XIIth International Symposium on Nuclear Symmetry Energy
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Possibility to examine the transportation model by charge-changing reactions at intermediate energies

- Charge changing reactions
- Experiments and Results
- View from IQMD+GEMINI
- Summary

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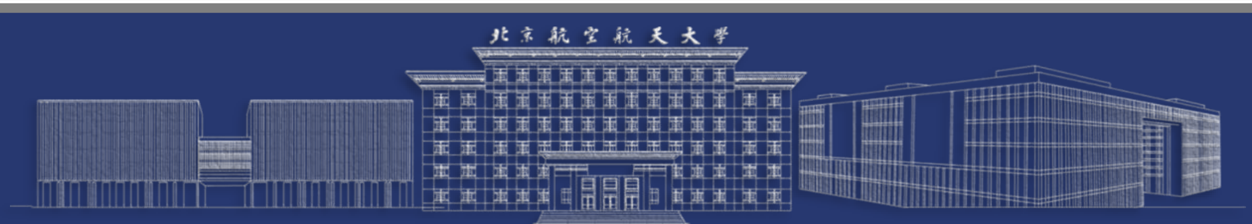

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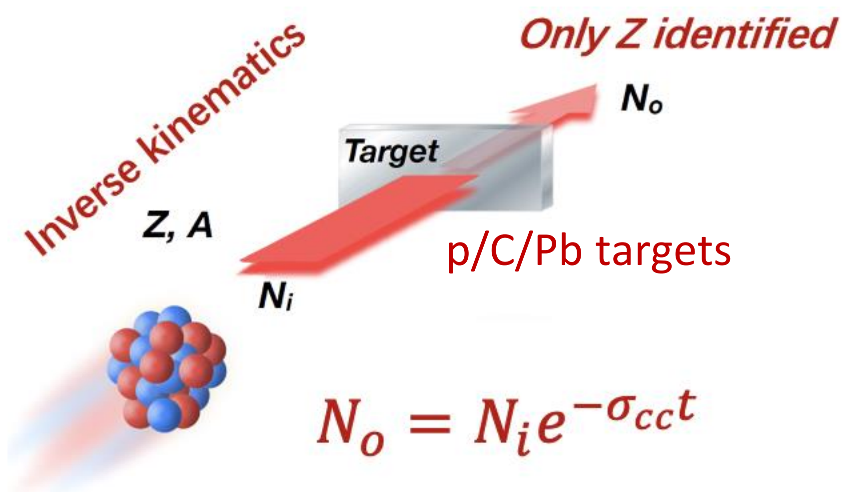
Charge-changing cross sections of atomic nuclei

Transmission method

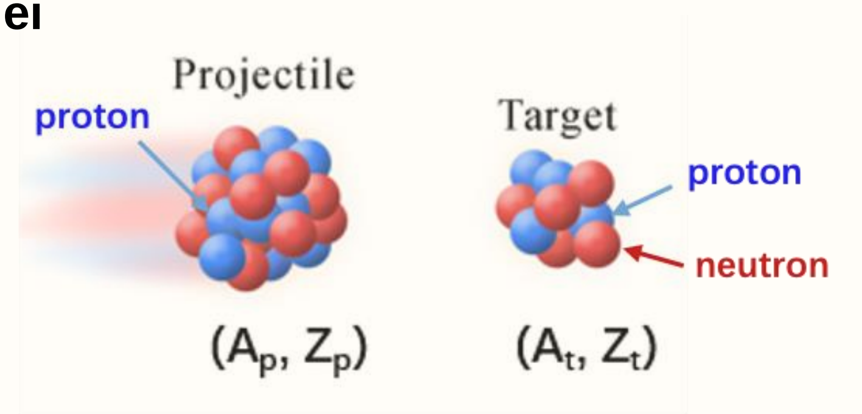
Short-lived nuclei



@100-1000 AMeV

Reaction probability of knocking out one or more protons *(Z)* from projectile nuclei after collisions. It is correlated with the point-proton density distribution in projectile (ρ_p)

Glauber-type model



Projectile's neutron as spectators

Glauber Model

NN cross section

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

Point-proton density dist. of projectile nuclei

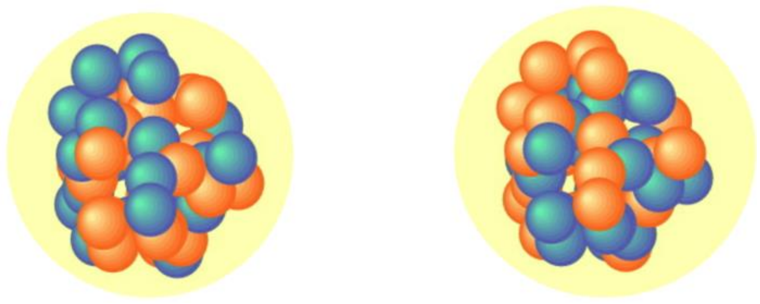
Point- proton and neutron density distribution of target nuclei

Effective method by correlating x-sections with point-proton distribution density (ρ_p, thus R_p)

R_p from CCCS & R_m from interaction x-section give R_n and thus neutron skin thickness!

Constraining EOS by σ_{cc} difference of mirror nuclei

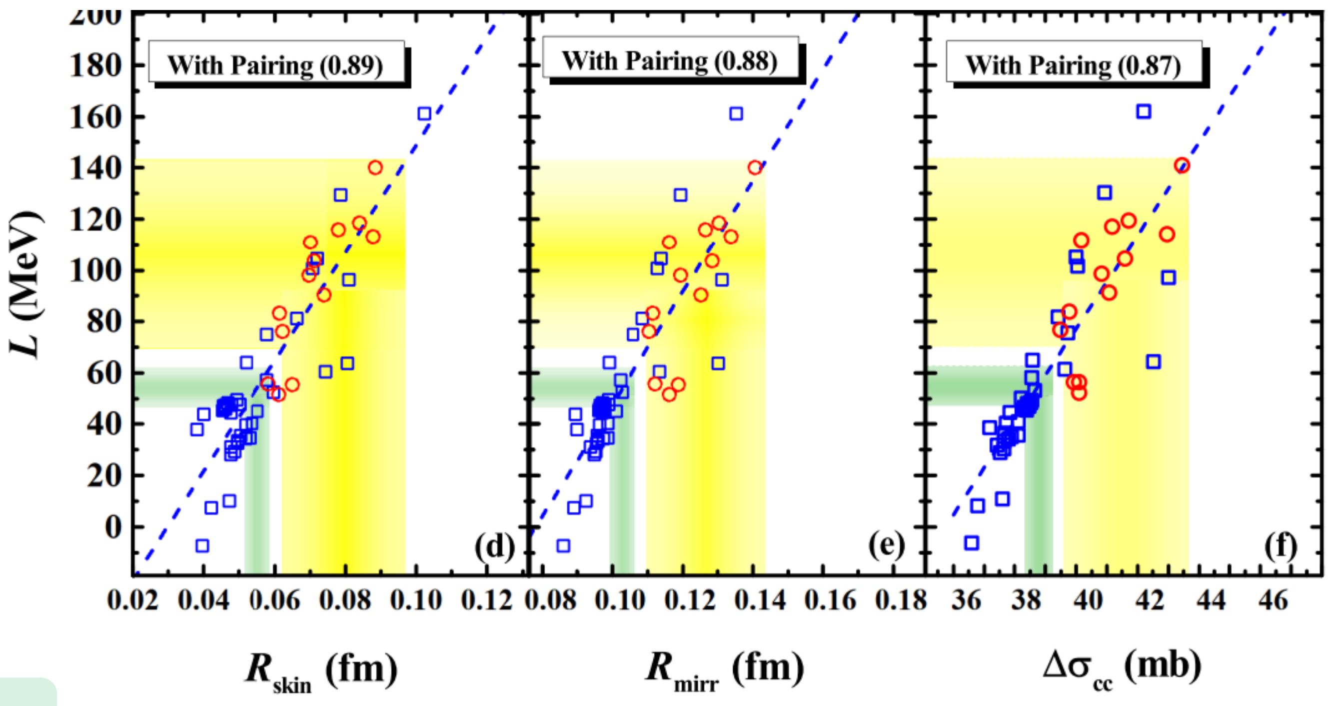
$\Delta\sigma_{cc}$: difference in charge-changing cross sections of mirror pairs on the same target at the same energy



^{30}Si ^{30}S

isospin symmetry

nearly identical properties



$$\Delta\sigma_{cc} \approx 2\pi(1 + af^2)[R^{mat}_{targ} + afR^{prot}_{proj}(Z,N) - c]R_{mirr}$$

Xu, Li, BHS, Niu, Roca-Maza, Sagawa, Isao Tanihata, *et al.*, arXiv:2205.05276， PLB833(2022) 137333

