Deduction of matter and charge radii of unstable nuclei via interaction and charge-changing cross sections

σ_I σ_{cc}

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- Our results of σ_{I} in RIBF (^{A}Ne, ^{A}Mg, and ^{A}Ca)
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- New project of TRIP-S3CAN
- Summary

Introduction

Introduction

Why are **NOT** the radii data shown in “Table Of Isotope” ?

$^{8}_{3}$Li

Δ: 20945.2 *6* S$_n$: 2033.8 *3* S$_p$: 12450 *30*
Q$_{\beta-}$: 16003.6 *6*

Levels and γ-ray branchings:

0, 2$^+$, 838 *6* ms, *[BCFGHIKL]*, T=1,
%β$^-$=100, %β$^-$2α=100,
μ=+1.653560 *18*, Q=0.0317 *4*

980.8 *1*, 1$^+$, 8 *3* fs, *[ABFGHIKL]*, T=1
γ$_0$ *980.7* (†$_\gamma$100) M1

2255 *3*, 3$^+$, Γ=33 *6* keV, *[BCDFGHI]*, T=1
γ$_0$ *2255* (†$_\gamma$100) M1

mass

E_x, J^π, $T_{1/2}$, μ, Q, BR, *etc*

$\langle r_{\mathrm{ch(p)}} \rangle^{1/2}$

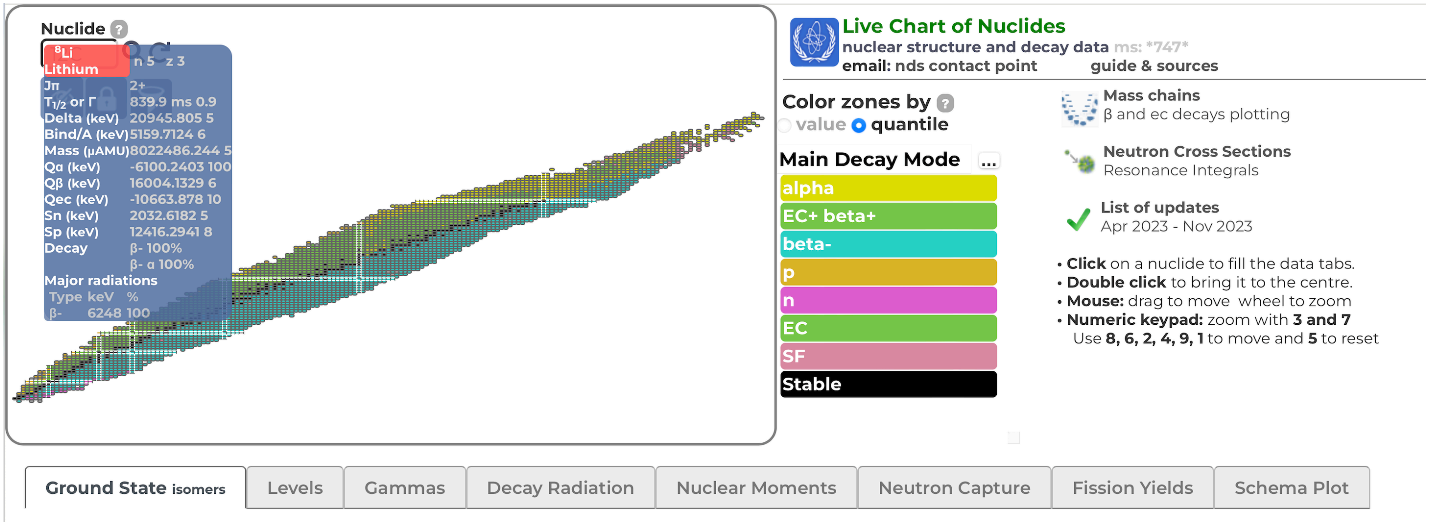
$\langle r_{\mathrm{n}} \rangle^{1/2}$

$\langle r_{\mathrm{m}} \rangle^{1/2}$

Richard B. Firestone, Table of Isotope, Eighth edition (1996).

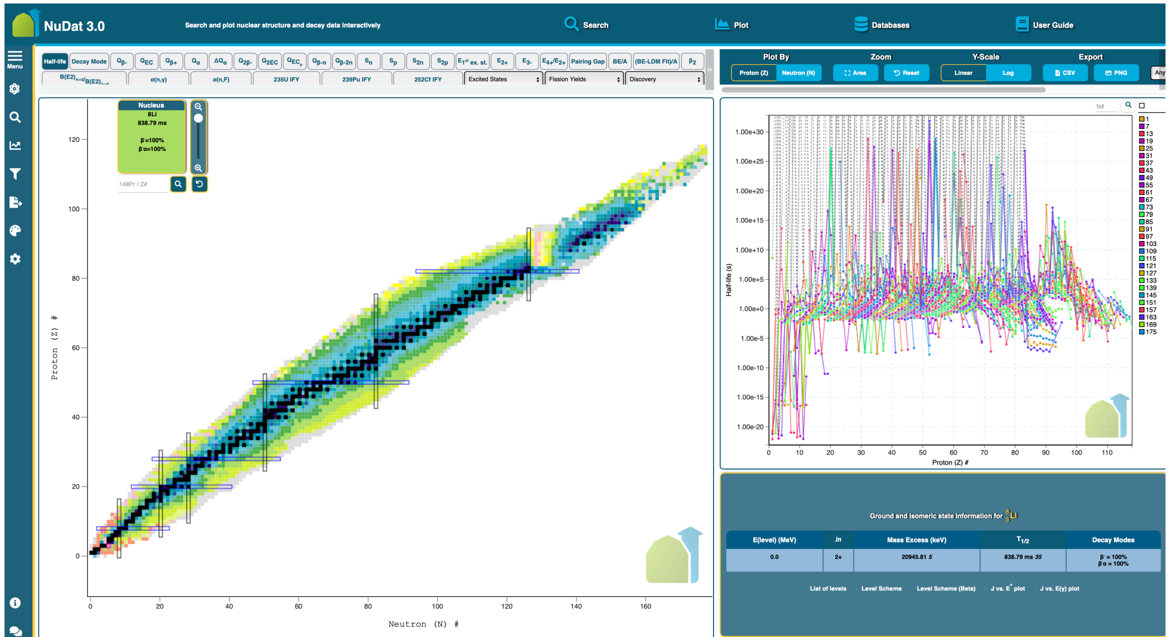
Introduction

Why are NOT the radii data shown in "Nuclear chart" ?



IAEA

NNDC



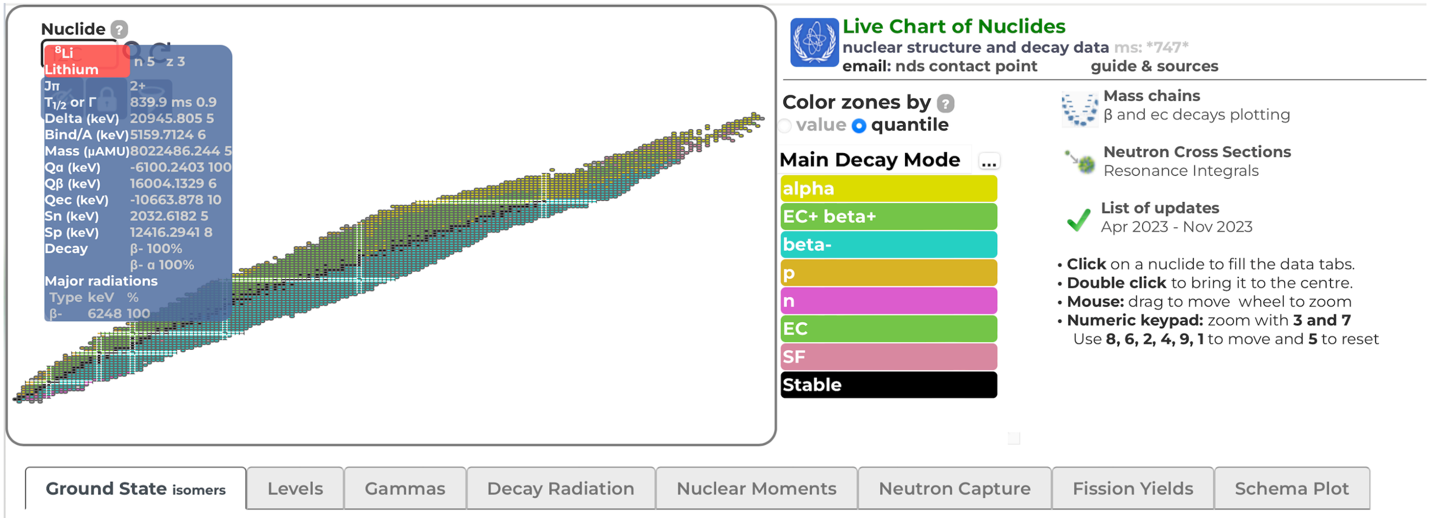
Just a historical convention?

Precision?

Applicability to unstable nuclei?

Introduction

Why are **NOT** the radii data shown in “Nuclear chart” ?



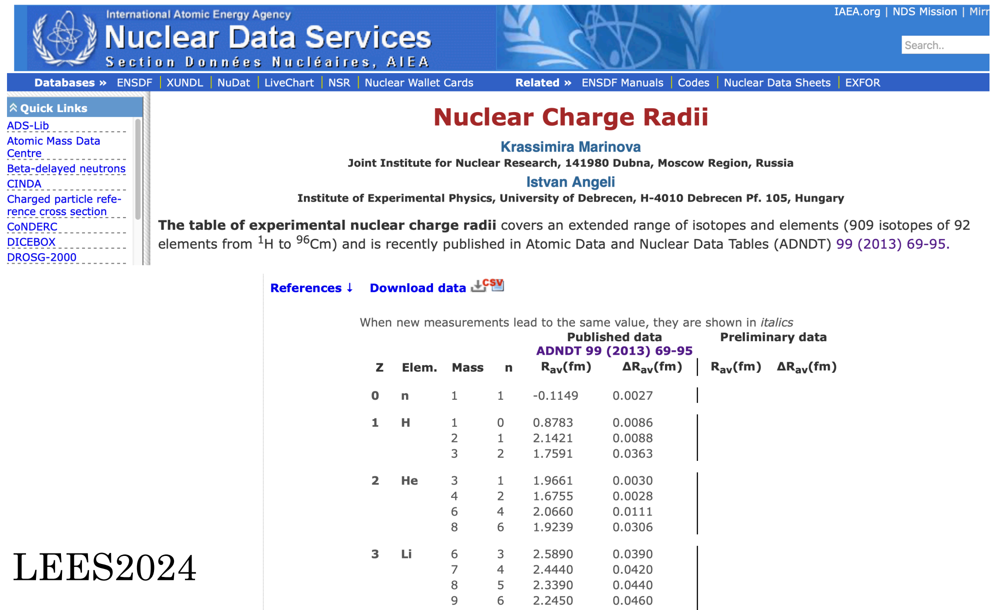
IAEA

c.f. https://www-nds.iaea.org/radii/

Just a historical convention?

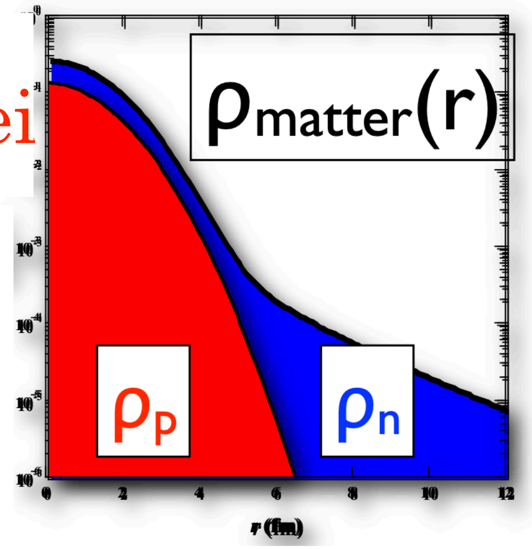
Precision?

Applicability to unstable nuclei?



How to study r & ρ of unstable nuclei?

