International Symposium on Nuclear Science
Sofia, Bulgaria, Sept. 9 – 13, 2024

Study of exotic nuclei at RIKEN

Hiroyoshi Sakurai
RIKEN Nishina Center for Accelerator-Based Science

H. Sakurai
"First Physics Results after the RIKEN Upgrade",
VI Balkan School on Nuclear Physics, Trojan, Bulgaria, September 2008

RIBF Facility Layout

Old facility

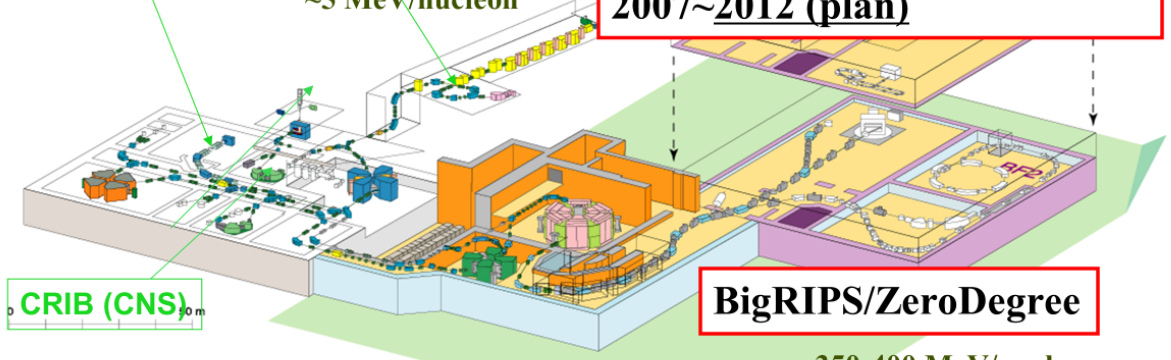
RIPS

~100 MeV/nucleon

GARIS

~5 MeV/nucleon

Phase-II
Further construction for experimental instrumentations
2007~2012 (plan)



New facility

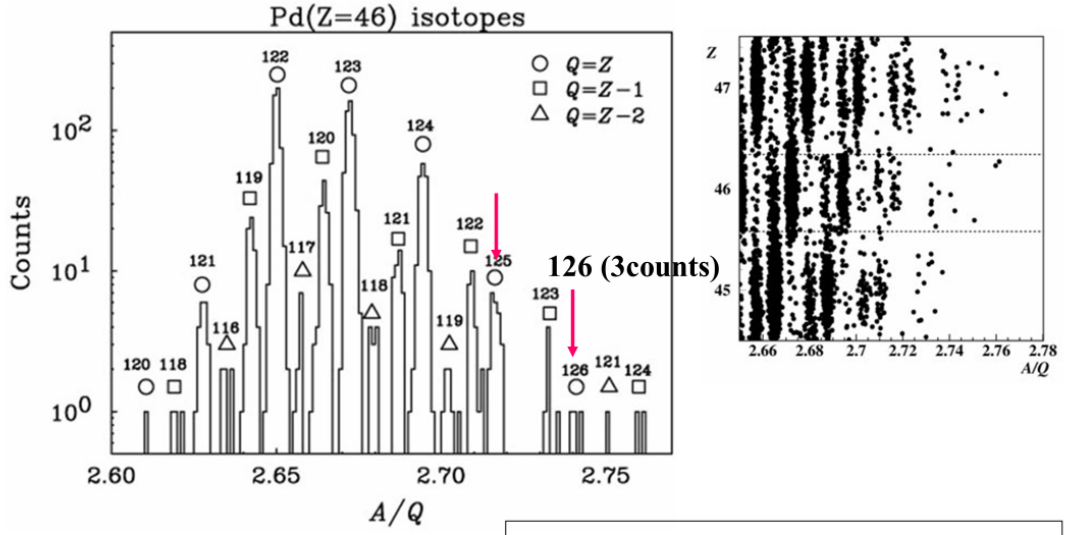
350 MeV/nucleon
up to U

1st beam in 2006

Phase–I 2007-
Accelerators + BigRIPS/ZeroDegree

Identification of new isotopes ^{125,126}Pd

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

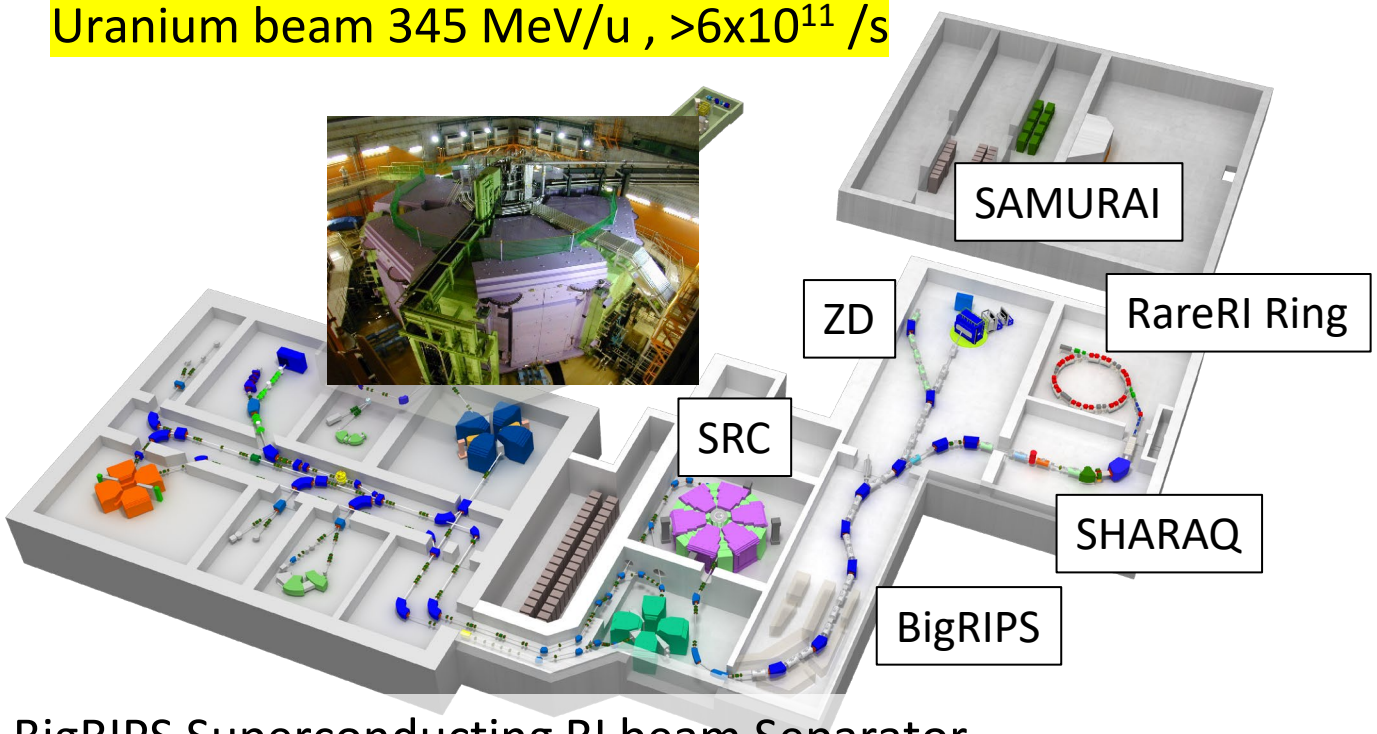


A/Q resolution(r.m.s): 0.041% at Z=46
Bρ resolution (r.m.s): 0.02%

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

Radioactive-isotope (RI) Beam Factory (RIBF)

SRC: Superconducting Ring Cyclotron
World's First and Strongest K2600MeV
Uranium beam 345 MeV/u , >6x10^{11} /s



BigRIPS Superconducting RI beam Separator
In-flight separator
World's Largest Acceptance
High magnetic rigidity 9 Tm
~250 MeV/u

Three spectrometers
for reaction studies with fast RI beams

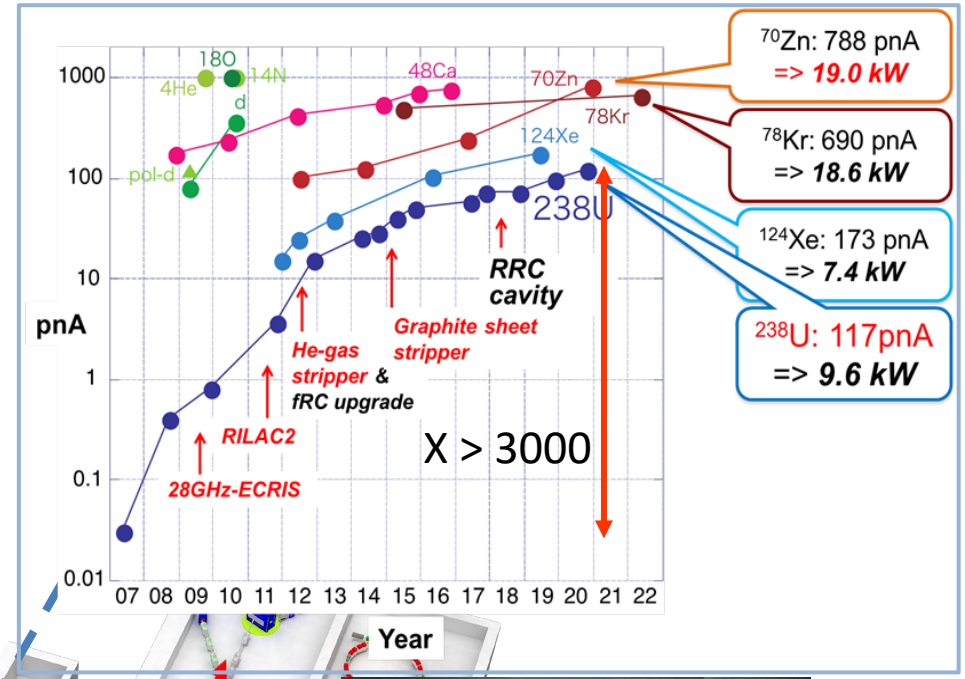
ZeroDegree

SAMURAI

SHARAQ + OEDO (univ. of Tokyo, CNS)

