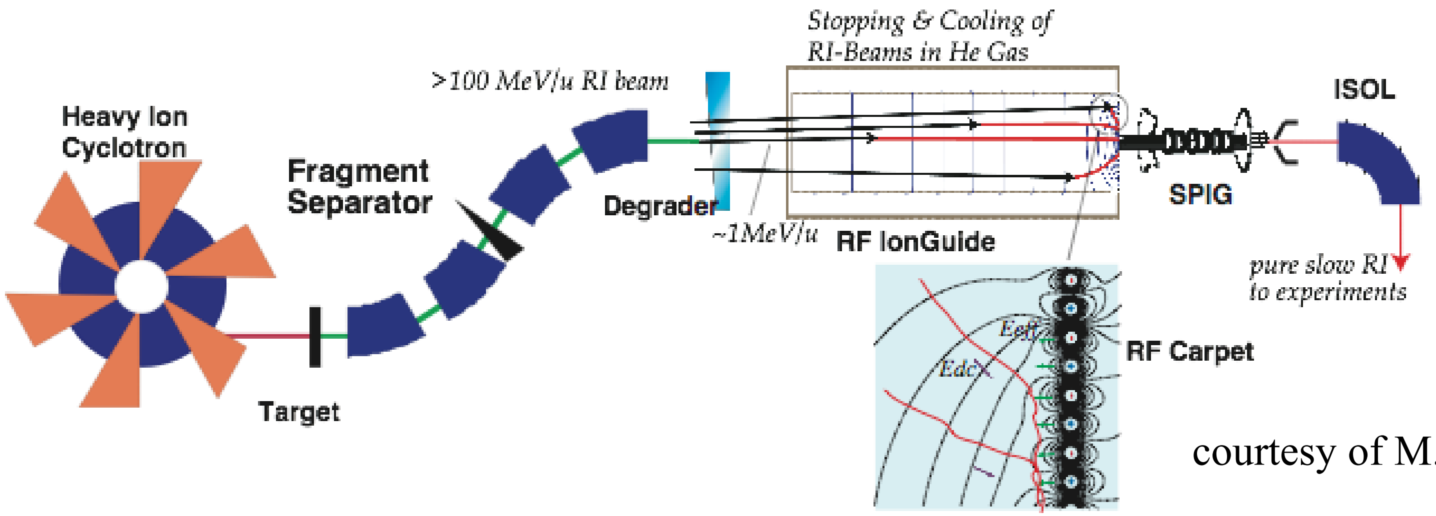


ISOL Method



New experimental techniques to have very slow RI beams

RIKEN, NSCL/MSU, ANL, GSI



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

Takamine san

History of In-flight Method

T. Nakamura, HS, H.Watanabe, Prog. Part. and Nucl. Phys. (2017)

0th Generation (70's-80's) LBNL
"Discovery" of Projectile Fragmentation

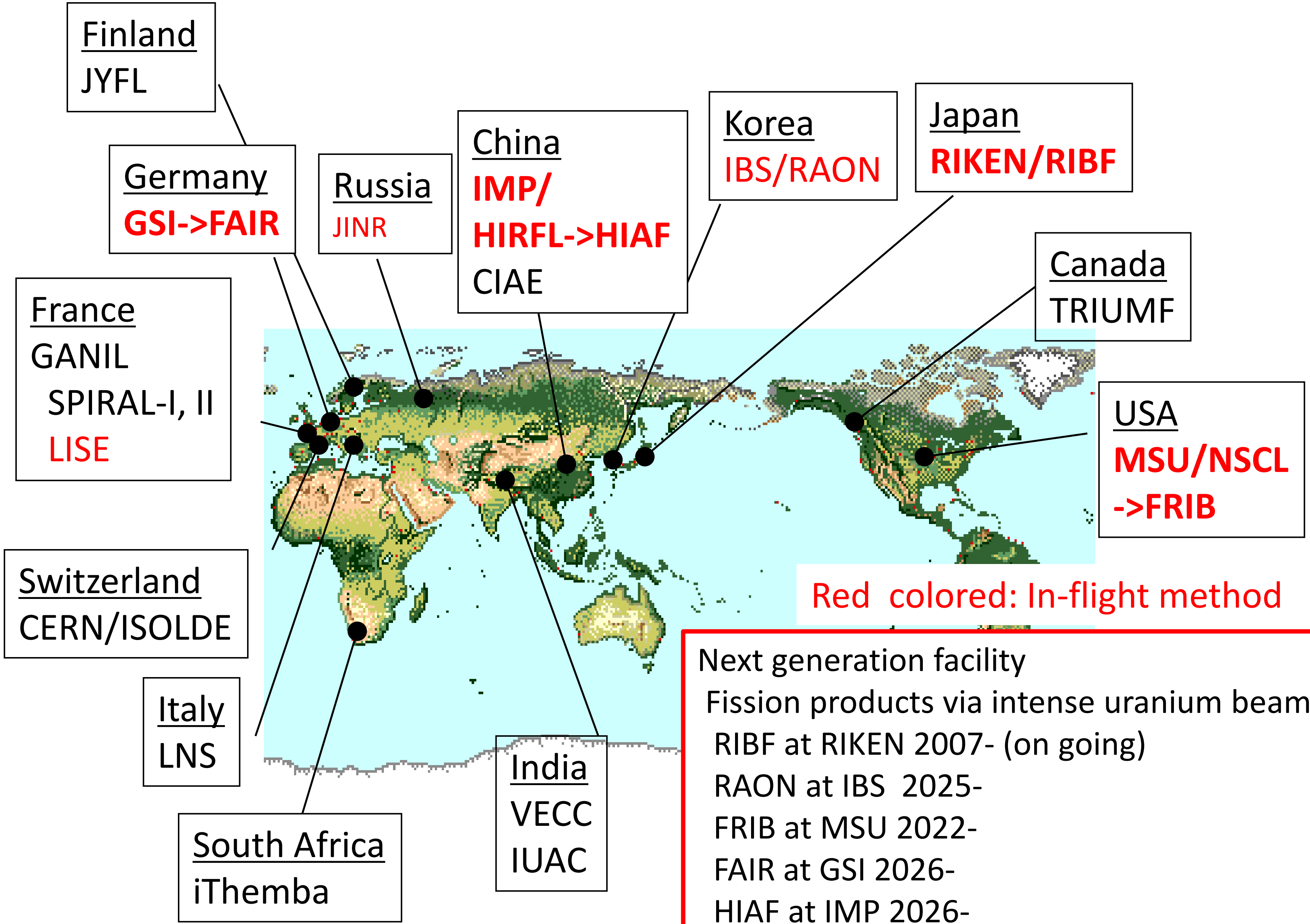
1st Generation (80's) GANIL/LISE — LISE was originally designed for atomic-physics
Establishment of Separation Technique — $B\rho$-ΔE-$B\rho$ Method

2nd Generation (90's) GSI/FRS, NSCL/A1200-1900, GANIL/SISSI, RIKEN/RIPS, RIBLL/IMP…..

Large-Collection Technique	
Max. $B\rho$ and Large Acceptances	RIKEN/RIPS
Emittance-transformation	GANIL/SISSI
Further Purification Methods	
ExB filter	GANIL/LISE, NSCL
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

3rd Generation (00's-20's) RIKEN/RIBF, MSU/FRIB, GSI/FAIR, IMP/HIAF, IBS/RAON
High-Power Heavy-Ion Beams up to U

Major RI Beam Facilities in the world

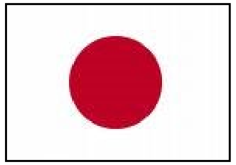


Next generation facility

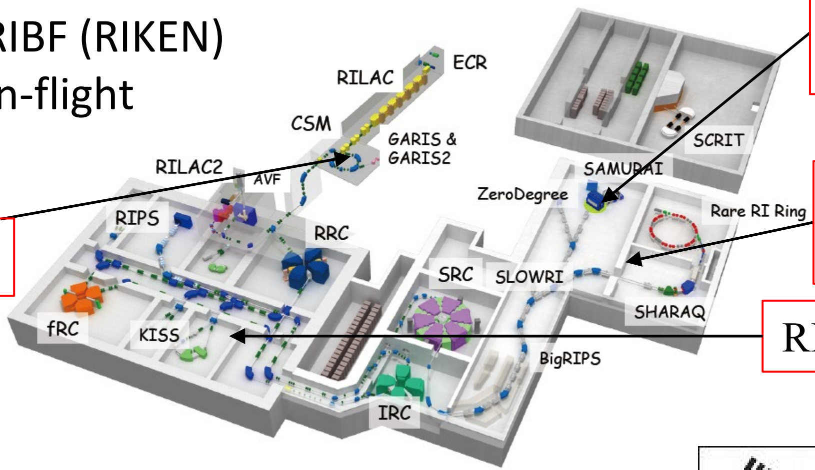
Fission products via intense uranium beams

- RIBF at RIKEN 2007- (on going)
- RAON at IBS 2025-
- FRIB at MSU 2022-
- FAIR at GSI 2026-
- HIAF at IMP 2026-

Large-scale facilities in operation and under construction in North-East Asia



RIBF (RIKEN)
In-flight



119th, 120th

10 MeV/u

Reaction study at ~300MeV/u
EOS w/ RI beams (high density ~2ρ_0)

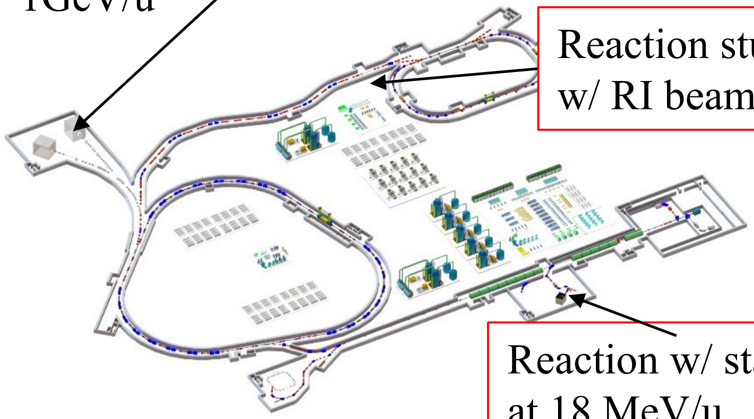
E-degraded RI beams at ~20 MeV/u or less
Low-E reactions w/ RI beams

RI production at 10MeV/u w/ stable HI

HIAF (in-flight)

EOS w/ stable beams
HI collisions (high density ~5ρ_0)

1GeV/u



Reaction study at ~1 GeV/u
w/ RI beams

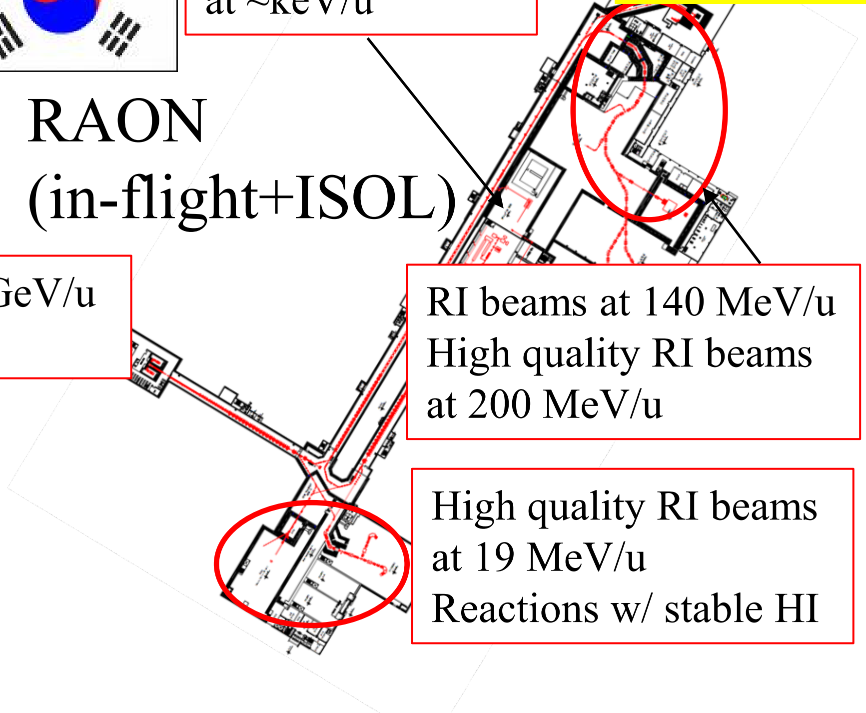
Reaction w/ stable HI
at 18 MeV/u

Youjin Yuan

Material sciences
at ~keV/u

RAON
(in-flight+ISOL)

Seung-Woo Hong



RI beams at 140 MeV/u
High quality RI beams
at 200 MeV/u

High quality RI beams
at 19 MeV/u
Reactions w/ stable HI

NSFC(China)-NRF(Korea)-JSPS(Japan) A3 Symposium on "Nuclear Physics in the 21st Century", Nagoya, 18-20th Sept., 2018

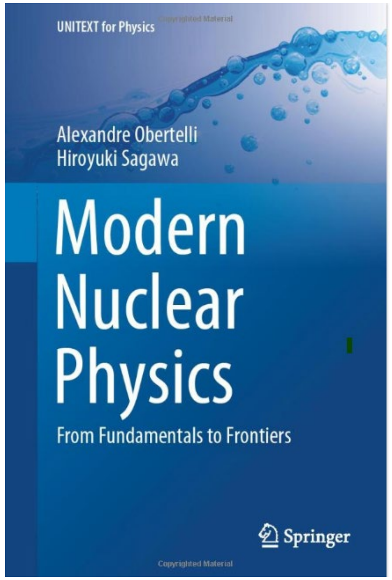
A3 Foresight Program launched in 2019 for five years

Exotic nuclei explored at in-flight separators

T. Nakamura, H. Sakurai, H. Watanabe
Prog. Part. and Nucl. Phys. 97, 53-122 (2017)
https://doi.org/10.1016/j.ppnp.2017.05.001

Modern Nuclear Physics
From Fundamentals to Frontiers

Alexandre Obertelli and Hiroyuki Sagawa
UNITEXT for Physics, Springer, 2021

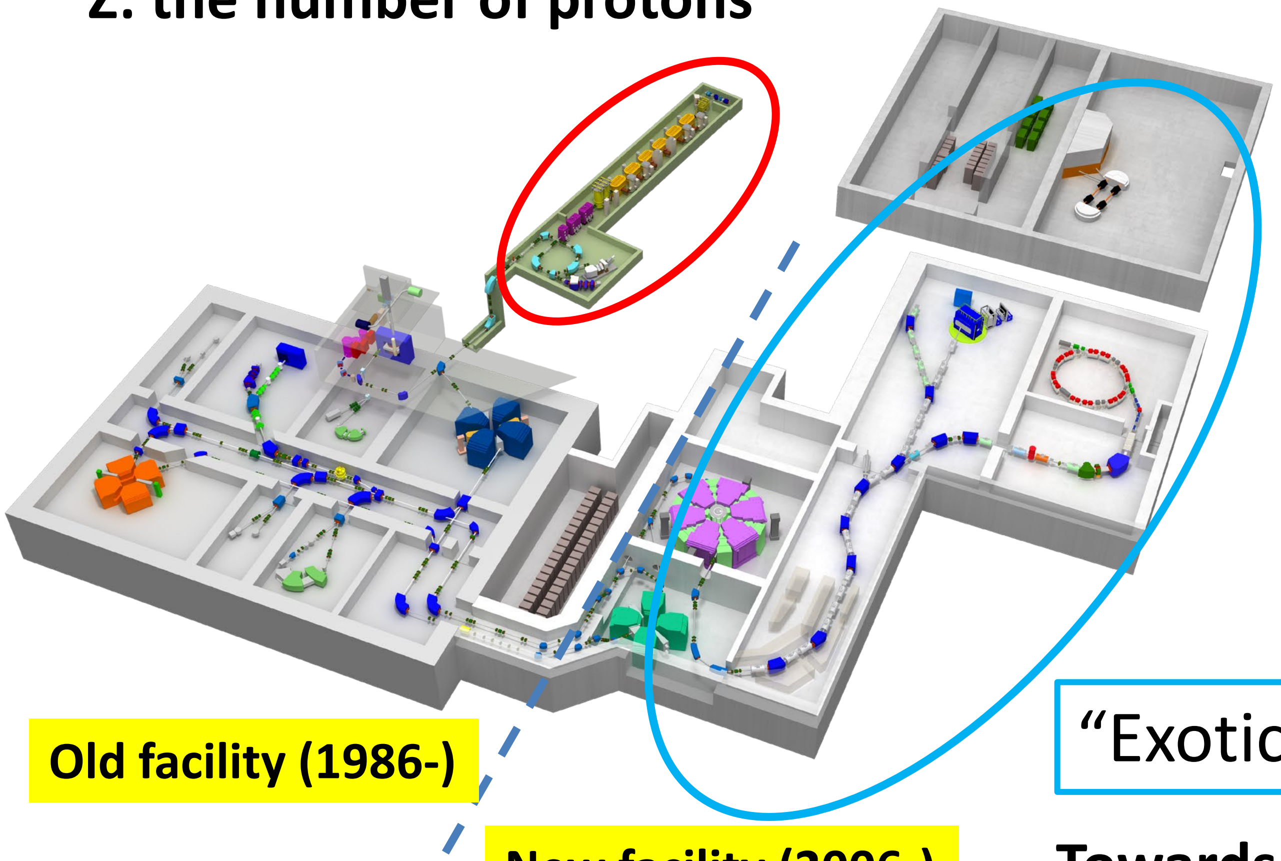


Low-energy nuclear physics at RI Beam Factory

“Super-Heavy Elements”

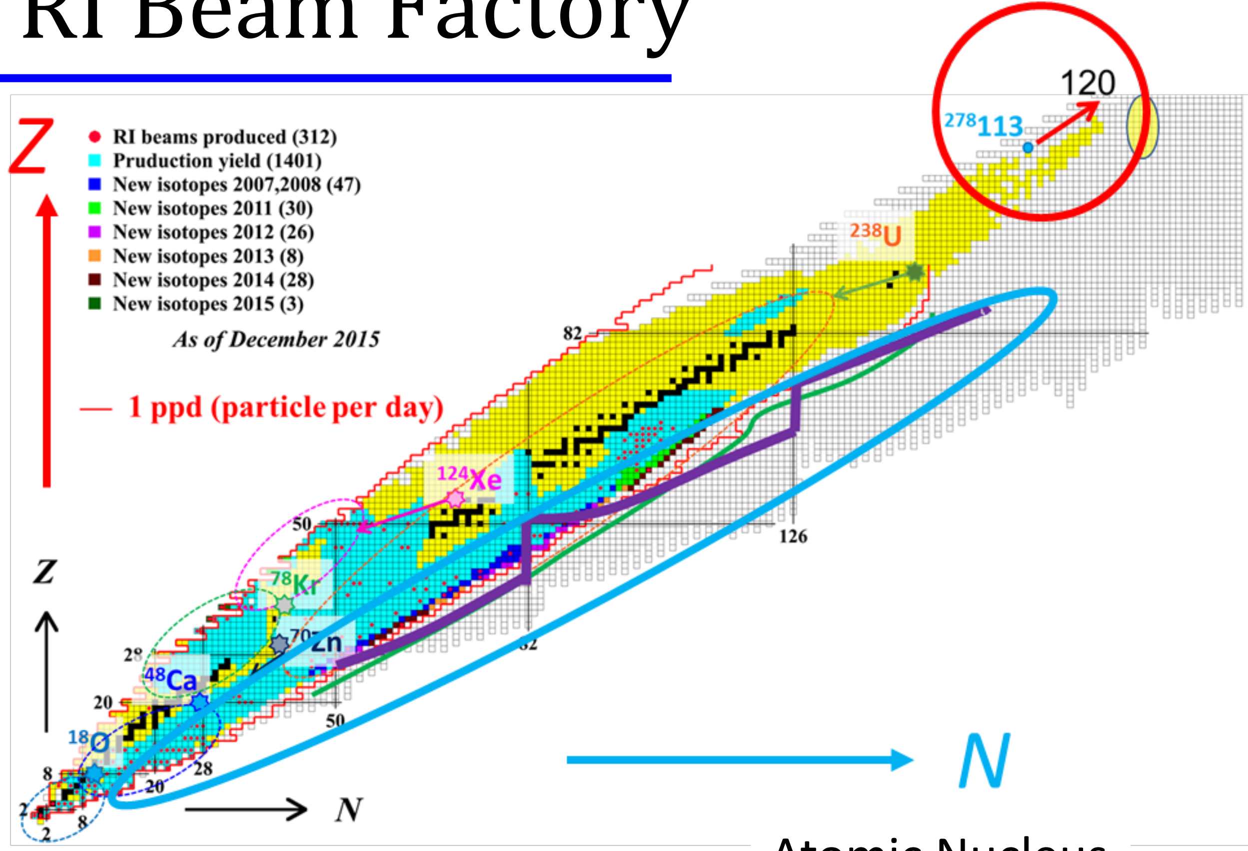
Towards a high Z

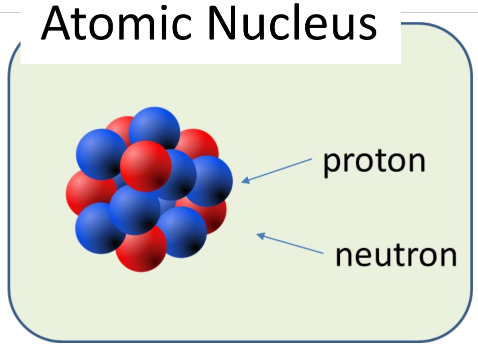
Z: the number of protons



Old facility (1986-)

New facility (2006-)





“Exotic Nuclei”

Towards a high N

N: the number of neutrons

RI Beam Factory

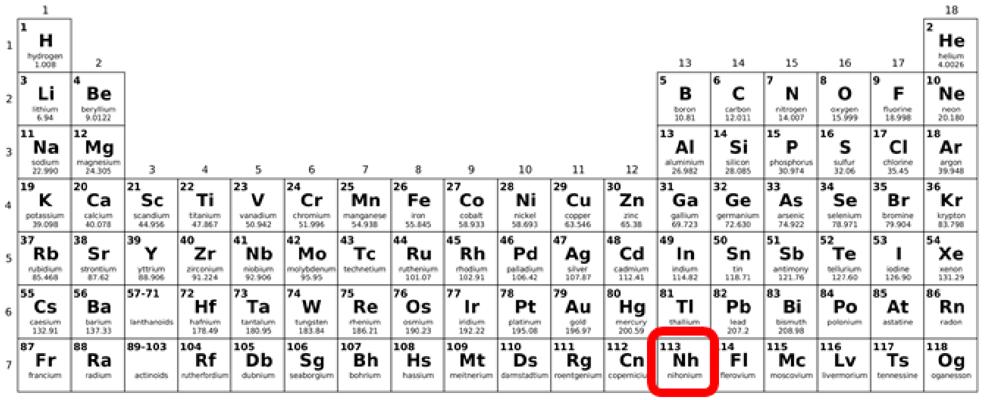
"Super-Heavy Elements"