Stable nuclei → ✓ Unstable nuclei



r_p, ρ_p

- μ-Xray,
- EM electron scattering, ✓ SCRIT
- ✓ Isotope shift,
- Hadron scattering,
- ✓ **σ_{cc} (charge-changing cross section)**

r_m, ρ_m

- ✓ Proton elastic scattering,
- ✓ **σ_I (interaction cross section)**

r_n, ρ_n

- Parity Violating electron scattering,
- SDR, GDR , ν-N scattering,
- ✓ Proton elastic scattering with diff. E
- ✓ $\left(\frac{A r_m^2 - Z r_p^2}{N}\right)^{1/2}$

Advantage of σ_I and σ_{cc} measurement

- only ~10^5 ions are needed
- all nuclei can be measured

without (atomic properties (ionization, lazer) / nuclear properties ($T_{1/2}$, J^{π}))

Disadvantage

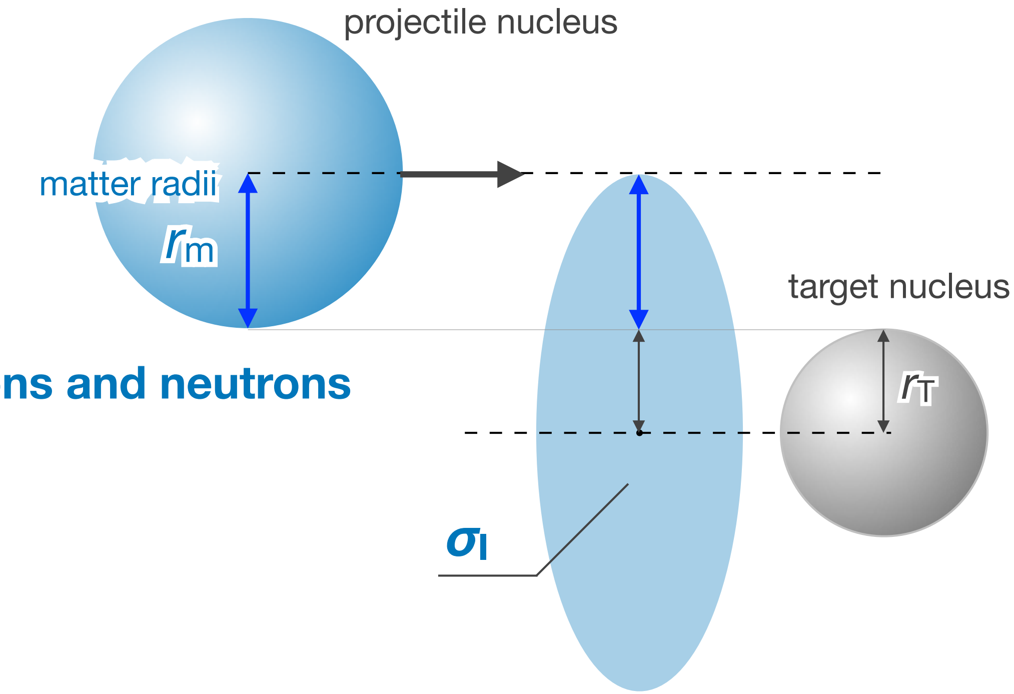
- $\Delta\sigma_I/\sigma_I$ =0.5~1% -> Δr_m = 0.01~0.02 fm
- uncertainty of nuclear reaction theory

Introduction

Interaction cross section σ_I

Total cross section with varying nuclides

$$\sigma_I \sim \pi \left(r_m + r_T\right)^2$$



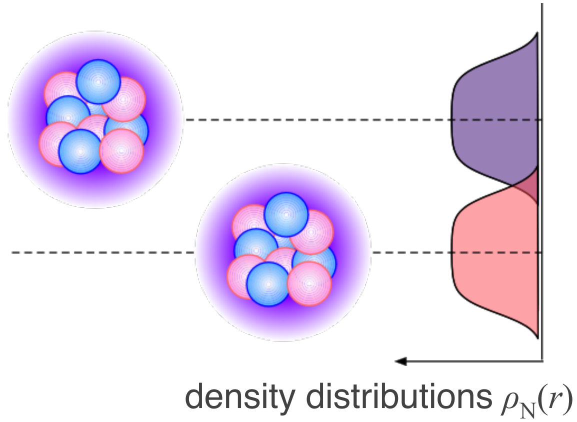
matter: sum of protons and neutrons

Glauber-type calculation

→ Sum of scattering of nucleons

Zero range optical limit approx.

$$\sigma_I(E) = \int d\boldsymbol{b} \left[1 - \exp\left(-\int d\boldsymbol{s} \sum_{i,j=(\mathrm{p\ or\ n})} \sigma_{i,j}(E)\rho^{\mathrm{T}(j)}(\boldsymbol{s}-\boldsymbol{b})\rho^{\mathrm{P}(i)}(\boldsymbol{s})\right)\right]$$

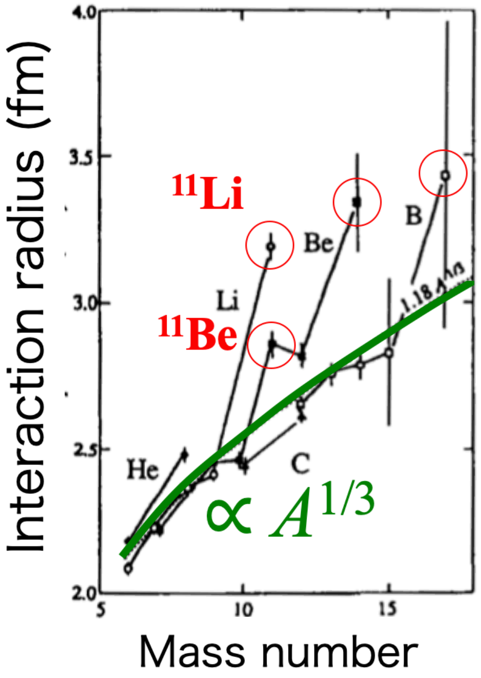


- $\sigma_{NN}(E)$ — nucleon-nucleon scattering cross sections
- $\rho^T(r)$ — density distribution of target nuclei
- $\rho^P(r)$ — **density distribution of projectile nuclei**
  ⇄ matter radii of projectile nuclei

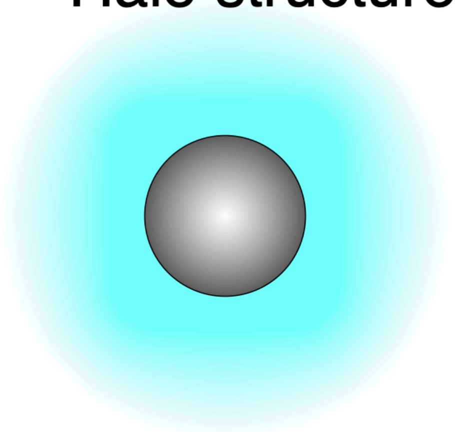
Introduction

- Disappearance of $N = 8$

I. Tanihata *et al*., Proc. for Conf. "Radioactive Nuclear Beams", p.429 (World Scientific Berkeley, California, USA, 1989)

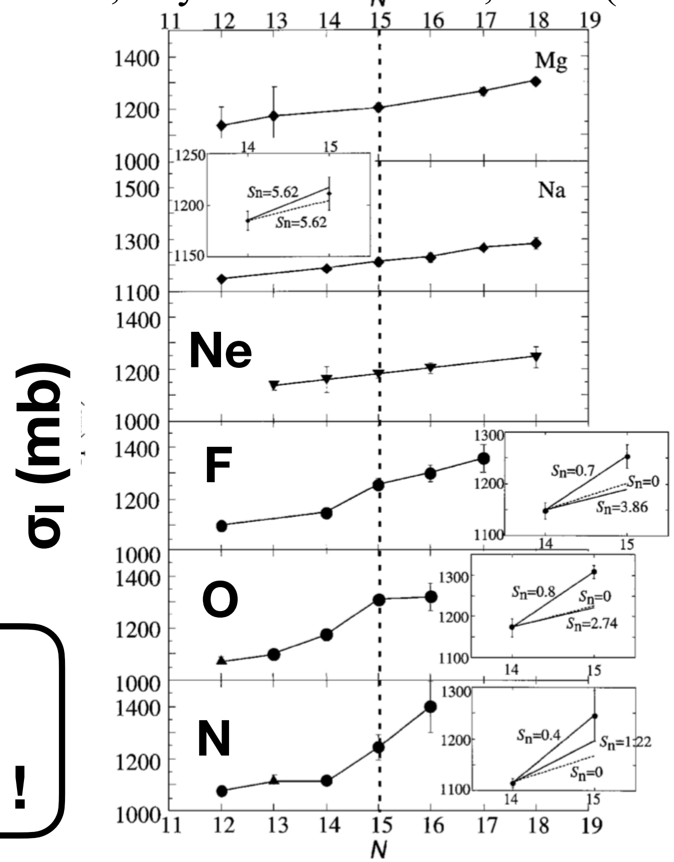


Halo structure



- New Magic number of $N = 16$

A. Ozawa et al., Phys. Rev. Lett. 84 , 5493 (2000).

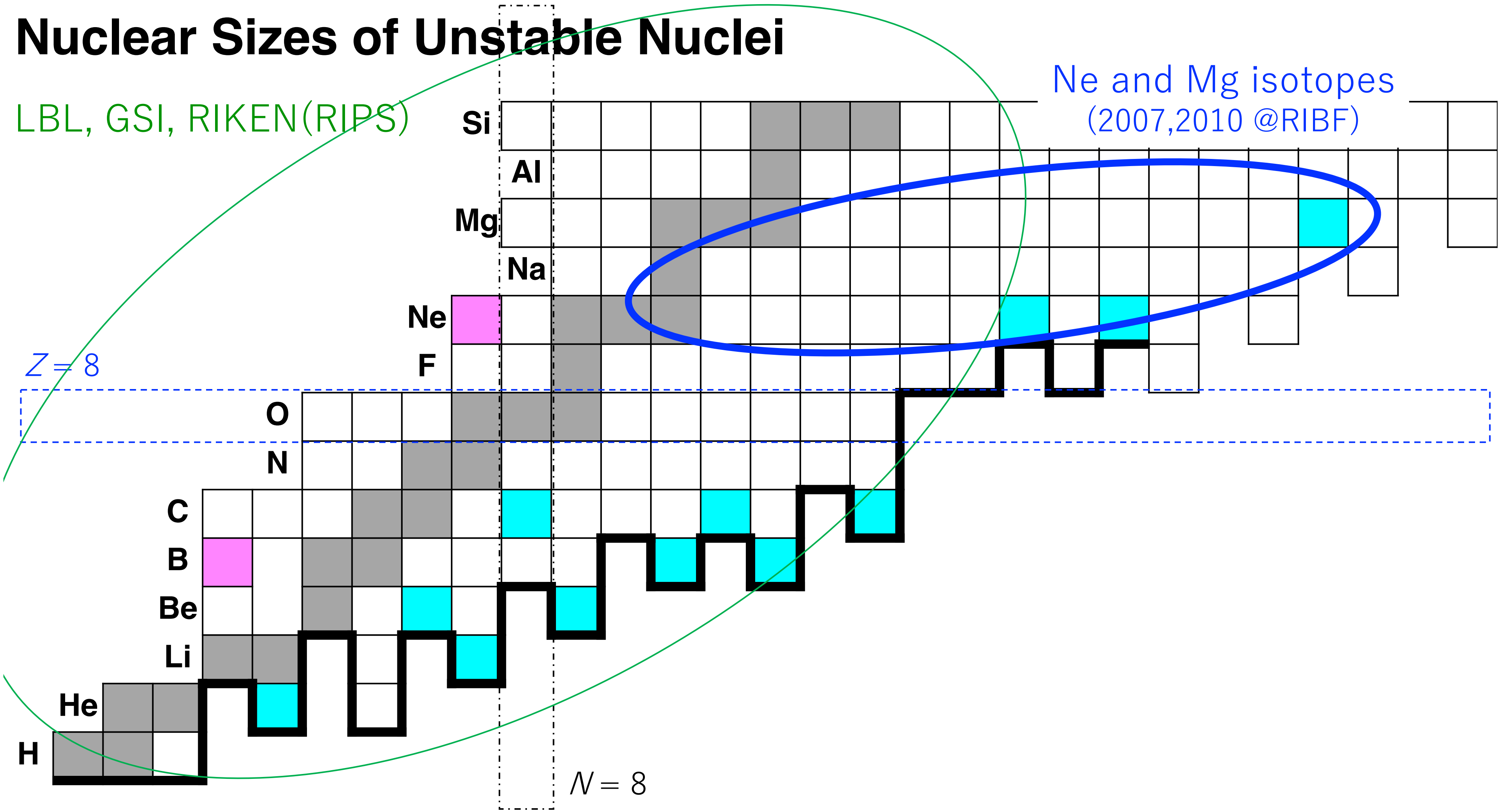


For weakly bind system,

large σ_I → halo → valence *n* is *s* orbital !

