Measurements of neutron-skin thickness of exotic nuclei via integrated reaction cross section measurements

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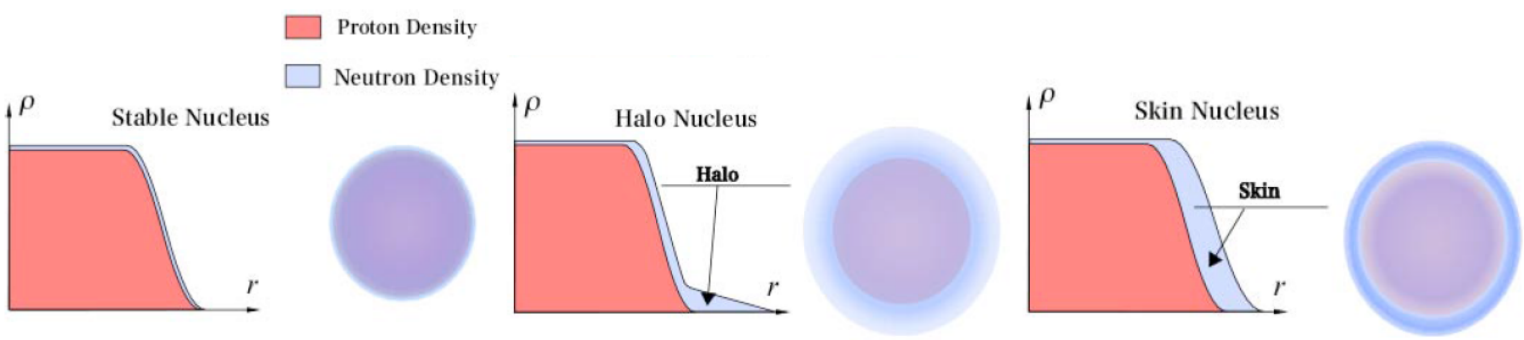
- Introduction: nuclear size & structure
- Experiments, results, perspective
- Summary

NuSYM2018, South Korea, September 10 - 13, 2018

Nuclear size

Radius of atomic nuclei is one of the most fundamental physical quantities to characterize the atomic nucleus, the finite open quantum many-body system.

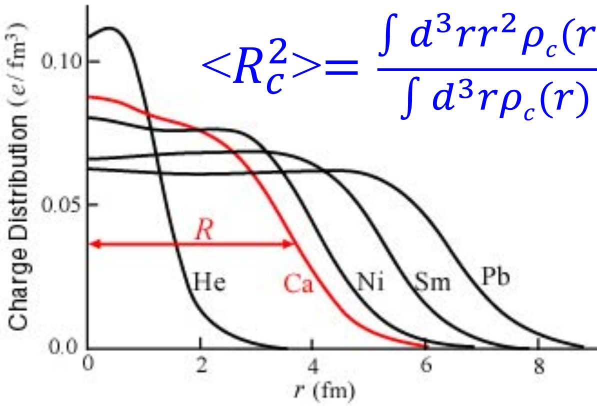
With the high-precision measurement of the radius of unstable nuclei, new interesting phenomena such as "halo" and "skin" have been found. → triggered the radioactive ion beam (RIB) physics worldwide; studies of nuclear radii has been one of attractive topics in nuclear physics



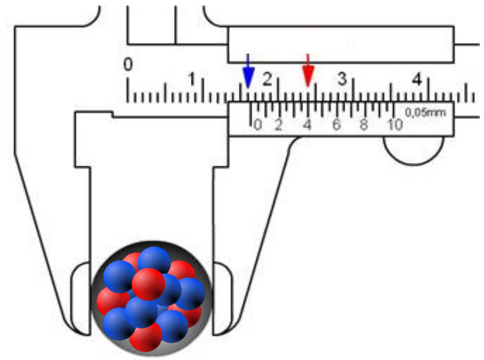
Tanihata, Savajols, Kanungo, Prog. Part. Nucl. Phys. 68(2013)215

Nuclear size

$\rho_c(r)$



$$<R_c^2> = \frac{\int d^3r\, r^2 \rho_c(r)}{\int d^3r\, \rho_c(r)}$$



Nuclear extension in space, often characterized by

- **(rms) proton/charge radius** – mostly due to proton distribution

  via Coulomb interaction of charged particles (e, p) with nucleus $\langle R^2 \rangle_{c(p)}^{1/2}$

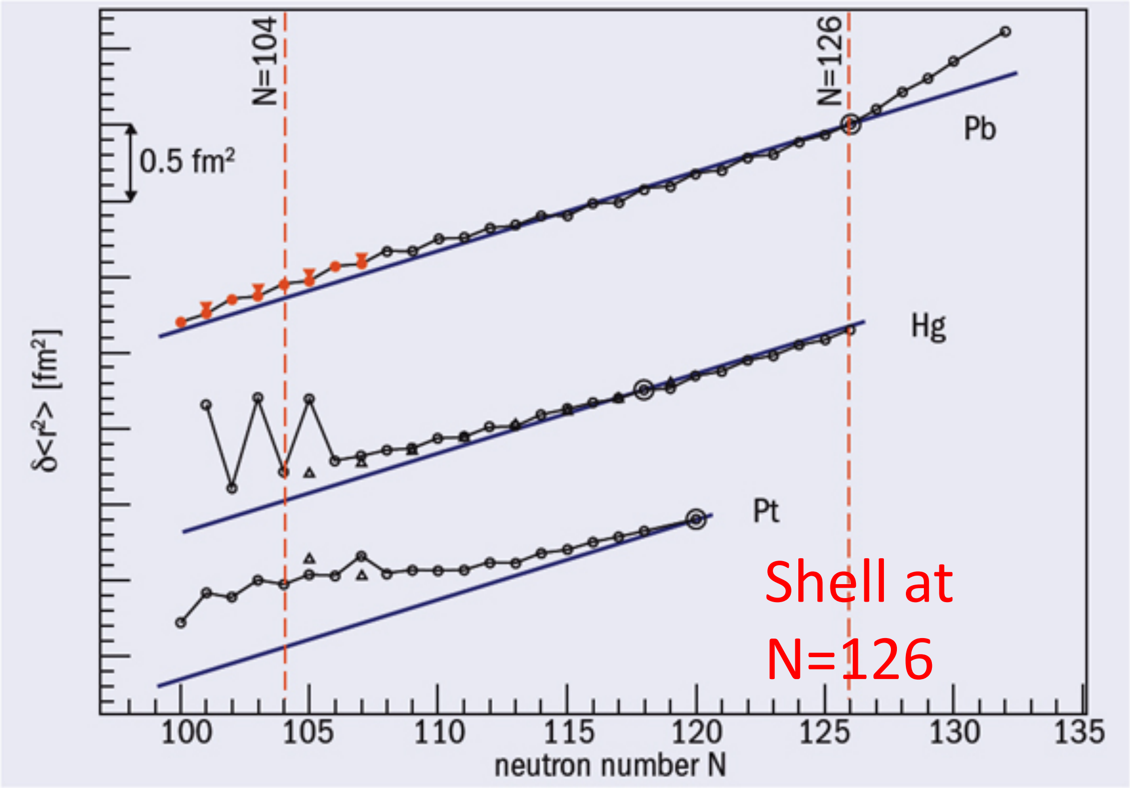
- **(rms) matter radius** – distribution of protons and neutrons

  via strong interaction of nuclei and particles (p) $\langle R^2 \rangle_{m}^{1/2}$