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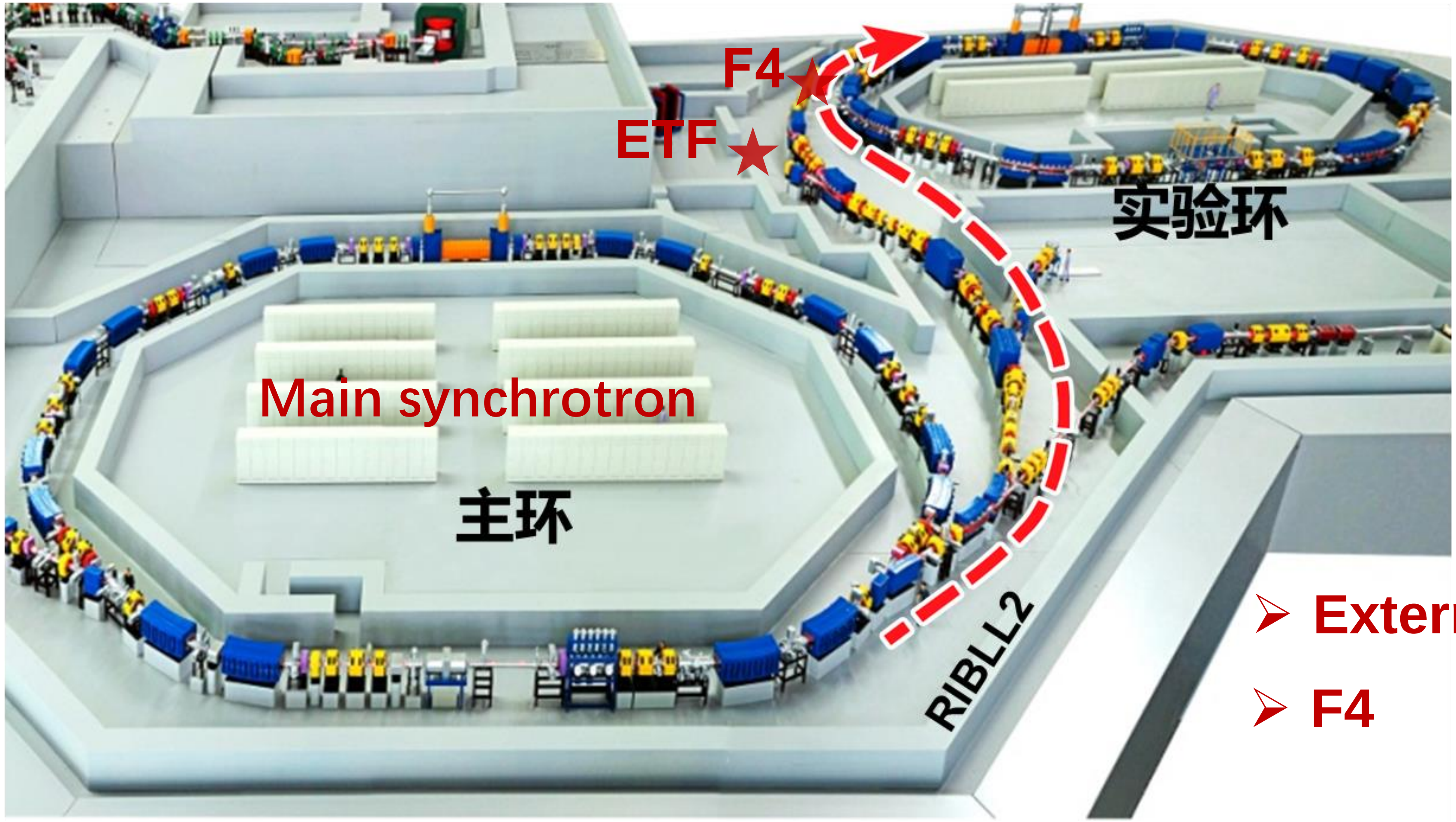
HIFRL/Lanzhou
GSI/Darmstadt

Heavy Ion Research Facility in Lanzhou (HIRFL)

RIBLL2: the only radioactive ion beam line at relativistic energy (300-500 MeV/nucleon) in China

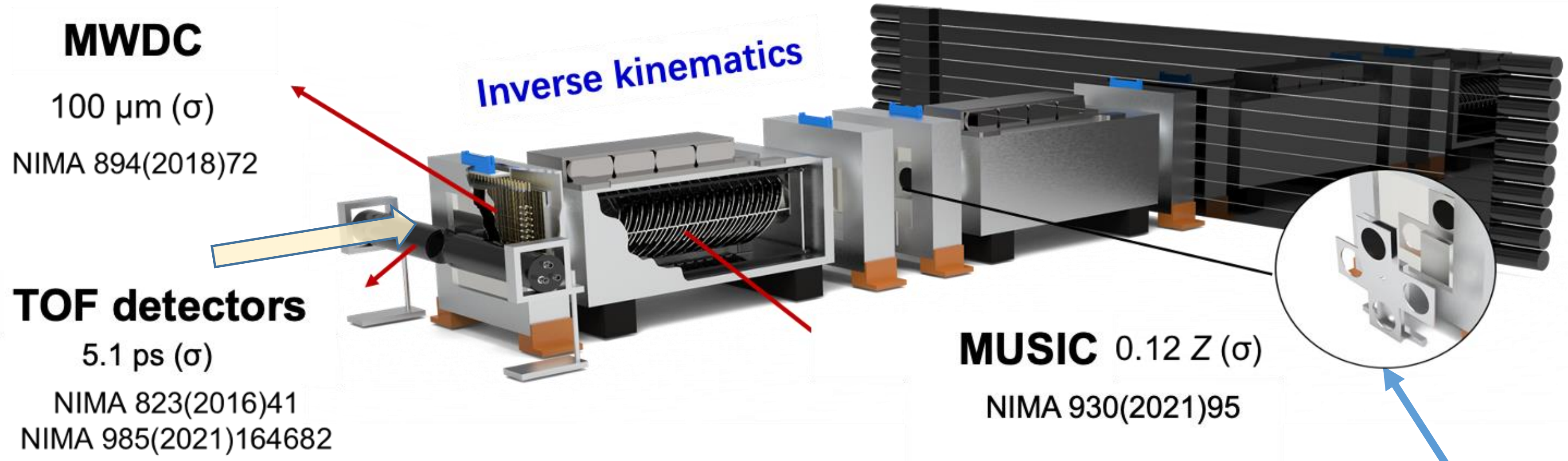


Experimental storage ring

- External-target facility
- F4

Experiment station @ F4, RIBLL2/HIRFL, Lanzhou

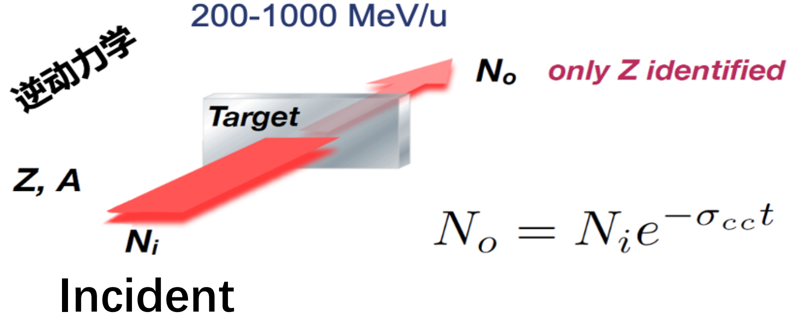
- ^{18}O, ^{40}Ar, ^{78}Kr beam @ 280, 350, 400 AMeV
- Target: C, CH_2, Ag, Pb



- Absolute x-section measurement： precision<2%
- Counting of incident and forward products

  Event by event identification; Purity: >99.9%;

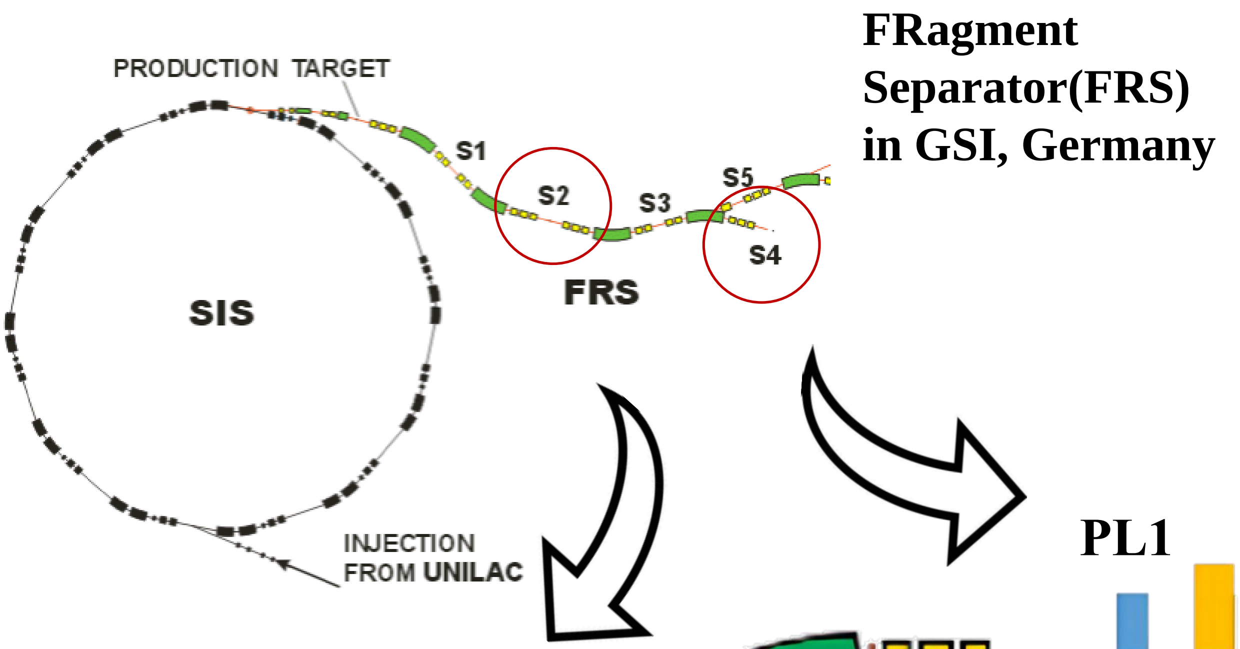
  Detector: sensitivity, resolution, acceptance