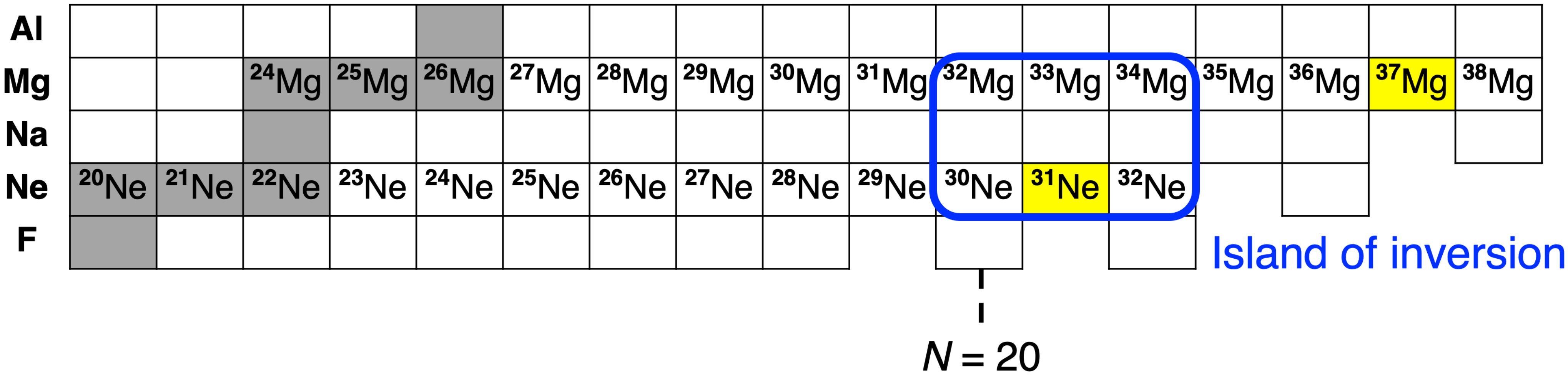
Our results of σ_I in RIBF (^{A}Ne, ^{A}Mg, ^{A}Ca)

Deformed halo of ^{31}Ne & ^{37}Mg



Deformed halo of ^{31}Ne & ^{37}Mg

σ_I measurements at RIBF, RIKEN ~ Ne and Mg isotopes ~



σ_I on C target @240*A* MeV

$^{20\text{-}32}$Ne, $^{24\text{-}38}$Mg

M. Takechi *et al.*, PLB **707**, 357-361 (2012).
M. Takechi *et al.*, PRC **90**, 061305(R) (2014).

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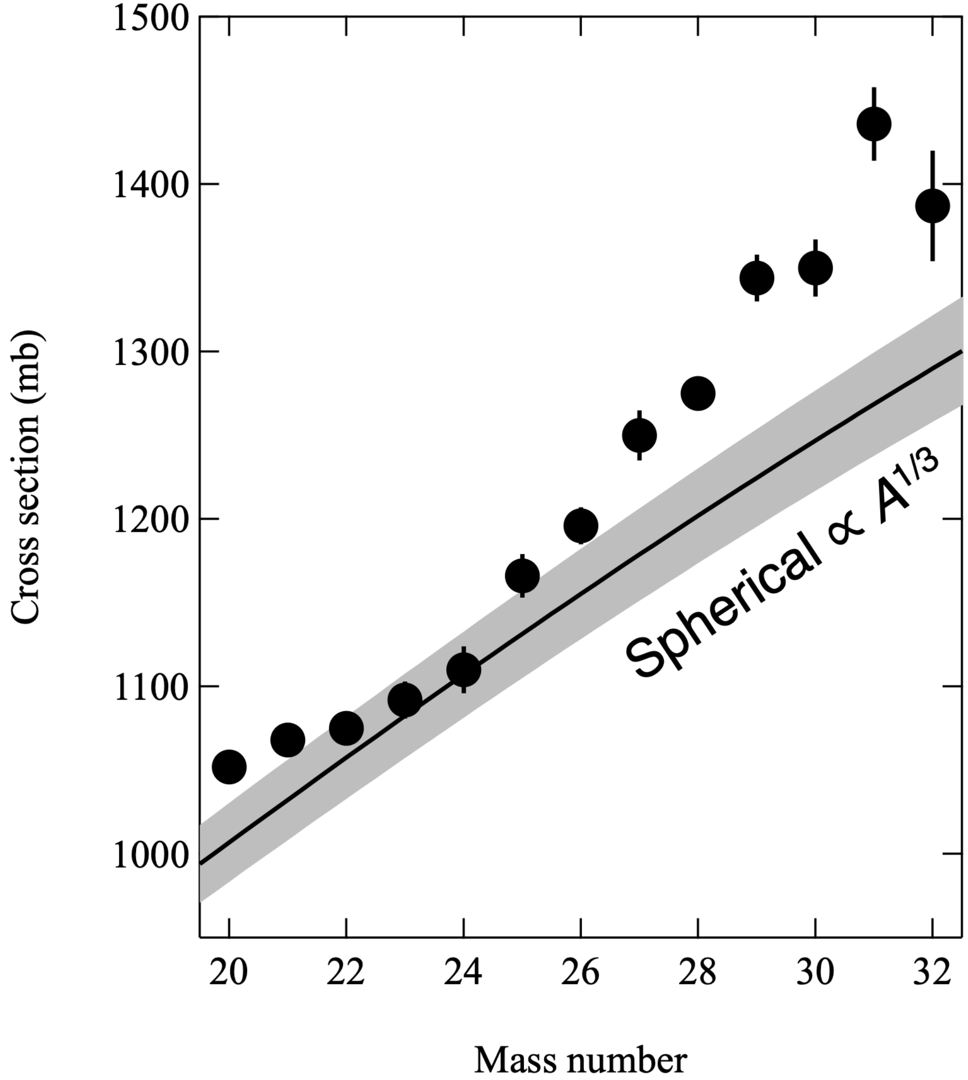


Deformed halo of ^{31}Ne & ^{37}Mg

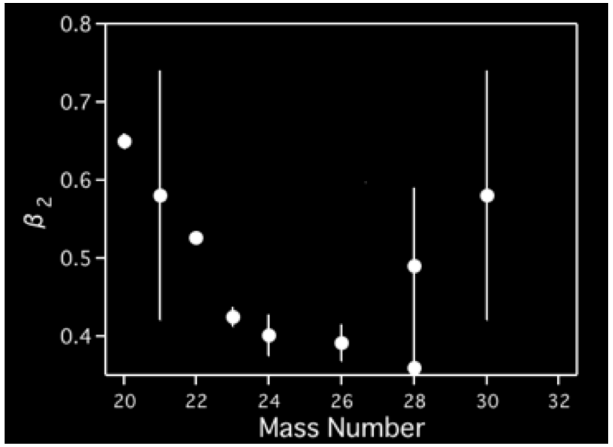
σ_I measurements at RIBF, RIKEN ~ Ne and Mg isotopes ~

σ_I on C target @240A MeV

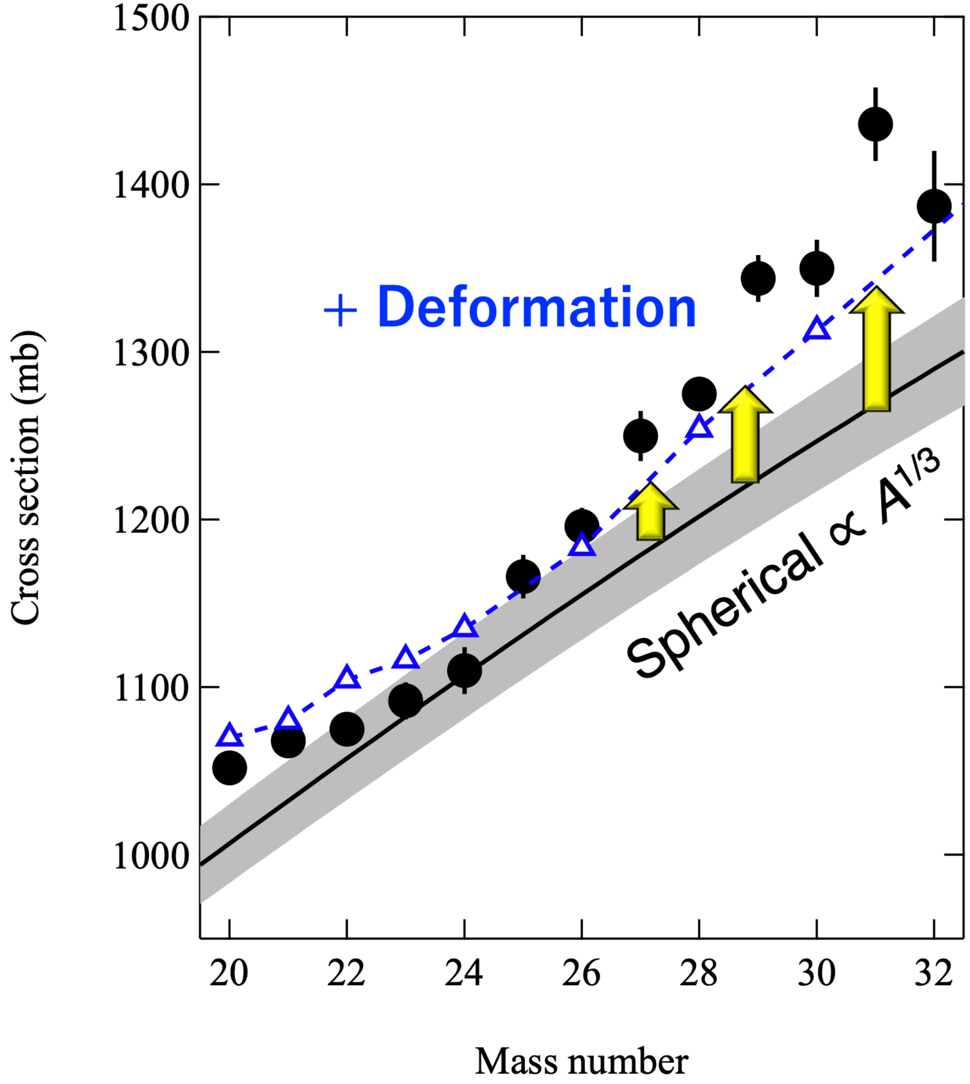
$^{20-32}$Ne

M. Takechi *et al.*, PLB **707**, 357-361 (2012).

$$\langle r^2\rangle^{1/2}_{\rm def} = \langle r^2\rangle^{1/2}_{\rm sph}\sqrt{1+\frac{5}{4\pi}\beta_2^2}$$



Deduced from Q moments, B(E2)



Deformed halo of ^{31}Ne & ^{37}Mg

σ_I measurements at RIBF, RIKEN ~ Ne and Mg isotopes ~

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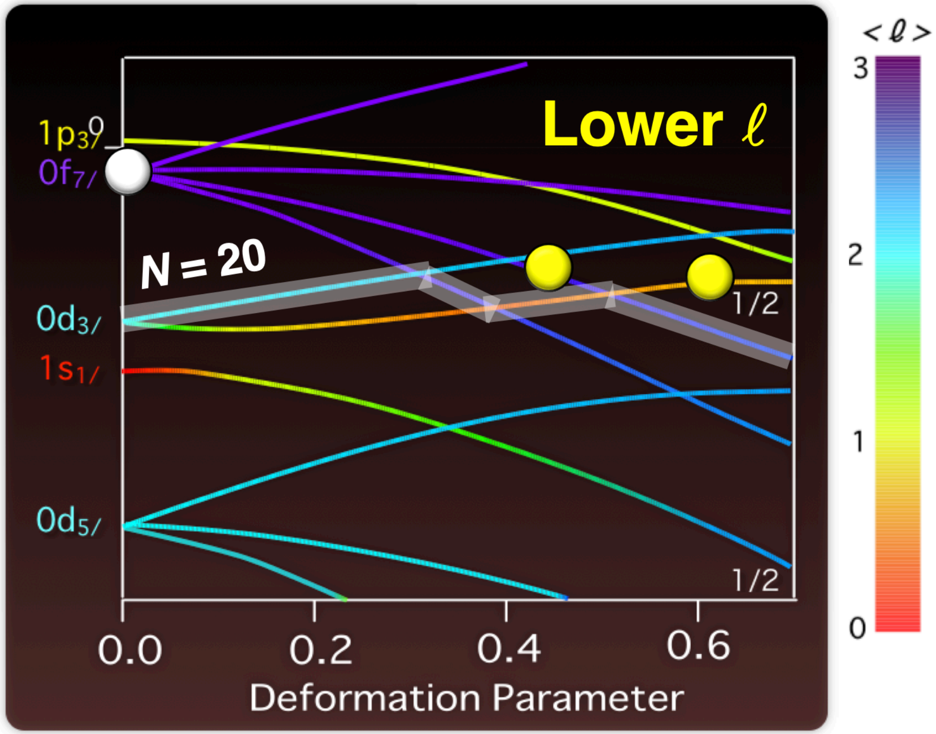
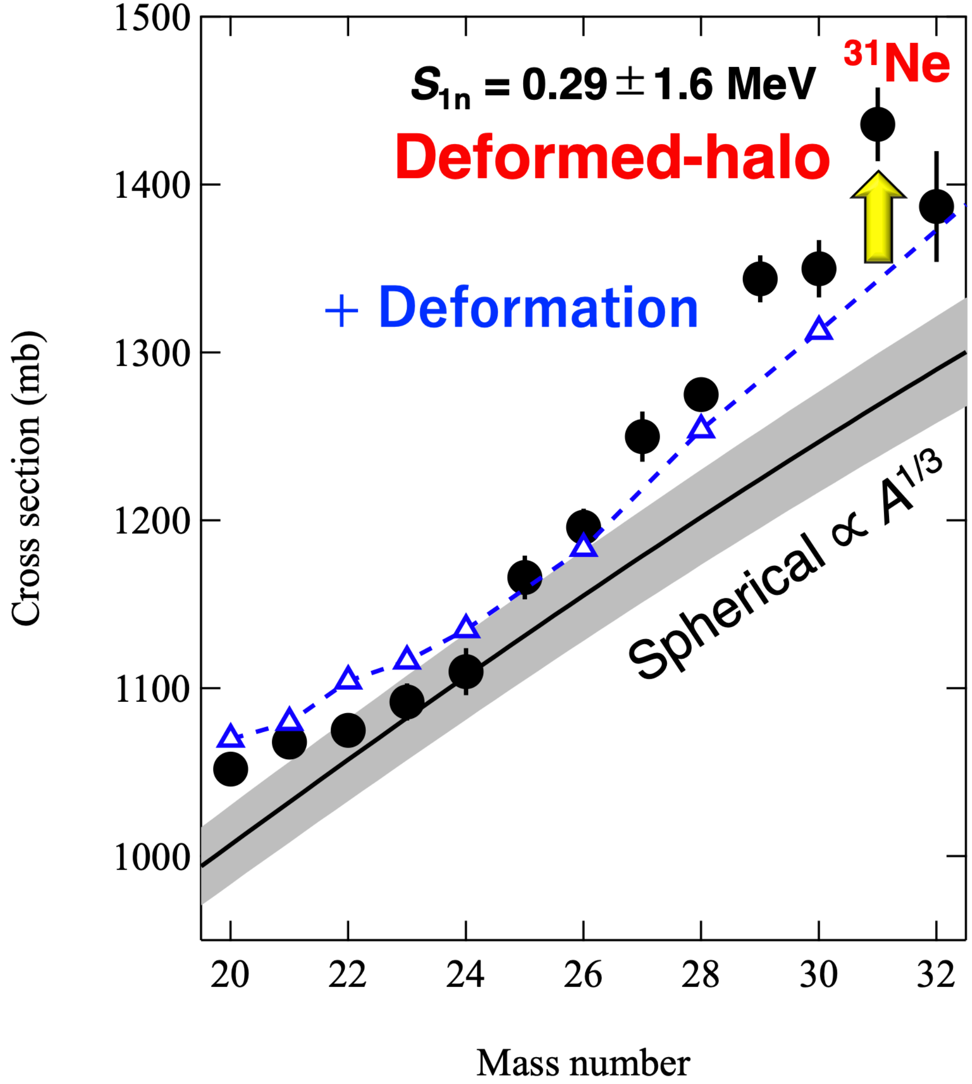
$^{20\text{-}32}$Ne

