

GeV/nucleon 能区原子核的电荷改变反应研究 --- 系统及规律

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高能与低能核物理交叉学术研讨会

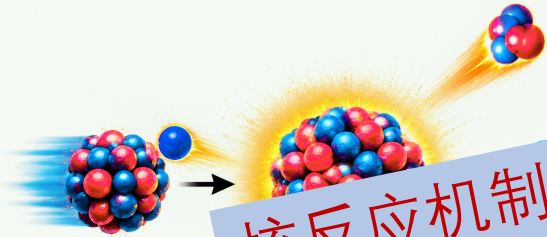
2026年5月15-18日, 华东师范大学, 上海

Nuclear Reactions from Low to High Energies

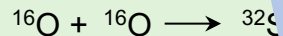
1) Low Energies

$$E_{\text{lab}} < \sim 10 \text{ MeV/nucleon}$$

Overcoming Coulomb barrier



Fusion, multi-n

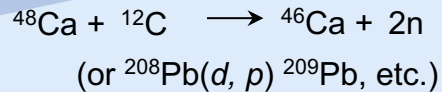


Formation of an excited compound nucleus
Evaporation of light particles or gamma rays
Probes structure and reaction mechanisms

2) Intermediate Energies

$$E_{\text{lab}} \sim 30\text{-}1000 \text{ MeV/nucleon}$$

Above Fermi energy

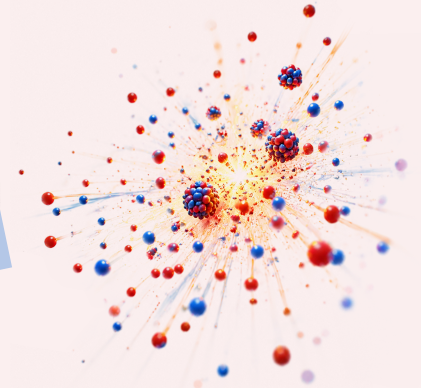


Peripheral (large impact parameter)
Projectile and target mostly remain intact
Probes single-particle structure and correlations

3) High Energies

$$E_{\text{lab}} > \sim 1 \text{ GeV/nucleon}$$

on and high density



Particle production

$A + B \longrightarrow$ compressed matter ($\rho > \rho_0$, $T > 0$)
 $\longrightarrow$ many particles (N , Δ , π , K , ...)

Production of multiple hadrons and fragments
Constrains the nuclear Equation of State
Phase transition

核反应机制经常并存
核子核子相互作用介质效应
体系自由度
从多个能区去研究原子核结构是非常有意义、且相互补充的

10

100

1000

Beam Energy (E_{lab}) [MeV/nucleon]

Intermediate Energies

Low Energies

High Energies

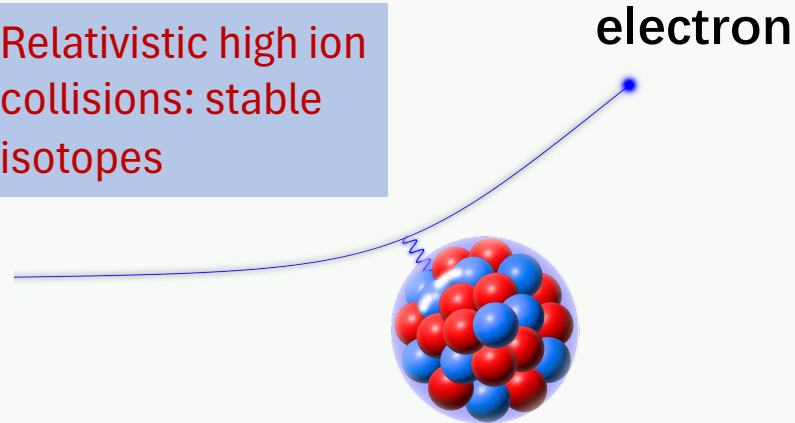
Probing atomic nuclide

放射性核束物理、稀有同位素物理

Electromagnetic probe

Stable/long-lived isotopes

Relativistic high ion collisions: stable isotopes



- electron scattering (ρ_{ch})
- Muonic X-ray
- Optical isotope shifts
- K_α X-ray isotope shifts

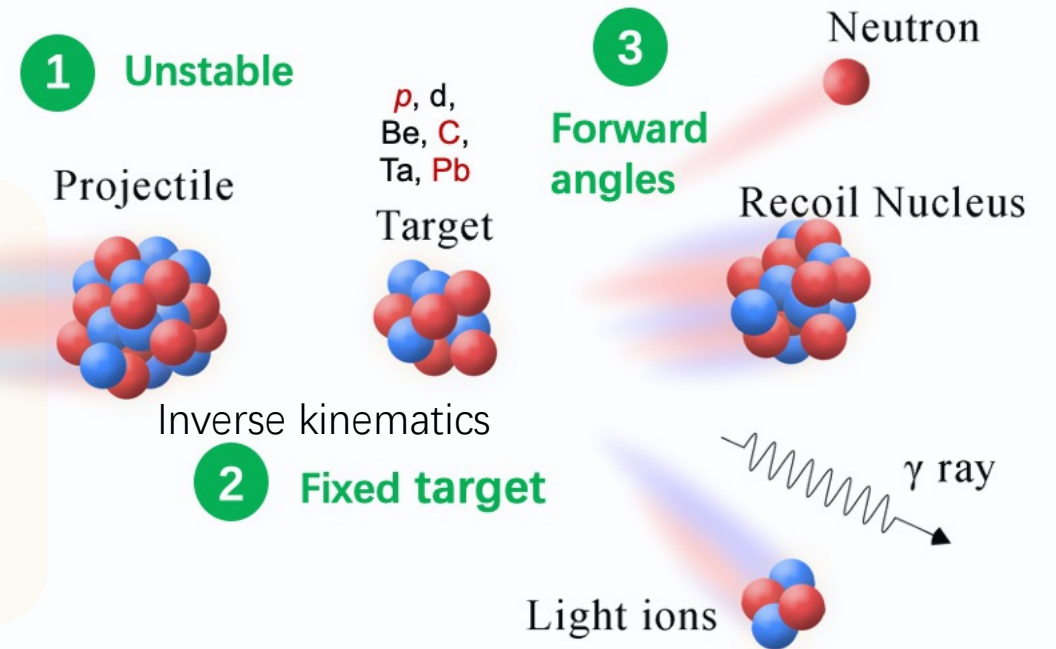
Strong interaction

Observable
(Cross section)

Structure
&
Reaction

Hadronic/heavy ion probe

Short-lived isotopes



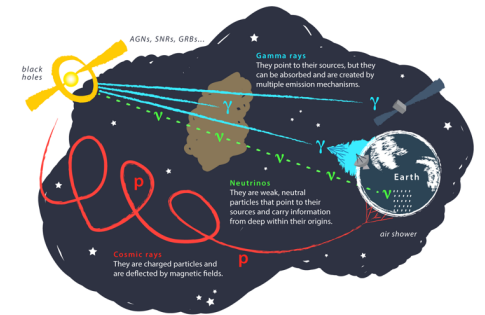
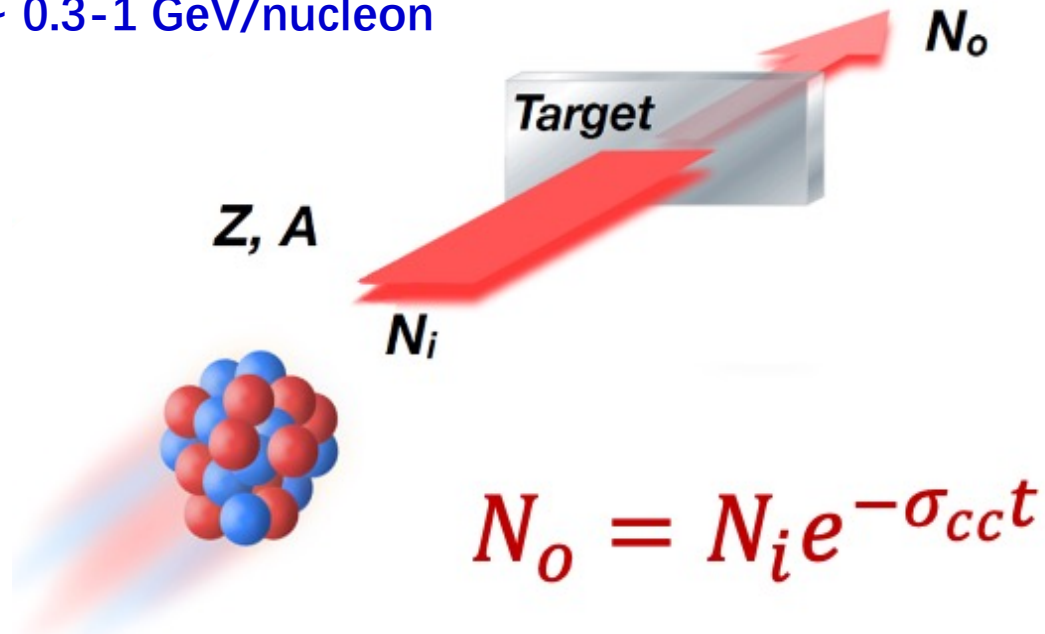
At intermediate and high energy (several 0.1 to ~ 1.0 AGeV)
Reaction & structure governed by **strong** interactions
Reaction/Interaction/Charge-changing X-sections as first hints

Charge-changing reaction and cross section

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

Transmission method
at $\sim 0.3-1$ GeV/nucleon

Only Z identified



- 关键核数据：宇宙线传播及起源问题
- 电荷改变截面的大小反映了待研究原子核内点质子的密度分布



Experiment simple absolute xs



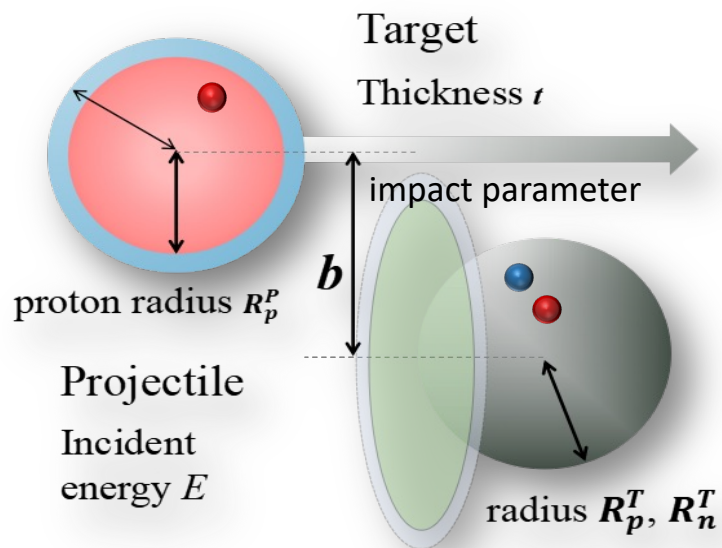
High precision



Bulk properties of nuclide

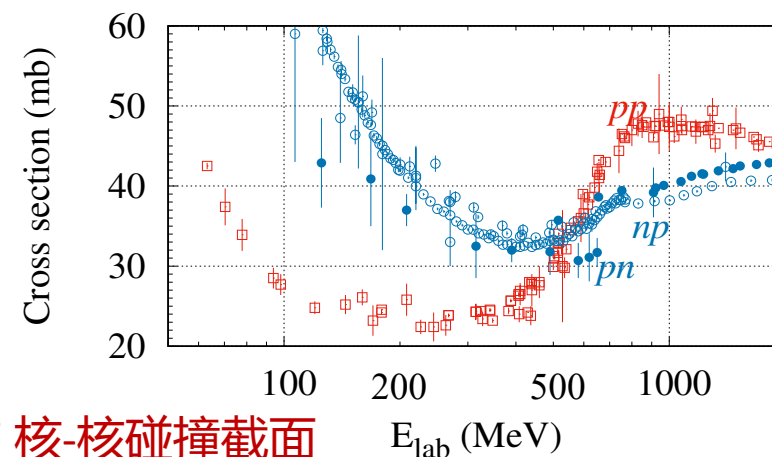
Glauber model interpretation of charge-changing reaction

Adapted the Glauber model, assuming σ_{cc} comes from only the collisions between **projectile protons with the target nucleon at the collision energy of about GeV/nucleon**



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

Zero-range optical limit Glauber model



用核子-核子作用+密度分布“合成”核-核碰撞截面

Glauber model + RCHB/RMF densities can reproduce nicely the experimental data (NPA2000), linking the density with the cross sections for the first time

Meng, Zhou, Tanihata, Phys. Lett. B 532 (2002) 209

目前依旧是基准模型!