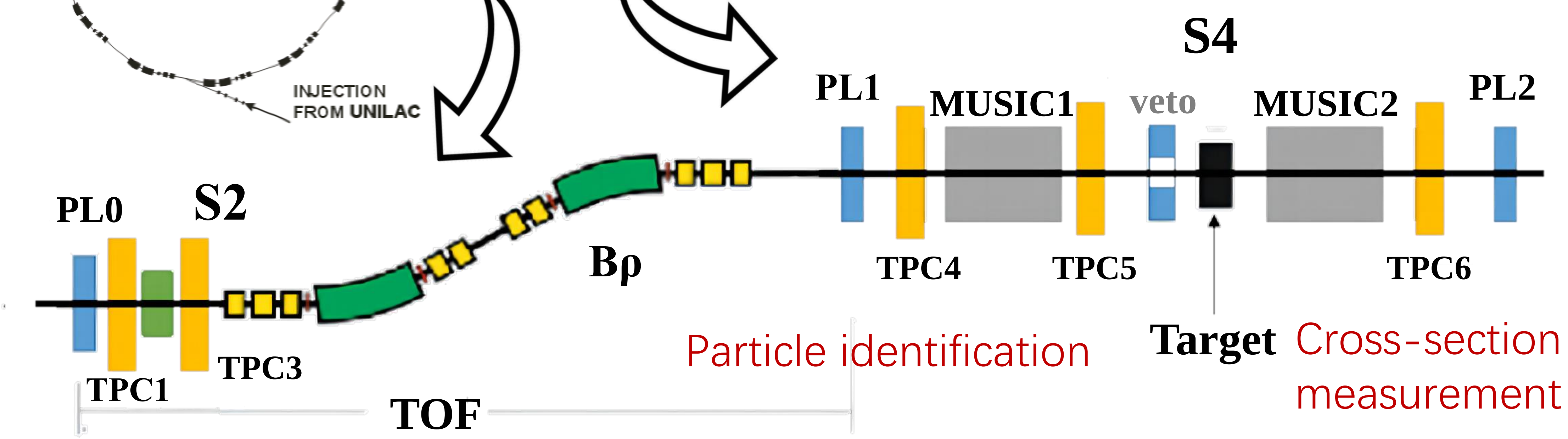


$$N_o = N_i e^{-\sigma_{cc} t}$$

p-shell measurements at 900 AMeV at FRS/GSI

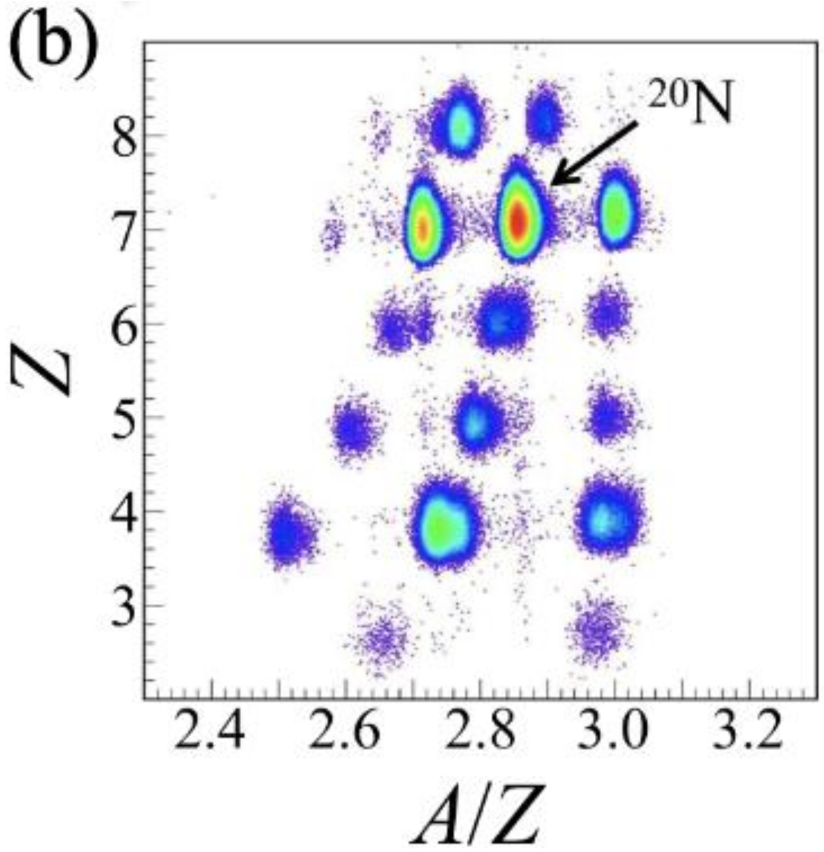
- Primary beam: ^{22}Ne @ 1 GeV/u
  ^{40}Ar @ 1 GeV/u
- Production Target: Be 6.33 g/cm^2
- Reaction Target: C(4, 2.5 g/cm^2),
  CH_2(3.375 g/cm^2)
- PID of RIBs: *Bρ*-dE-TOF
- Z-identification: Music 1&2
- Beam tracking: TPCs



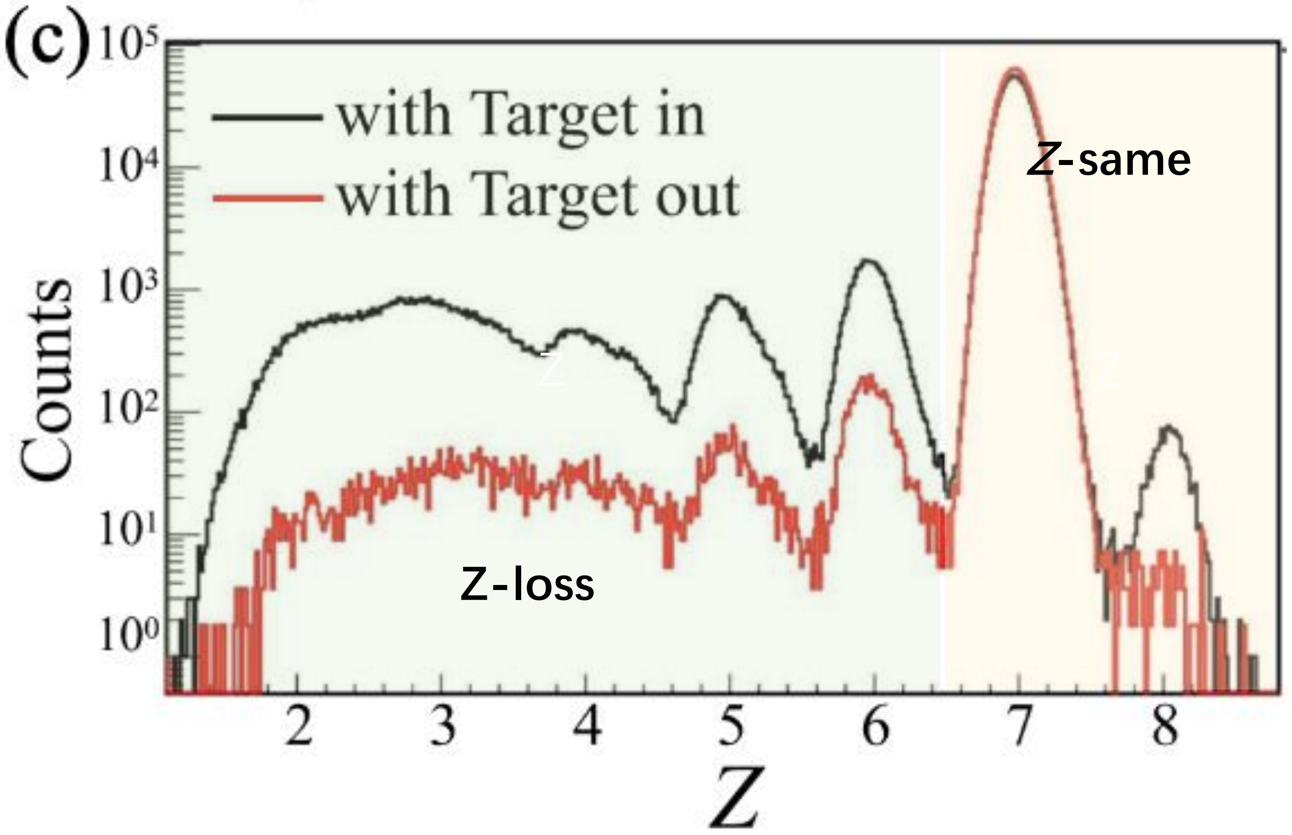


Particle identification

Incident particles

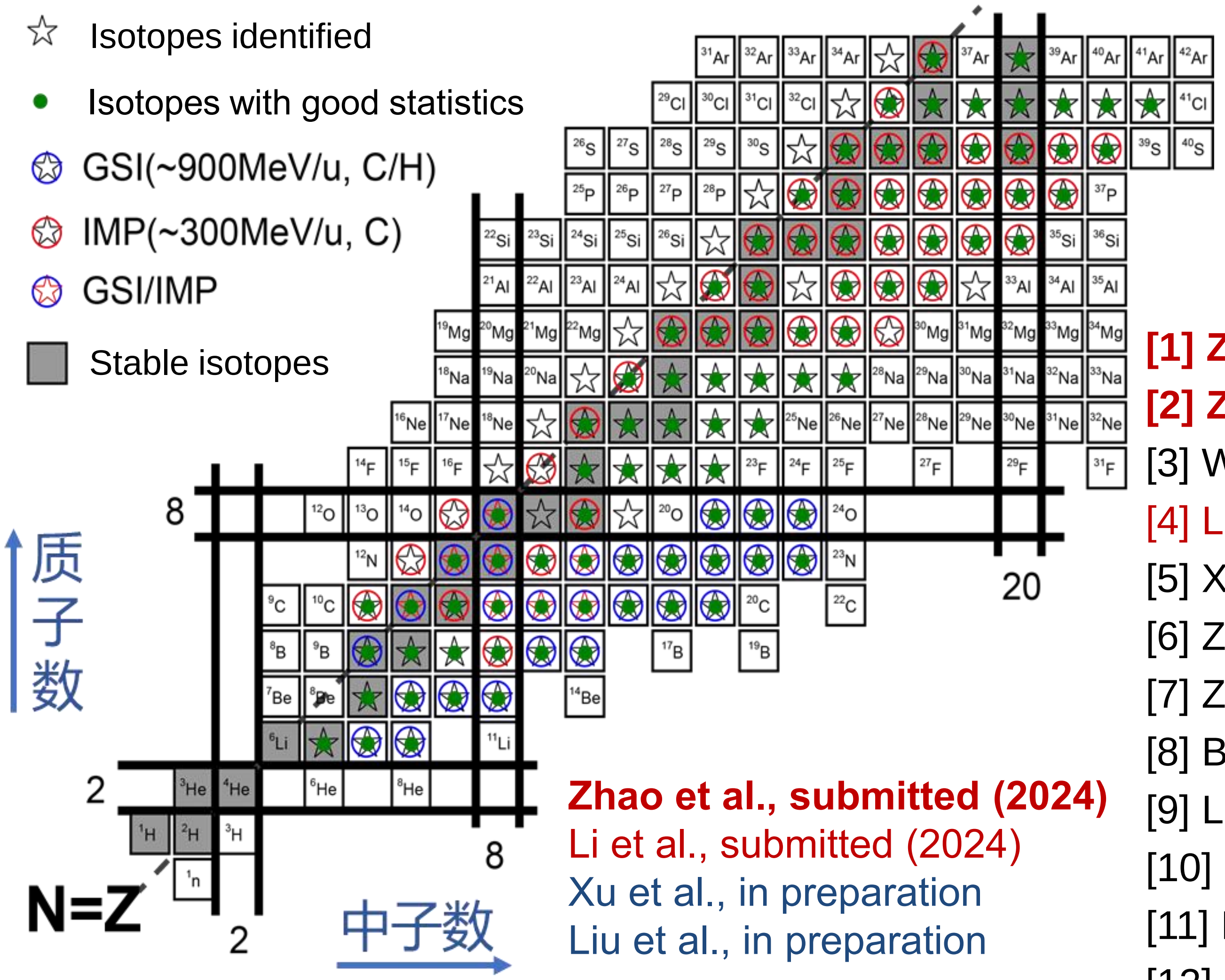


Z distribution of residual particles



Zhang et al., Sci. Bull. 69 (2024) 1647

Consistent (largest) database for σ_{cc} (2014-2022)

