北京航空航天大學
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Deducing charge radii of rare isotopes from charge-changing reactions

- Charge-changing reactions
- Results and discussions
- Summary and perspective

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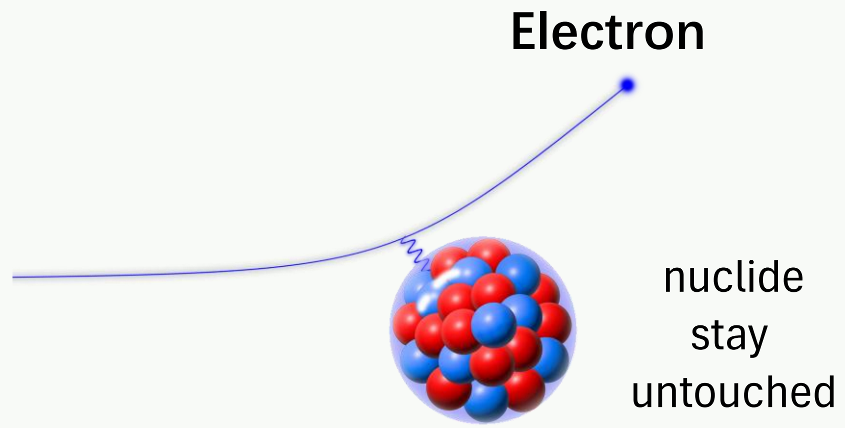
Radius determination of atomic nuclide

Electromagnetic probe

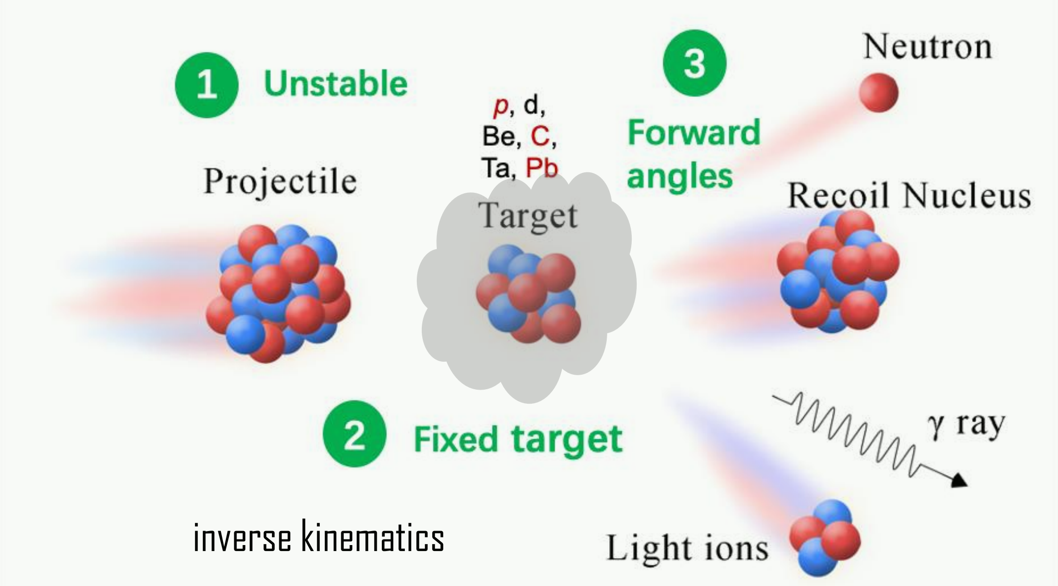
Well developed, high precision; short-lived



- Elastic electron scattering (ρ_{ch} and R_{ch})
- Muonic X-ray
- Optical isotope shifts
- Kα X-ray isotope shifts

Hadronic probe

Short-lived, universal; strong interaction



At intermediate and high energy (several 0.1 to ~1.0 AGeV)

Reaction & structure governed by strong interactions

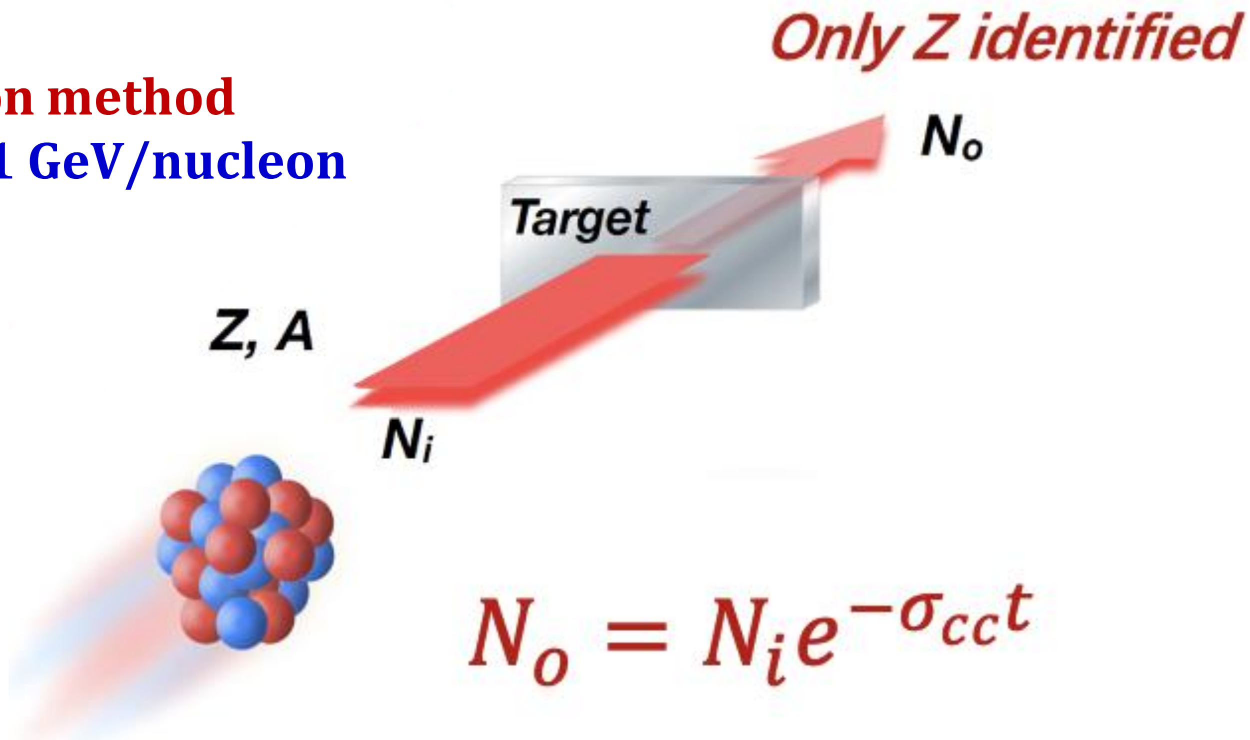
Reaction/Interaction/Charge-changing X-sections as first hints

Matter radii R_m R_{ch}

Charge-changing cross section

The charge-changing cross section (σ_{CC}) is defined as the total cross section of removing at least one proton from the projectile nucleus during the collision with the target nucleus.

Transmission method
at ~ several 0.1-1 GeV/nucleon

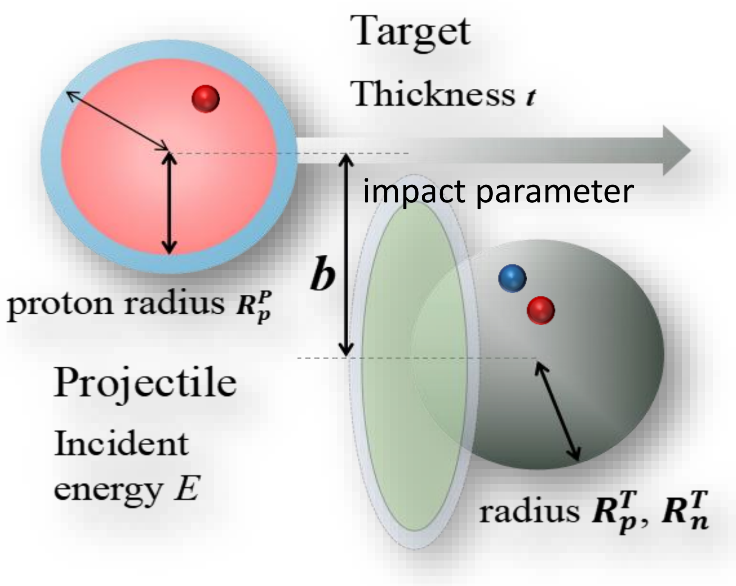


$$N_o = N_i e^{-\sigma_{cc} t}$$

- Experiment simple
- High precision
- Bulk properties of nuclide
- Cosmic ray physics, exploring reaction mechanisms and exotic structure

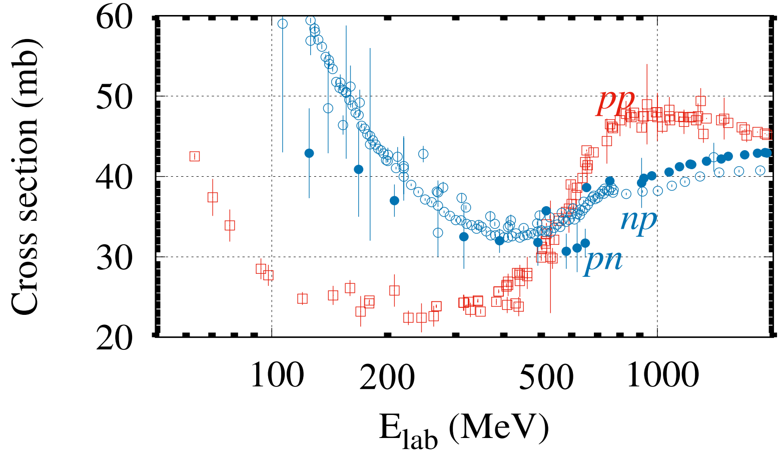
Glauber model interpretation of charge-changing reaction

Adapted the Glauber model, assuming σ_{cc} comes from only the collisions between projectile protons and the target nucleons at the collision energy of 0.1-1 GeV/nucleon



$$\sigma_{\rm cc} = 2\pi \int b\Big\{1 - \exp\Big[-\int dr \rho_p^P \left(\sigma_{pp}\rho_p^T + \sigma_{pn}\rho_n^T\right)\Big]\Big\}db$$

Zero-range optical limit Glauber model



Charge-changing cross section: Nucleon-nucleon cross section folded with nucleon density distribution

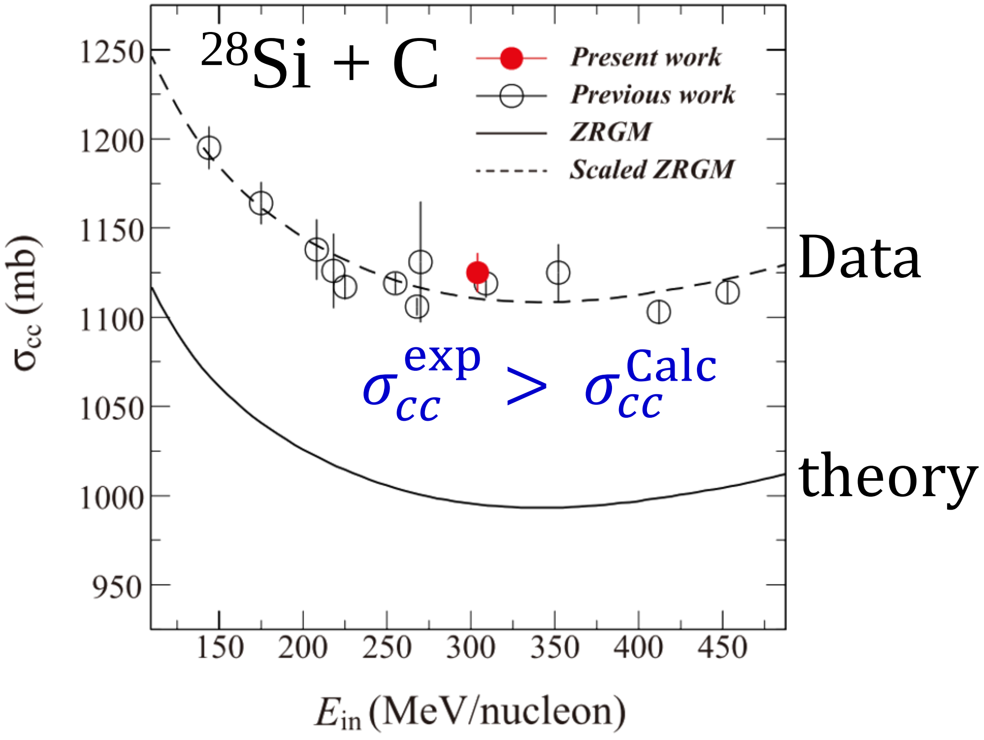
Glauber model + RCHB/RMF densities can reproduces nicely the experimental data, linking the density with the cross sections for the first time

Meng, Zhou, Tanihata, Phys. Lett. B 532, 209 (2002)
Chulkov et al., NPA674,330(2001)

Precise σ_{cc} data revealing systematic difference with models

A question of two decades

The zero-range Glauber model (ZRGM), which only considers the collisions of projectile protons with target neutrons and protons, underestimates the data by ~10%:



Chulkov et al., NPA 674, 330 (2000)
Meng, Zhou, Tanihata, PLB 532, 209 (2002)
Bhagwat & Gambhir, PRC 69, 014315 (2004)