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

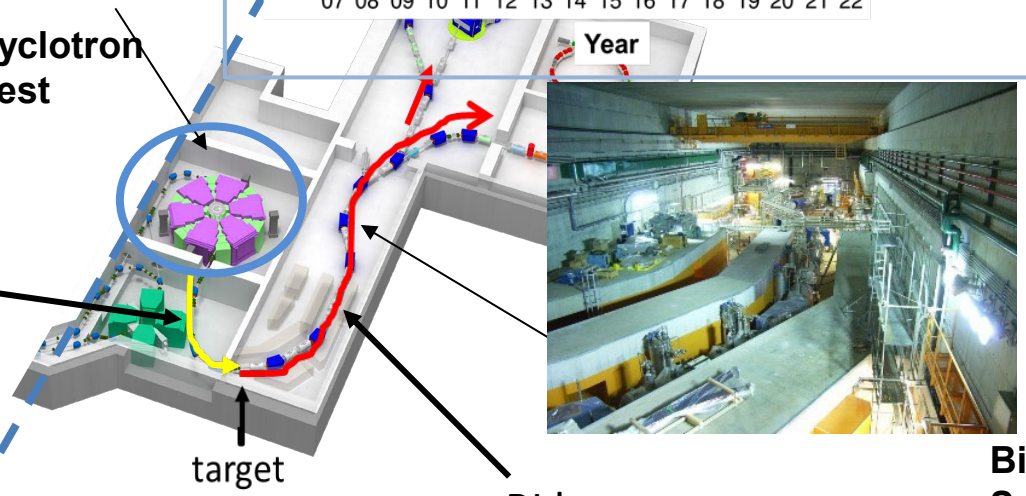
Accelerators and In-flight Separator at RI Beam Factory



Beam Intensity of SRC as a function of year

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

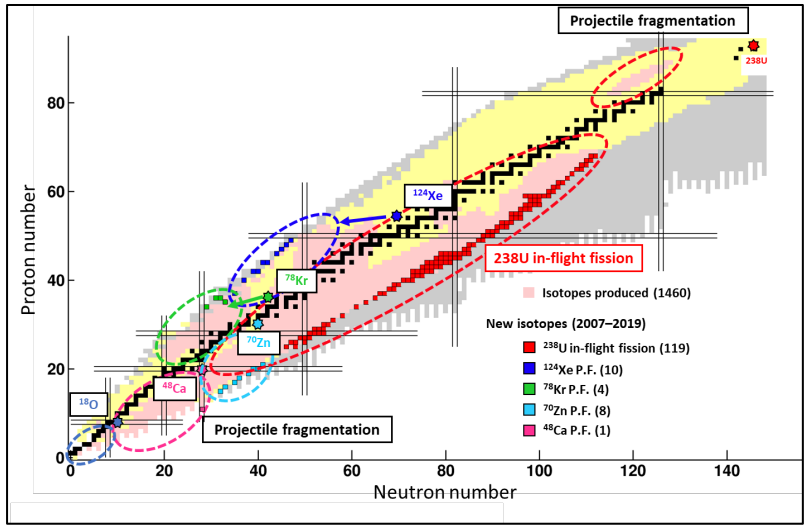
primary beams
at 345 MeV/u



RI beams
at ~250 MeV/u

New facility (2006-)

>170 new isotopes created since 2007

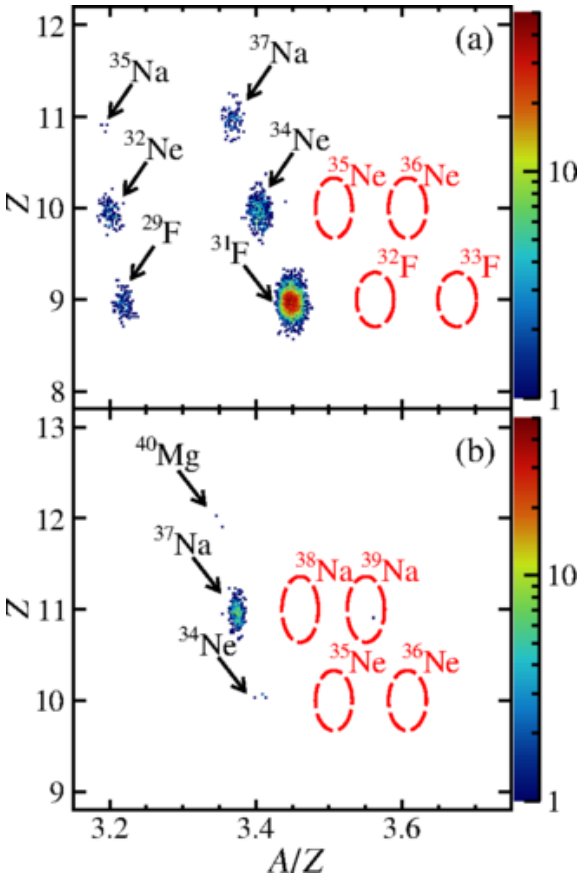


BigRIPS:
Superconducting RI beam Separator
In-flight separator
World's Largest Acceptance
High magnetic rigidity 9 Tm

Recent Discovery of New N-rich Isotopes at RIBF

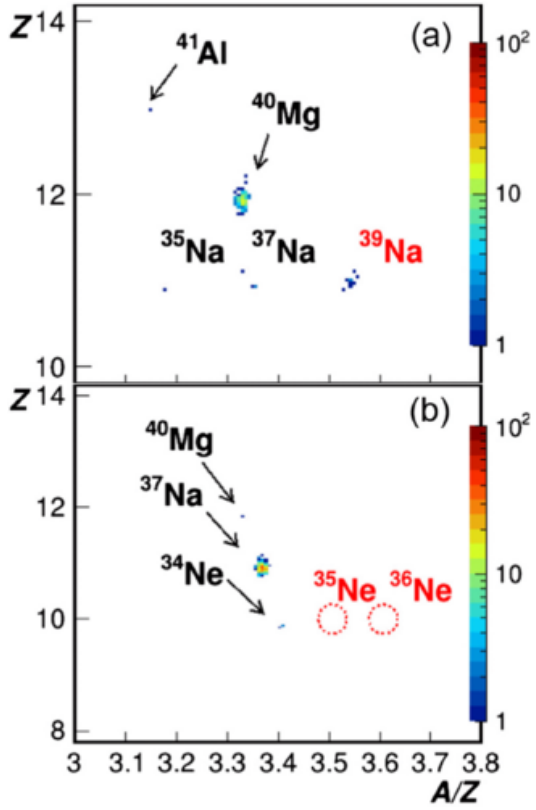
Location of neutron drip line in F and Ne

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

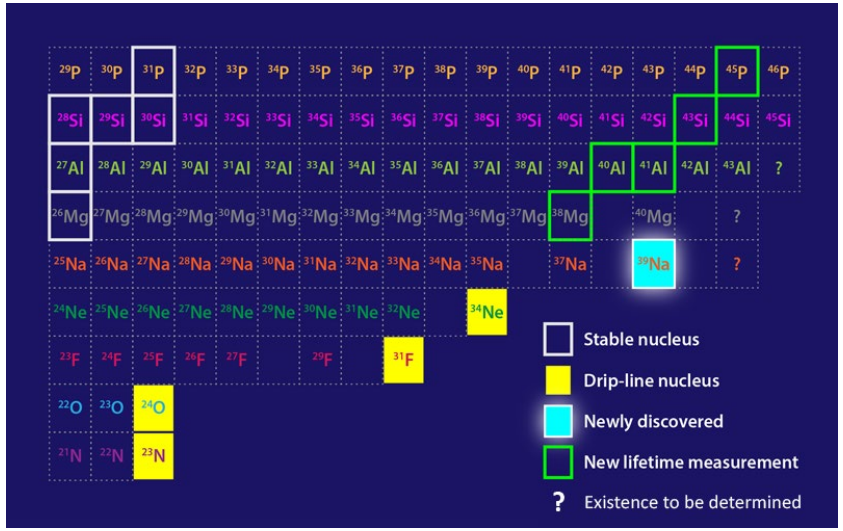


Discovery of ^{39}Na

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



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

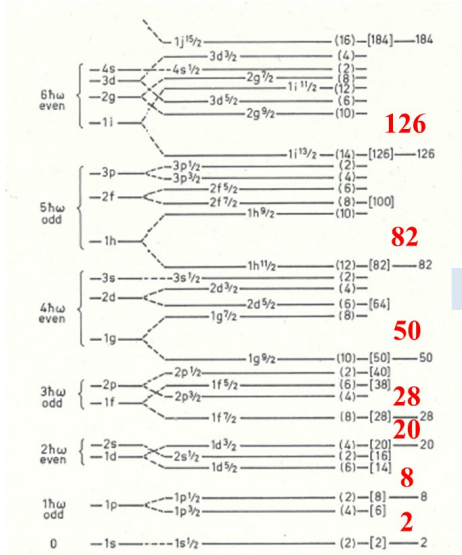


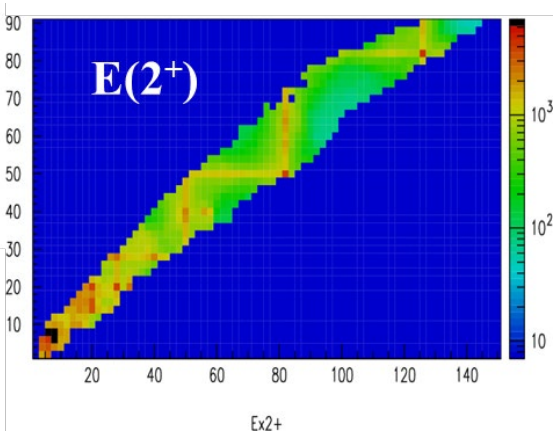
A New Isotope of Sodium - Periodic Table of Videos

Prof. Martyn Poliakoff, University of Nottingham in UK

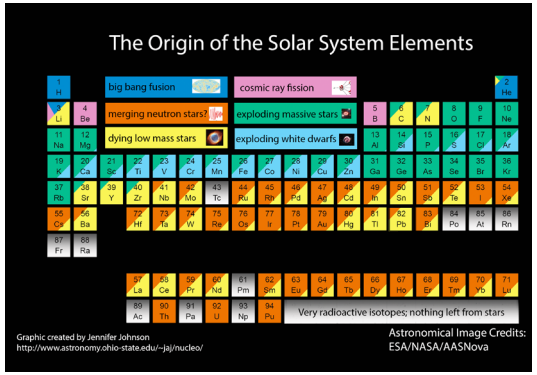
Why neutron-rich nuclei?: Large isospin-asymmetry

