Proton radius of ^{14}Be from measurement of charge changing cross sections

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Radii of nucleon distributions in nuclei (proton, neutron, nucleon)

- **They provide basic information on the structure of nuclei**
- **In particular the difference of proton and neutron radii are important in halo and neutron skin nuclei**
  - ***Decoupling of protons and neutrons in nuclei***
  - ***Movements of a core and a halo, correlation between halo neutrons, core modification, ...***
  - ***EOS of the asymmetric nuclear matter***
  - ***...***

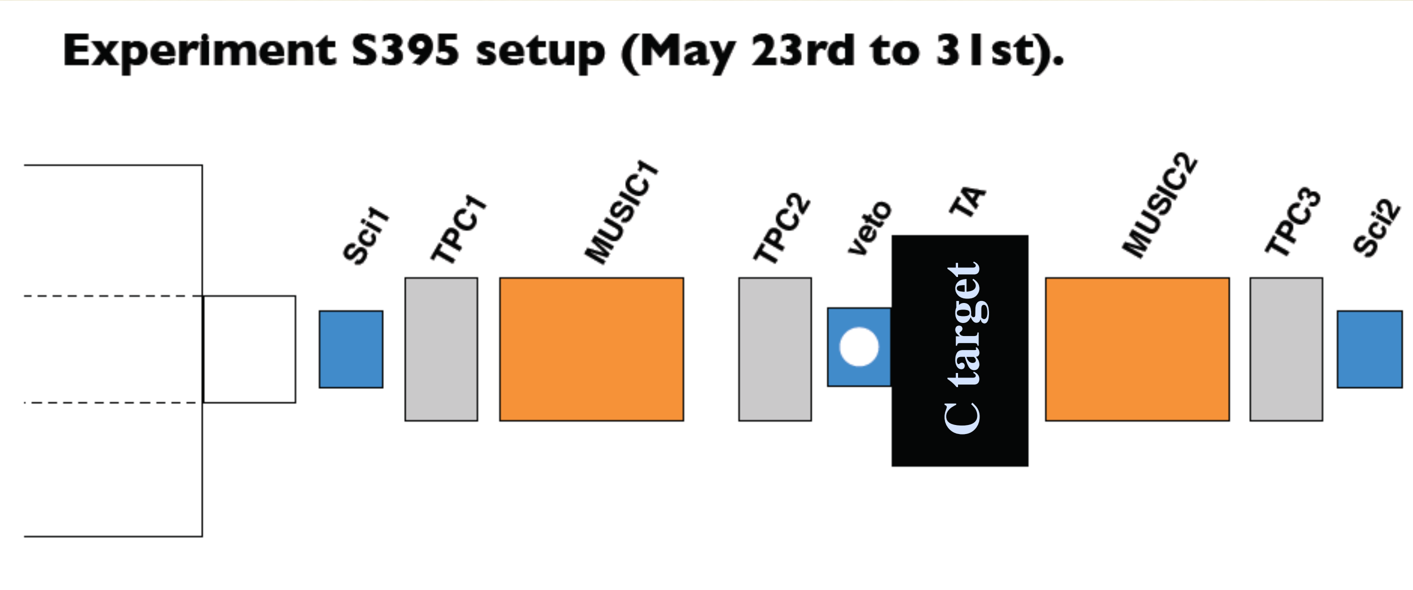
Recent Developments in Proton Radii of Light Nuclei

- **A great progress has been made in determination of charge radii of He, Li, and Be isotopes by isotope-shift measurements.**
  - ^{6}He: L. -B. Wang et al., Phys. Rev. Letters **93** (2004) 142501. @ANL
  - ^{8}He: P. Mueller et al., Phys. Rev. Letters **99** (2007) 252501. @GANIL with ANL group
  - ^{6,8,9}Li: G. Ewald et al., Phys. Rev. Letters **93** (2004) 113002. @ GSI
  - ^{6,8,9,11}Li: R. Sánchez et al., Phys. Rev. Letters **96** (2006) 033002. @TRIUMF with GSI group
  - ^{7,9,10,11}Be: W. D. Nörtershäuser., Phys. Rev. Letters **102** (2009) 062503. @GSI
  - Development of atomic structure calculation up to three-electron system.
  - G. W. F. Drake Nucl. Phys. **A737c**, 25 (2004), Z. C. Yan et al., Phys. Rev. Letters **100** (2008) 243002.
- **Proton radii measurements by charge changing cross sections (σ_{cc})**
  - B-F isotopes: Chulkov et al; Nucl. Phys A674 (2000) 330.
  - ^{9,10,11}Be, ^{14,15,16}C, ^{16,17,18}O isotopes: Phys. Rev. Lett. 107 (2011) 032502.

Proton radii of Be isotopes except ^{14}Be has been determined but ^{14}Be (2-n halo nucleus) is not known!