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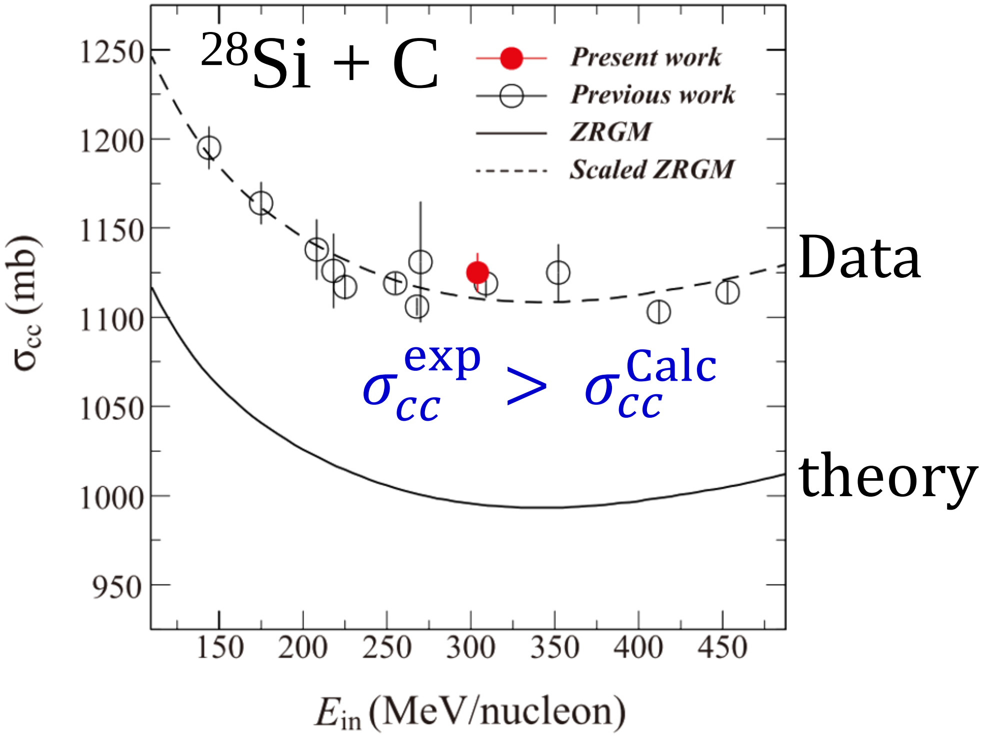
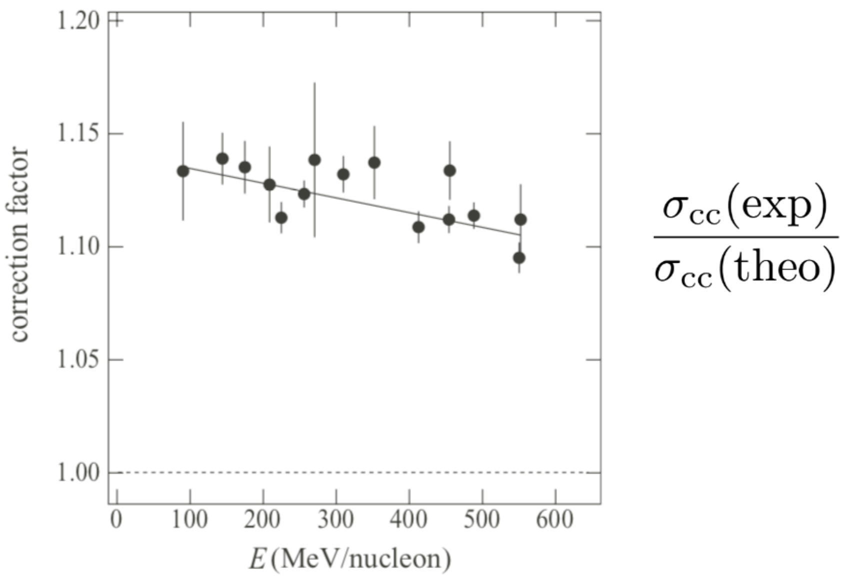


Chulkov et al., NPA 674, 330 (2000)
Meng, Zhou, Tanihata, PLB 532, 209 (2002)
Bhagwat & Gambhir, PRC 69, 014315 (2004)

phenomenological correction factor to account for the weak energy-dependence

$$\sigma_{cc} = 2\pi \int b[1 - T^p(b)]\mathcal{E}(E)db$$

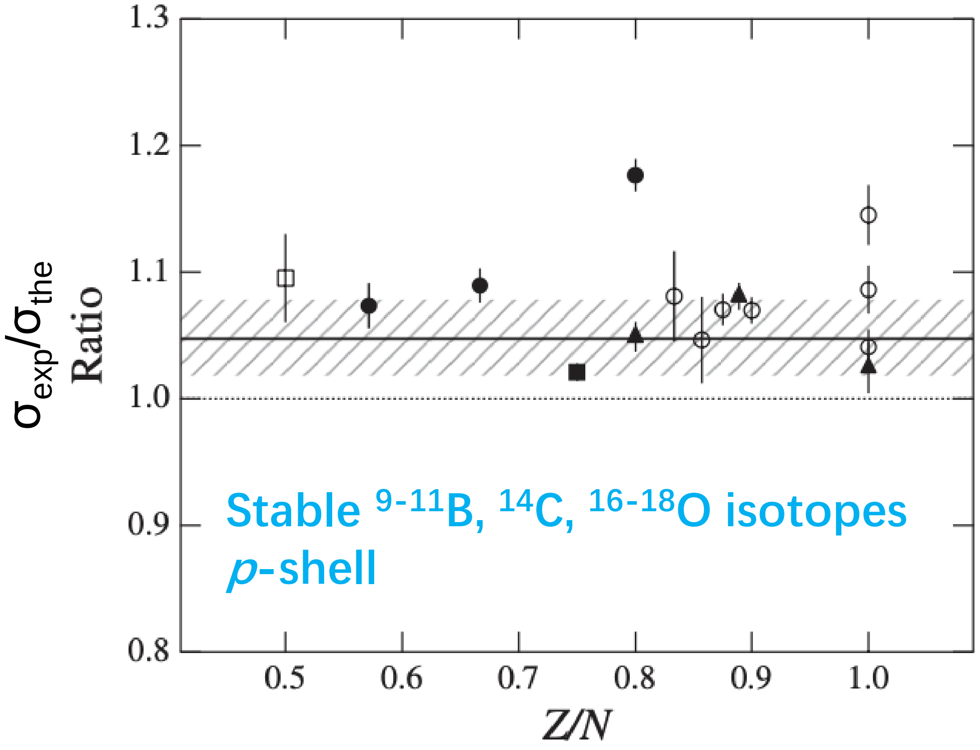
$$\mathcal{E}(E) = 1.141 - 6.507 \times 10^{-5} \times E$$



Yamaguchi *et al.*, PRC 82, 014609 (2010)
Wang *et al.*, Chin. Phys. C 47, 084001 (2023)

First application to deduce R_p of unstable nuclei

The Glauber model with the phenomenological correction factor was used to extract the rms proton radius of the projectile nuclide from the charge-changing cross sections.



$$\sigma_{cc} = 2\pi \int b[1 - T^p(b)]\mathcal{E}(E)db$$

! Assuming the correction factor is a constant in the same energy range, and is insensitive to *Z/N* ratios

TABLE II. Root-mean-square point-proton ($\tilde{r}_p$) and matter ($\tilde{r}_m$) radii of carbon isotopes.

Nuclide	$\tilde{r}_p$ (fm)	$\tilde{r}_m$ (fm)
^{12}C	2.320 ± 0.007 [14]	2.31 ± 0.02 [22]
^{13}C	2.315 ± 0.008 [14]	2.28 ± 0.04 [22]
^{14}C	2.364 ± 0.011 [14]	2.30 ± 0.07 [22]
^{15}C	2.33 ± 0.11	2.48 ± 0.03 [22]
^{16}C	2.25 ± 0.11	2.70 ± 0.03 [22]

Yamaguchi et al., PRL107, 032502 (2011)

σ_{cc} of ^{30}Ne, ^{32,33}Na @ ~300 MeV/nucleon on a proton target

The same correction factor was used to study very *n*-rich nuclei on a proton target.

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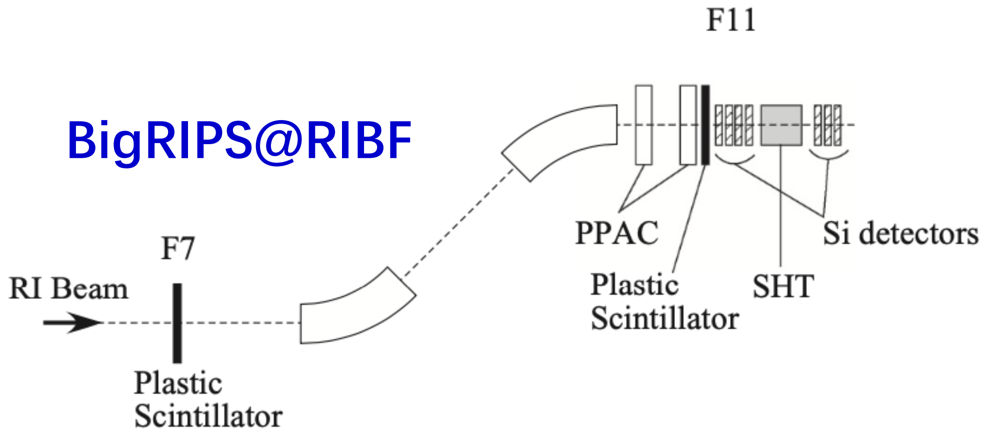
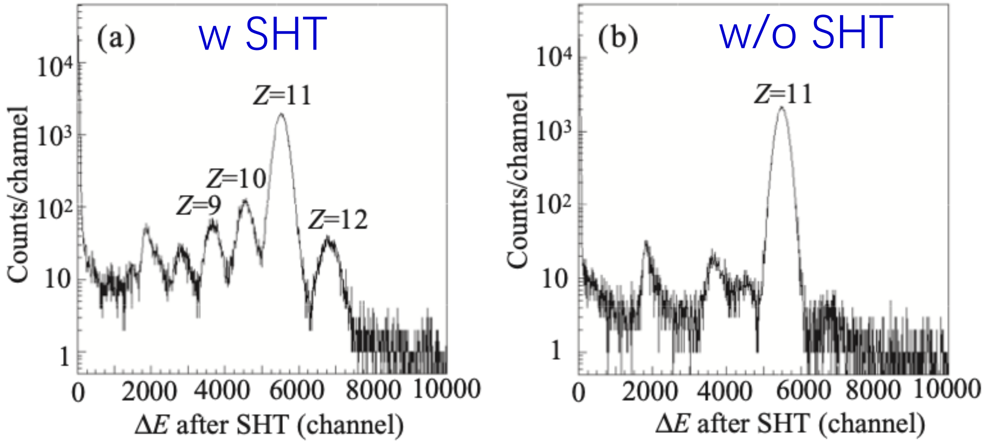
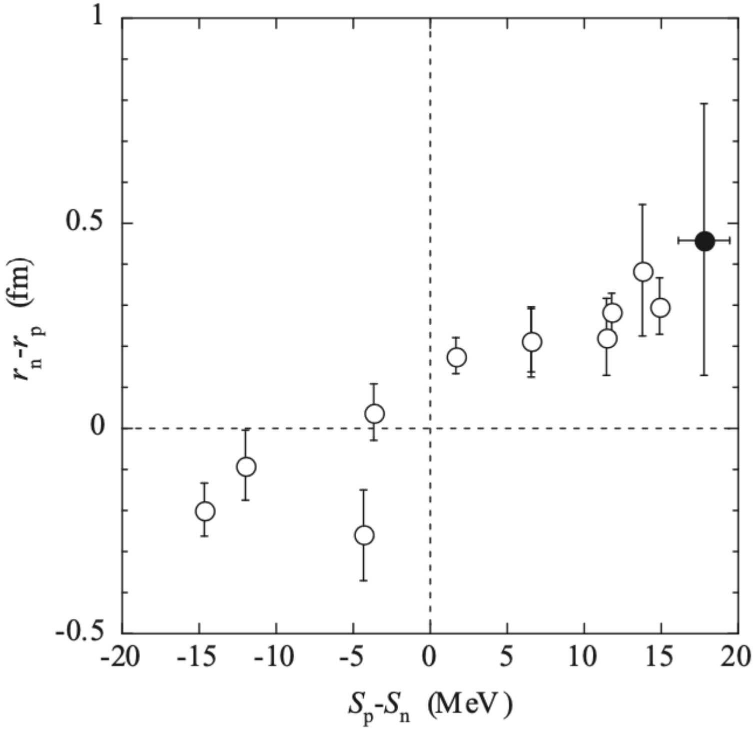




Ozawa et al., Phys. Rev. C **89** (2014) 044602

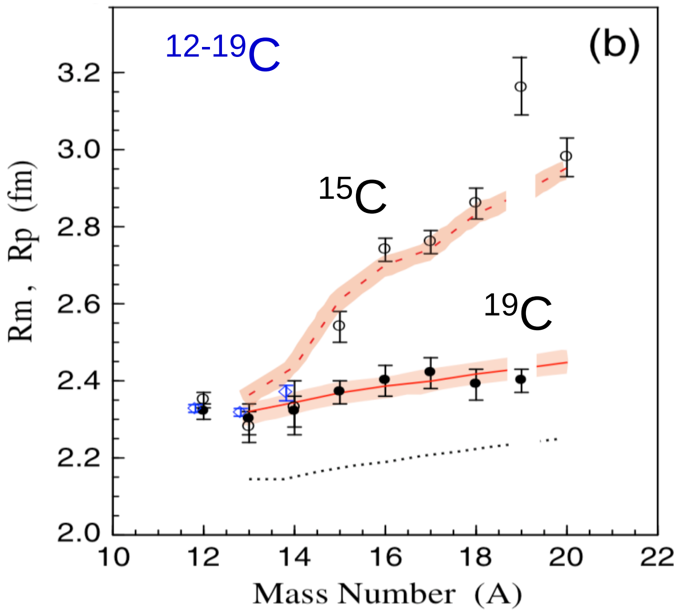
Extend the same correction factor
from C target data to H data,
from *p*-shell nuclei to *sd*-shell nuclei



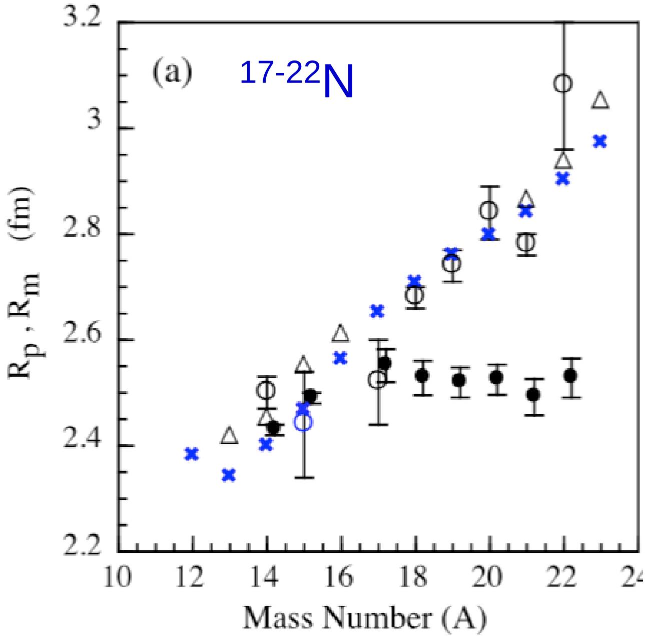
Using the same scaling ratio as the one in PRL11

