

RI 스토리지 링으로 중성자 과잉 핵(Neutron-rich nucleus)에서 나타나는 새로운 집단성과 반응 동역학

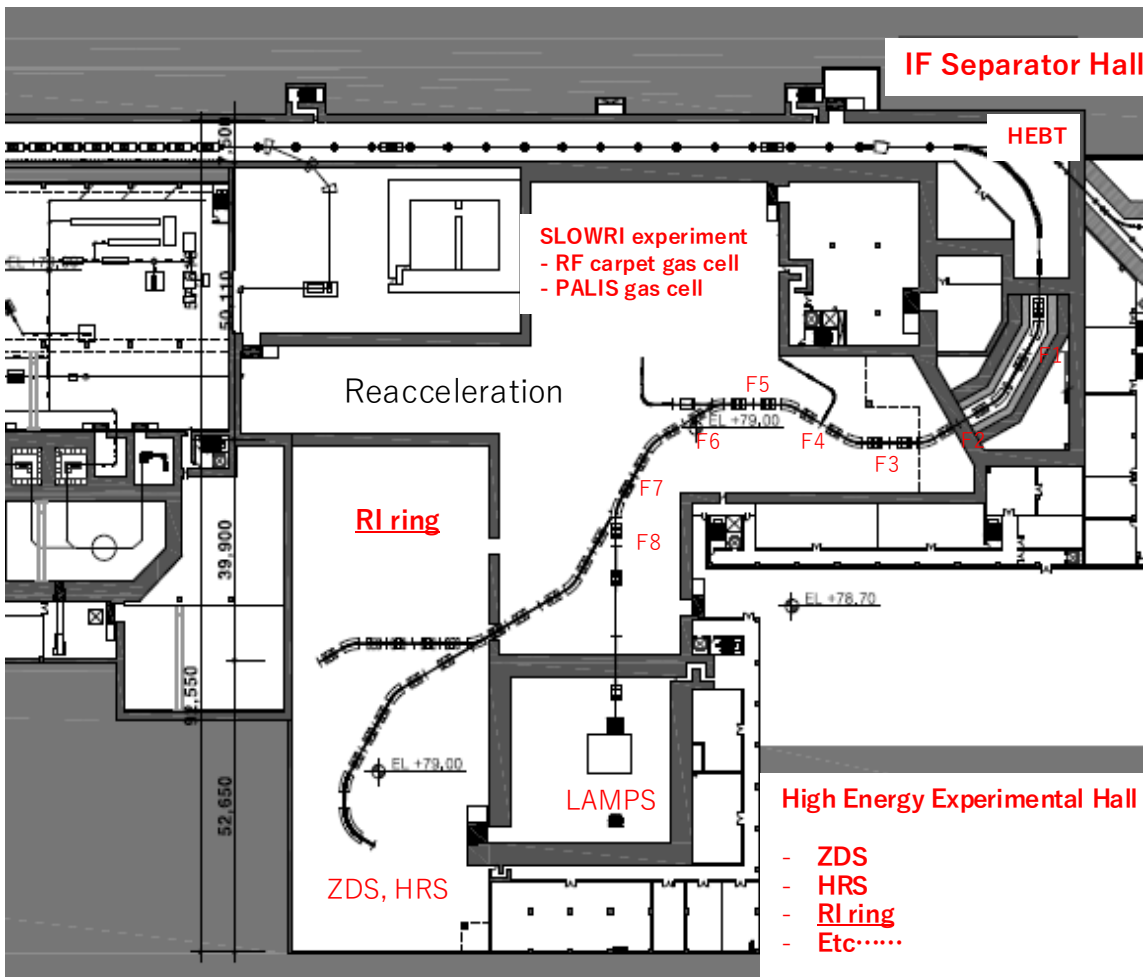
- 약한속박 유한양자다체계에서의 질서운동과 존재한계의 규명 -

원자핵의 존재 한계를 결정하는 것은 무엇일까?

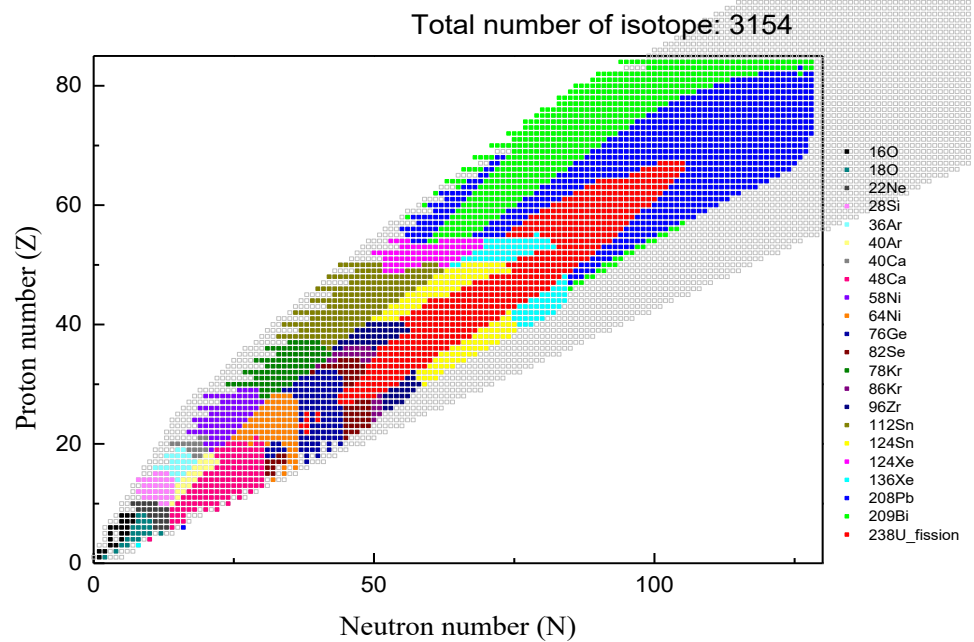
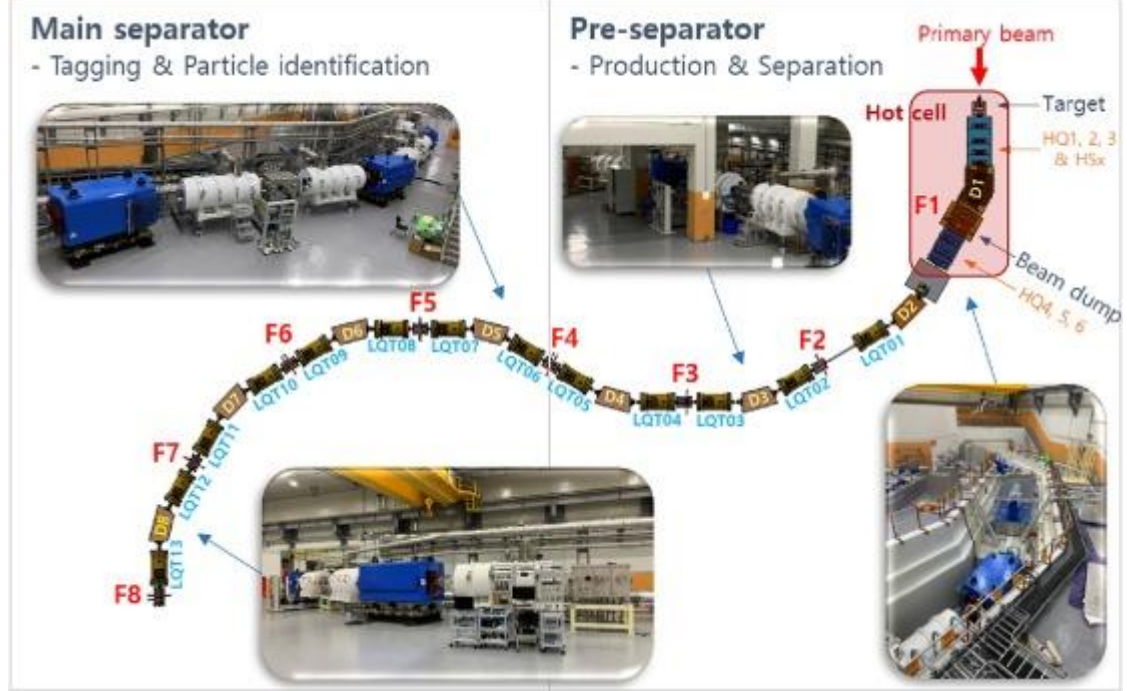
약한 결합 (weak binding)하에서의 새로운 집단성과 형성-생존 역학(dynamics)
Approach: RI storage ring

윤종철, 하시모토 타카시, 이청수

중이온가속기 연구소
기초과학연구소



3rd RISP SPAC Meeting – 26-27 July 2016



22 primary beam으로 부터 > 3000개 RI 빔 생성가능

주요 과학 질문

What kinds of states can a finite quantum many-body nucleus sustain, and how are they constrained by formation and survival dynamics near the limit of existence?

We address this question by changing neutron excess, which modifies shell structure, binding, pairing, and reaction pathways.

Mini-subjects

1. 재 구성된 평균장(mean field) 에서 어떤 상태가 가능한가?
“Banana-like deformation”
2. 반응 동역학은 생성과 생존을 어떻게 좌우하는가?
“Island of stability”

재 구성된 평균장(mean field) 에서 어떤 상태가 가능한가?