M. Takechi *et al.*, PLB **707**, 357-361 (2012).

^{30}Ne + 1n





Deformed halo of ^{31}Ne & ^{37}Mg

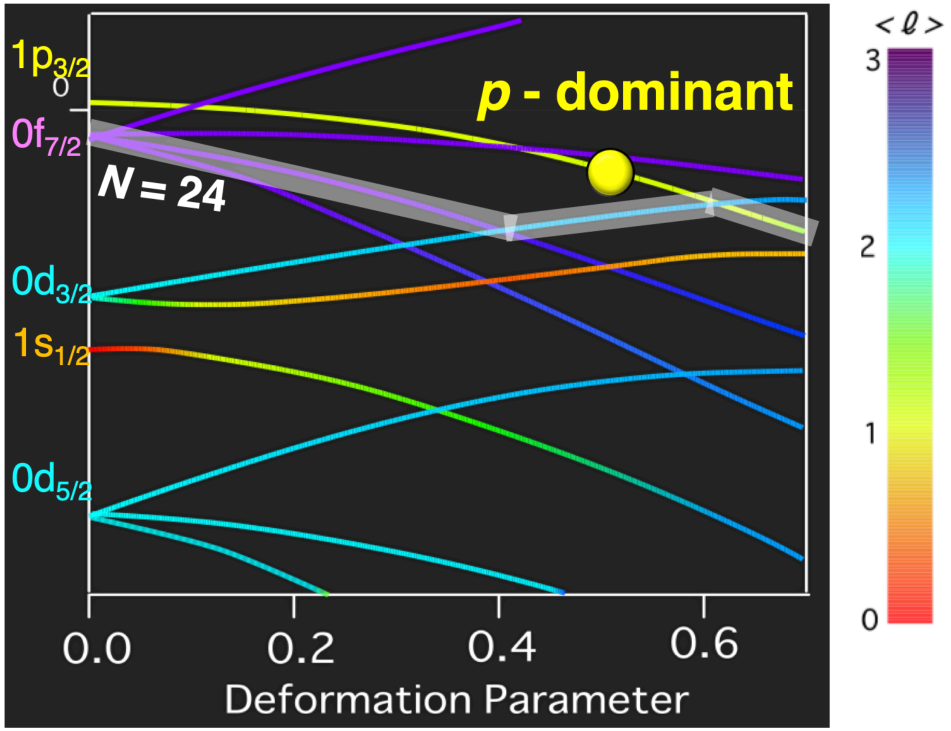
σ_I measurements at RIBF, RIKEN ~ Ne and Mg isotopes ~

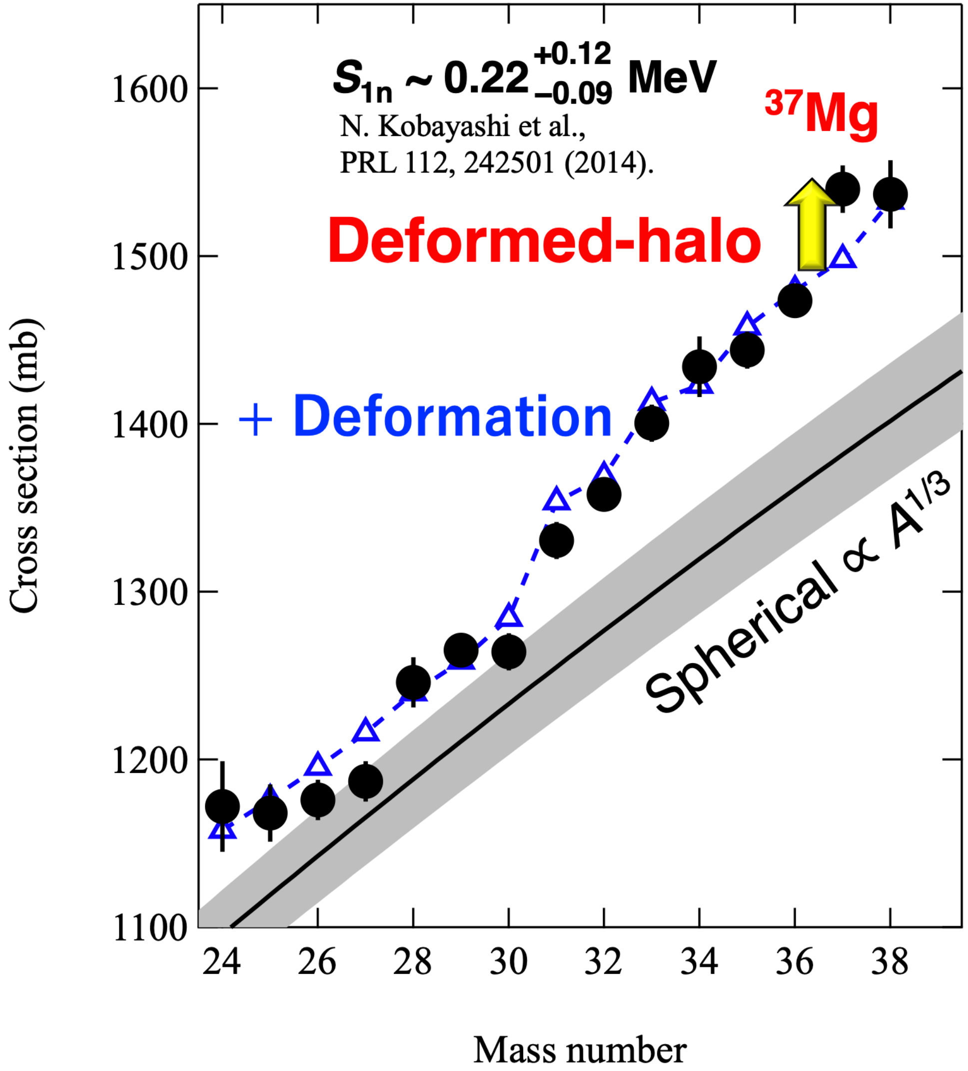
σ_I on C target @240*A* MeV

$^{24\text{-}38}$Mg

M. Takechi *et al.*, PRC **90**, 061305(R) (2014).

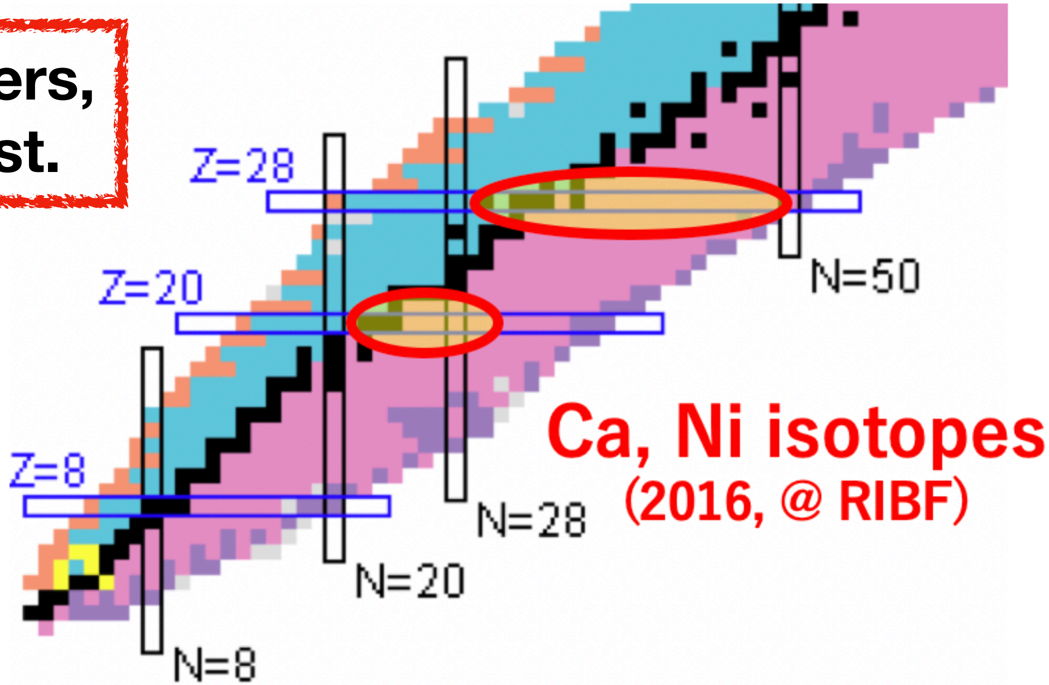
^{36}Mg + 1n





Swelling of Doubly Magic ^{48}Ca

Since Z = 20 & 28 are magic numbers, many theoretical calculations exist.



Nuclear Size of Ca Isotopes beyond *N* = 28

Charge radius

Unexpectedly large enhancement beyond *N* = 28

R. F. Garcia Ruiz *et al.*, Nature Phys. **12**, 594 (2016).

Isotopic chain ⟺ Excess neutrons

Matter / Neutron radius

Only stable isotopes $^{40,42,44,48}Ca$

(hadron elastic scattering)

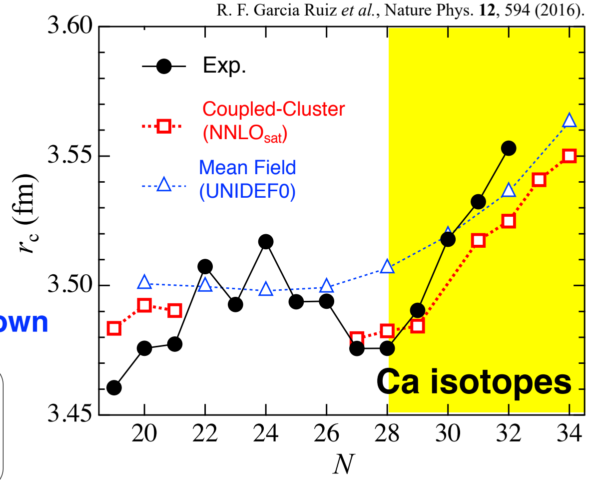
Change of matter/neutron radii is unknown