Glance at exp.

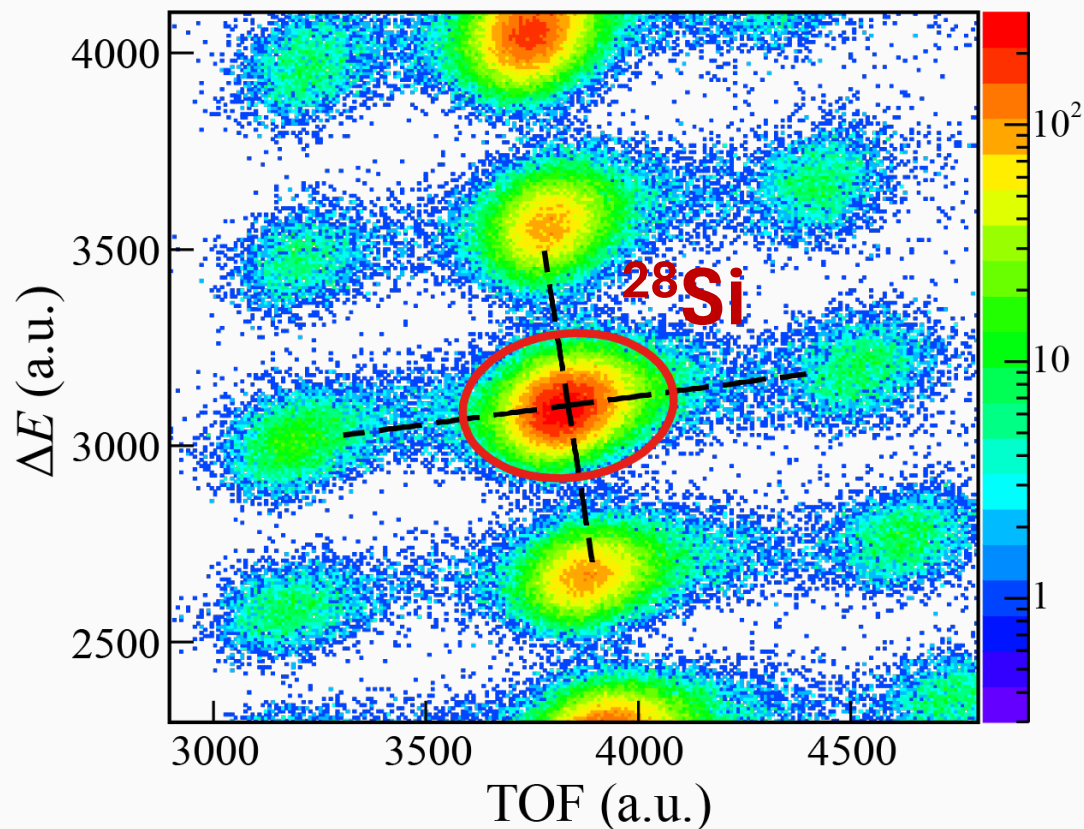


$\sigma_{cc} = \sigma_{\Delta Z > 0}$ 电荷改变截面

$\sigma_{\Delta Z = 1, 2, 3 \dots}$ 电荷改变分截面

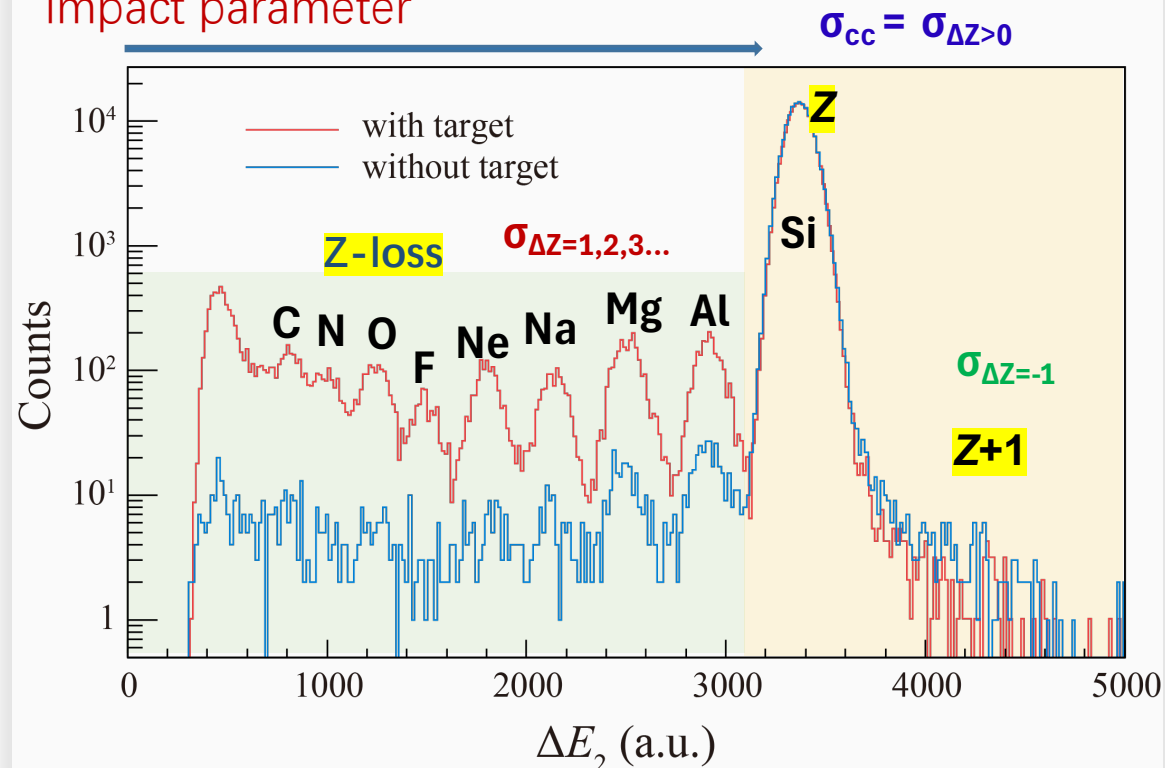
$\sigma_{\Delta Z = -1}$ 电荷交换截面

Incident particles before reaction target



Z distribution of reaction products

Impact parameter



机制：中心碰撞 --- 擦边碰撞

王长建 et al., Chin. Phys. C 47 (2023) 084001

Consistent (and largest) database for σ_{cc} (2014-2024)

Total beam time at HIRFL ~ 30 days

☆ Isotopes identified

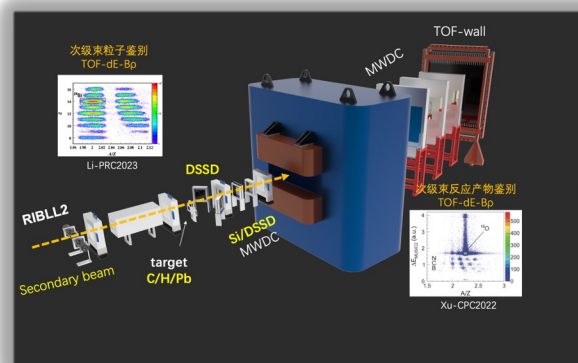
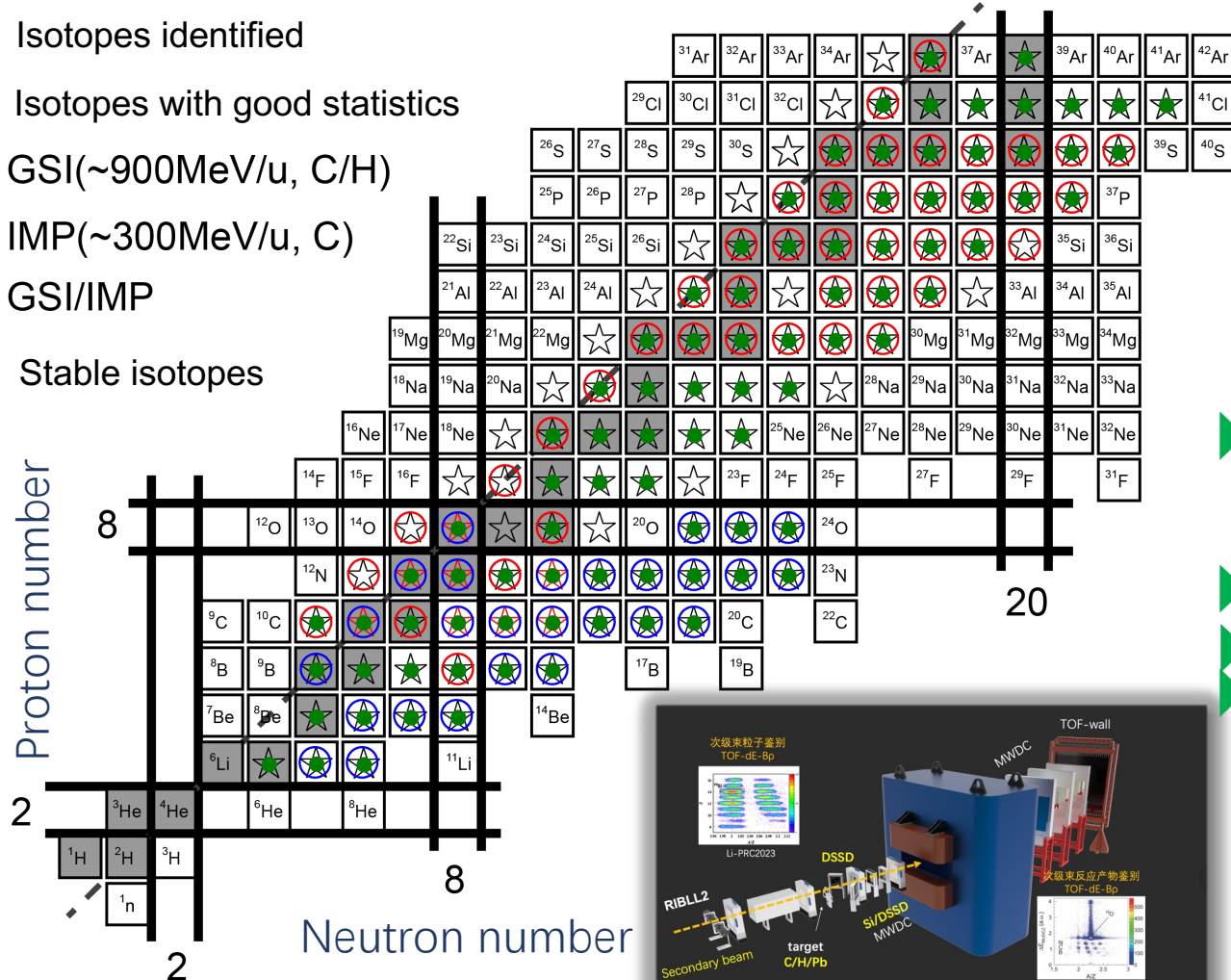
● Isotopes with good statistics

⊗ GSI (~900 MeV/u, C/H)

⊗ IMP (~300 MeV/u, C)

⊗ GSI/IMP

■ Stable isotopes



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

Zhang *et al.*, NIMA 1084, 171267 (2026)

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.*, CPC47, 084001 (2023)

Li *et al.*, PRC107, 024609 (2023)

Xu *et al.*, PLB833, 137333 (2022)

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)