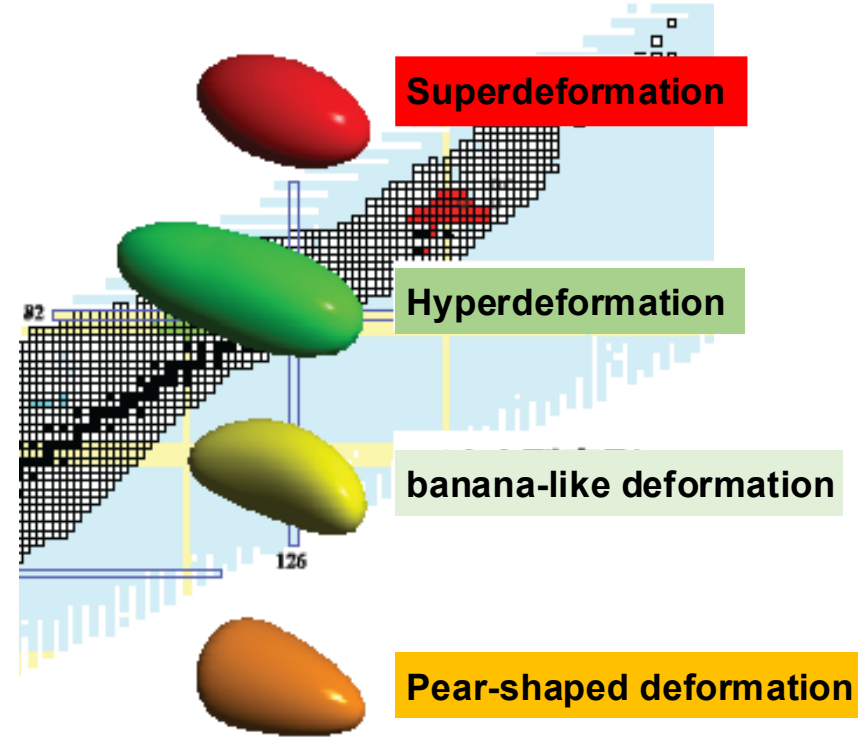
Gamma-ray spectroscopy of superdeformed states in the nucleus ^{152}Dy
M A Bentley, A Alderson, G C Ball, H W Cranmer-Gordon, P Fallon, B Fant, P D Forsyth, B Herskind, D Howe, C A Kalfas

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[Journal of Physics G: Nuclear and Particle Physics, Volume 17, Number 4](#)

Citation M A Bentley *et al* 1991 *J. Phys. G: Nucl. Part. Phys.* **17** 481

DOI 10.1088/0954-3899/17/4/009



Abstract
A gamma -ray spectroscopic study of the high spin states of the nucleus ^{152}Dy has been performed using the reaction $^{108}\text{Pd}(^{48}\text{Ca},4n)^{152}\text{Dy}$ at a bombarding energy of **205 MeV**. [Gamma rays were detected using the TESSA3 multi-detector array](#). A set of discrete-line states forming a rotational band has been observed in the data and has been shown to extend up to a spin of around $60\hbar$ (cross) and an excitation energy of about 30 MeV. The gamma -ray energy data are consistent with dynamic moment of inertia $F^{(2)}$ of $(85 \pm 3)\hbar^2 \text{MeV}^{-1}$, indicating a large quadrupole deformation. A measurement of the collectivity of the band has been made using the Doppler shift attenuation method, with the data for the lower spin states yielding a quadrupole moment of $Q_0 = (18 \pm 3) \text{e b}$.

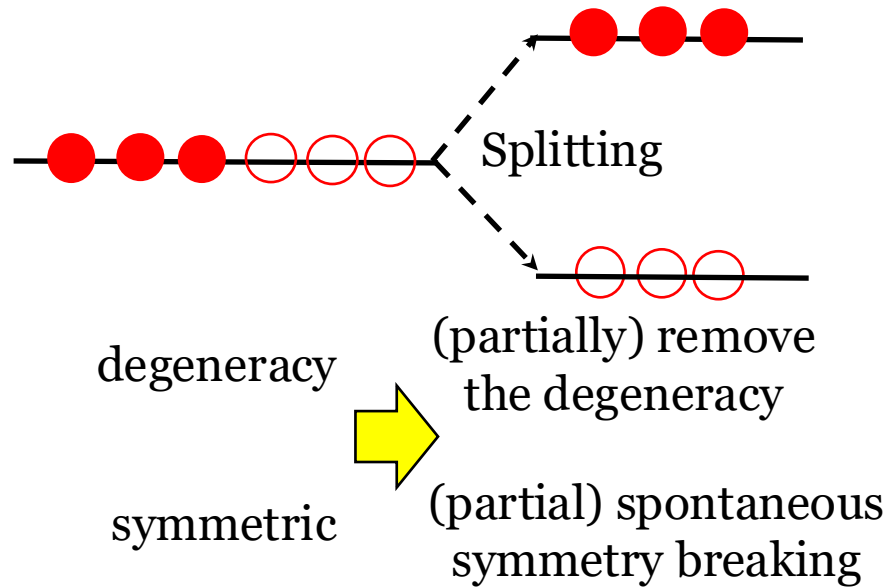
- 초변형핵 : 1986년 발견, 그 이후 현재 까지 250여종
Spontaneous symmetry breaking → Deformed mean field → Deformation of the atomic nucleus →
Rotational mode & Vibration mode → γ ray spectroscopy

- 바나나형 핵의 존재

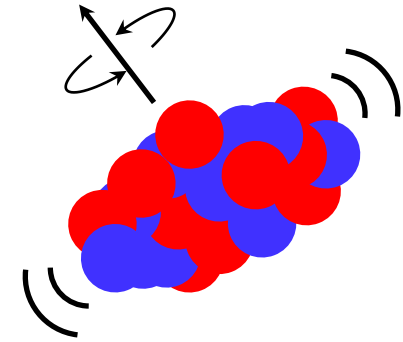
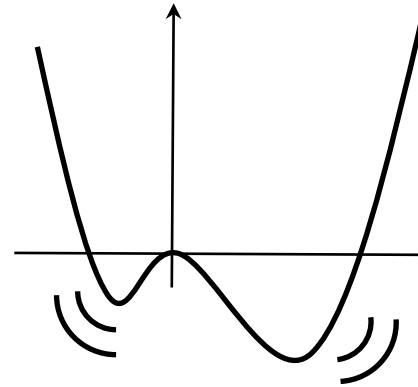
Basic picture of nuclear deformation

Deformation can arise by lifting degeneracy to gain binding energy (spontaneous symmetry breaking).

Spontaneous symmetry breaking



Deformed Mean field



- ✓ Rotational mode is associated with restoration of broken symmetry.
- ✓ Vibration modes correspond to oscillations of the deformed mean field.

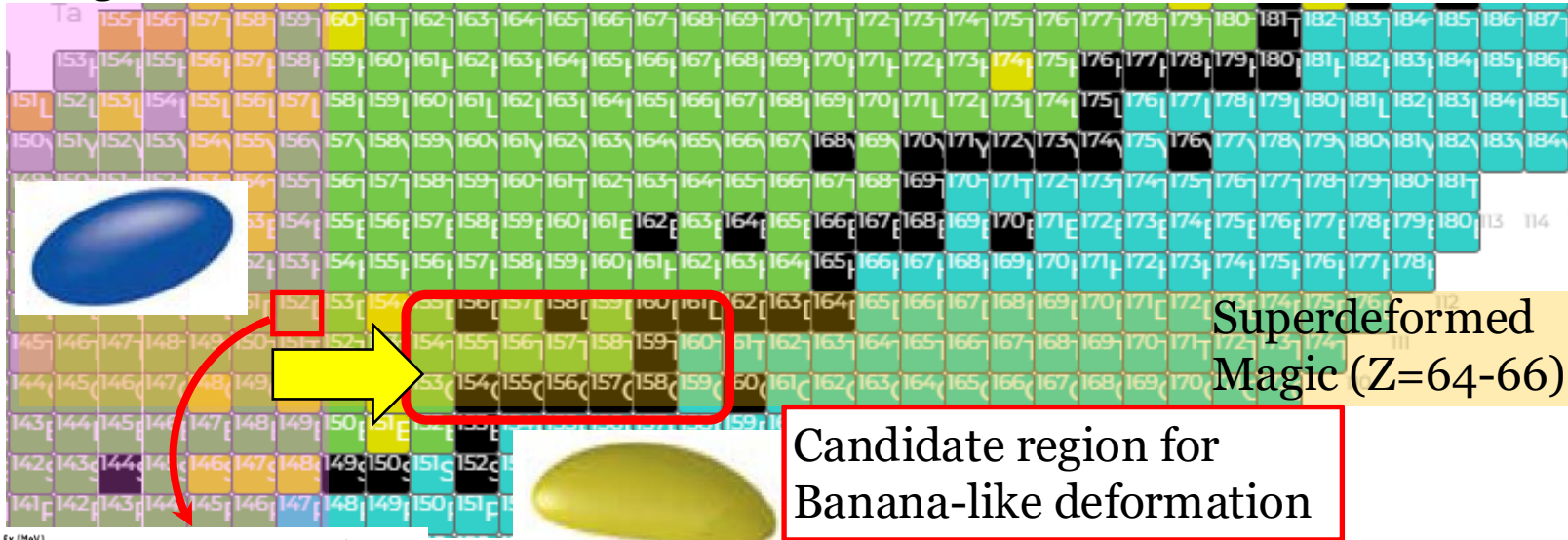
Collective motions appear as discrete states and band structures with characteristic γ -ray transitions

γ -ray spectroscopy tests which of these high-spin states are actually realized

This allows us to investigate experimentally the dynamical mechanisms of symmetry breaking in atomic nuclei.