Purpose

σ_I measurements of $^{42-51}Ca$

→ Matter radii across *N* = 28

R. F. Garcia Ruiz *et al.*, Nature Phys. **12**, 594 (2016).



large enhancement beyond *N* =28 for

R_{ch}

Swelling of Doubly Magic ^{48}Ca

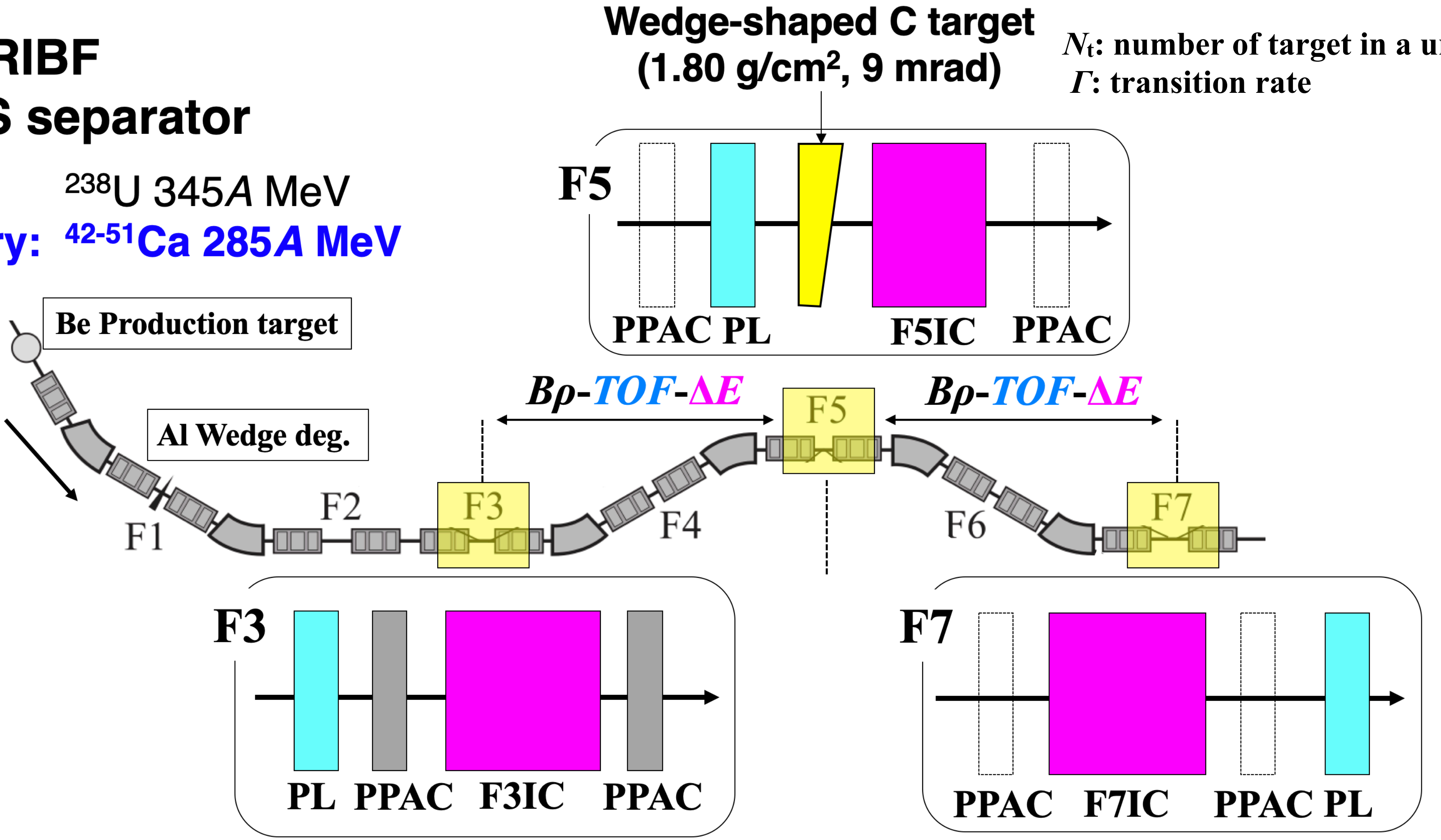
$$\sigma_{\mathrm{I}} = -\frac{1}{N_t}\ln\left(\frac{\Gamma}{\Gamma_{\mathrm{empty}}}\right)$$

σ_I Measurements at RIBF

N_t: number of target in a unit area
Γ: transition rate

RIKEN RIBF
BigRIPS separator

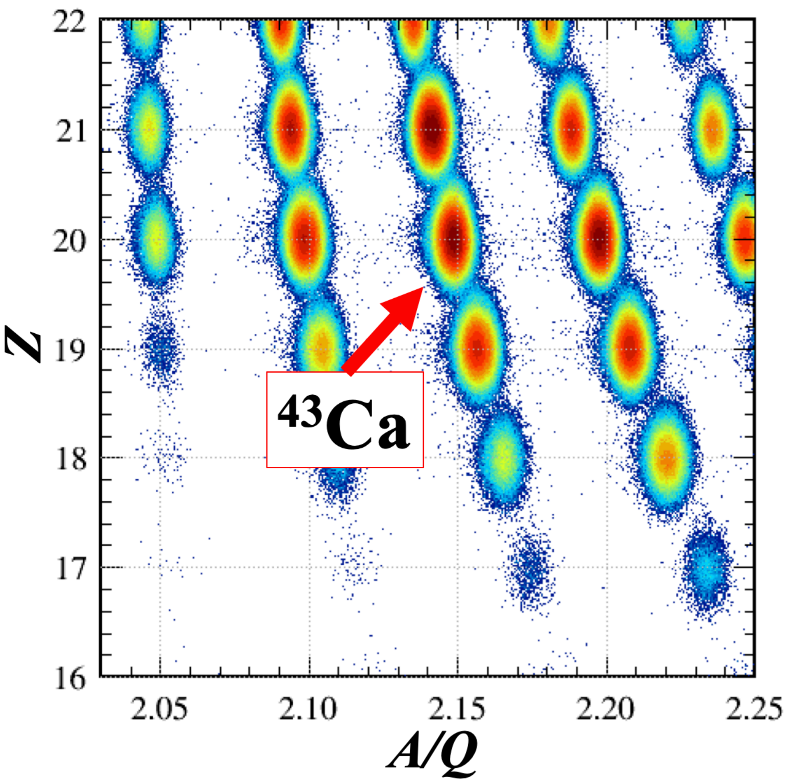
Primary: ^{238}U 345*A* MeV
Secondary: $^{42-51}$Ca 285*A* MeV



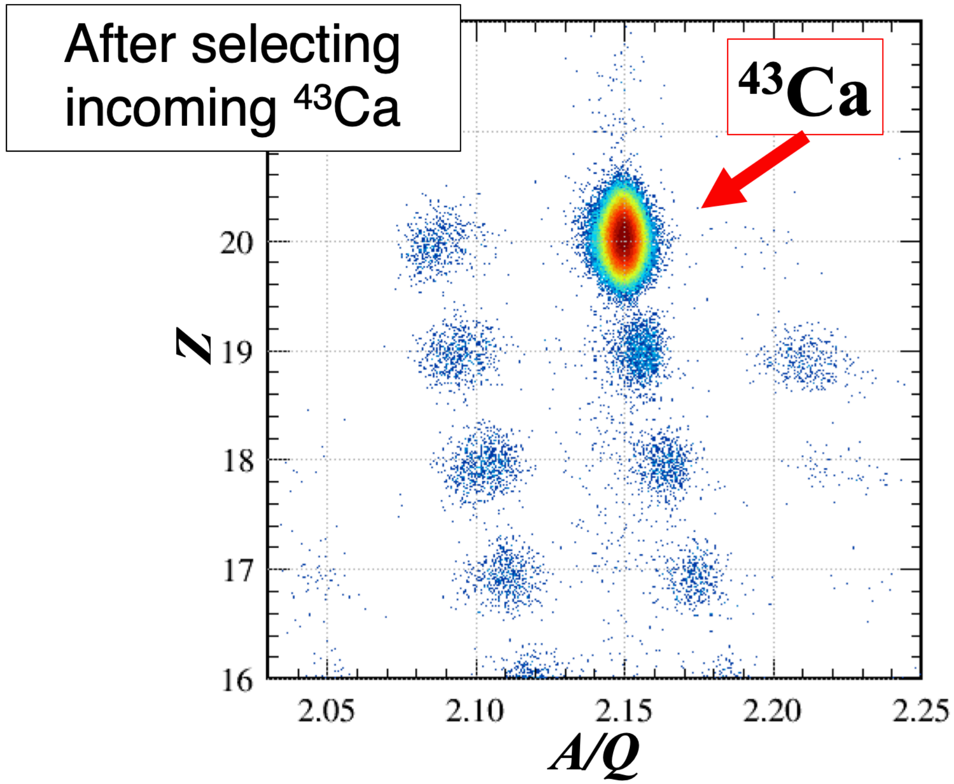
Swelling of Doubly Magic ^{48}Ca

Particle Identification for σ_I

Upstream (F3-F5)
Bρ – TOF – ΔE

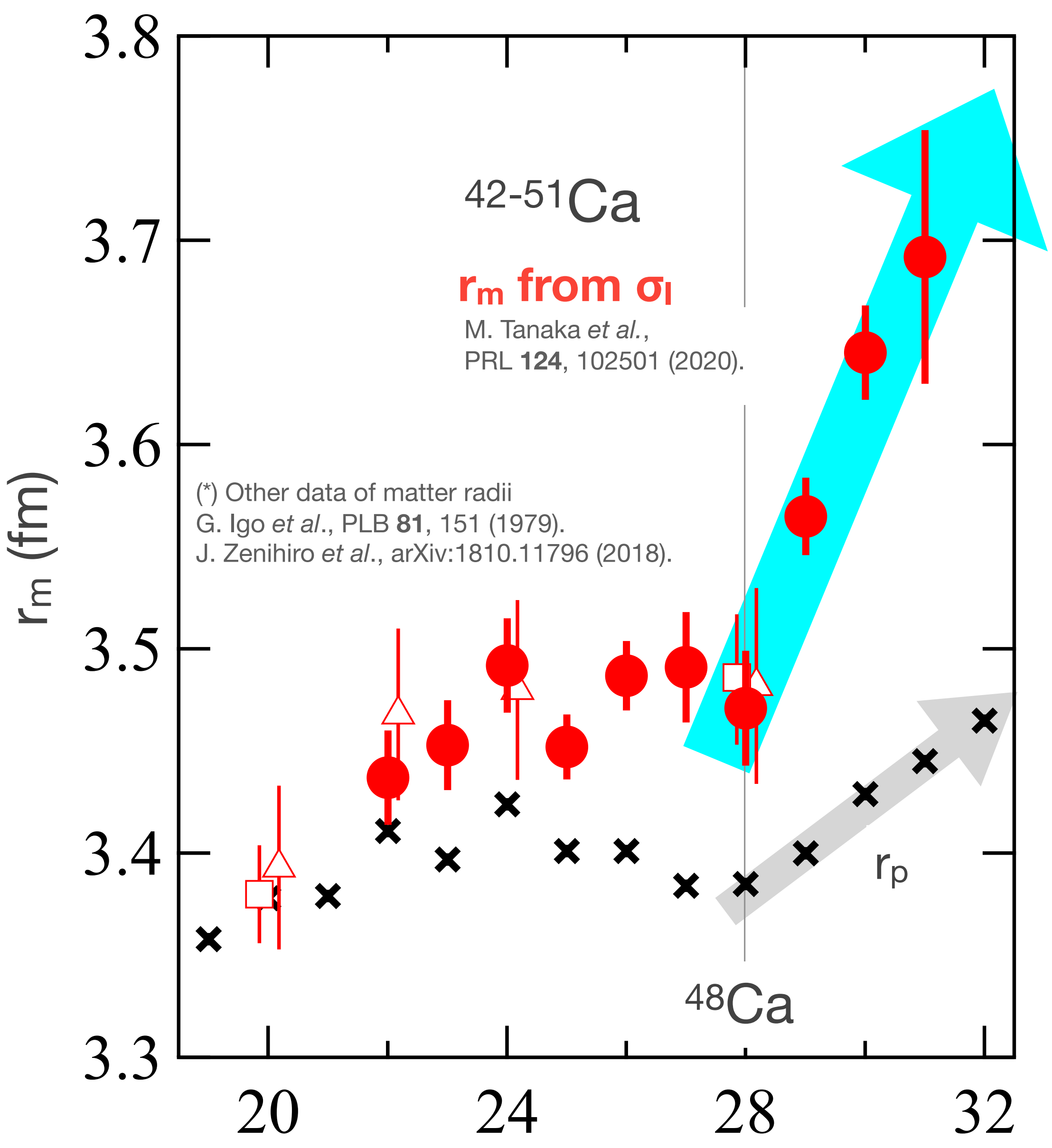


Downstream (F5-F7)
Bρ – TOF – ΔE

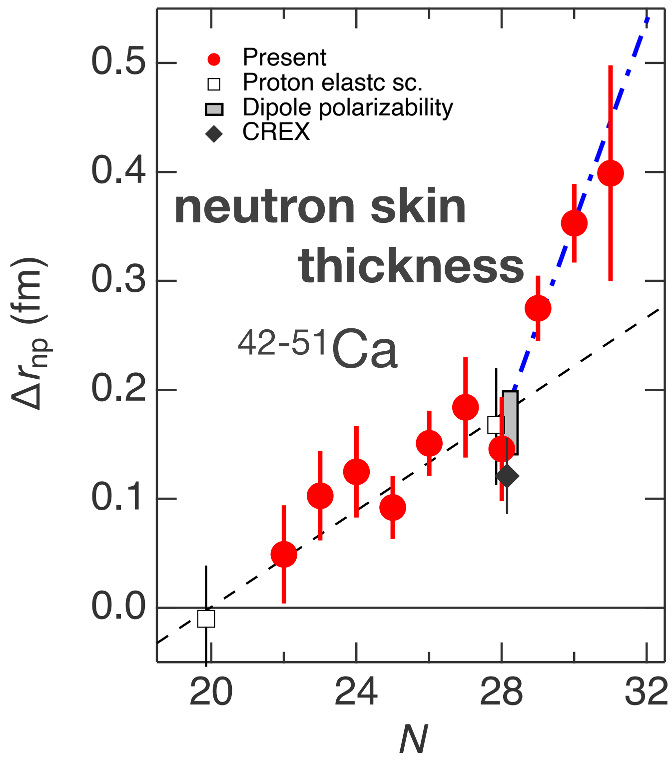


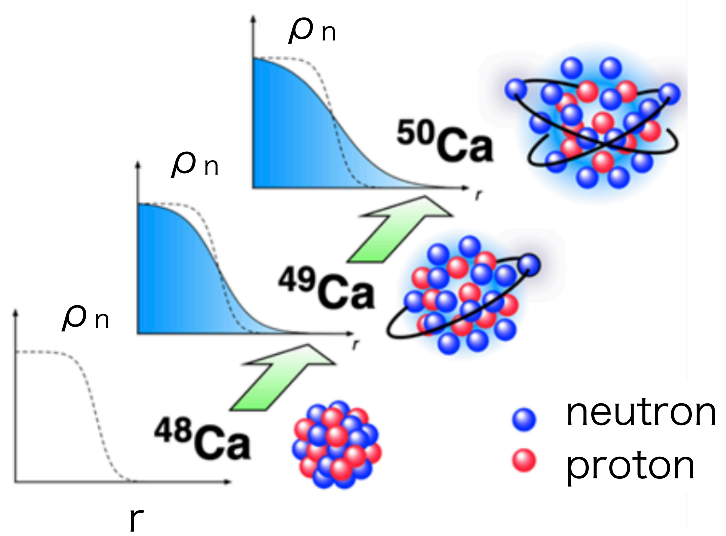
Swelling of Doubly Magic ^{48}Ca

Other data of neutron skin
J. Zenihiro *et al.*, arXiv:1810.11796 (2018).
J. Birkhan *et al.*, PRL **118**, 252501 (2017).
D. Adhikari *et al.*, PRL **129**, 042501 (2022).