Towards a high Z

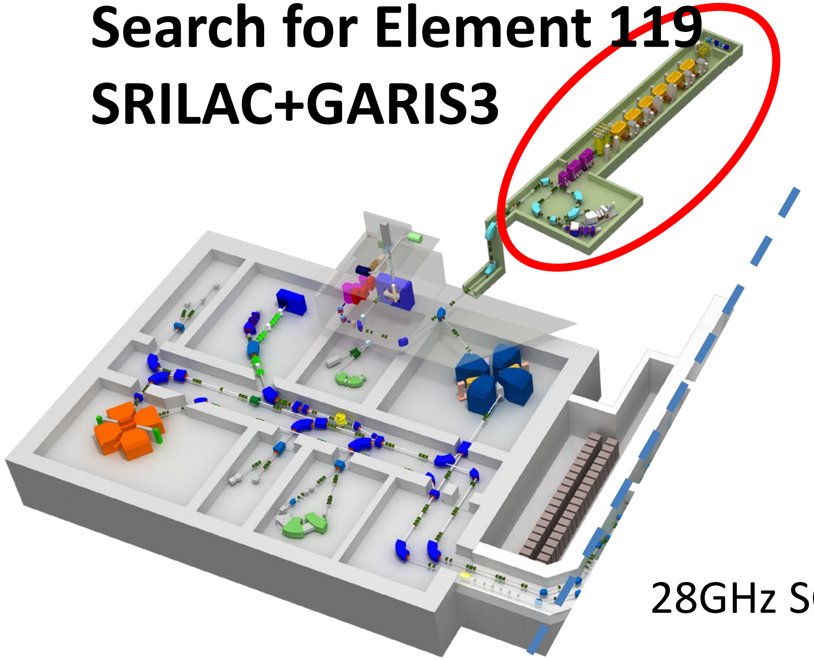
Z: the number of protons

Search for Element 119

SRILAC+GARIS3



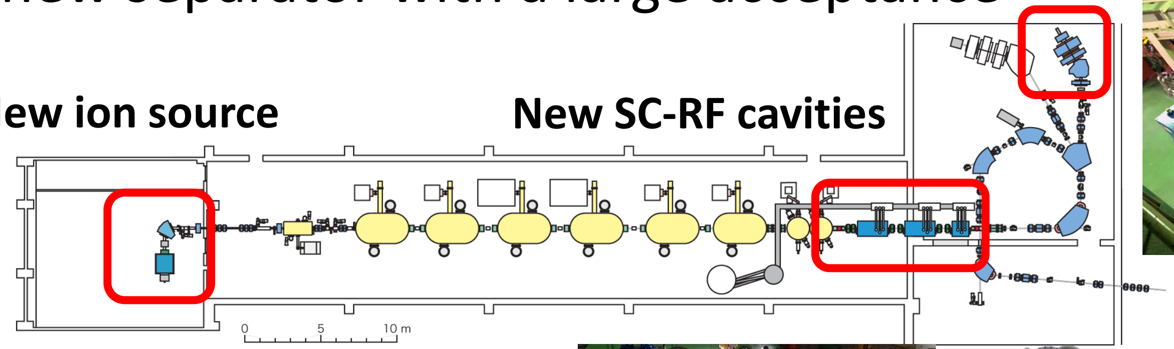
Element 113 "Nihonium"

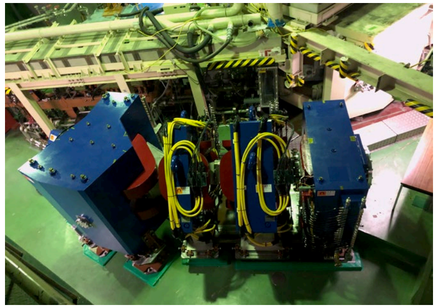


Old facility (1986-)

New setup towards the element 119 and beyond

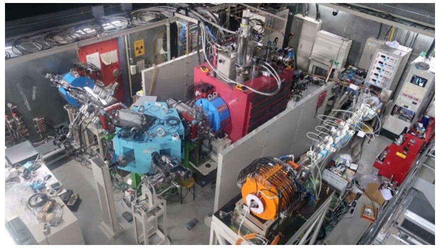
intensity and energy upgrade of the heavy-ion linac
new separator with a large acceptance

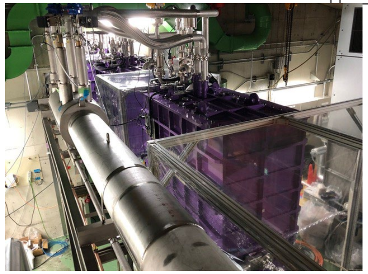


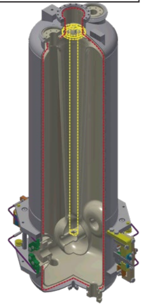


New separator

28GHz SC-ECR

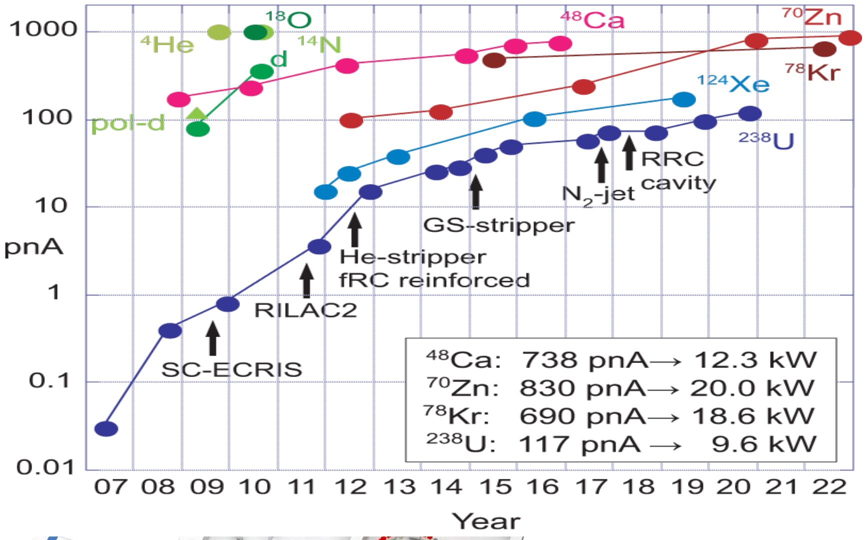




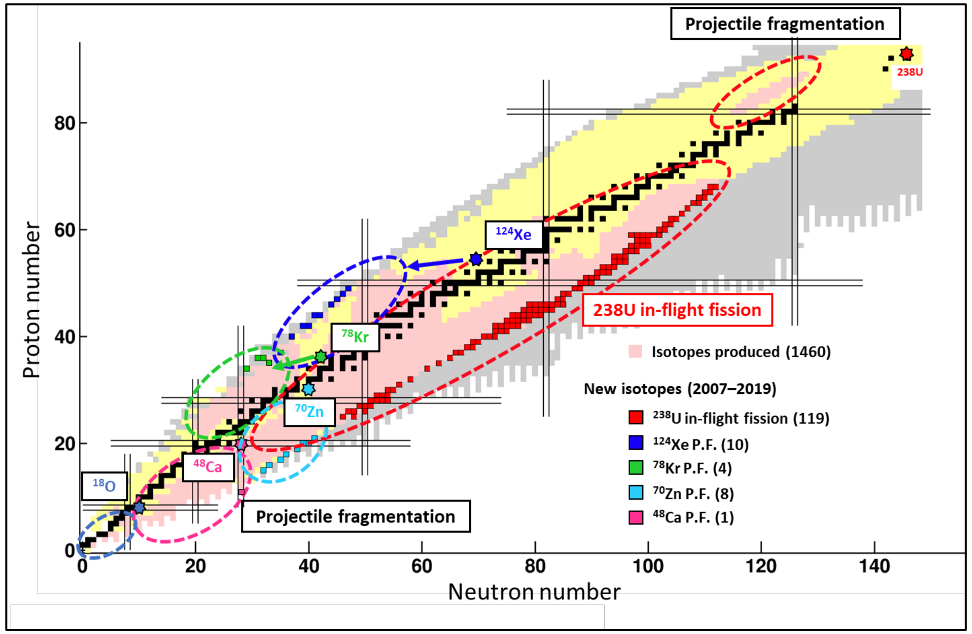


Accelerators and In-flight Separator at RI Beam Factory

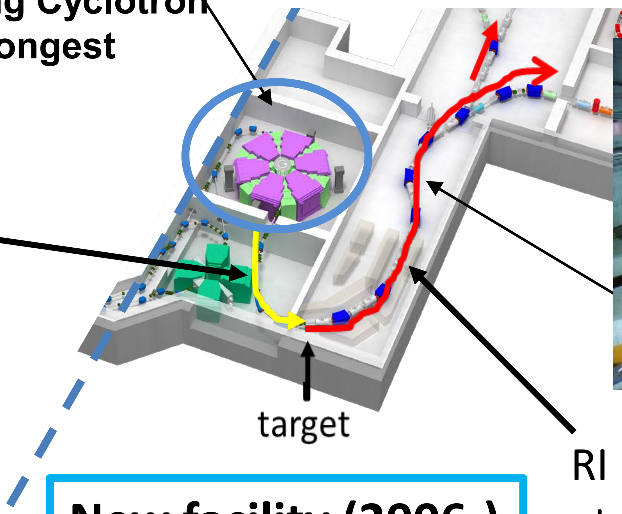
Beam Intensity of SRC as a function of year



156 new isotopes created since 2007



SRC:
Superconducting Ring Cyclotron
World's First and Strongest
K2600MeV



primary beams
at 350 MeV/u

target

New facility (2006-)

RI beams
at ~250 MeV/u

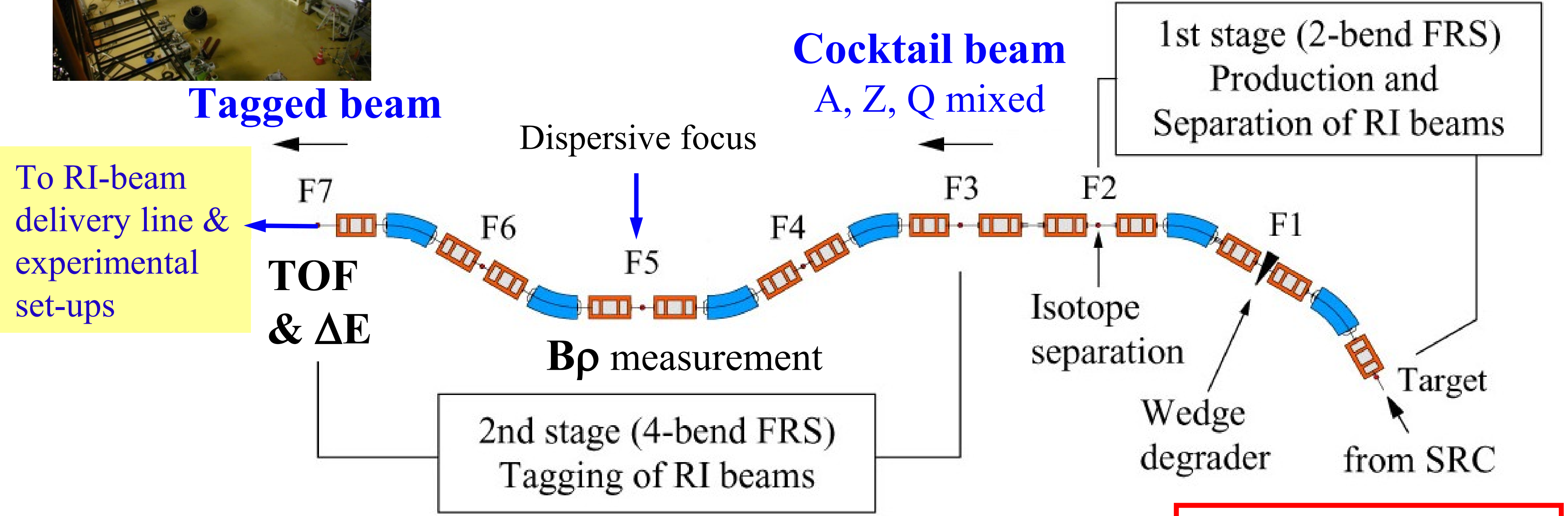
BigRIPS:
Superconducting RI beam Separator
In-flight separator
World's Largest Acceptance
High magnetic rigidity 9 Tm

Delivery of tagged RI-beam

T. Kubo et al.

Based on two-stage separator scheme

Bρ-ΔE-Bρ Method

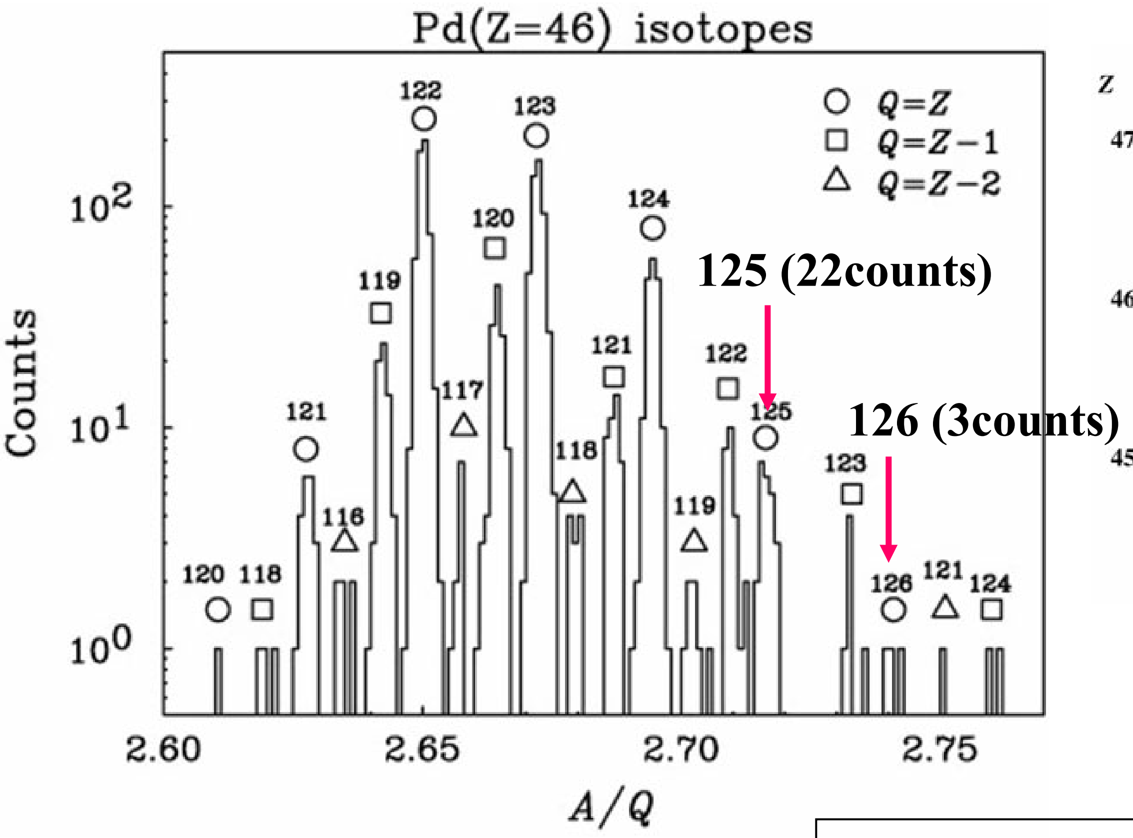


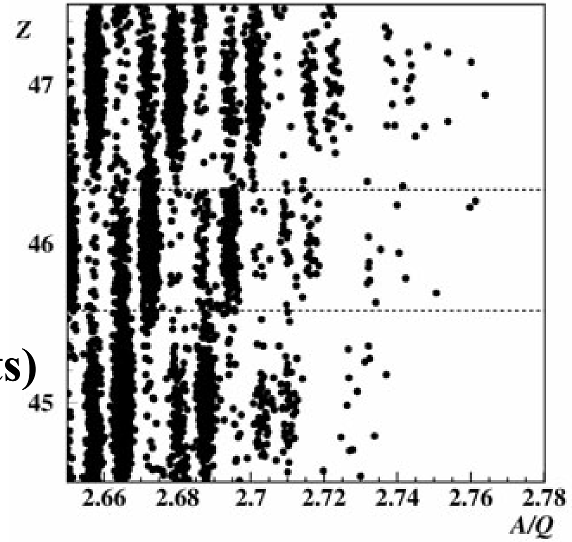
Identify RI-beam species Z, A/Q by measuring ΔE, Bρ, TOF in an event-by-event mode using beam-line detectors on the 2nd stage. Aim at tagging rate up to 1 x 10^6 pps.

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

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

Identification of new isotopes ^{125,126}Pd





Total dose 3.6×10^{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

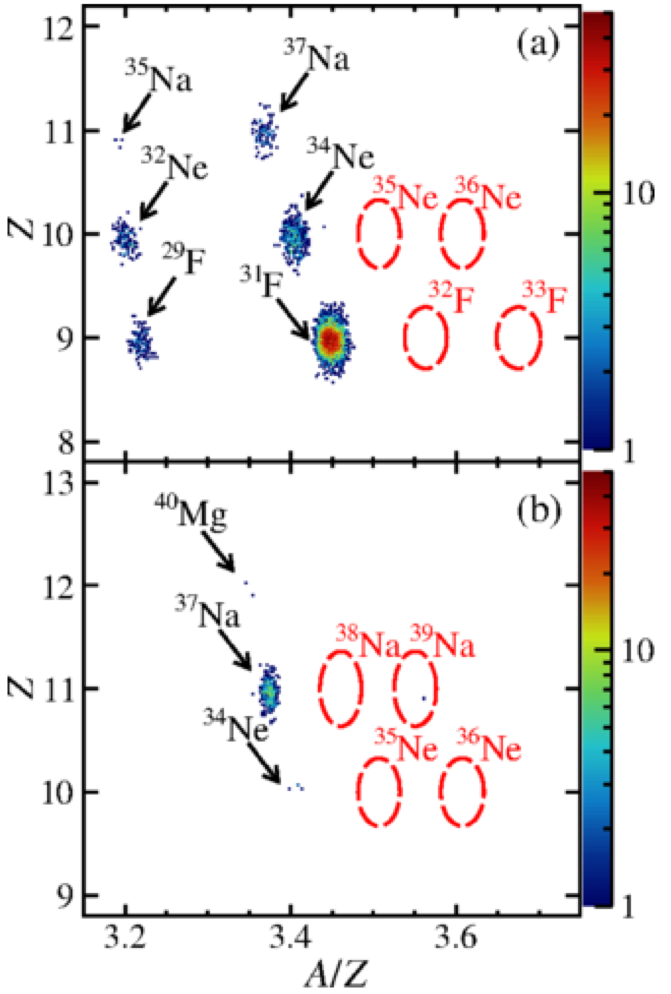
Cf. ^{124}Pd 19 counts, ^{125}Pd(cand.) 1count at GSI, 1997
PLB 415, 111 (97); total dose ~1×10^{12}

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

Recent Discovery of New N-rich Isotopes at RIBF

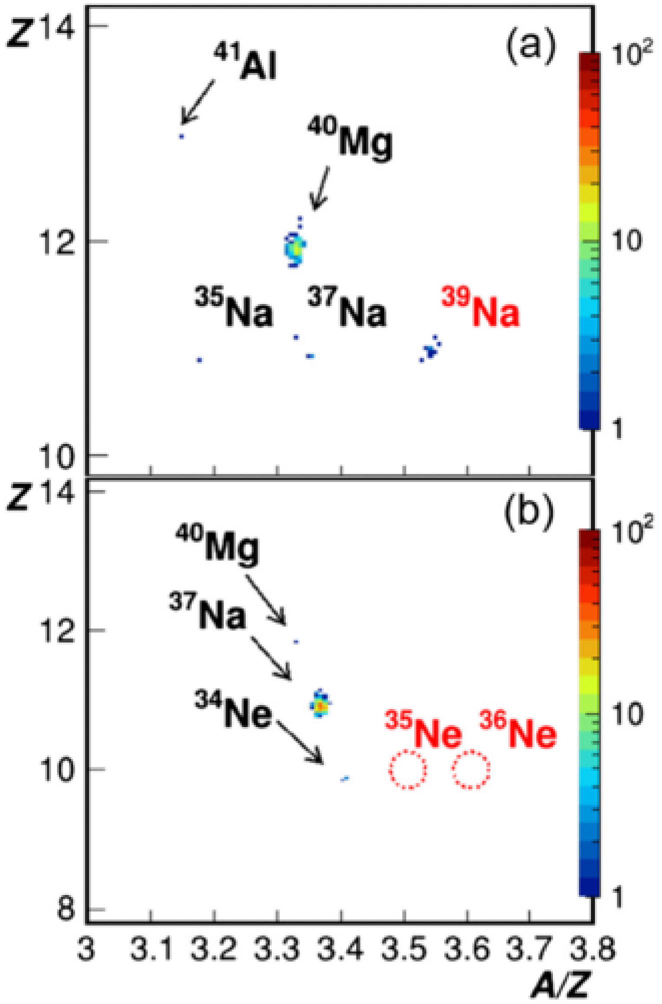
Location of neutron drip line in F and Ne

Ahn et al., PRL 123, 212501 (2019)



Discovery of ^{39}Na

Ahn et al., PRL 129, 212502 (2022)



See also "Probing the Limits of Nuclear Existence" Blumenfeld, *Physics* 15, 177 (Nov. 16, 2022)

A YouTube on Na-39 !