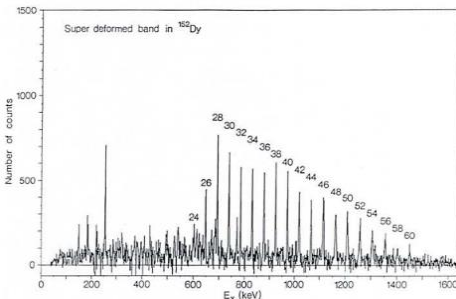
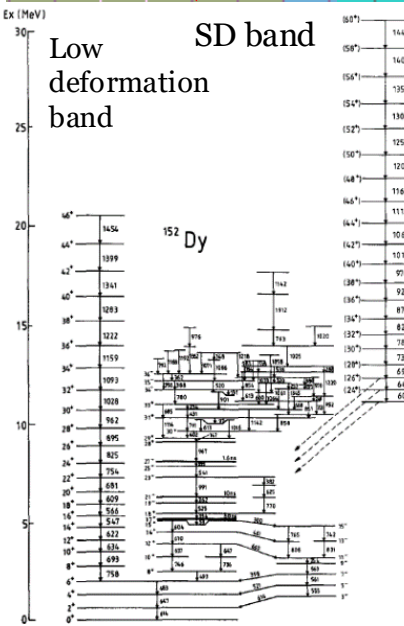
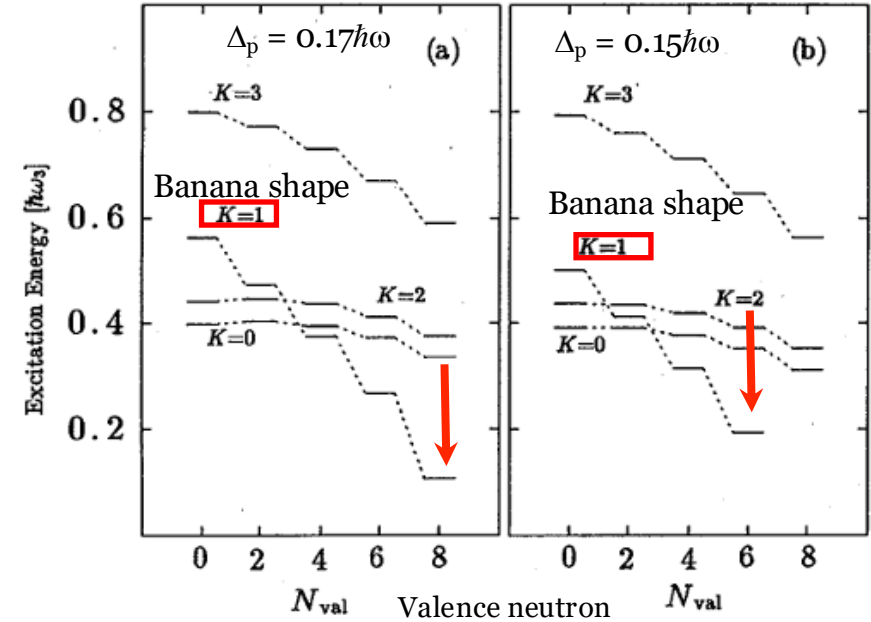
Superdeformed Magic (N=80-86)

Soft K= 1 octupole instability in open deformed shell



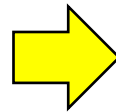
Superdeformed Magic (Z=64-66)

Candidate region for Banana-like deformation



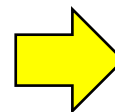
M A Bentley et al., J. Phys. Part. Phys. 17(1991)481

**Is there banana deformation?
If yes, is it only soft vibration?
is there (rotational) band structure on the banana shape?**



γ-ray spectroscopy for high-spin state on ¹⁵⁶Dy by fusion reaction of ⁵²Ca+¹⁰⁸Pd

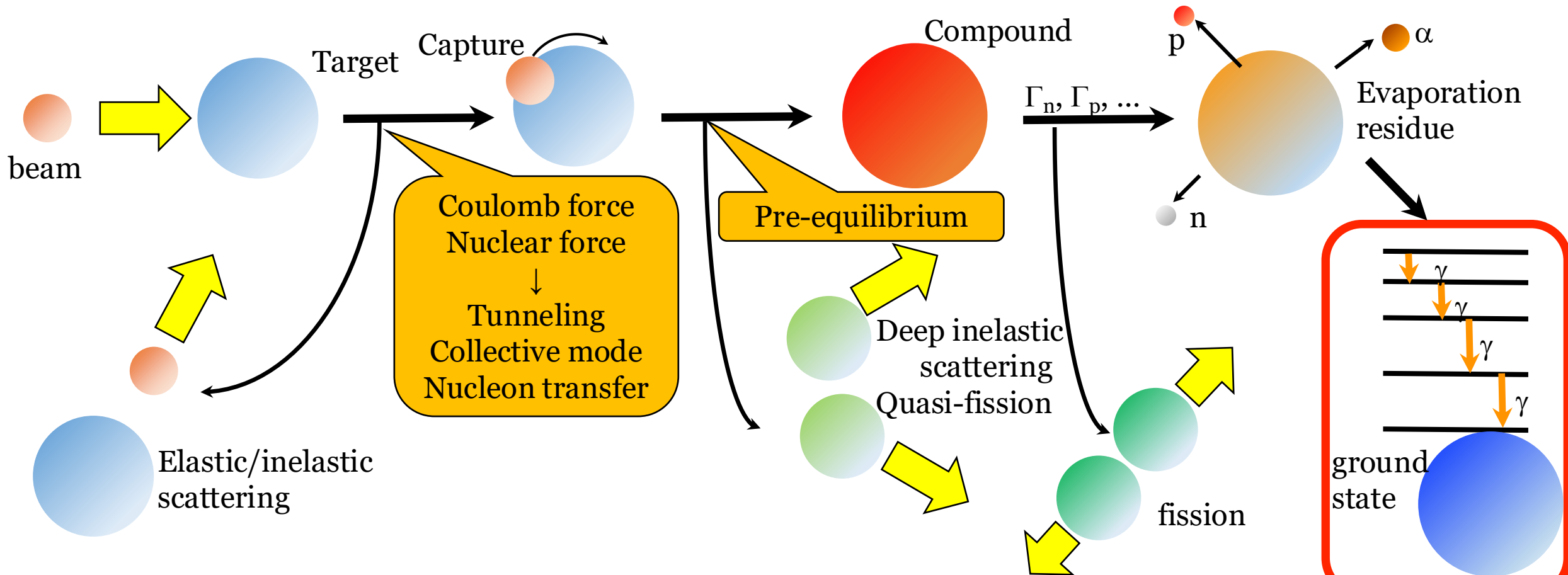
Expected ⁵²Ca intensity from ISOL: ~6x10⁵ pps
It is insufficient for high-statistics spectroscopy as in the ¹⁵²Dy case



How can we reach the luminosity required to test these states?

⁴⁸Ca+¹⁰⁸Pd->¹⁵²Dy@E=205 MeV

핵융합-핵분열 반응은 핵물리학에서 가장 복잡한 동적 과정 중 하나

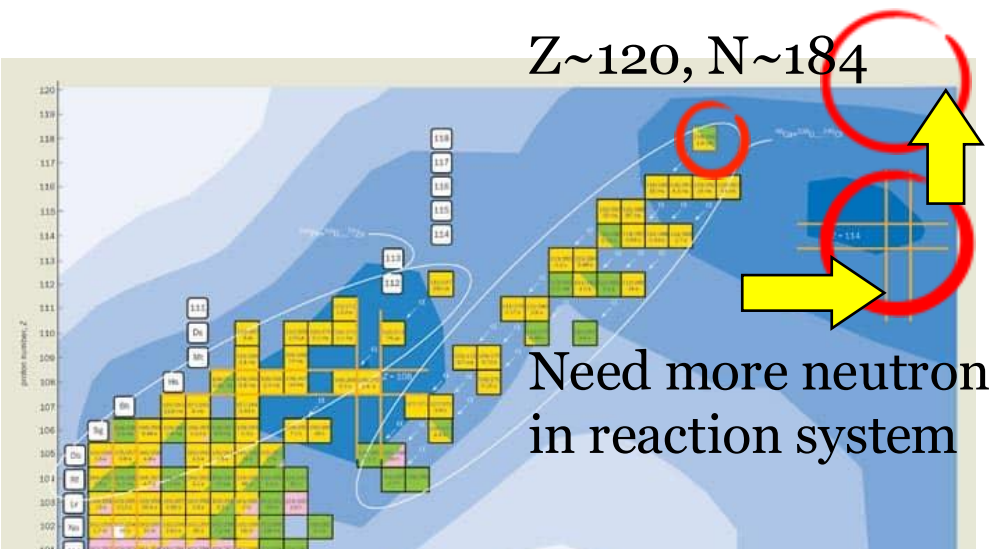


Fusion–fission reactions provide a testing ground for how a transient quantum many-body system is formed, evolves, and survives.

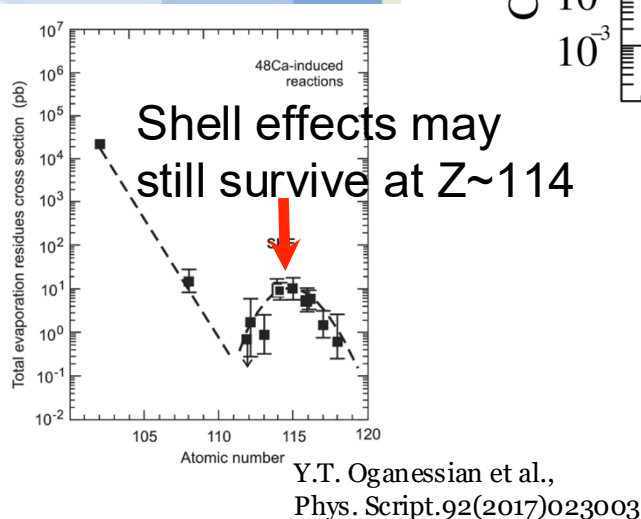
Population and γ -decay of high-spin states

Does neutron richness change the formation–survival pathway by modifying shell-driven fission barriers?

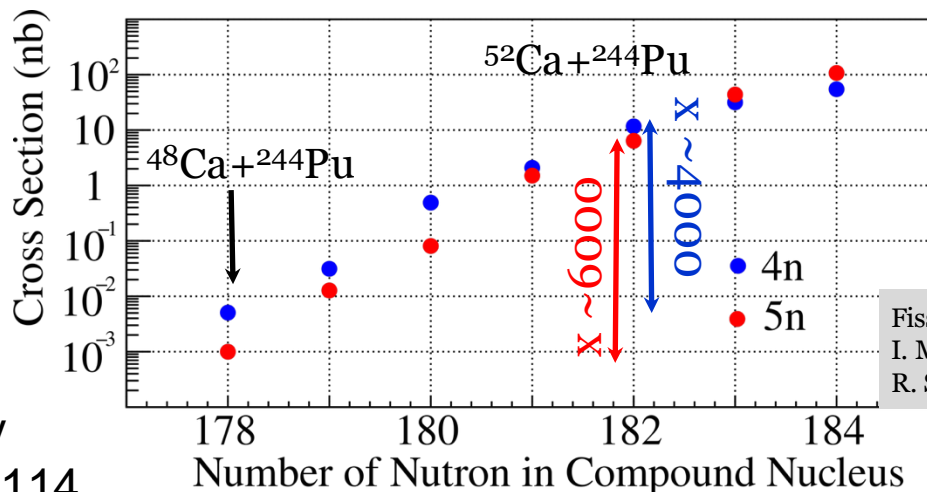
The key question is whether shell stabilization near the island of stability can enhance survival enough to change this situation.