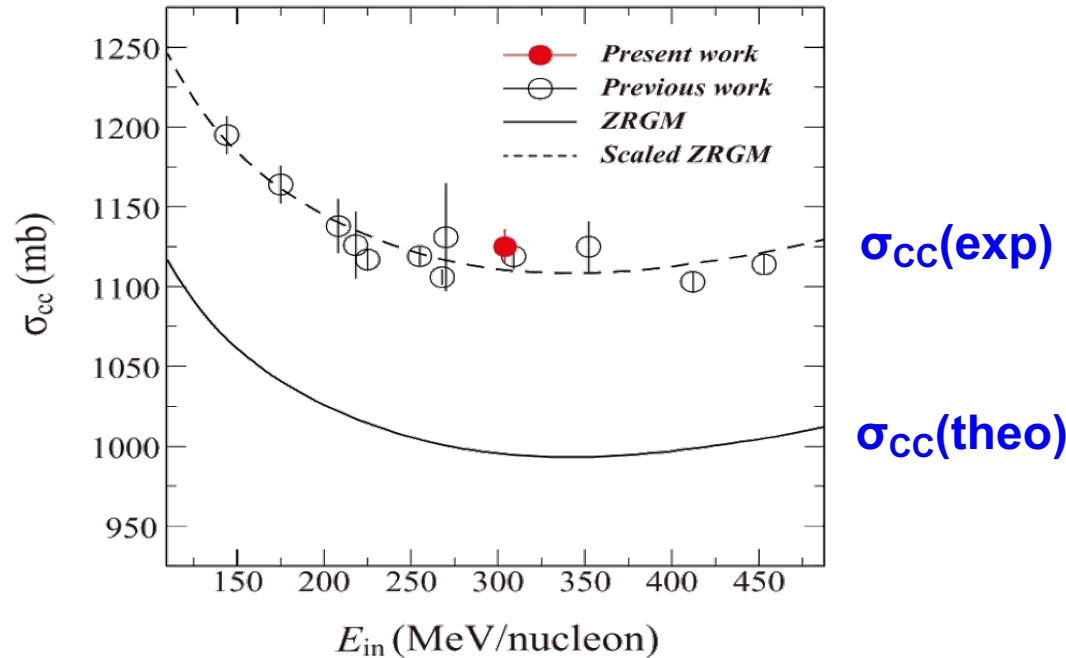
Physics

Best paper award of
Chin. Phys. C
in 2023

Instrumentation

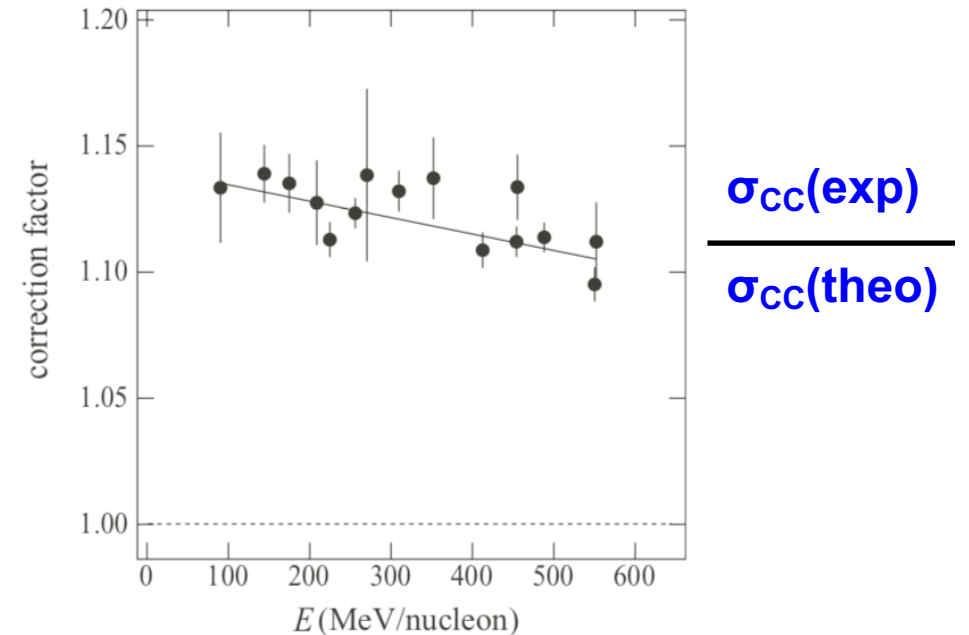
Precise σ_{cc} data revealing systematic difference with models

$^{28}\text{Si} + \text{C}$ target



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

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



- **Energy-dependent correction factor** needed for the **Glauber-type** calculation to reproduce the experimental data

Yamaguchi et al., PRL107,032502(2011)

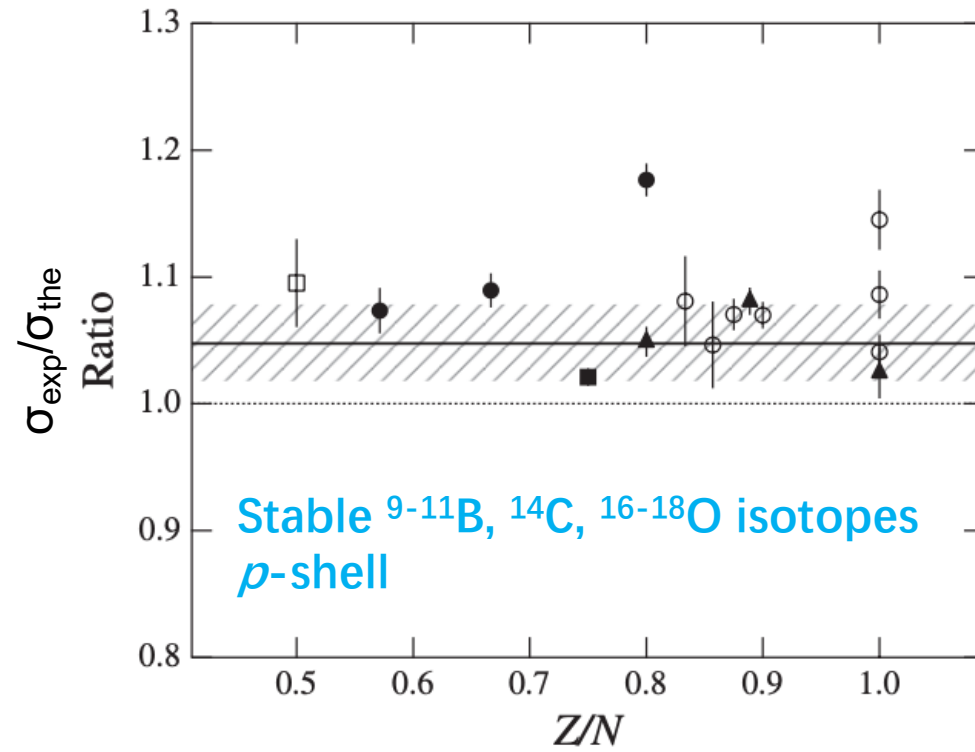
Yamaguchi *et al.*, PRC 82, 014609 (2010)

王长建 *et al.*, Chin. Phys. C 47, 084001 (2023)

First application to deduce R_p of unstable nuclei

Zero-Range optical-limit Glauber Model (ZRG) calculations with the phenomenological correction factor

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



The Glauber model, together with the scaling, was used to extract the rms proton radius of the projectile nuclide from the charge-changing cross section

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

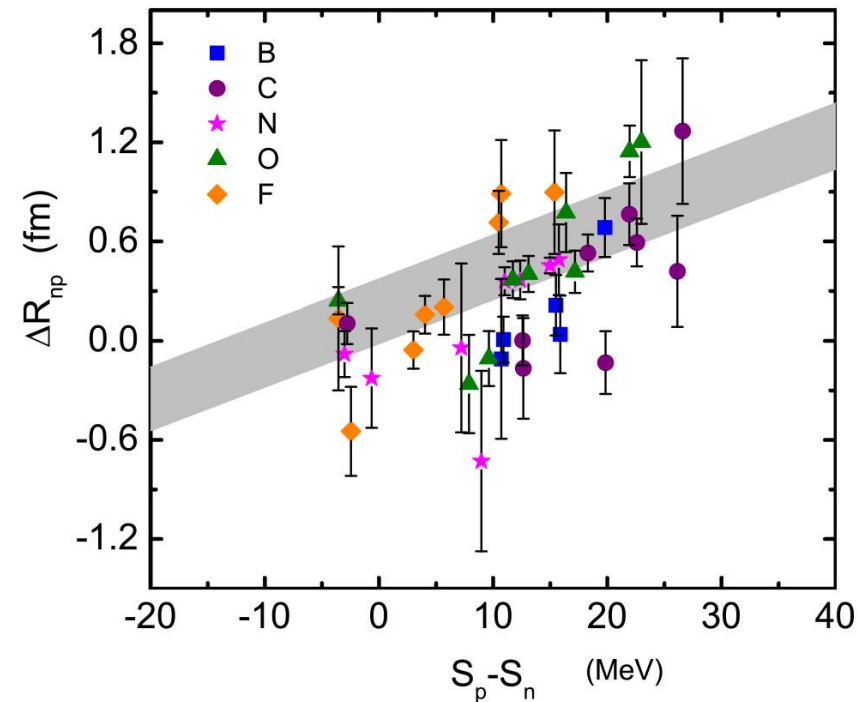
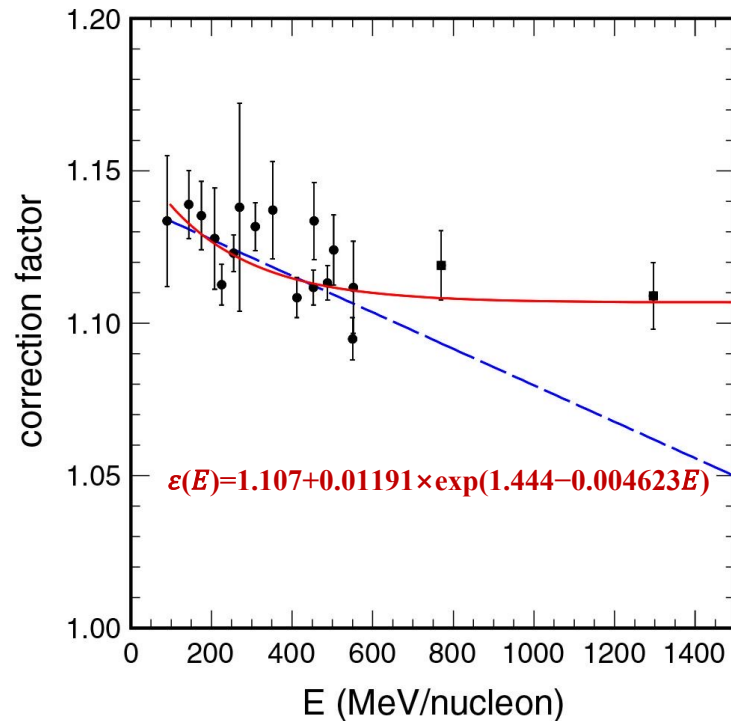
Nuclide	$\tilde{r}_p$ (fm)	$\tilde{r}_m$ (fm)
^{12}C	2.320 ± 0.007 [14]	2.31 ± 0.02 [22]
^{13}C	2.315 ± 0.008 [14]	2.28 ± 0.04 [22]
^{14}C	2.364 ± 0.011 [14]	2.30 ± 0.07 [22]
^{15}C	2.33 ± 0.11	2.48 ± 0.03 [22]
^{16}C	2.25 ± 0.11	2.70 ± 0.03 [22]

Yamaguchi-PRL107,032502(2011)

Assuming the scaling ratio is a constant in the same energy range, and is insensitive to Z/N ratios

Determination of the neutron skin thickness from interaction cross section and **charge-changing cross section** for B, C, N, O, F isotopes

Xiu-Fang Li, De-Qing Fang, Yu-Gang Ma, *Nucl. Sci. Tech.* 27,71(2016)



R_p is extracted using the scaling method from NPA 2020 data.