σ_{cc} Measurements of ^{7,9,10,11,12,14}B

GSI
790*A* MeV



N_{inc}= No. of the incident nuclei
N_{ncc}= No. of the out going nuclei without charge change

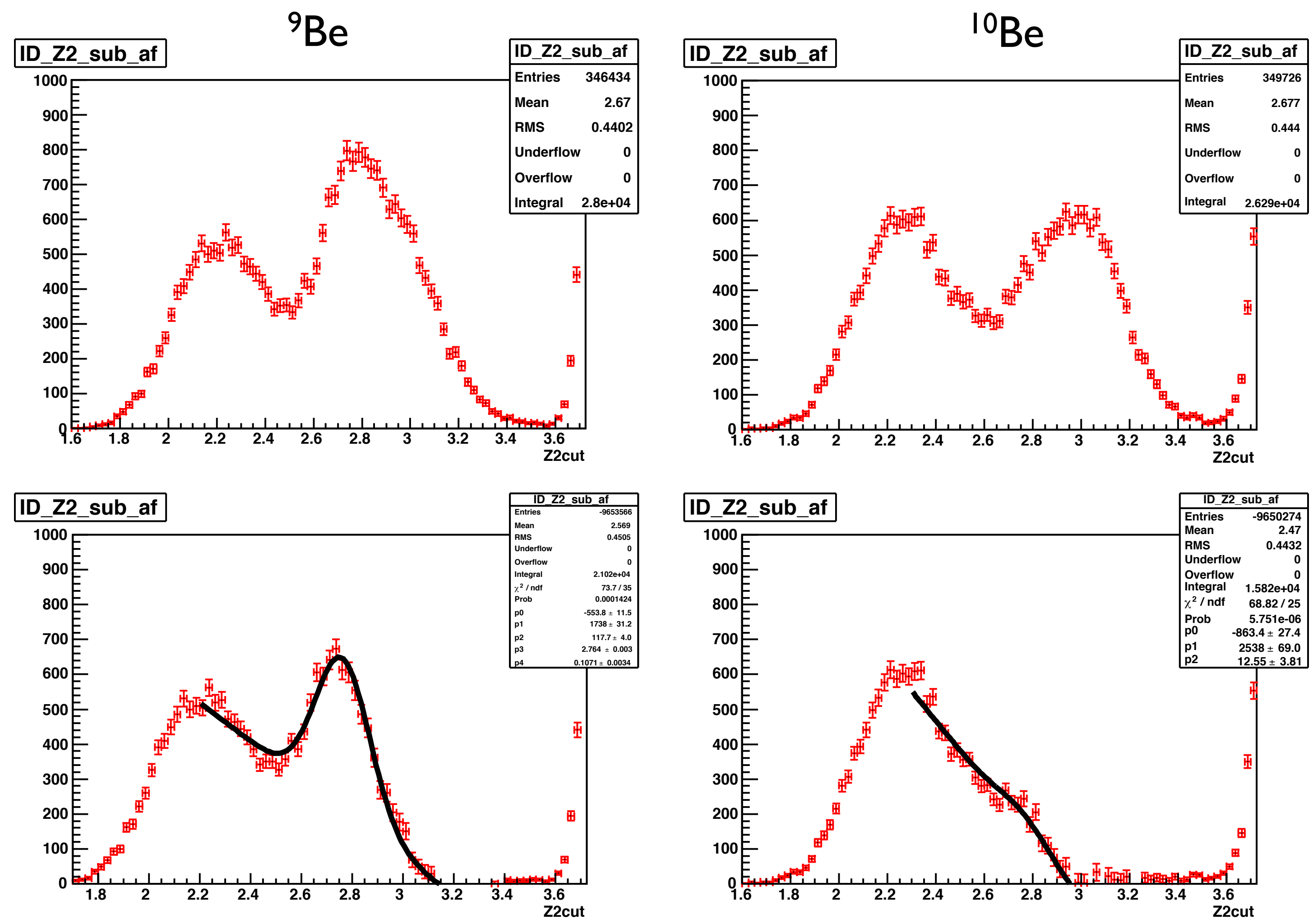
$\gamma=N_{ncc}/N_{inc}$ with target
$\gamma_0=N_{0ncc}/N_{0inc}$ without target

$$\sigma_{cc} = \frac{1}{t}\ln\frac{N_{0ncc}/N_{0inc}}{N_{ncc}/N_{inc}} \equiv \frac{1}{t}\ln\frac{\gamma_0}{\gamma}$$