Production of ^{294}Og
 $^{48}\text{Ca}(^{249}\text{Cf}, 3n)^{294}\text{Og}$
 Luminosity: 3.38×10^{33} /cm²/s
 cross section: ~ 2 pb
 data accumulation: 45 days
 number of event: 3 events

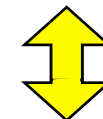


Estimated cross section normalized by $^{48}\text{Ca}+^{244}\text{Pu}$ (simple statistical model)



Fission barrier taken from
 I. Muntian et al., Acta. Phys. Pol. B34(2003)2141
 R. Smolanczul et al., Pays. Rev. C 56(1997)812

If the calculation is realistic, ^{292}Fl will obtain 1 event/10 days @ ^{52}Ca with 10^8 pps



Expected ^{52}Ca intensity from ISOL: $\sim 6 \times 10^5$ pps

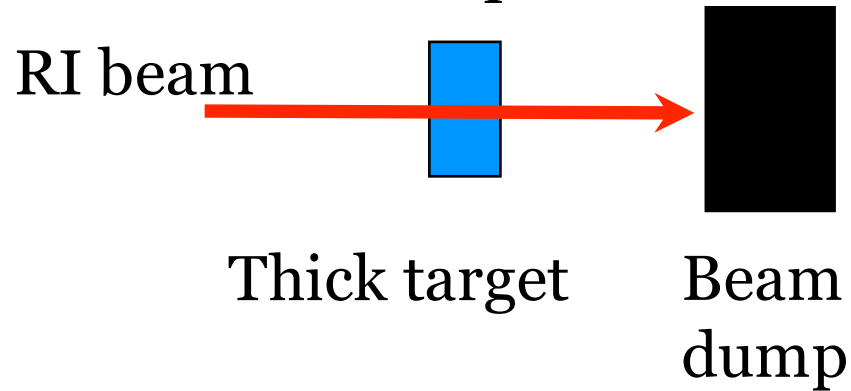
For the ^{52}Ca case, testing this question directly would require an unrealistically intense beam.

How to solve the luminosity issues

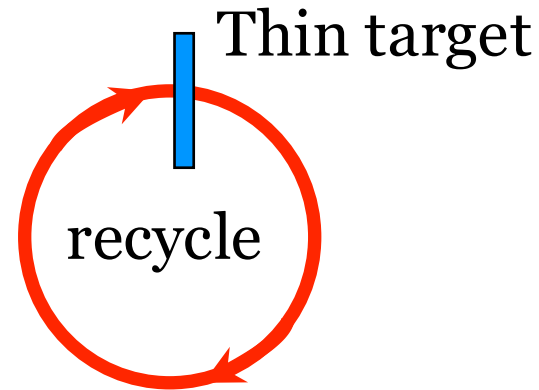
The bottleneck is effective luminosity at the target

RI storage ring concept: beam reuse after target passage

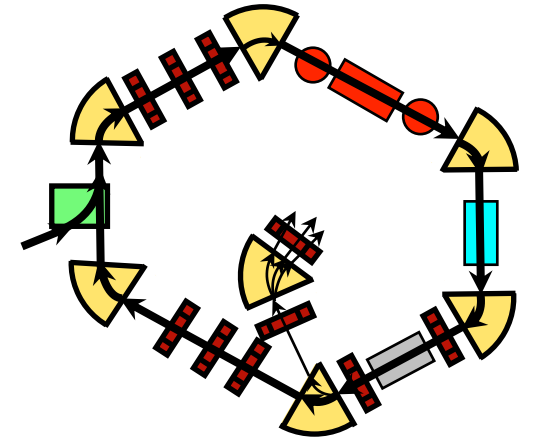
Conventional method of
RI beam experiment



Proposed method



Conceptual ring design



Luminosity using a storage ring

$$L = N_{\text{BeamStored}} f N_{\text{target}} \text{ Advantage!}$$

L: Luminosity

$N_{\text{BeamStored}}$: Stored ion in the ring

f : frequency of ring

N_{target} : Area density of target

If f is 10^6 Hz,

effective beam intensity of ^{52}Ca is 10^{11} pps!

$L \sim 10^{28} \text{ cm}^{-2}\text{s}^{-1}$ with $10 \mu\text{g}/\text{cm}^2$ ^{108}Pd target

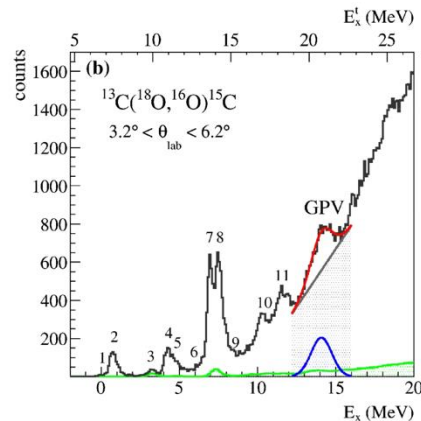
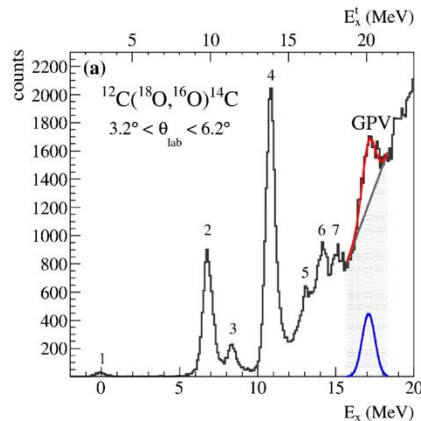
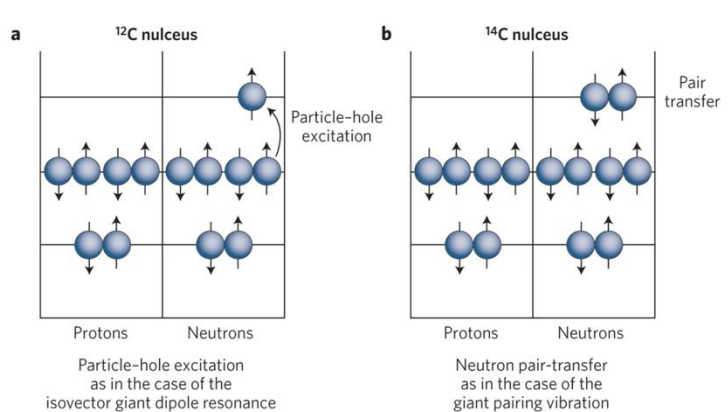
$L \sim 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ with $400 \mu\text{g}/\text{cm}^2$ ^{244}Pu target

Enough effective luminosity to make these
fusion studies with RI beams realistic

Applications

Giant pairing vibration (GPV)

Collective vibration of particle - particle or hole-hole pairs, analogous to the IVGDR



(predicted by R.A Broglia 1977)

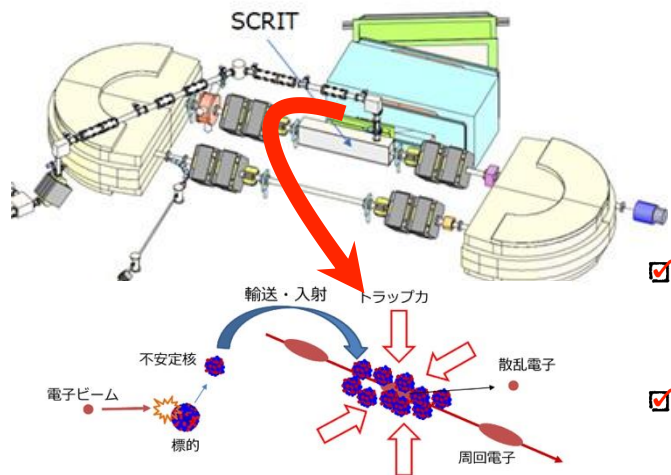
Only two cases are found

(Eur. Phys. J. 57(2021)34)

Is matching condition of two-neutron transfer essential?

Try to search using $^{6,8}\text{He}$, $^{9,11}\text{Li}$ probe

Self-Confining RI Ion Target (SCRIT) as technical application



- ☑ Electromagnetic response of unstable nuclei
- ☑ charge/matter density distribution

Atomic physics

- ☑ Test of QED using highly charged ions
- ☑ Lifetime of forbidden and rare atomic decays in highly charged ions
- ☑ Resonant atomic–nuclear coupling via NEEC

Applicant and potential collaboration

Core team				
Name	Affiliation	Role in the project		Relevant expertise
C.C Yum	IRIS/IBS	Project lead RI ring design		Storage-ring design Ion optics
Takashi Hashimoto	IRIS/IBS	Physics case for the RI ring ISOL interface	Spectrometer concept	Low and medium energy nuclear physics
C.S Lee	IRIS/IBS	Direct reaction physics	Detector concepts	Direct-reaction measurement mass ring