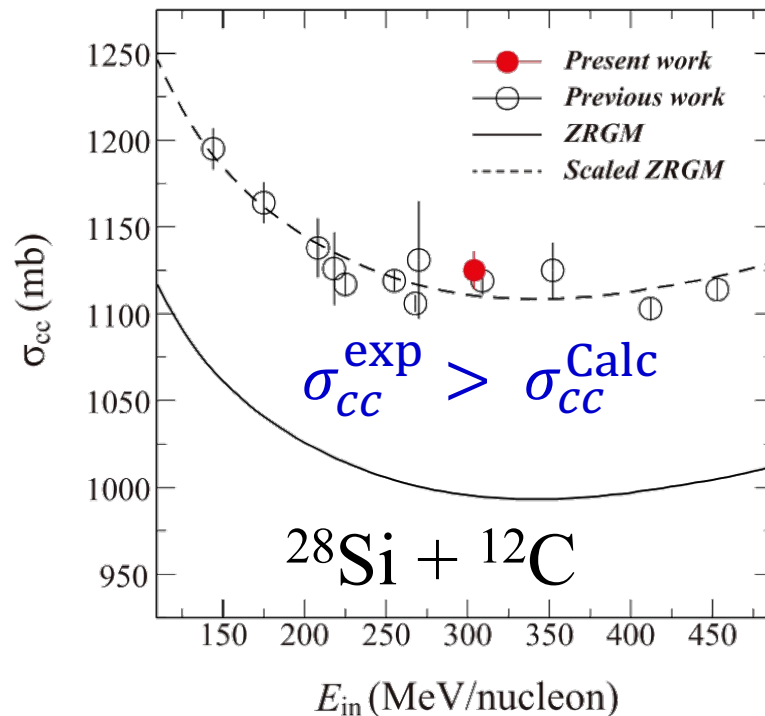
+ ~ 10 PRL, determining 20 charge radii of unstable p-shell isotopes



Key questions remain!

- What is the reaction mechanism of charge-changing reactions (CCR)?
- Is the scaling universal and robust as isospin, collision energy, target?
- Is it accurate enough to deduce R_p from CCR?

Or, can we decouple the structure from the reactions, which are governed by the strong force?

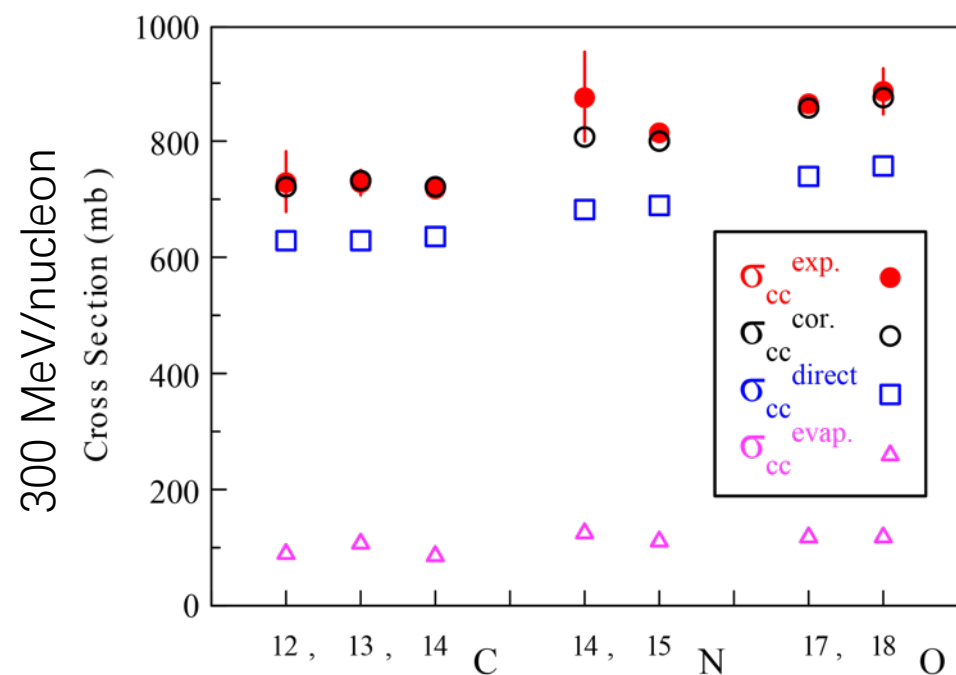


$$\sigma_{cccs} = 2\pi \int b \{1 - \exp[-\int dr \rho_p^P (\sigma_{pp} \rho_p^T + \sigma_{pn} \rho_n^T)]\} db$$

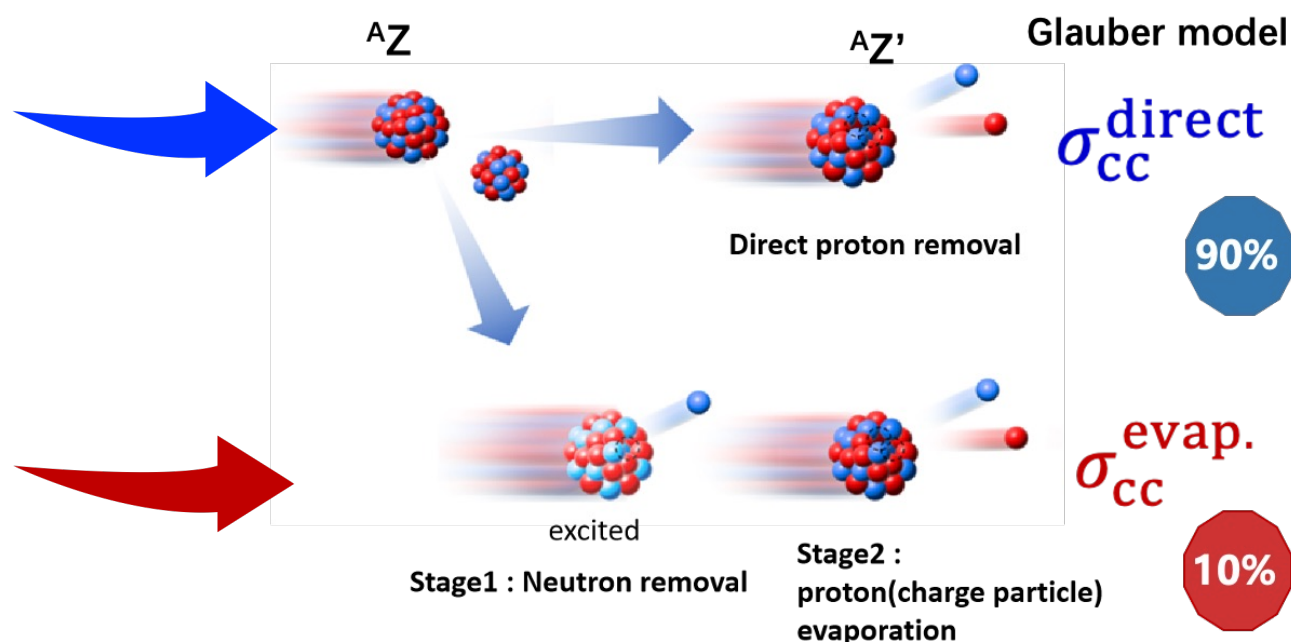
Reaction mechanism of charge-changing reactions

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

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



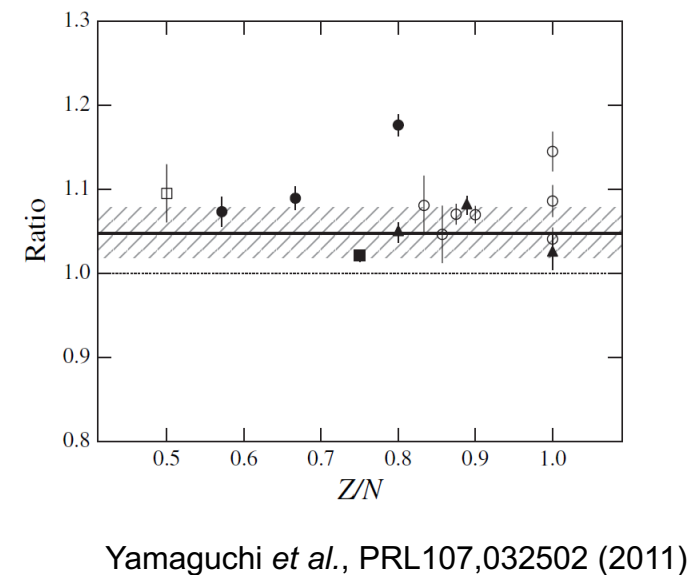
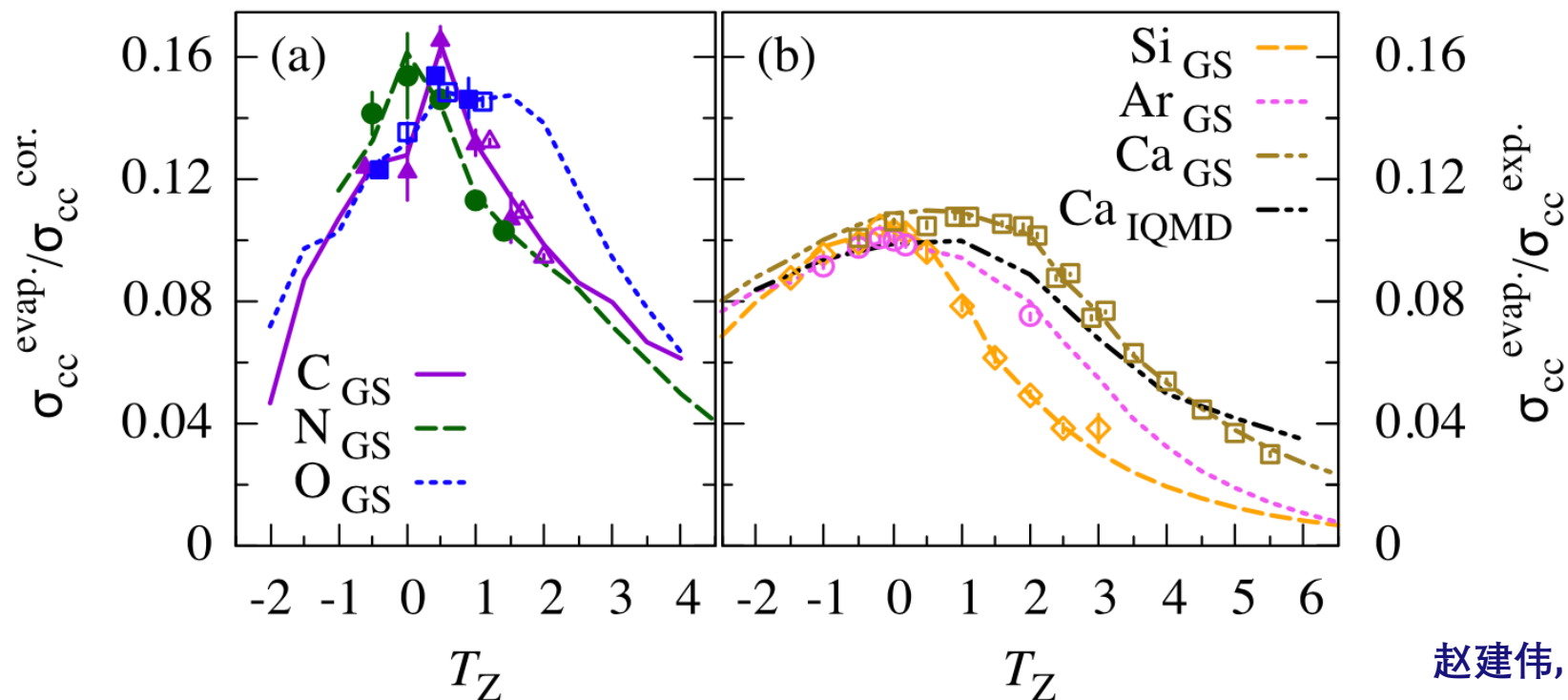
Both the direct reaction and **evaporation** are essential.



赵建伟, *et al.*, PLB 847 (2023)138269
Tanaka *et al.*, PRC106(2022)014617

Q: is evaporation contribution constant?