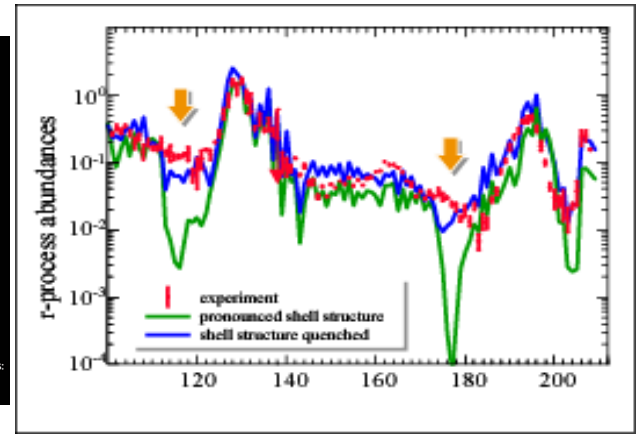
Shell-evolution: magicity loss and new magicity





r-process path : nucleo-synthesis up to U



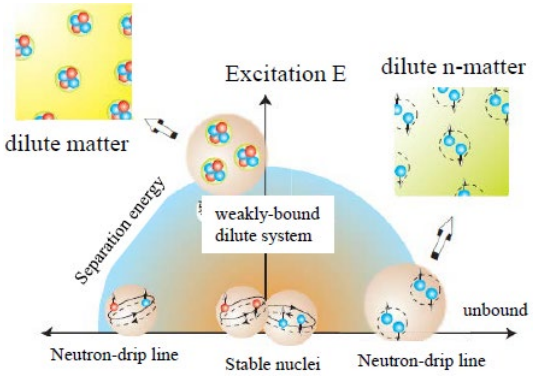


Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

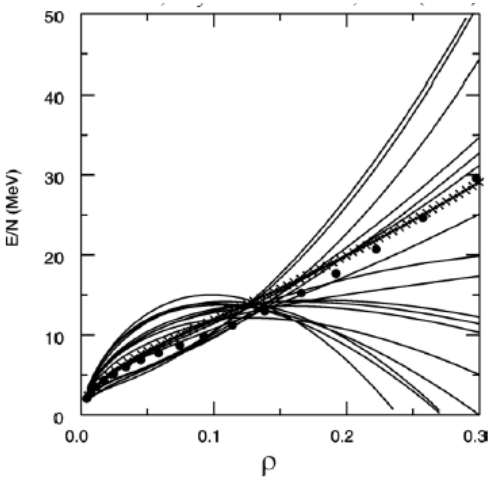
Neutron-neutron correlation in the vicinity of the dripline

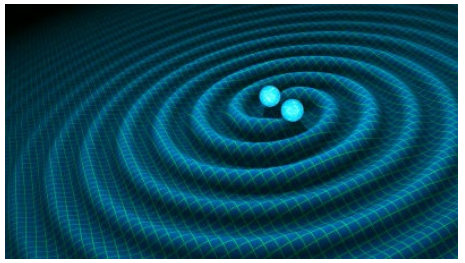
^{11}Li
(two neutron halo)

^{208}Pb



Equation-of-state in asymmetric nuclear matter
SN explosion, neutron-star, gravitational wave



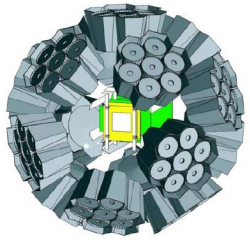


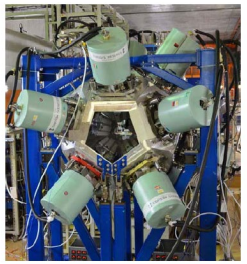
gravitation wave
from neutron-star mergers
Space.com

Large-Size International Collaborations

EURICA (2011-2016):

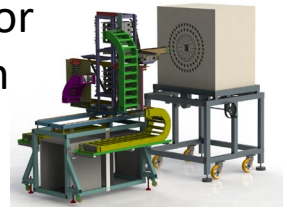
EUroball-RIKEN Cluster Array





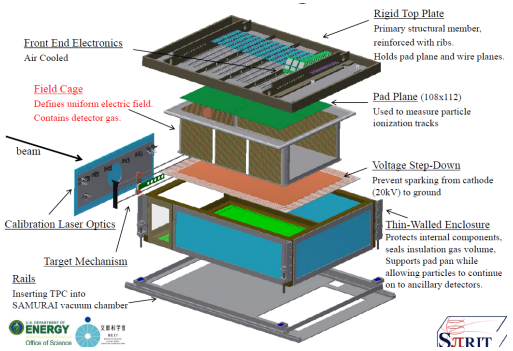
BRIKEN(2017-2021):

He-3 detector array for beta-delayed neutron



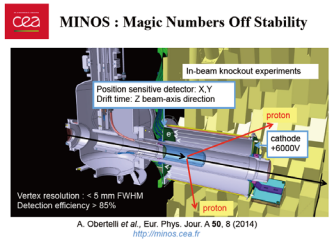
SpiRIT TPC (2015-):

heavy-ion collision program for EOS



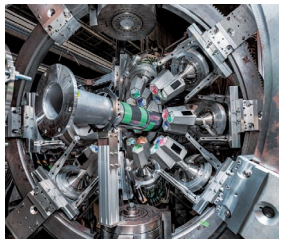
SEASTAR (2014-2017):

thick liq. H_2 +TPC+NaI for in-beam gamma spectroscopy



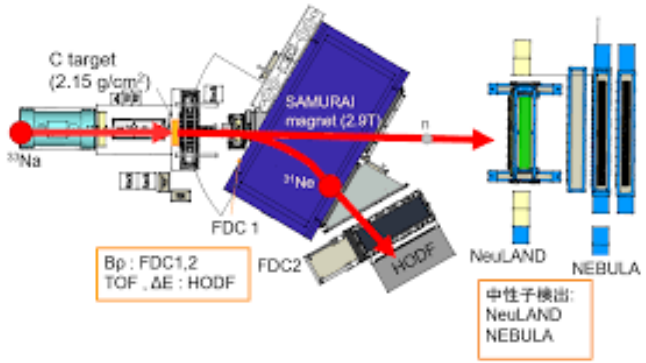
HiCARI (2019-2021):

Tracking Ge detectors for in-beam gamma spectroscopy



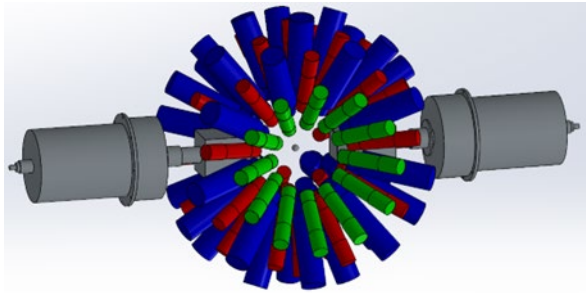
SAMURAI (2012-):

neutron detectors + CsI+… for neutron correlation



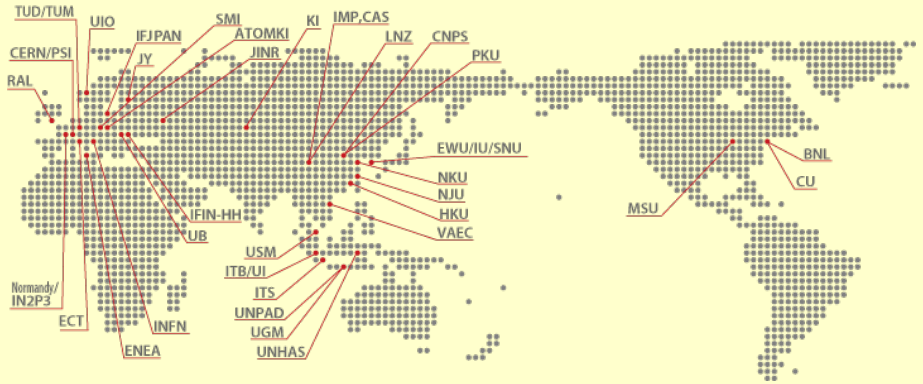
IDATEN (2021-):

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



MoUs with

48 institutions and universities in 20 countries

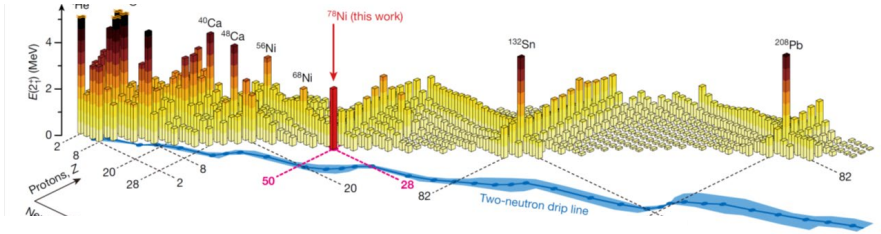


Very selected highlights in 2007-2022

Shell-evolution: magicity loss and new magicity

New magicity at N=34 (Nature 2013)

Double magicity of Ni-78 (Nature 2019)

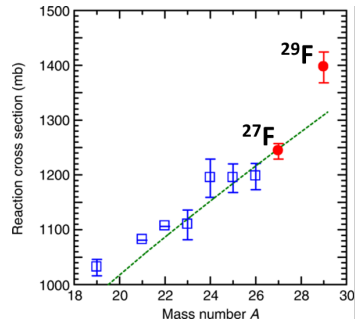


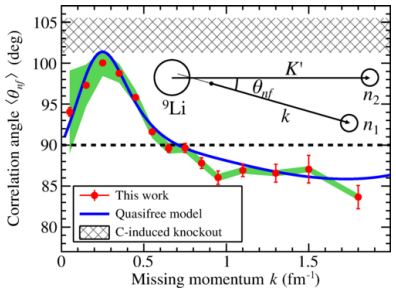
Shell evolution in the Cu isotopes
(Nature Physics 2019)

Ichikawa on 11th

Neutron-neutron correlation in the vicinity of the dripline

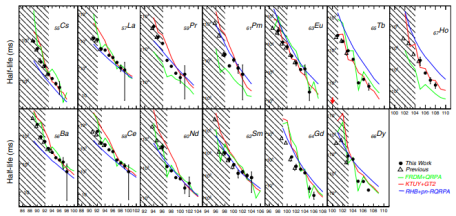
Two-neutron halo F-29 (PRL 2020)
Surface localization of dineutron in Li-11 (PRL 2020)
Tetra-neutron system
(PRL 2016, Nature 2022)





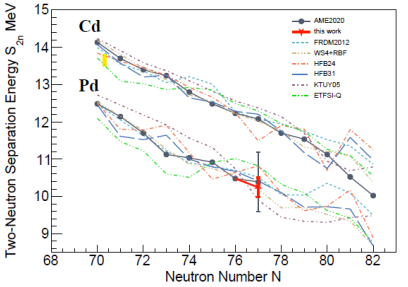
r-process path : nucleo-synthesis up to U

T1/2



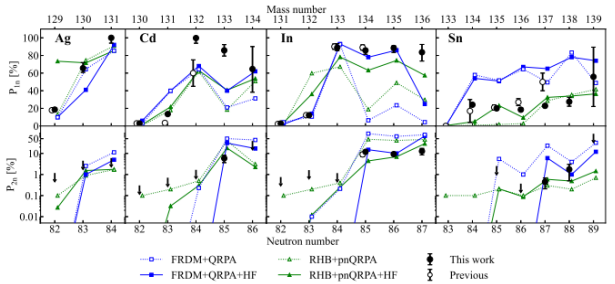
Wu, PRL 118, 072701 (2018)