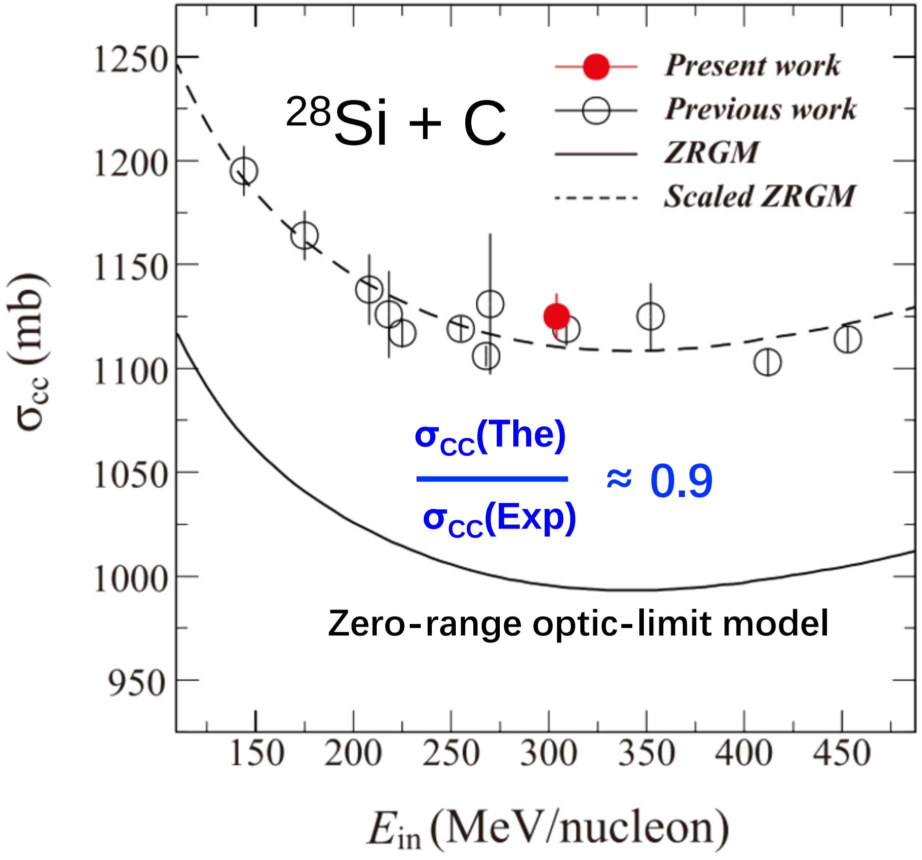


Zhao et al., submitted (2024)
Li et al., submitted (2024)
Xu et al., in preparation
Liu et al., in preparation

- **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)**

[1] Zhang et al., Sci. Bull. 69 (2024) 1647
[2] Zhao *et al.*, PLB 847 (2023)138269
[3] Wang et al., CPC47(2023) 084001
[4] Li et al., PRC107(2023)024609
[5] Xu et al., PLB833(2022)137333
[6] Zhao et al., JPSCP(2020)010023
[7] Zhao et al., NIMA 930(2019)95
[8] BHS et al., Sci. Bull. 63(2018)78
[9] Lin et al., CPC41(2017)066001
[10] Zhao et al., NIMA 823(2016)41
[11] BHS, Chin. Sci. Bull. 65 (2020), 3886 (in Chinese)
[12] Zhao et al., Nuc. Phys. Rev. 35 (2018) 362 (in Chinese)

① What is missing in the model?



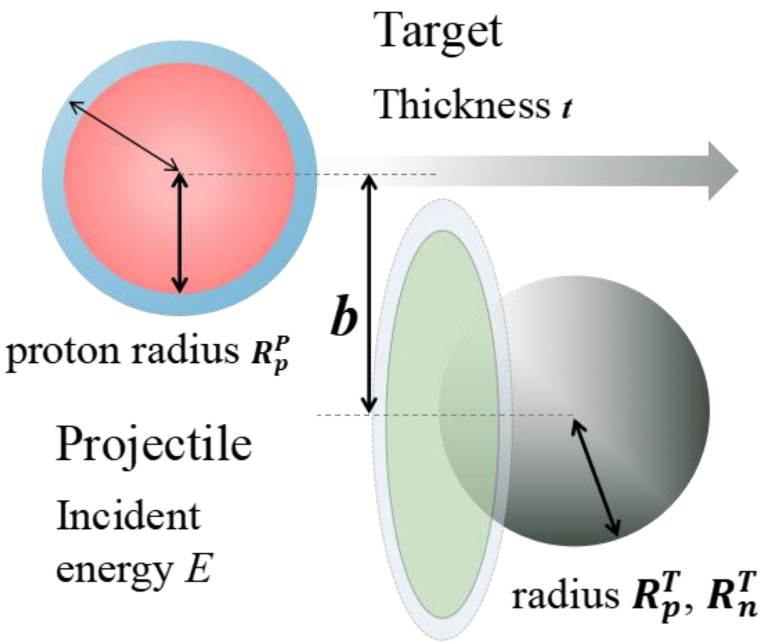
σcc(exp)

σcc(theo)

Wang et al., CPC47, 084001 (2023)
Yamaguchi et al., PRC 82, 014609 (2010)
Yamaguchi et al., PRL107,032502 (2011)

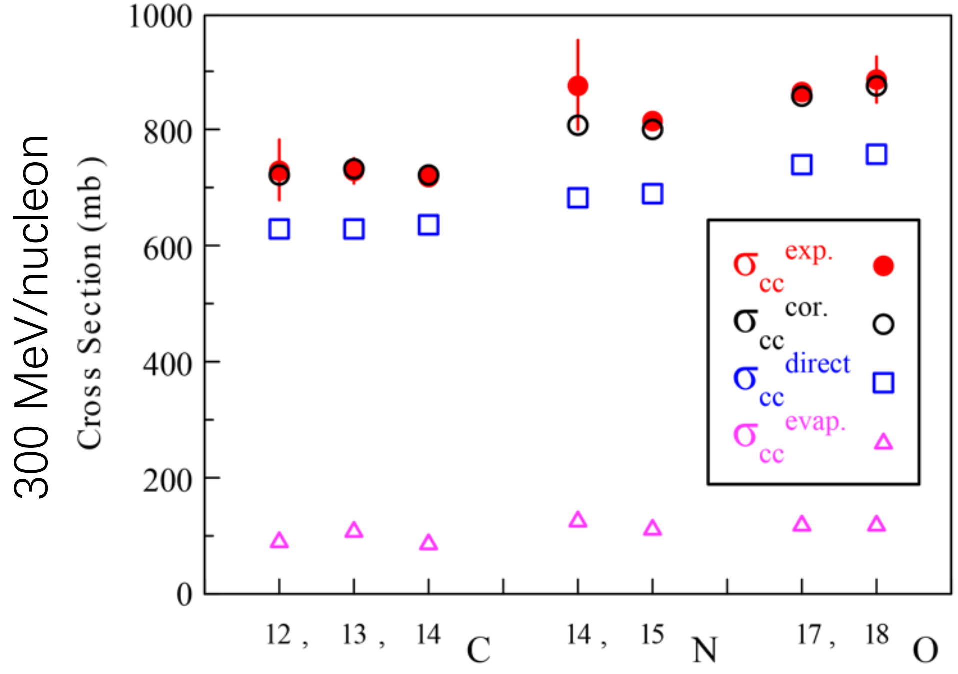
$$\sigma_{cc}^{calc} = 2\pi \int b[1 - T^P(b)]db$$

$$T^P(b) = \exp[-(\sigma_{pp}(E)\rho_p^T\rho_p^P + \sigma_{np}(E)\rho_n^T\rho_p^P)]$$



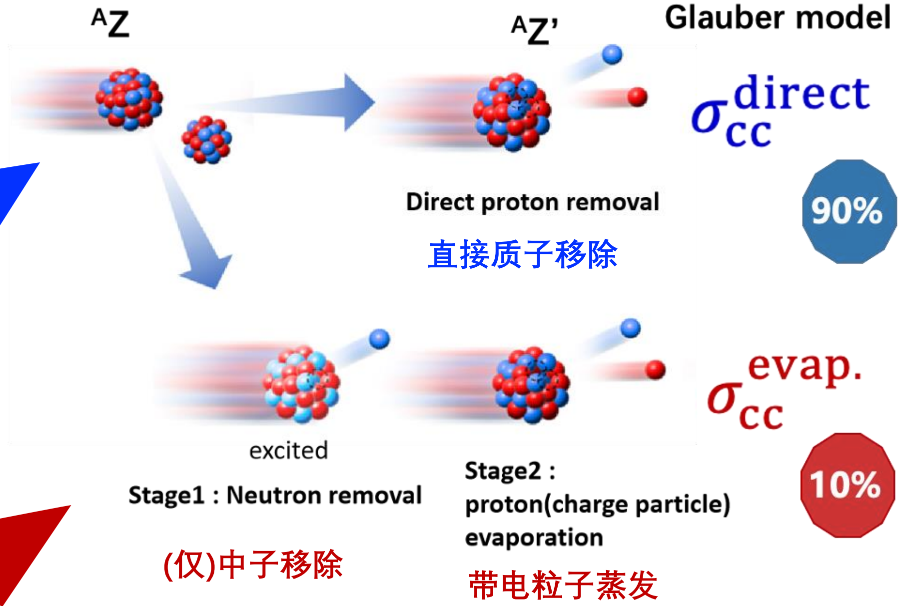
Reaction mechanism of charge-changing reactions