Isospin-dependent evaporation



赵建伟, *et al.*, PLB 847 (2023)138269

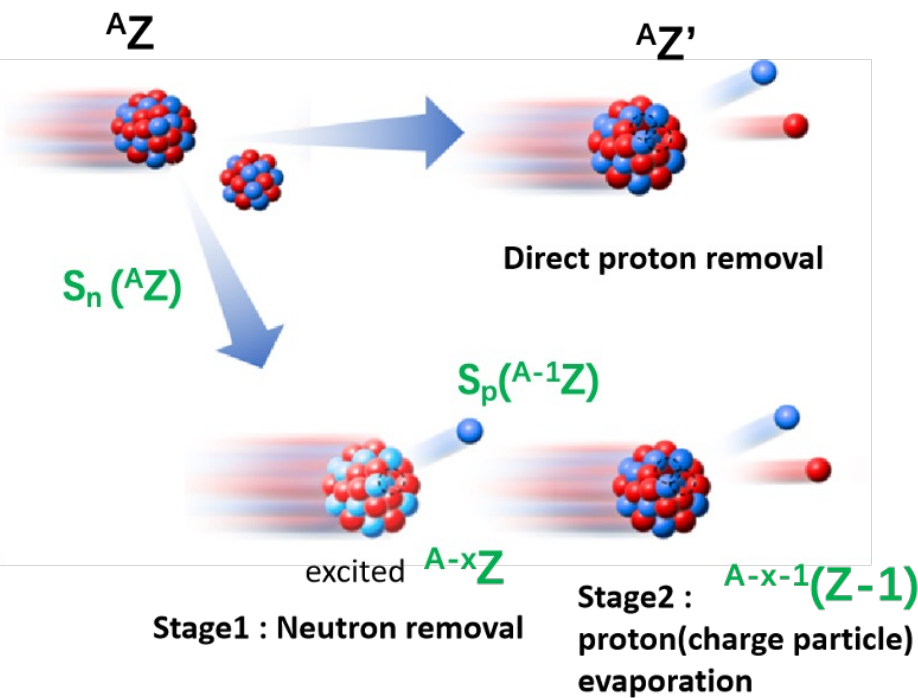
- Isospin-dependent evaporation with **peaks at nuclei with an isospin symmetry.**
- **Peak values** vary as for *p*-shell (~16%) and *sd*-shell (~10%) nuclei.

Evaporation calculations rely on excitation energies, level densities etc. for the pre-fragments, thus precision calculations are challenging.

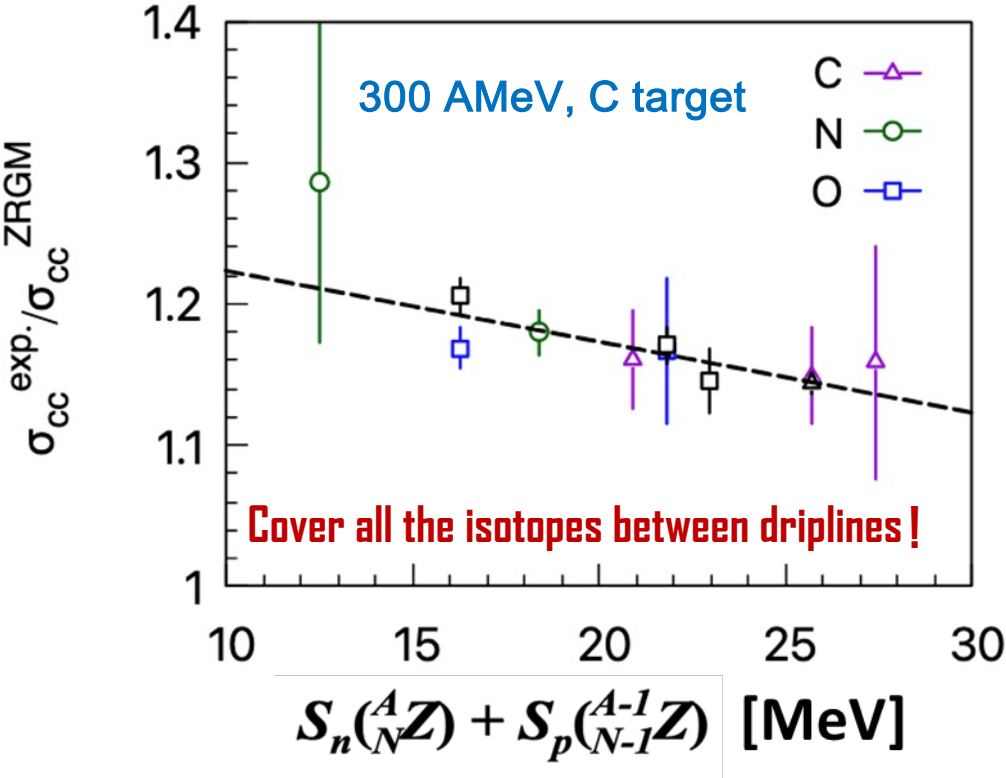
Parameterize the evaporation by *Separation energies*

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

All the points have well known R_p for calibration



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

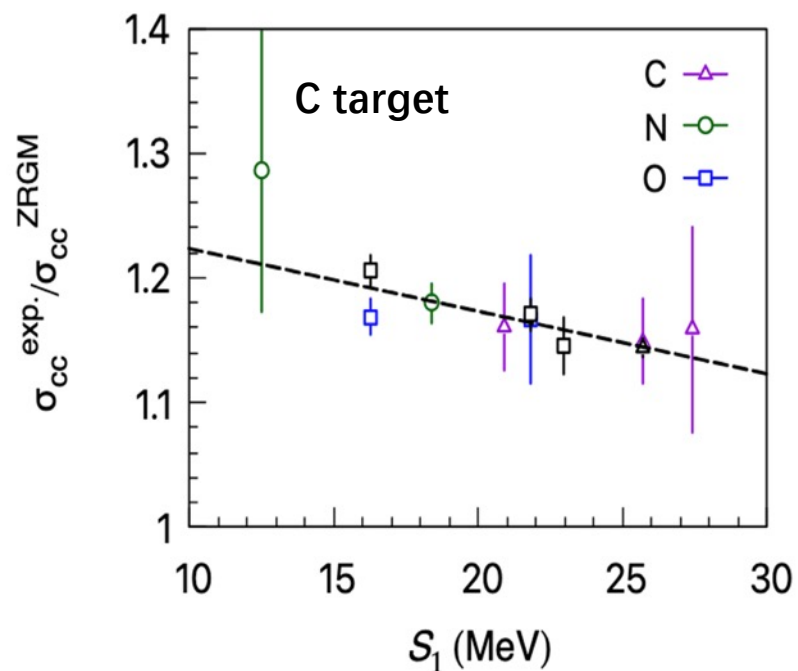


The linear correlation makes model calibrations feasible!

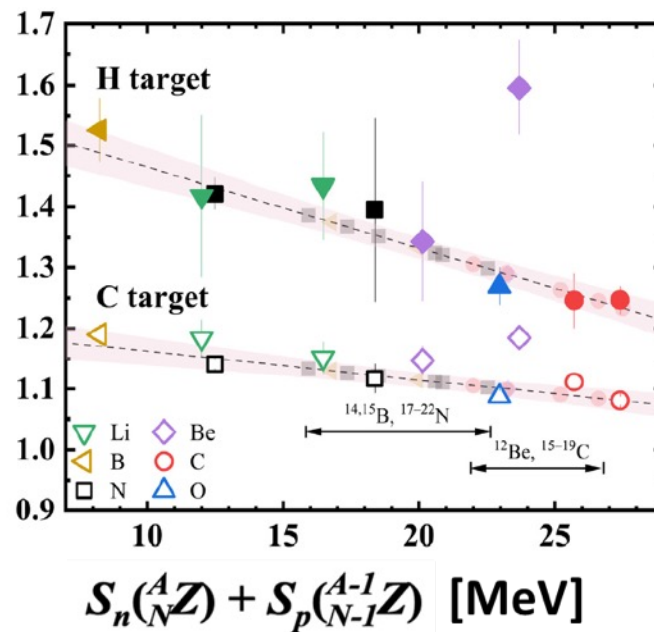
赵建伟 *et al.*, PLB 858(2024)139082

S-factor : reaction energies and targets for *p*-shell isotopes

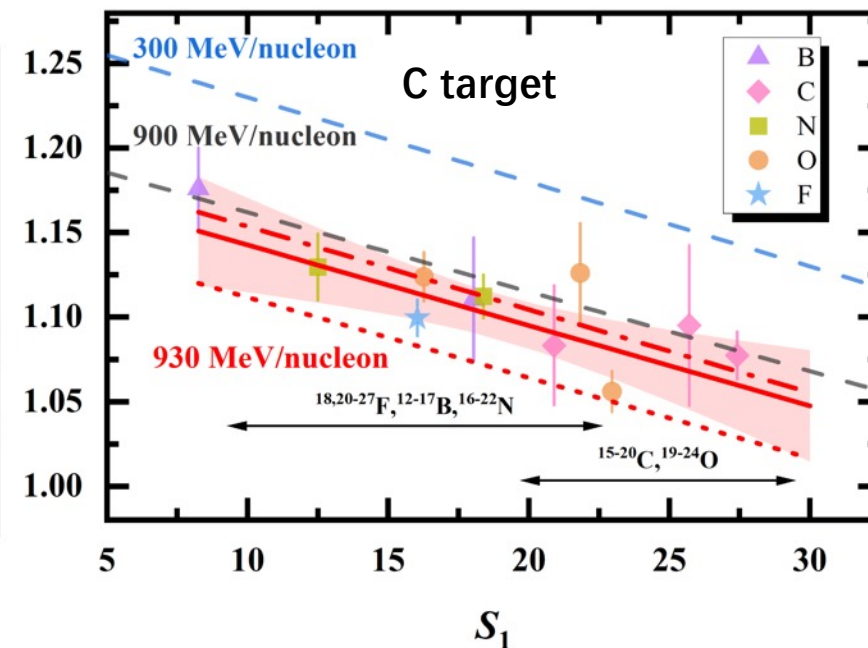
300 AMeV, C target



900 AMeV, C/H target



300/900/930 AMeV, C target @GSI



The **linear correlation** of the ratio on the *S*-factor holds well for **all the *p*-shell data**.

The slope is independent on **reaction energies** (240, 300, 900, 930 AMeV),

but is sensitive to **reaction targets** (H, C)

赵建伟 *et al.*, PLB 858(2024)139082; 张寂潮 *et al.*, Sci. Bull. 69 (2024) 1647; 徐俊瑶 *et al.*, in revision



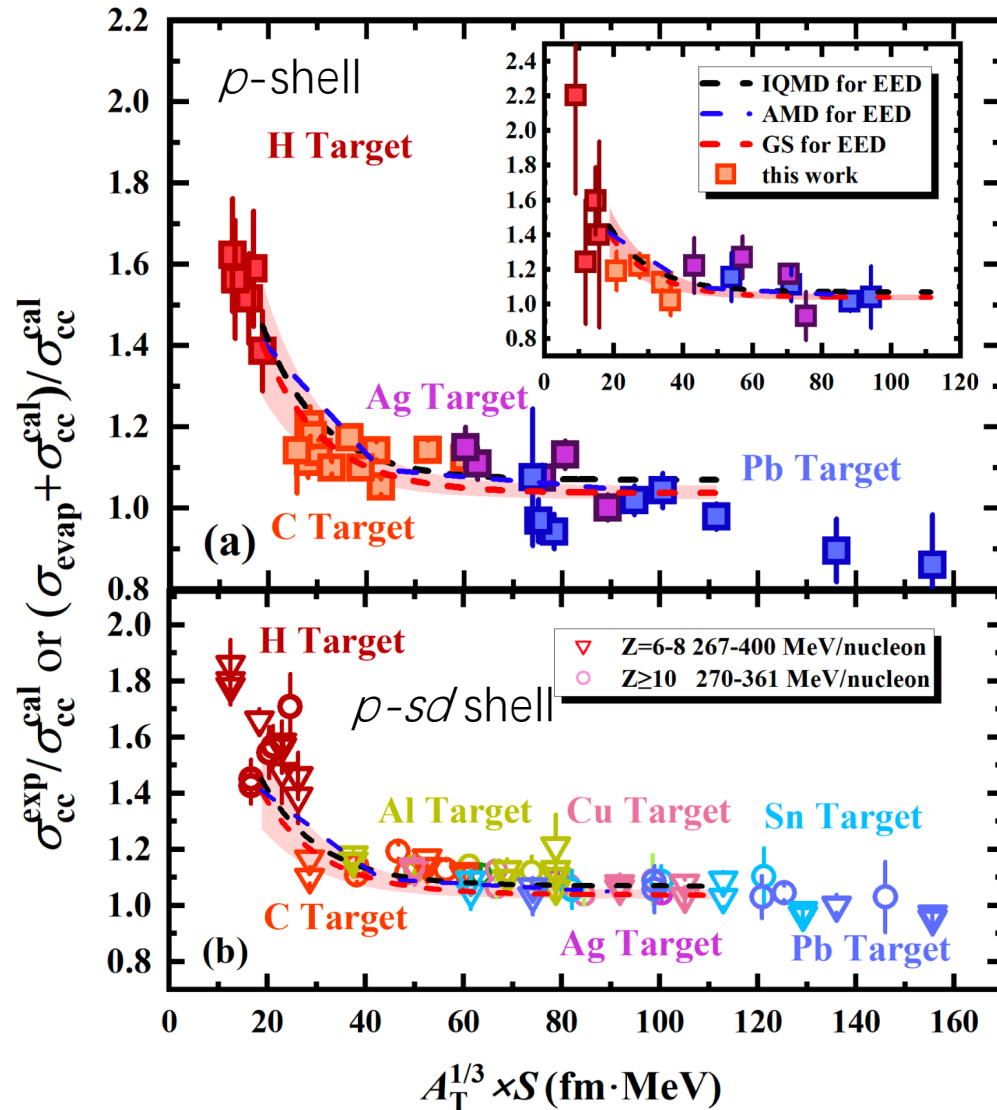
Richard Phillips Feynman

“If we can reproduce a wide range of phenomena with just a few parameters, that means we have discovered an important law.”