New measurements @ 900 MeV/nucleon

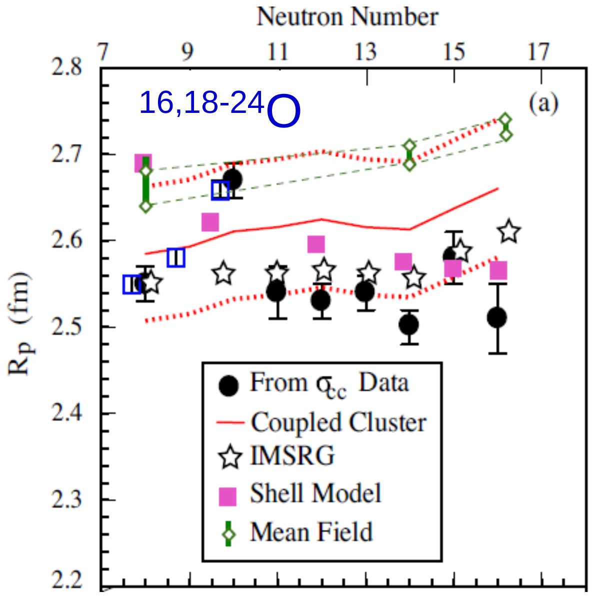
- High-precision σ_{cc} *for p*-shell nuclei at about 900 MeV/u on C at FRS, GSI
- "Self-calibration" of the finite-range Glauber model using stable isotopes with known R_{ch}
- Experimental data varied by about 5% depending on how to treat the Veto data in front of the target



Halo radius in ^{19}C



^{22}N neutron halo-like structure



N=14/16 subshell closure due to the tensor force

Estrade *et al.*, PRL113, 132501(2014); Tershima *et al.*, PTEP 101D02(2014); Kanungo *et al.*, PRL117, 102501(2016); Bagchi *et al.*, PLB790, 251(2019); Kaur et al., PRL129, 142502 (2022)

σ_{cc} of Ca isotopes on C @ 300 MeV/nucleon

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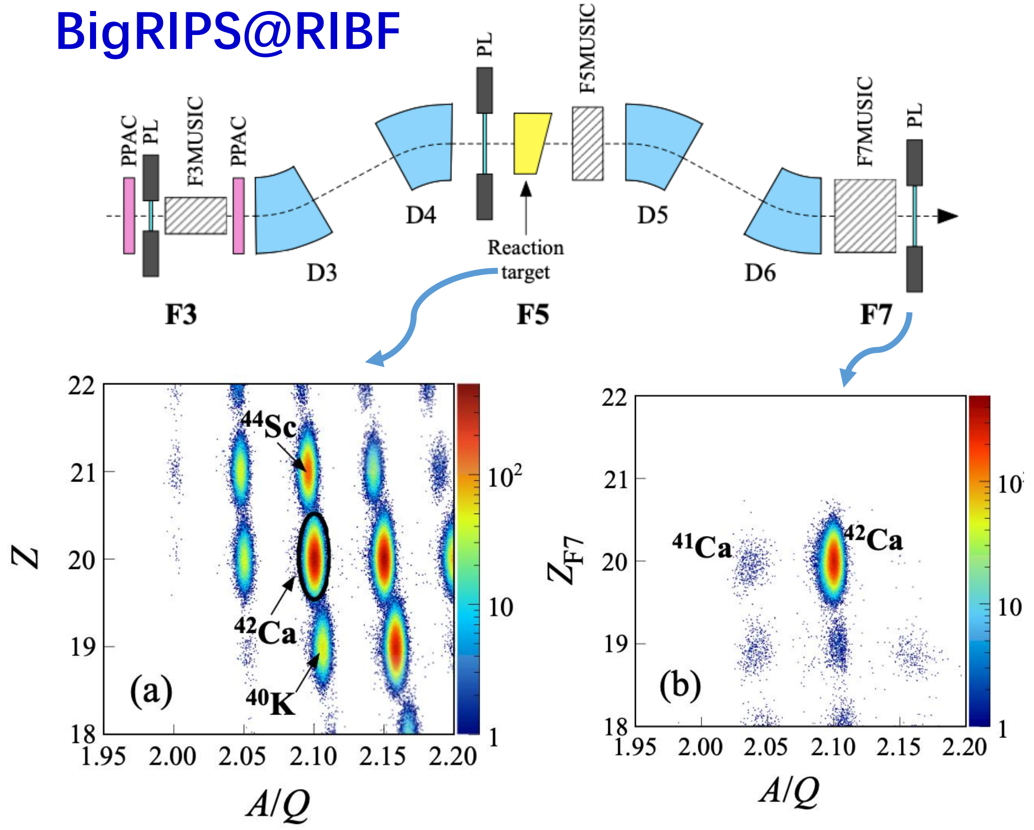
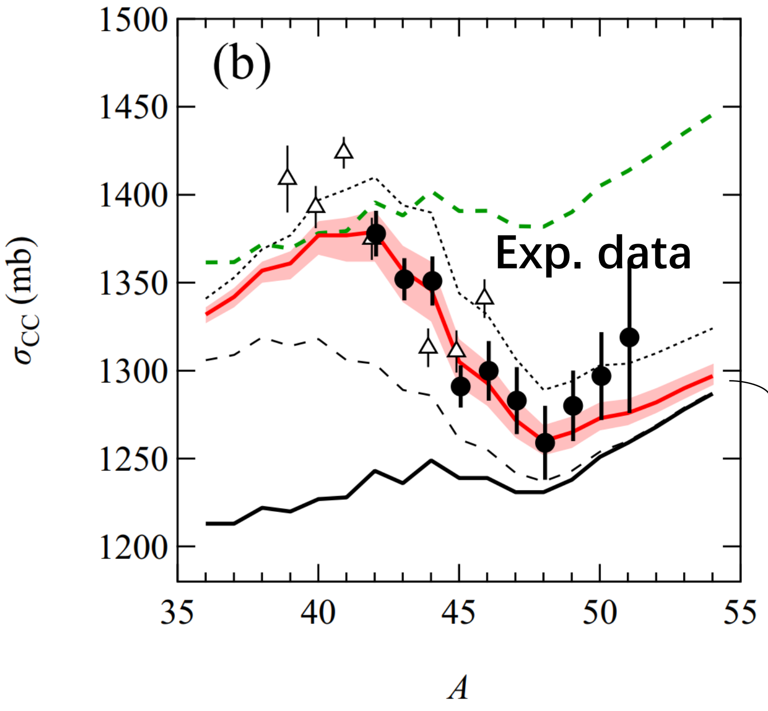


GM with correction fails to capture the Ca isotopic trend.



σ_{cc}(theo) with the correction factor

σ_{CPE} correction

σ_{cc}(theo)

σ_{cc} data, Tanaka et al., PRC106(2022)014617

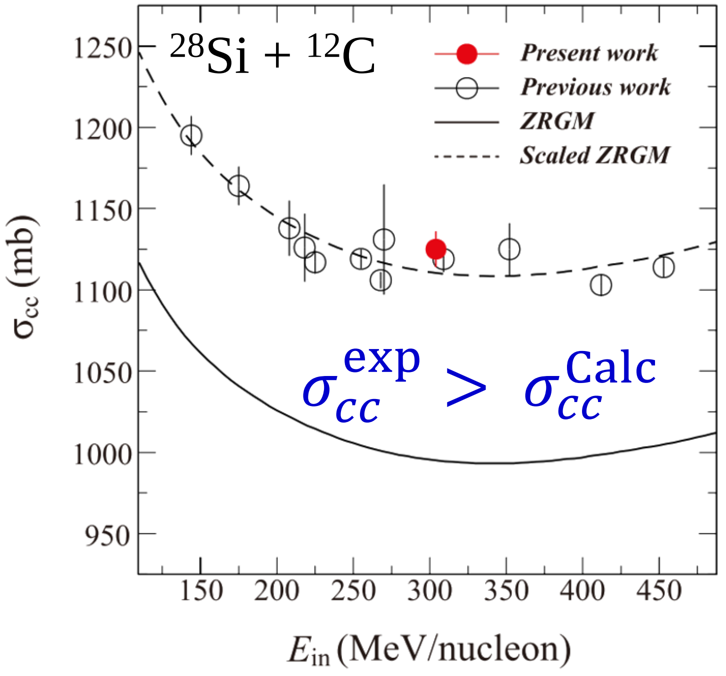
R_m data, Tanaka et al., PRL**124**(2020)102501

R_{ch} data, Ruiz *et al.* Nat. Phys. (2016)

- GM corrected for the secondary charge-particle evaporation induced by neutron-removal reaction (CPE), with the parameters (E*) tuned, can reproduce the data

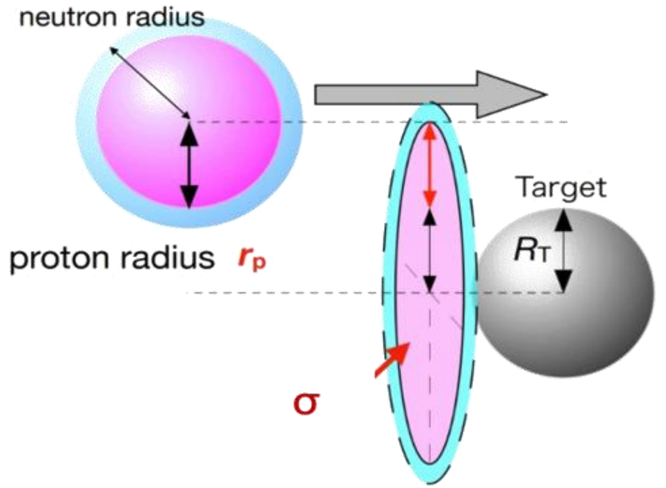
Key questions remain!

- What is the **reaction mechanism** of charge-changing reactions (CCR)?
- Is the correction factor **universal and robust** with respect to the isospin of the projectile nuclide, the collision energy, and the reaction target nuclide?
- Is it **accurate** enough to deduce R_p from CCR?



$\sigma_{cc}^{exp} > \sigma_{cc}^{Calc}$

Projectile neutron contributions?

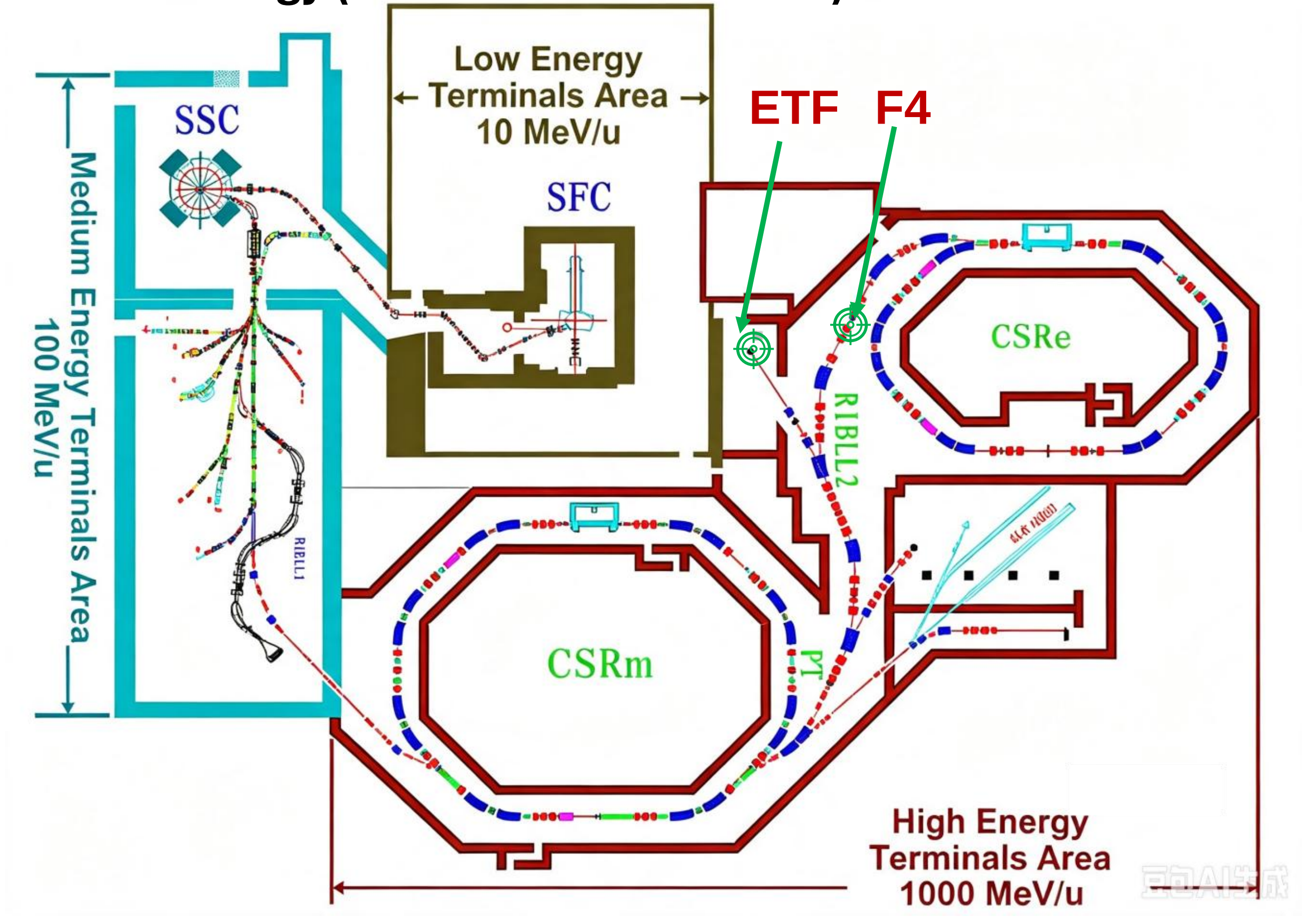


$$\sigma_{cc} = 2\pi \int b[1 - T^p(b)]\mathcal{E}(E)db$$

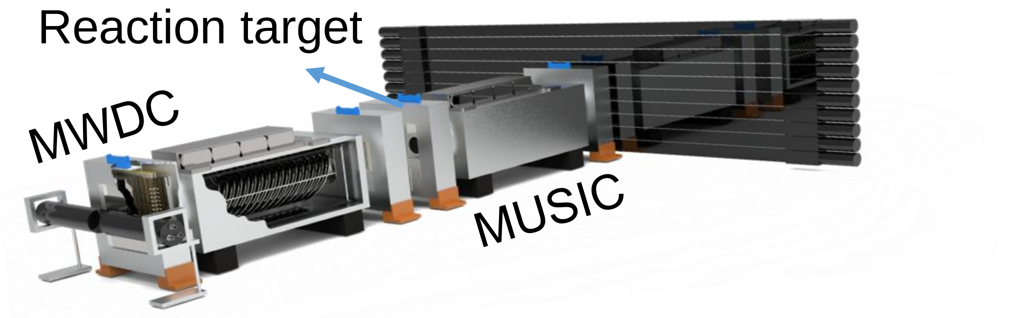
Bhagwat, Gambhir, PRC 69, 014315 (2004)
Suzuki et al., PRC 94, 011602 (2016)