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

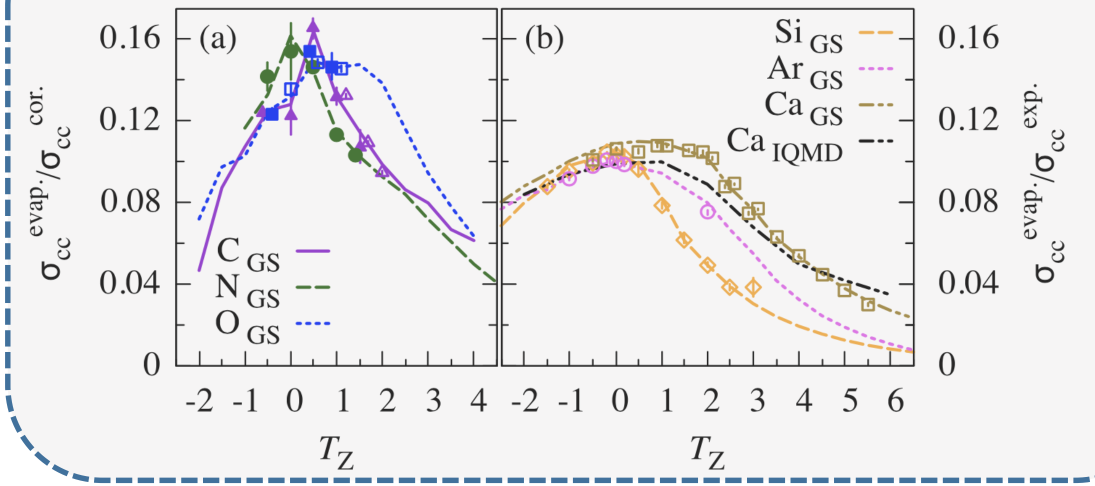


Zhao, *et al.*, PLB 847 (2023)138269

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



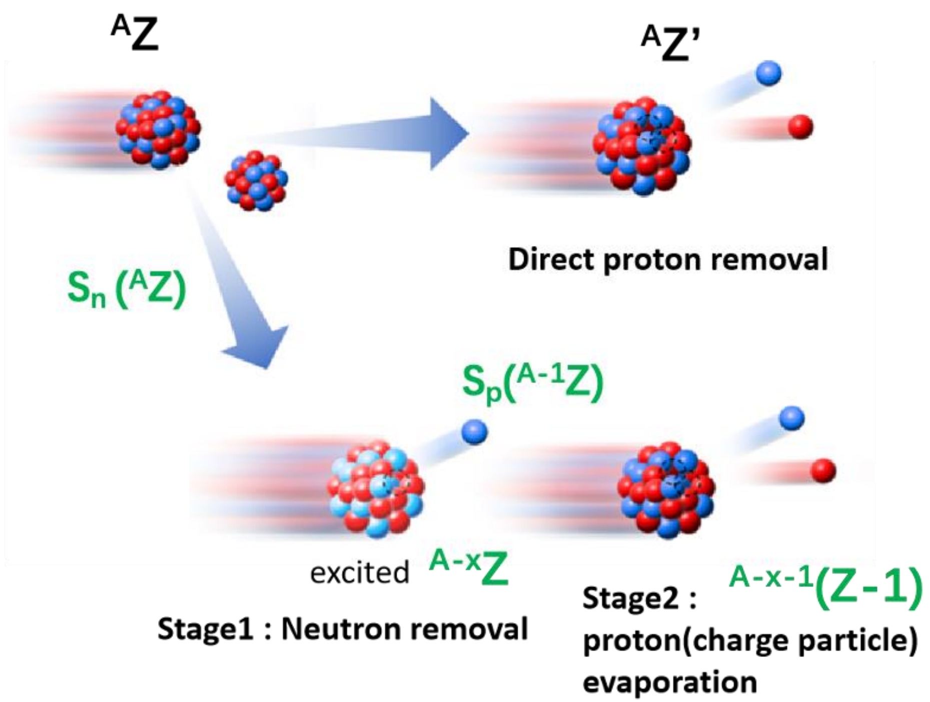
Isospin-dependent evaporation with peaks at ~T_z=0



Q: Model-independent evaporation is required

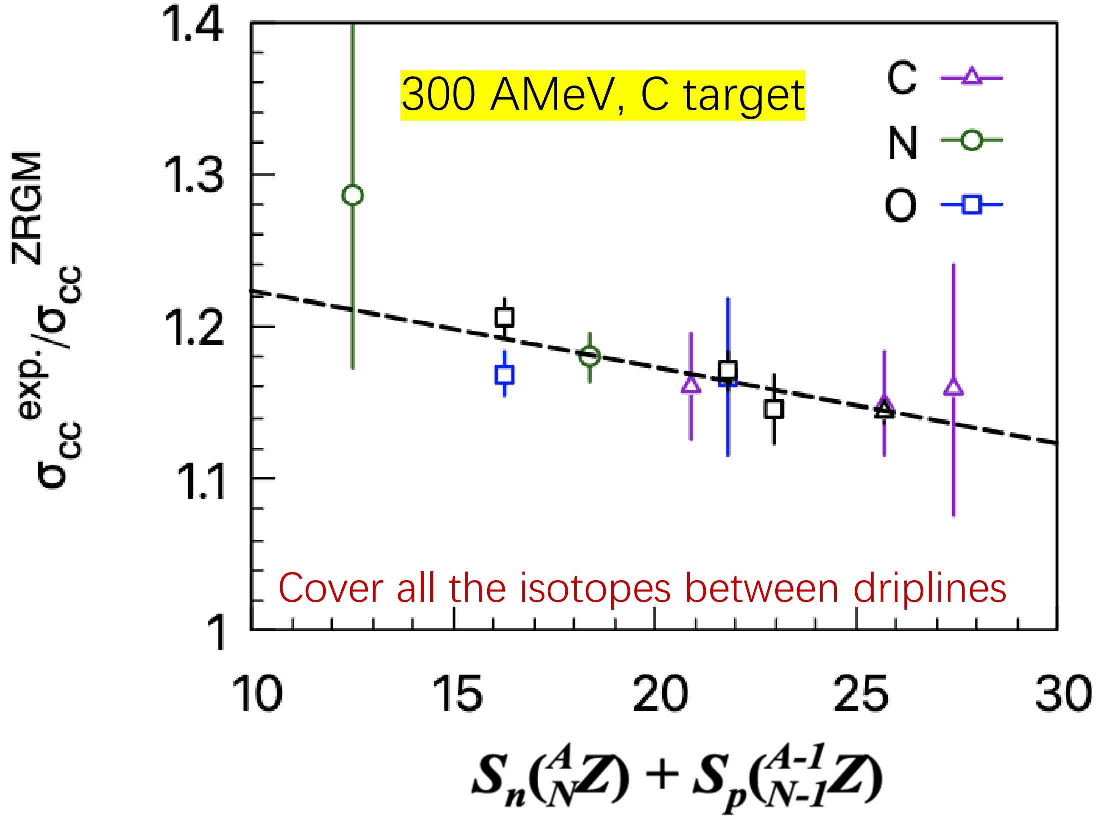
② Parameterize the evaporation effect by the *S* factor

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



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

All the points have well known R_p for calibration



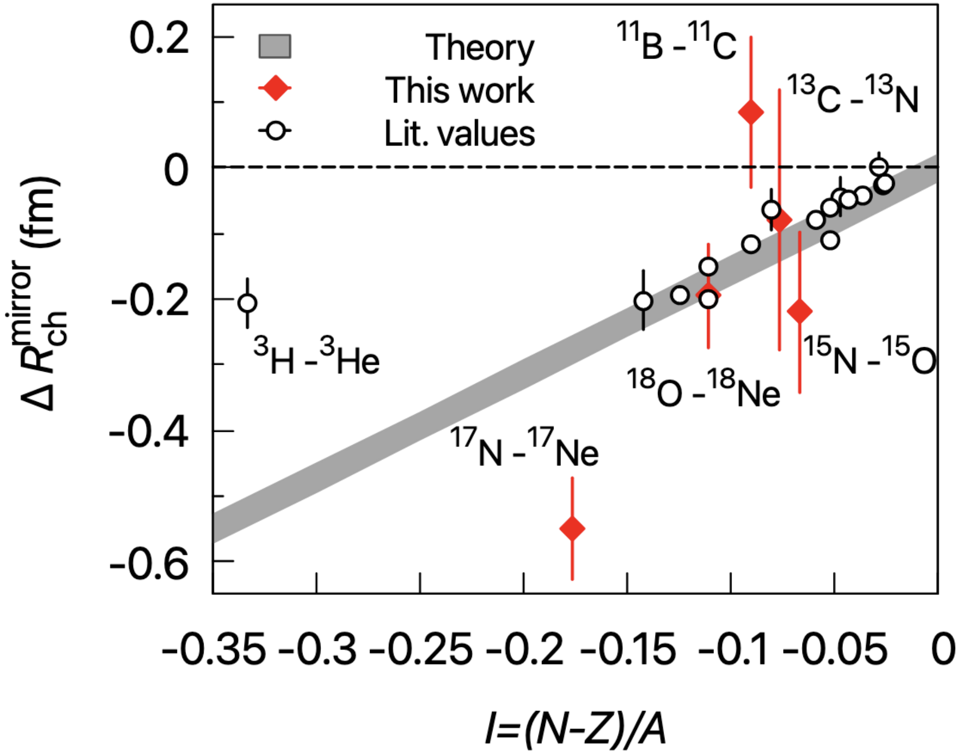
The linear correlation makes model calibrations feasible!