Mass



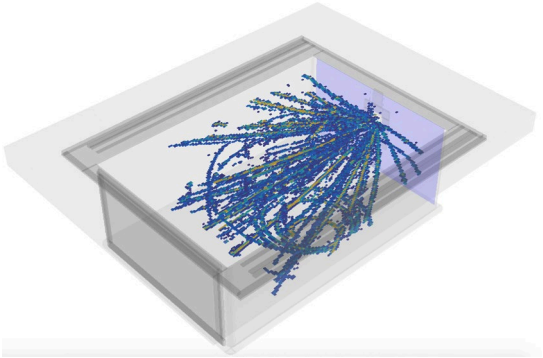
Li, PRL 128, 152701(2022)

Pn

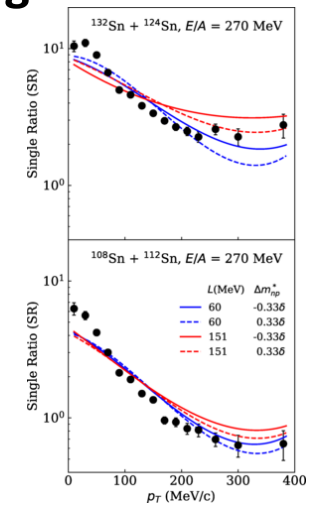


Phong,
PRL 129, 172701 (2022)

Equation-of-State in asymmetric nuclear matter
SN explosion, neutron-star, gravitational wave

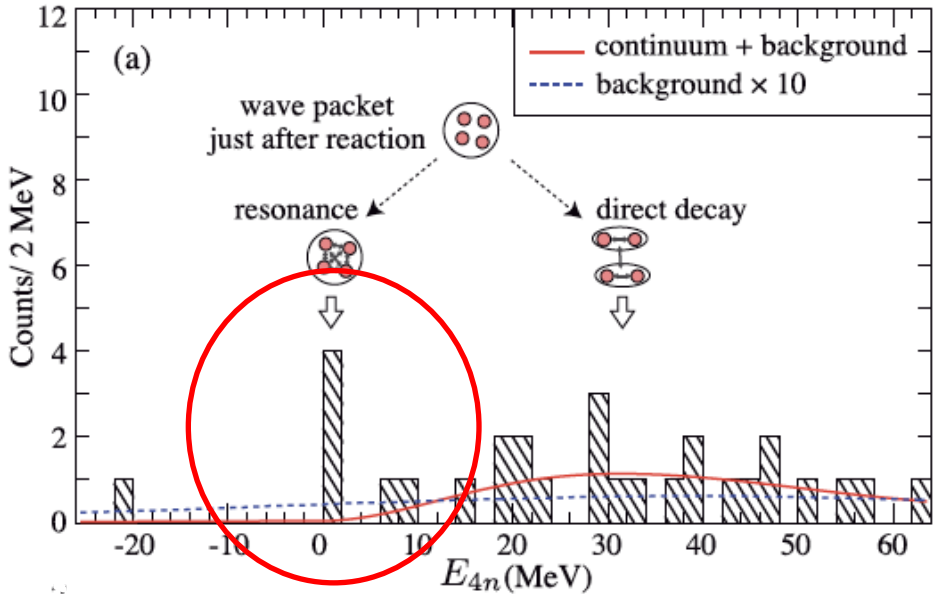


Estee, PRL 126, 162701 (2021)



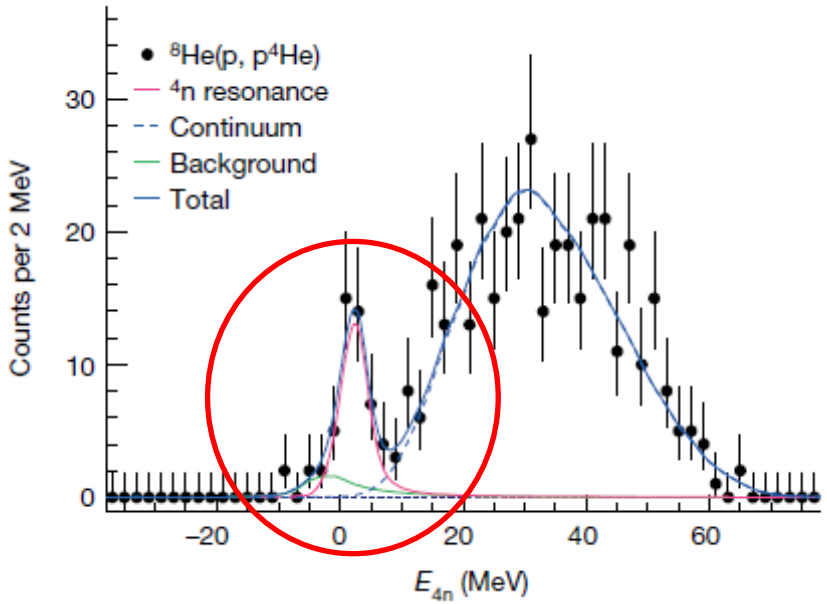
A “nucleus” with Atomic-Number Z=0: Observation of Tetra-neutron system

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



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

^{8}He(p,pα) ^{4}n at SAMURAI



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

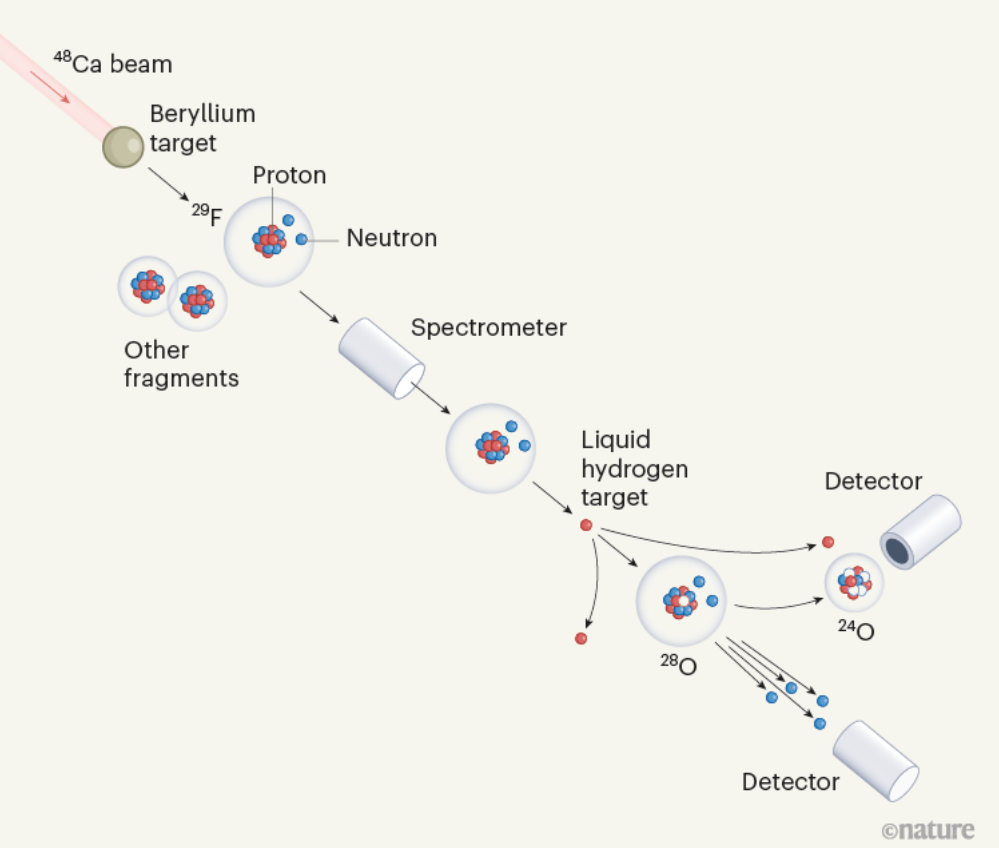
T=3/2 3NF ?
EOS in asymmetric nuclear matter?
Other reactions such as ^{6}He(p,3p) ^{4}n ?

First observation of ^{28}O

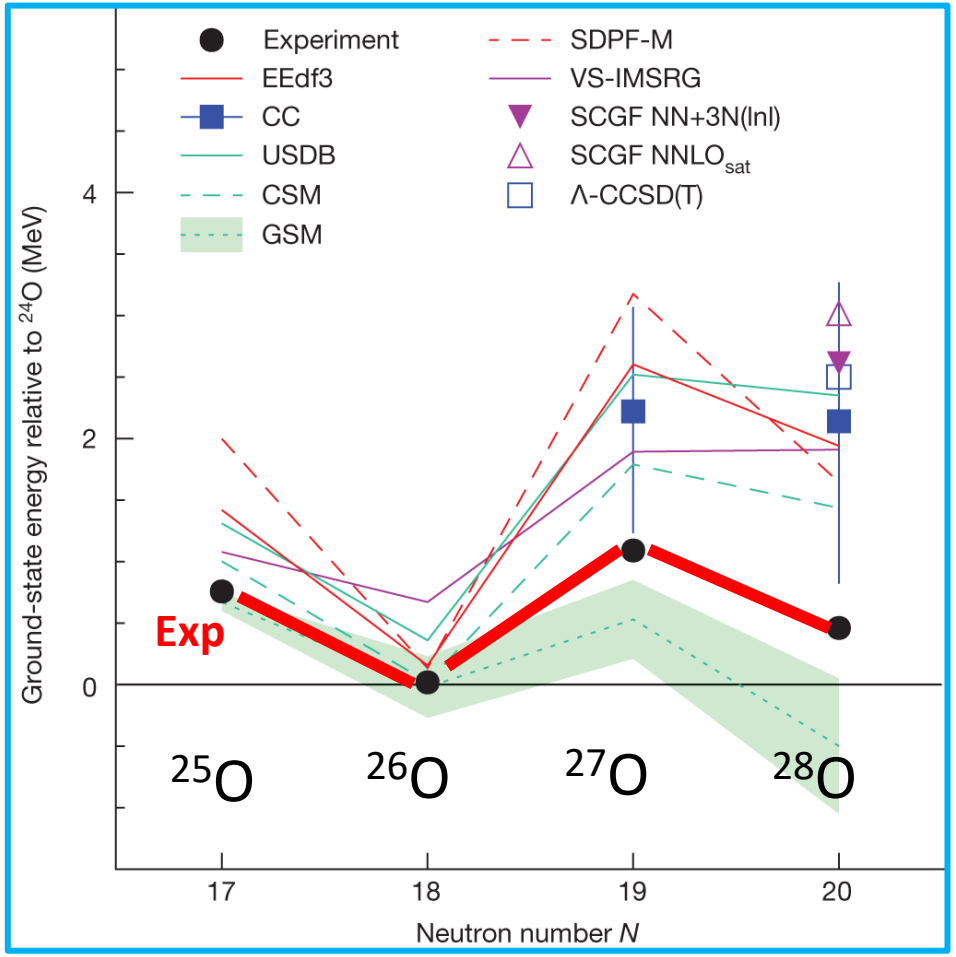
Kondo et al., Nature 620, 965-970 (2023)