A New Isotope of Sodium - Periodic Table of Videos April 4th, 2023

https://www.youtube.com/watch?v=vl0_DElyTZU

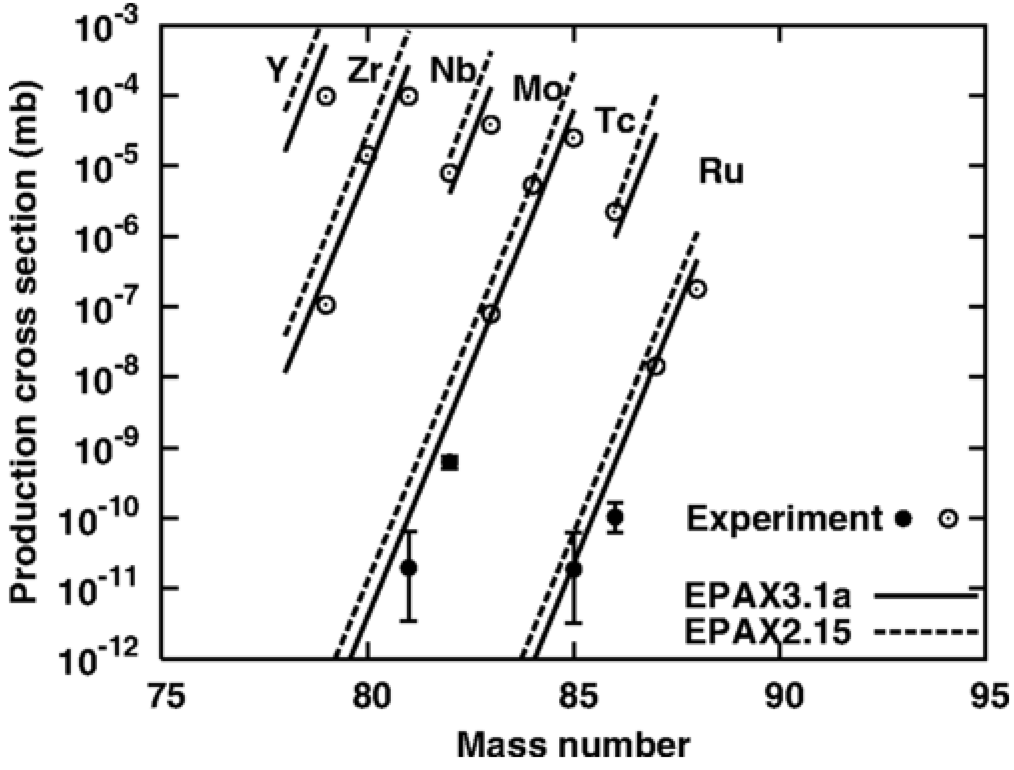
Prof. Martyn Poliakoff, University of Nottingham in UK

Production cross section measurements at BigRIPS

When you design an experiment, you need to estimate an intensity of radioactive isotope beams.
The intensity depends on not only intensity of primary beam and target thickness
but also production cross sections.

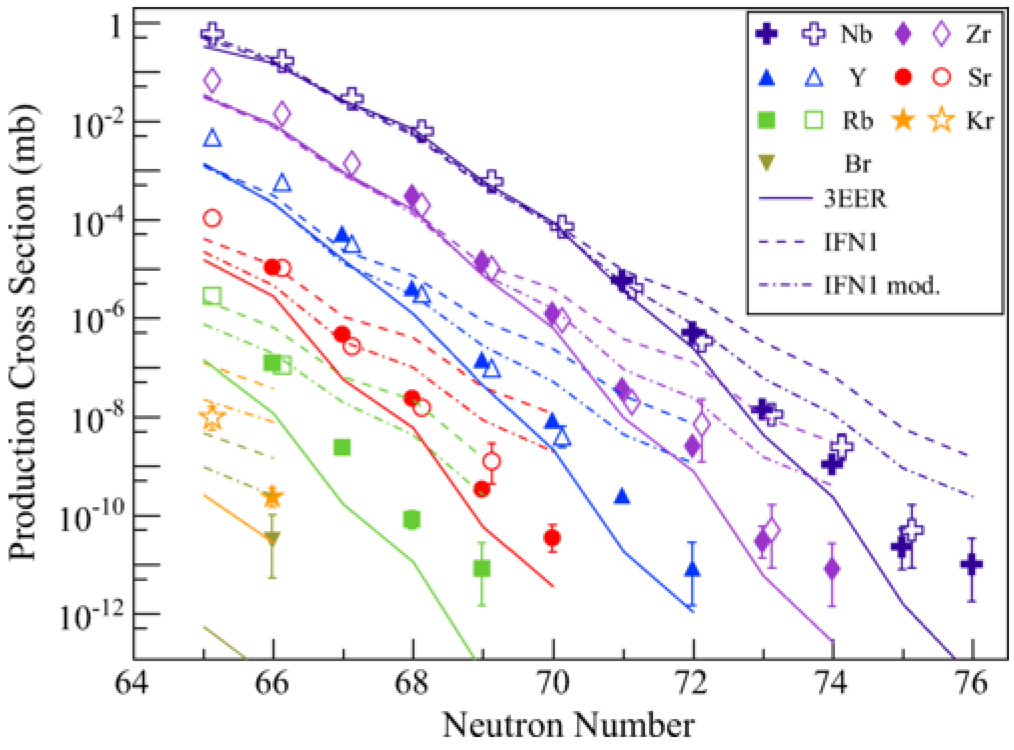
Sumikama et al., PRC 96, 034604 (2017)

345 MeV/u Xe-124 beam + Be target



Sumikama et al., PRC 103, 014614 (2021)

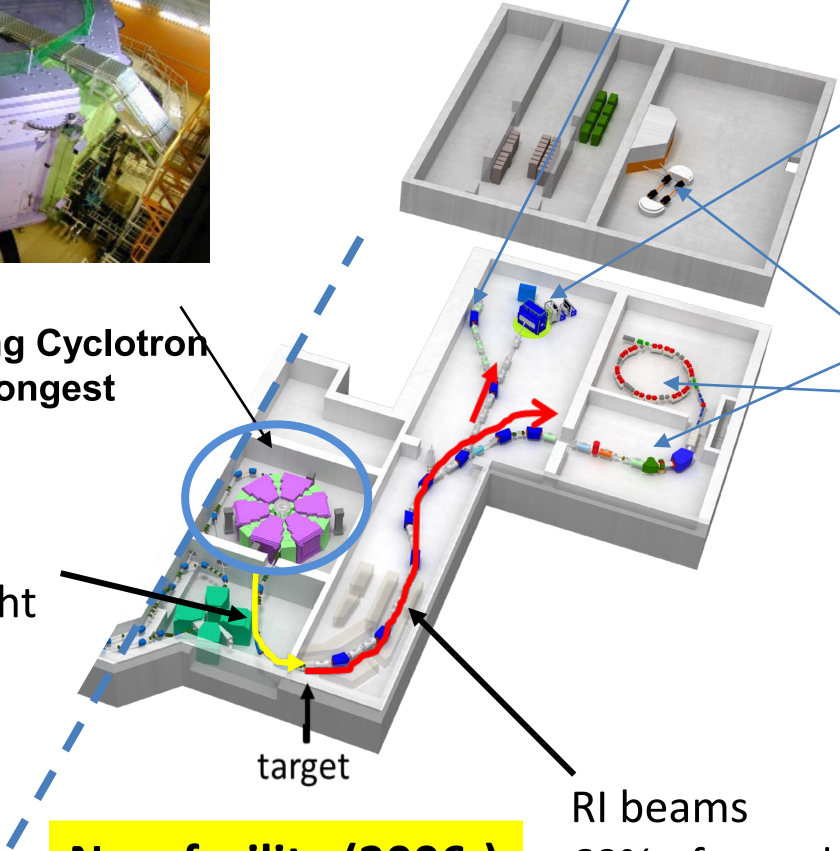
345 MeV/u U beam + Be target



Experimental Devices

Three spectrometers for reaction studies with fast RI beams

SRC:
Superconducting Ring Cyclotron
World's First and Strongest
K2600MeV



primary beams
70% of speed-of-light

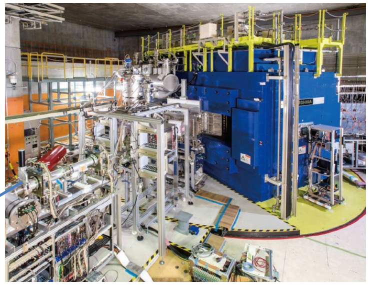
target

RI beams
60% of speed-of-light

New facility (2006-)

ZeroDegree

SAMURAI



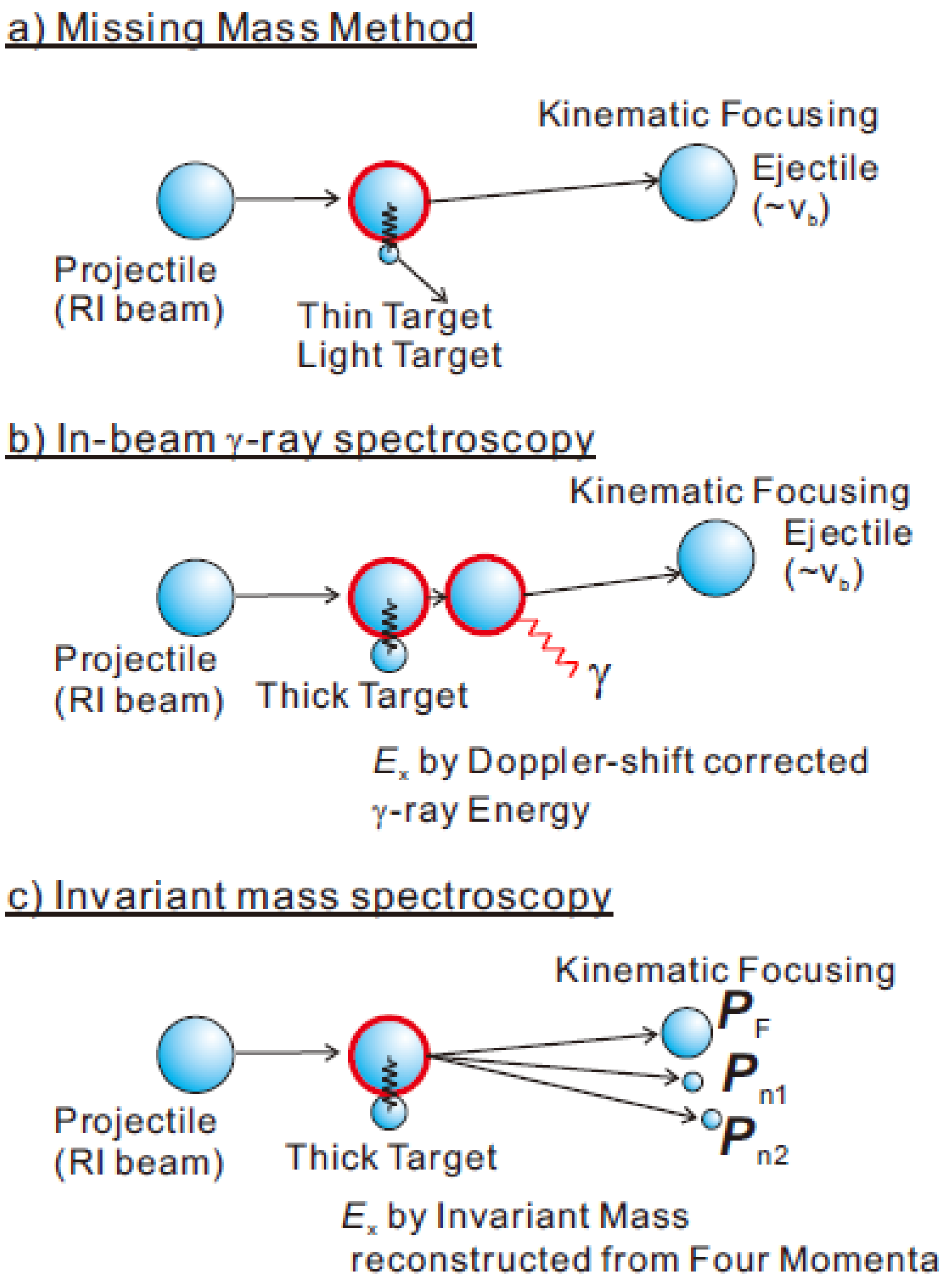
Nakamura san

SHARAQ + OEDO (Univ. of Tokyo, CNS)

A storage ring (Rare RI Ring) dedicated to mass measurement

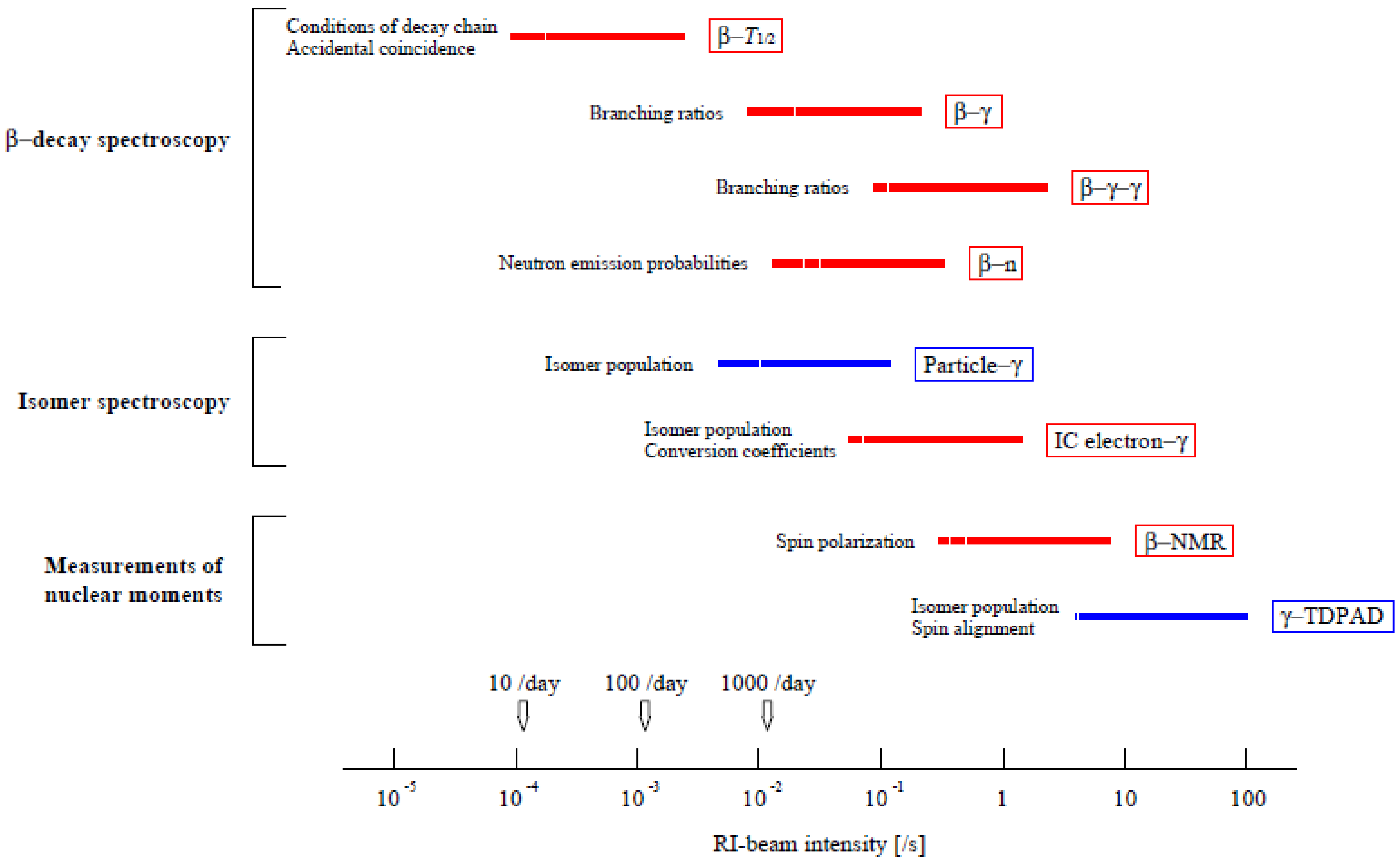
SCRIT + RUNBA based on ISOL

SCRIT: Suda san



Harakeh san

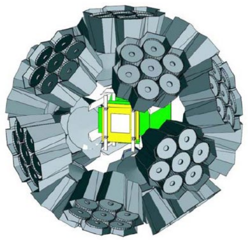
Nakamura san

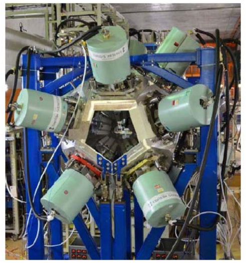


β–decay spectroscopy
Conditions of decay chain
Accidental coincidence
β–T1/2
Branching ratios
β–γ
Branching ratios
β–γ–γ
Neutron emission probabilities
β–n
Isomer spectroscopy
Isomer population
Particle–γ
Isomer population
Conversion coefficients
IC electron–γ
Measurements of nuclear moments
Spin polarization
β–NMR
Isomer population
Spin alignment
γ–TDPAD
10 /day
100 /day
1000 /day
10^-5
10^-4
10^-3
10^-2
10^-1
1
10
100
RI-beam intensity [/s]

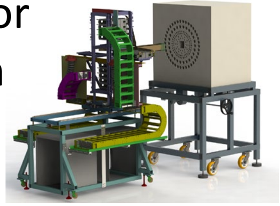
Large-Size International Collaborations

EURICA (2011-2016):
EUroball-RIKEN Cluster Array

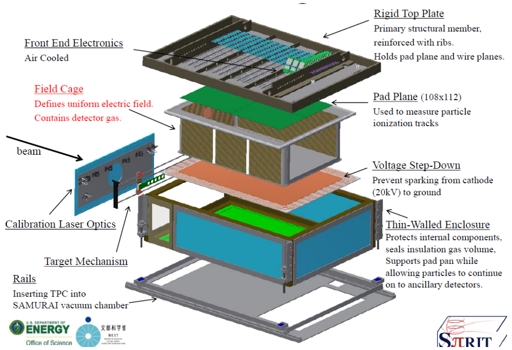




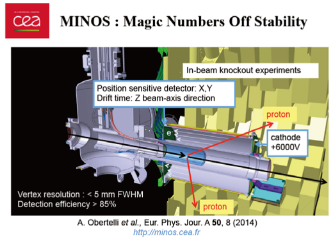
BRIKEN(2017-2021):
He-3 detector array for beta-delayed neutron



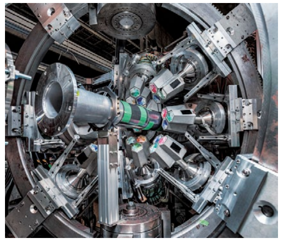
SpiRIT TPC (2015-):
heavy-ion collision program for EOS



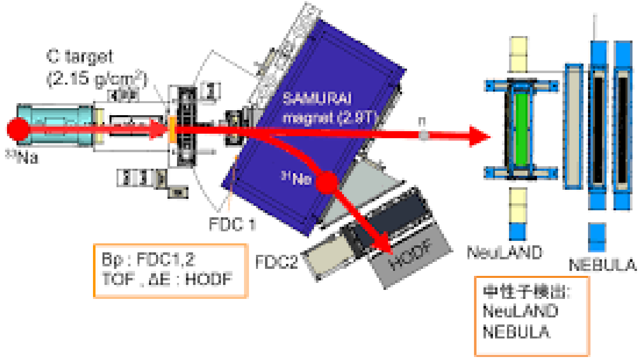
SEASTAR (2014-2017):
thick liq. H_2 +TPC+NaI
for in-beam gamma spectroscopy



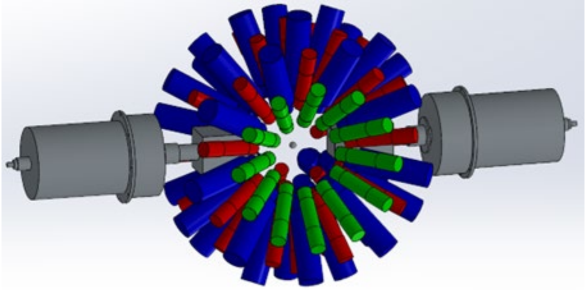
HiCARI (2019-2020):
Tracking Ge detectors
for in-beam gamma spectroscopy



SAMURAI (2012-):
neutron detectors + CsI+…
for neutron correlation

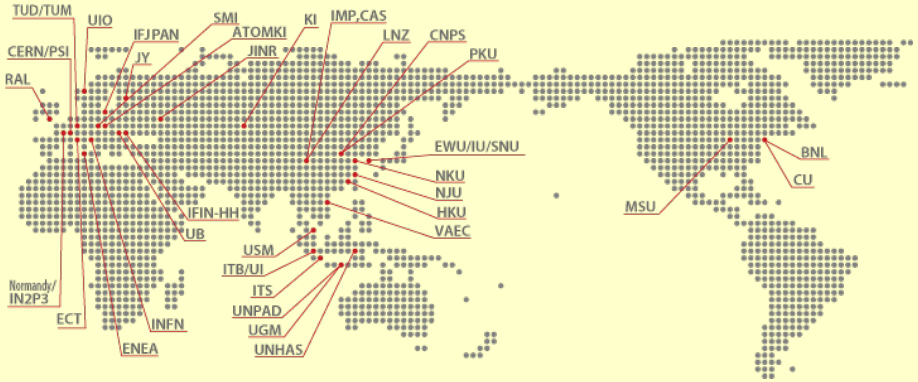


IDATEN (2021-):
84 $LaBr_3$ (Ce) + 2 Cover Ge detectors
to measure lifetime of excited states



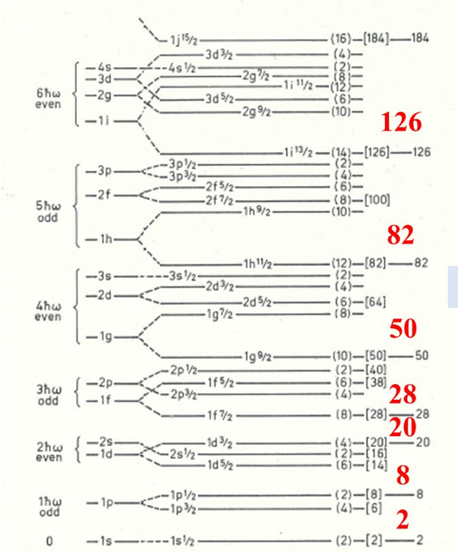
UK-Korea-China Collaboration

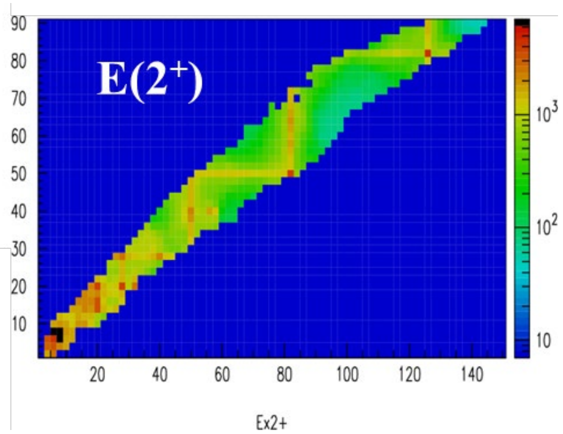
MoUs with
48 institutions and universities in 20 countries



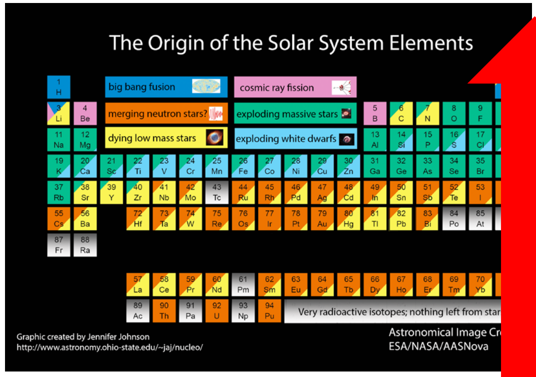
Why neutron-rich nuclei?: Large isospin-asymmetry