Sensitive probe for nuclear structure

Isotopic shift: first order derivative of nuclear charge radii over N

Shell closure



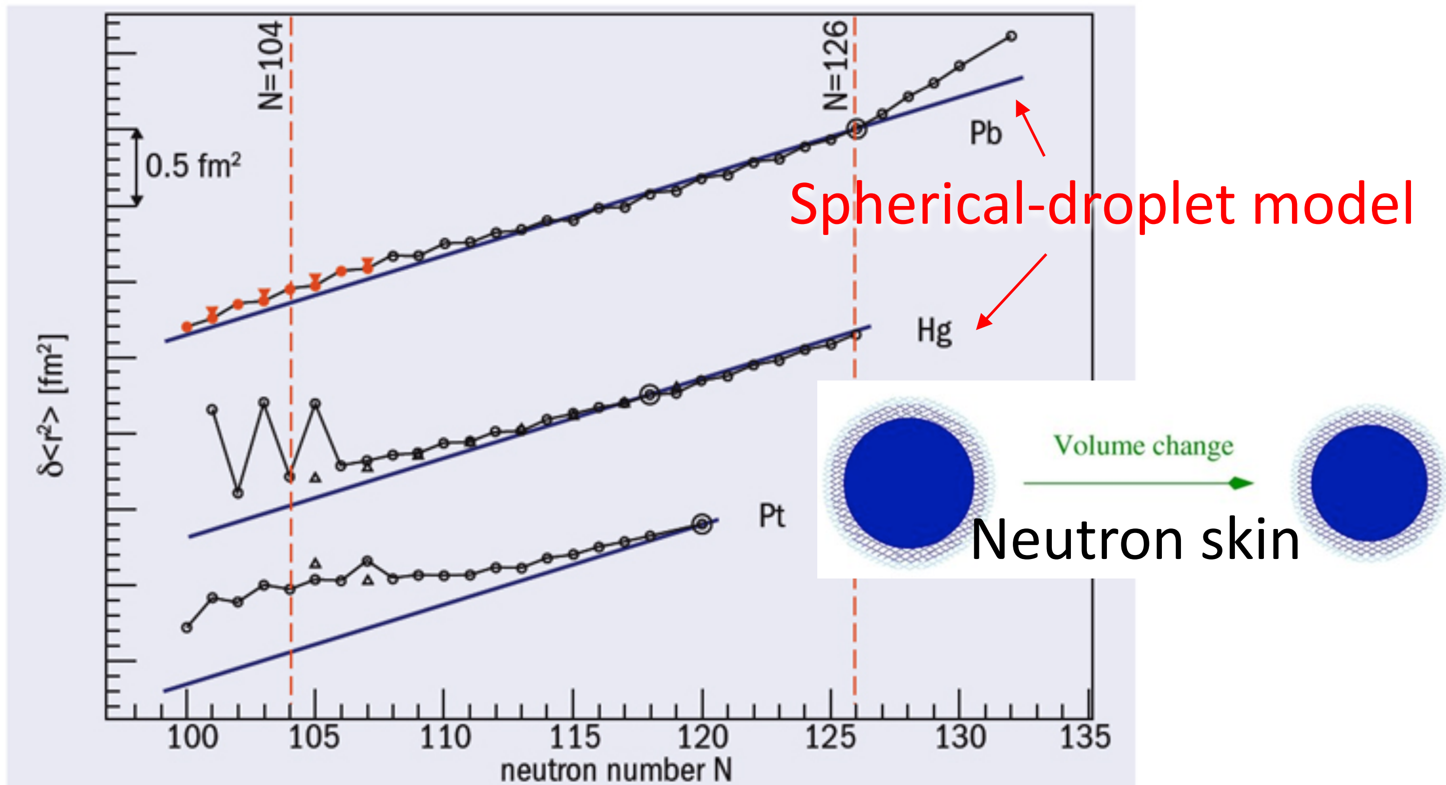
Shell at N=126

Sensitive probe for nuclear structure

Isotopic shift: first order derivative of nuclear charge radii over N

Shell closure

Neutron skin



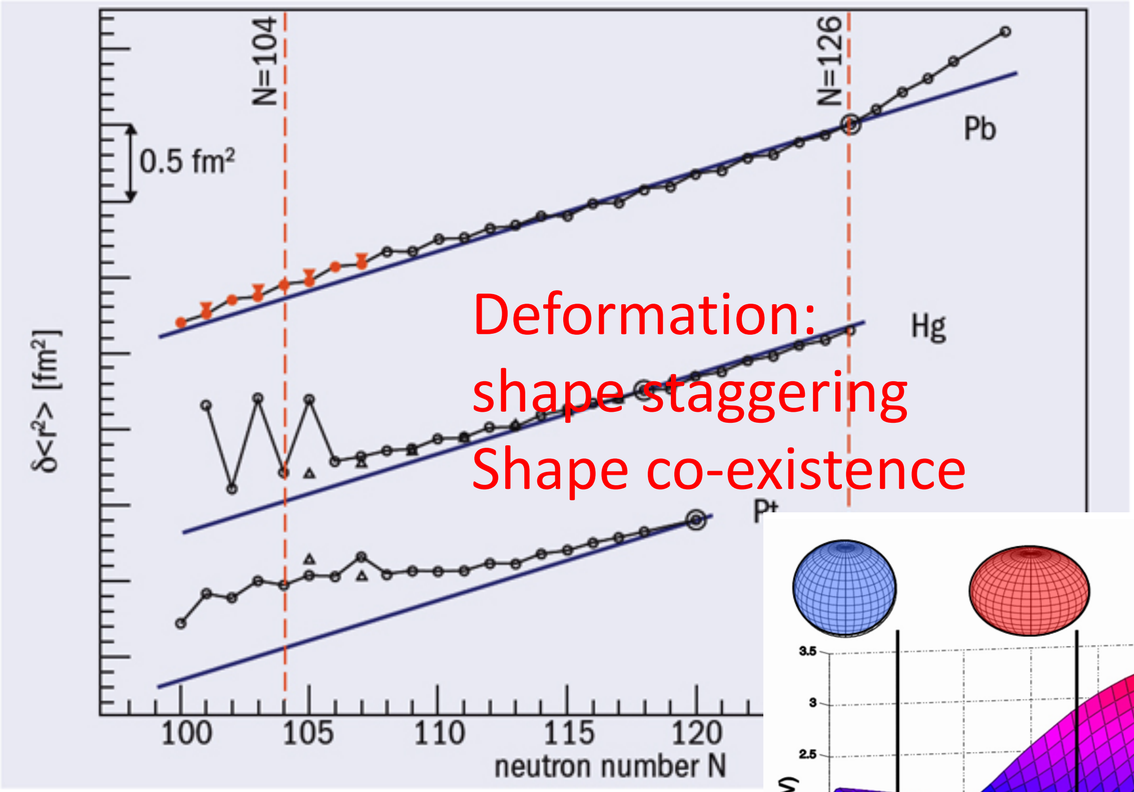
Sensitive probe for nuclear structure

Isotopic shift: first order derivative of nuclear charge radii over N

Shell closure

Neutron skin

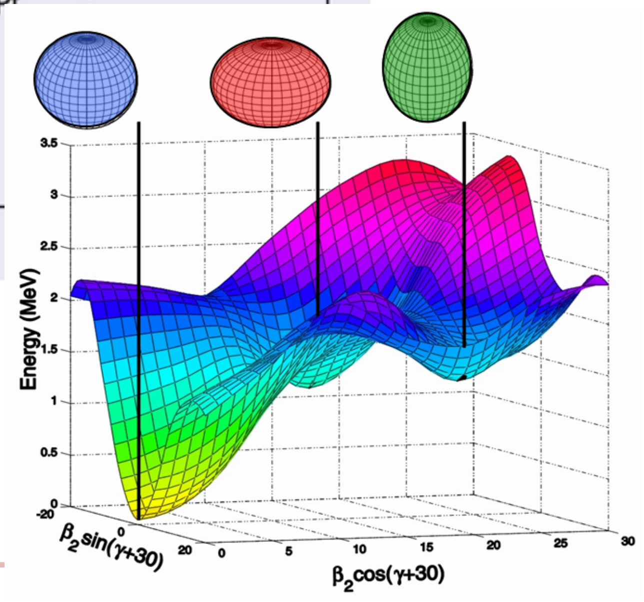
Deformation



Deformation:

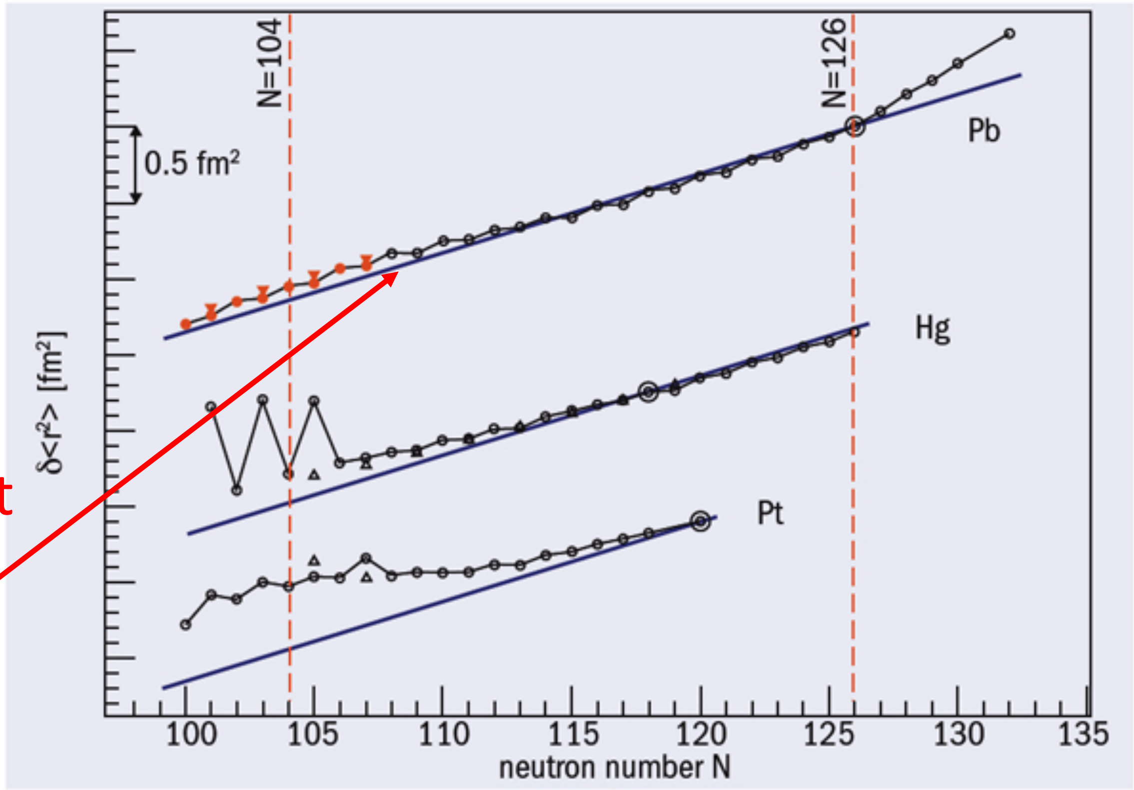
shape staggering

Shape co-existence



Sensitive probe for nuclear structure

Isotopic shift: first order derivative of nuclear charge radii over N



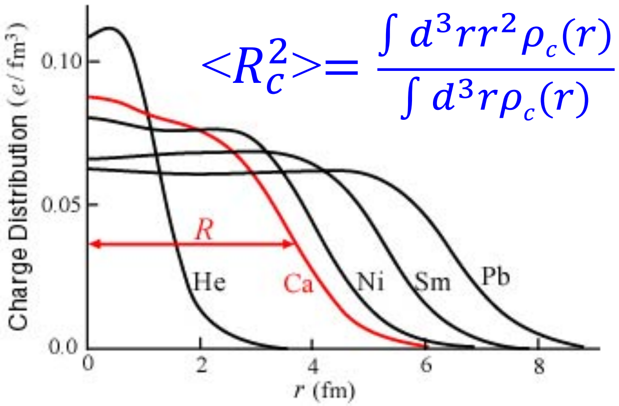
Shell closure
Neutron skin
Deformation
Dynamic effect

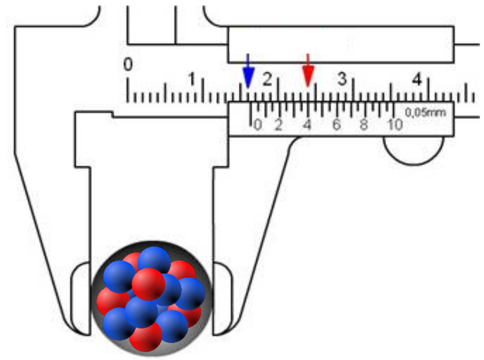
Odd-even staggering

Can be used to study the single-particle levels...

Nuclear size

$\rho_c(r)$





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- **(rms) matter radius** – distribution of protons and neutrons

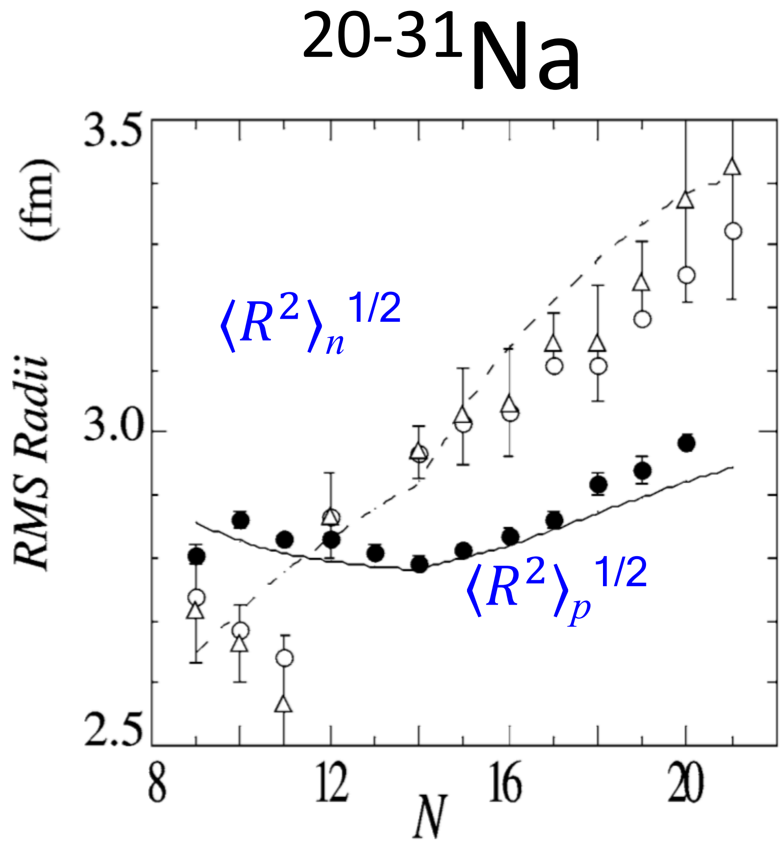
  via strong interaction of nuclei and particles (p) $\langle R^2\rangle_m^{1/2}$

- **(rms) neutron radius** – distribution of neutrons

$$A\langle R^2\rangle_m = Z\langle R^2\rangle_p + N\langle R^2\rangle_n$$

- **Neutron skin-thickness** $\Delta R_{np} = \langle R^2\rangle_n^{1/2} - \langle R^2\rangle_p^{1/2}$

Na isotopes as examples



Ozawa et al., NPA693 (2001) 32

- The value of 0.3-0.4 fm for ^{31}Na is larger than that observed in neutron-rich β-stable ^{48}Ca (0.14–0.20 fm)
- Neutron-rich nuclei provide a natural laboratory for thick neutron skin.

Outline

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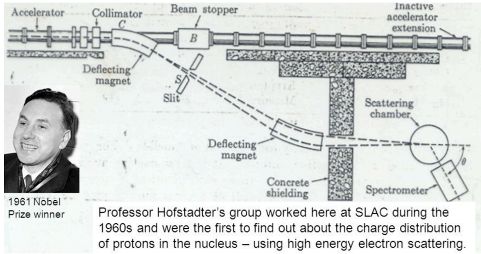
Experimental determination of nuclear radii

Proton radii

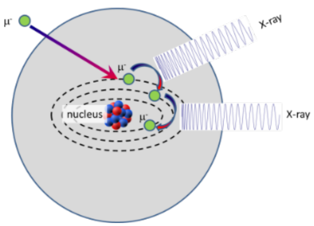
Stable nuclei

Electron scattering

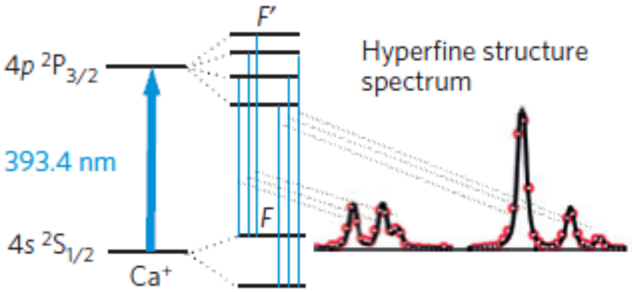


μ – atom

Stable nuclei

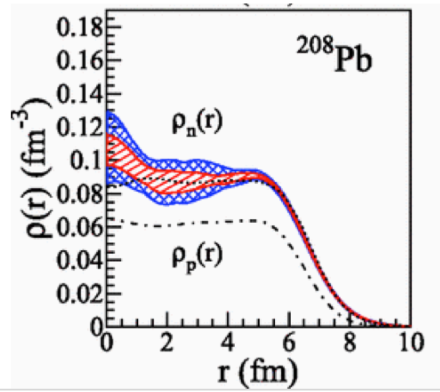


Isotope shift



Matter radii

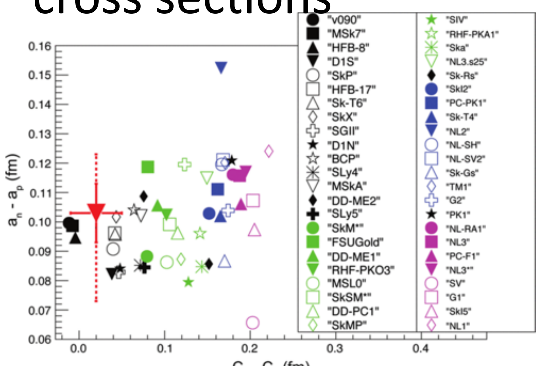
Proton elastic scattering



Zenihiro et al., PRC82(2010)044611

coherent pion photoproduction cross sections

Stable nuclei

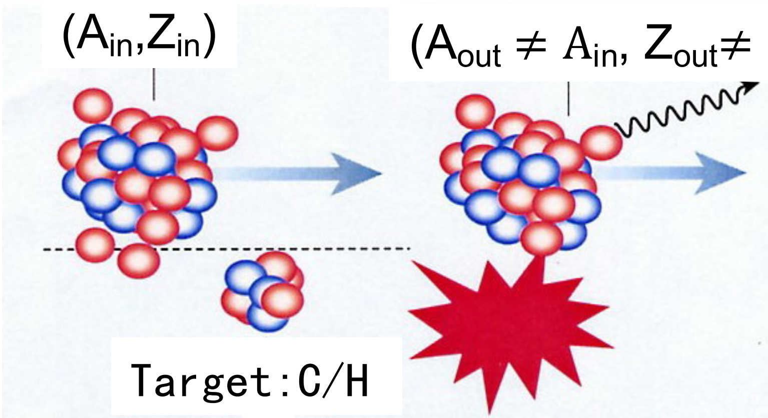


Tarbert et al., PRL112(2014)242502

reaction c.s. vs. charge changing c.s.