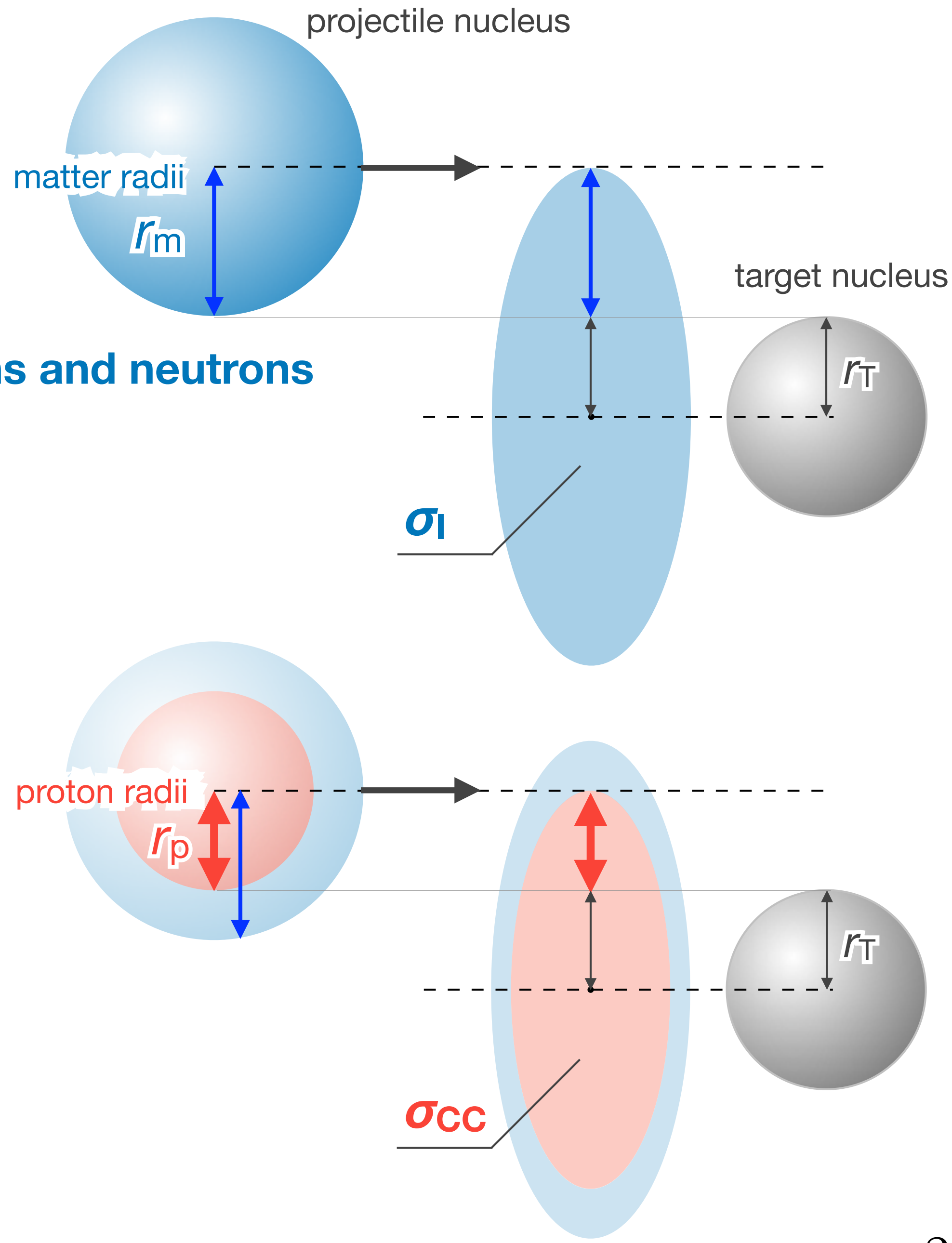
R. F. Garcia Ruiz *et al.*,
Nature Phys. **12**, 594 (2016).
A. J. Miller *et al.*,
Nature Phys. **15**, 432 (2019).





Recent progress of $<r_{ch}>^{1/2}$ deduction with σ_{CC}

Charge-changing cross sections



Interaction cross section σ_I

Total cross section with varying nuclides

$$\sigma_I \sim \pi \left(r_m + r_T\right)^2$$

matter: sum of protons and neutrons

Analogy

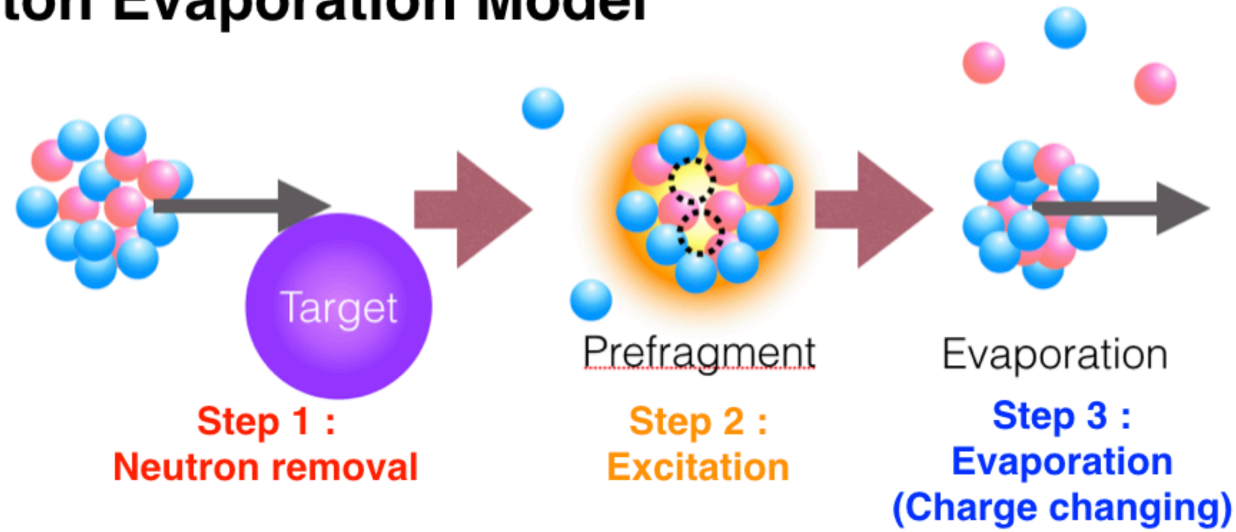
Charge-changing cross sections σ_{CC}

Total cross section with varying atomic number Z

$$\sigma_{CC} \sim \pi(r_p + r_T)^2 \text{ ?}$$

Charge-changing cross sections

Proton Evaporation Model



Step 1 : Neutron removal σ_I (Expt.) - σ_{CC} (Glauber)

Step 2 : Excitation

$$g(y) = g_0 - g_1 y$$

$$\rho_a(E) = \sum_{m=0}^{a} \frac{(-1)^m}{m!(a-m)!(a+m-1)!} g_1^m g_0^{a-m} E^{a+m-1}$$

g_0 and g_1 is determined from Ca data

Step 3 : Evaporation (Charge changing)

Prefragment excites more than $S_p \rightarrow$ **Evaporation**

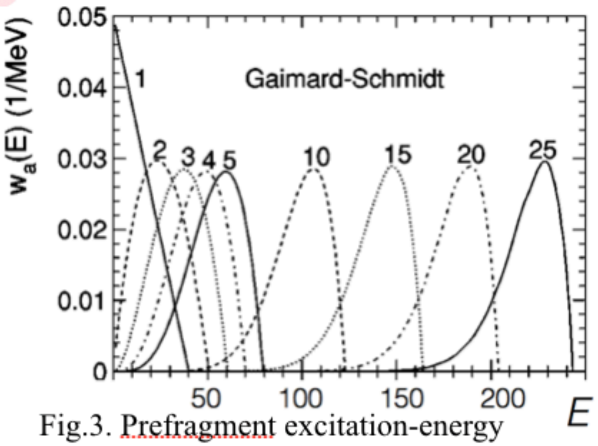


Fig.3. Prefragment excitation-energy distributions created after the reaction of a given number of nucleons. [3]

New Model = Glauber Model + Proton Evaporation

Charge-changing cross sections

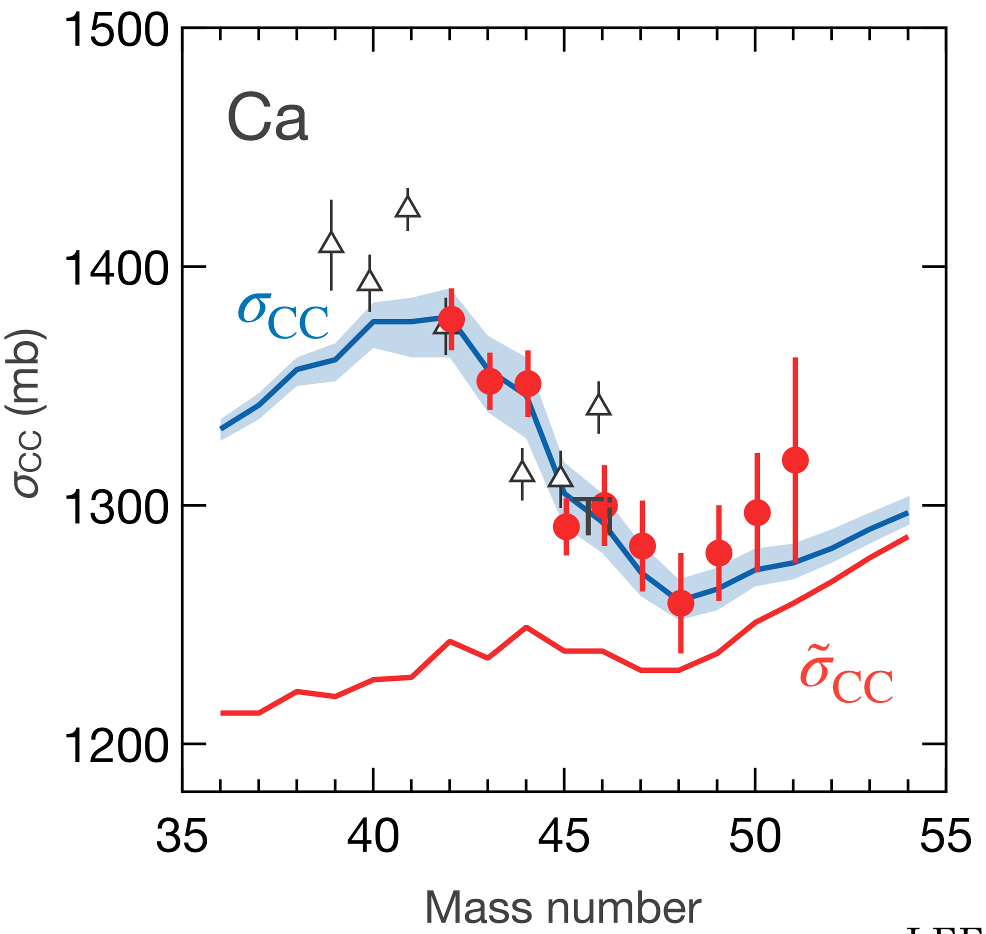
$$\sigma_{CC} = \tilde{\sigma}_{CC} + \tilde{\sigma}_{\Sigma-xn} P_{evap}$$