（如果能用少数几个参数再现大量现象，那就意味着我们发现了重要规律。）

“The fact that a great many phenomena can be explained by a few simple laws is one of the greatest triumphs of science.”（大意：能用少数简单定律解释大量现象，是科学最伟大的胜利之一。）

Discovery of a universal scaling with reaction targets



Scaling: reaction energy, projectile isospin ✓
reaction target?

A universal pattern from our **new data** and **the existing data** of p - sd shell nuclei ($Z=3-20$)

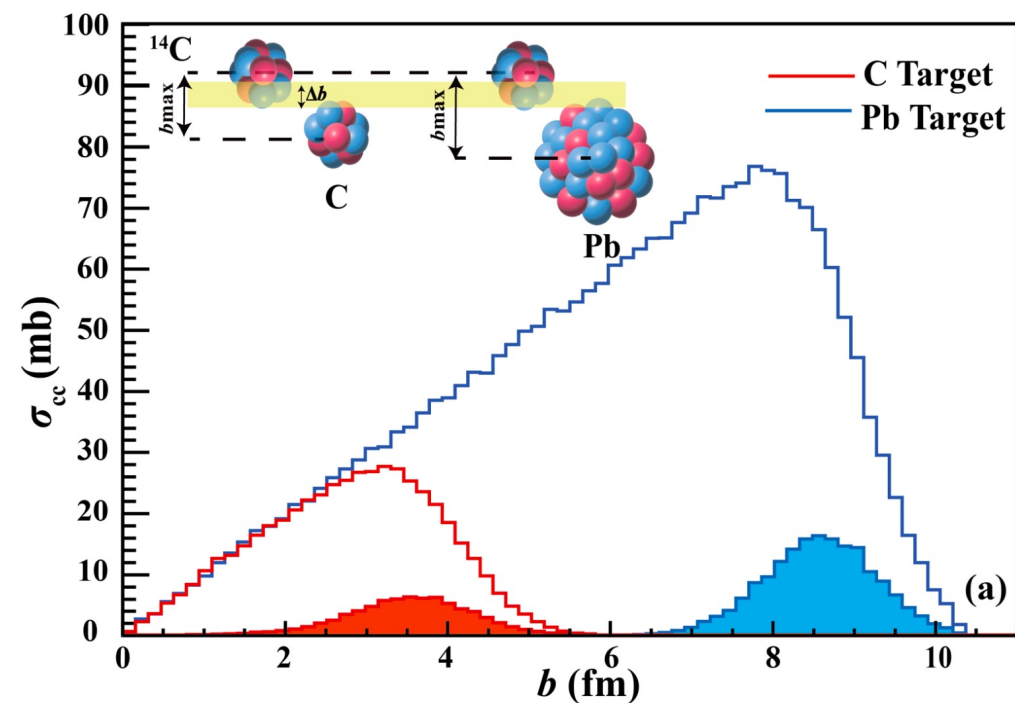
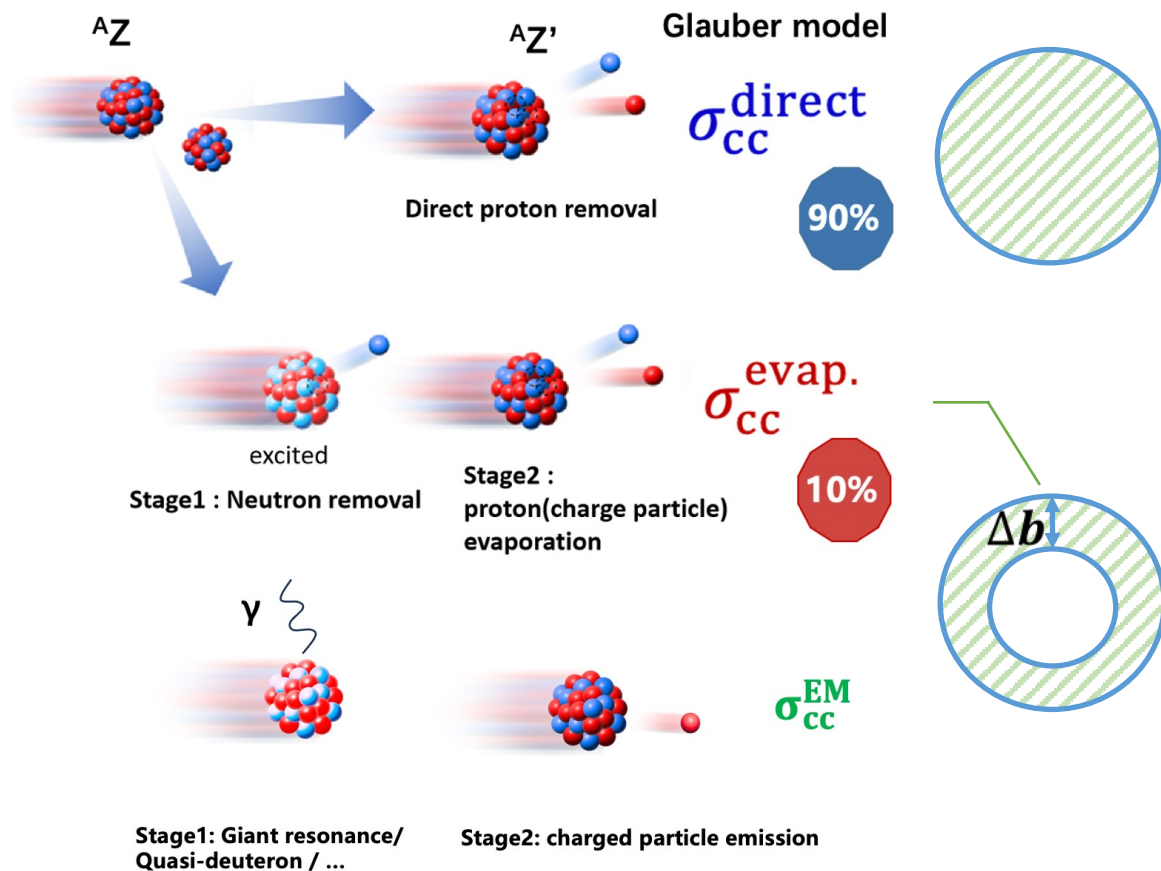
Suggesting that a heavy reaction target is an optimal solution for extracting charge radii of unstable isotopes.

This **can have important impact**: all the experiments proposed at RIKEN/GSI plan to use C targets; less model dependent

徐俊瑶 et al., in revision

Reaction mechanism of charge-changing reactions

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

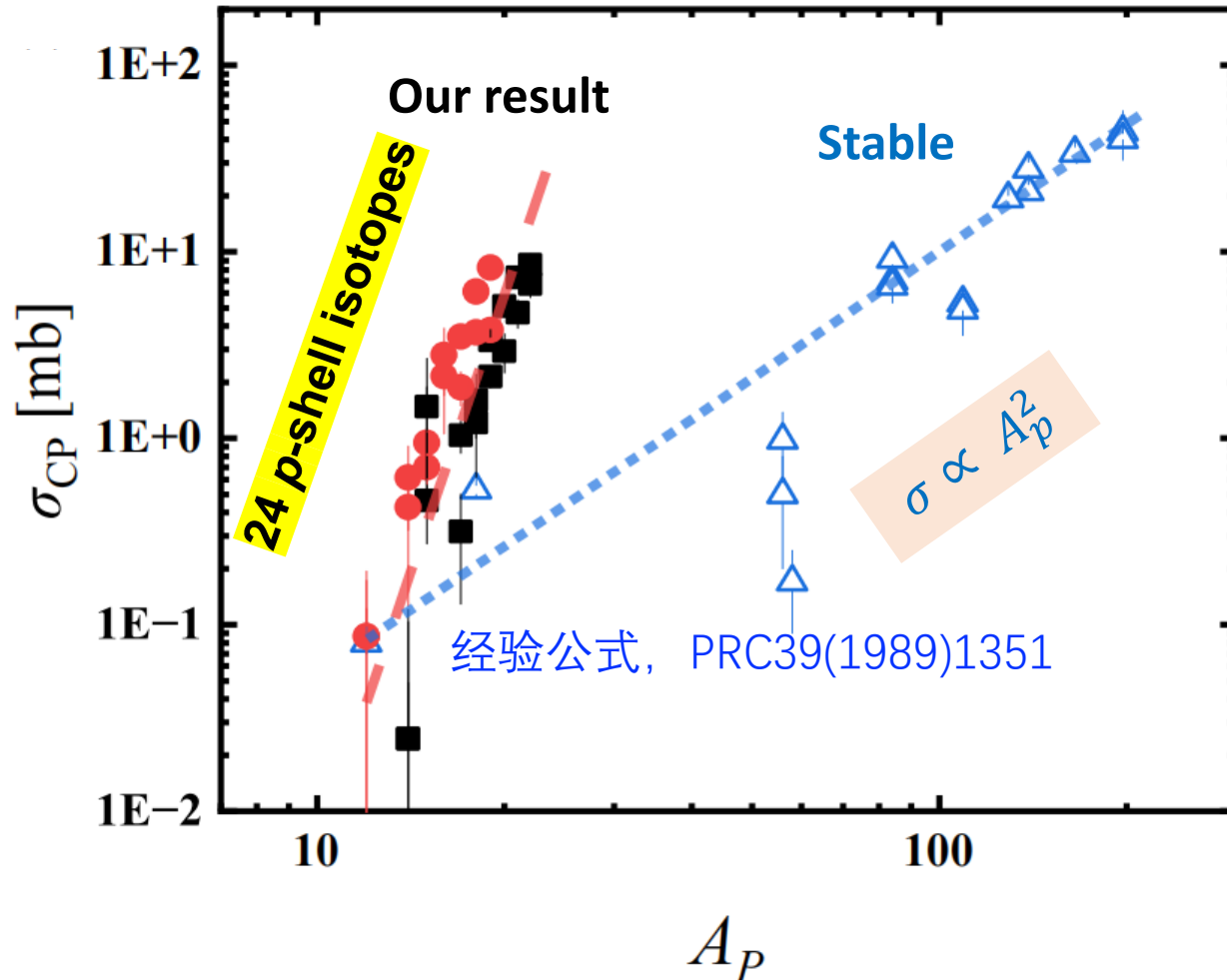


Courtesy: 苏军 (IQMD+GEMINI)

徐俊瑶 *et al.*, in revision

Charge pickup reactions (charge-exchange reaction) (p,n)