Integrated cross section; hadronic interaction

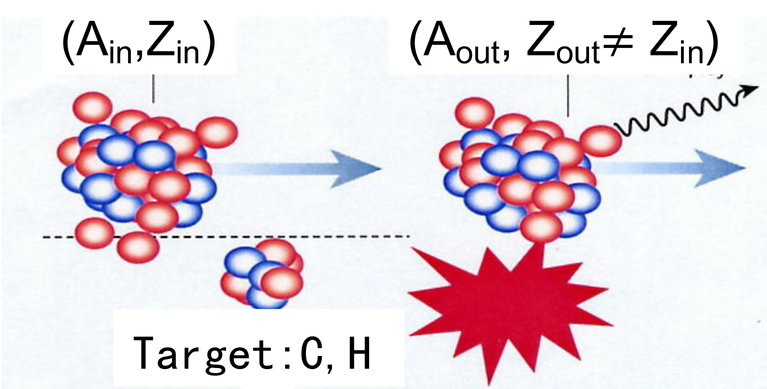
- Reaction cross section: σ_R



$$\sigma_R = \Sigma\sigma_i(Z_R \neq Z_p, A_R \neq A_p)$$

distribution of *p* and *n* in projectile
→ nuclear matter radius

- Charge-changing c.s. : σ_{cc}

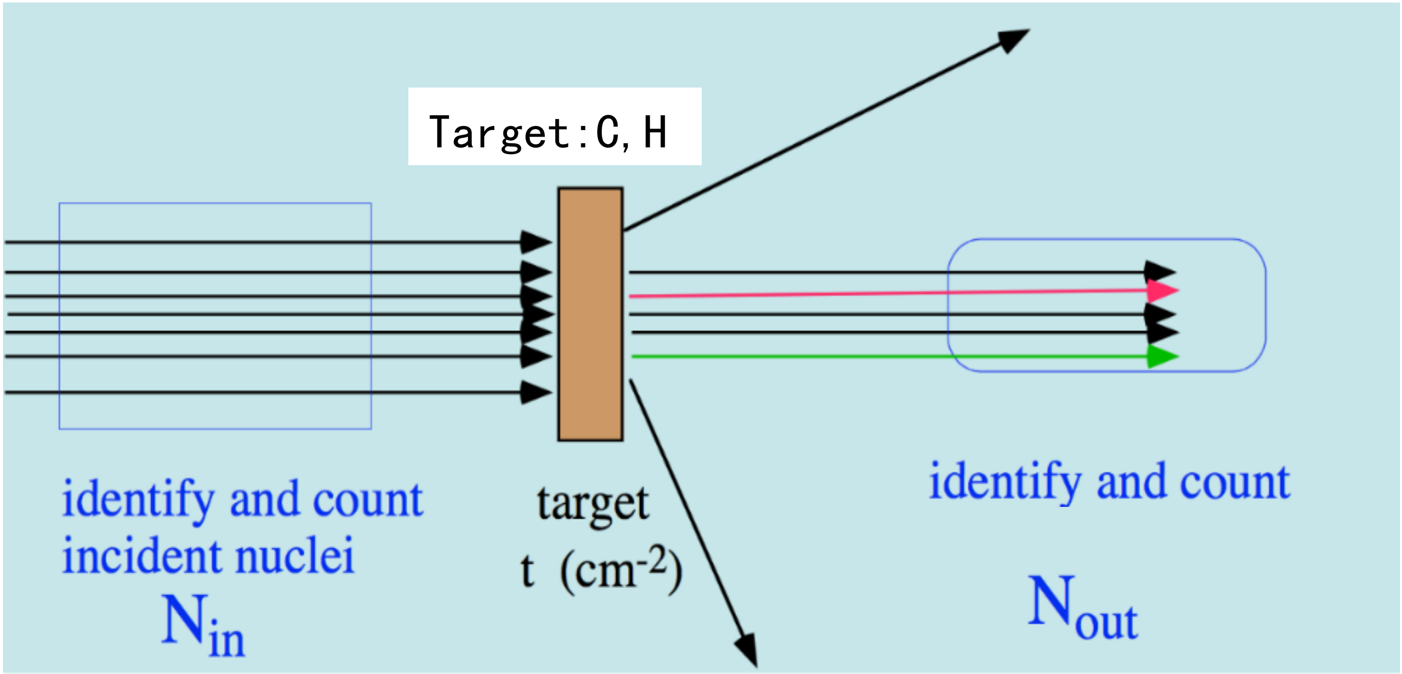


$$\sigma_{cc} = \Sigma\sigma_i(Z_R \neq Z_p)$$

distribution of *p* in projectile
→ nuclear charge radius

Transmission method

Taking charge-changing cross section as an example



(A_{in}, Z_{in})

$(Z_{out} = Z_{in})$

Integrated cross section: $\sigma_{cc} = \Sigma\sigma_i(Z_R \neq Z_p)$

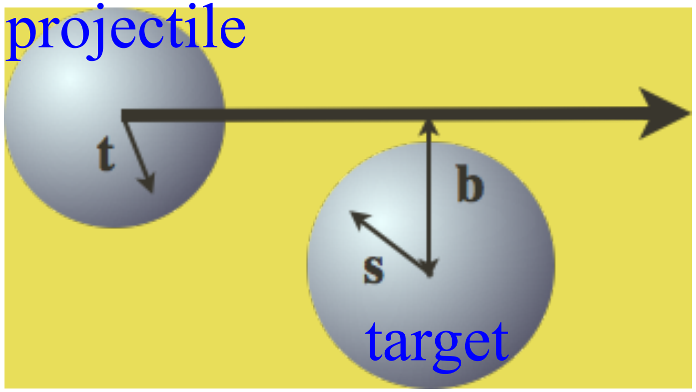
→ Universal, relative simple and controllable

σ_{cc} and Glauber model

A microscopic reaction theory of high-energy collisions based on the eikonal approximation and on the bare nucleon-nucleon interaction **(also can be extended to intermediate energy)**

Glauber model within optical limit approximation

$$\sigma_{cc} = \int [1 - T_c(\mathbf{b})]\, d\mathbf{b}$$



transmission function for proton removal from the projectile at impact parameter b;

$$T_c(\mathbf{b}) = |\exp[i\chi(\mathbf{b})]|^2$$

$$\langle R_c^2 \rangle = \frac{\int d^3 r\, r^2 \rho_c(r)}{\int d^3 r\, \rho_c(r)}$$

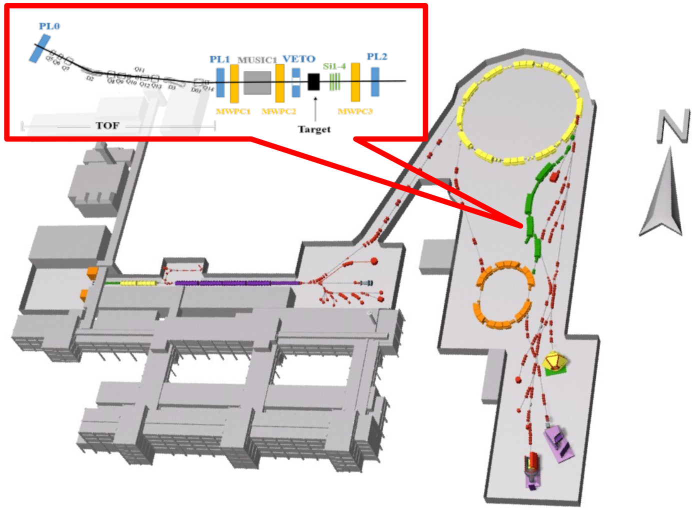
$$i\chi(\mathbf{b}) = \iint_P \iint_T \sum_i \left[\rho^z_{Pp}(\mathbf{s})\rho^z_{Ti}(\mathbf{t})\Gamma_{pi}(\mathbf{b}+\mathbf{s}-\mathbf{t})\right] d\mathbf{s}\, d\mathbf{t},$$