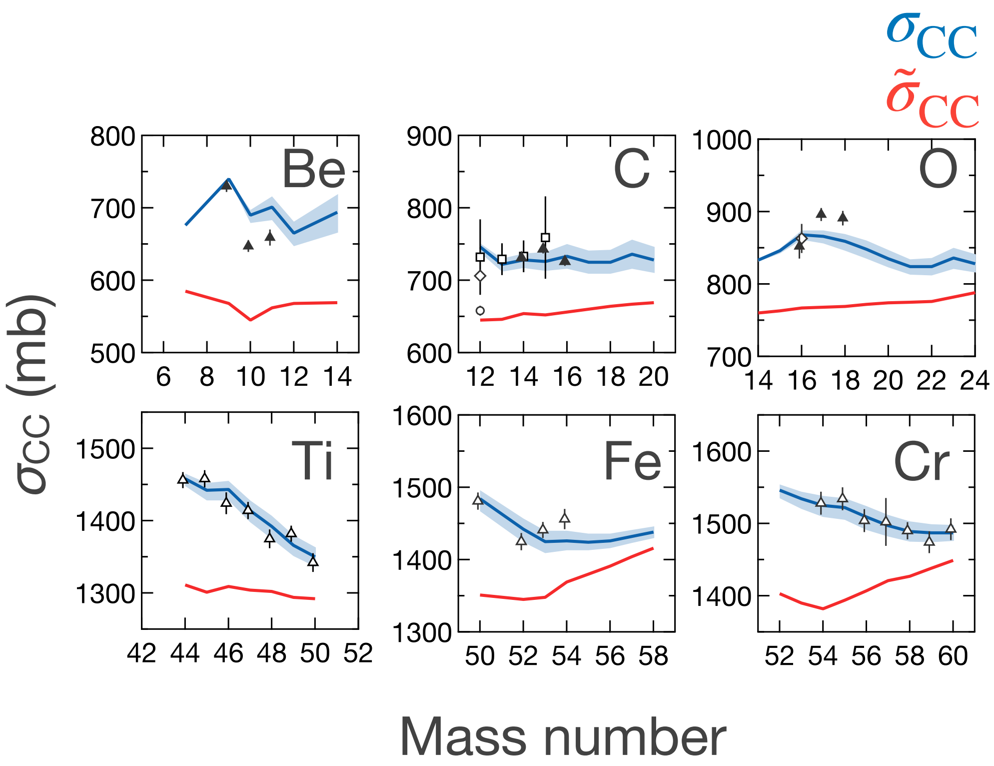
- $\tilde{\sigma}_{\Sigma-xn}$: depend on r_n
- $\tilde{\sigma}_{CC}$: depend on r_p

Existing data

T. Yamaguchi et al., PRL **107**, 032502 (2011).
S. Yamaki et al., NIM B **317**, 774-778 (2013).
J. Zhao et al., JPS Conf. Proc. 32, 010023 (2020).
W. Webber et al., PRC **41**, 520 (1990).
C. Zeitlin et al., PRC **83**, 034909 (2011).

※ Theoretical r_p values are used in some isotopes

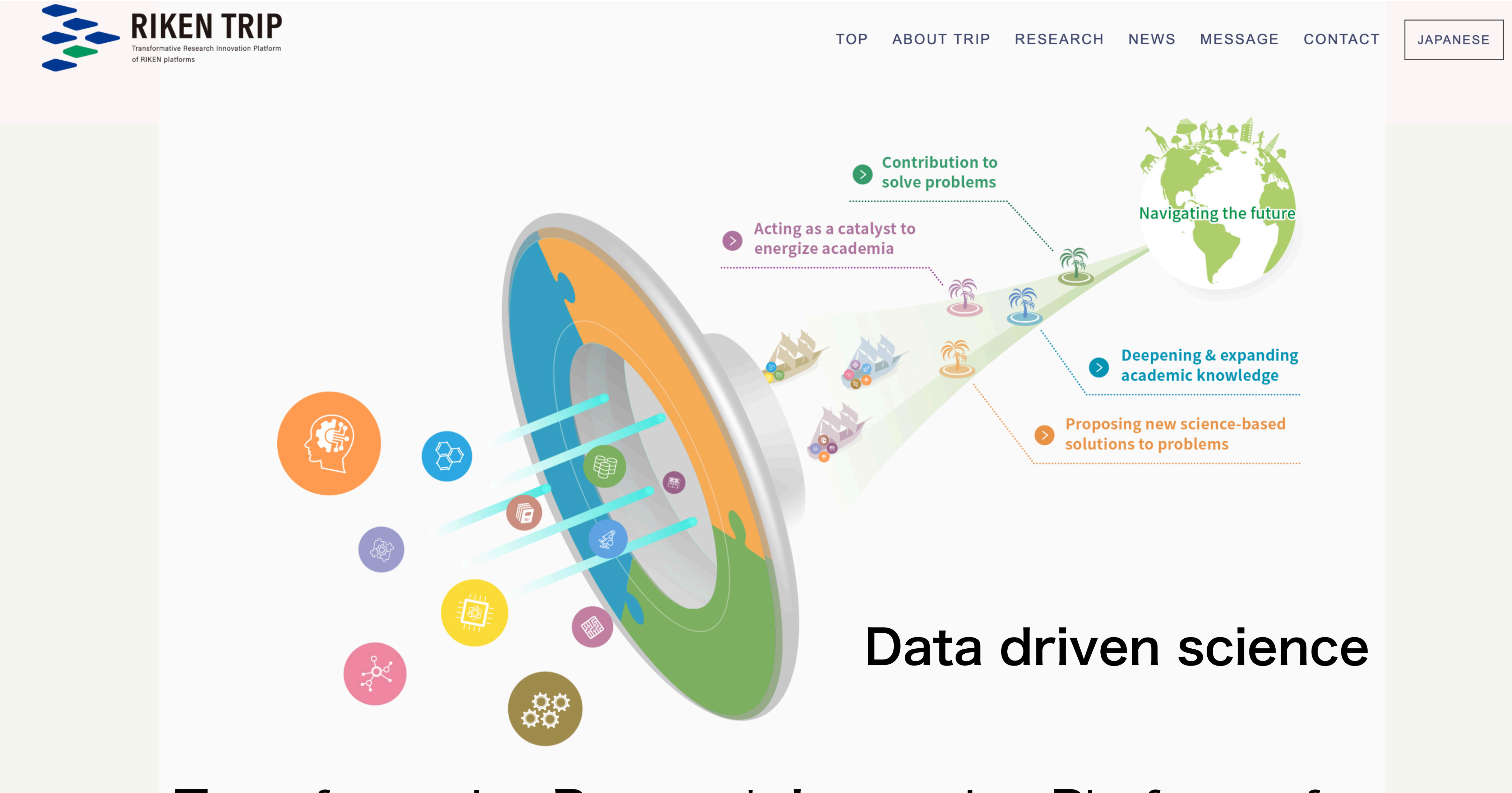




"Charge-changing cross sections for $^{42-51}$Ca and effect of charged-particle evaporation induced by neutron removal reaction"
M. Tanaka *et al.*, Phys. Rev. C **106**, 014617 (2022).

New TRIP-S3CAN project

RIKEN TRIP



Transformative **R**esearch **I**nnovation **P**latform of RIKEN platforms

TRIP in RIBF

MESA: proton elastic scattering to determining the optical potential and density distribution

GT5: in-beam gamma ray spectroscopy with tracking Ge detectors

S^{3}CAN: **S**ymbiotic, **S**ystematic and **S**imultaneous **C**ross-section measurements for **A**ll over the **N**uclear chart