SAMURAI Collaboration

Rituparna Kanungo,
Nature, NEWS AND VIEWS, 30 August 2023



Ground-state energy relative to ^{24}O

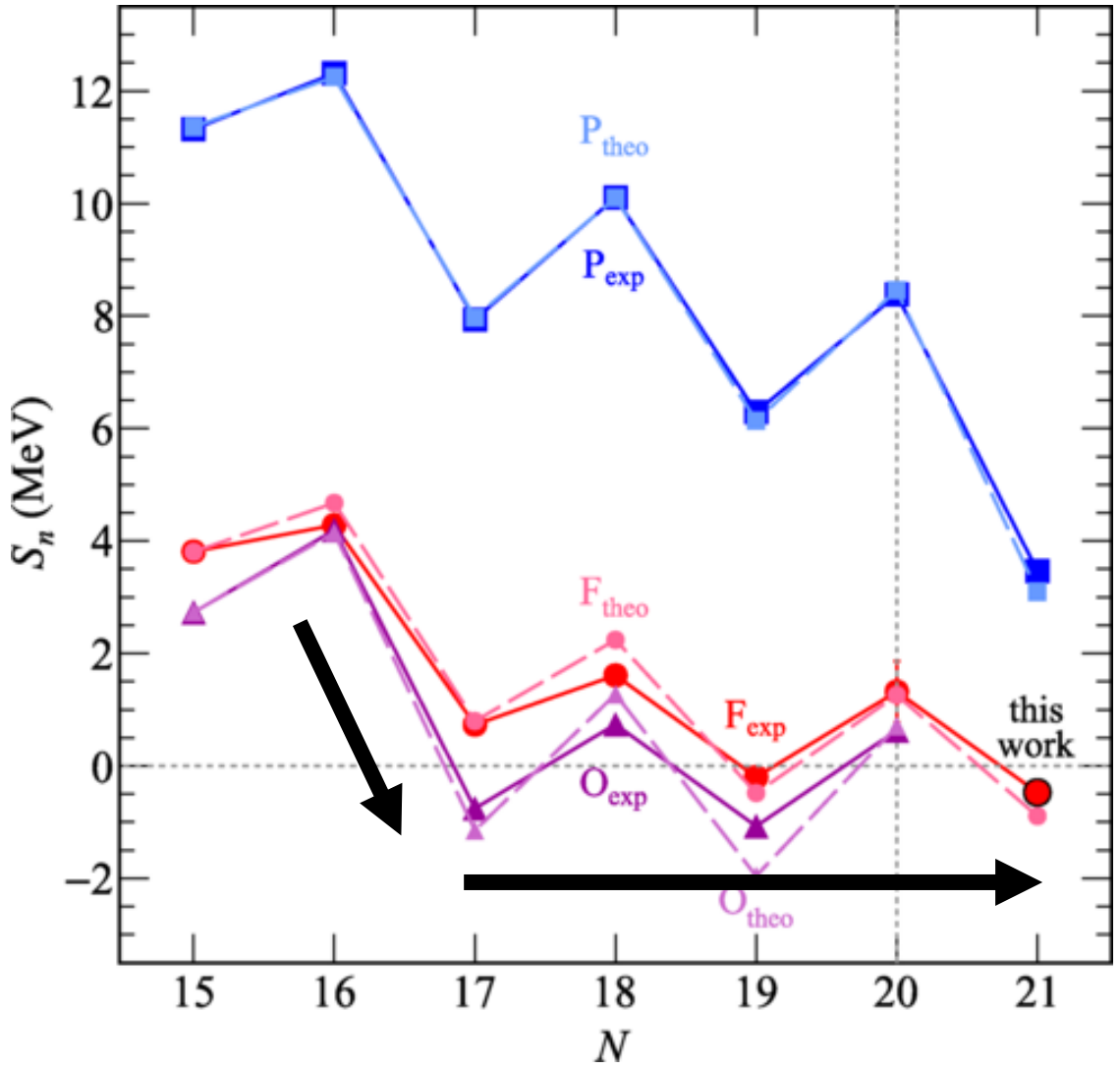


No stability enhancement at N=20

^{28}O is not double-magic

Magicity versus Superfluidity around ^{28}O viewed from the Study of ^{30}F

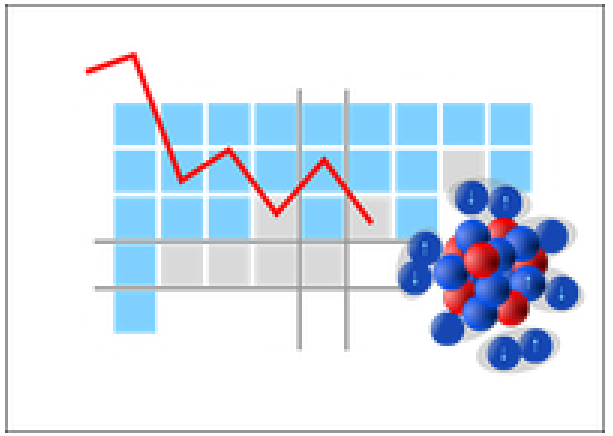
Kahlhow et al., PRL 133, 082501 (2024)



Large drop of stability at N>16

Sn stays constant at N>16

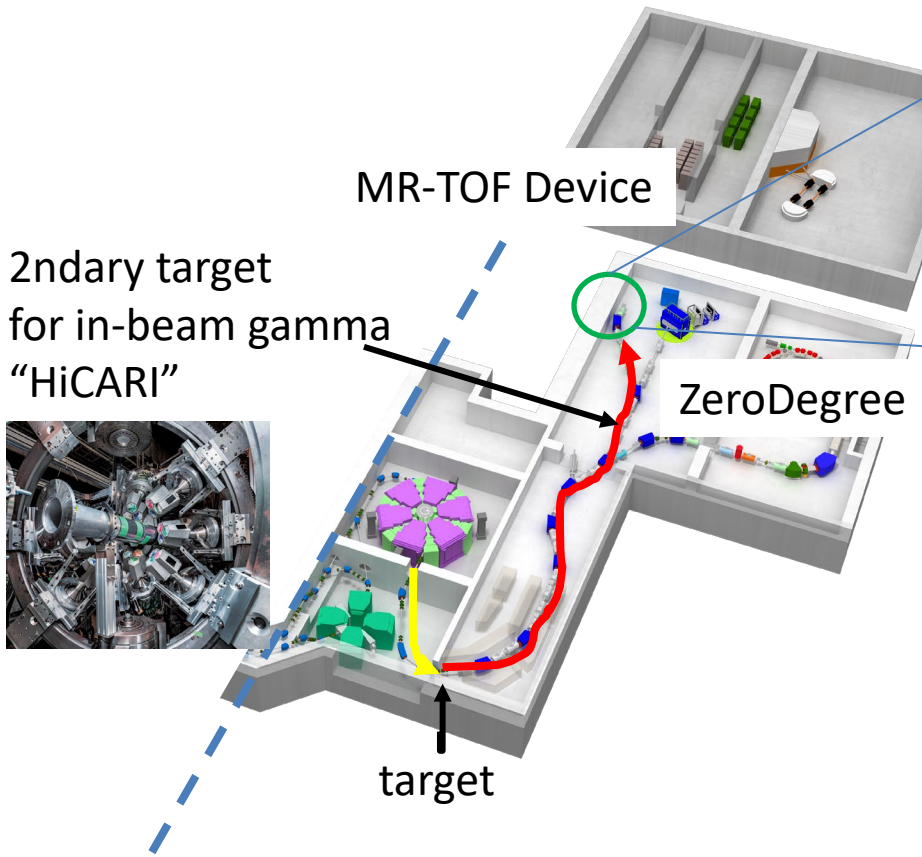
Large mixing of sd and pf shells?

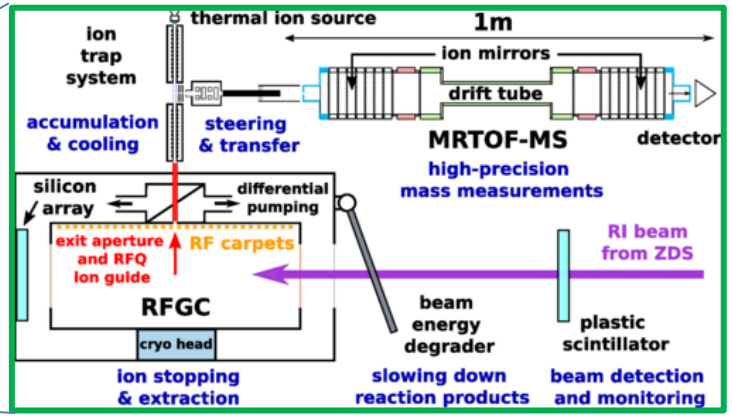


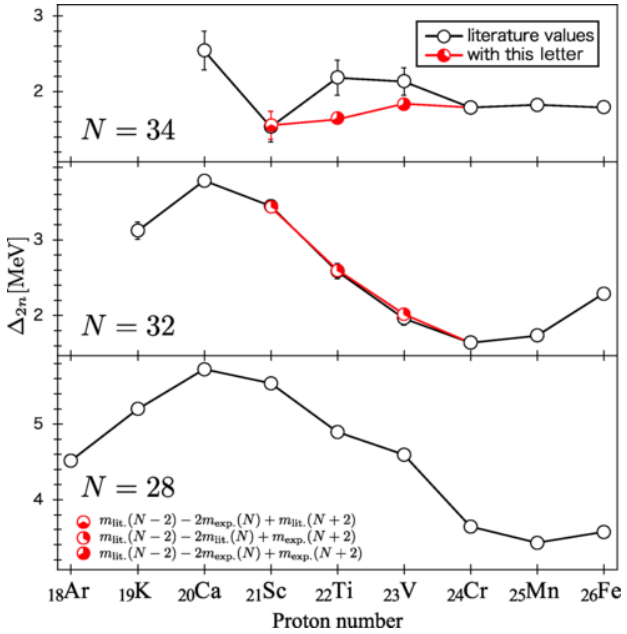
Mass Measurements in Parasitic Use

KEK-RIKEN Collaboration

Combination between in-beam programs and mass measurements with MR-TOF
Development of an efficient way in utilizing costly radioactive beams