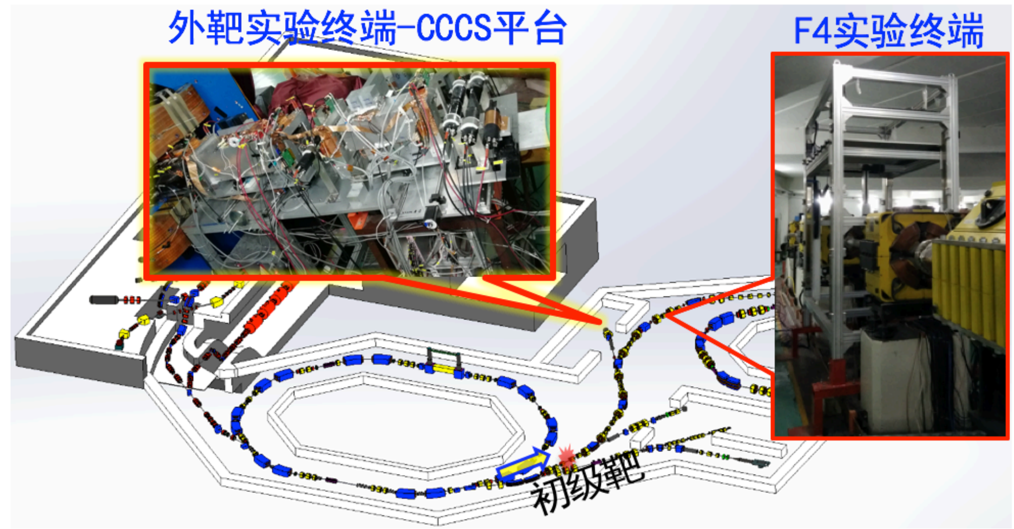
profile function

proton density of the projectile

densities of the proton and neutron

CCCS Experiments at GSI, HIRFL-CSR





GSI, 900 MeV/u

F.Wang, PhD thesis (2018)
Wang et al., in preparation (2018)

HIRFL-CSR, ~300 MeV/u

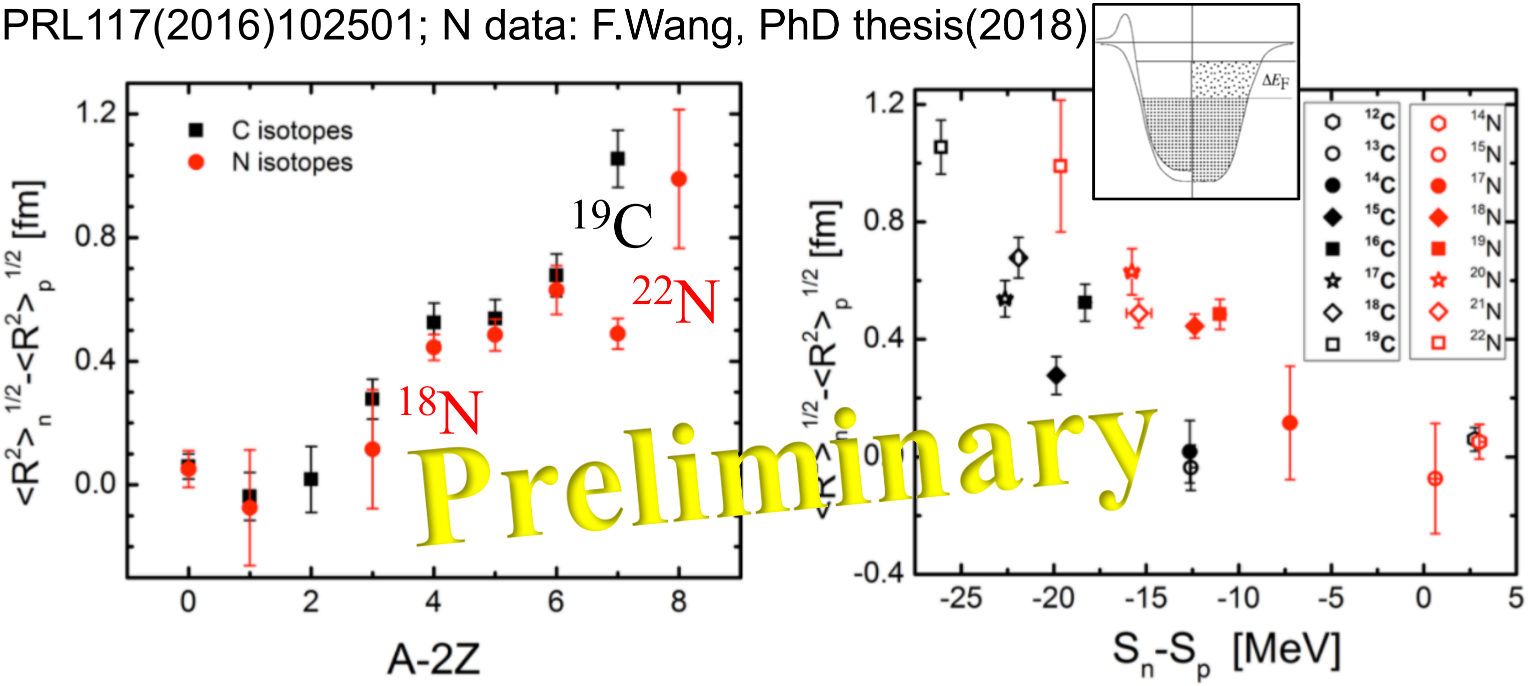
BHS et al., Sci. Bull. 63(2018)78
Zhao, BHS, Tanihata *et al.*, NIMA823(2016)41
Lin, Zhao, BHS *et al.*, CPC41(2017)066001

^{18}O, ^{22}Ne, ^{40}Ar primary beam → $^{14-22}$N isotopes

Preliminary results for $^{14-22}$N

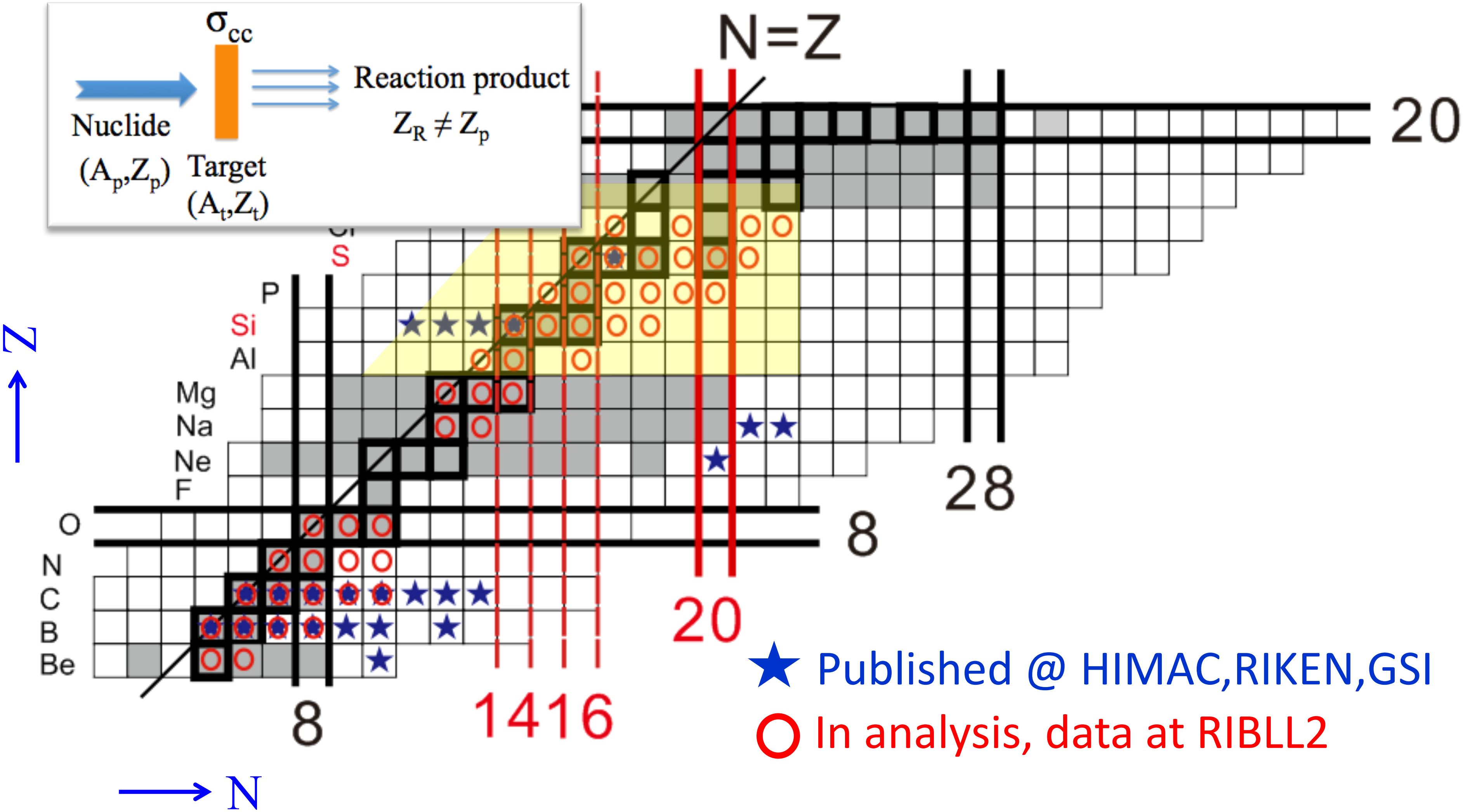
Combining the known σ_R and our σ_{cc} at energy ~900 MeV/u