TRIP-S3CAN project

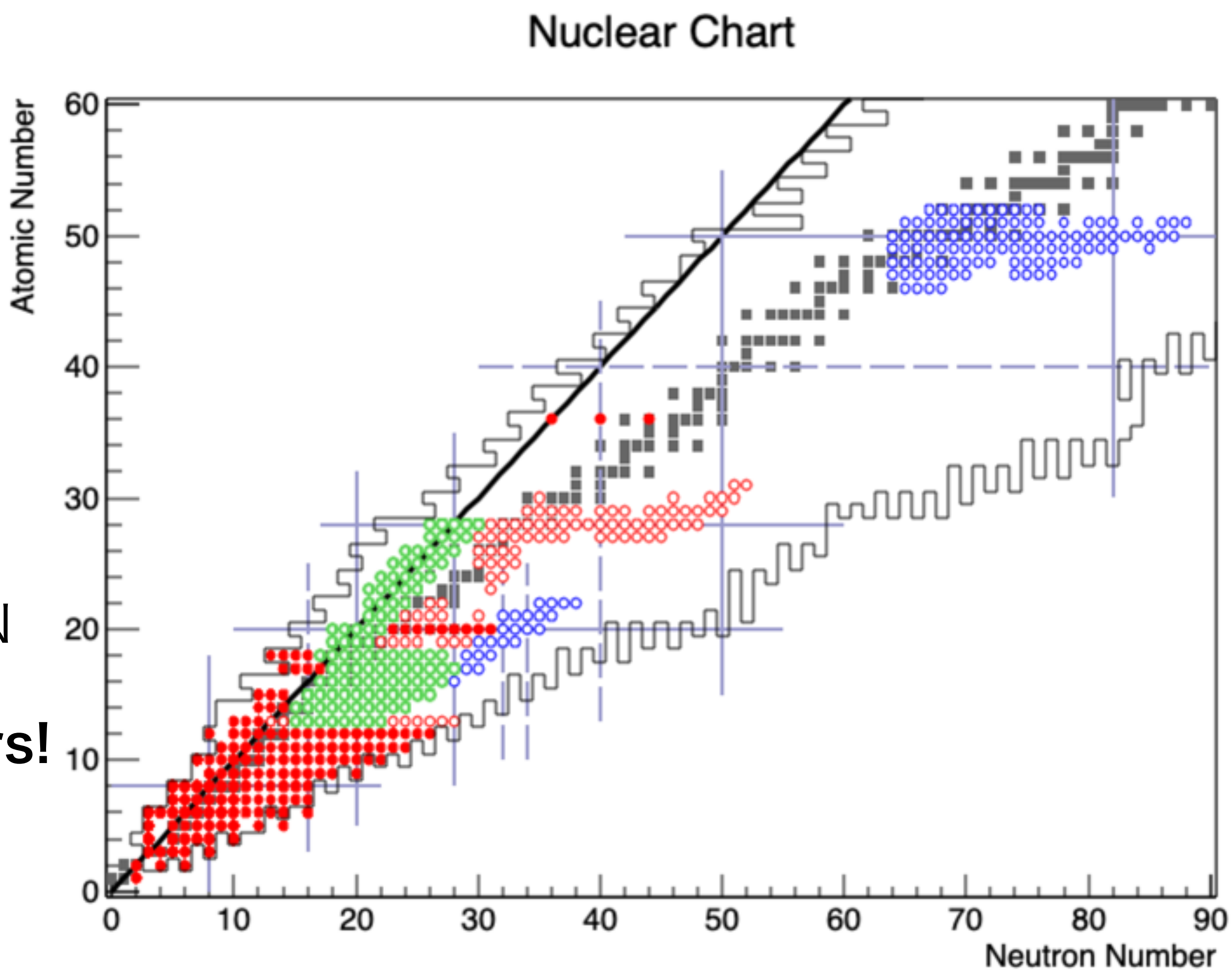
published
including other groups

measured

scheduled in RIBF

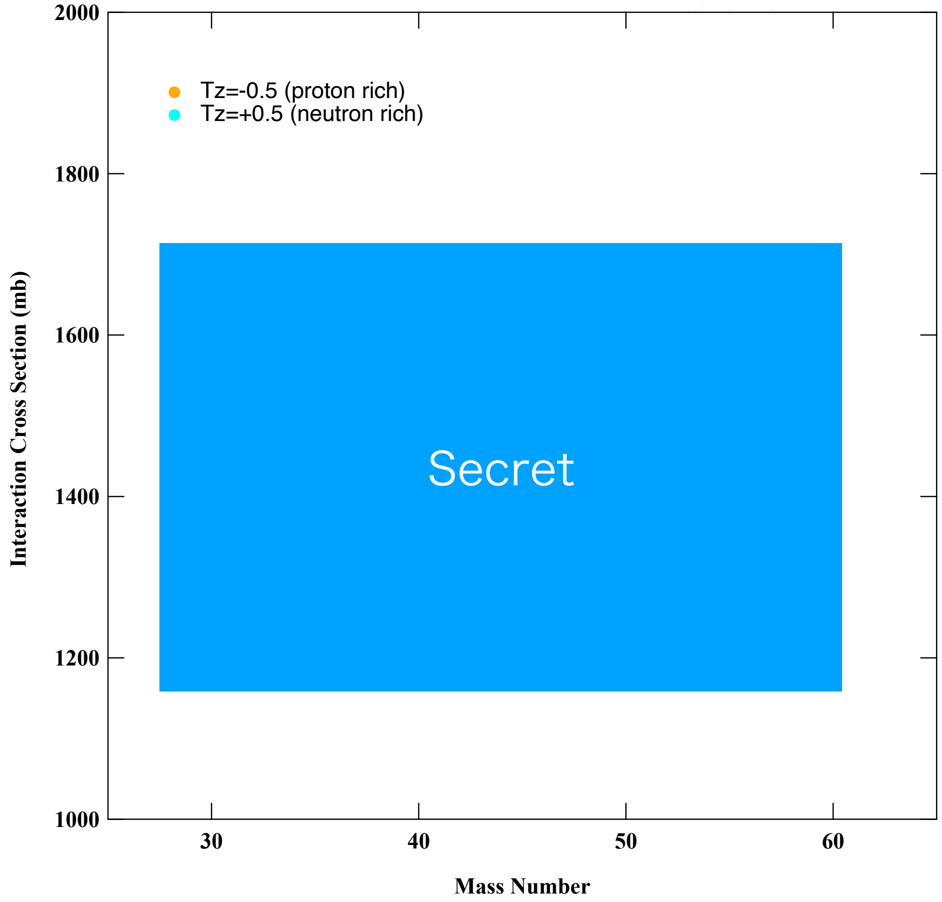
measured in S3CAN

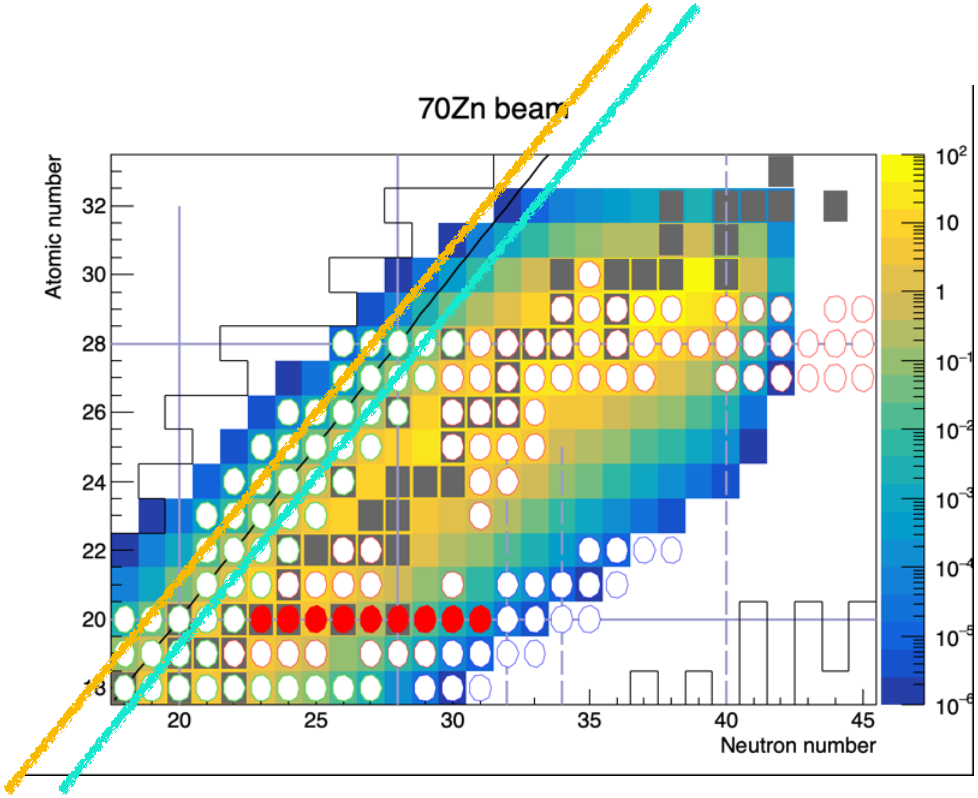
~100 nuclei in 36 hours!



TRIP-S3CAN project

very very preliminary





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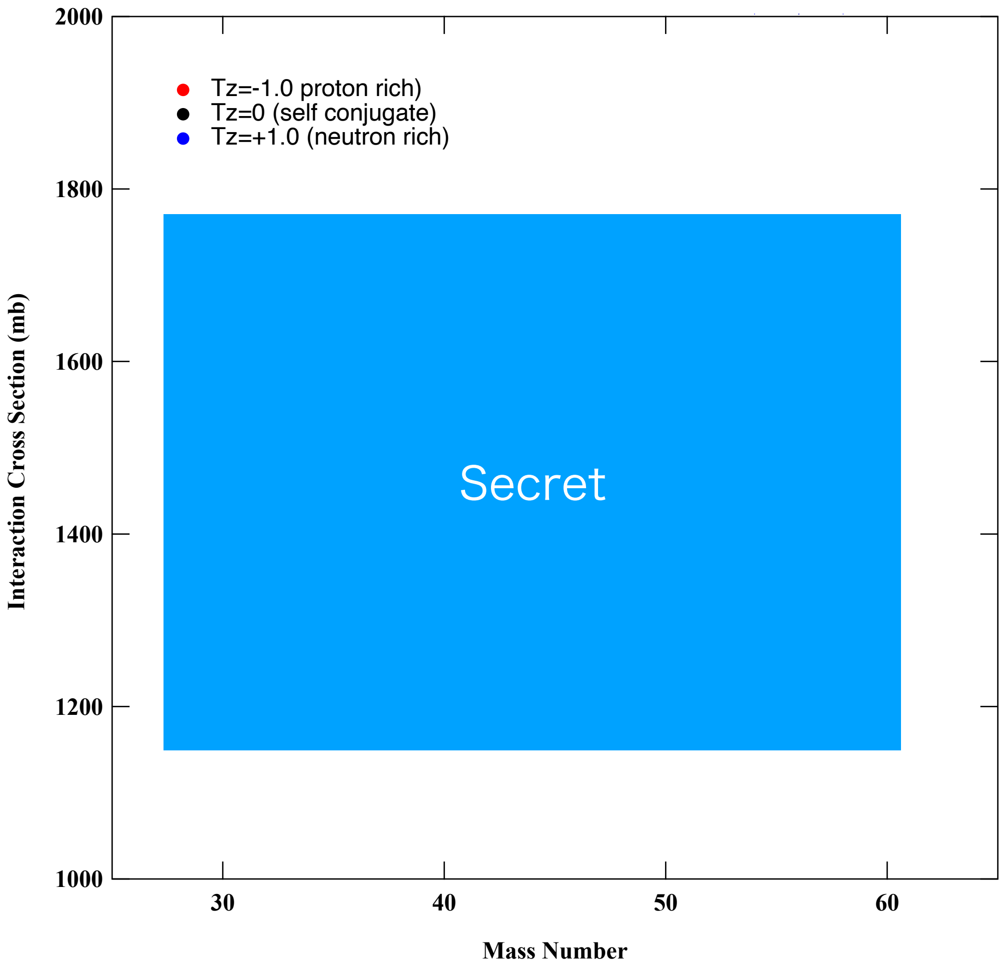
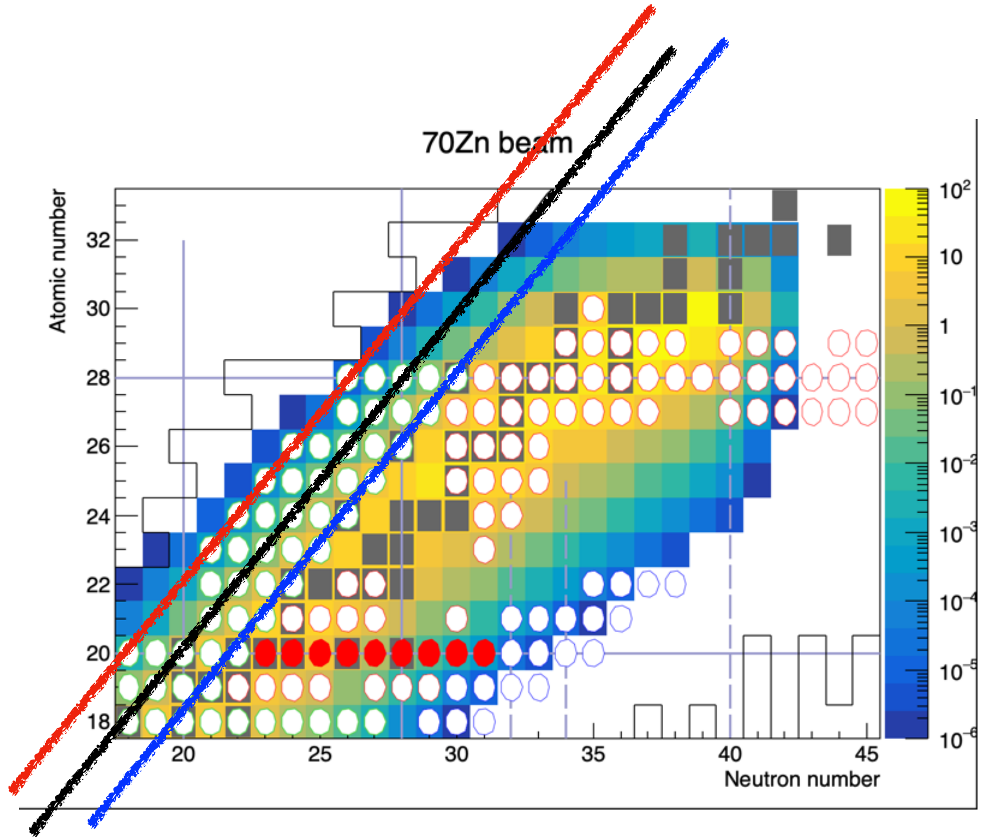
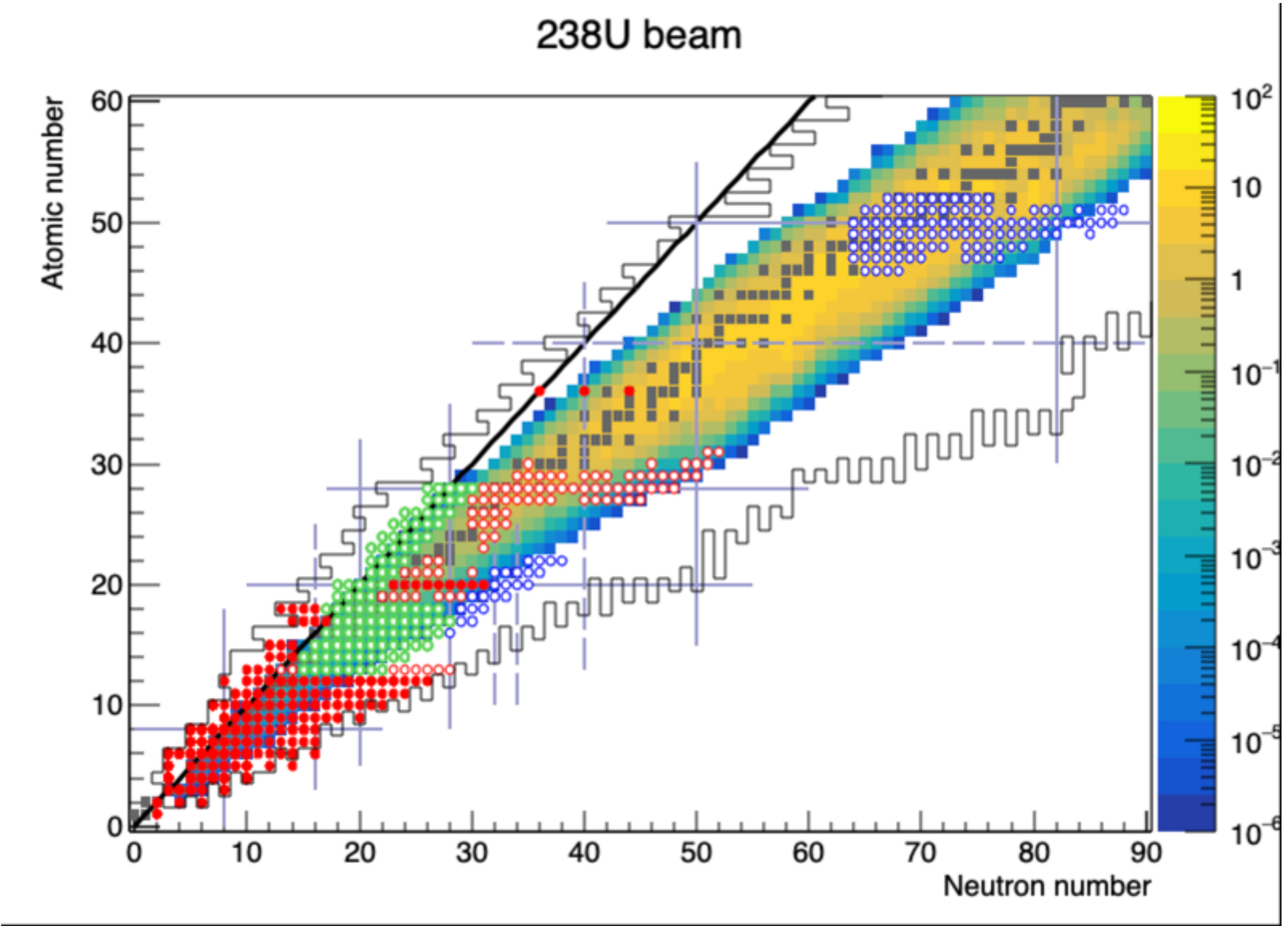




TRIP-S3CAN project



we can measure 60 nuclei/1day. -> 600 in 10 days of 5 years

S^3CAN: **S**ymbiotic, **S**ystematic and **S**imultaneous **C**ross-section measurements for **A**ll over the **N**uclear chart

Summray

- Our results of σ_I in RIBF (^{A}Ne, ^{A}Mg, and ^{A}Ca)

  Deformed halo structure for ^{31}Ne and ^{37}Mg and swelling core of ^{48}Ca are suggested.

- Recent progress of $\langle r_{ch} \rangle^{1/2}$ (r_p) deduction with σ_{cc}

  The r_p is possible to be deduced with σ_{cc}. But evaporation effect is important for near stable nuclei.

- New project of TRIP-S3CAN is now started.

  The radii of several hundreds ~ a thousand of nuclei can be access to determine.

S^{3}CAN: **S**ymbiotic, **S**ystematic and **S**imultaneous **C**ross-section measurements for **A**ll over the **N**uclear chart