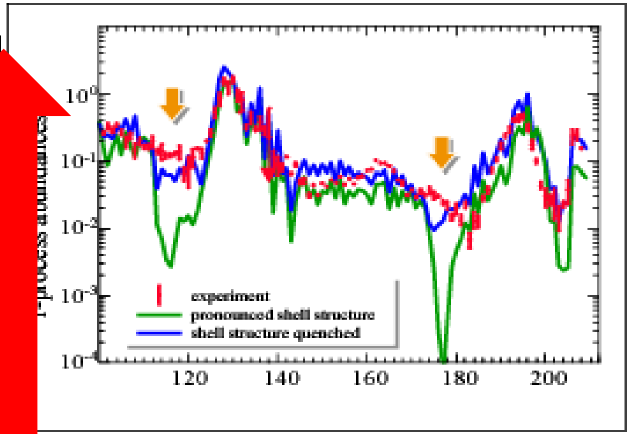
Shell-evolution: magicity loss and new magicity





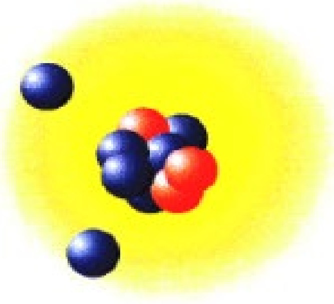
r-process path : nucleo-synthesis up to U



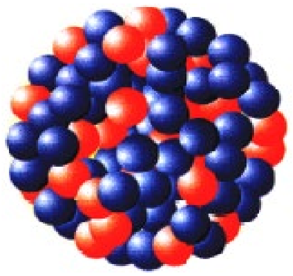


Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

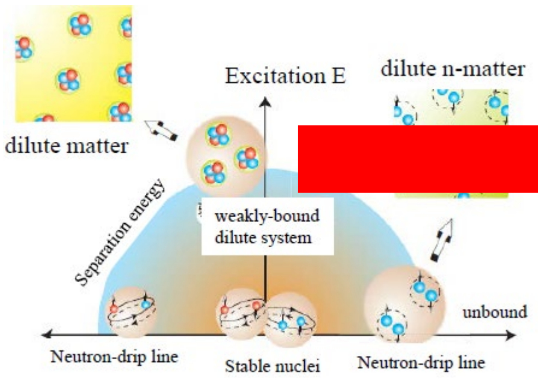
Neutron-neutron correlation in the vicinity of the dripline



^{11}Li
(two neutron halo)

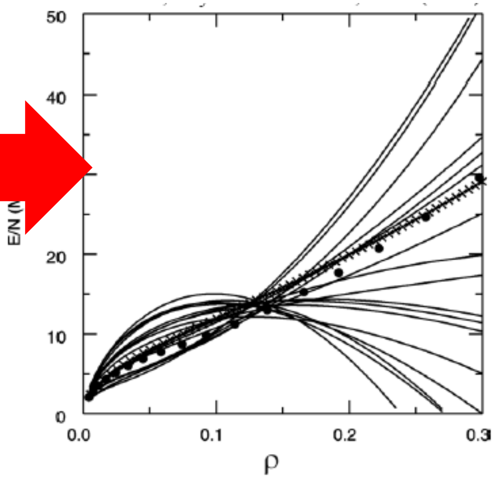


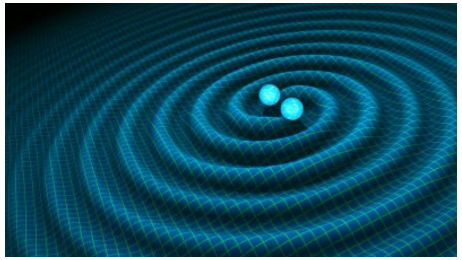
^{208}Pb



Equation-of-State in asymmetric nuclear matter

SN explosion, neutron-star, gravitational wave





gravitation wave
from neutron-star mergers
Space.com

Shell Evolution



Mayer & Jensen

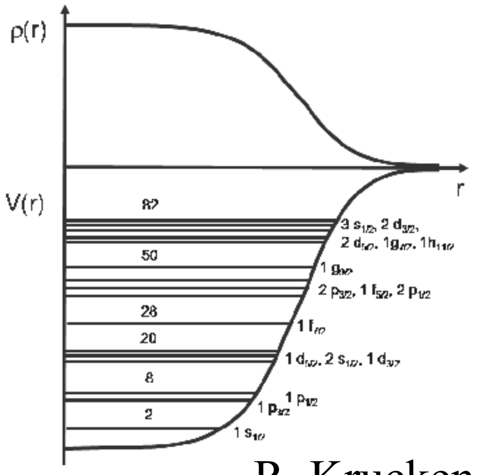
Nobel Prize 1963

Shell Structure

One-body potential

Large LS term

(surface contribution)

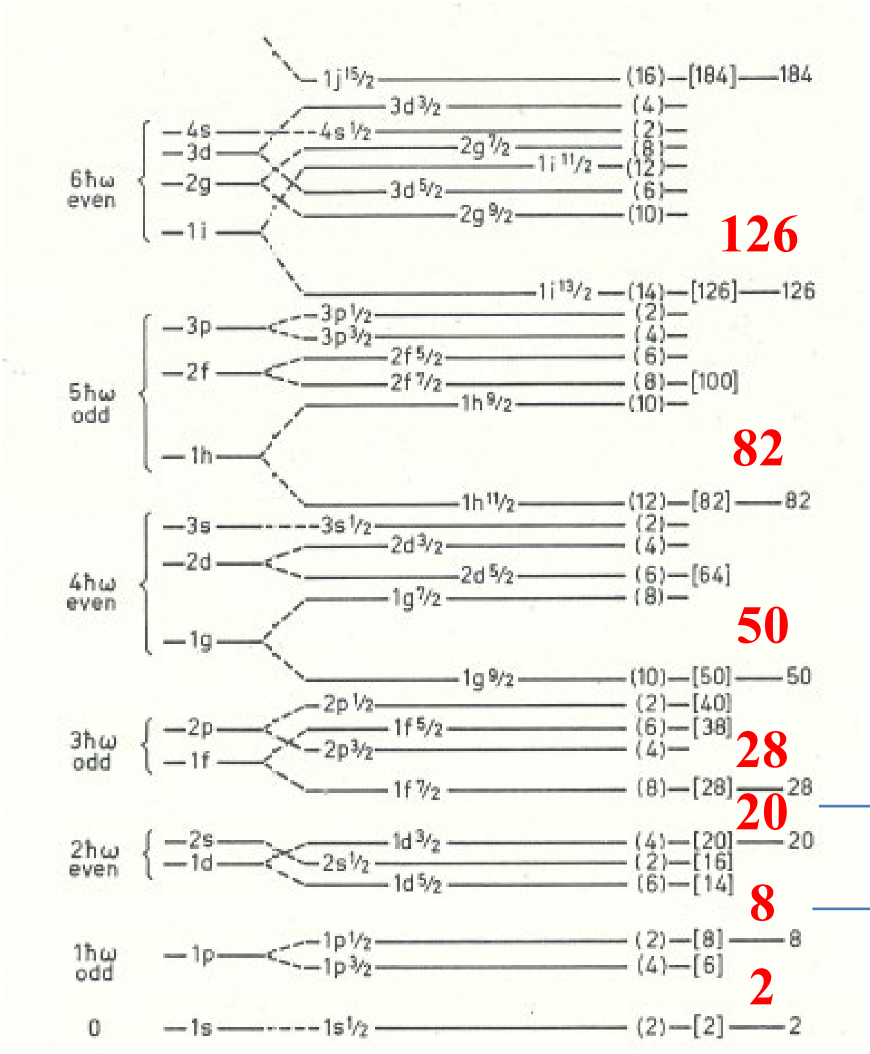


R. Krucken

Magic numbers ->

2, 8, 20, 28, 50 …

Stable nuclei



Neutron-rich nuclei

?

?

?

?

loss

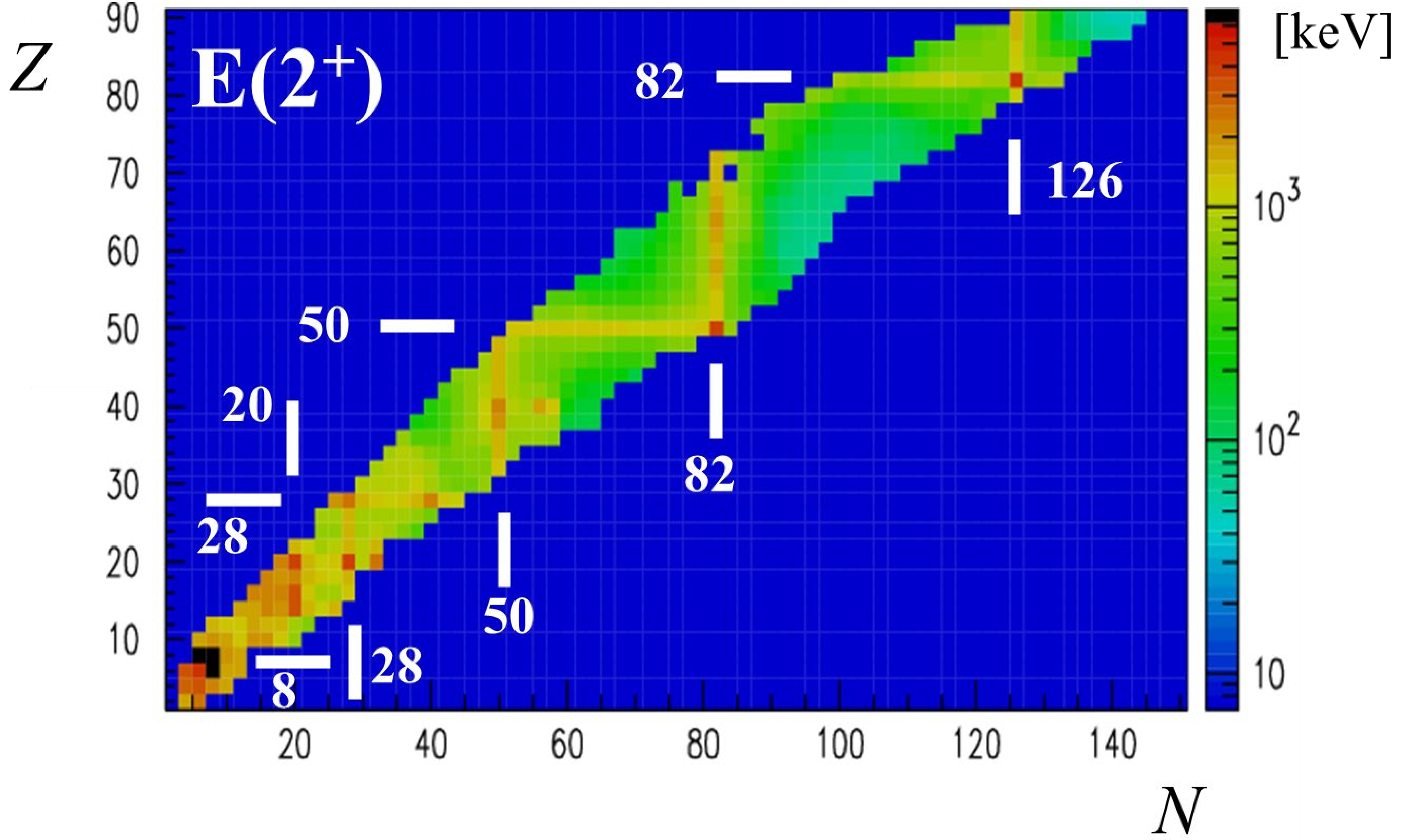
N=16

New magicity
In Oxygen

loss

Otsuka san

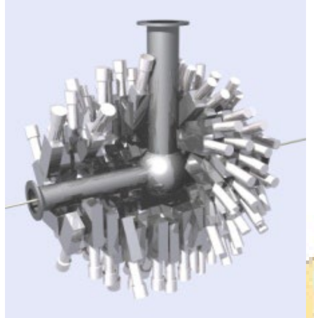
Magicity and its loss through determining E(2+)



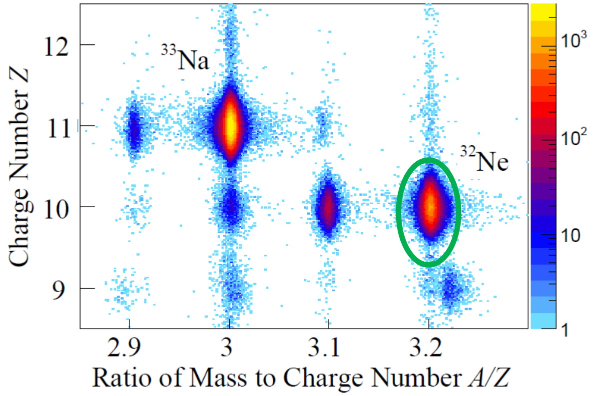
Spectroscopy via reactions with in-beam gamma method

Sunflower Collaboration

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

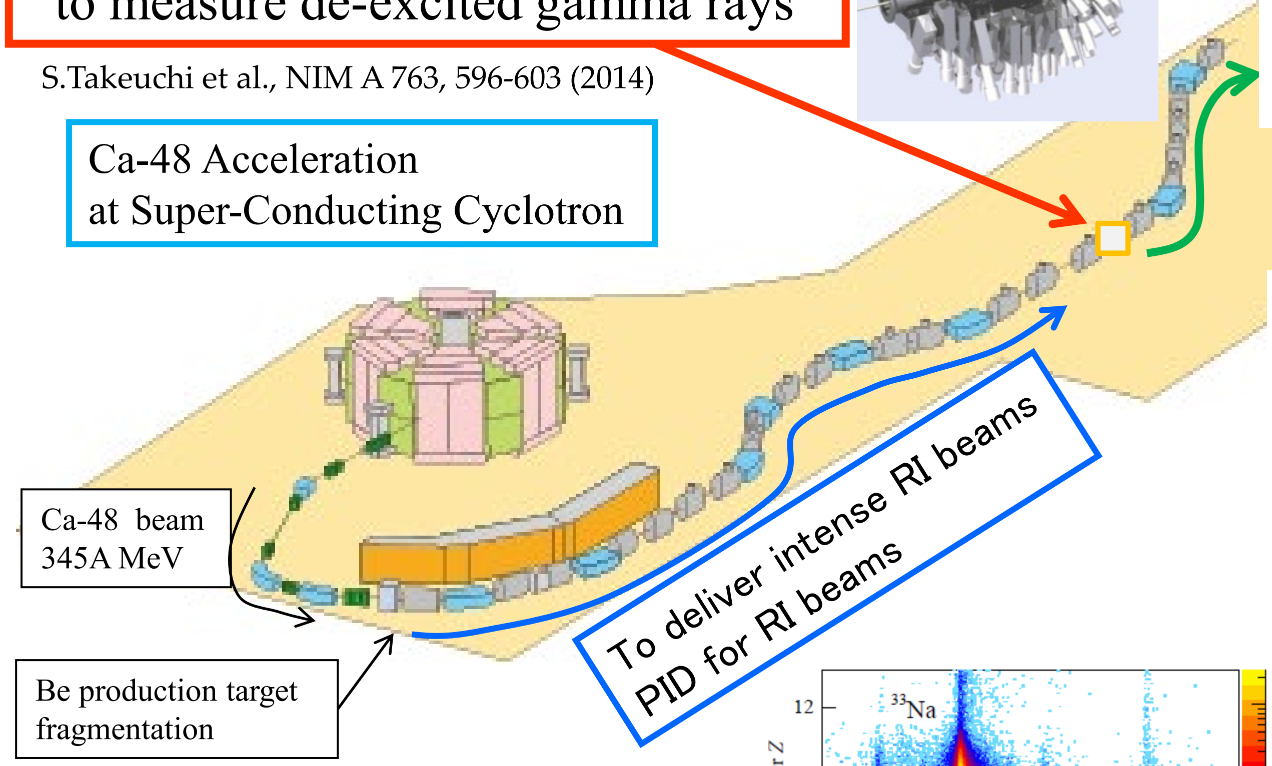


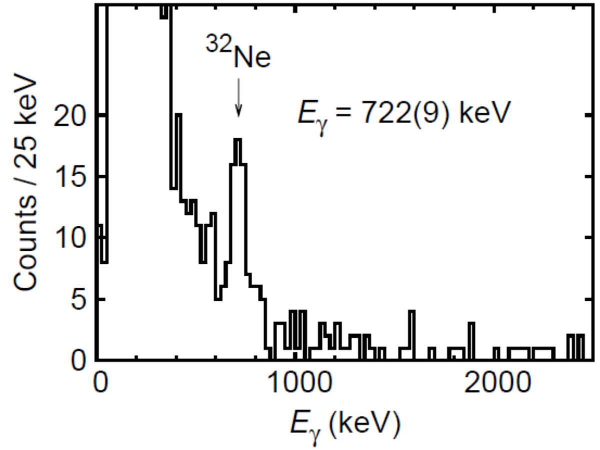
S.Takeuchi et al., NIM A 763, 596-603 (2014)



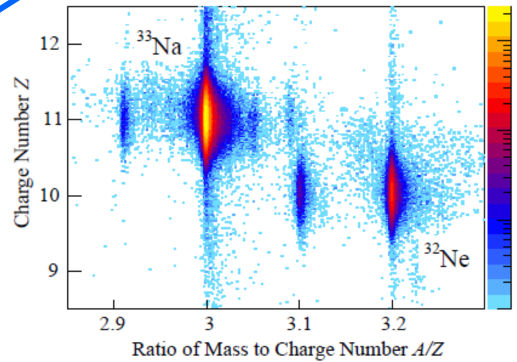
Ca-48 Acceleration at Super-Conducting Cyclotron

PID at ZeroDegree

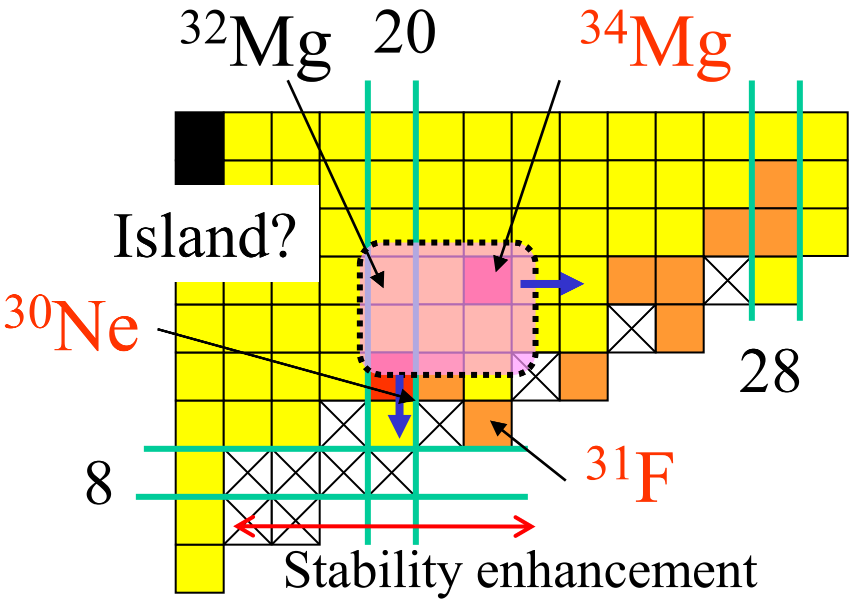




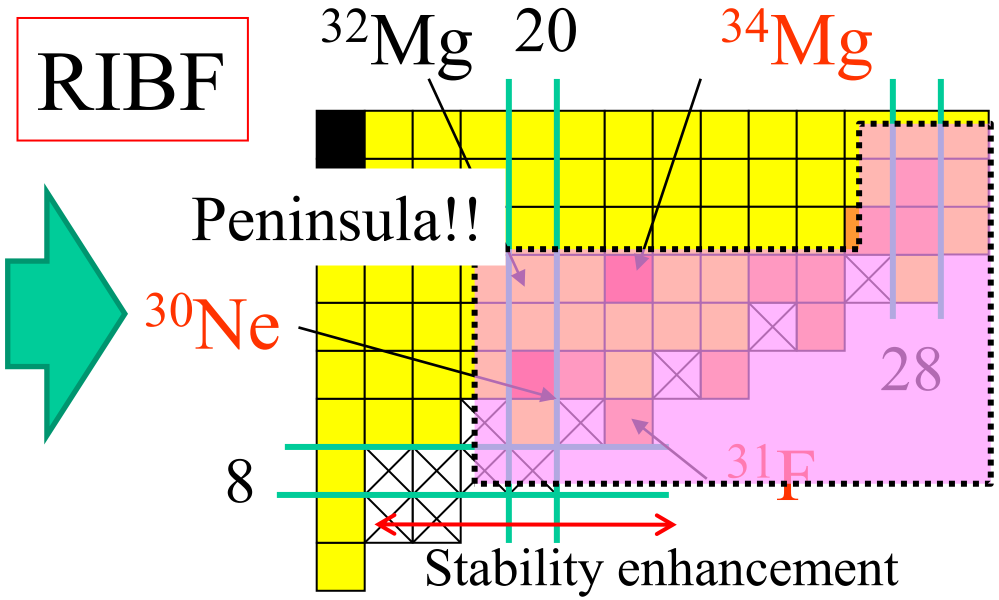
Doornenbal, Scheit et al.
PRL 103, 032501 (2009)