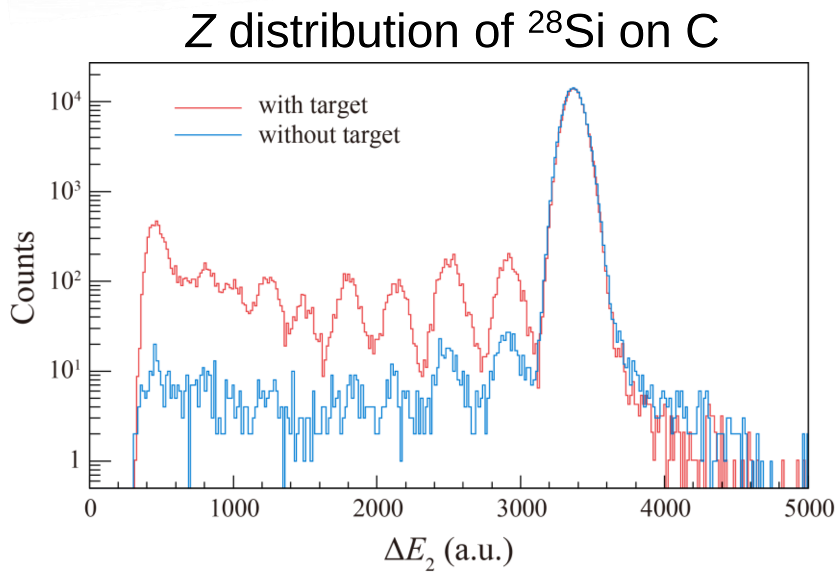
Heavy Ion Research Facility in Lanzhou (HIRFL)

Second Radioactive Ion Beam Line in Lanzhou (RIBLL2): the only radioactive ion beam line at relativistic energy (300-500 MeV/nucleon) in China before 2025



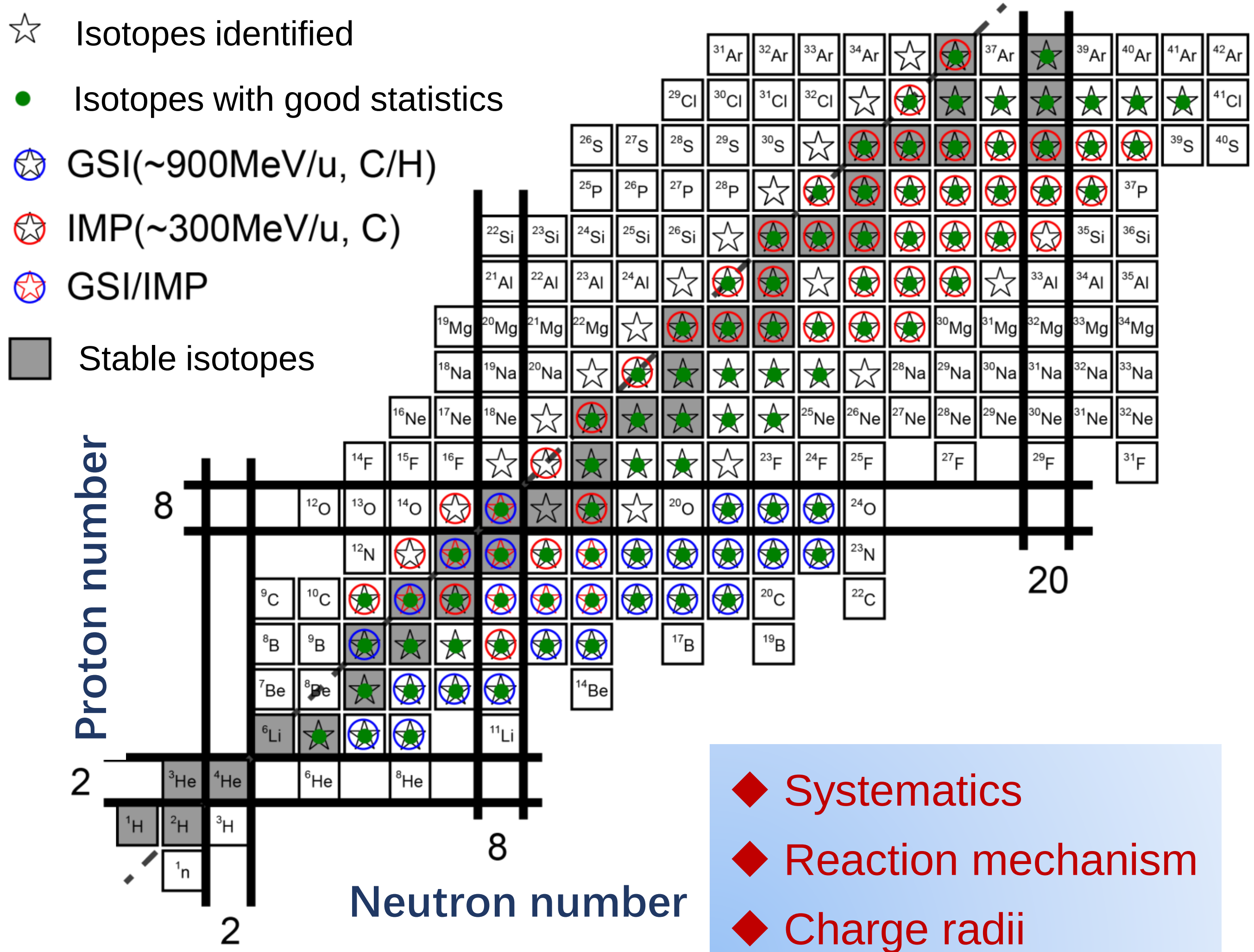
Xia, Zhan, Wei, *et al.*, NIMA 488,11 (2002)





BHS *et al.*, Science Bulletin 63, 78 (2018)
Xu *et al.*, Science Bulletin 70, 1026 (2025)

Consistent (and largest) database for σ_{cc}



- Systematics
- Reaction mechanism
- Charge radii

- **Cross sections of >70 *p-sd* isotopes on C, > 10 on H, Ag, Pb @ ~300 MeV/nucleon**
- **Cross sections of 24 isotopes on C and H @~900 MeV/nucleon (GSI)**

Physics

- Xu *et al.*, PRL. (2026) in press
- Xiao *et al.*, PLB 880, 140787 (2026)
- Zhang *et al.*, NIMA 1084,171267(2026)
- Wei *et al.*, Nucl. Sci. Tech. 36,195 (2025) NST COVER PAPER (2025.10)
- Wei *et al.*, PRC 112, 064604(2025)
- Liu *et al.*, PRC 112, 014611 (2025)
- Wu et al., ADNDT 165, 101733 (2025)
- Zhang *et al.*, PRX 15, 031004 (2025)
- Xu *et al.*, Sci. Bull. 70, 1026 (2025)
- Li *et al.*, PLB 859, 139143 (2024)
- Zhao *et al.*, PLB 858, 139082 (2024)
- Zhang *et al.*, Sci. Bull. 69, 1647 (2024)
- Zhao *et al.*, PLB 847, 138269 (2023)
- **Wang *et al.*, Chin. Phys. C 47, 084001 (2023)** CPC Best paper award in 2023
- Li *et al.*, PRC107, 024609 (2023)
- Xu *et al.*, PLB833, 137333 (2022)

Instrumentation

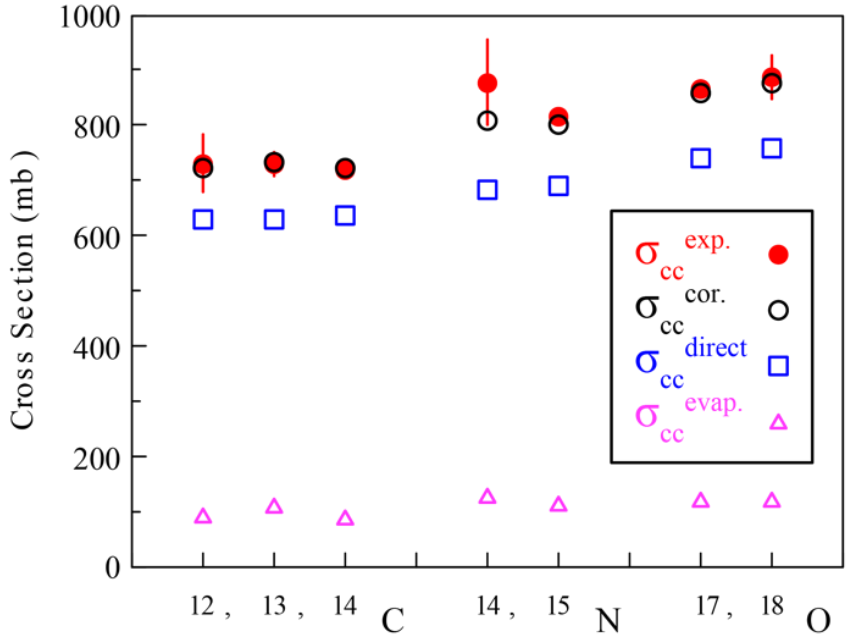
- Zhao *et al.*, NIMA 930, 95 (2019)
- BHS *et al.*, Sci. Bull. 63, 78 (2018)
- Lin *et al.*, CPC41, 066001(2017)
- Zhao *et al.*, NIMA 823, 41(2016)

Reaction mechanism of charge-changing reactions

Differences between theo. and exp. can be well explained by charged-particle evaporation (CPE) after neutron removal.

$$\sigma_{cc}^{cor.} = \sigma_{cc}^{direct} + \sigma_{cc}^{evap.}$$

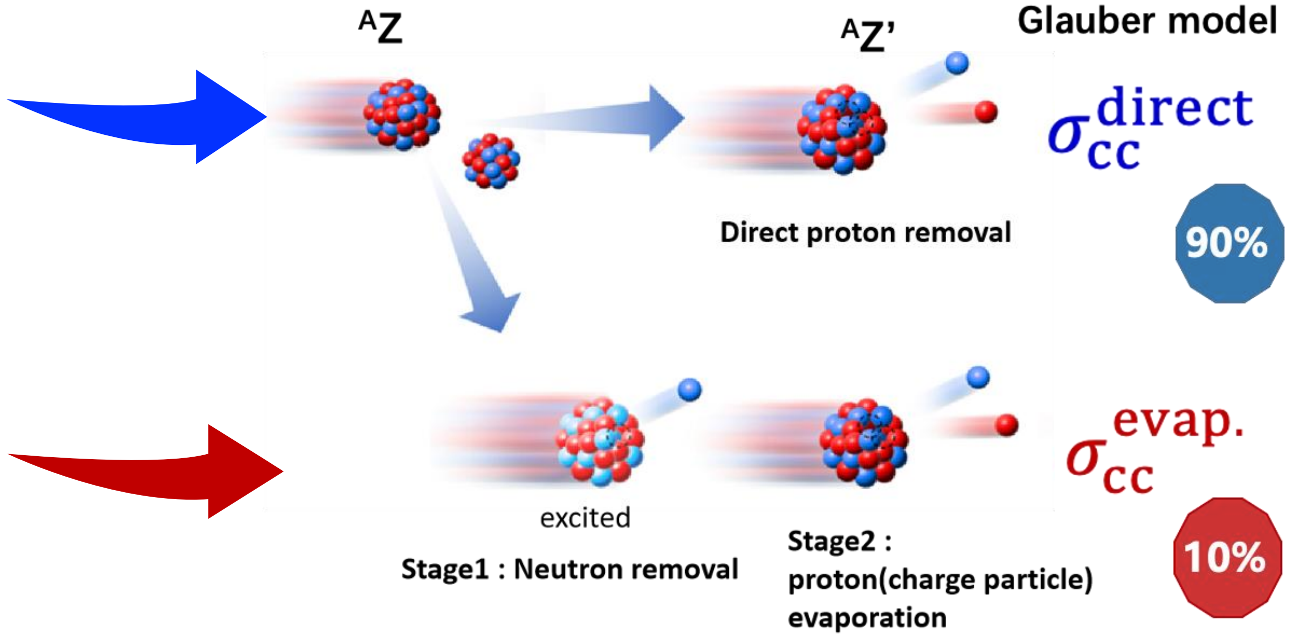
300 MeV/nucleon



Zhao, BHS, Tanihata *et al.*, PLB 847, 138269 (2023)

A sophisticated model for charge particle evaporation after neutron removal was developed.

Key properties: excitation energy distribution of pre-fragments

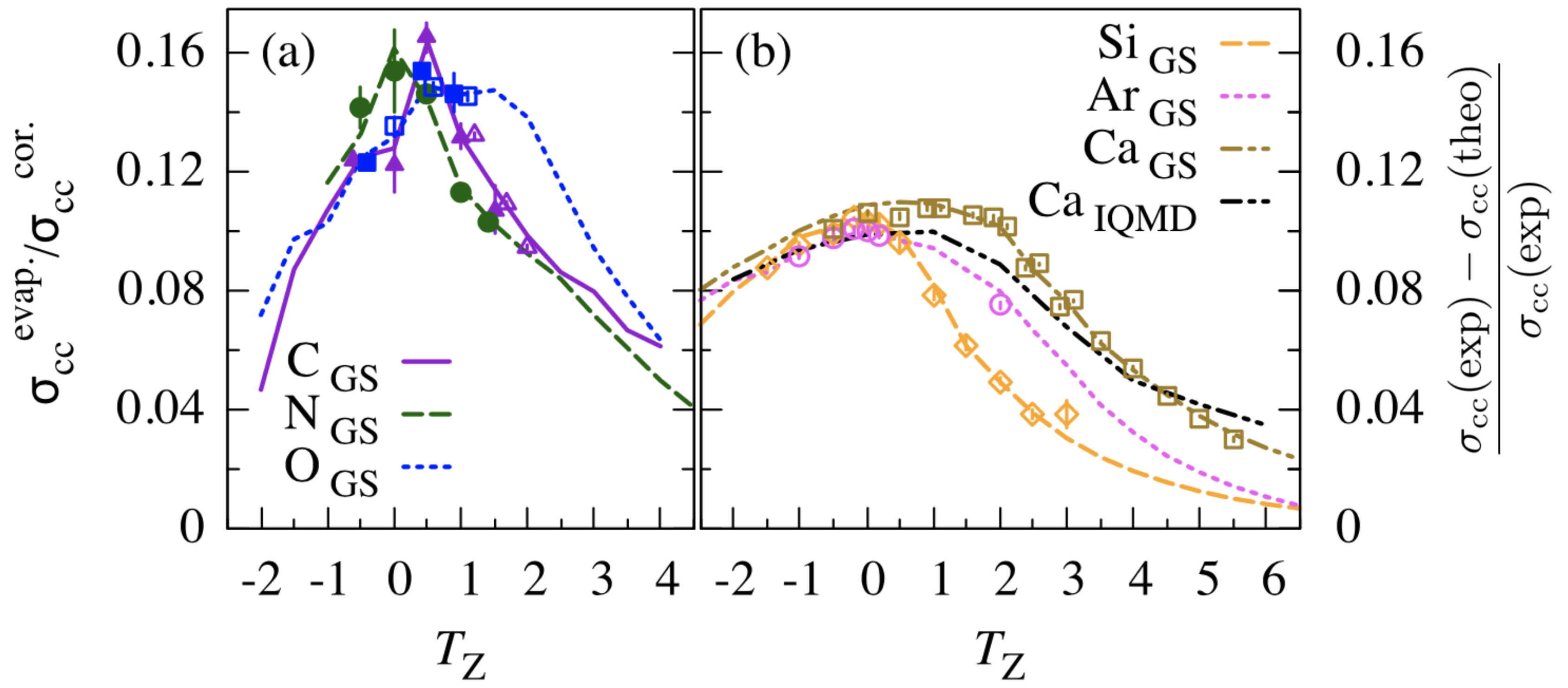


e.g., one-neutron removal e.g., one-proton evaporation

It remains unclear to what extent this evaporation process contributes to the CCCS and how it depends on reaction energy, projectile nuclear mass, and proton-to-neutron ratio.