C data: PRL117(2016)102501; N data: F.Wang, PhD thesis(2018)



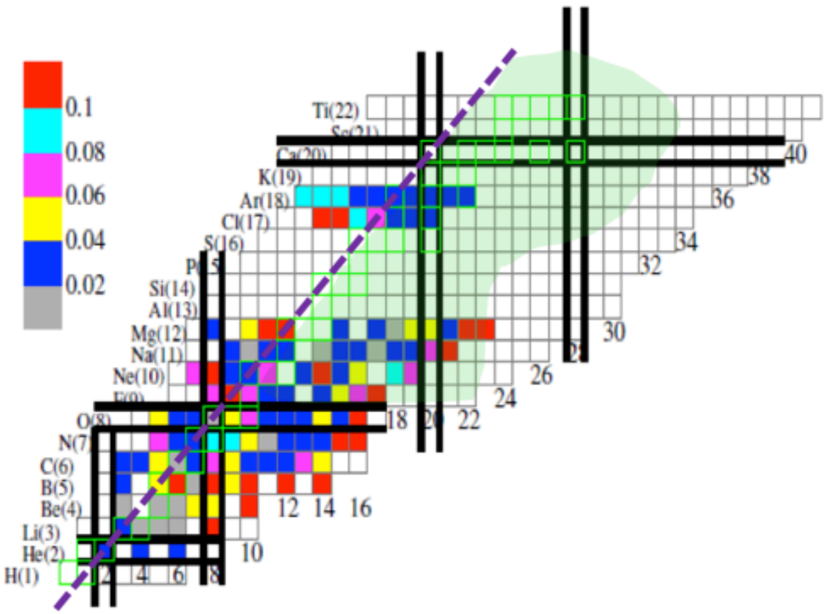
- A thick neutron surface evolves from ~0.5 fm in ^{18}N to ~1 fm in ^{22}N
- Typical uncertainty of down to a few percent (10%) is achievable
- Indication of halo structure: ^{19}C, ^{22}N
- strong correlation: points out a thick neutron skin (surface) being associated with the large Fermi-level difference of neutrons and protons

rms proton radii from CCCS (σ_{cc})

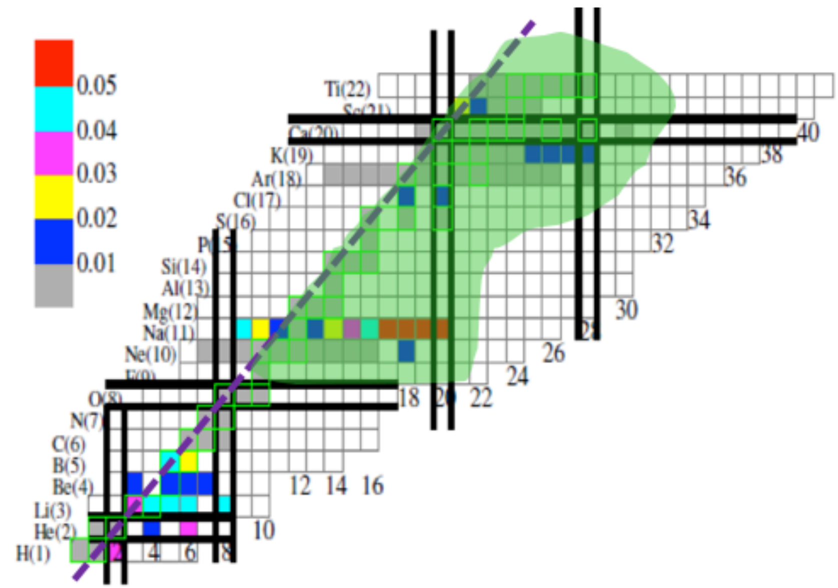


Towards heavier system

Matter radii



Proton radii

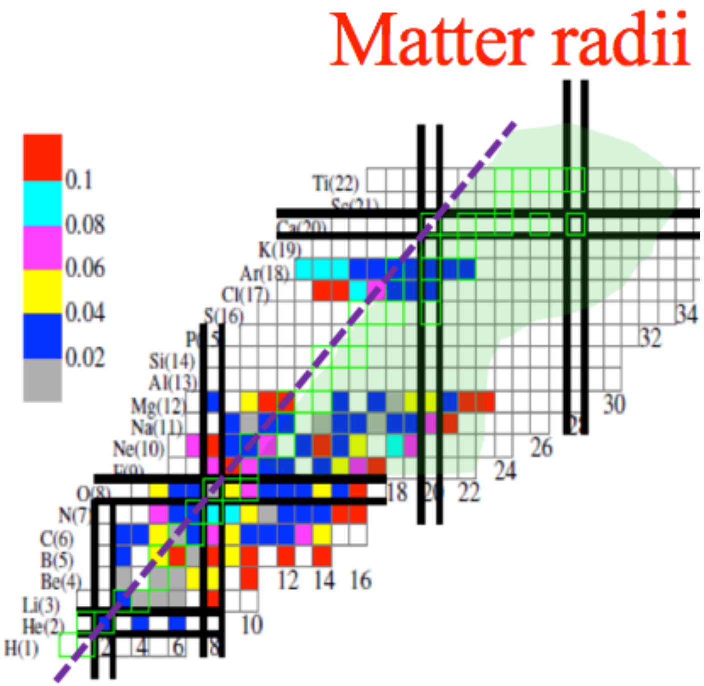


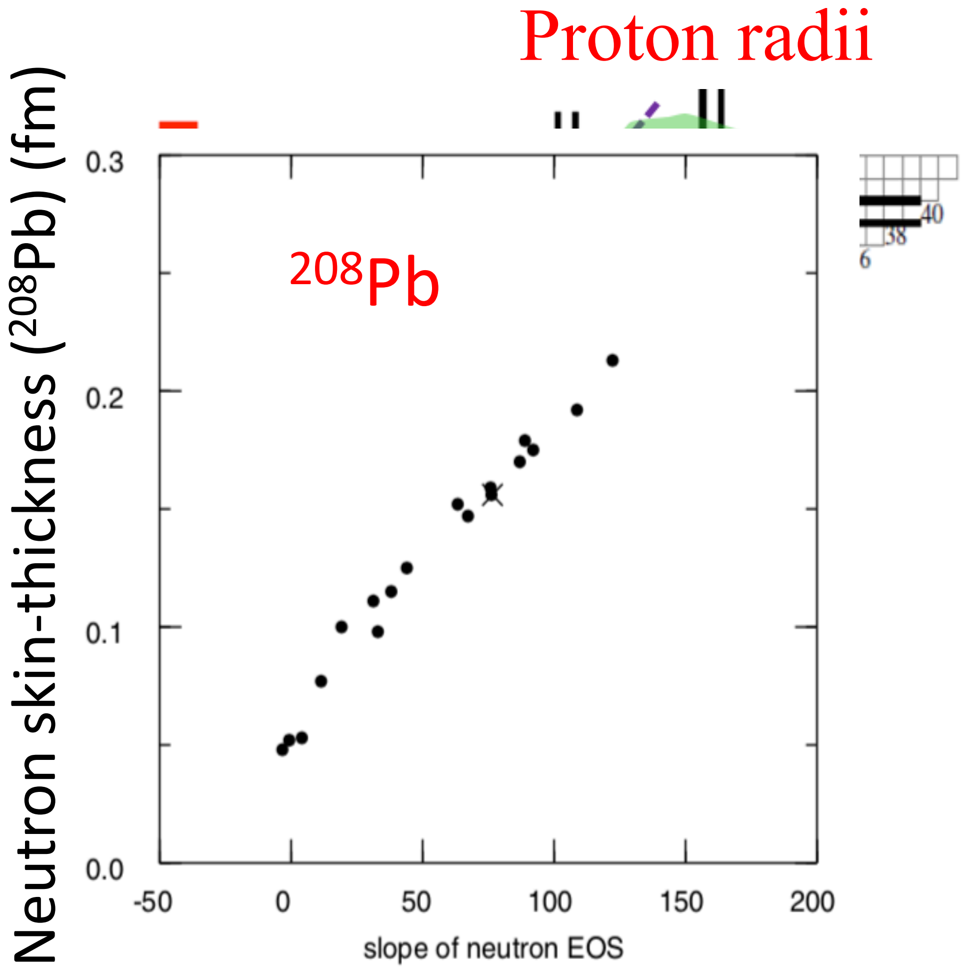
Ca/Ni isotopes: from stable to unstable nuclei