Island-of-inversion and beyond



RIBF



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

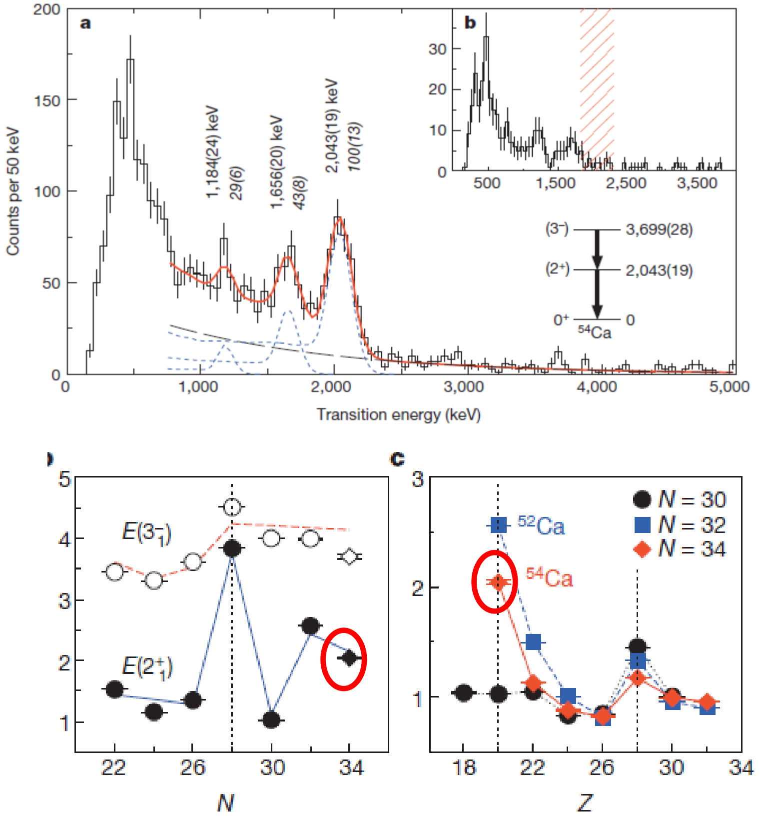
<u>Doornenbal, Scheit, et al.</u>
Ne-32 1st excited states: PRL 103, 032501 (2009)
New states in ^{31,32,33}Na: PRC 81, 041305R (2010)
Mg-36,-38: PRL111, 212502 (2013)
F-29: in preparation
<u>Takeuchi et al.</u>
Si-42 : PRL109, 182501 (2012)
<u>P.Fallon et al.</u>
Mg-40 : PRC 89, 041303 (2014)

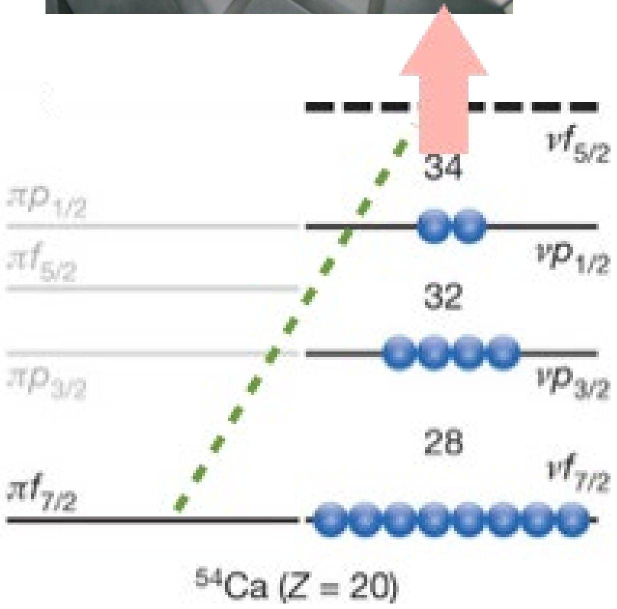
New “Magicity” of N=34 in the Ca isotopes

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

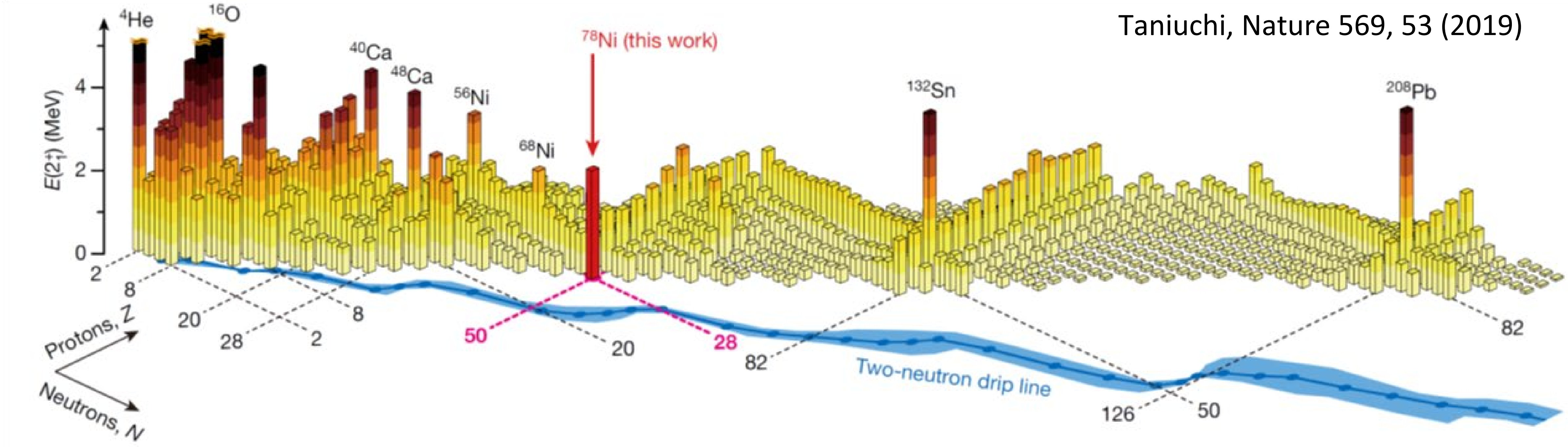




Magicity and its loss through determining E(2^+) in even-even nuclei

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

Taniuchi, Nature 569, 53 (2019)

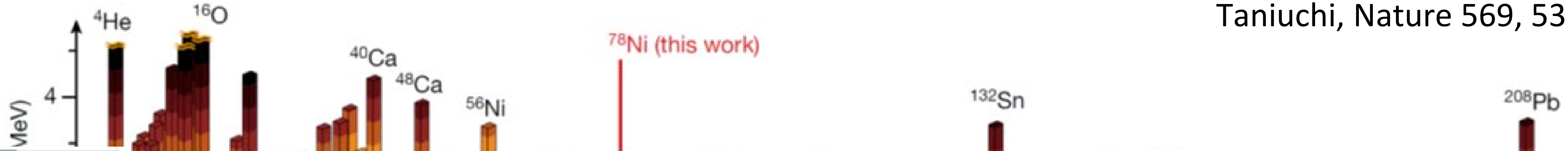


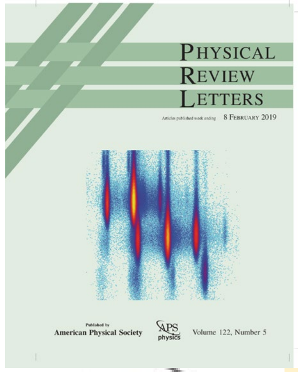
Beyond ^{78}Ni, no magicity at Z=28 or N=50?

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

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

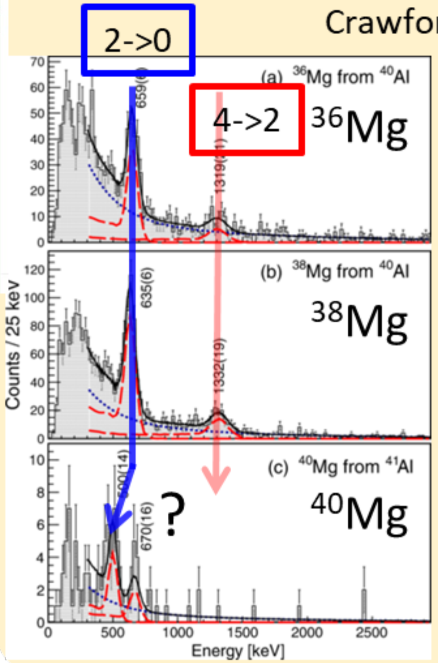
Taniuchi, Nature 569, 53 (2019)





Mysterious structure in ^{40}Mg

Crawford et al., PRL 122, 052501 (2019)



Sudden change of the structure between ^{38}Mg and ^{40}Mg

^{40}Mg has larger deformation than ^{38}Mg.

Origin of the 2nd excited state is mystery.
No theory reproduces the data.

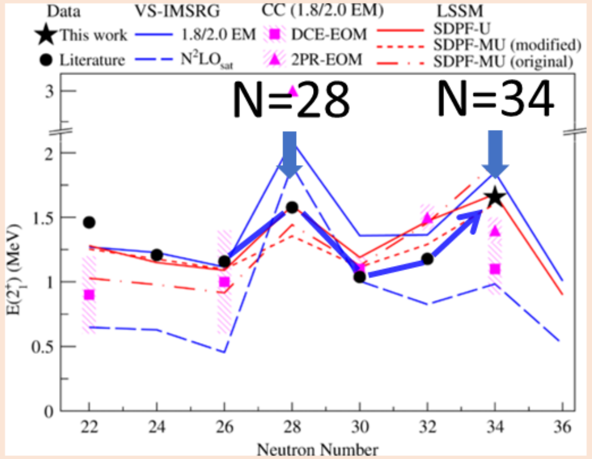
Magicity loss at N=28 upto Z=12

sub-shell gap at N=34
Nature 2013

Robustness of the N = 34 Subshell Closure

H.N. Liu et al., PRL 122, 072502 (2019)

E(2^+) of ^{52}Ar is higher than that of ^{50}Ar !

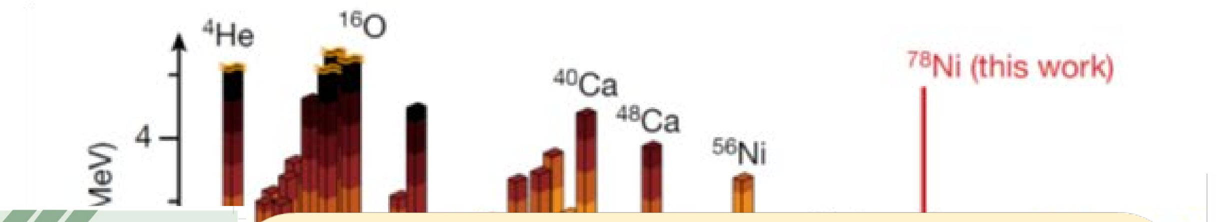


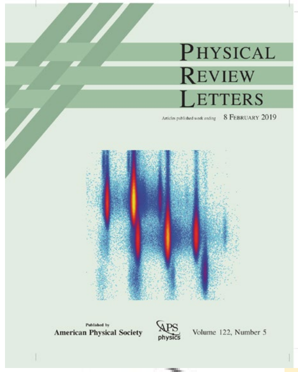
No big shell gap at N=32 but N=34 in Ar

Recent mass measurements show N=32 gap in Sc, but no gap at N=34
Leistenschneider, PRL **126**, 042501 (2021)
NSCL+ TRIUMF

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

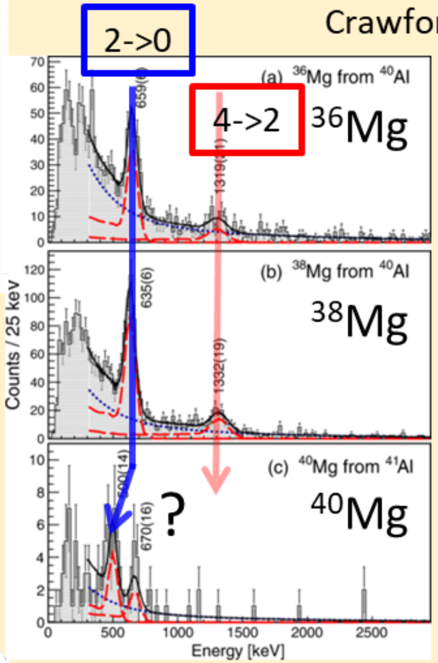
^{78}Ni revealed as a doubly magic stronghold





Mysterious structure in ^{40}Mg

Crawford et al., PRL 122, 052501 (2019)



Sudden change of the structure between ^{38}Mg and ^{40}Mg

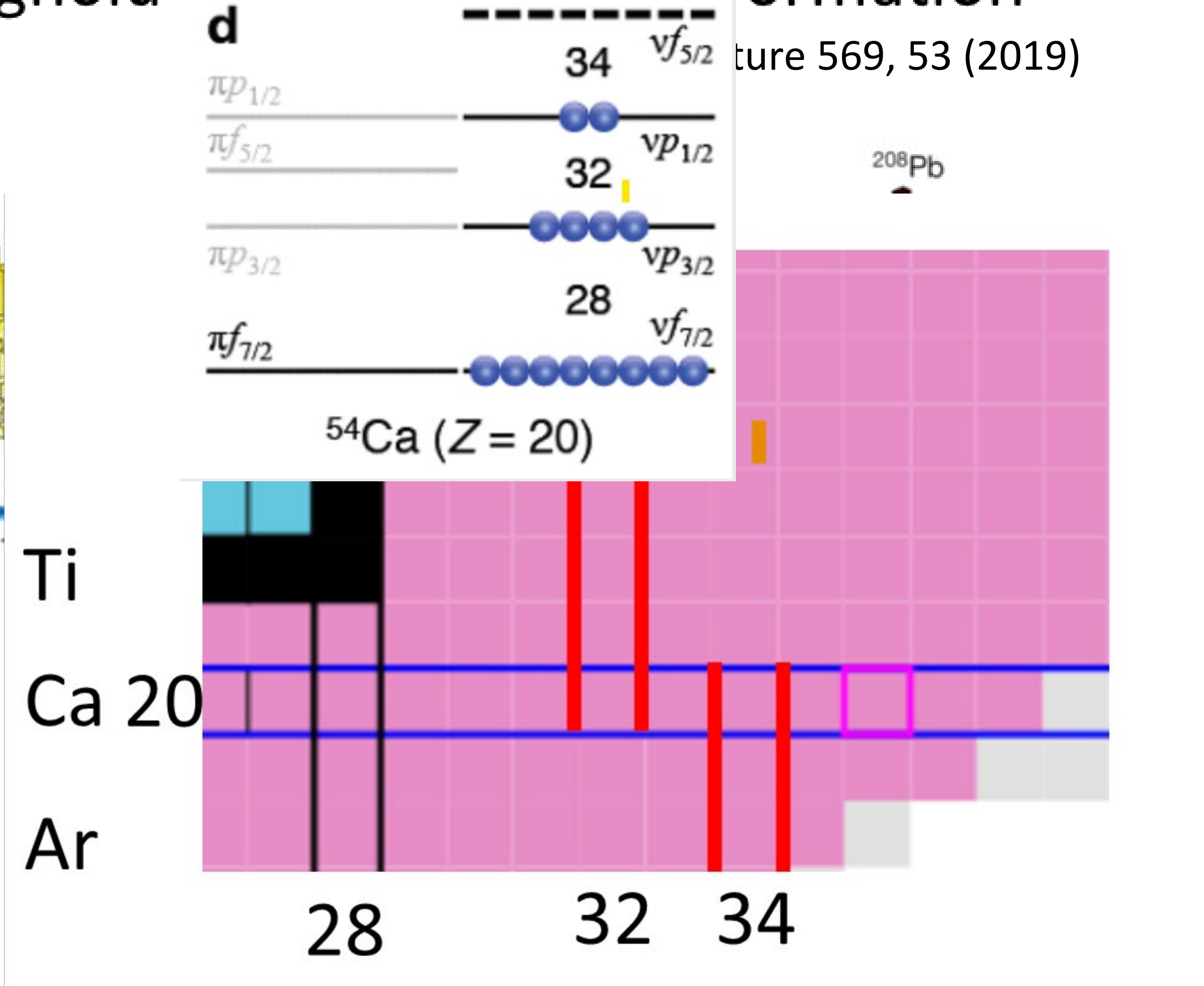
^{40}Mg has larger deformation than ^{38}Mg.

Origin of the 2nd excited state is mystery.
No theory reproduces the data.

Magicity loss at N=28 upto Z=12

formation

ture 569, 53 (2019)



How about N=34 subshell gaps at Z=16?

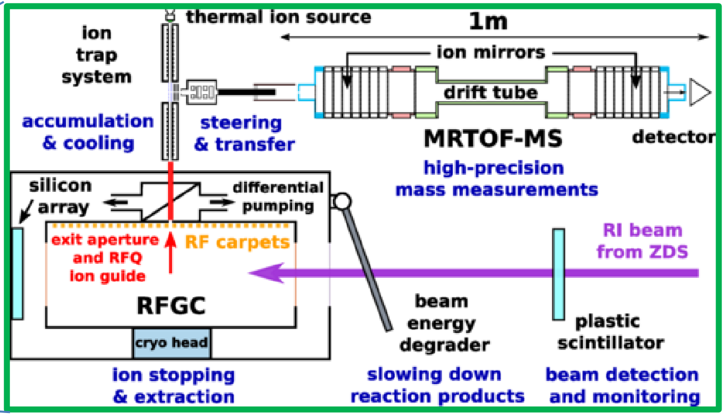
Mass Measurements in Parasitic Use

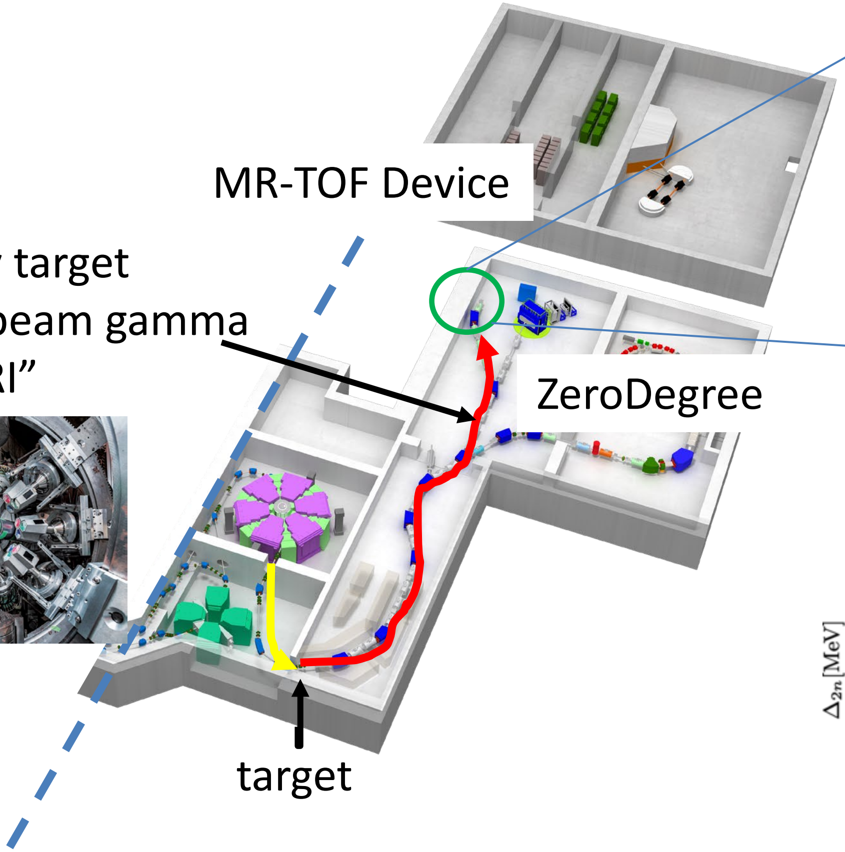
KEK-RIKEN Collaboration

Combination between in-beam programs and mass measurements with MR-TOF

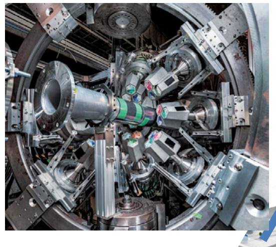
Development of an efficient way in utilizing costly radioactive beams

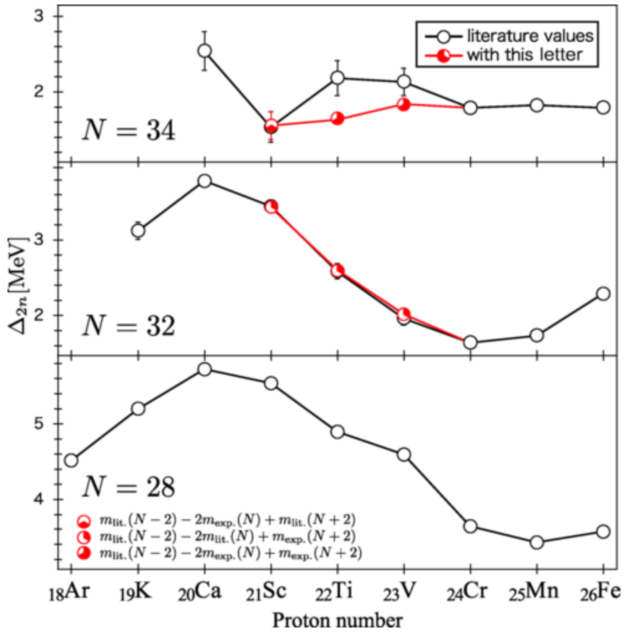
Takamine san





2ndary target
for in-beam gamma
"HiCARI"

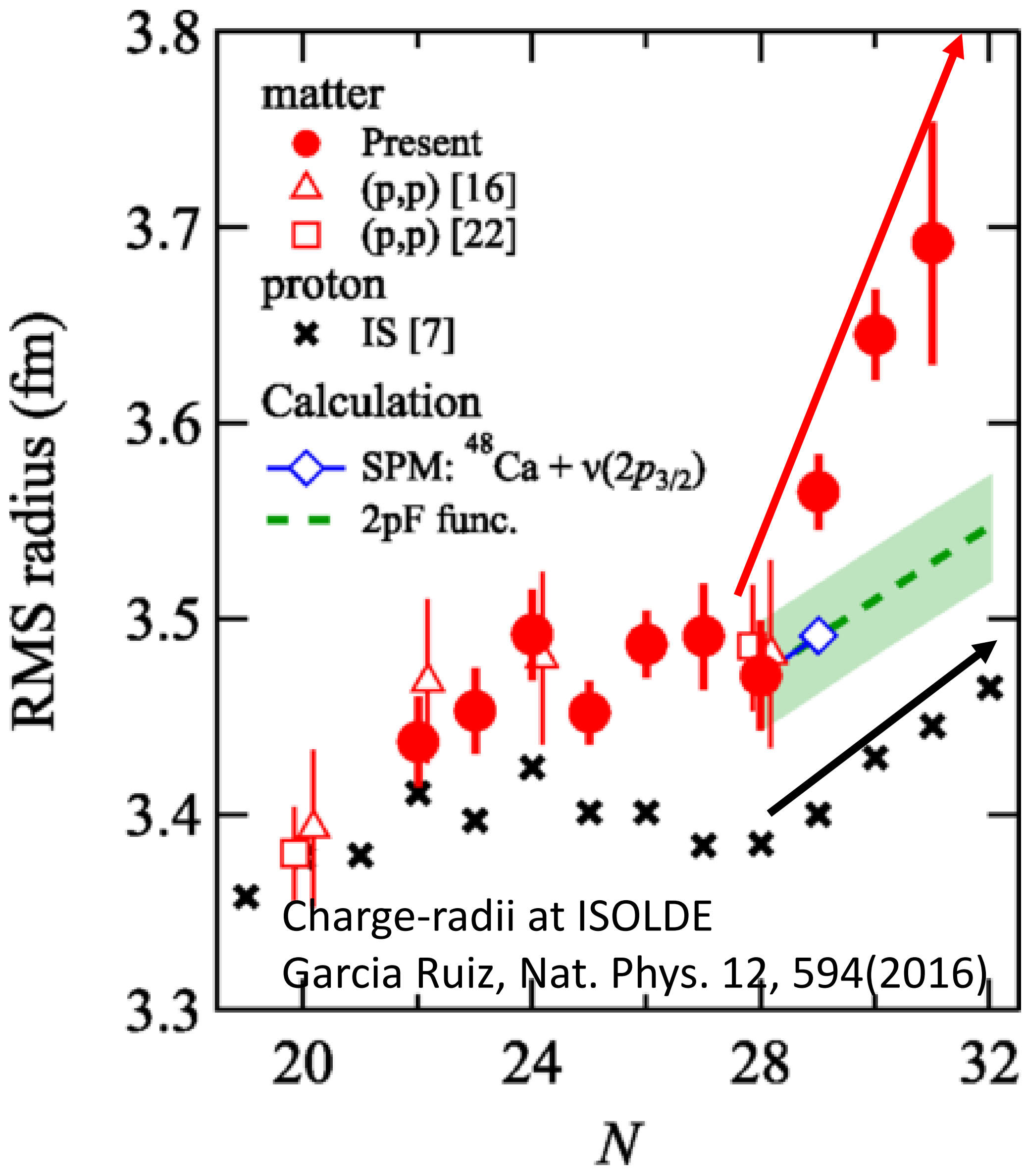




Study of the N=32 and N=34 Shell Gap for Ti and V by the First High-Precision Multireflection Time-of-Flight Mass Measurements at BigRIPS-SLOWRI