Isospin-dependent evaporation: NOT a constant!

Evaporation calculations rely on excitation energy distributions, level densities, etc., for the pre-fragments.

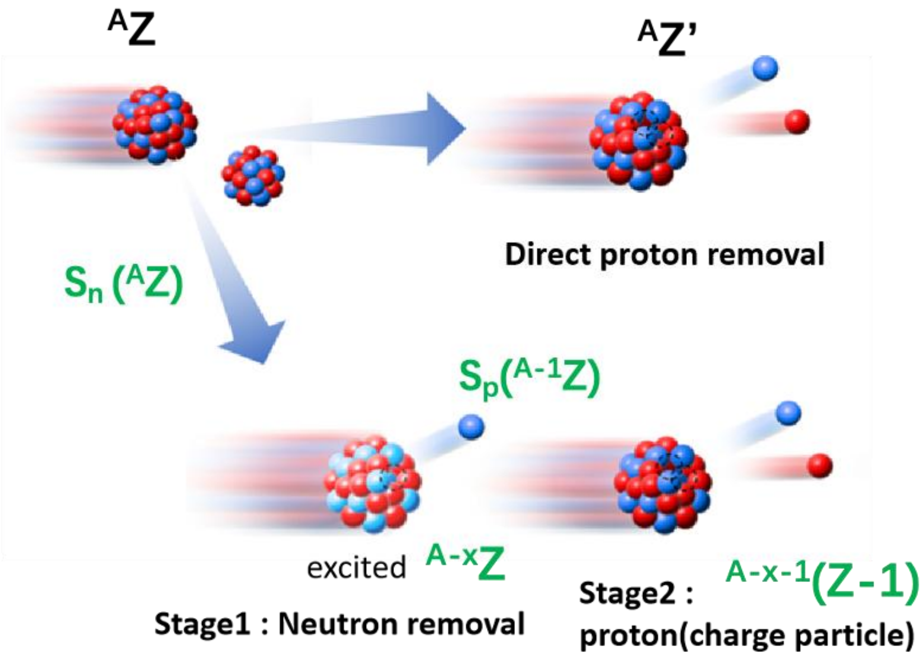


- Isospin-dependent evaporation with peaks in nuclei with isospin symmetry.
- Peak values vary for *p*-shell (~16%) and *sd*-shell (~10%) nuclei.
- Impossible for a reliable radius determination due to a non-constant correction factor!

Jian-Wei Zhao, BHS, Tanihata *et al.*, PLB 847, 138269 (2023)

Parameterize the evaporation by Separation energies

$$\sigma_{cc}^{cor.} = \sigma_{cc}^{direct} + \sigma_{cc}^{evap.}$$



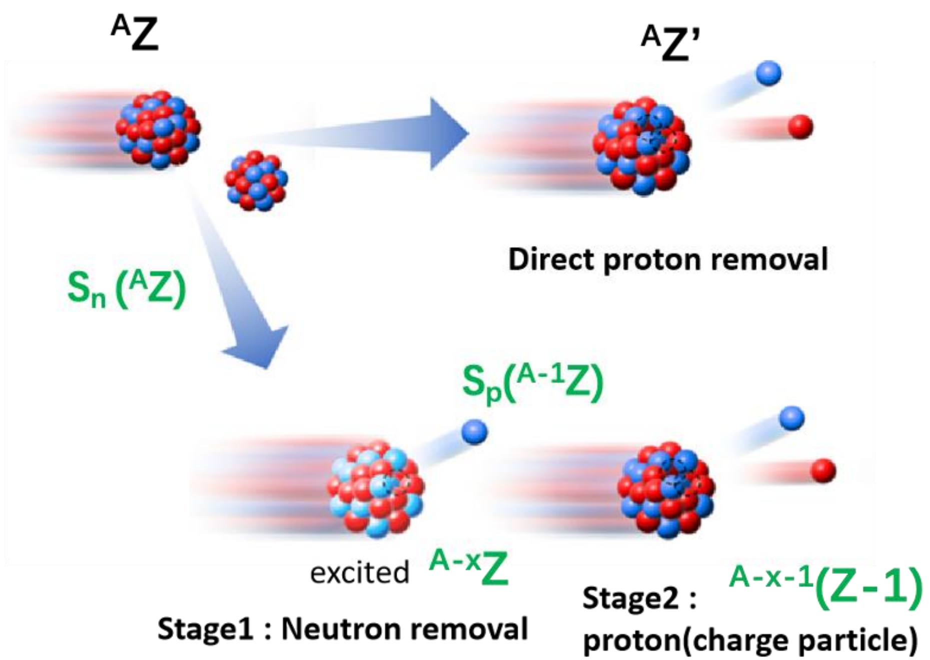
e.g., one-neutron removal

e.g., one-proton evaporation

Dominant case: One-proton evaporation after one-neutron removal

Parameterize the evaporation by Separation energies

$$\sigma_{cc}^{cor.} = \sigma_{cc}^{direct} + \sigma_{cc}^{evap.}$$

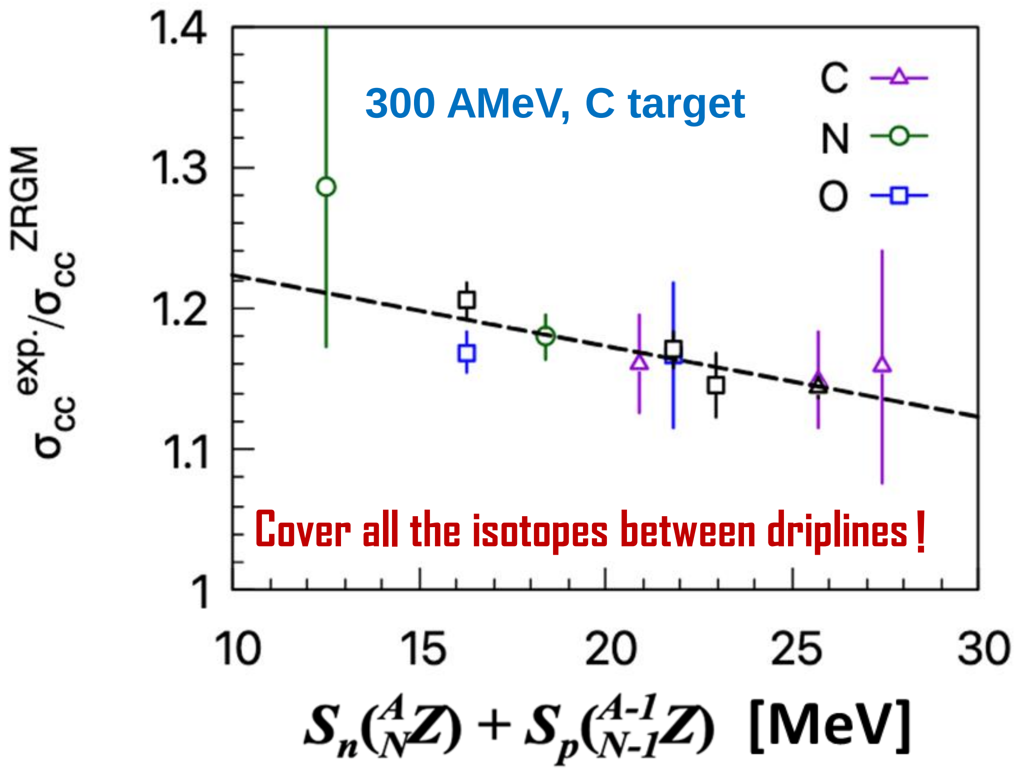


e.g., one-neutron removal

e.g., one-proton evaporation

Dominant case: One-proton evaporation after one-neutron removal

All the points have a well-known R_p for calibration



The linear correlation makes model calibrations feasible!

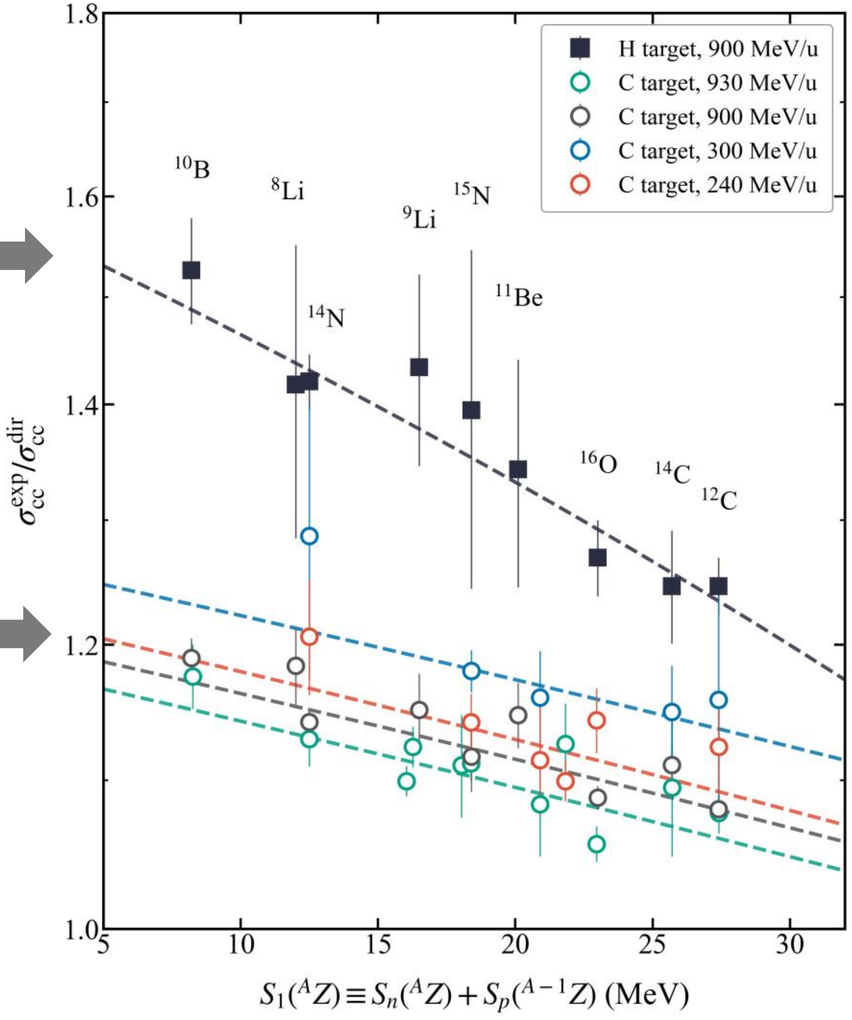
Zhao, BHS, Tanihata *et al.*, PLB 858(2024)139082

Robust correlations offer a way to deduce radii

Isotopes with known R_p for calibrations

H-target 900

C-target 240,300,900,930



Zhao *et al.*, PLB 858(2024)139082; Zhang *et al.*, Sci. Bull. 69 (2024) 1647

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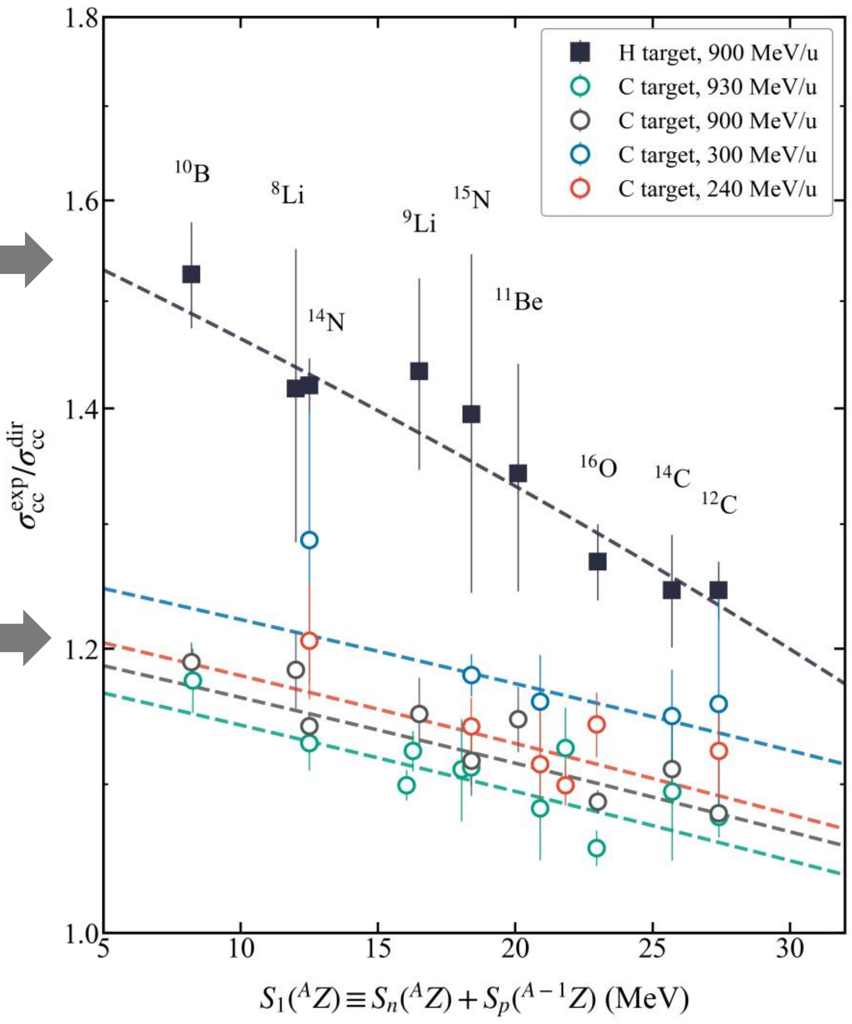