Questions:

- ☐ Can the relevant data help to understand EoS?
- ☐ How …

Towards heavier system





Questions:

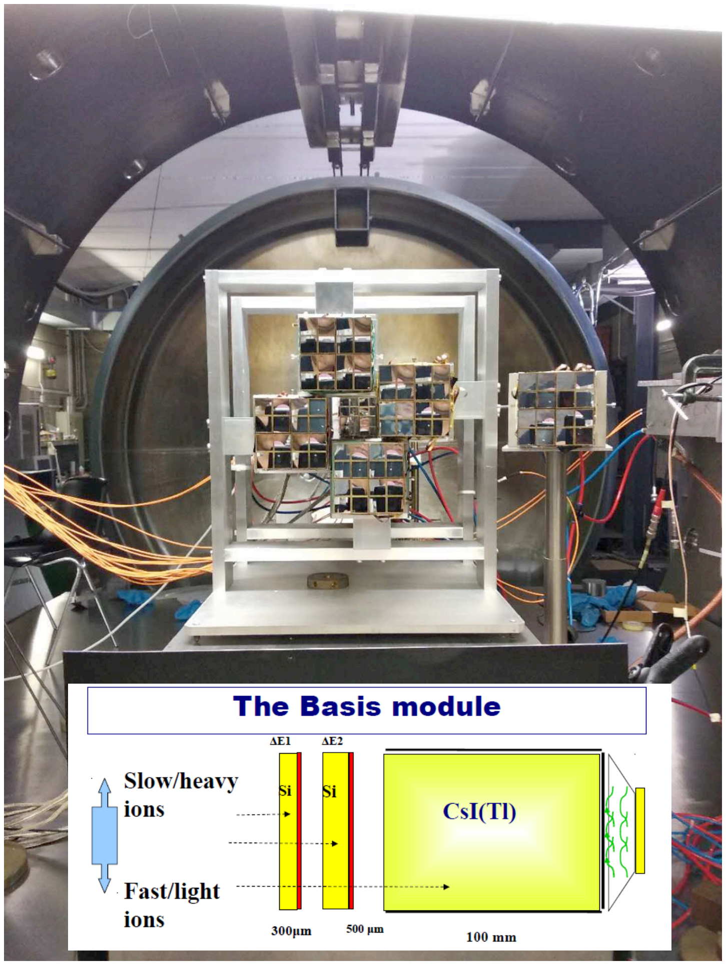
- ☐ Can the relevant data
- ☐ How …

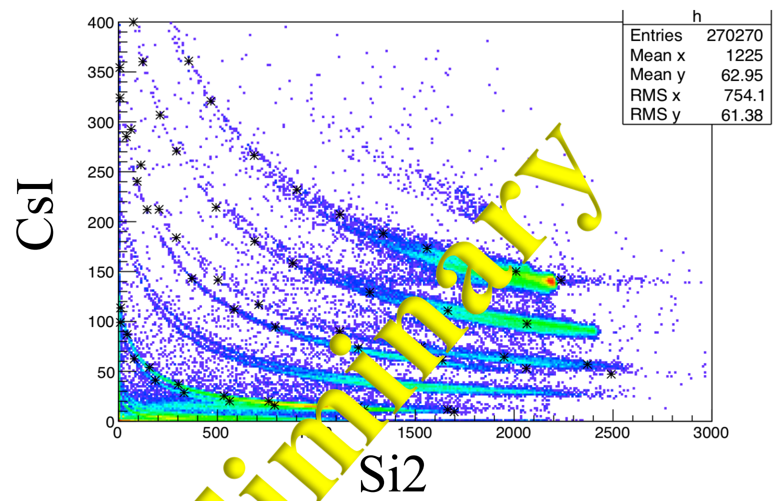
Brown, PRL85(2001)5276

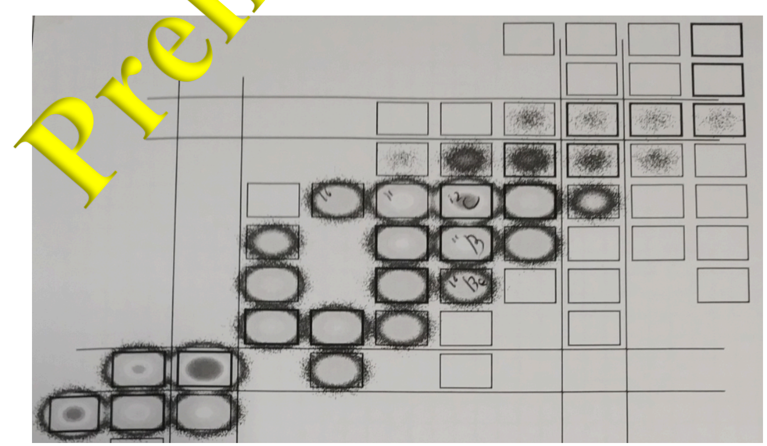
Reaction cross sections + FAZIA detector

^{12}C@60MeV/u+^{12}C → reaction cs, charge-changing cs,

total neutron-removal cs at the same time



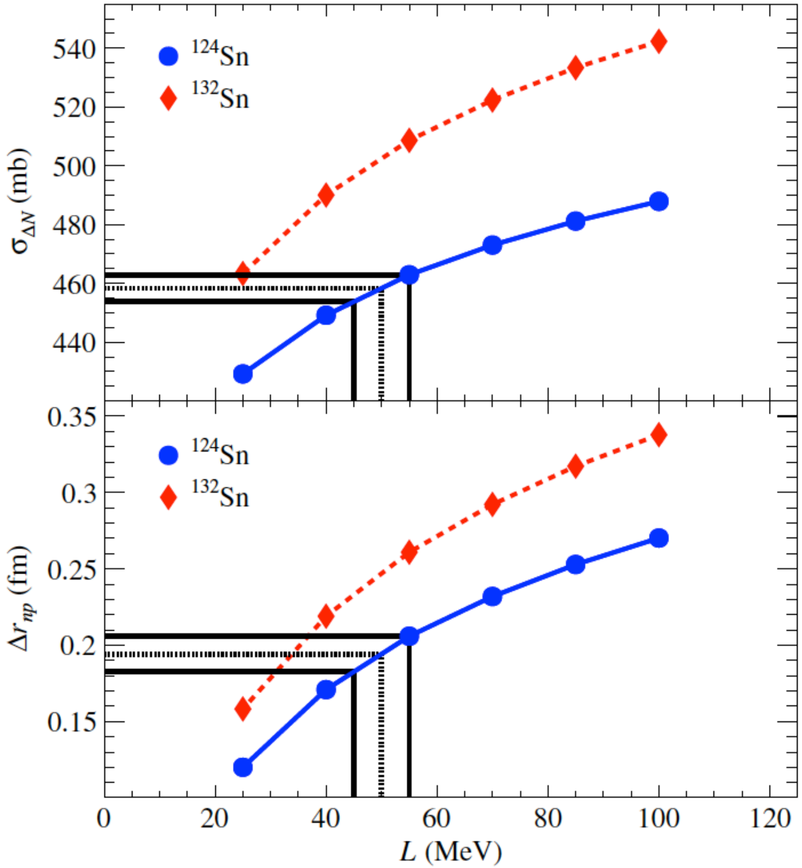




LNS Catania, July 18-20, 2018

Total neutron-removal cs

Constraints on the Symmetry Energy from Neutron-Removal Cross Sections



- Total reaction cross section
- Charge-changing cross section
- Total neutron-removal c.s.

Total neutron-removal cs may be a more sensitive probe than neutron-skin thickness

Aumann, Bertulani, Schindler, Typel, PRL119, 262501(2017)

Summary

- Reaction cross section, charge-changing cross section can be used to deduced neutron skin-thickness of short-lived nuclei with large N/Z.
- We have performed relevant experiments at different energies at GSI, HIRFL-CSR, LNS. A few percent accuracy (10%) for ΔR_{np} can be obtained.
- This method is in particular useful for a systematic studies, to reveal the evolution of neutron surface along isotopic chains, which can be used to constrain nuclear models.
- Towards to medium-heavy system with large neutron excess, e.g., Ca, Ni isotopes
- Practically, how to use such data to constrain EoS ?