Zhang *et al.*, Science Bulletin 69 (2024) 1647; Zhao *et al.*, arXiv:2407.10199v1

Mirror-difference charge radii

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

N>Z



Zhao et al., arXiv:2407.10199v1

- $^{11-16}$C, $^{13-17}$N and $^{15-18}$O: 15 radii
- 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,

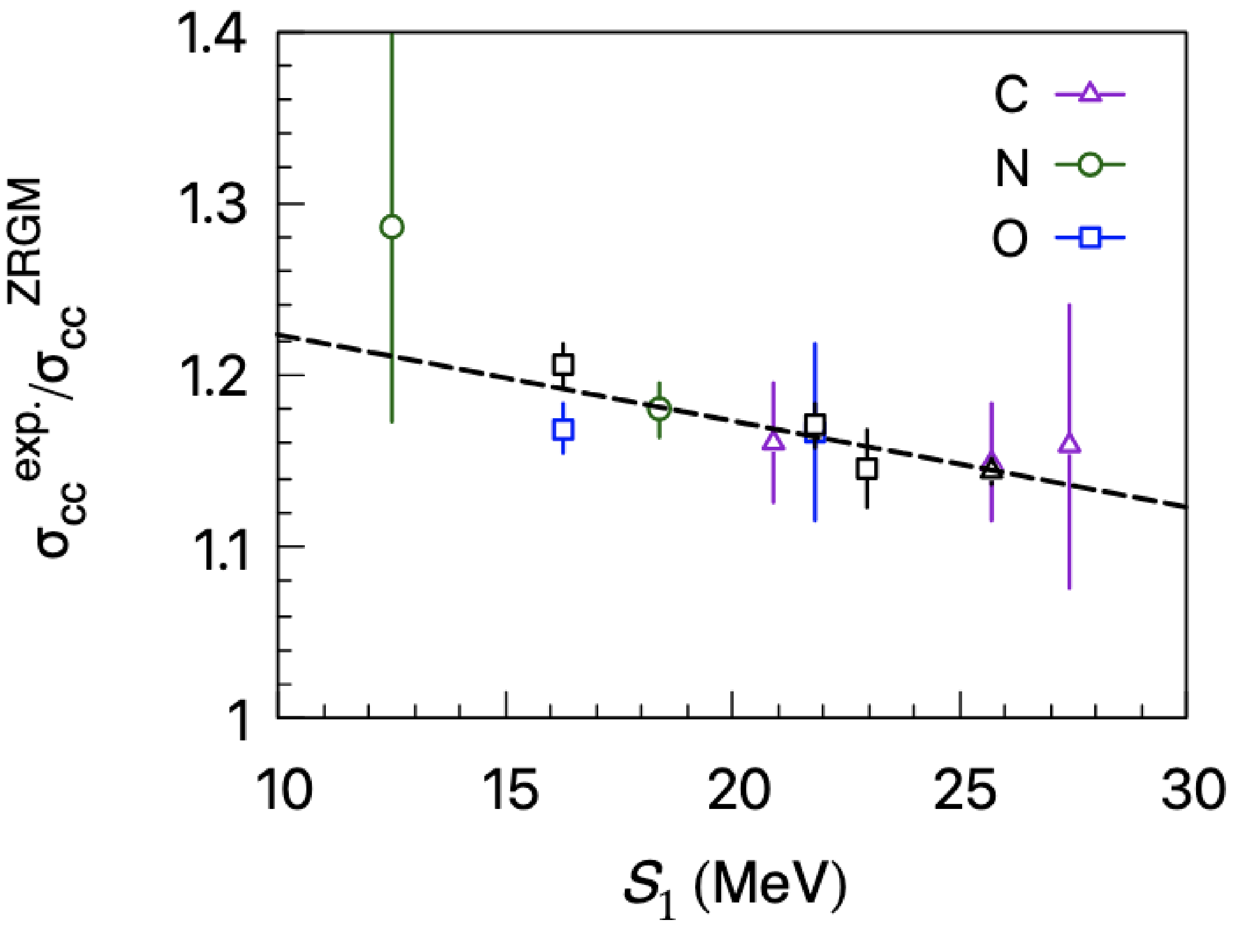
^{17}N-^{17}Ne (proton halo), σ_I, σ_{-p}, $P_{//}$

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

PRL 122, 182501 (2019)

③ How robust is the *S*-factor correlation?

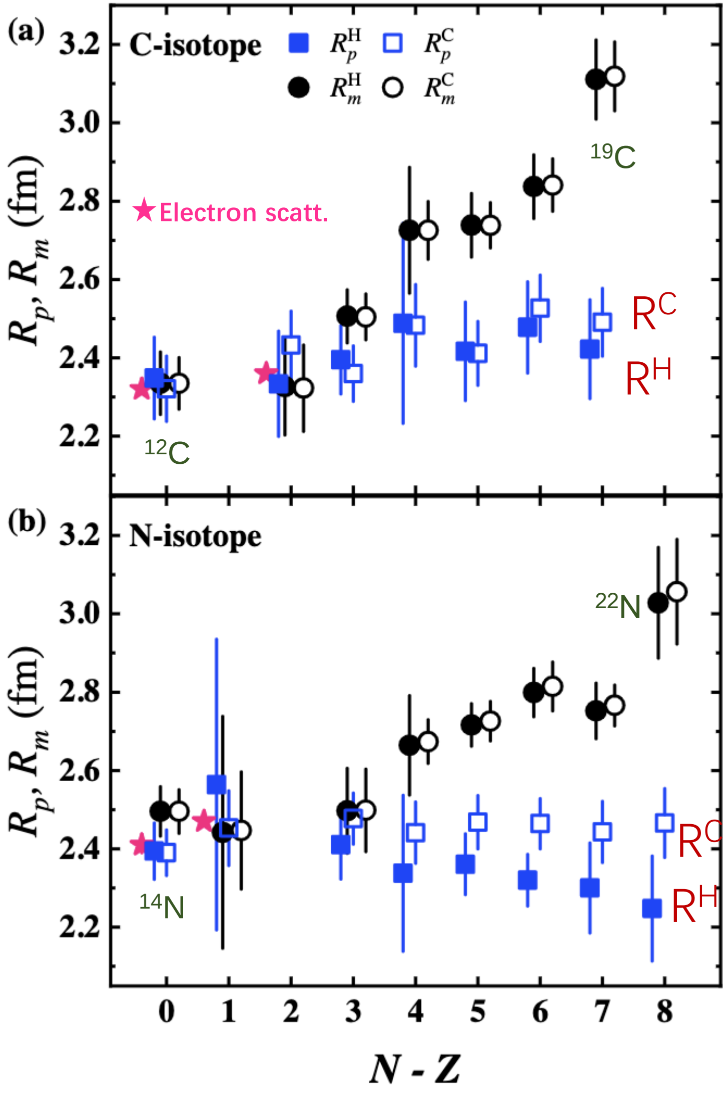
Q: Is the S-factor correlation universal when employing different targets at different energies?



Data wanted!

④ Deduction of R_p from C, H target data

R_m: matter distribution radii, R_p: point-proton distribution radii



For C isotopes, very consistent R_p values are determined from C- and H-target data.

This is the first time that both target data have been dealt with in a self-consistent way.

Consistent R_m values for interaction x-sections on both C- and H-target.

For N isotopes, systematically small R_p values are determined from H-target data compared to R_p from C-target data.

Experimental uncertainties or natural effects?

Zhang *et al.*, Science Bulletin 69 (2024) 1647

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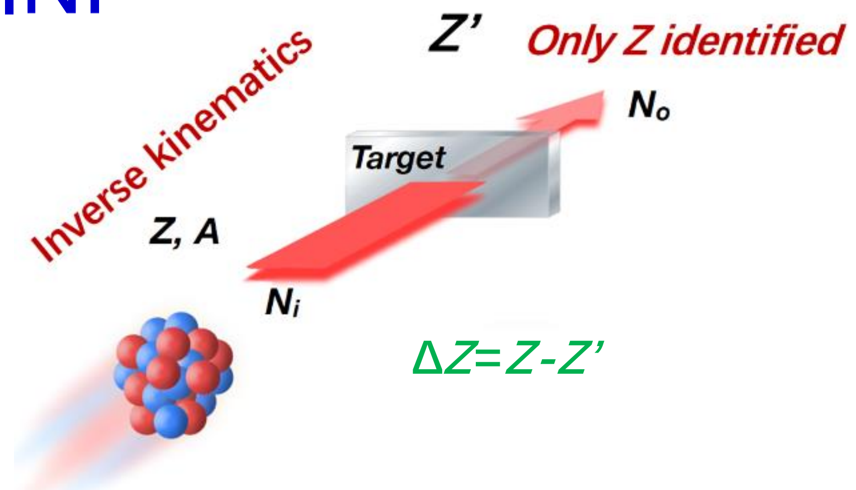
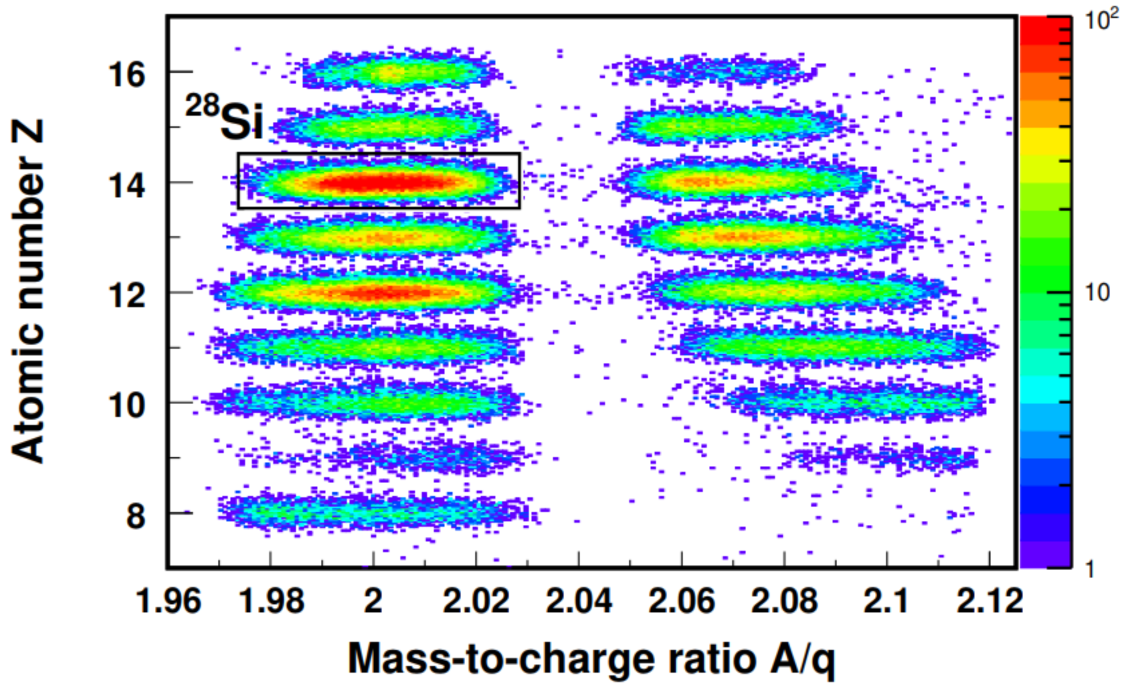