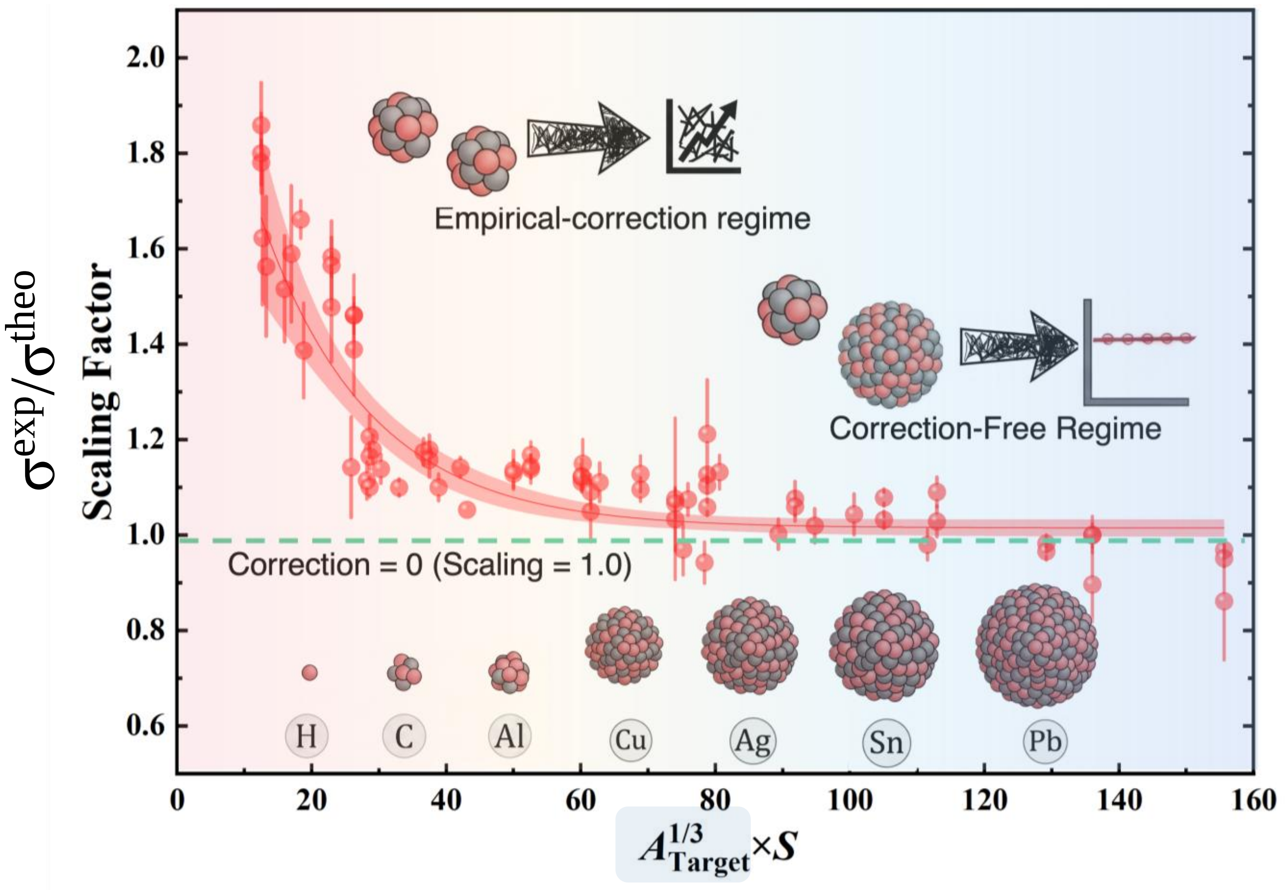
- Identical slopes for *p*-shell nuclei on carbon at 240, 300, 900 and 930 AMeV
- H-target data have a much significant evaporation contribution than C-target data.
- Offer a realistic way to map theory to experimental data, thus Rp from cross sections

What happens for various targets?

Zhao *et al.*, PLB 858(2024)139082; Zhang *et al.*, Sci. Bull. 69 (2024) 1647

Discovery of a universal scaling with reaction targets

p-sd shell Isotopes with known R_p for calibrations



target nuclear mass

We demonstrate that with increasing target nuclear mass,

the evaporation channel contribution gets smaller;

minor contribution from electromagnetic dissociation (EMD) (<1%), e.g., coulomb interaction induced proton dissociation

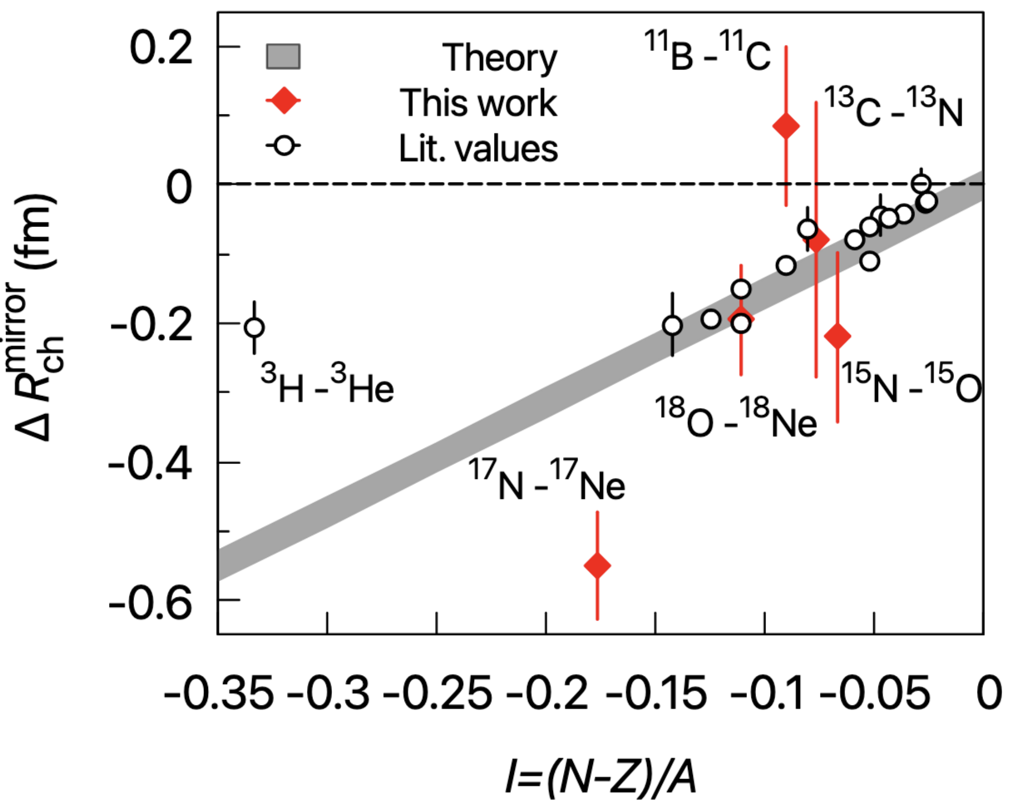
Heavy-isotope targets (Pb) instead of light-isotope targets (C, H) when inferring the charge radii of unstable isotopes from charge-changing cross sections.

Xu, BHS, Tanihata *et al.*, PRL(2026), in press

Mirror-difference charge radii: charge symmetry breaking

$$\Delta R_{\mathrm{ch}}^{mirror} = R_{\mathrm{ch}}({}^{A}_{N}Z) - R_{\mathrm{ch}}({}^{A}_{Z}N)$$

N>Z



Zhao, BHS, Tanihata *et al.*, PLB 858,139082(2024)

- Radii of ^{11}C, ^{13,16}N, ^{15}O for the first time
- Four mirror pairs for the first time, ^{18}O-^{18}Ne redetermined

Typical uncertainty: 2.5%
(dominated by statistics)

$$\Delta R_{\mathrm{ch}}^{\mathrm{mirror}} = 1.574 \cdot I \pm 0.021$$

Theory: PRL130(2023)032501

Discrepancies seen for

^{3}H-^{3}He

^{17}N-^{17}Ne (proton halo)

^{11}B-^{11}C (uncertainty in $^{10\text{-}11}$B?)

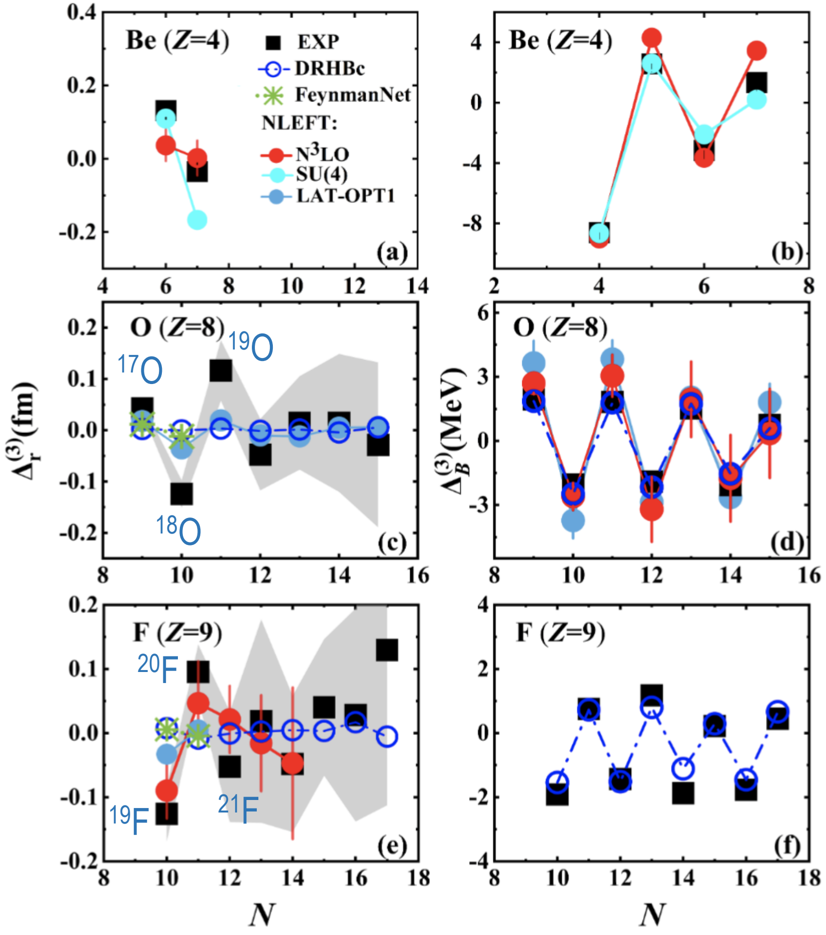
A new fingerprint of charge symmetry breaking due to halo?

PRL 122, 182501 (2019)

Large odd-even staggering in charge radii of the lightest isotopes

Charge radii: $\Delta_r^{(3)}(\mathrm{Z,N}) = \frac{1}{2}[\mathrm{R_{ch}(Z,N+1)} - 2\mathrm{R_{ch}}(Z,N) + \mathrm{R_{ch}}(Z,N-1)]$

Binding energies: $\Delta_E^{(3)}(\mathrm{Z,N}) = \frac{1}{2}[E(\mathrm{Z,N}+1) - 2E(Z,N) + E(Z,N-1)]$



Xu et al., to be submitted (2026)

- The hadronic probe is the only tool so far to deduce the radii of unstable O and F isotopes.
- Larger $\Delta_r^{(3)}$ at near ^{18}O and ^{19}F, are seen in comparison with the typical 0.01 fm in other isotopic chains
- NLETF, nuclear lattice effective field theory, well reproduces $\Delta_r^{(3)}$ and $\Delta_E^{(3)}$, where all the other models reproducing well the OES in binding energies but seem fail to capture the OES in charge radii

Theories: Shi-Hang Shen, Zheng-Xue Ren, Bing-nan Lv
Peng-Wei Zhao, Yi-Ping Wang, Yi-Long Yang, Kai-Yuan Zhang, Jian-Guo Li

Summary

Data – global pattern – interpretation

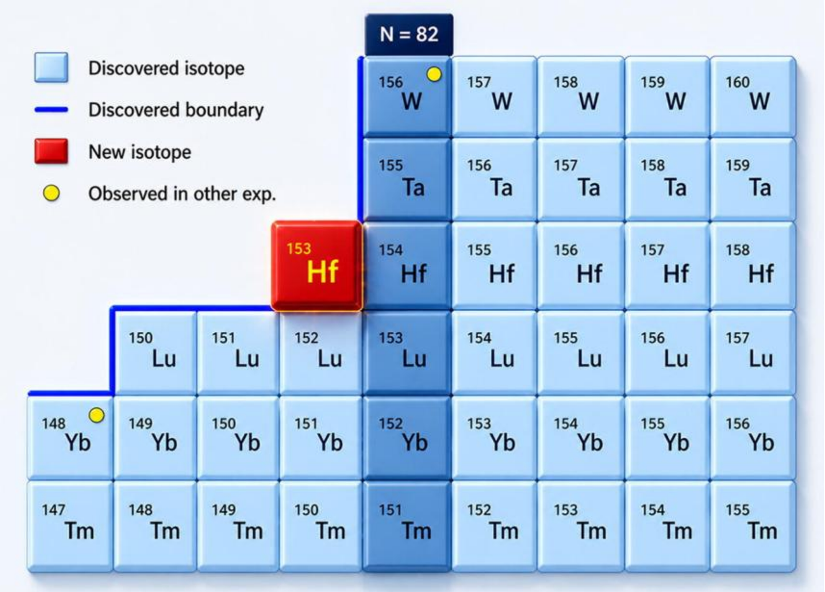
- We studied the charge-changing reactions of *p-sd* shell nuclei on various targets (H, C, Ag, Pb) at various collision energies.
- We identified a robust correlation with the *S* factor for *p-sd* shell nuclei, which allows us to develop an empirical but universal approach to deducing R_p.
- Selected examples are shown, including mirror-difference radii and large odd-even staggering in charge radii of *p*-shell nuclei.