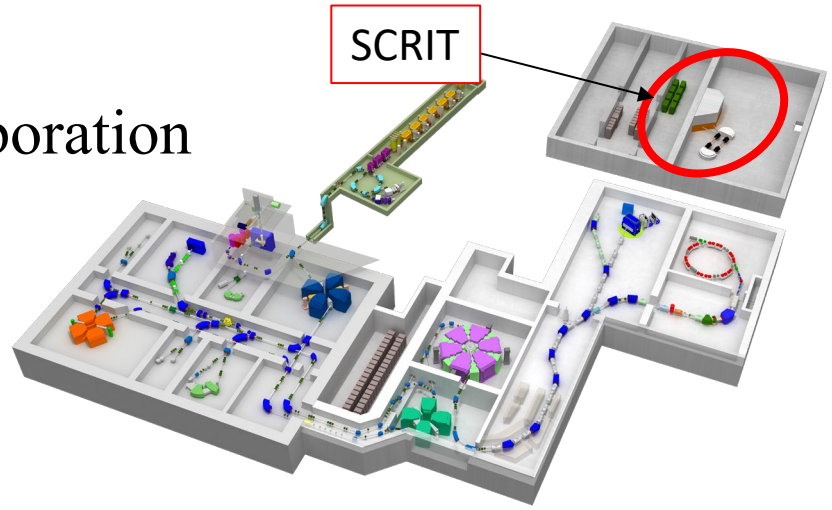
Study of the N=32 and N=34 Shell Gap for Ti and V by the First High-Precision Multireflection Time-of-Flight Mass Measurements at BigRIPS-SLOWRI

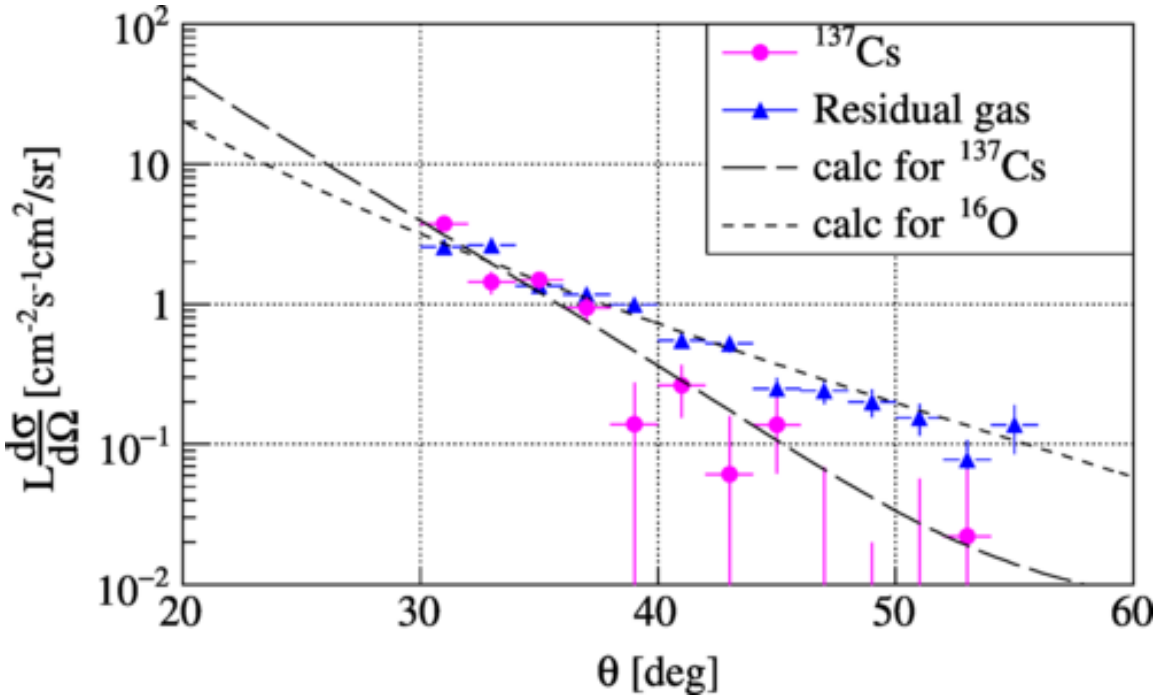
Iimura, PRL 130, 012501 (2023)

First Observation of Electron Scattering from Online-Produced Radioactive Target

Tsukada, Wakasugi, Suda, Onishi et al.,
PRL 131, 092502 (2023)

SCRIT Collaboration

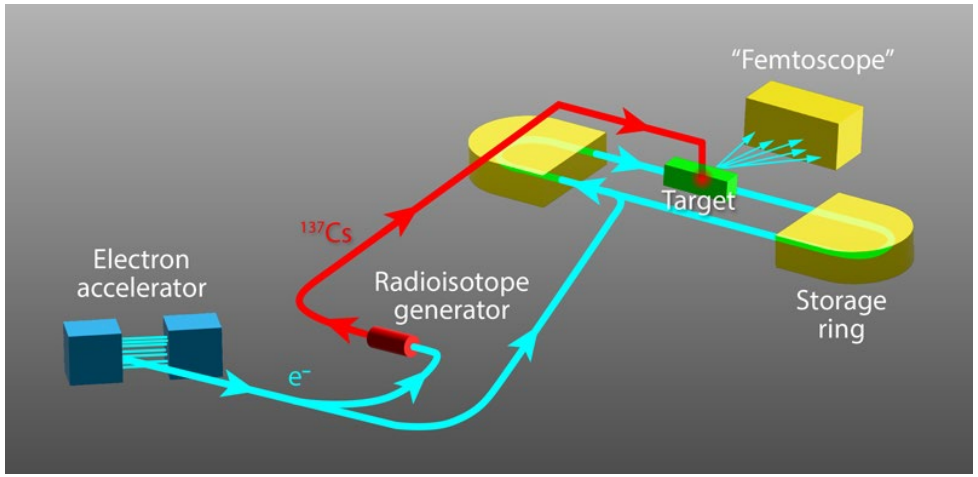




Towards Sn-132 by increasing the electron-beam power

Ohnishi in the afternoon today!

What Do Unstable Atomic Nuclei Look Like?
Patrick Achenbach, Physics 16, 144, 2023
August 30, 2023



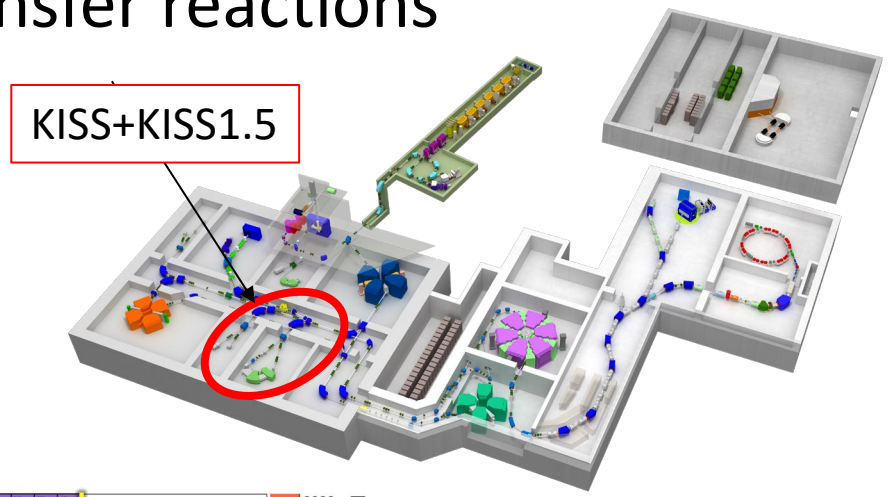
KEK Wako Nuclear Science Center : KISS1.5 project has been launched

Production of exotic nuclei via multinucleon transfer reactions

KISS : Ar-gas cell + laser-induced ionization

KISS1.5 : He-gas cell

Construction budget for KISS1.5 has been supported by the JSPS grant since 2024 for 5 years.



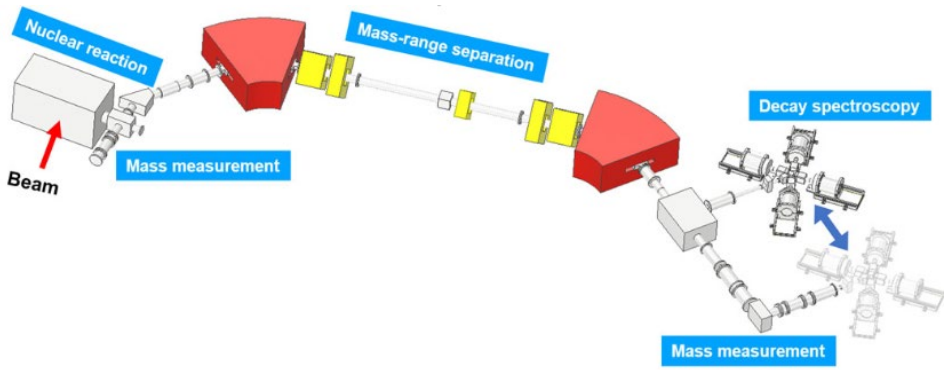


Figure 2. Schematic view of KISS-1.5

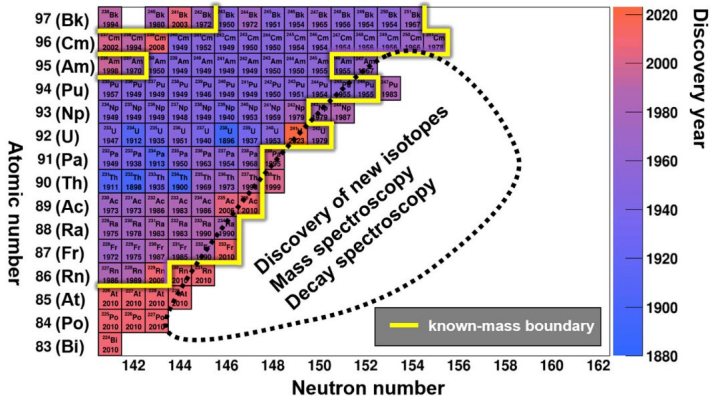
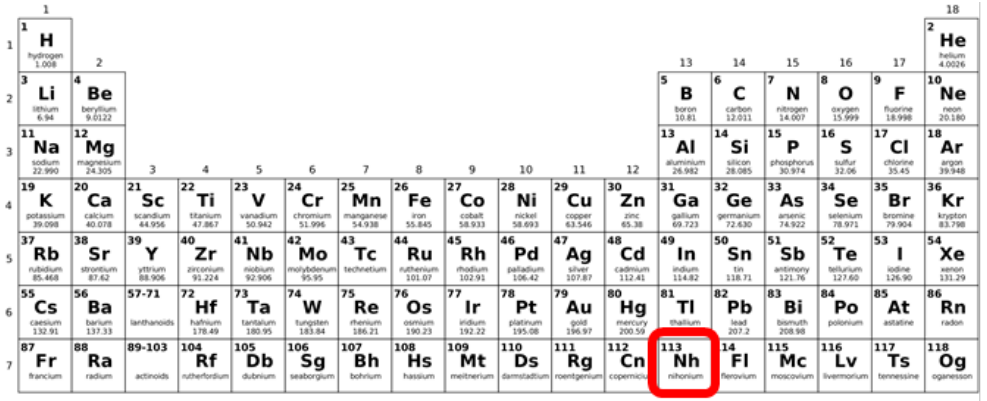


Figure 3. Discovery years of neutron-rich actinides and area of interest in this research

https://www.jsps.go.jp/file/storage/kaken_25_shinki06/24h00008_saitaku_gaiyo_en.pdf