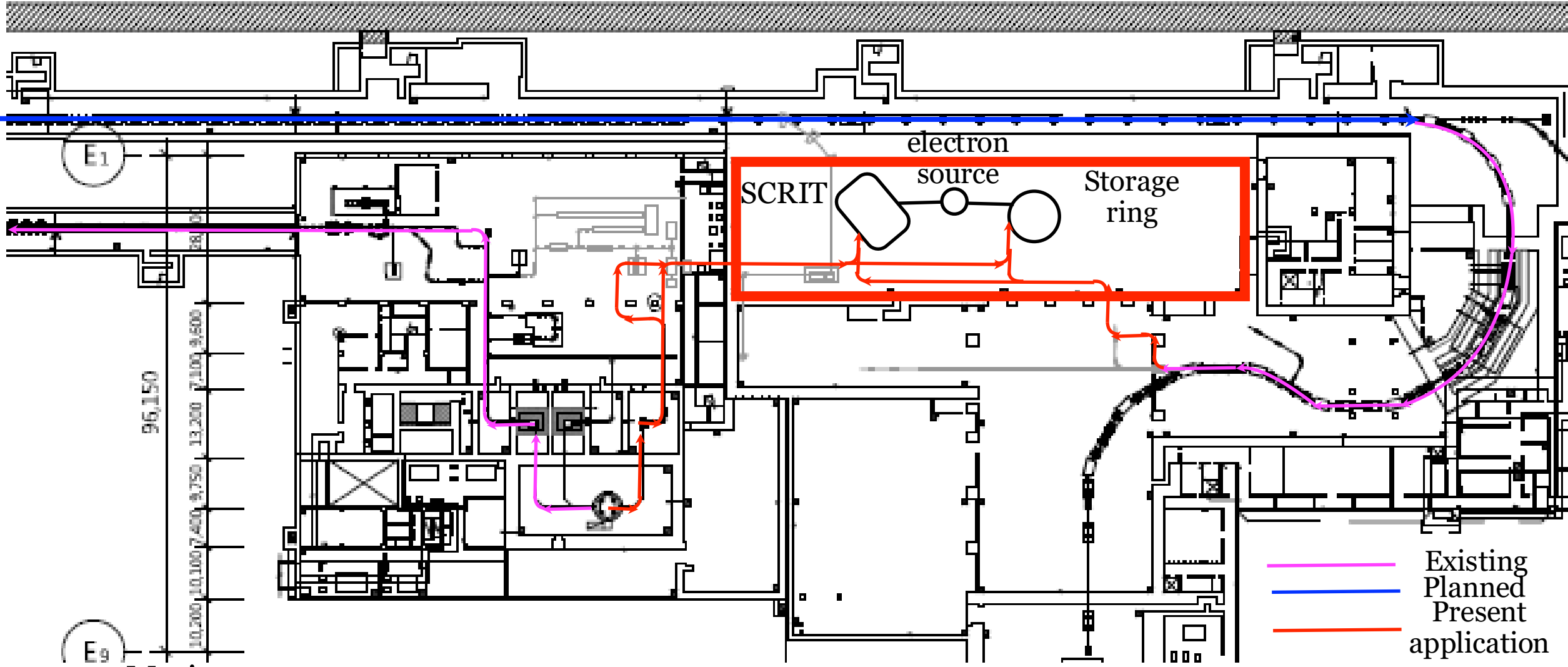
Potential collaborators and expected roles

RIKEN (**Storage ring, SCRIT, superheavy element production**),
CNS, U. Tokyo (**detector development for low-energy particles**), Tohoku University (**SCRIT**),
Kyoto University (**Storage ring, SCRIT**), JAEA (**Fusion-fission, Nuclear chemistry**),
Institute of Science Tokyo (**Atomic physics**)

Why this team can deliver

- ☑ The science goals are already mapped one by one onto the required ring functions.
- ☑ The key technical risks have already been identified and translated into an R&D plan.
- ☑ The same platform supports both the core nuclear-physics program and future expansion to SCRIT, atomic physics, and an RI–RI collider.

Possible installation Layout plan using existing IRIS facility



- Existing
- Planned
- Present application

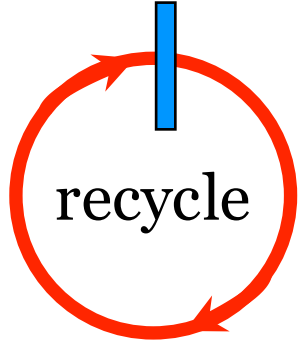
Merit

RI production can be supplied either ISOL or IF
RI from ISOL case, the experiments can run in parallel with other experiments.

Future plans

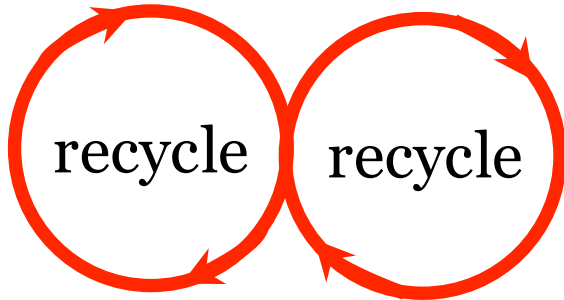
Present application

Thin target

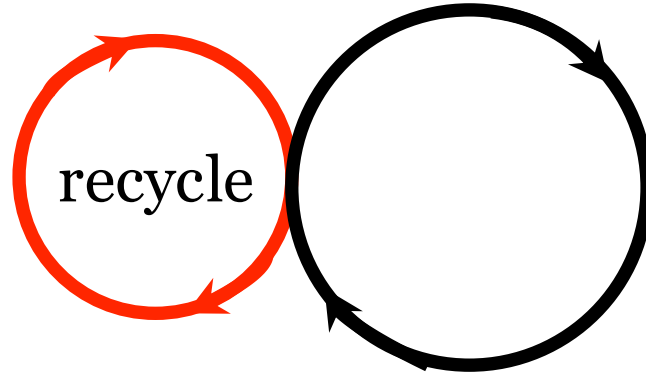


Storage ring with an internal target

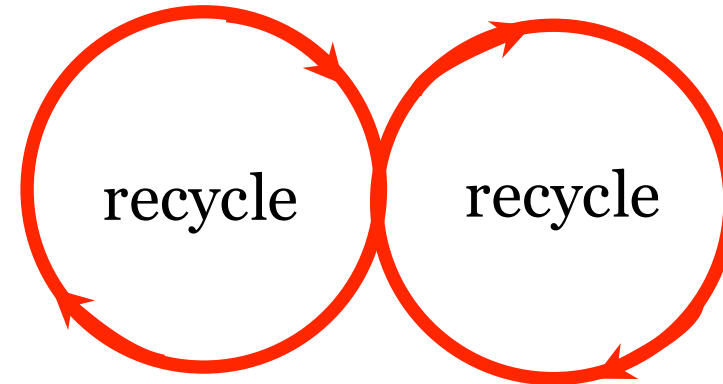
Future plans



Low-energy RI-RI collider to access more exotic region



Low-energy RI-high-energy stable ion collider to control Lorentz boost



high-energy RI-RI collider to research exotic EOS

Summary

- ☑ Science: Existence limits of nuclei from structure and reaction dynamics
- ☑ Need: One-pass + fixed targets cannot reach the required statistics
- ☑ Solution: RI storage ring as a shared platform for science, and future expansion.
- ☑ Uniqueness: Unlike existing mass rings (R3 at RIKEN, CRS at IMP) or higher-energy internal-target rings (ESR, CRYRING at FAIR, SRing at HIAF), this project targets a low-energy storage ring with an internal target for fusion reactions.

Korea now has an opportunity to take a leading role in
RI storage-ring science and infrastructure for
unstable nuclei

Backup

탁월성, 시급성 그리고 준비성

탁월성

Addresses the fundamental question of the existence limits of atomic nuclei as finite quantum many-body systems, from both structure and reaction dynamics.

시급성

With one-pass beam transport and fixed targets, low beam intensities and reaction cross sections impose severe statistical and resolution limits.

준비성

The key physics goals, performance indicators, and required ring functions are already clearly identified.

리더십 기회

There are only a few precedents worldwide for this approach.

Korea now has an opportunity to take a leading role in unstable nuclear physics.

Technical Difficulties

내부 표적을 사용하여 빔 품질을 유지하는 방법

- ☑ Electron cooling
 - velocity matching, recovery beam quality, beam loss by recombination, electron beam diagnostics...
- ☑ Non-resonant Ferrite cavity
 - mean energy-loss compensation vs. target induced energy straggling,
 - required gap voltage and RF power in wide-band ferrite cavity, longitudinal stability,
 - phase noise, beam loading under beam reuse,
- ☑ Beam spot size at target position
 - micro-beam technique to increase effective luminosity
- ☑ Ultra-high vacuum ($\sim 10^{-11}$ torr)
- ☑ Beam diagnostics for low-intensity beam

Each required technology is challenging, but none is conceptually new.

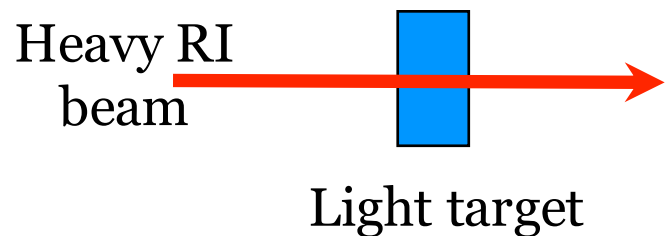
The real challenge is

to use low-energy, low-intensity RI beams continuously for long periods while maintaining sufficiently high beam quality in a ring containing an internal target.

Release from Inverse kinematics

Forward angle scattering in cm system is critical to identify transfer L

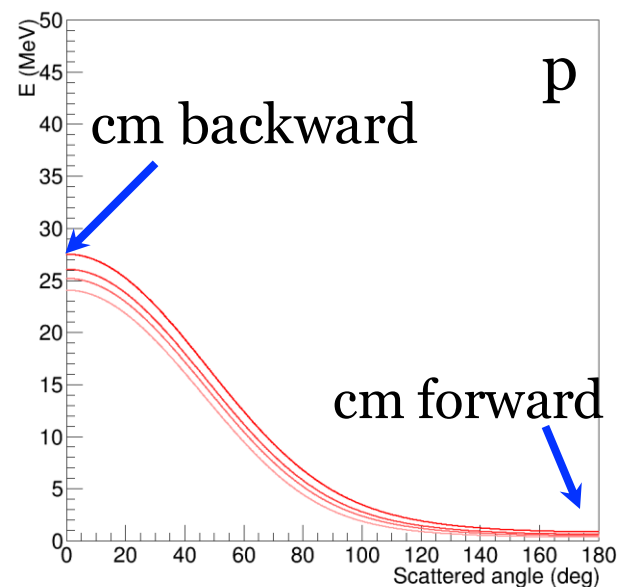
Conventional method of RI
beam experiment