Next steps:

- Experimentally **disentangle** charge particle evaporation from the direct proton removal process
- ***S*-factor scaling**: robust when moving from *p*-shell to heavier isotopes?
- Can one get identical R_p or ρ_p from **different target data**?
- **Proton halo candidates** at HIAF by simultaneous measurements of cross sections and momentum distribution of 1p knockout reactions

Ions	HIAF-BR	
	Energy (A MeV)	Intensity (ppp)
^{18}O	2600	2.5×10^{11}
^{78}Kr	1700	3.0×10^{11}
^{209}Bi	851	3.2×10^{10}
^{238}U	800	1.0×10^{11}

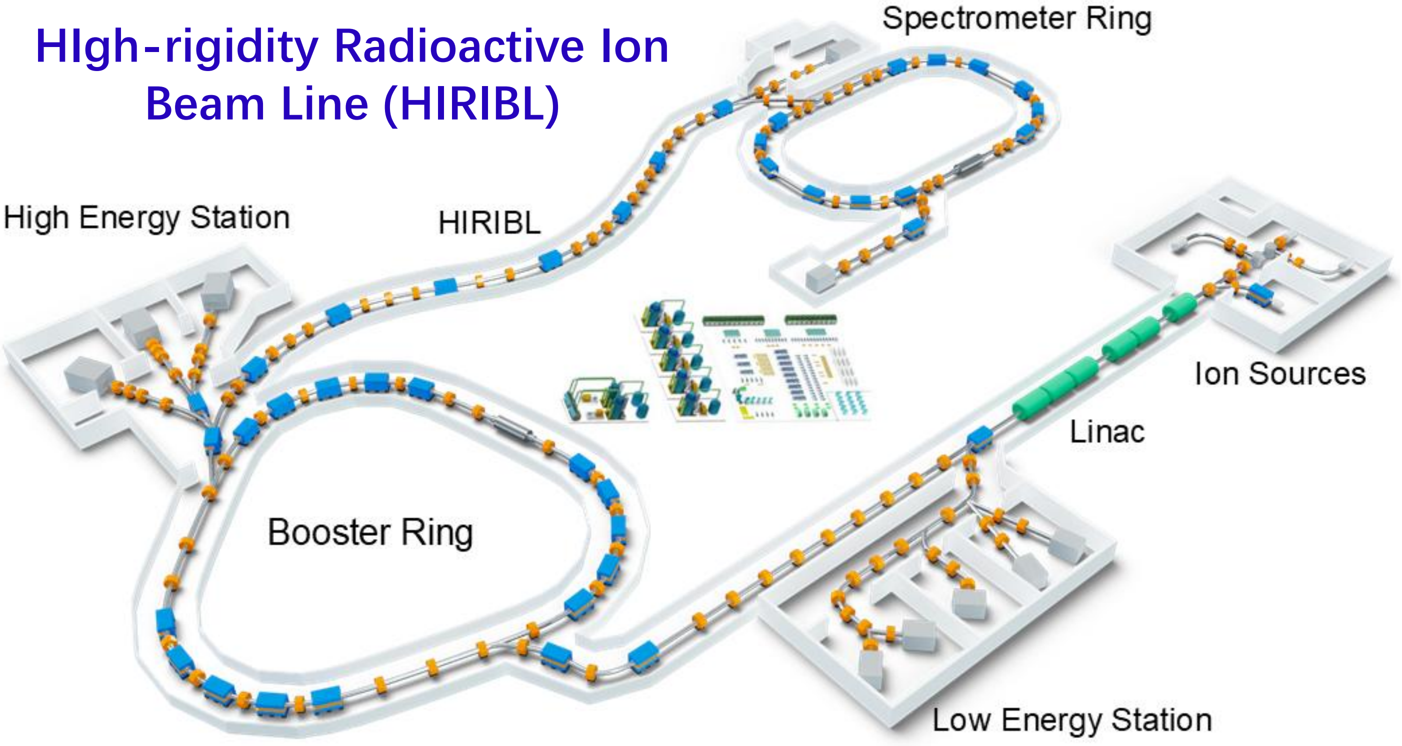
Discovery of isotope ^{153}Hf



Science Bulletin 71 (2026) 4099

Possible way to enhance the yields of most exotic nuclei

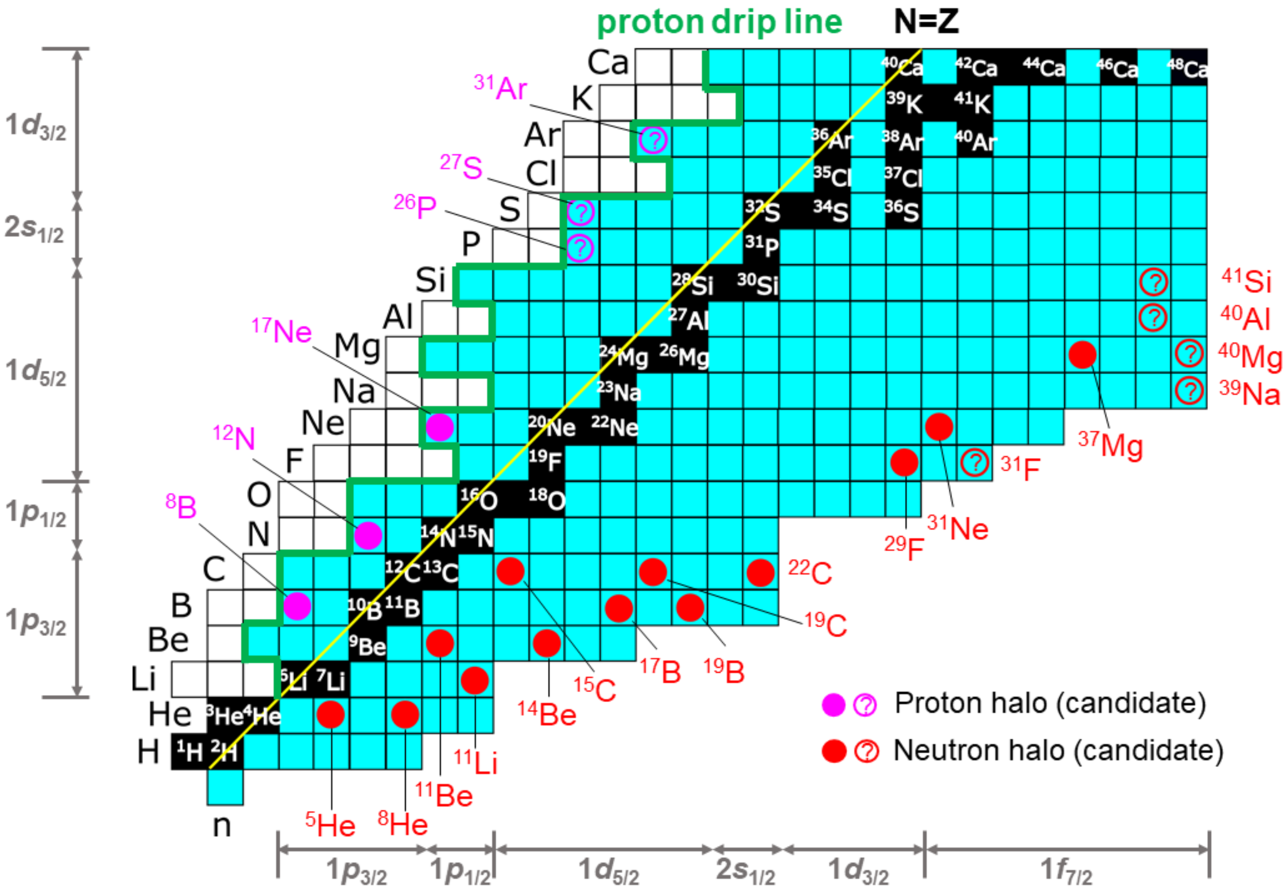
HIgh-rigidity Radioactive Ion Beam Line (HIRIBL)



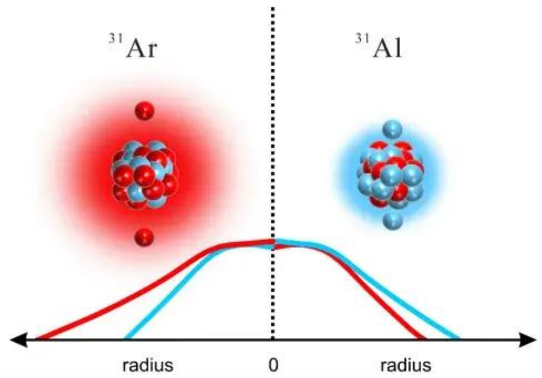
Multi-Step Fragmentation of High-Energy Projectiles in Thick Targets could significantly enhance the yield of very neutron-rich isotopes by several orders of magnitudes

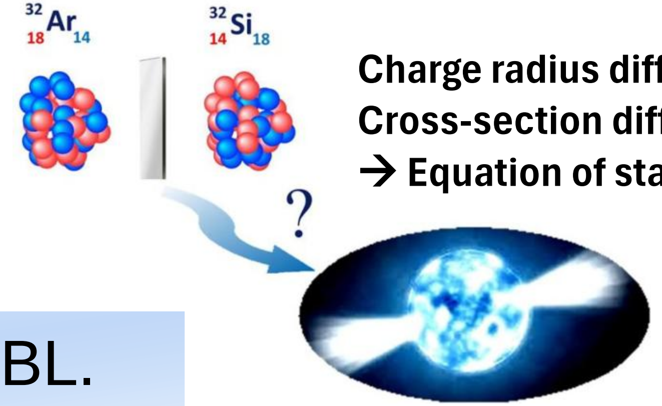
Wei, BHS, Terashima et al., Nucl. Sci. Tech. 36,195 (2025)

Size of most proton-rich nuclei: ^{31}Ar, ^{27}S, and ^{26}P



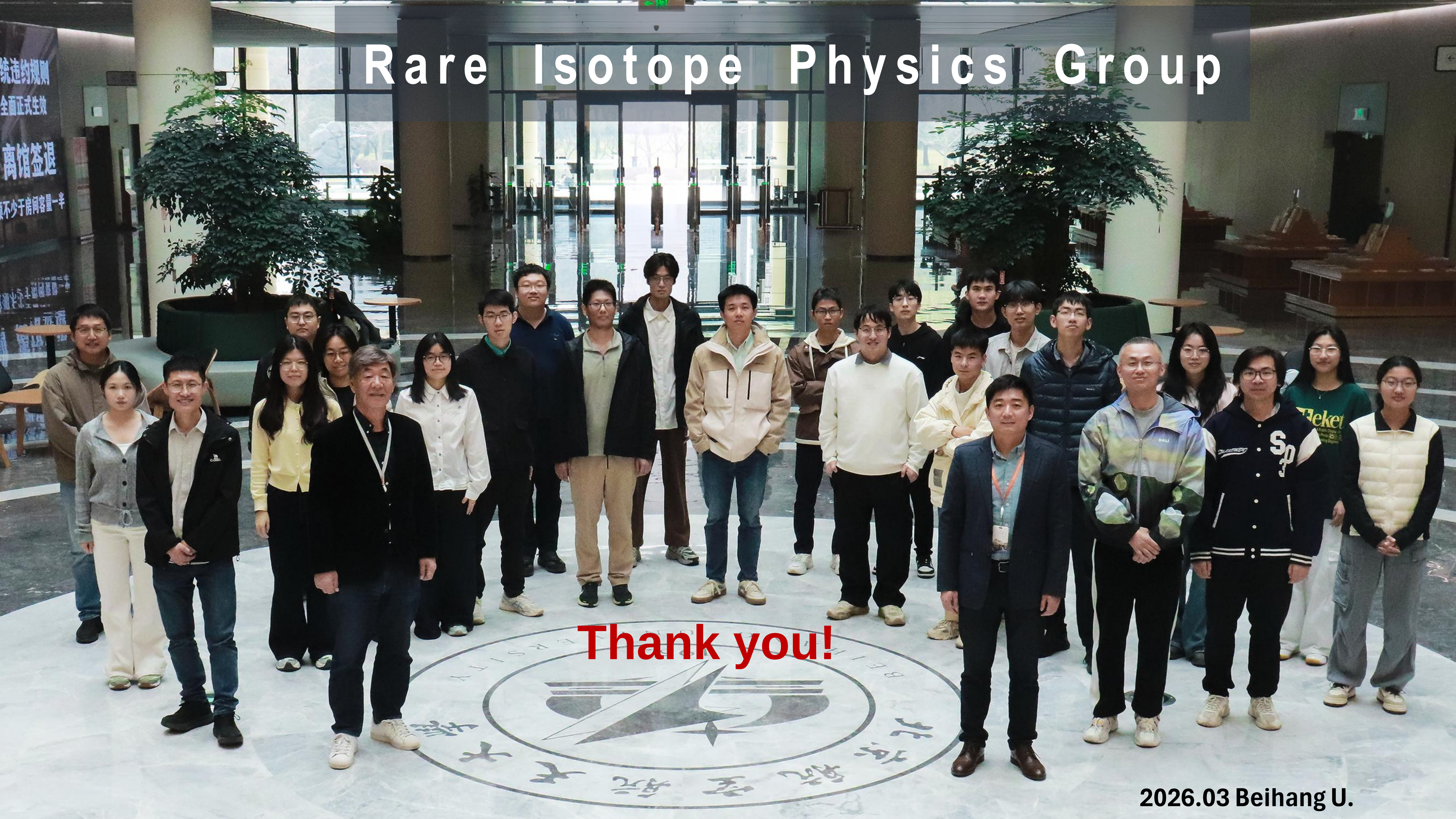
- ☐ Proton halo candidate
- ☐ Charge symmetry & EOS





Charge radius difference
Cross-section difference
→ Equation of state, L

- ☐ σ_I, σ_{-1p} , and $P_{||}$ distribution with HIRIBL.
- ☐ σ_{cc}, σ_F measured simultaneously

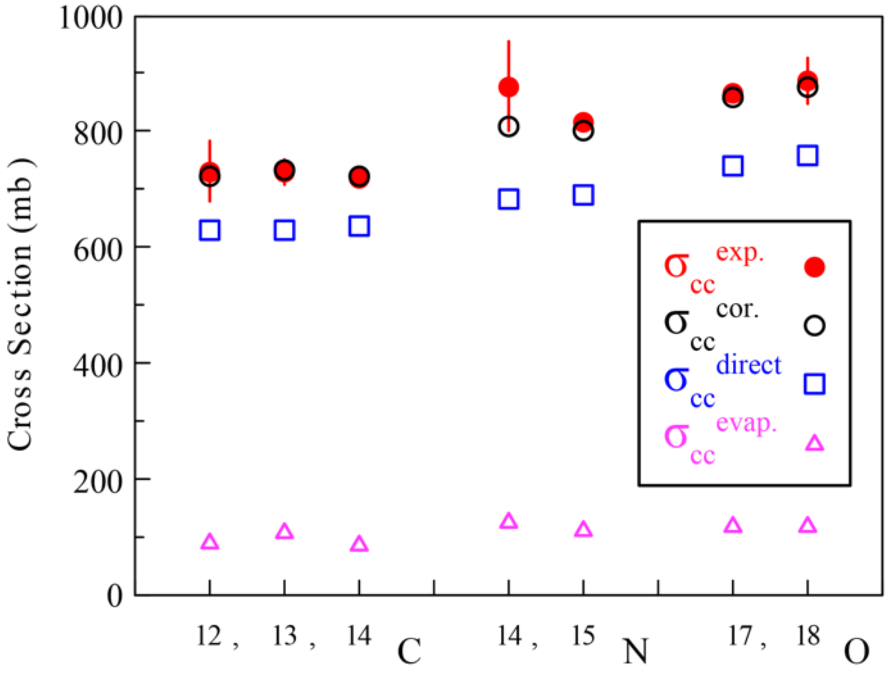

Rare Isotope Physics Group
Thank you!
2026.03 Beihang U.