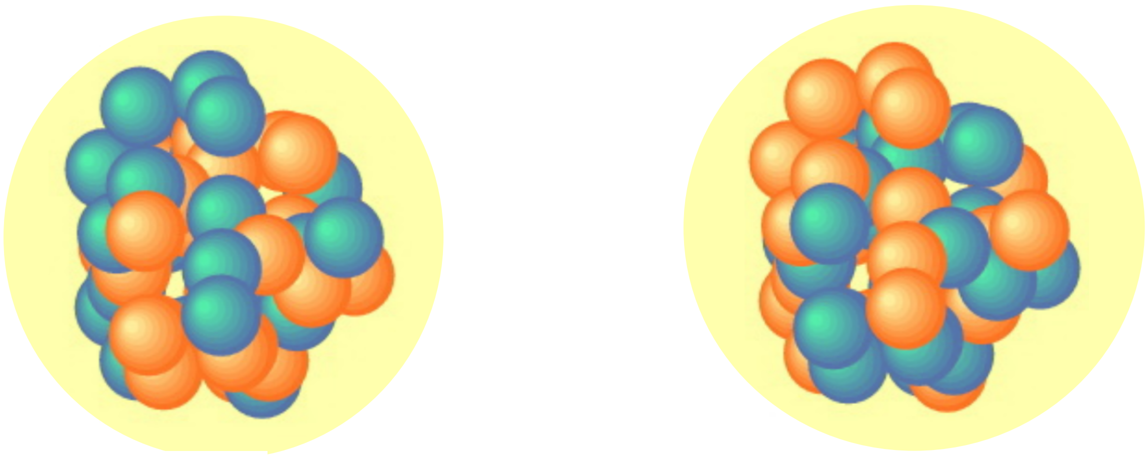
A small international workshop on nuclear radii of exotic nuclei will be hold at Beihang Univ. (Beijing), around 10-20 December, 2018.
It will focus on different experimental details, challenges and possible impact to other topics

You are highly welcome to join if you are interested.

Thank you very much for your attention!

Mirror nuclei as a laboratory

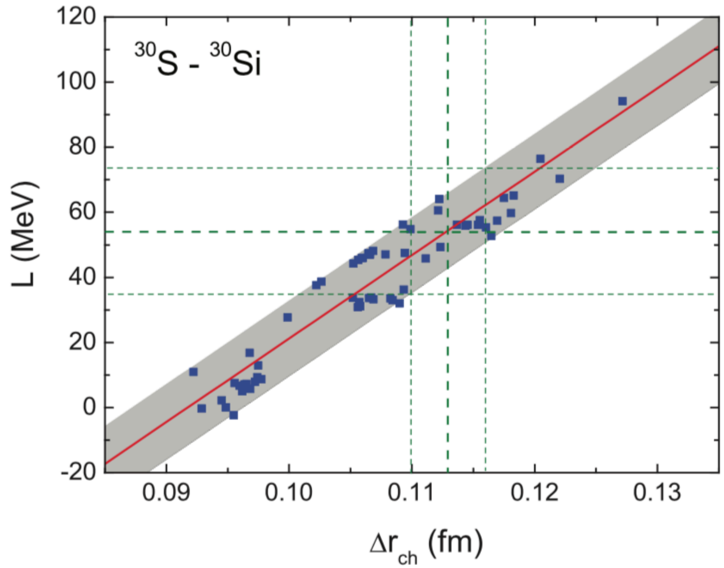
Mirror nuclei are those with the same atomic number but with the numbers of protons and neutrons interchanged.



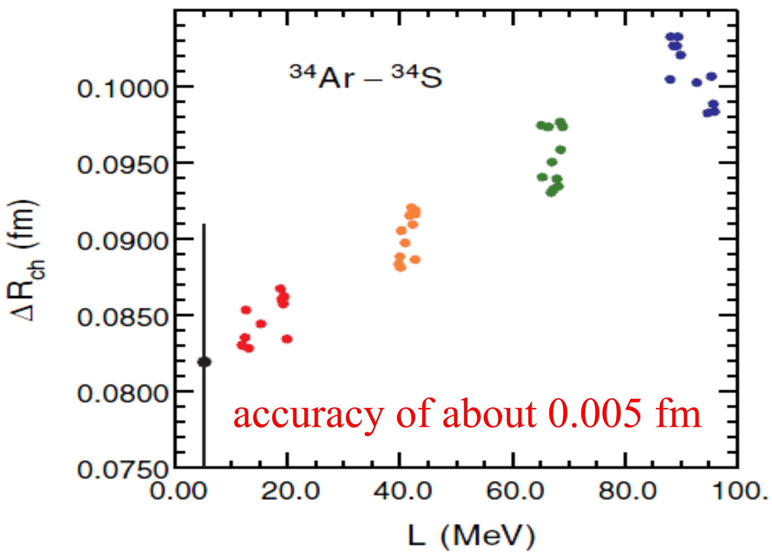
$^{A}_{Z}\mathrm{X}_{N}$ $\quad$ $^{A}_{N}Y_{Z}$

Due to the isospin symmetry of the nuclear forces, the properties of these two nuclei are nearly identical except that the protons (red) and neutrons (blue) are interchanged.

Mirror nuclei as a laboratory



Wang & Li, Phys. Rev. C **88**, 011301(R) (2013)

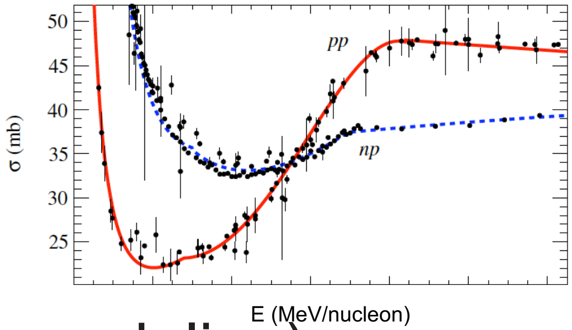


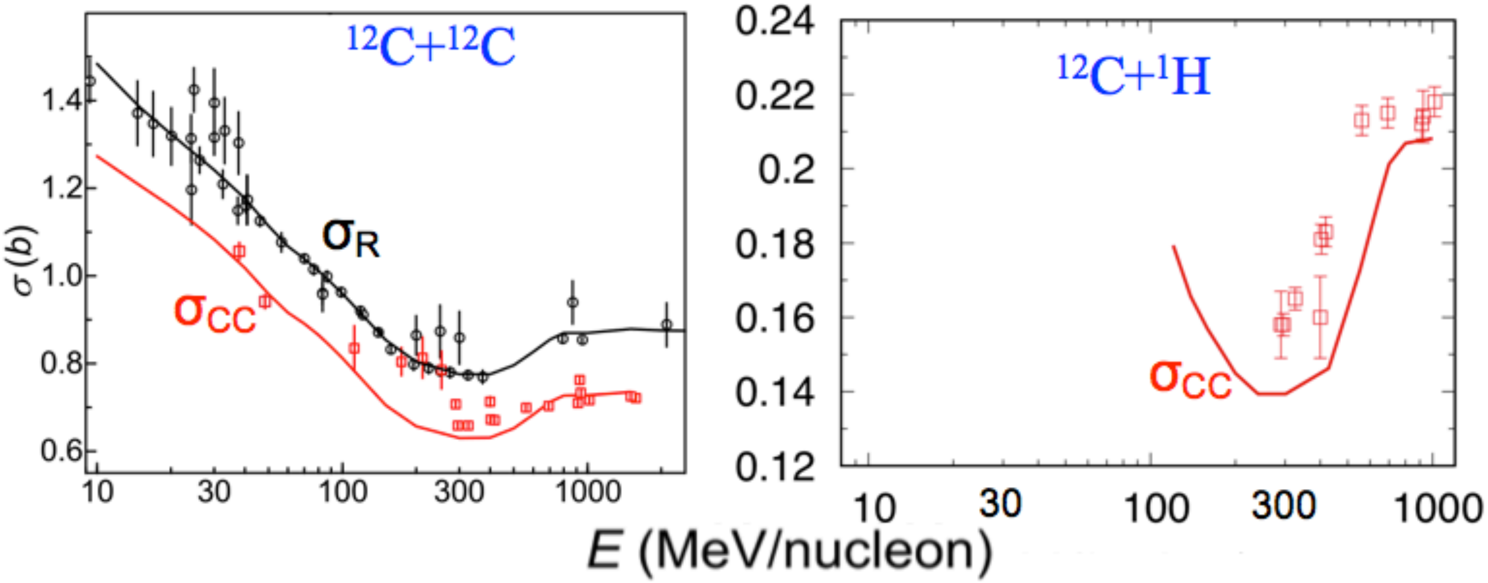
Brown, PRL 119, 122502(2017)
Yang & Piekarewicz, PRC97,014314(2018)

- The differences in the charge radii of mirror nuclei are shown to be proportional to the derivative of the symmetry energy *L* at nuclear matter saturation density.
- … the experimental uncertainty for the rms charge radius measurement is much smaller than that for the rms neutron radius, precise measurements of the rms charge radii for the pair of mirror nuclei, especially the unmeasured , could be very helpful for the extraction of the slope parameter.

Energy dependent

- ^{18}O beam @ 450 MeV/u + Be → ^{12}C
- ☐ Different primary beam energies
- ☐ C/H/Pb target: σ_{pp}, σ_{np}; $\sigma_{cc}(C)/\sigma_{cc}(H)$
- ☐ Different C/H target thicknesses (verify modeling)





Reaction mechanism?