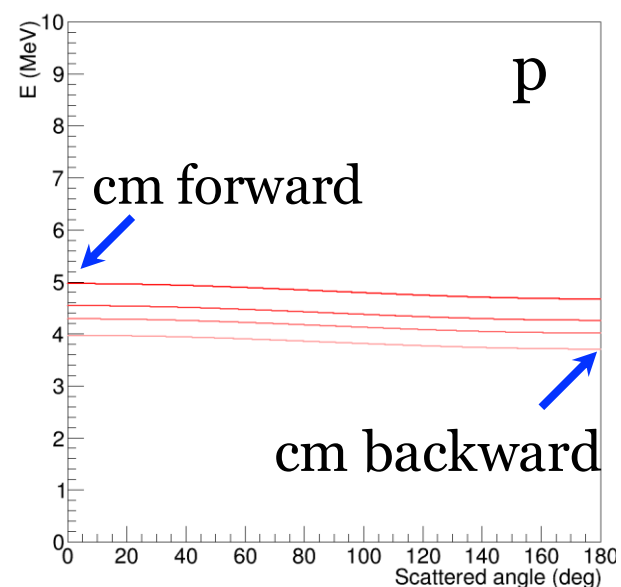
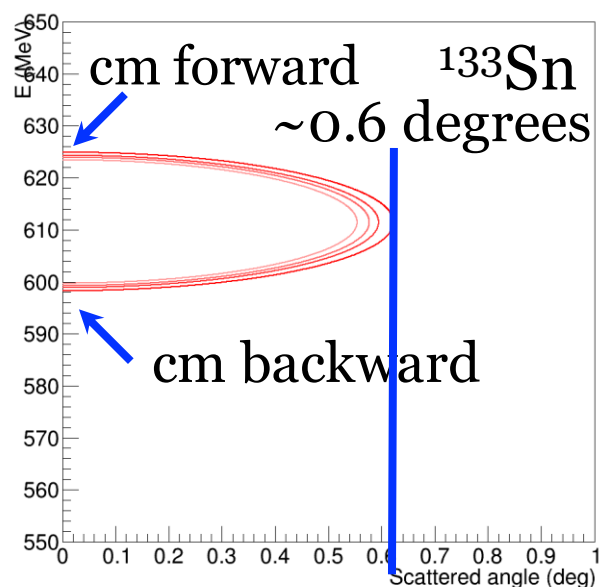
Collider experiment



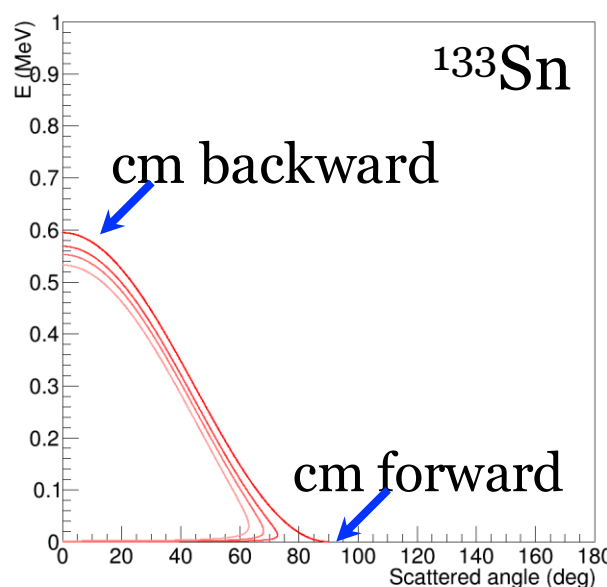
$^{132}\text{Sn}(d, p)^{133}\text{Sn}$ reaction @ 630 MeV

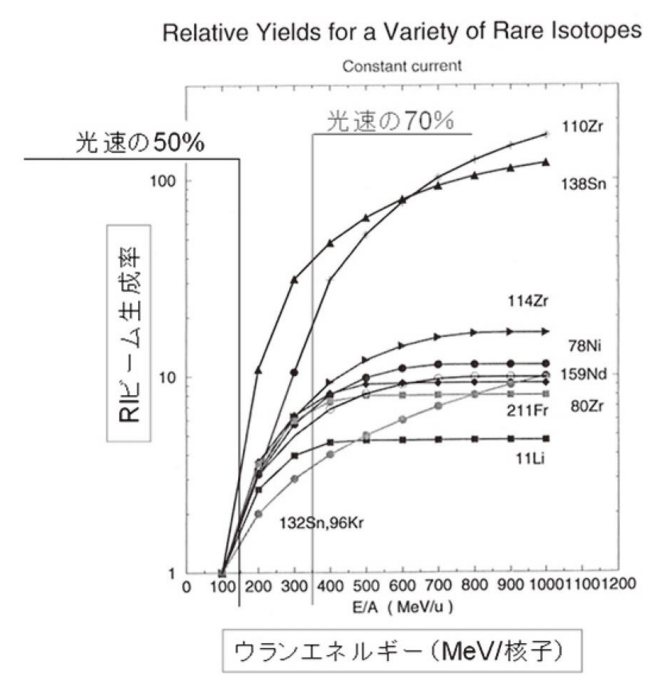
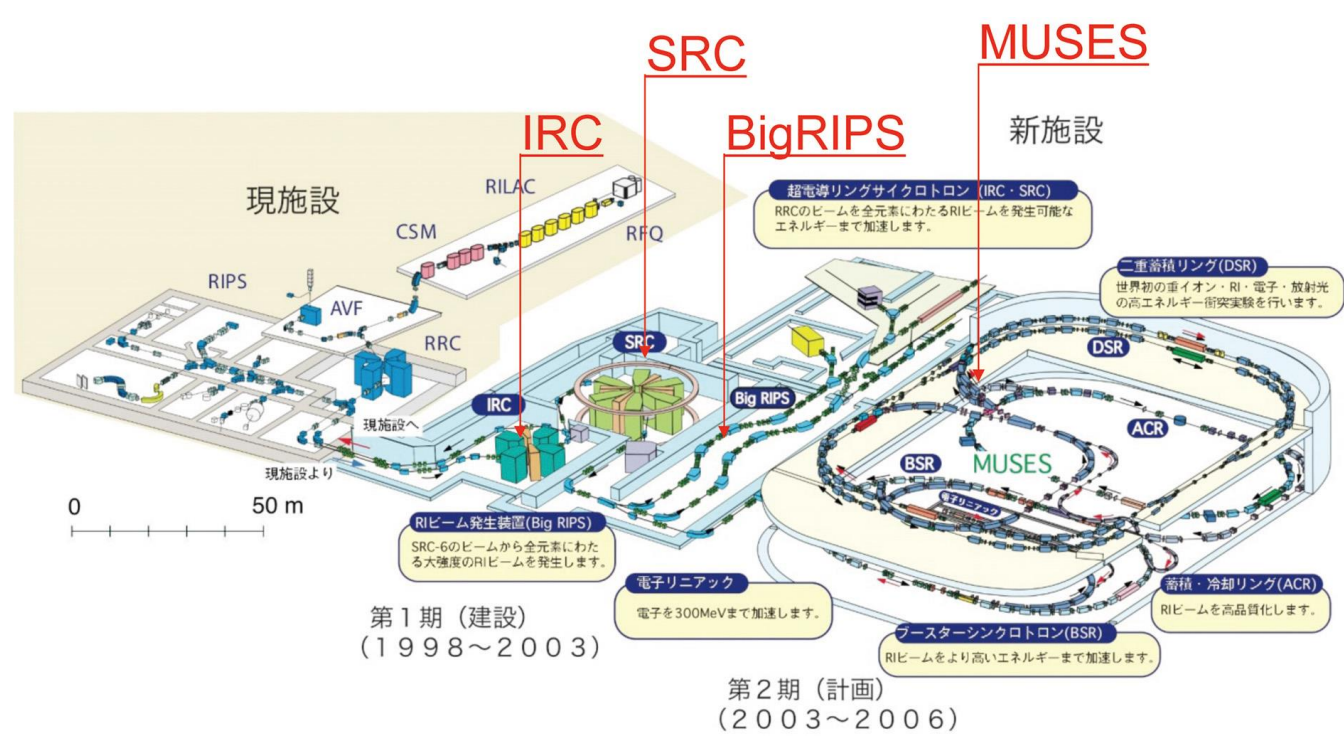


Forward angle scattering measurement is almost impossible

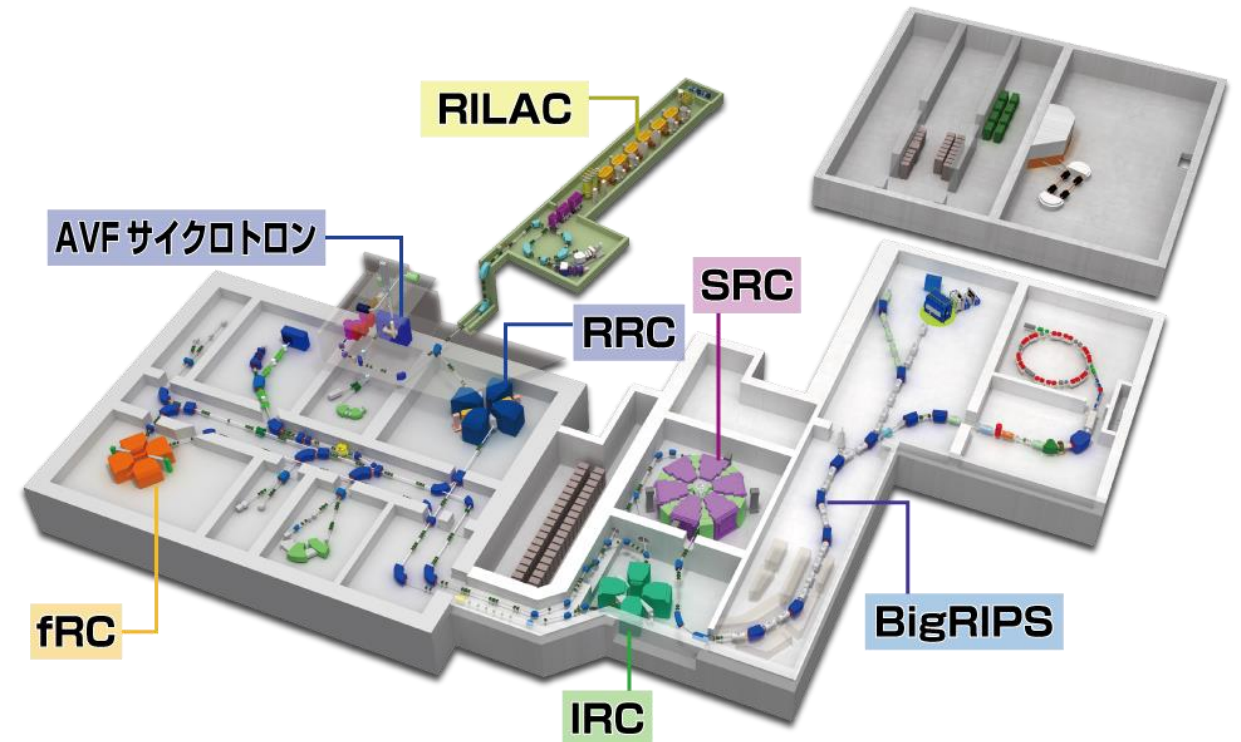
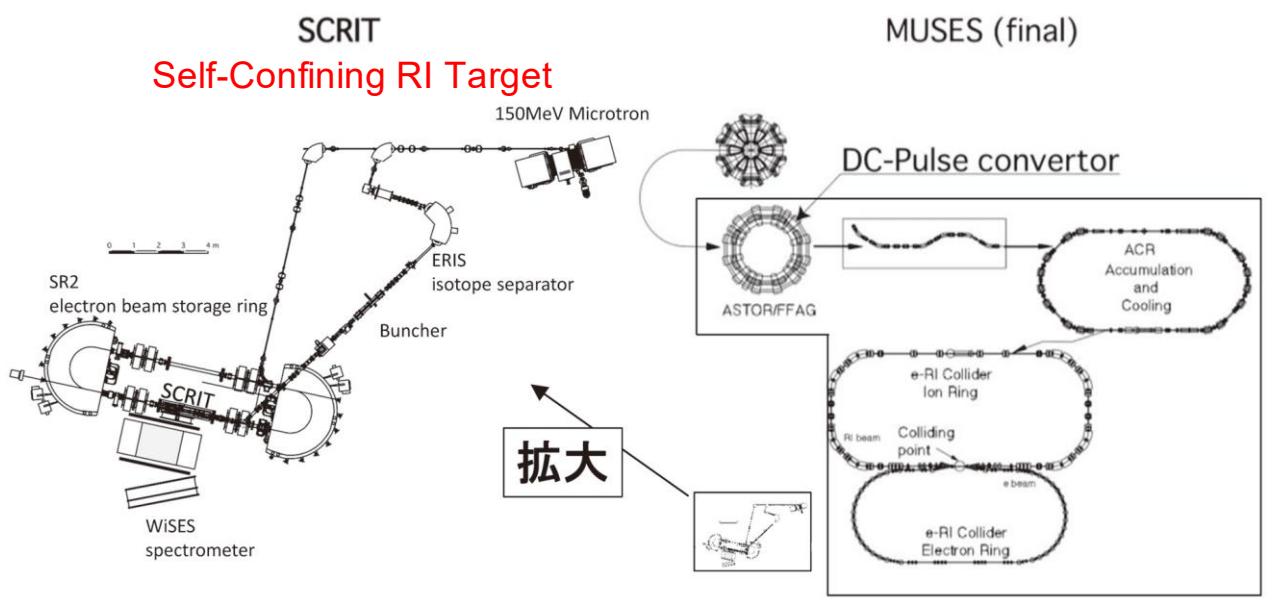