Reaction mechanism of charge-changing reactions

The difference between the. and exp., can be well explained by the charge particle evaporation after neutron removal.

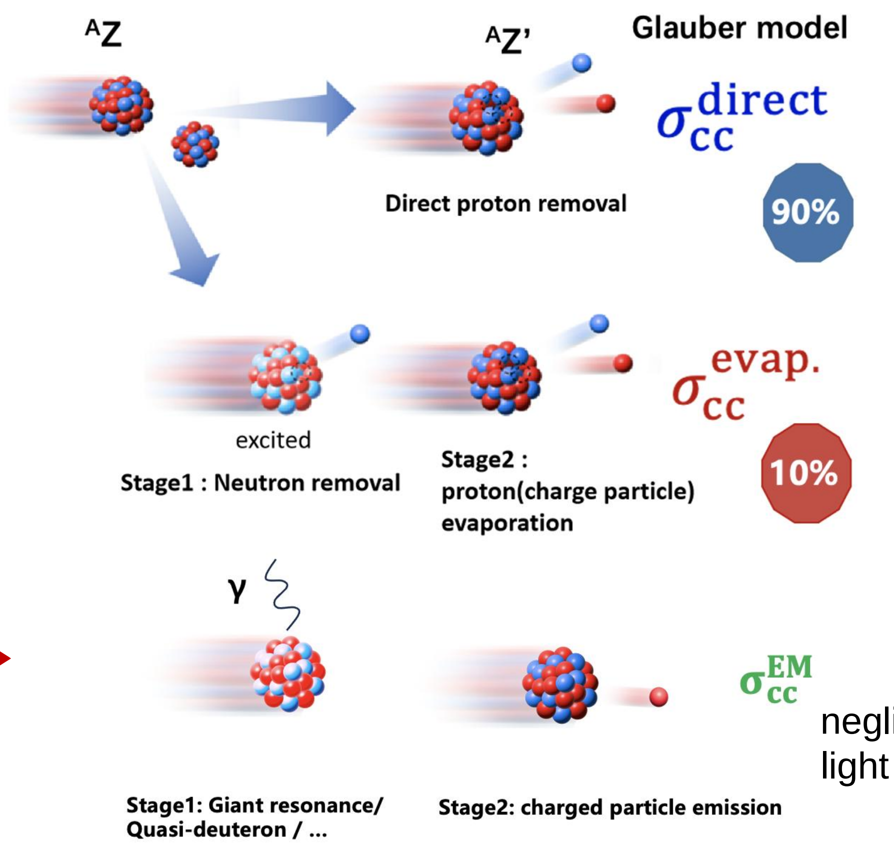
$$\sigma_{cc}^{cor.} = \sigma_{cc}^{direct} + \sigma_{cc}^{evap.}$$

300 MeV/nucleon



Zhao, *et al.*, PLB 847 (2023)138269

Tanaka *et al.*, PRC106(2022)014617



negligible for light mass target

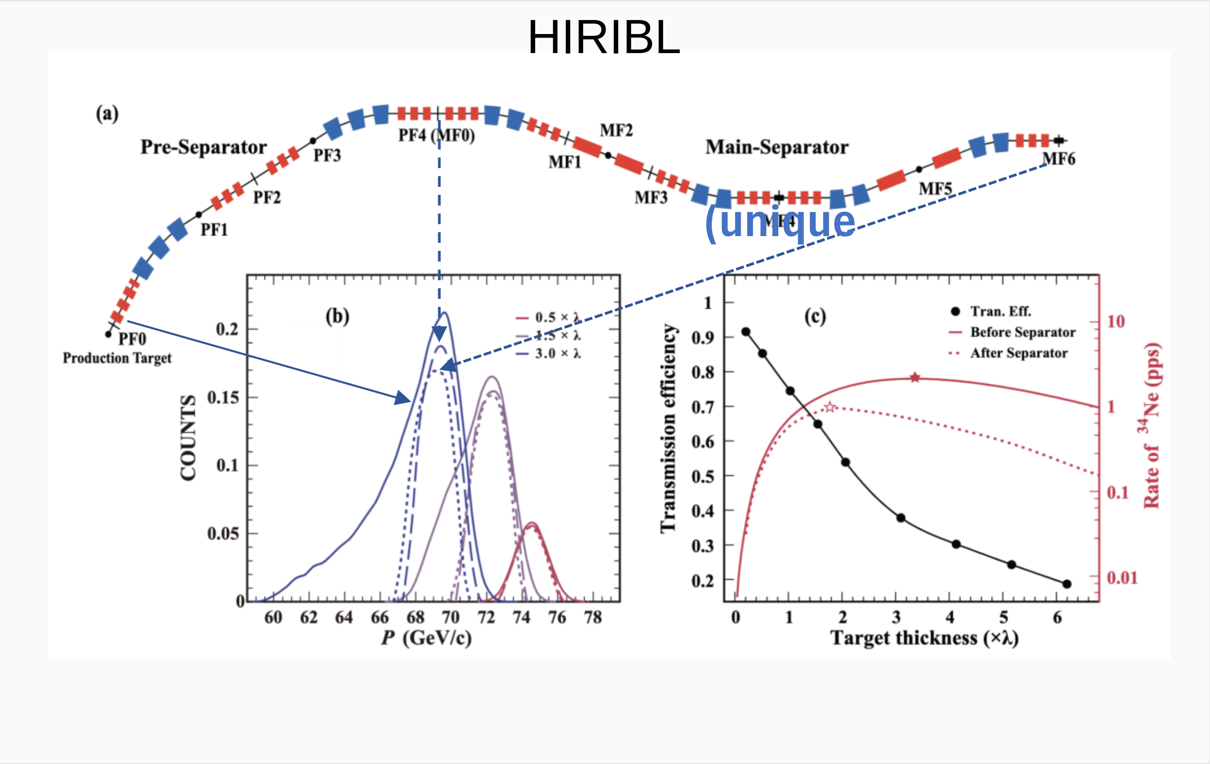
Liu *et al.*, Phys. Rev. C 112(2025)014611

Q: Is the evaporation contribution constant?

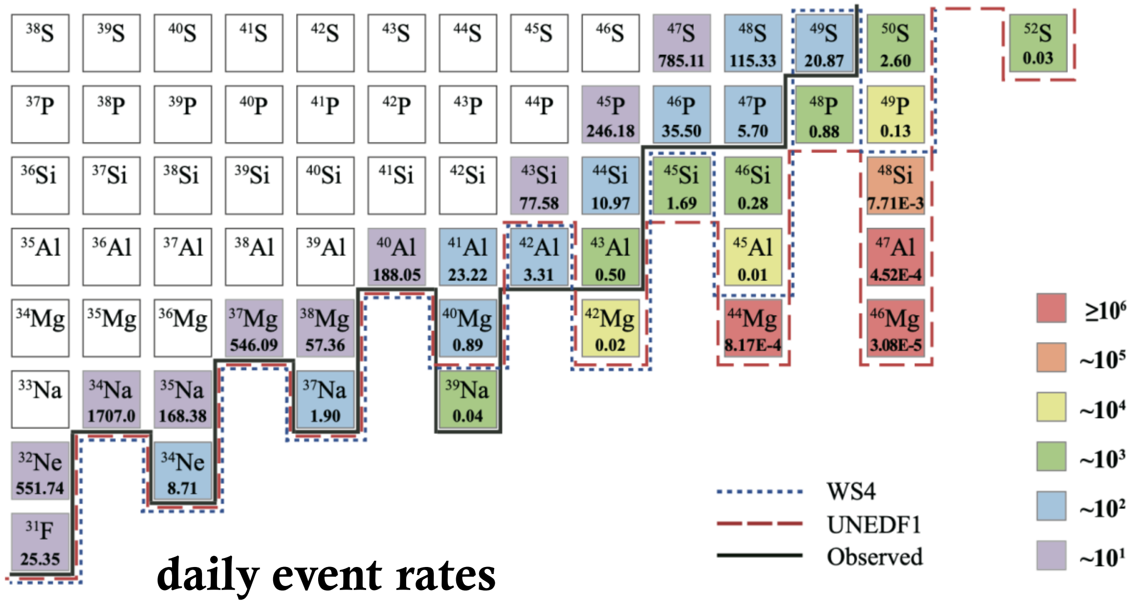
Multi-step fragmentations of AGeV projectiles in thick targets

1.5 AGeV, 3×10^{11} pps ^{48}Ca + Be (~10cm):

- ➢ **large yield but large momentum spread**



- ✓ yield of most n-rich isotopes can be enhanced by 1-6 orders of magnitude
- ✓ the more n-rich, the higher enhancement

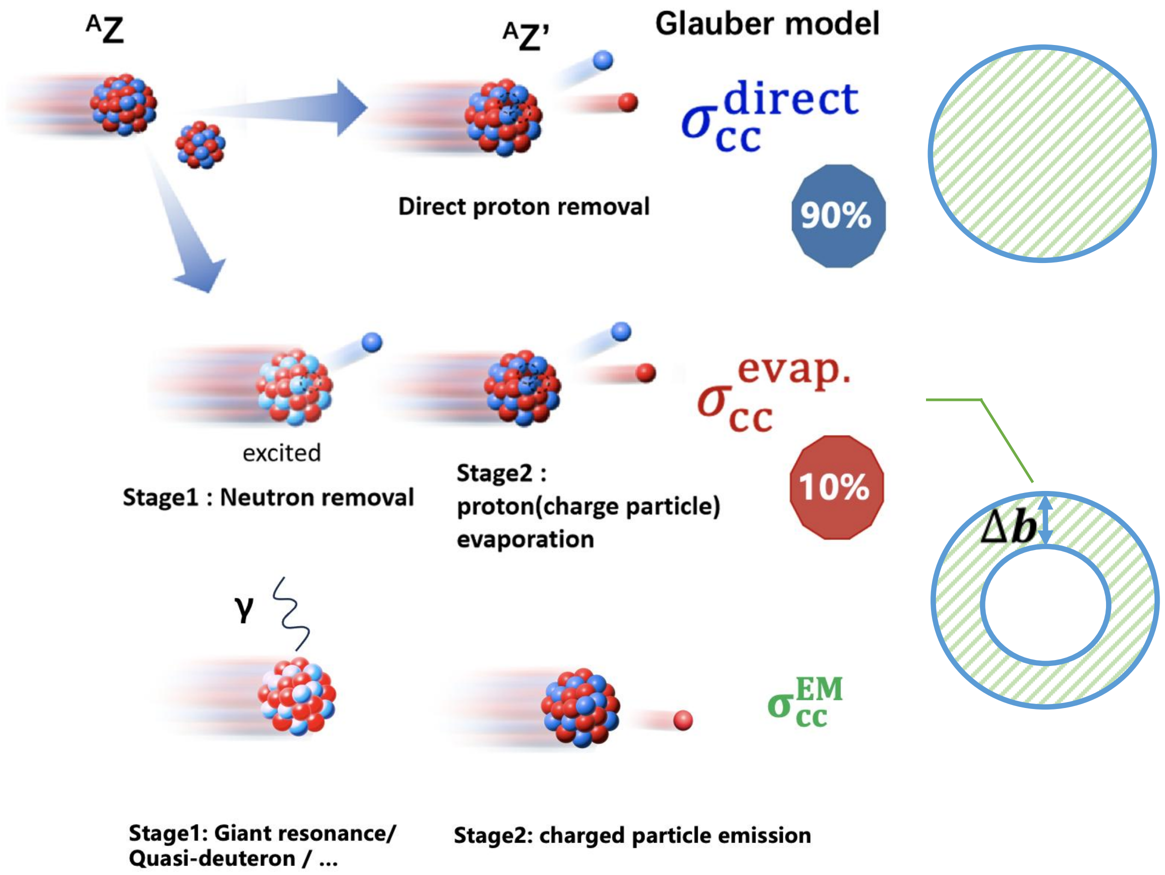


Enhancement factor

Wei, BHS, Terashima, Tanihata, Wu, Wang, Nucl. Sci. Tech. 36,195 (2025)

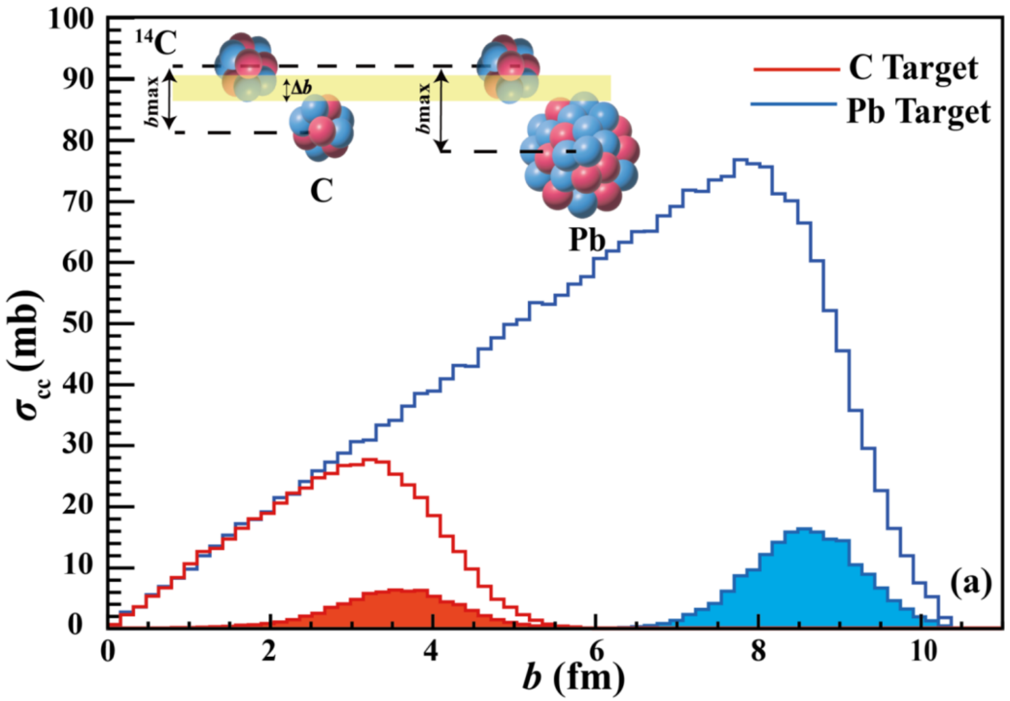
Reaction mechanism of charge-changing reactions

$$\sigma_{cc}^{cor.} = \sigma_{cc}^{direct} + \sigma_{cc}^{evap.} + \sigma_{cc}^{EM}$$



Liu *et al.*, PRC 112 (2025) 014611

Smaller CPE contribution with increasing target nuclear masses



Courtesy: Jun Su (IQMD+GEMINI)

Xu, BHS, Tanihata et al., PRL(2026)