Partial charge-changing cross sections $\sigma_{\Delta Z}$

Partial charge-changing cross sections: $\sigma_{\Delta Z}$

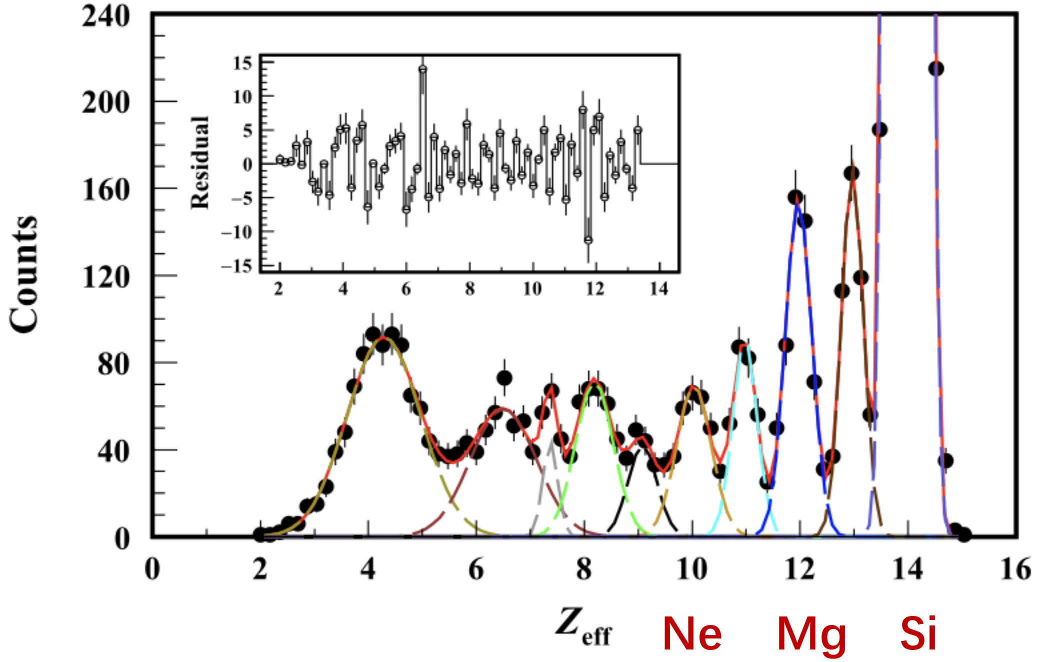
$\sigma_{\Delta Z=1}$: ^{28}Si (Z=14) ➔ Al (Z=13); $\sigma_{\Delta Z=2}$: ^{28}Si (Z=14) ➔ Mg (Z=12)

$\sigma_{\Delta Z=3}$: ^{28}Si (Z=14) ➔ Na (Z=11). ……



Cocktail beam

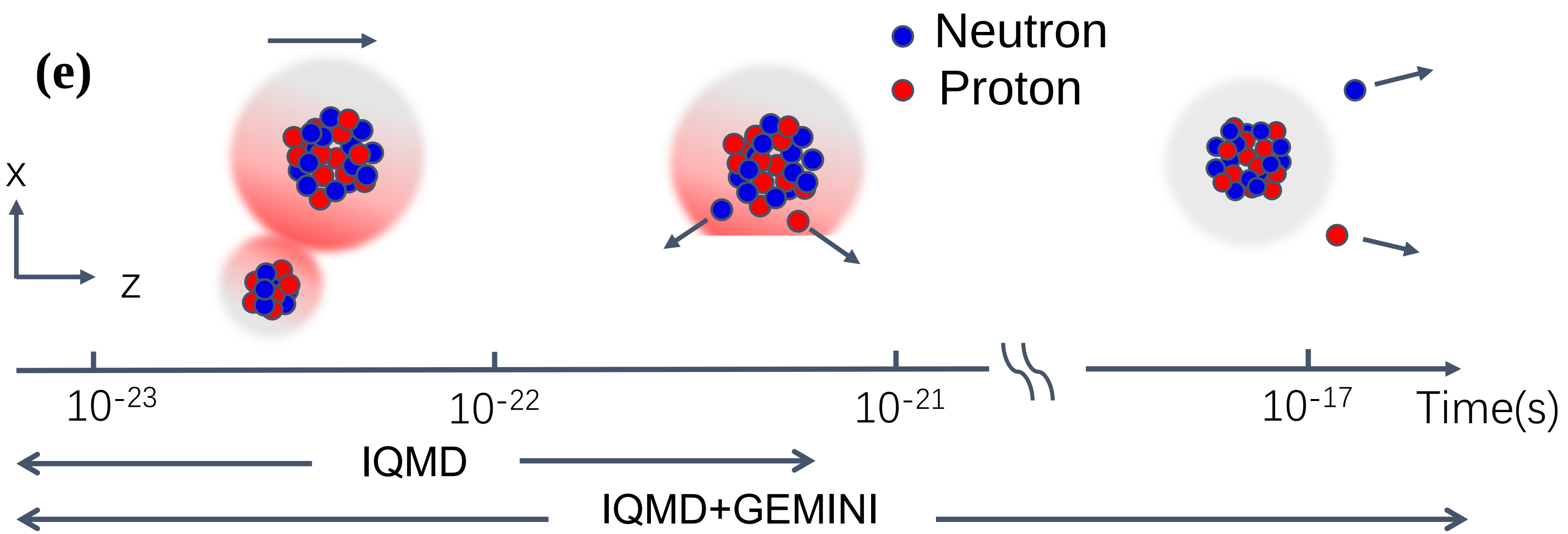
Charge dis. of ^{28}Si+C reaction



Li, Su, BHS et al., PRC 107, 024609 (2023)

IQMD+GEMINI: another way to understand σ_{cc}

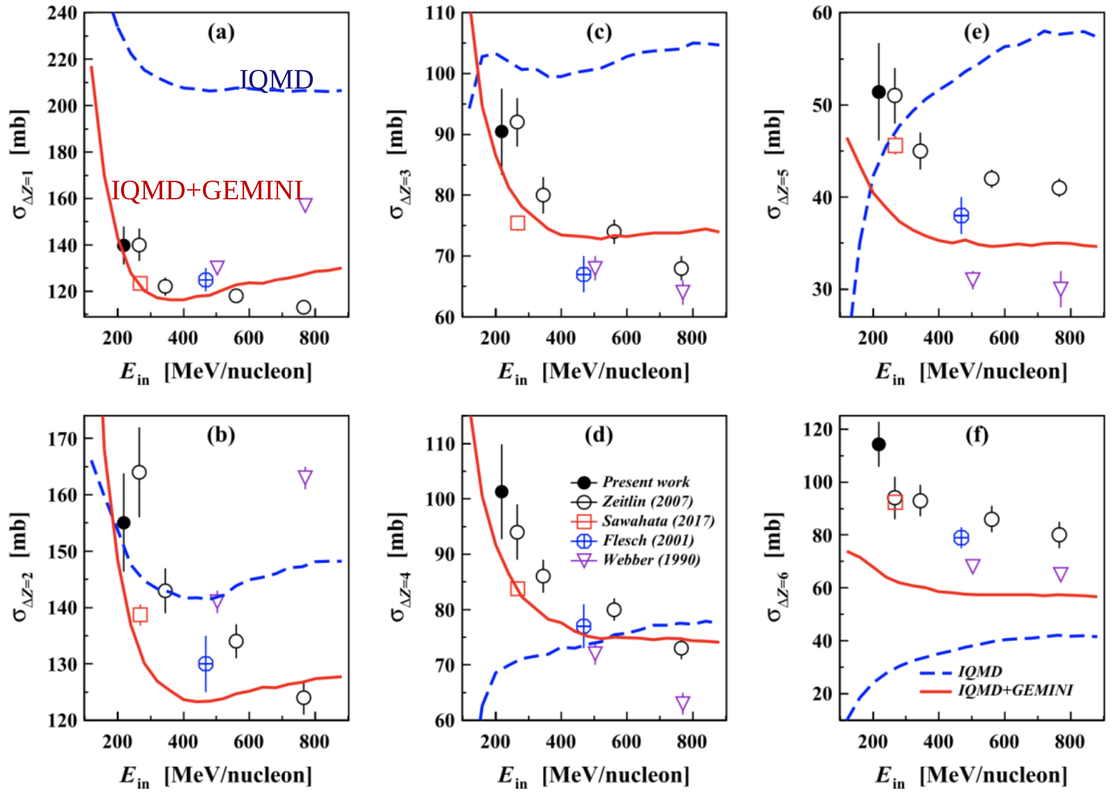
IQMD+GEMINI model: dynamical collision process (IQMD) and the following statistical de-excitation of intermediate residues (GEMINI)



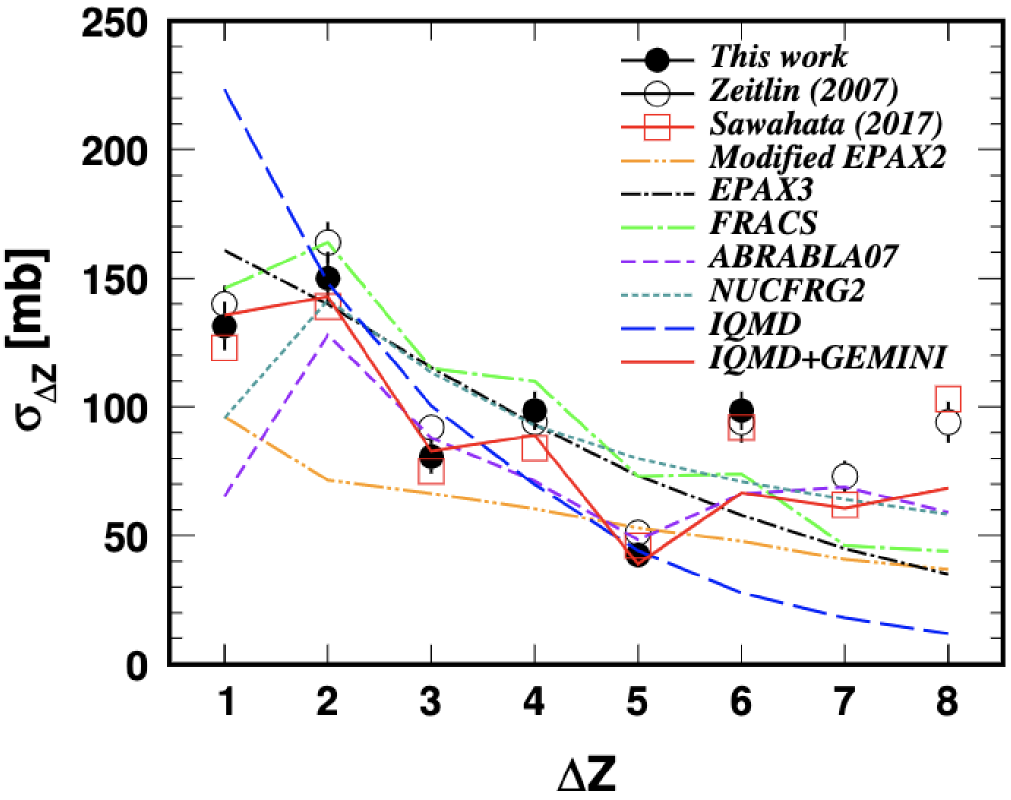
e.g., Jun Su et al., Phys. Rev. C ***83****, 014608 (2011)*