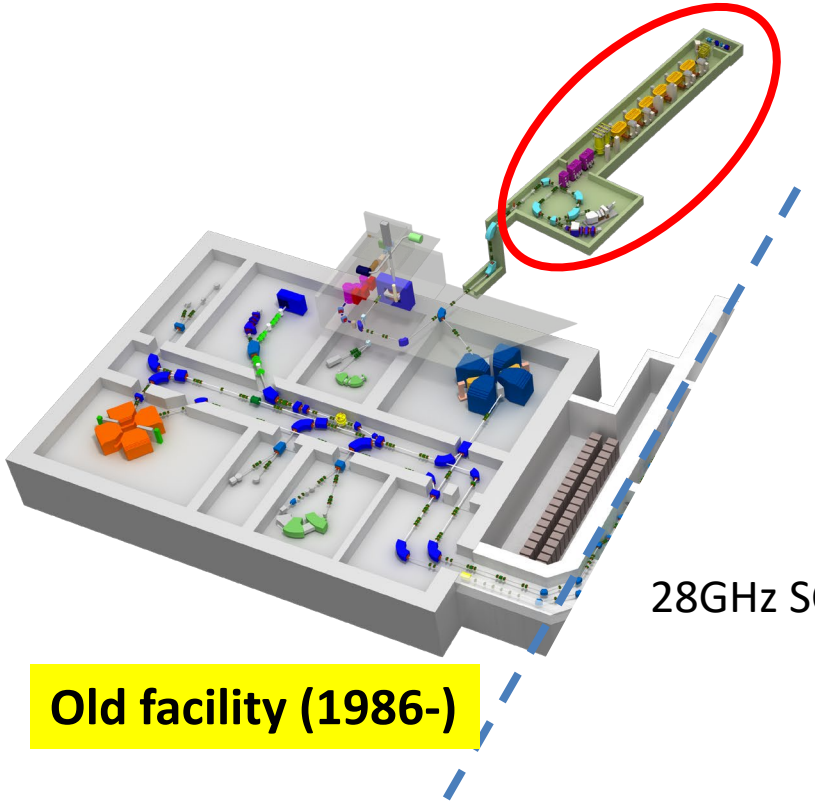
International Workshop (KEK-WNSC, Univ of York, RIKEN and JAEA)
MNT24 “Exploring the heavy exotic neutron-rich nuclides via multinucleon transfer reactions”
July 2-5, 2024 at RIKEN

Super-Heavy Elements



Element 113 “Nihonium”

Search for Element 119
SRILAC+GARIS3

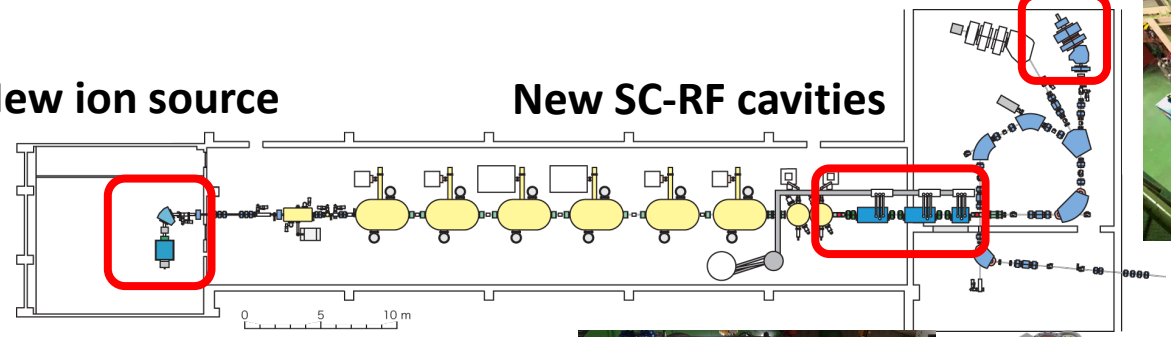


Old facility (1986-)

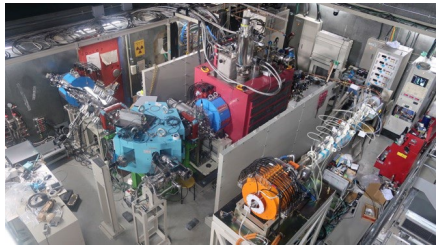
New setup towards the element 119 and beyond

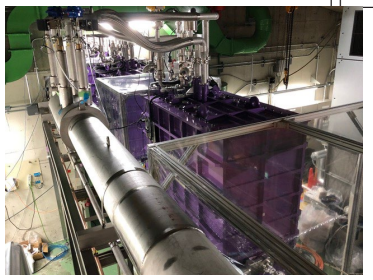
intensity and energy upgrade of the heavy-ion linac
new separator with a large acceptance

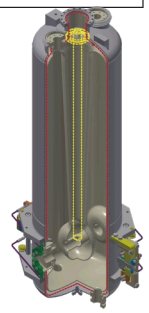
New ion source **New SC-RF cavities**

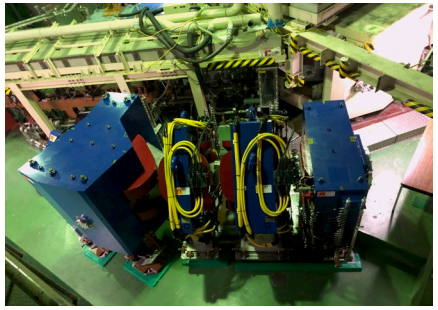


28GHz SC-ECR









New separator
GARIS3

RIBF upgrade toward the heavy mass region

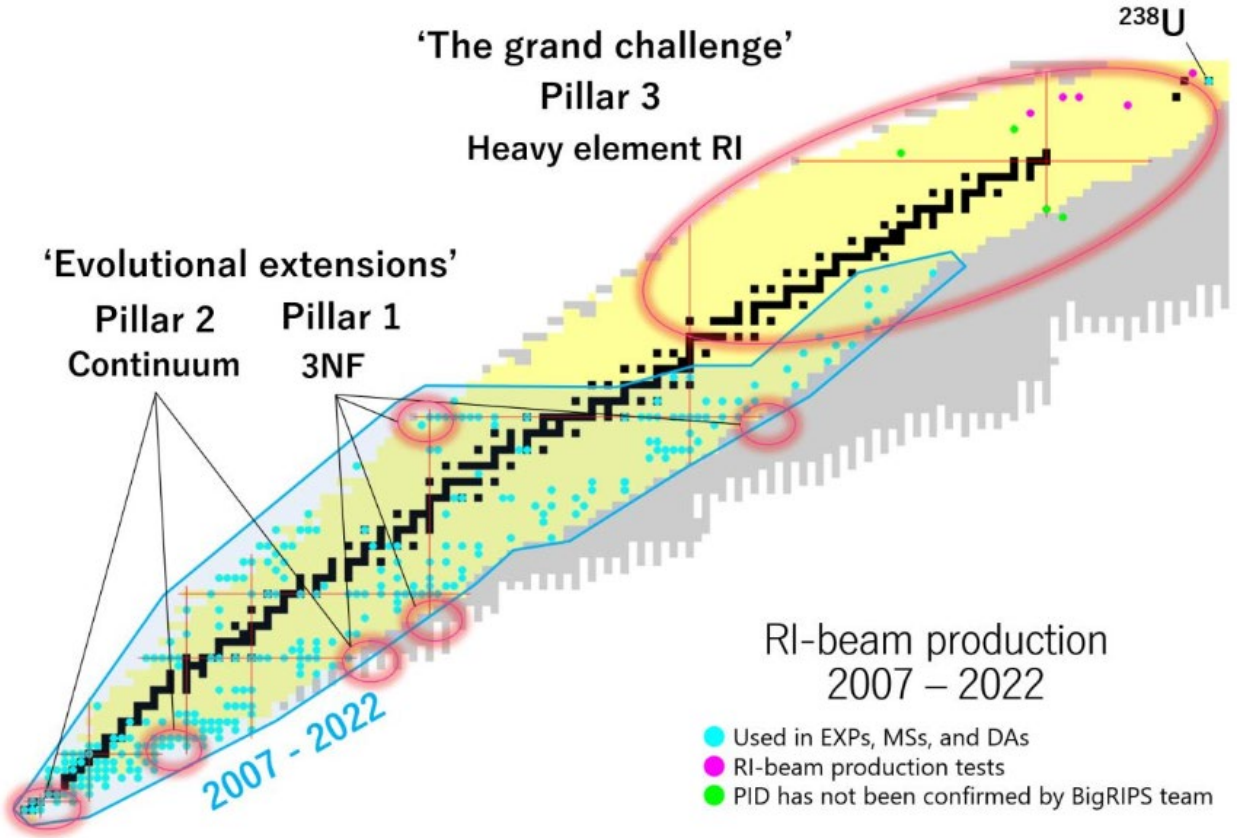
"RIBF Facility Upgrade Project"

https://www.nishina.riken.jp/researcher/RIBFupgrade/RIBF_Upgrade_NCAC.pdf

Heavier mass region to be newly explored

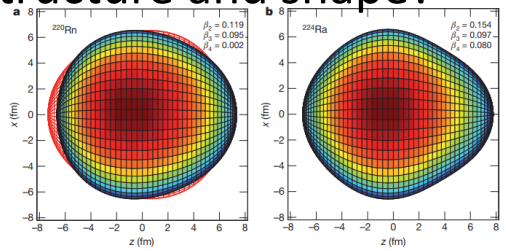
Reaction study at ~250 Me/u and lower with three spectrometers

Compared with FRIB and RAON , thicker 2ndary target can be utilized because of higher energy of RI beams

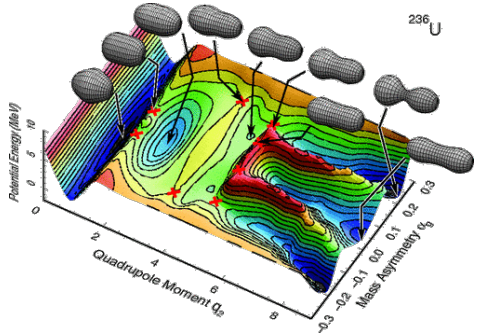


N-force and Coulomb,
both are strongly correlated

Structure and shape?