Iimura, PRL 130, 012501 (2023)

Neutron-rich Ca isotopes



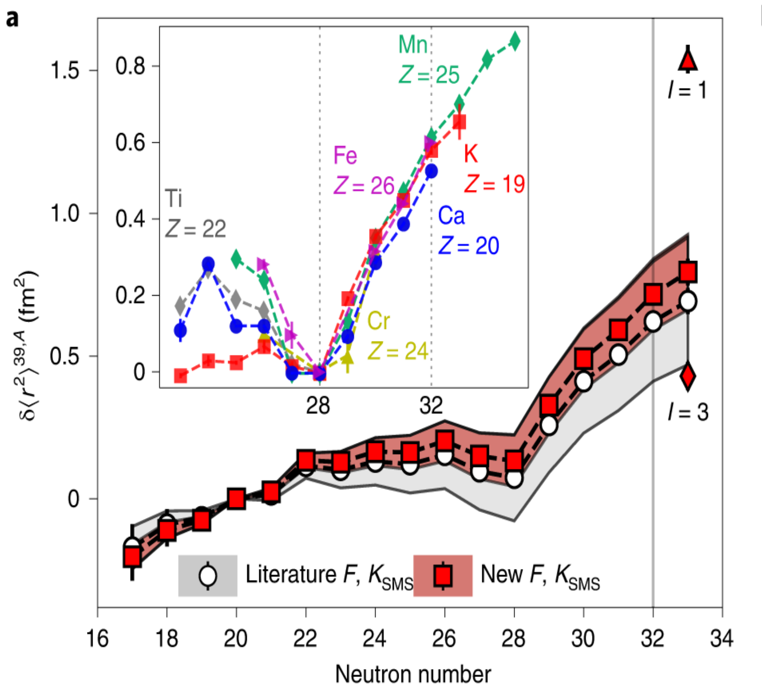
Charge-radii at ISOLDE
Garcia Ruiz, Nat. Phys. 12, 594(2016)

Nuclear-matter radii at RIKEN
Tanaka, PRL 124, 102501 (2020)

Transmission method

Why nuclear matter radii
dramatically increase beyond N=28?
How about beyond N=32, 34 subshell closures?

Charge-radii of the K isotopes
ISOLDE
Smooth change over N=32
Koszons, Nat. Phys. 17, 439(2021)

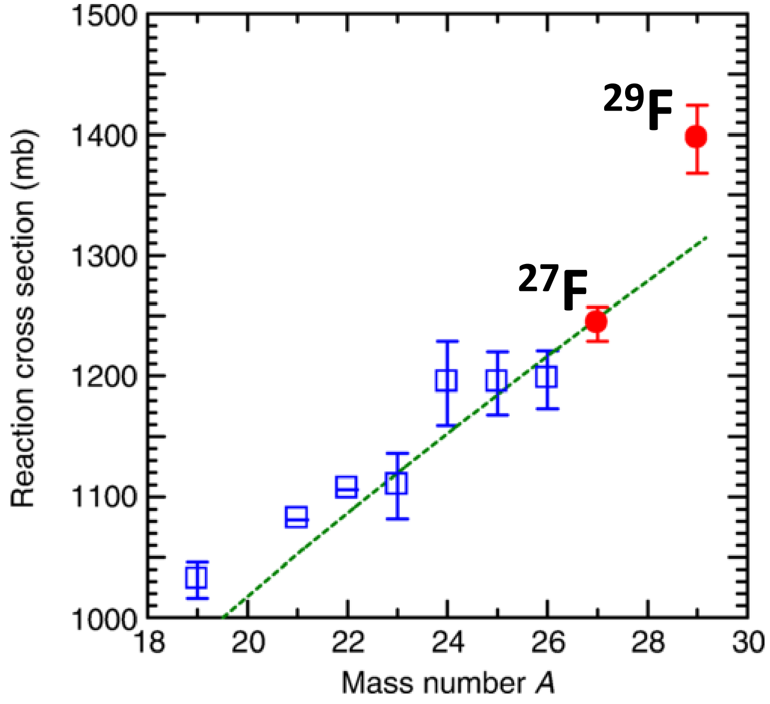


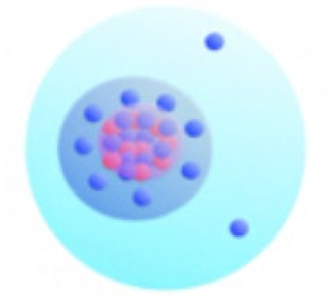
The Ca isotopes are unique
to study neutron-dynamics
including 3NF.
Spin-parity and location of excited
states in the Ca isotopes
are to be studied in the future.

Neutron-neutron correlation

Discovery of Two-neutron halo ^{29}F

Bagchi, PRL 124, 222504 (2020)

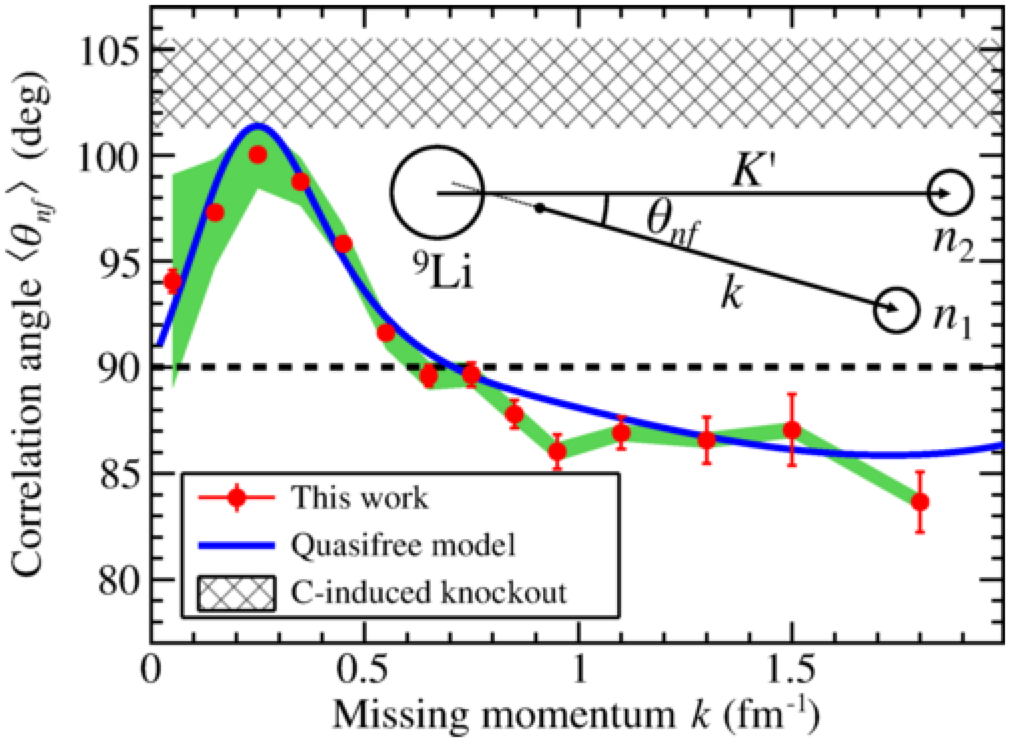




Core deformation
One neutron halo ^{31}Ne and ^{37}Mg have deformed cores.
Magicity loss at N=20, the deformation of the core nucleus ^{27}F may contribute to the halo formation
Revel, PRL 124, 152502 (2020)

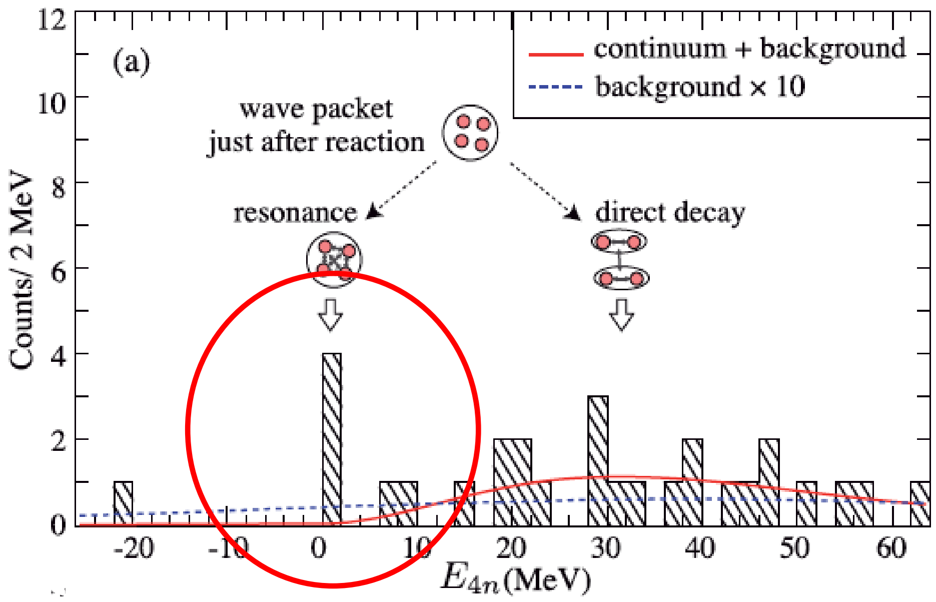
Surface Localization of The Dineutron in ^{11}Li

Kubota, PRL 125, 252501 (2020)



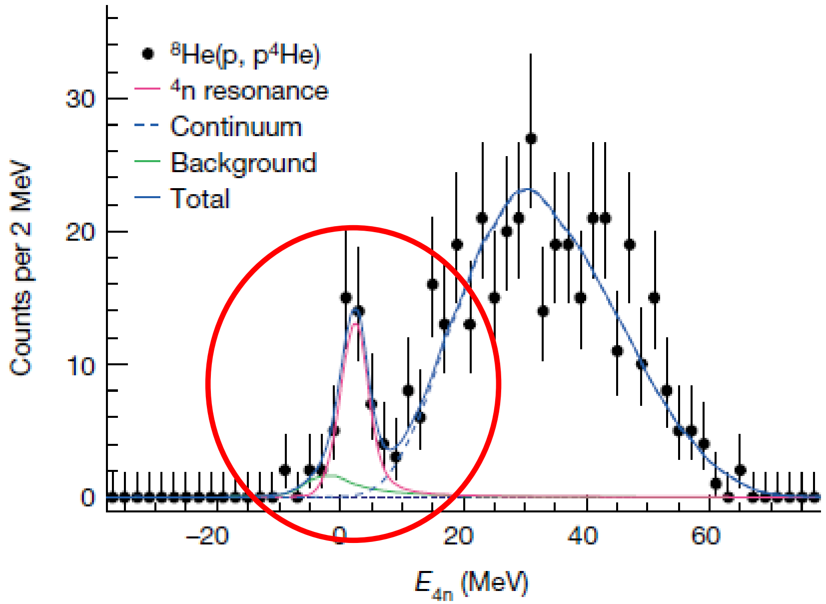
A “nucleus” with Atomic-Number Z=0: Observation of Tetra-neutron system

$^{4}He(^{8}He,^{8}Be)\ ^{4}n$ at SHARAQ



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

$^{8}He(p,p\alpha)\ ^{4}n$ at SAMURAI

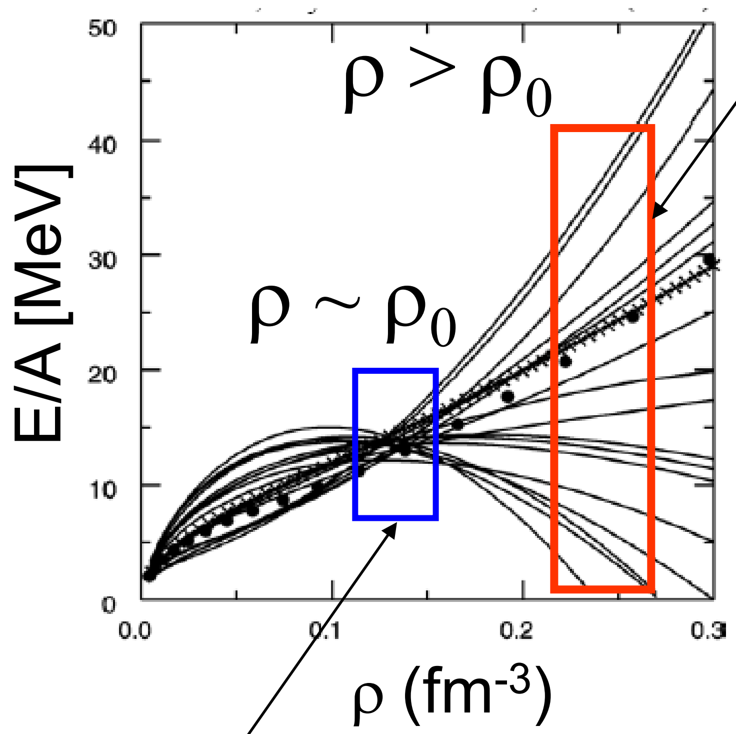


Duer, Aumann, et al., Nature 606, 678 (2022)

T=3/2 3NF ?
EOS in asymmetric nuclear matter

EOS in Asymmetric Nuclear Matter

Theoretical predictions of
EOS for pure neutron matter



BA Brown PRL, 2000

many works on-going
at the world-wide facilities

How to obtain information of EOS
at high densities or to give constraints?

1.Interactions?

T=3/2 3NF is becoming important at a high density

For example, tetra neutron system

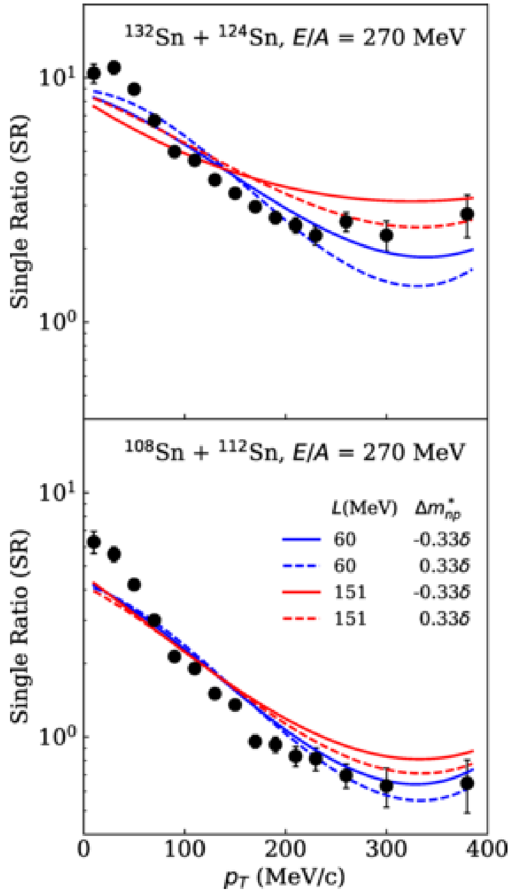
2. Mean-field effects?

Mean-field at a high-density
created by n-rich HI collisions
at 270 MeV/u
SpiRIT Collaboration

Bao-An Li

constraints given by pion-
production, light-fragment

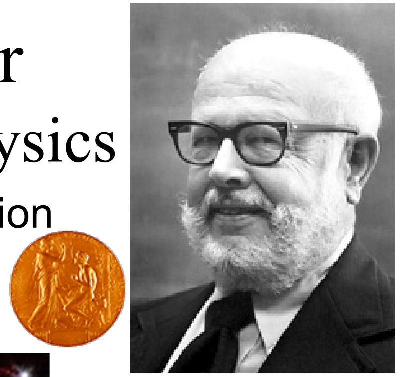
Jhang, PLB 813, 136016 (2021)
Estee, PRL 126, 162701 (2021)
Kaneko, PLB 822, 136681 (2021)

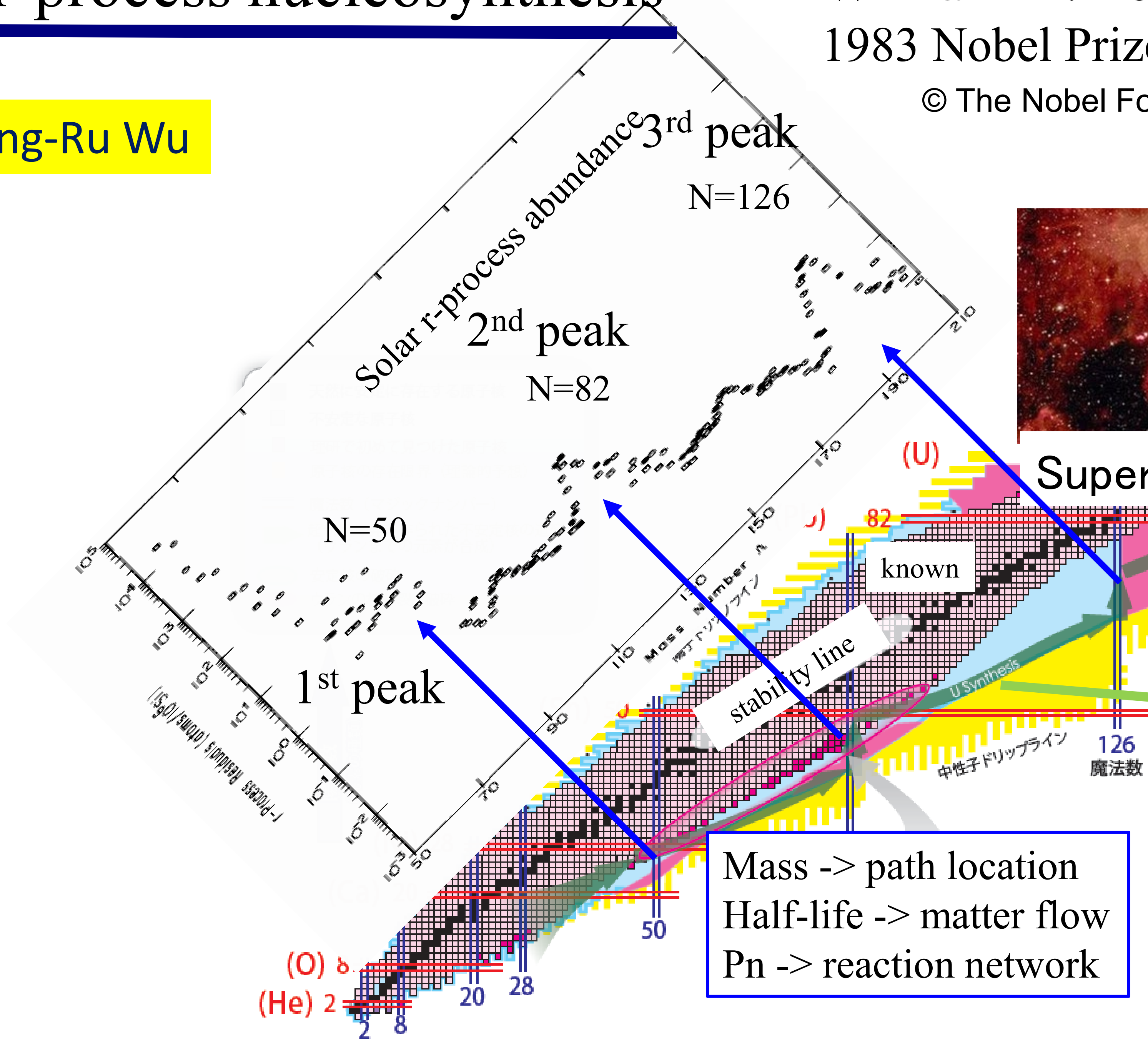


The r-process nucleosynthesis

Meng-Ru Wu

William A. Fowler
1983 Nobel Prize Physics
© The Nobel Foundation





Supernova? NS merger?

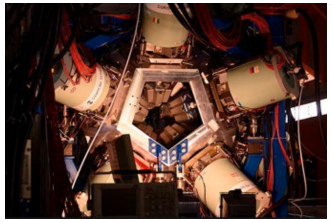
Mass -> path location
Half-life -> matter flow
Pn -> reaction network

r-process path
rapid neutron-capture
vs beta-decay

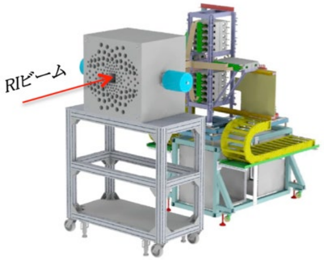
Supernova explosion?
NS merger?
Or both?