IQMD+GEMIN well reproduces $\sigma_{\Delta Z}$ of ^{28}Si+C

^{28}Si @ 200-800 A MeV + C target

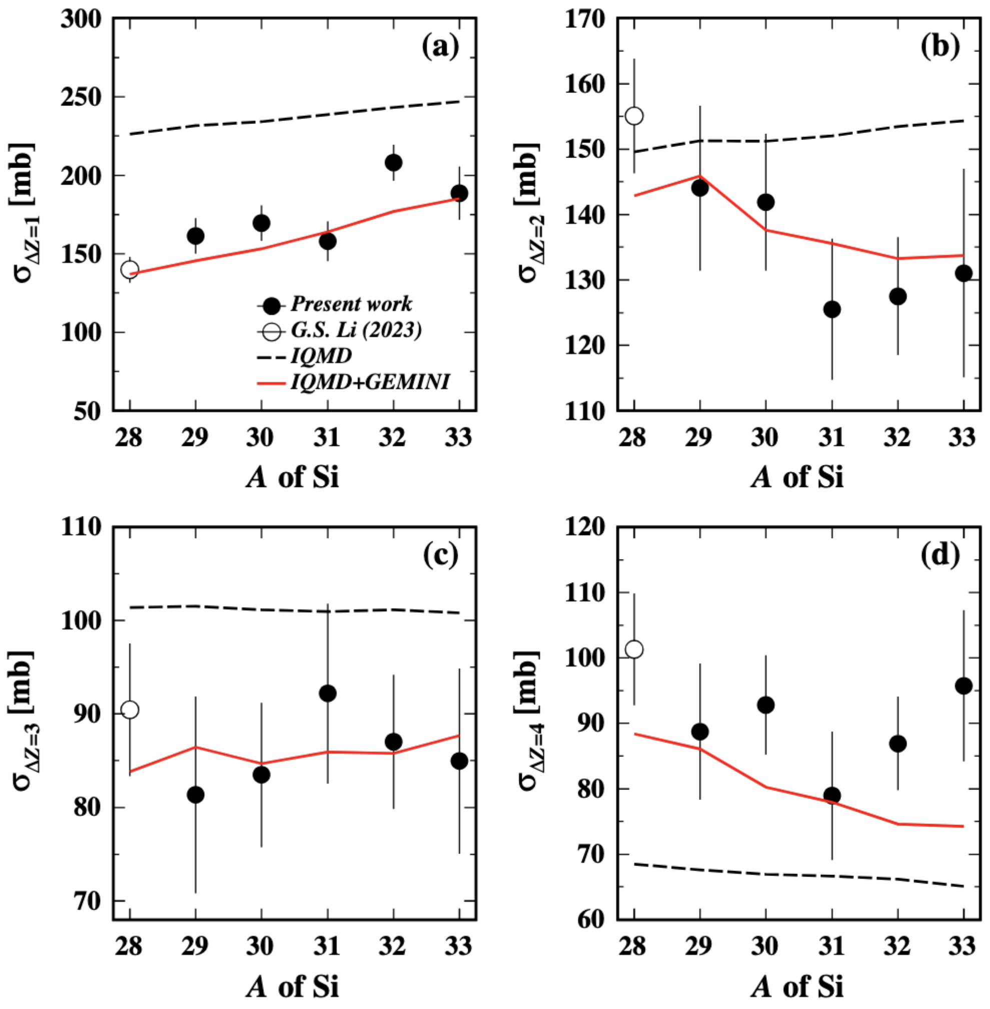


^{28}Si@300 AMeV + C



Li, Su, BHS *et al.*, PRC 107, 024609 (2023)

IQMD+GEMIN for $^{28\text{-}33}Si$

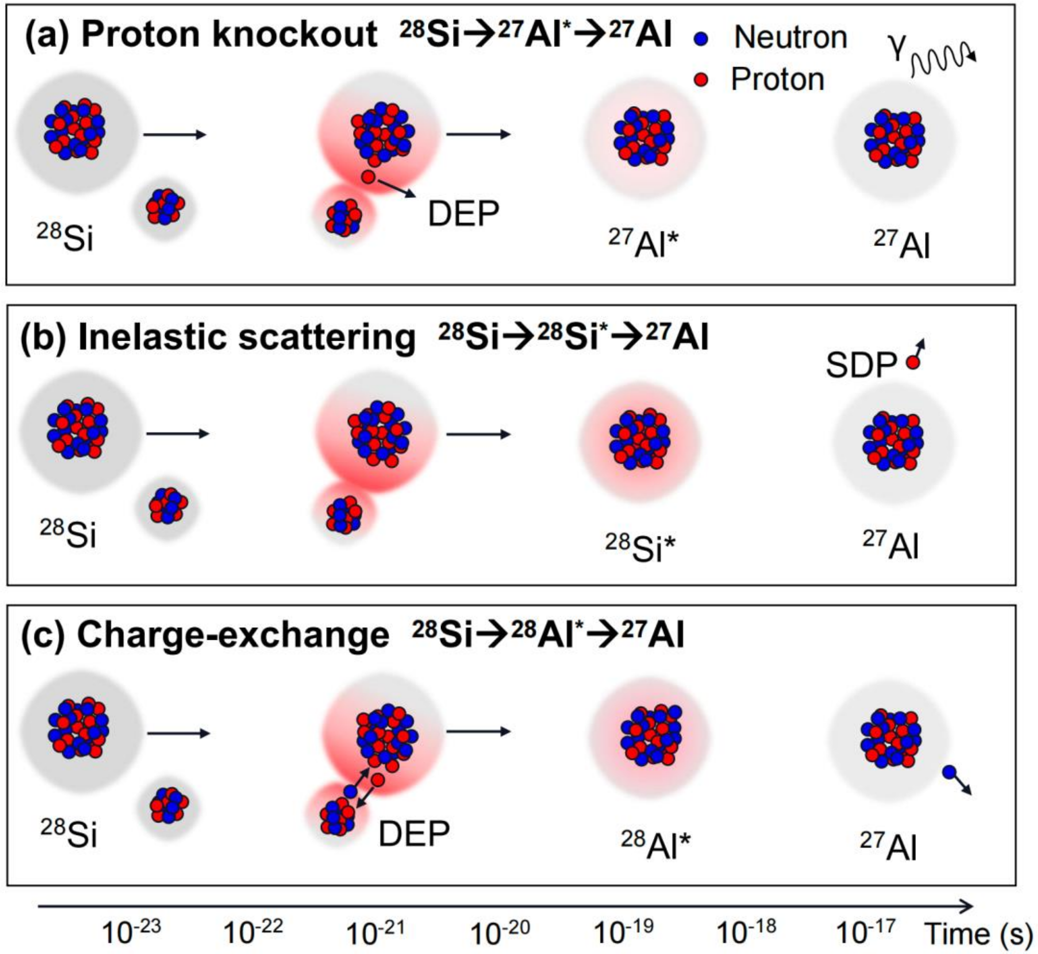


- IQMD+GEMINI: can reproduce the Si chain
- Experimental data serve as the critical benchmarks to validate the In the IQMD+GEMINI model.
- Fairly good agreement allows to examine the knockout, multiple scattering, and nucleon evaporation within the model framework.

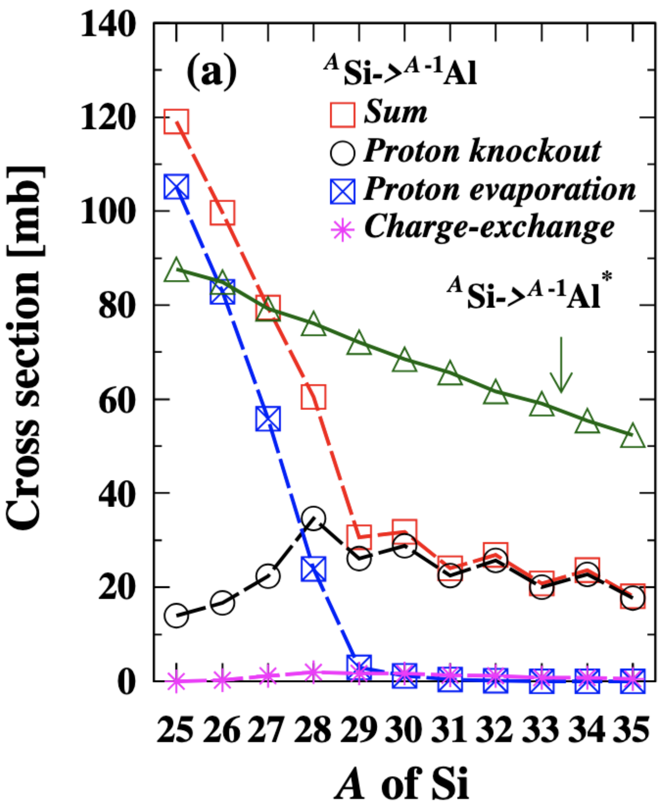
Li, BHS, Su *et al.*, arXiv *2407.14697*

Prediction of 1-proton removal xs in IQMD+GEMINI

$^{28}Si + C \rightarrow\, ^{27}Al$



Li, BHS, Su, *et al.* arXiv *2407.14697*



- Contribution from inelastic scattering channels is increasing towards T_z<0
- This may help to resolve the long-standing puzzle in the proton knockout reactions (Gade et al., 2002 PRC)

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Summary

Data – global pattern – interpretation

- We have been focusing on charge-changing reactions of *p-sd* shell nuclei on various targets (H, C, Ag, Pb) at 240, 300 and 900 MeV/nucleon.
- We identified a robust correlation with the *S* factor for p-shell nuclei. This allows us to develop an empirical but universal approach for deducing R_p. However, understanding the *S* factor correlation microscopically is not yet available.
- Next steps:

  Experimental evidence of direct proton removal process vs. charge particle evaporation

  Is the linear correlation with the *S* factor robust when moving from *p*-shell to heavier isotopes?

  Can one get identical R_p or ρ_p from different target data?

- IQMD+GEMINI can nicely reproducing the partial change-changing cross sections. **Systematics data up to Kr fragments are on the way.**