Forward angle scattering measurement is possible





RIA project Report@1999



Progress of RIKEN RI Beam Factory Project

Y. Yano, A. Goto, and T. Katayama

In 1995, two year R&D Budget up to \$2M was Approved!

atomic-mass range with the world-highest level of intensity in a wide energy range up to several hundreds MeV/nucleon. A very preliminary plan of the factory is illustrated in Fig. 1. The existing facility will be expanded to the adjacent site where a two-story building will be constructed underground.

able the efficient generation are needed high-intensity primary heavy-ions, up to uranium ions, with the energies exceeding 100 MeV/nucleon. Such heavy-ions will

Multi-Use Experimental Storage rings (MUSES)

World's first e-RI beam collider

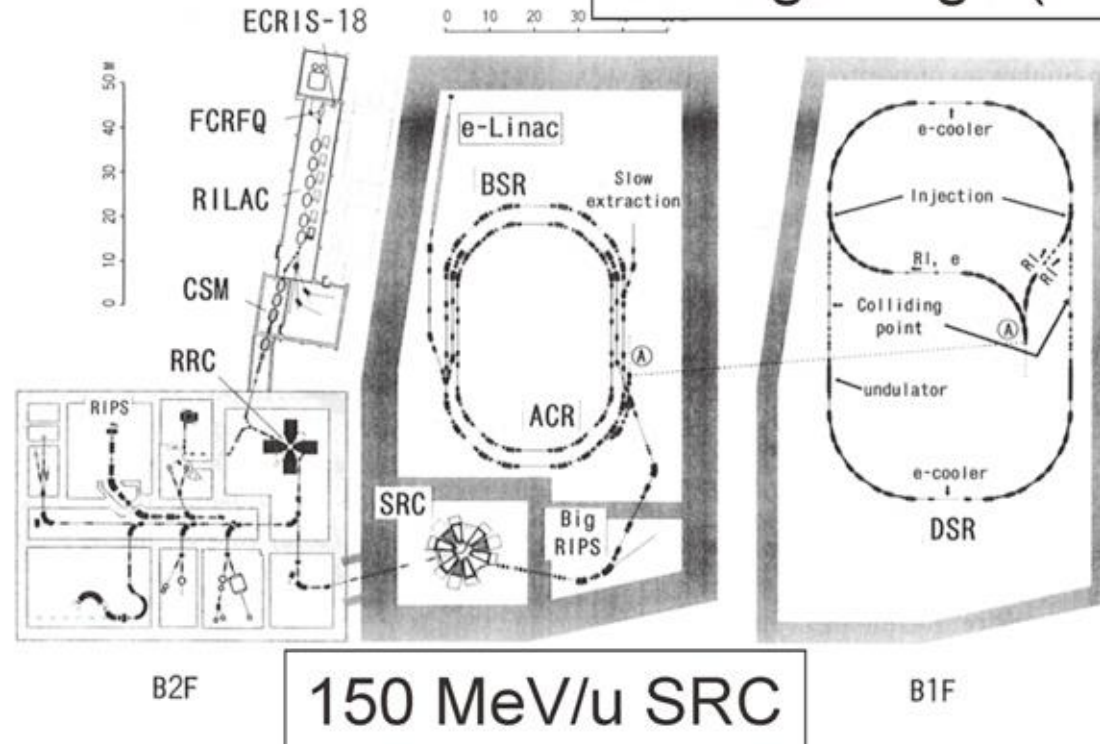


Fig. 1. Preliminary layout of the RIKEN RI Beam Factory. The SRC and the MUSES are housed in a two-story building underground. Experimental setups are not depicted.

RIKEN (The Institute of Physical and Chemical Research)
2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan

RIKEN Radioactive Isotope Beam Factory

MUSES Conceptual Design Report

T. Katayama, Y. Batygin, Y. Chiba, N. Inabe, T. Nakagawa, K. Ohtomo, T. Ohkawa,
M. Okamura, H. Sakaguchi, A. Sakumi, H. Sakurai, T. Suda, M. Takanaka, T. Takeuchi,
T. Tanabe, M. Wakasugi, S. Watanabe, T. Watanabe, K. Yano and C. C. Yun

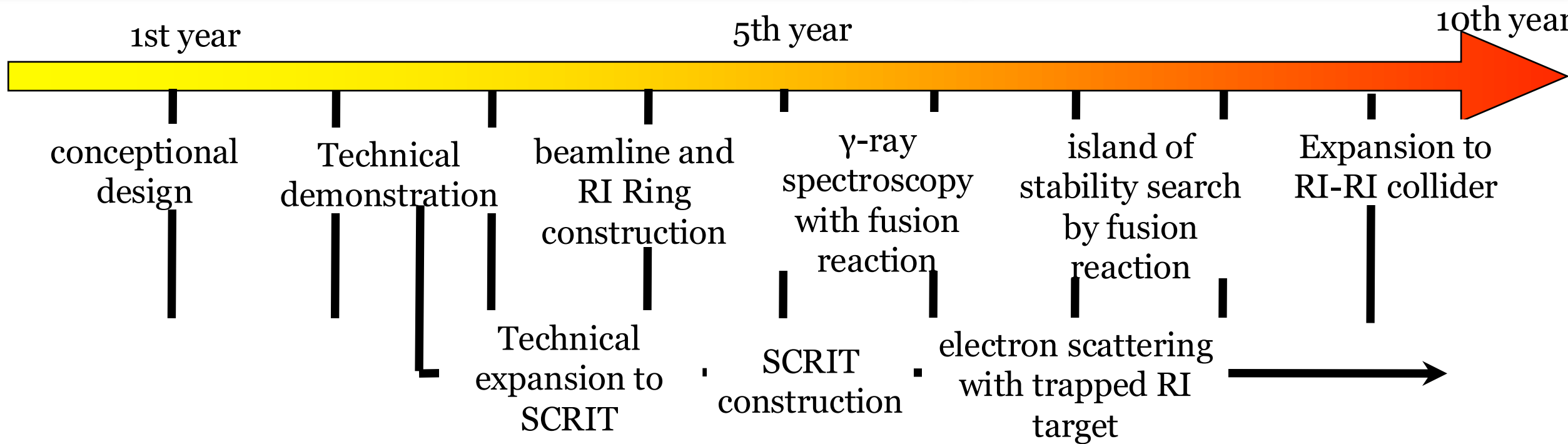
Collaboration with:

I. Meshkov, A. Sidorin, A. Smirnov, E. Syresin
Joint Institute for Nuclear Research, Dubna, Russia

A. Bolshakov, S. Kondrashev, P. Zenkevitch
Institute for Theoretical and Experimental Physics, Moscow, Russia

November 2000

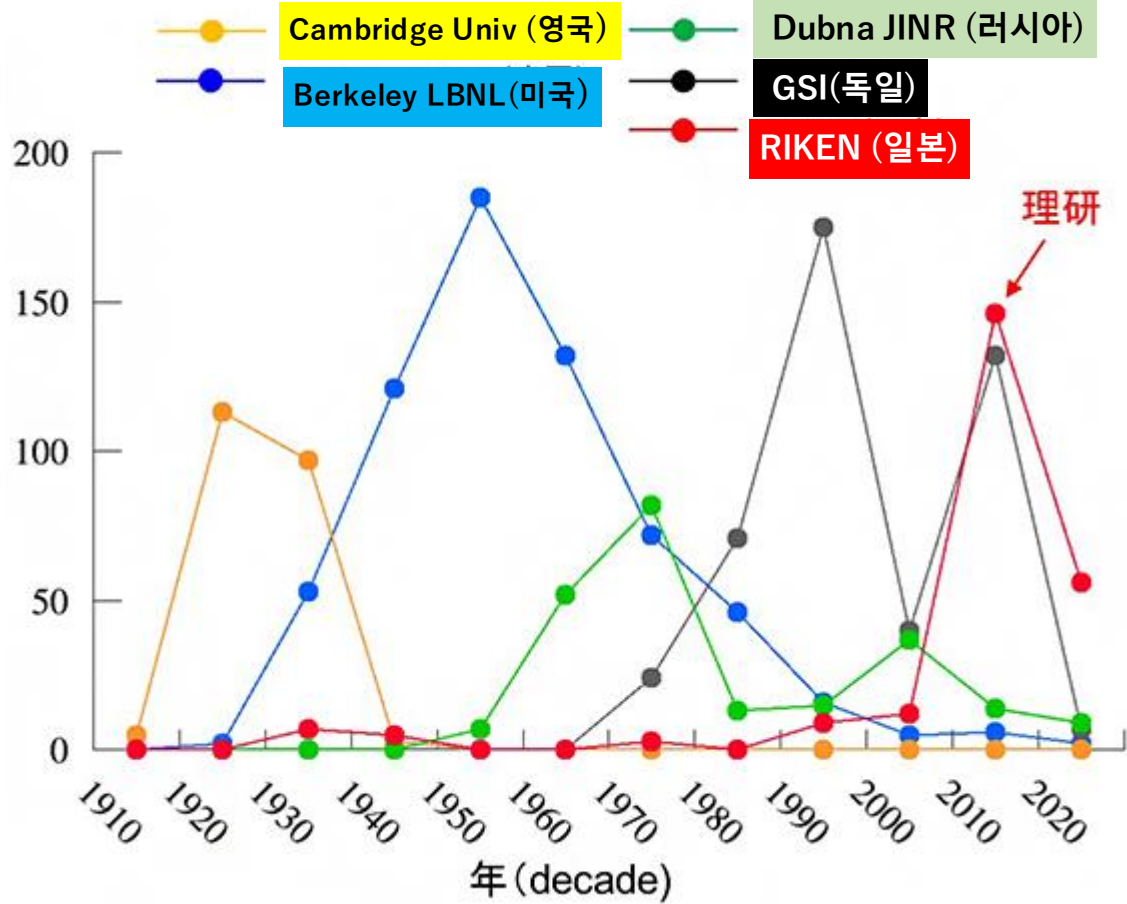
Time schedule and budget scale



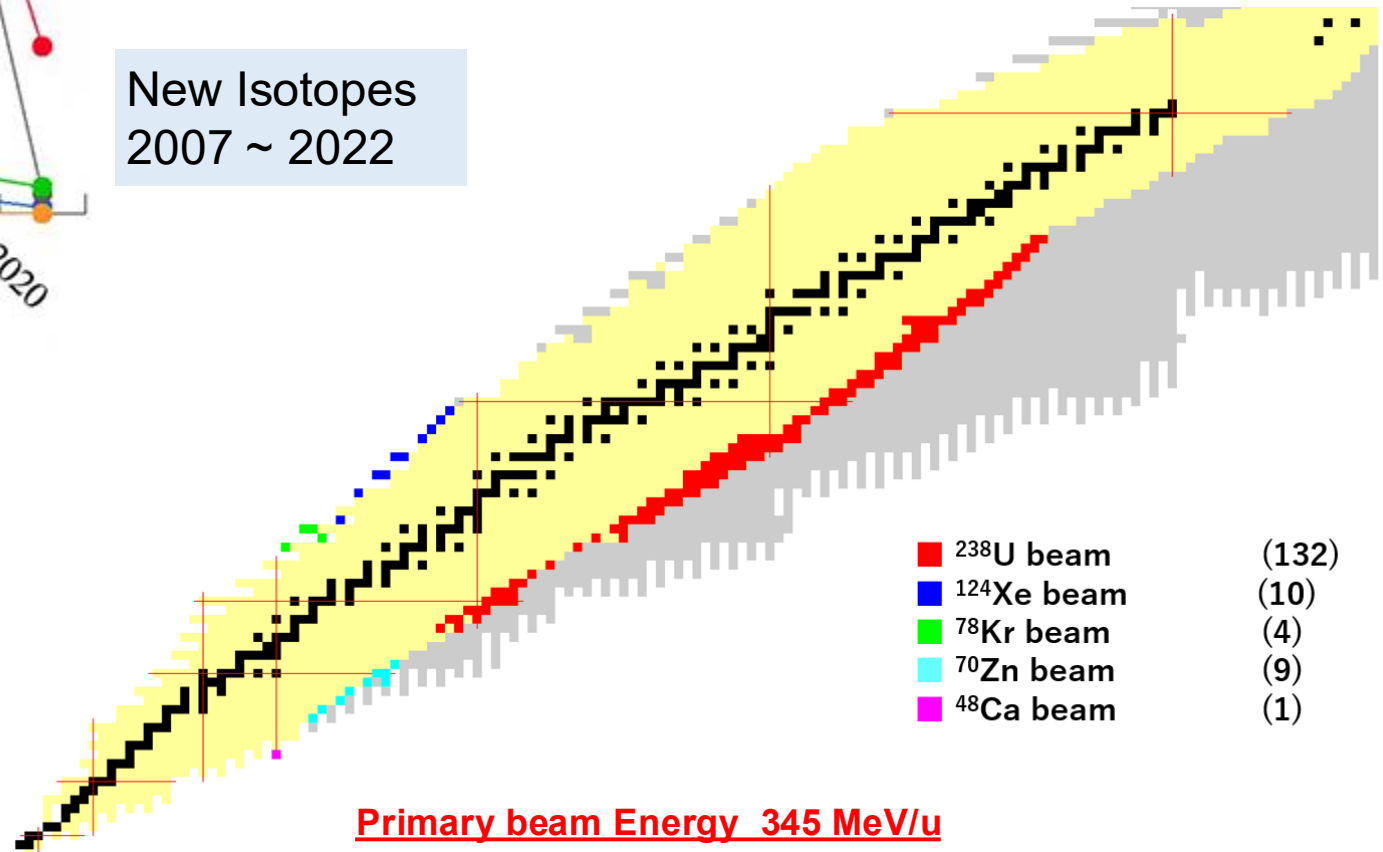
Budget scale

New terminal ion source at IRIS ISOL:	10B KRW
Beamline for ISOL to RI ring	: 2.0B KRW
RI ring	: 60B KRW
SCRIT	: 30B KRW
Personnel (PD/senior researcher)	: 10B KRW
Contingency	: 10B KRW (approx. 10% of all costs)
Total	: 122B KRW

새로운 동위원소 발견수 (10년 마다 누계수)



New Isotopes
2007 ~ 2022



Primary beam Energy 345 MeV/u

Observation of New Isotopes in the Fragmentation of Pt 198 at FRIB

JOURNAL ARTICLE · 15 2월 2024 · Physical Review Letters
DOI:<https://doi.org/10.1103/physrevlett.132.072501> · OSTI ID:2309727

Tarasov, Oleg B.

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[2]; [Kubo, T.](#) [4]; Morrissey, David J.

[2]; [Ostroumov, P. N.](#) [2]; Richardson, Isaiah

[2]; [Sherrill, B. M.](#) [2]; [Stolz, A.](#) [2]; Watters, Shane

[2]; Weisshaar, Dirk

[2]; Zhang, Tong

Five previously unknown isotopes ($^{182,183}\text{Tm}$, $^{186,187}\text{Yb}$, ^{190}Lu) were produced, separated, and identified for the first time at the Facility for Rare Isotope Beams (FRIB) using the Advanced Rare Isotope Separator (ARIS). The new isotopes were formed through the interaction of a ^{198}Pt beam with a carbon target at an energy of 186 MeV/u and with a primary beam power of 1.5 kW. Event-by-event particle identification of A, Z, and q for the reaction products was performed by combining measurements of the energy loss, time of flight, magnetic rigidity Bp, and total kinetic energy. The ARIS separator has a novel two-stage design with high resolving power to strongly suppress contaminant beams. Finally, this successful new isotope search was performed less than one year after FRIB operations began and demonstrates the discovery potential of the facility which will ultimately provide 400 kW of primary beam power.

RIBF : RI Beam Factory

FRIB : Facility for Rare Isotope Beams

First Observation of Twenty-two Exotic Isotopes Using a ^{208}Pb Primary Beam at RIBF **Open Access**

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Abstract

This letter reports the results from the first experimental study utilizing a 345-MeV/nucleon ^{208}Pb beam at the RI Beam Factory at RIKEN Nishina Center. This experiment aimed at searching for new proton- and neutron-rich isotopes beyond $Z = 50$. The BigRIPS in-flight separator and state-of-the-art radiation detectors were used to efficiently separate and reliably identify the produced isotopes. We confirmed a total of twenty-two new exotic isotopes: ^{118}Ce , ^{120}Pr , ^{179}Ho , $^{181,182}\text{Er}$, $^{184-186}\text{Tm}$, $^{188,189}\text{Yb}$, ^{191}Lu , $^{152,153,193,194}\text{Hf}$, $^{154,195,196}\text{Ta}$, $^{198,199}\text{W}$, and $^{200,201}\text{Re}$. This discovery significantly extends the known boundaries of the nuclear chart, paving the way to investigate the properties of unstable nuclei far from the β -stability line in the $Z = 58-75$ region. This region is of particular importance for exploring phenomena, such as exotic decay modes appearing on the proton-rich side and r -process nucleosynthesis associated with neutron-rich nuclei.



Projectile 208 Pb 82+
345 MeV/u
70 p nA

Fragment 42 S 16+.. 16+

Target 9 Be 180 mg/cm²

Stripper

D1 Bp=4.3633 Tm

I1_slits slits

D2 Bp=4.3633 Tm

I2_slits slits

I2_wedge

D3 Bp=4.3633 Tm

D4 Bp=4.3633 Tm

FP_PPAC0 Al 2 mg/cm²

FP_PPAC1 Al 2 mg/cm²

FP_slits slits

FP_PIN Si 504 μm

FP_SCI CsH10 100 mm

config A1900_2019 total
option FRIB_2026 dp/p
version 18.1.5 5.07%

cea

Projectile Fragmentation (E3)