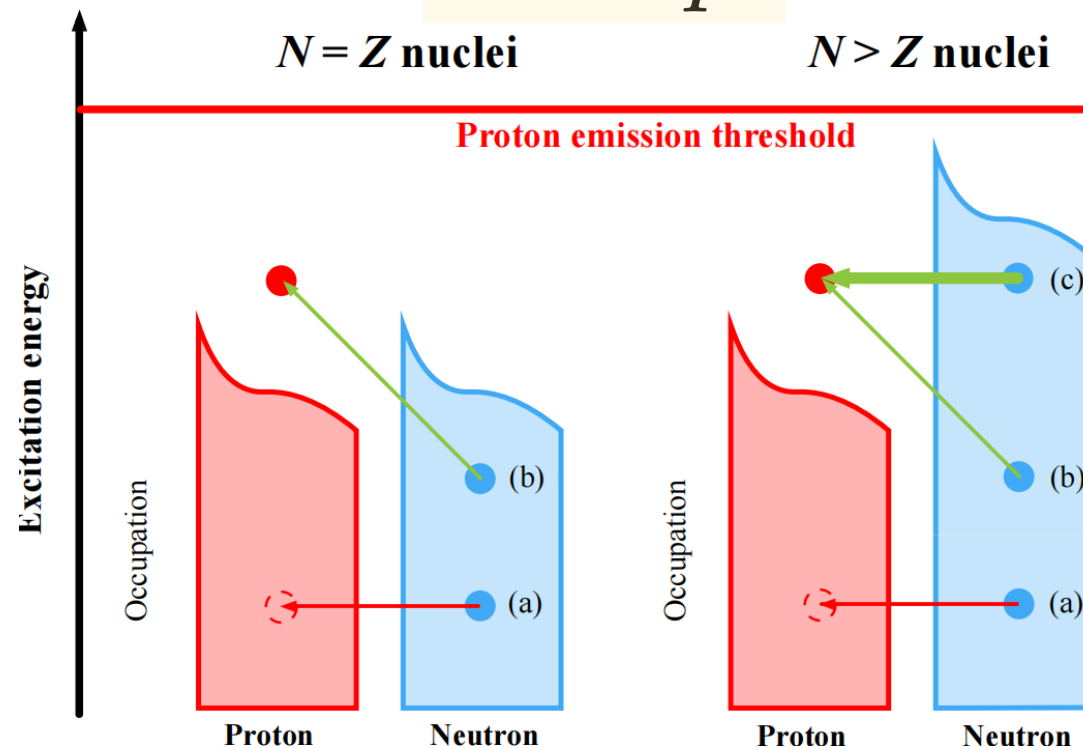
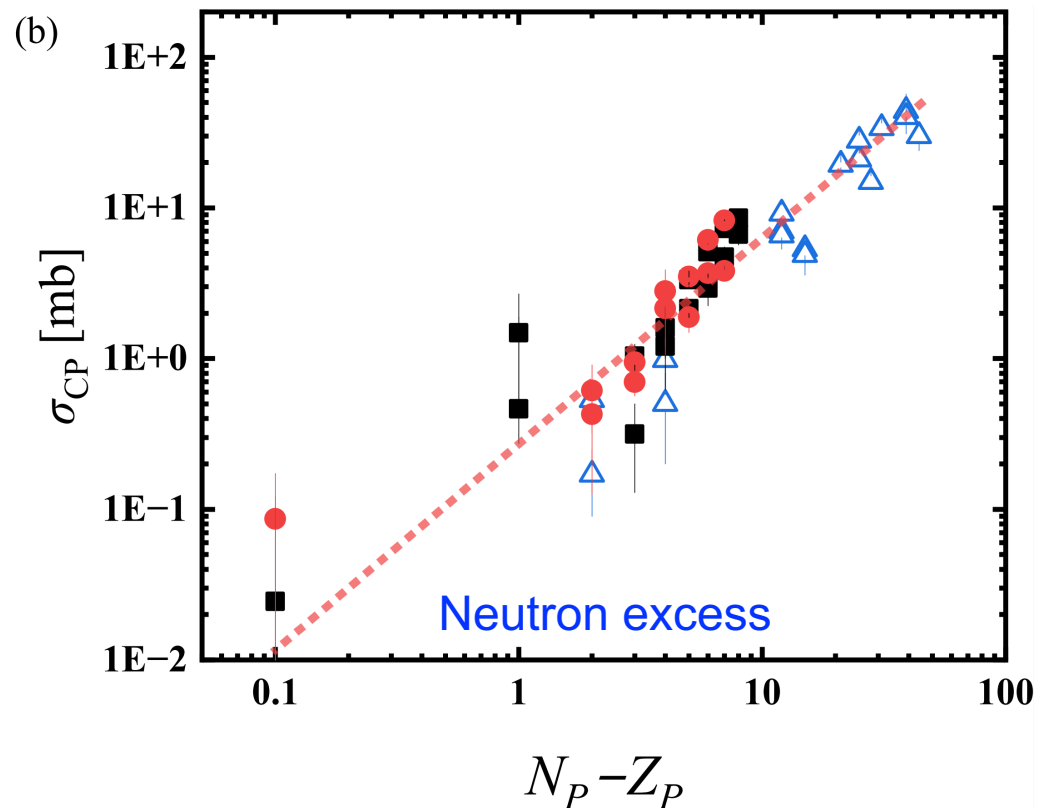
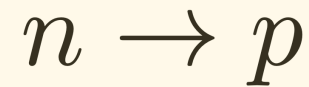
$\sigma_{\Delta Z=-1}$ $E > 700$ MeV/nucleon



The neutron-to-proton flip probability
grows far more rapidly with neutron
number than previously believed!
The widely used empirical formula
completely fails.

张寂潮 *et al.*, Phys. Rev. X 15(2025)031004

Neutron-proton imbalance plays a key role

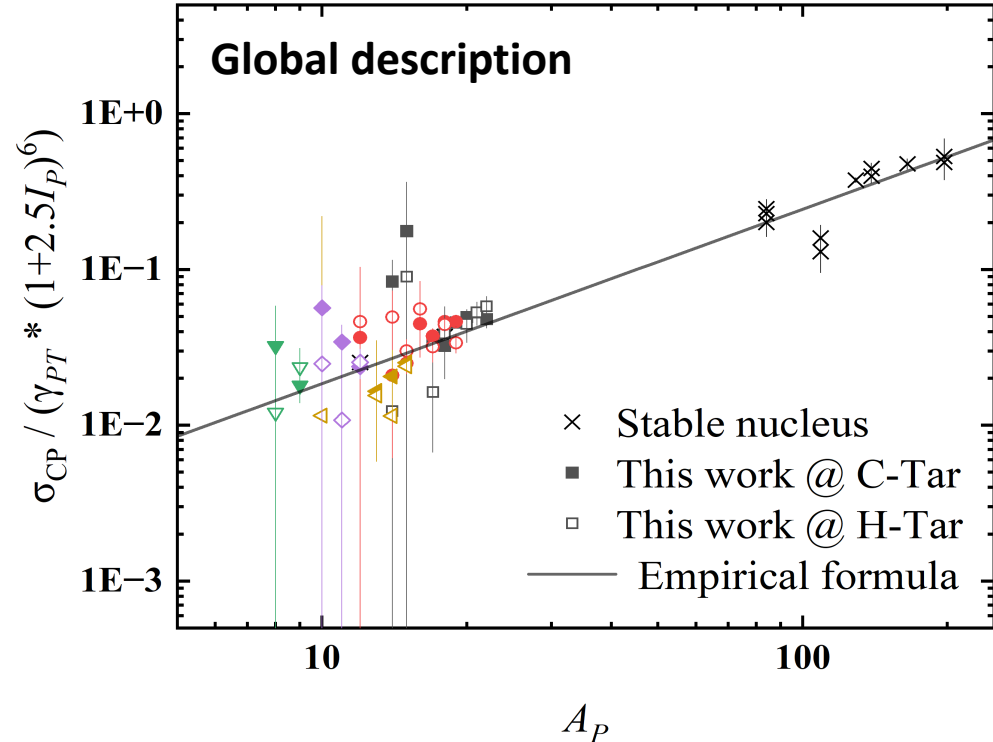
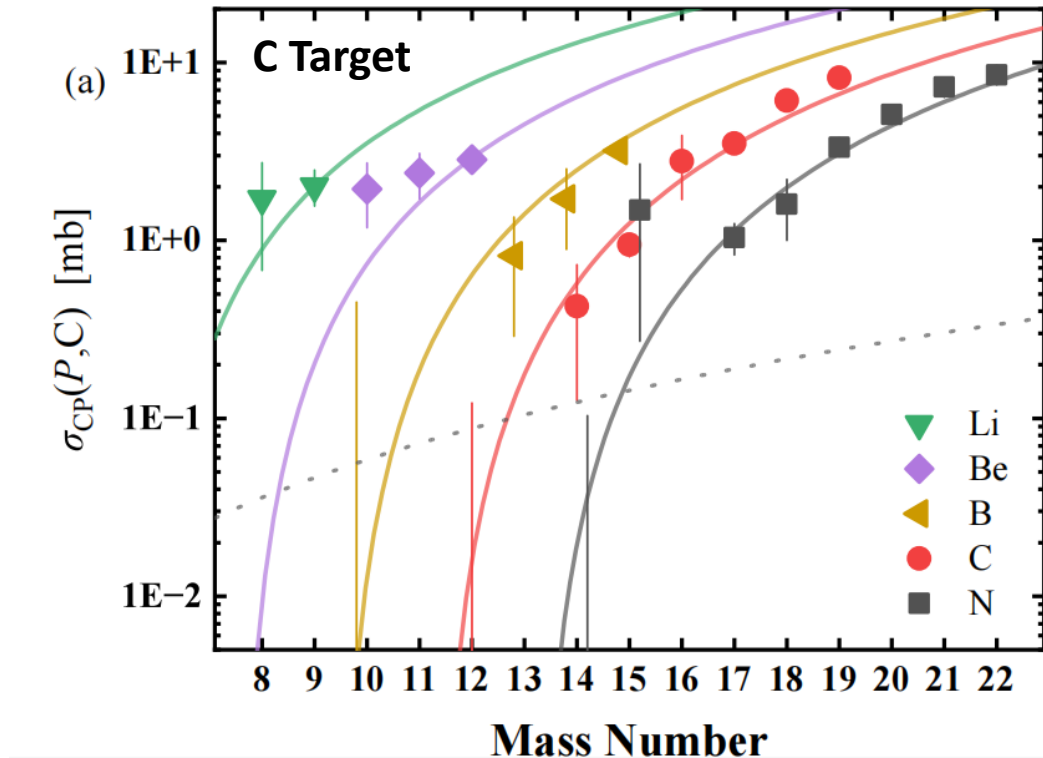


As the neutron number increases, the **superaligned transition channels open up**

张寂潮 *et al.*, Phys. Rev. X 15(2025)031004

New formula of “charge pickup” reactions

-- Important for nuclear data applications



$$\sigma_{\Delta Z=+1} = 1.4 \cdot 10^{-3} (A_P^{1/3} + A_T^{1/3} - 1.42) * A_P^{1.12} * \left(1 + 2.5 \frac{N_P - Z_P}{A_P}\right)^6 \text{ [mb]}$$

peripheral collisions

Isospin asymmetry dependence

张寂潮 *et al.*, Phys. Rev. X 15(2025)031004

Projectile mass dependence

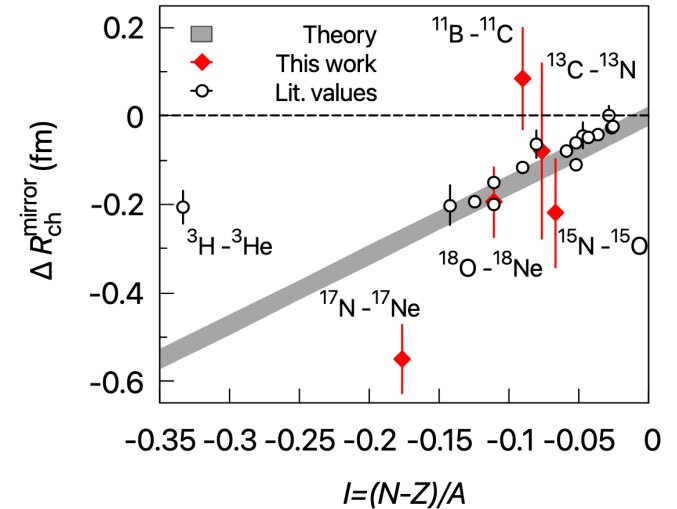
Many interesting physics

Interaction & charge-changing cross sections

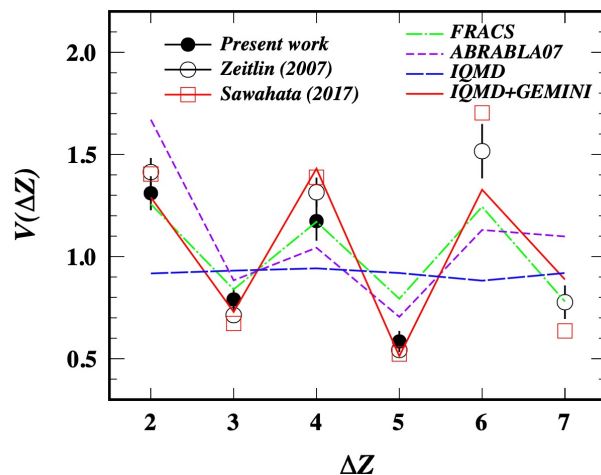
- Rms matter radii and charge radii
- Neutron skin thickness & EOS
- Nuclear physics model evaluation & devep.