Decay properties of neutron-rich nuclei: T/2 and Pn

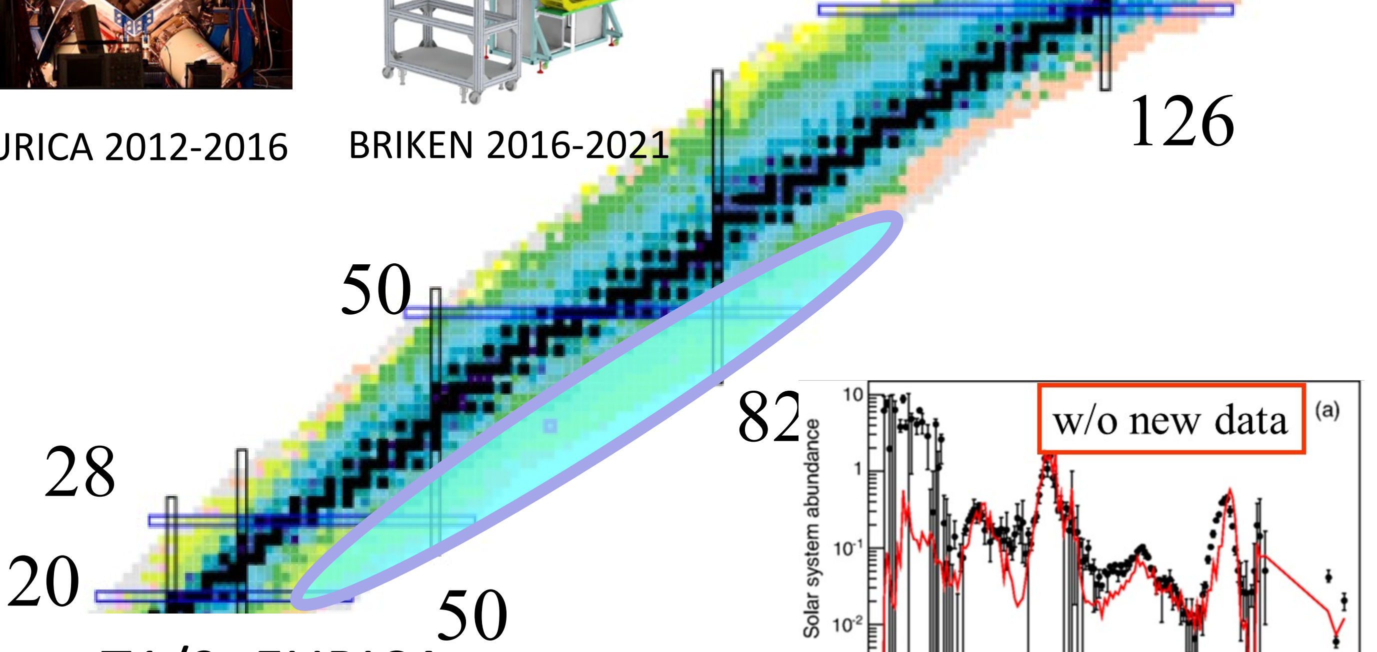
EURICA, BRIKEN Collaborations



EURICA 2012-2016

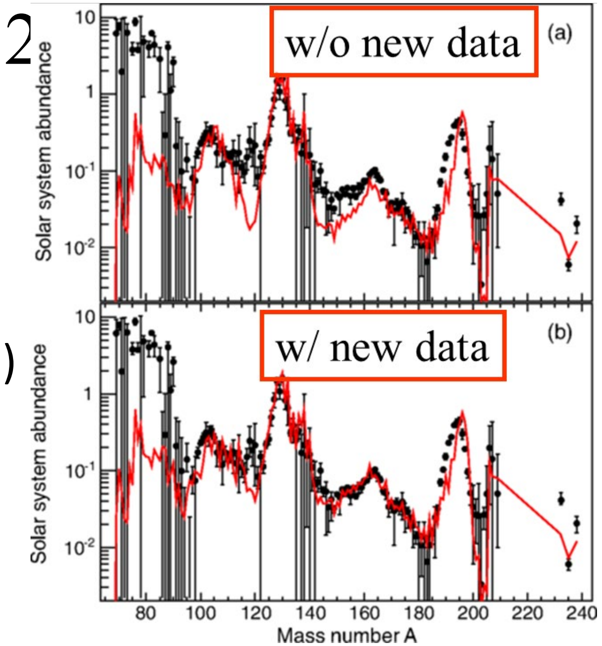


BRIKEN 2016-2021



T1/2: EURICA

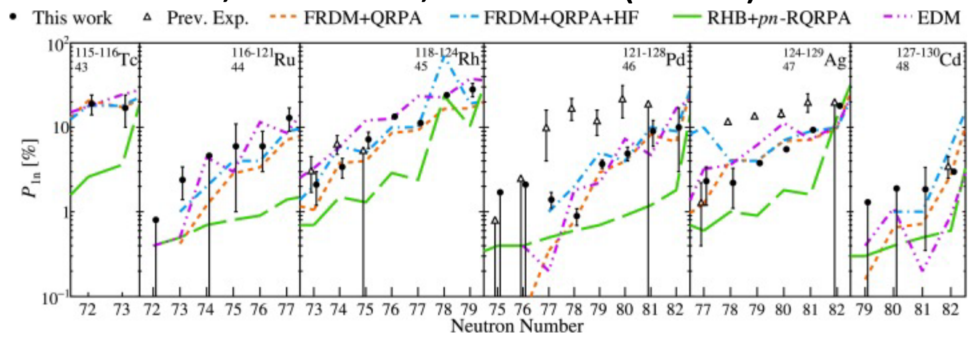
Nishimura, PRL 106, 052502 (2011)
Xu, PRL 113, 032505 (2014)
Lorusso, PRL 114, 192501 (2015)
Wu, PRL 118, 072701 (2017)
Wu, PRL 118, 072701 (2018)



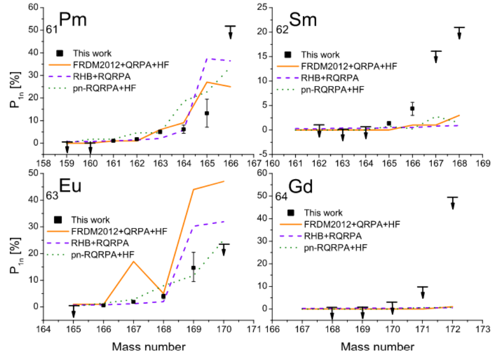
Pn: BRIKEN

Gd: Yokoyama, PRC 100, 031302(R) (2019)

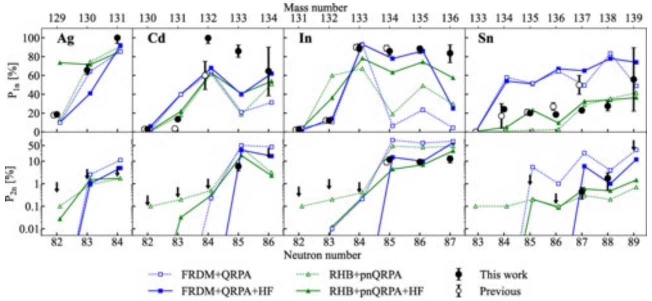
Tc-Rh: Hall, PLB 816, 136266 (2021)



Pm-Gd: Kiss, APJ 936, 107 (2022)

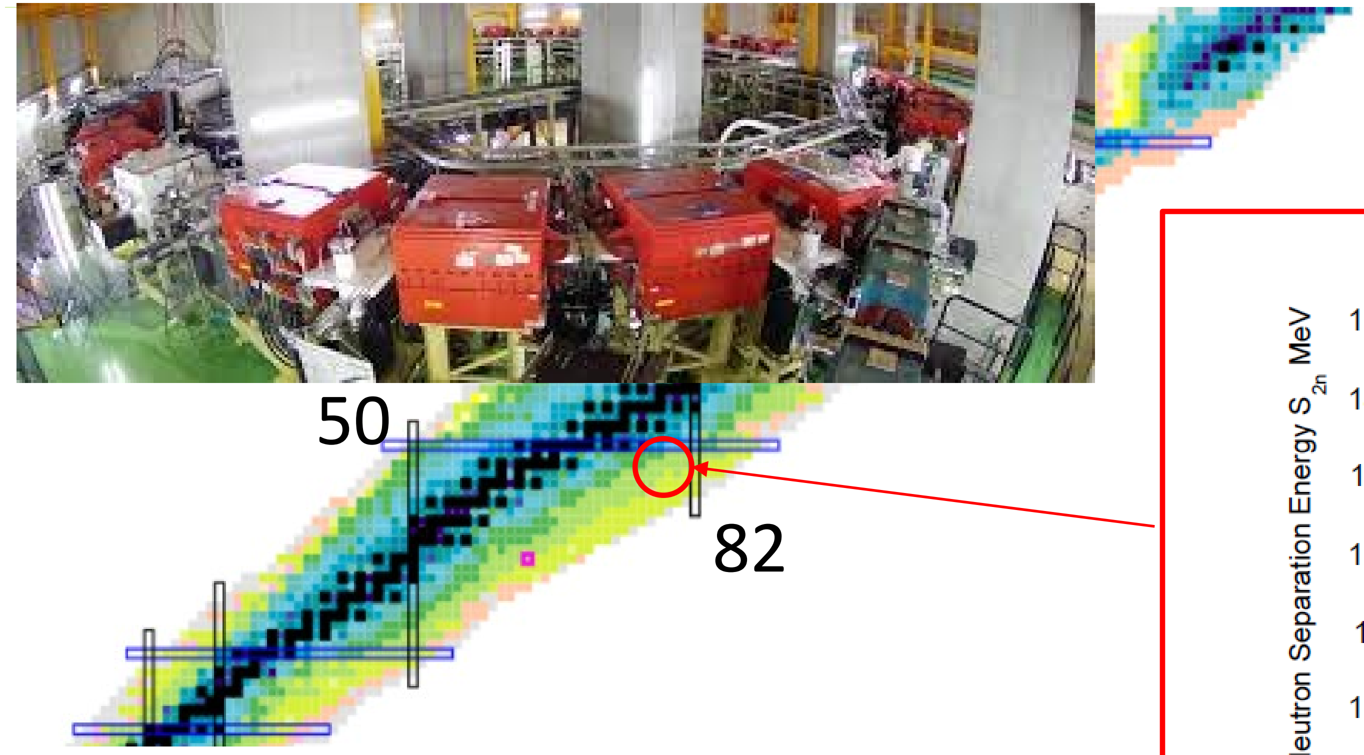


Ag-Sn: Phong, PRL 129, 172701 (2022)

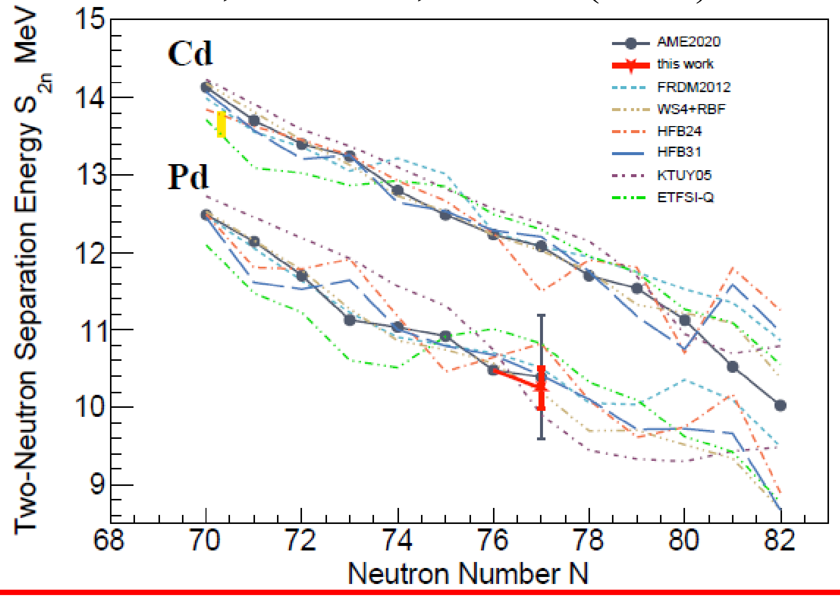


Recent mass measurements for the r-process path

First result with Rare-RI Ring at RIKEN!



Pd: Li, PRL 128, 152701(2022)

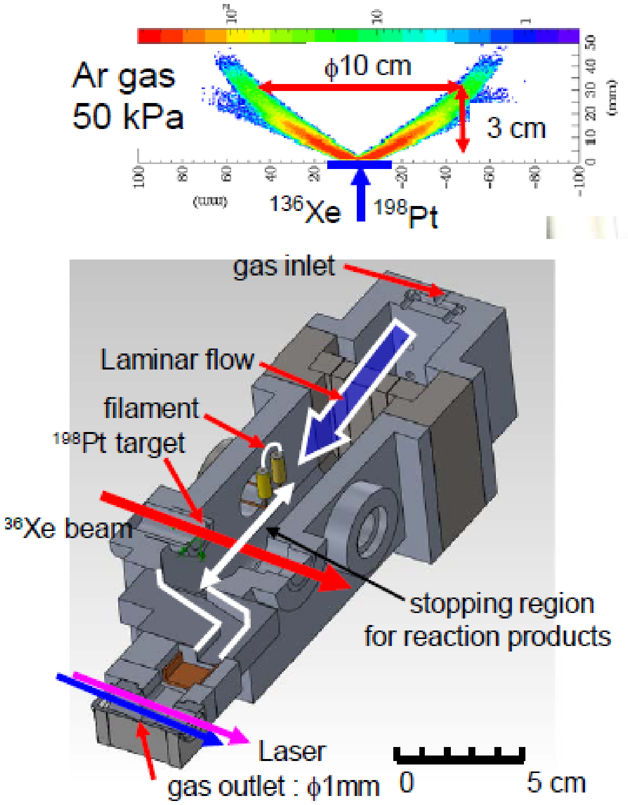


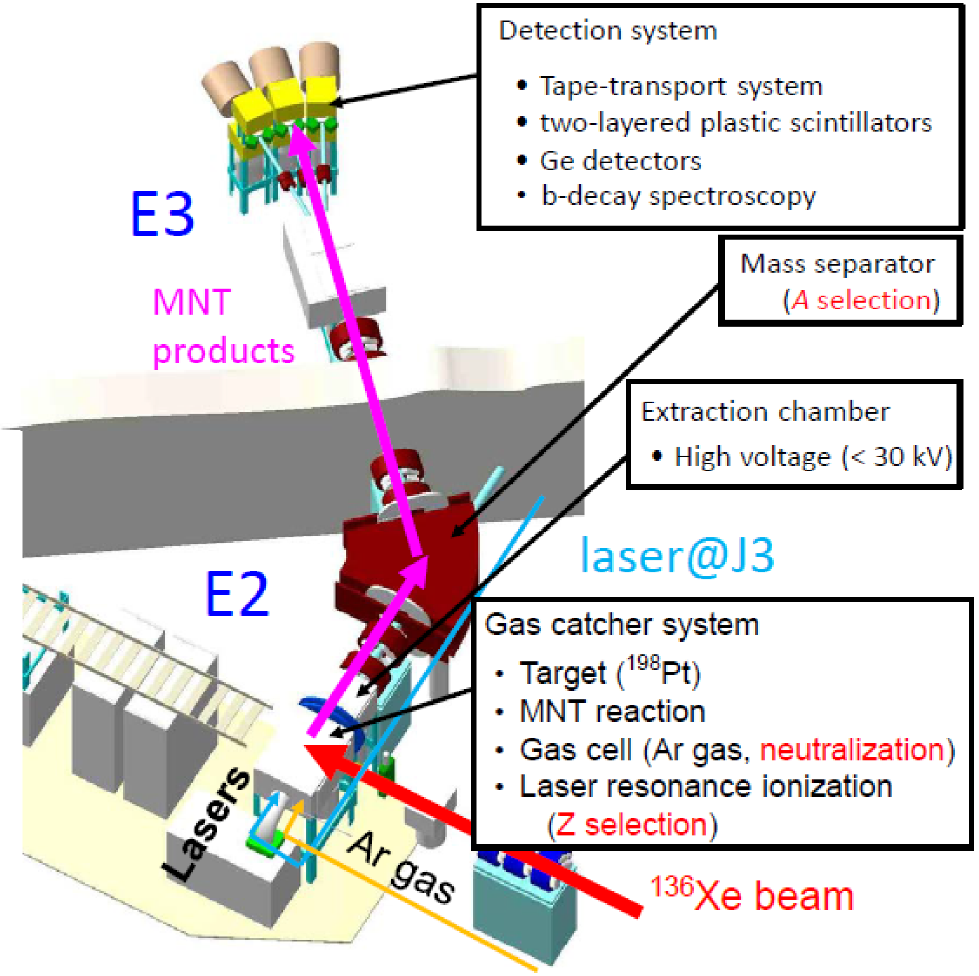
MR-TOF mass measurements are ongoing too!

KEK Isotope Separation System (KISS)

Identification of astrophysical site for 3rd peak on r-process

Lifetime measurement of N = 126 nuclei produced via deep inelastic scattering



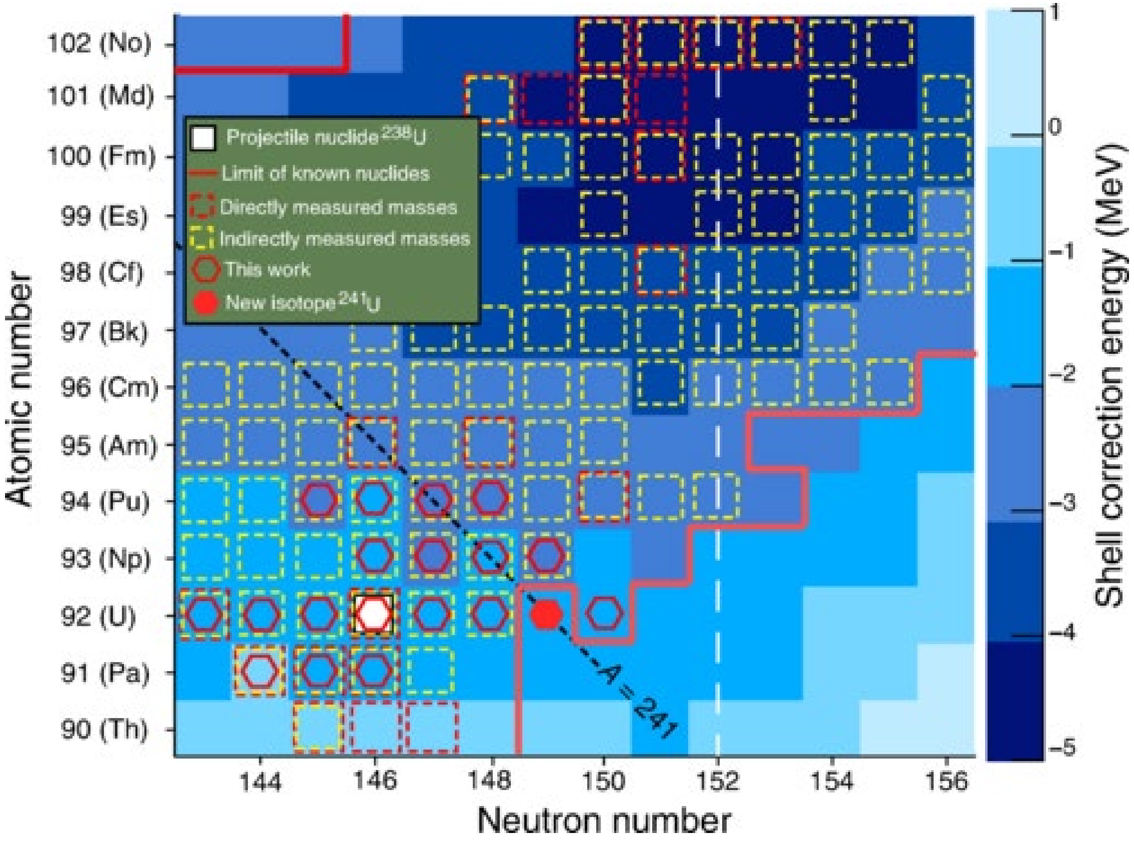


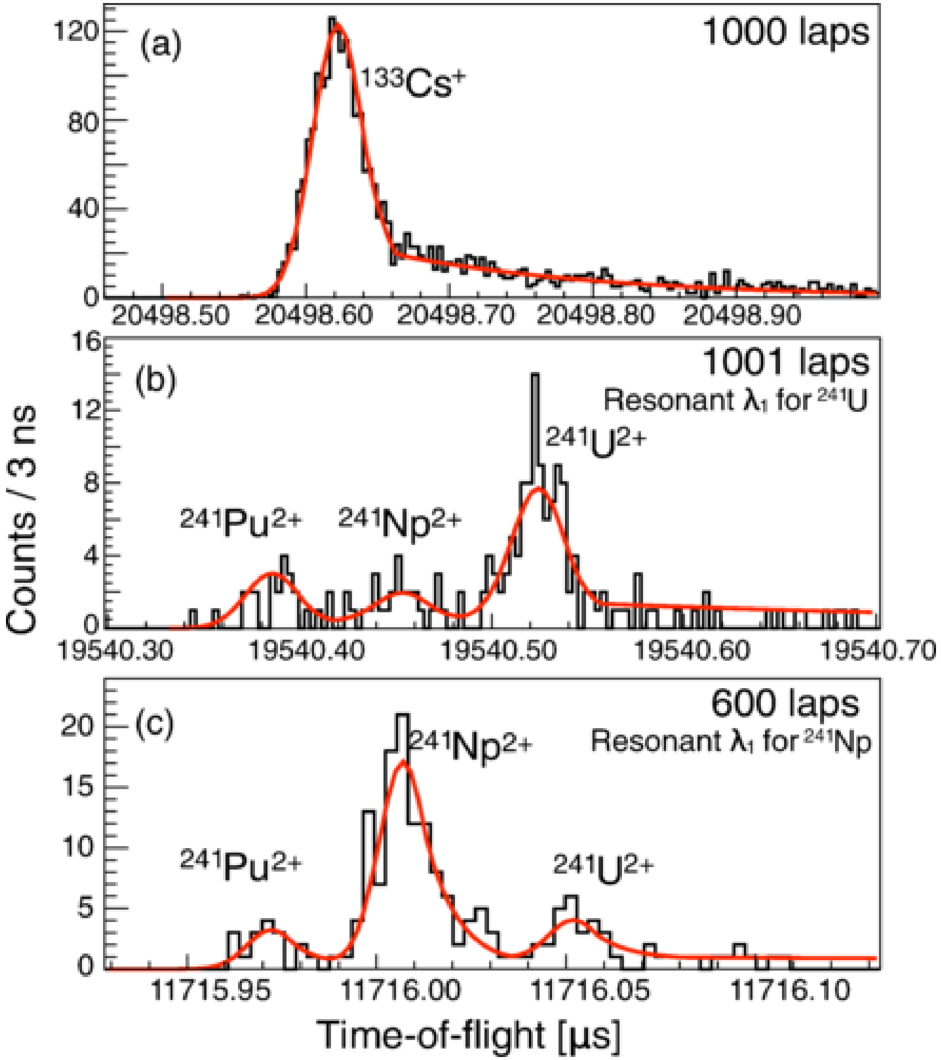
gas cell+ laser ionization + separator + detector

Discovery of New Isotope 241U and Systematic High-Precision Atomic Mass Measurements of Neutron-Rich Pa-Pu Nuclei Produced via Multinucleon Transfer Reactions

Niwase et al., PRL 130, 132502 (2023)