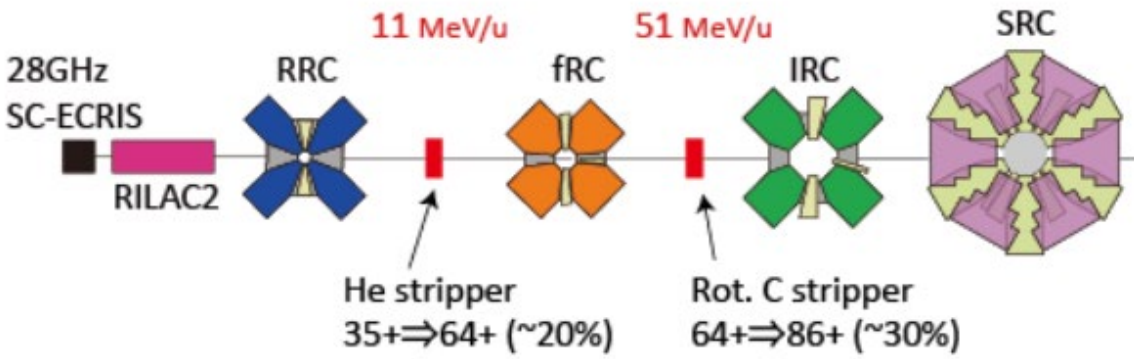
Dynamics of alpha-decay and fission?



RIBF upgrade plan to have more intense U beam

Courtesy of Imao

Present Acceleration Scheme



100 pnA

$6x10^{11}/s$

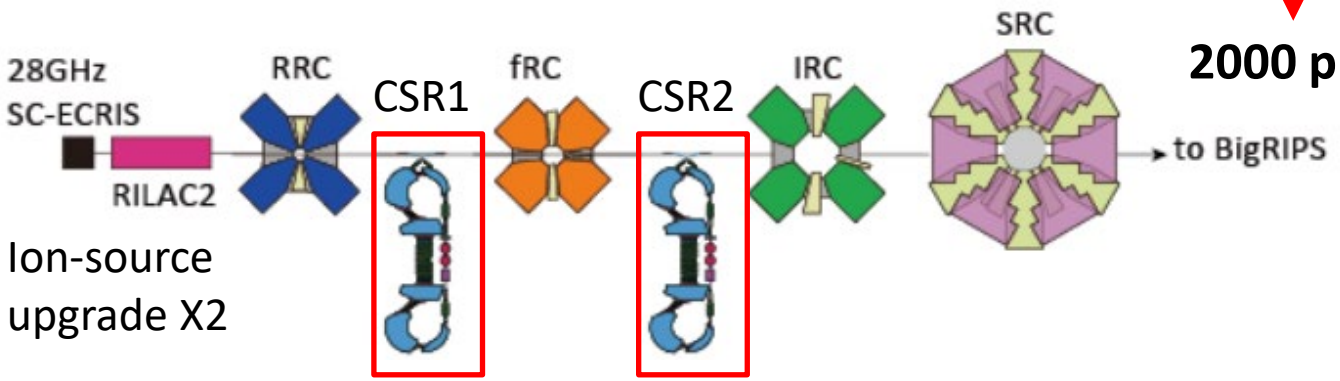
x20

$1x10^{13}/s$

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

"Recycling of heavy-ion beams"

Upgrade plan

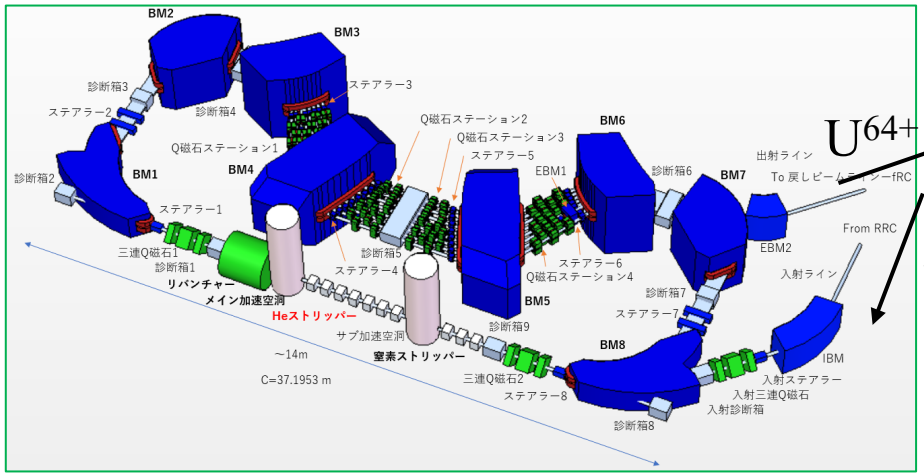


2000 pnA

Ion-source upgrade X2

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

CSR1



https://www.nishina.riken.jp/researcher/RIBFupgrade/RIBF_Upgrade_NCAC.pdf

Status Summary

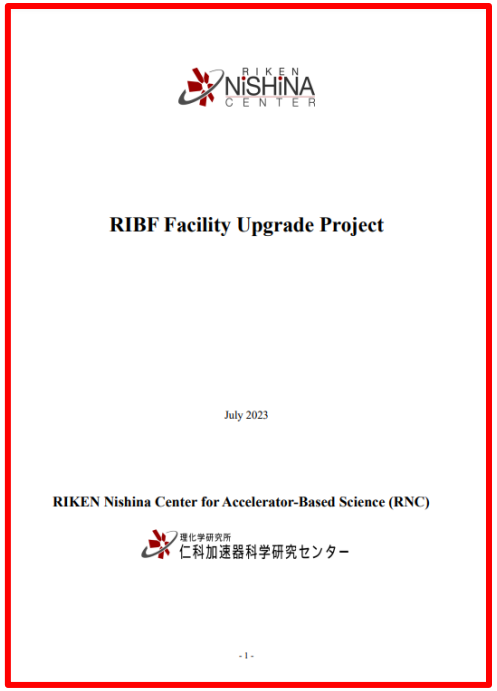
2023 June TAC dedicated to Charge Stripper Ring 1

2023 July Nishina Center Advisory Council (NCAC)

"RIBF Facility Upgrade Project" submitted to NCAC

https://www.nishina.riken.jp/researcher/RIBFupgrade/RIBF_Upgrade_NCAC.pdf

In light of the international landscape with major rare isotope accelerator facilities like FRIB and SPIRAL2 ramping up and FAIR and ARIEL in the future, it is critical for the sustained success of RIBF to stay at the forefront of the field. The science program enabled by the RIBF upgrade is exciting, in particular by opening access to isotopes at the extremes of the nuclear chart, which are important for understanding the origin of the heavy elements and the limits of existence of atomic nuclei. **The NCAC endorses the proposed RIBF upgrade in the strongest possible terms.**


RIBF Facility Upgrade Project

July 2023

RIKEN Nishina Center for Accelerator-Based Science (RNC)

理化学研究所 仁科加速器科学研究センター

- 1 -

2023 December RIKEN Advisory Council

IKEN's advanced scientific infrastructure remains world-leading and forms a powerful and effective basis for international collaboration, but there are concerns that some infrastructure is aging and in need of replacement or upgrade.

2024 Jan Int'l WS "Advancing physics at next RIBF (ADRIB24)"

more than 100 participants, 50% were young generations (20-30's years old)

Budget is being requested

Summary and Future Perspectives

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 is preparing to access the heavy mass region.
Budget for the RIBF upgrade is being requested.

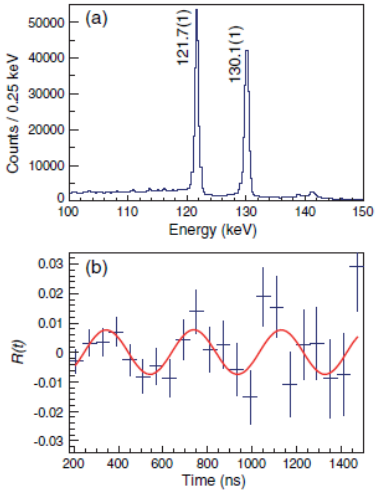
Welcome to join the nuclear physics programs at RIBF!

Co-authored papers of Dimiter L. Balabanski and Hideki Ueno

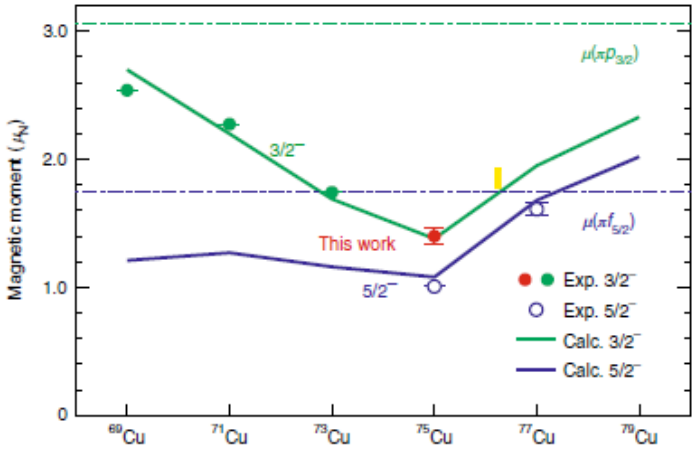
Nuclear-moment measurements at RIBF (BigRIPS, RIPS) and GANIL

Boulay, et al., PRL 124, 112501 (2020)
Ichikawa et al., Nature Physics 15, 321 (2019)
Kusoglu et al., PRC 93, 054313 (2016)
Ichikawa et al., NIM B 317, 769 (2013)
Ichikawa et al., Nature Physics 8, 918 (2012)
Shimada et al all, PLB 714, 246 (2012)
Chevrier, et al., PRL 108 162501 (2012)
Nagatomo et al., EPJA 42, 383 (2009)
De Rydt et al., PRC 80 037306 (2009)
De Rydt et al., PLB 678 344 (2009)

Zr-99m (2020)

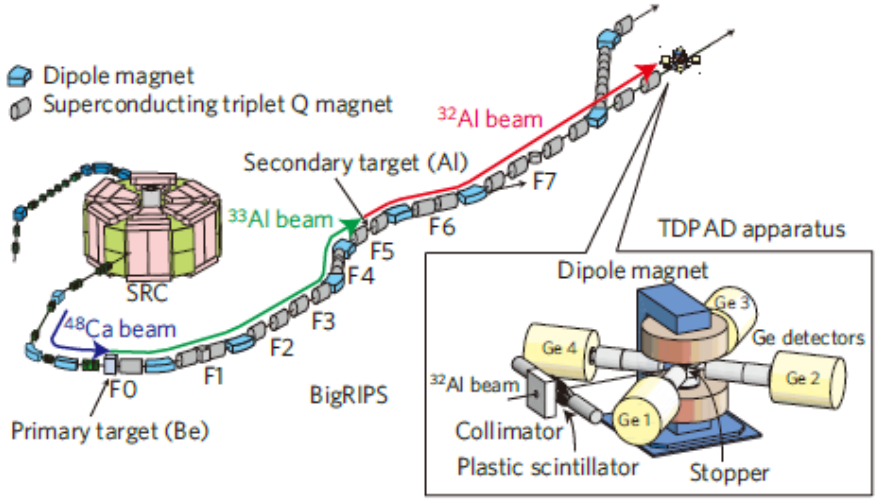


Cu-75m (2019)



Spin-aligned RI beam Production (2012, 2013)

Ichikawa on 11th



Dimiter, Happy 70th birthday !
I wish you every happiness