Isobaric charge-exchange reactions of unstable isotopes

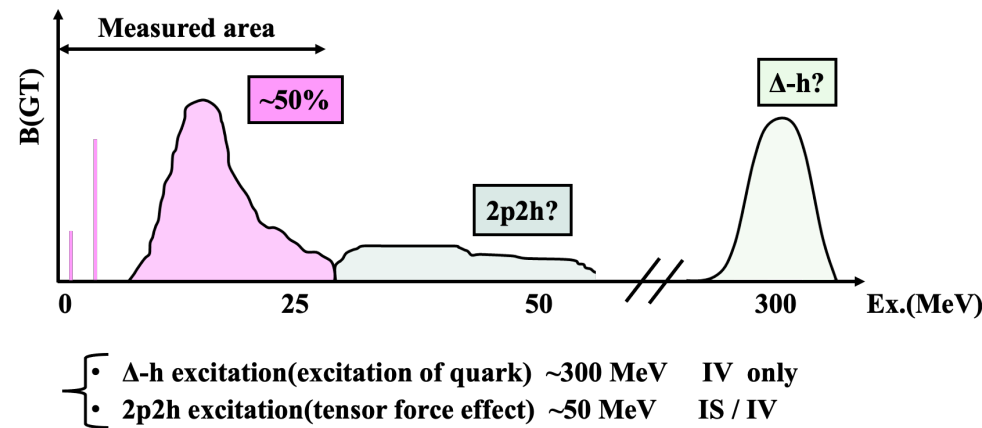
- Nuclear spin-isospin excitation: structure & astrophysics
- baryonic resonances in nuclear medium/matter
- π productions in heavy ion collisions



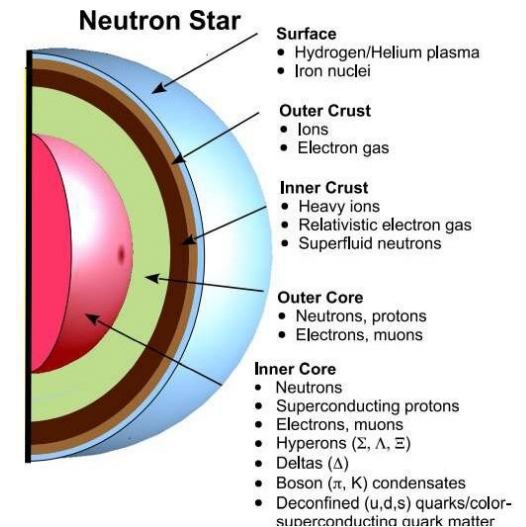
赵建伟 et al., PLB 858(2024)139082



李光帅 et al., PLB(2024); 魏秀琳 et al., PRC(2025)



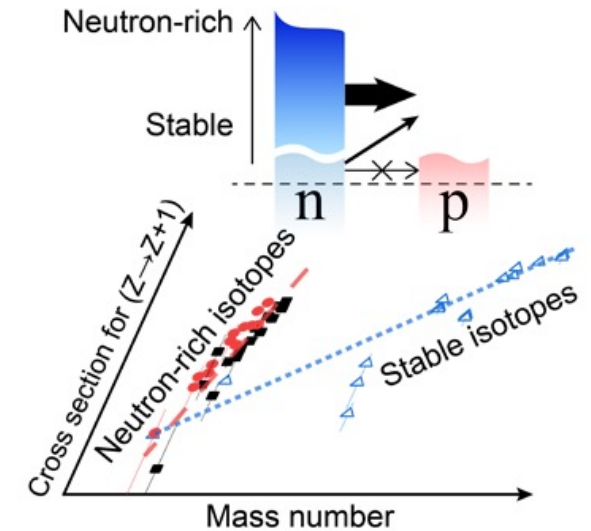
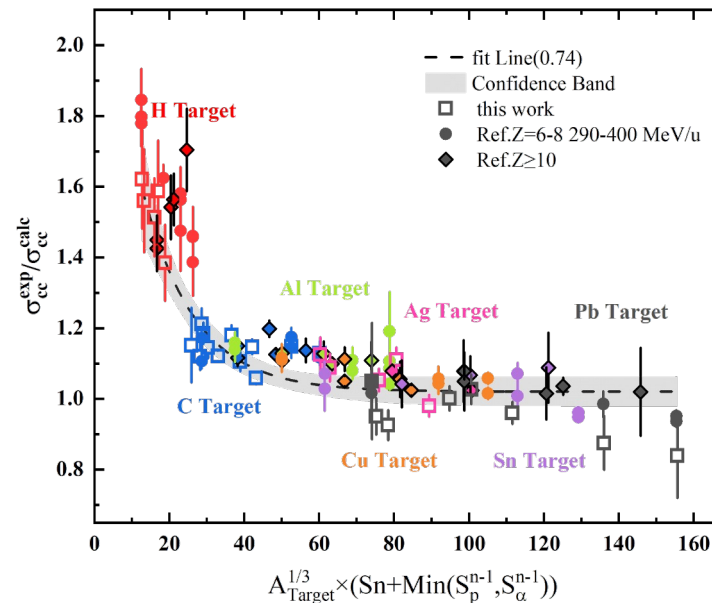
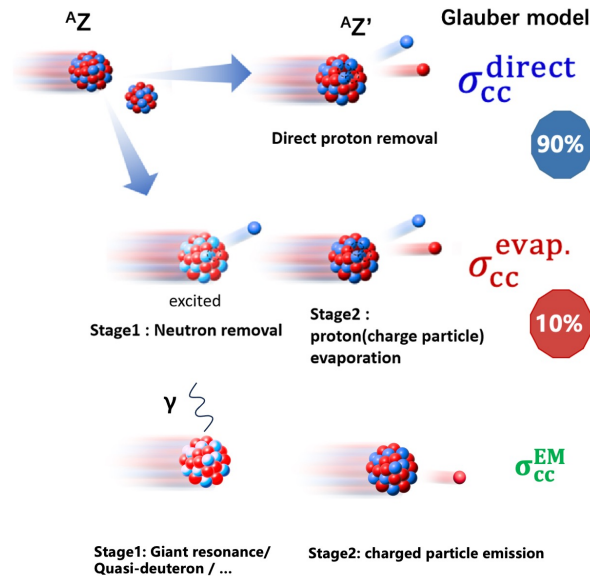
- Δ -h excitation(excitation of quark) ~ 300 MeV IV only
- 2p2h excitation(tensor force effect) ~ 50 MeV IS / IV



Summary

Systematic data on charge-changing cross sections reveals **universal scaling pattern**, which allows a more reliable extraction of charge radii of unstable isotopes.

New neutron-to-proton conversion in light nuclear reactions at relativistic energies rises exponentially with neutron number, challenging prior models and allowing for refined nuclear reaction and astrophysics predictions.



GeV/nucleon 能区原子核的电荷改变反应研究 --- 系统及规律

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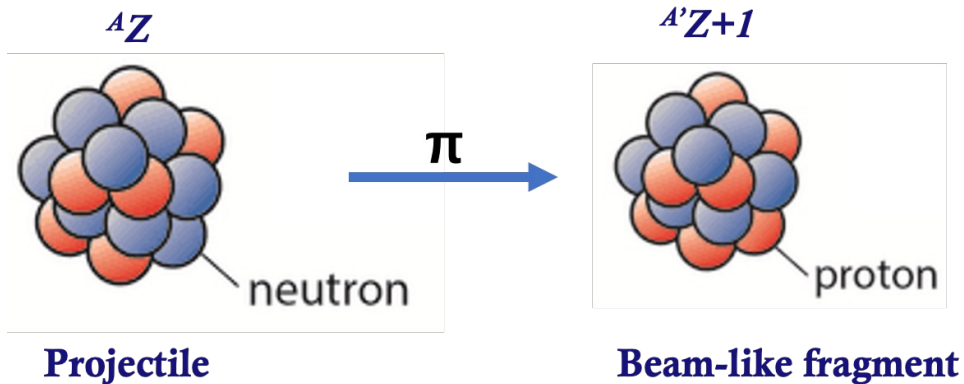
北京航空航天大学物理学院

高能与低能核物理交叉学术研讨会

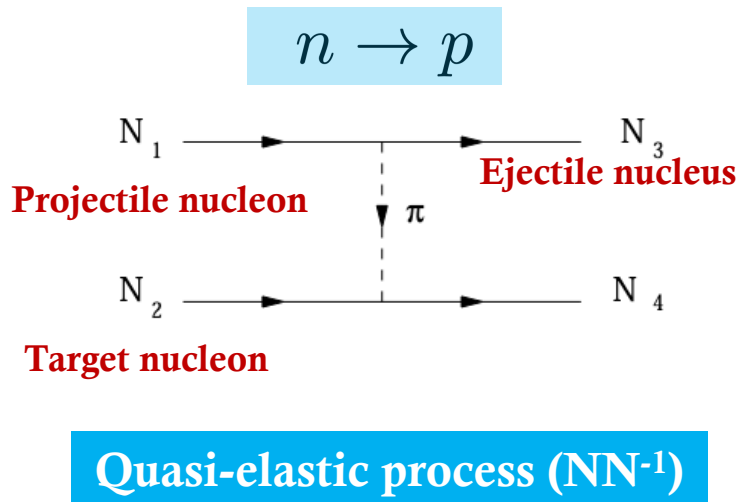
2026年5月15-18日, 华东师范大学, 上海

A second look on $Z \rightarrow (Z+1)$: (p, n) exchange

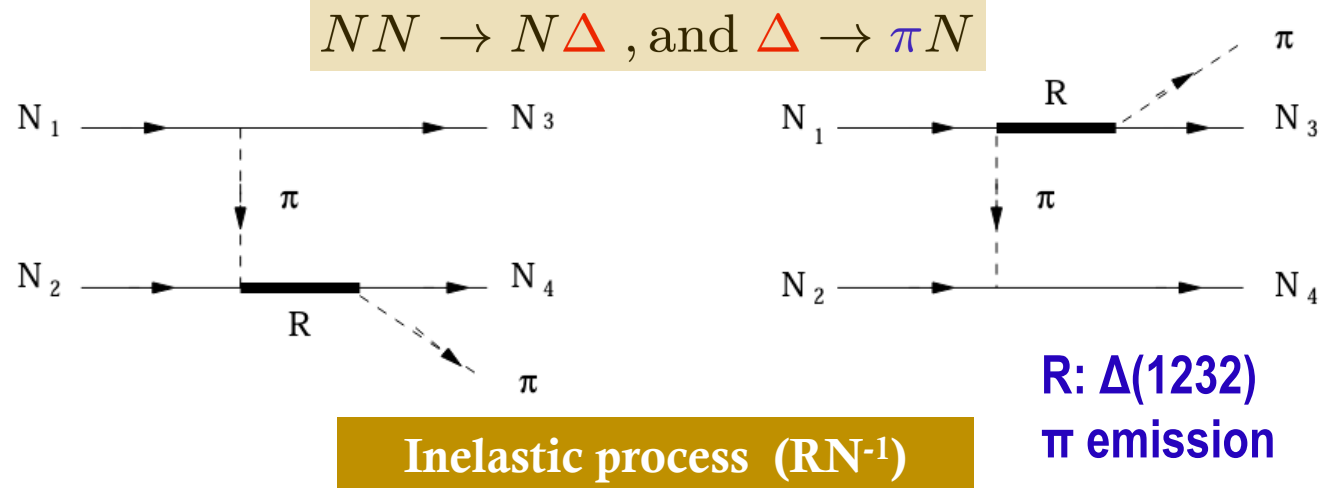
At high energies ($E/A \gg E_b$), the **one-step charge-exchange** via virtual **pion** comes into play.



σ_{CP} : dominated by (p, n) charge-exchange reactions, plus the sequential neutron emissions



Spin-isospin excitation



Nucleon excitation