10.75 MeV/u U-238 beam +Pt-198 target



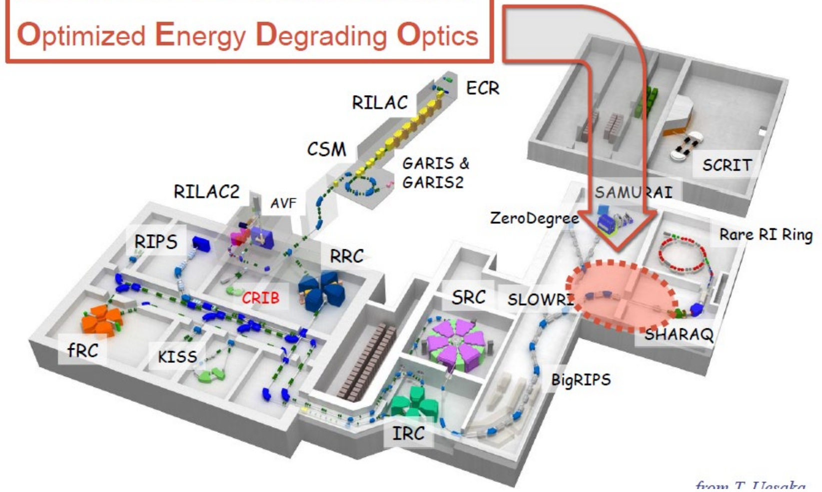


CNS-RIKEN: OEDO Project

Imai san

OEDO Beam-line

Optimized Energy Degrading Optics



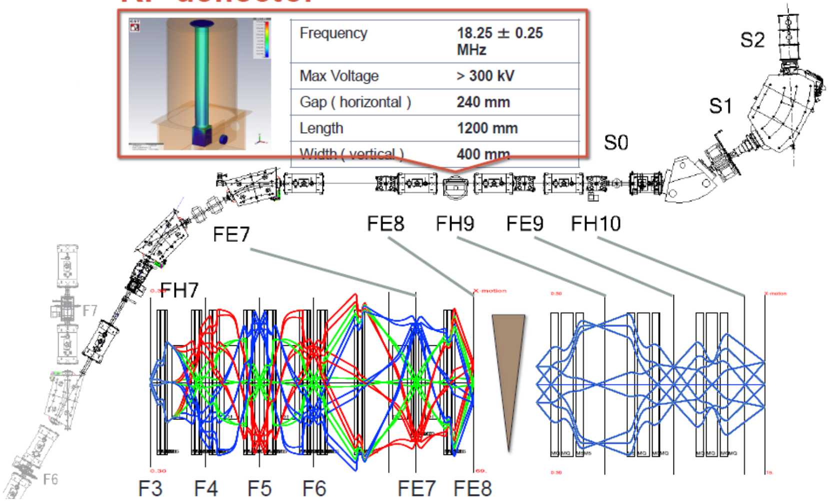
Energy-degraded radioactive isotope beams

- Nucleon transfer reactions (10A – 50A MeV)
- Pair transfer / Cluster transfer (10A – 20A MeV)
- Deep inelastic collisions (incomplete fusion) (5A – 30A MeV)
- Fusion reaction (~ 5A MeV)
- Coulomb excitation reactions for low-energy gamma rays (~ 50A MeV)

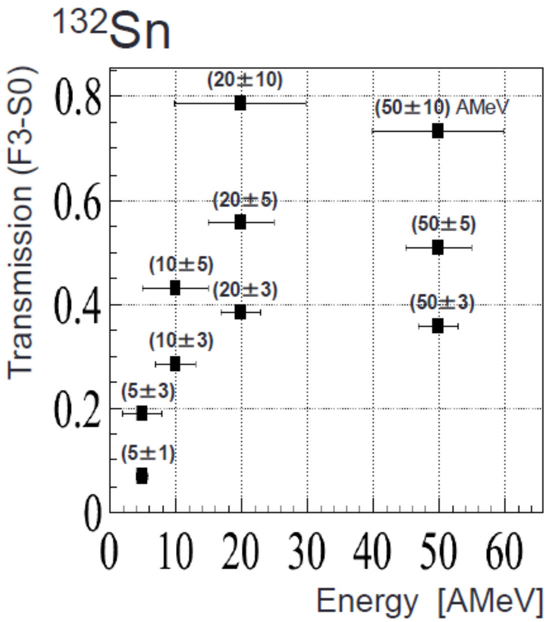
Magnet configuration and optical condition

RF deflector

Frequency	18.25 ± 0.25 MHz
Max Voltage	> 300 kV
Gap (horizontal)	240 mm
Length	1200 mm
Width (vertical)	400 mm



Transmission and intensity



Transmission (F3 - S0)
×
Intensity @ F3
||
Intensity @ OEDO (S0)

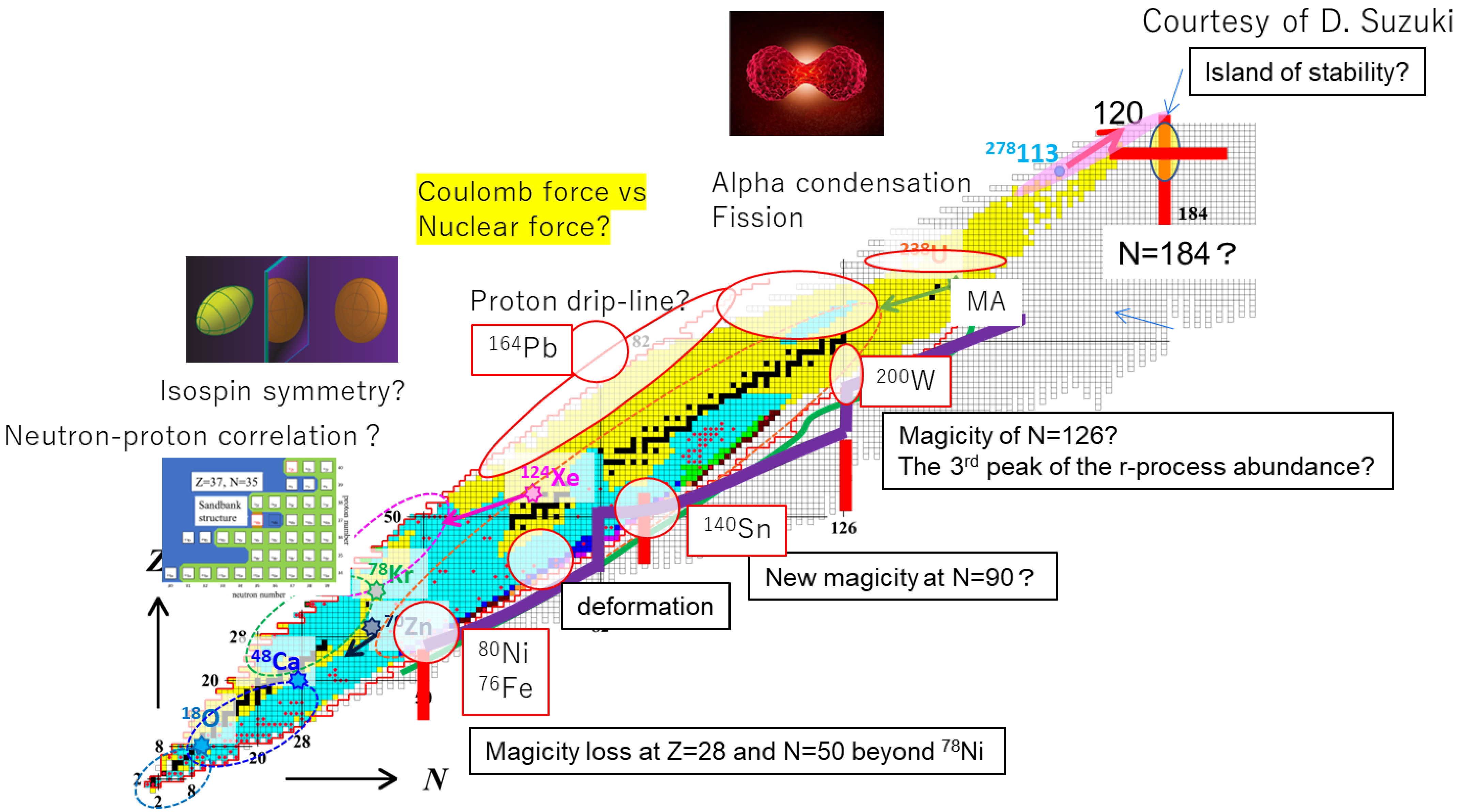
Typical example of ^{132}Sn

based on actual intensity in experiment by using 345 AMeV 30pnA U primary beam (Apr. 2015)

Intensity @ F3 (Apr. 2015)	2.5×10^6 [pps]
50 ± 5 AMeV @ S0	1.3×10^6
20 ± 3 AMeV @ S0	9.5×10^5
10 ± 3 AMeV @ S0	7.5×10^5
5 ± 1 AMeV @ S0	1.7×10^5

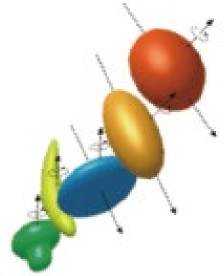
cf. 1.4×10^4 pps ^{132}Sn in CARIBU proposal

Further challenging towards more neutron-rich and heavy isotopes

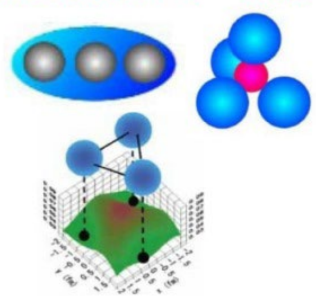


High Excitation Energy and High Spin States

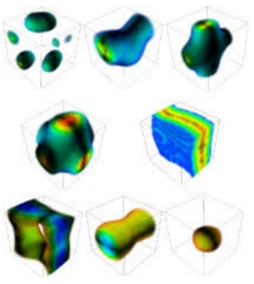
Exotic Shape

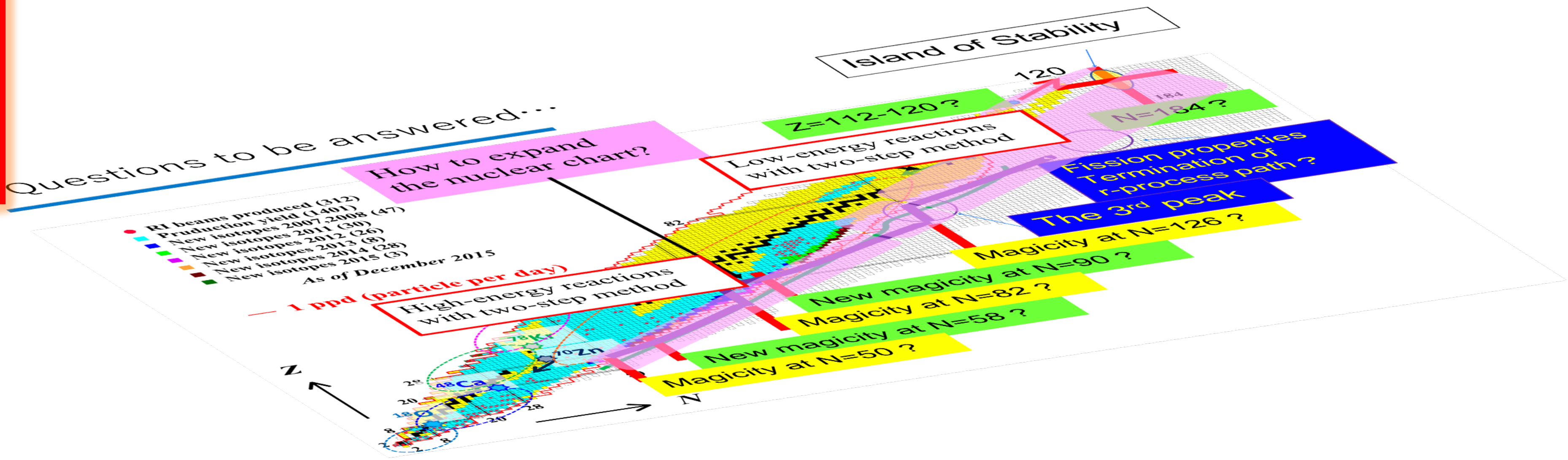


Condensation



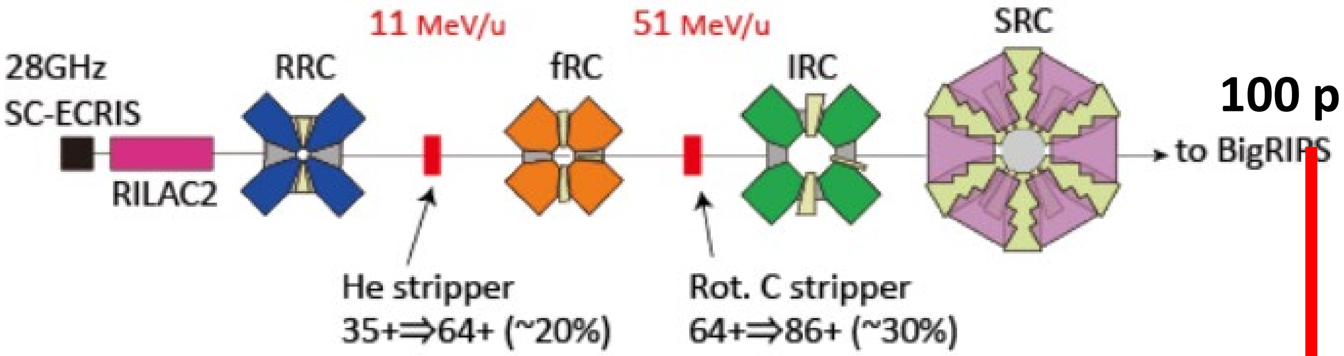
Structure at finite T





RIBF upgrade plan to have more intense U beam

Present Acceleration Scheme



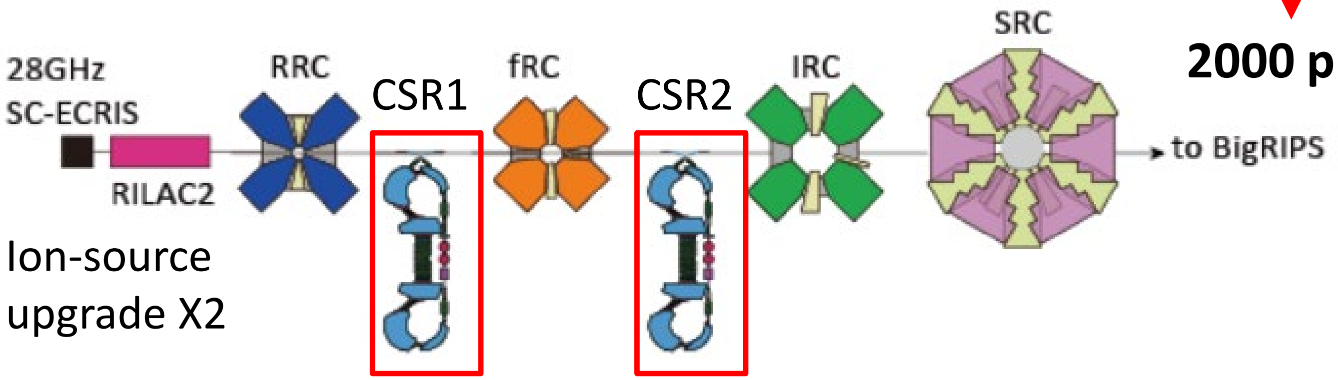
100 pnA

Large loss at the strippers : transmission efficiency is about 6%

x20

Upgrade plan

2000 pnA

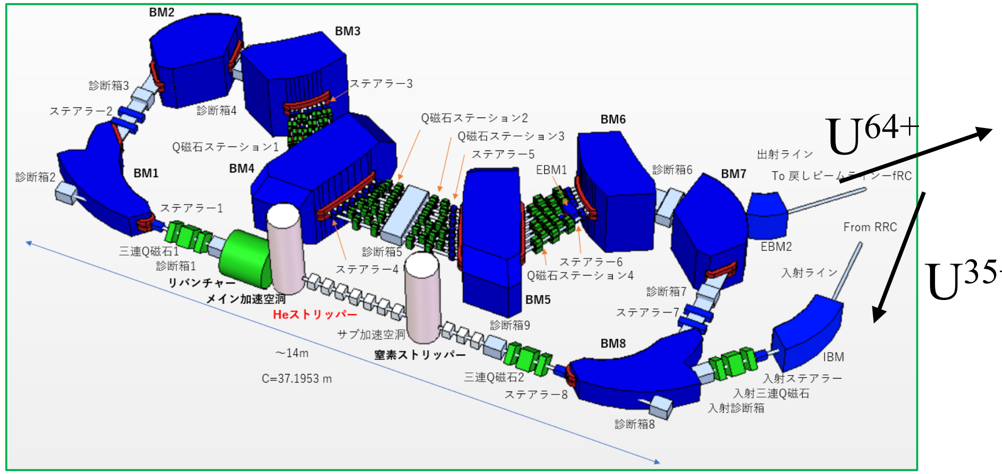


Ion-source
upgrade X2

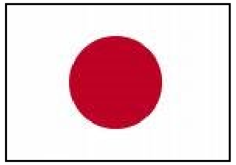
Charge Stripper Rings : beam recycling technology
to increase transmission efficiency by a factor of 10

Requesting the construction budget now

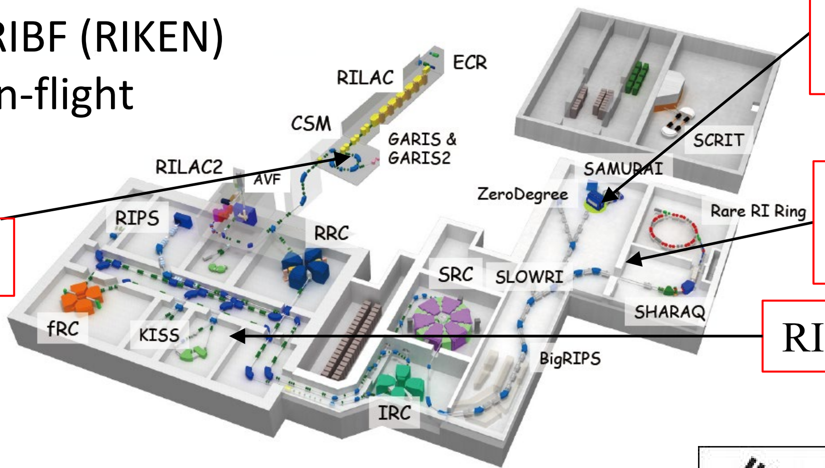
CSR1



Large-scale facilities in operation and under construction in North-East Asia



RIBF (RIKEN)
In-flight



Reaction study at ~300MeV/u
EOS w/ RI beams (high density ~$2\rho_0$)

E-degraded RI beams at ~20 MeV/u or less
Low-E reactions w/ RI beams

RI production at 10MeV/u w/ stable HI

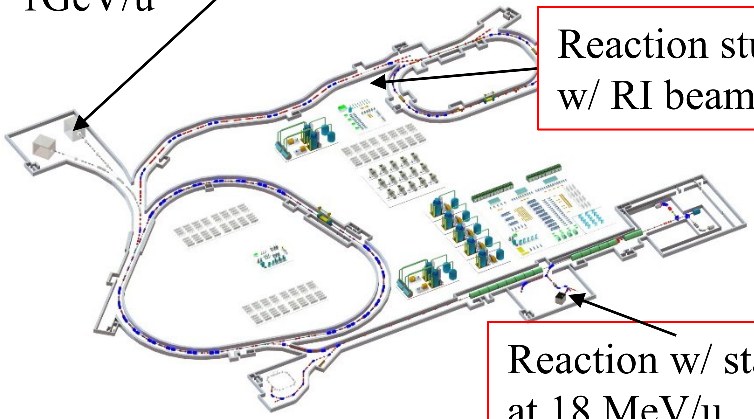
119th, 120th

10 MeV/u

HIAF (in-flight)

EOS w/ stable beams
HI collisions (high density ~$5\rho_0$)

1GeV/u



Reaction study at ~1 GeV/u
w/ RI beams

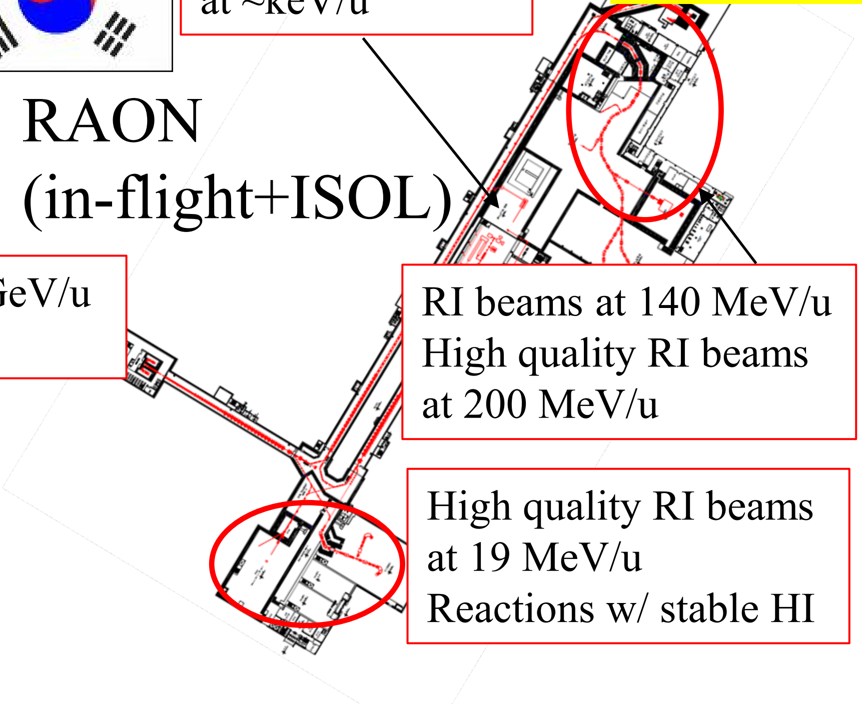
Reaction w/ stable HI
at 18 MeV/u

Youjin Yuan

Material sciences
at ~keV/u

Seung-Woo Hong

RAON (in-flight+ISOL)



RI beams at 140 MeV/u
High quality RI beams
at 200 MeV/u

High quality RI beams
at 19 MeV/u
Reactions w/ stable HI

Summary and Future Perspectives

RIBF is one of the world leading facilities in low energy nuclear physics

RIBF is maximizing discovery potentials and research opportunities
in low-energy nuclear physics.
RIBF is producing many of data for “neutron-rich” nuclei
and finding many of discoveries
in shell evolution, neutron-neutron correlation, EOS and the r-process path.

The RIBF intensity upgrade plan is at the top priority of Nishina Center
to further strengthen the RIBF facility.
The proposal has been submitted to MEXT in collaboration with
CNS, KEK and RCNP.

Welcome to join the nuclear physics programs at RIBF.
More collaboration works are being encouraged for nuclear physics.