Necessary collections for discussion of proton radii

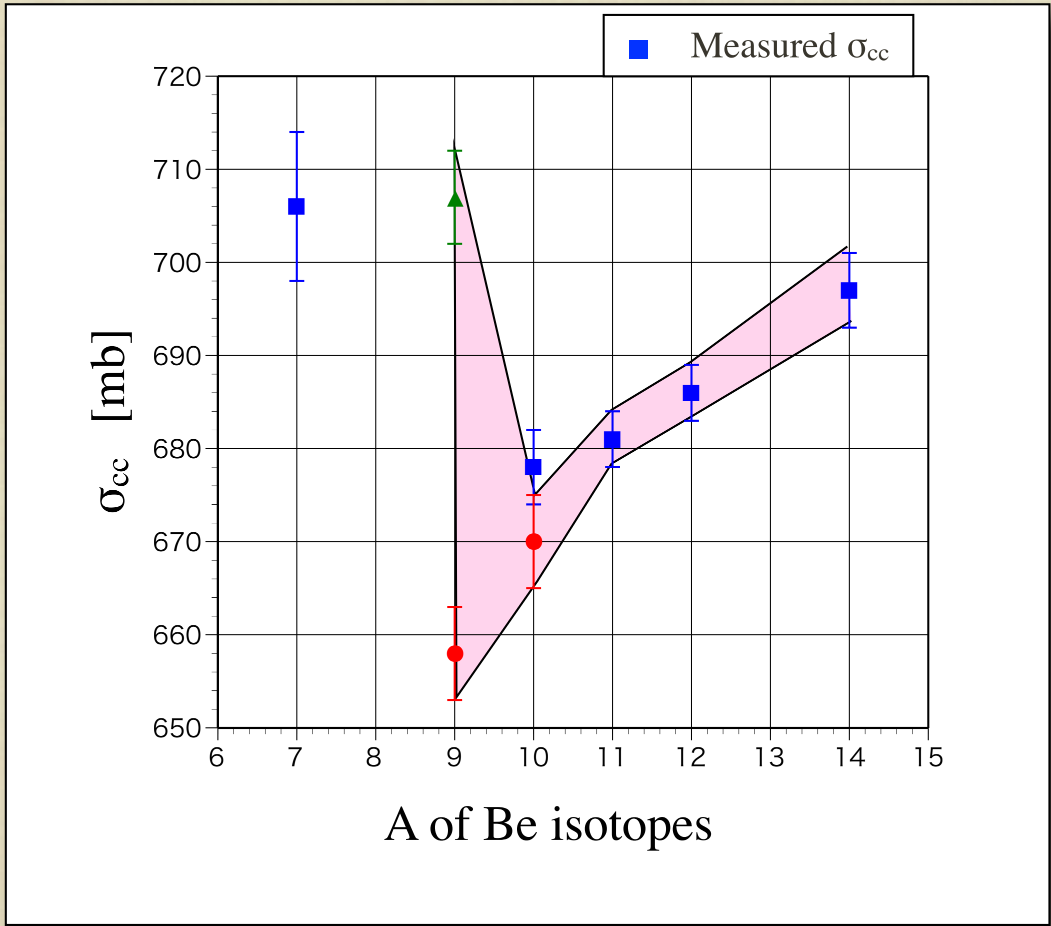
- When ^{8}Be is produced with only neutron removal, it is observed as charge changing because of the immediate decay of ^{8}Be to 2α.
- This cross section has to be removed from the observed charge changing cross section before the radii discussion.
- For ^{7}Be, any removal of neutron makes the change of proton number because it is a proton drip line nucleus. Therefore $\sigma_{cc} = \sigma_R$ and proton radii can not be determined from σ_{cc}.

Effects of 2a in ΔE spectra

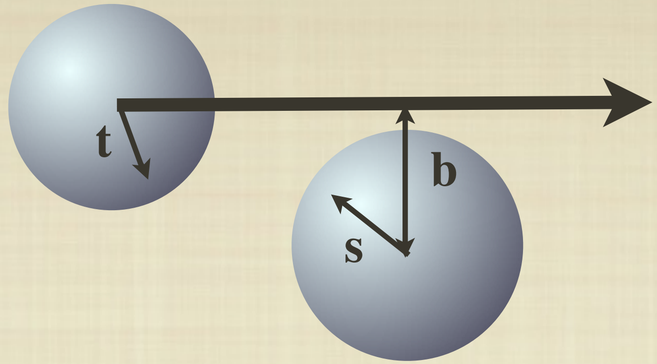


■ 757 ±4 mb

Determined σcc for Be isotopes



Glauber model for σ_I and σ_{cc}



Optical limit Calculation

$$\sigma_R = \iint \left[1 - T_R(\mathbf{b})\right] d\mathbf{b}$$

$$T_R(\mathbf{b}) = \left|\exp[i\chi_R(\mathbf{b})]\right|^2$$:Transmission function(probability not to have reaction)

$$i\chi_R(\mathbf{b}) = \iint_P \iint_T \sum_{i,j} \left[\rho_{Pj}^z(\mathbf{s})\rho_{Ti}^z(\mathbf{t})\Gamma_{ji}(\mathbf{b}+\mathbf{s}-\mathbf{t})\right] d\mathbf{s}d\mathbf{t}$$

(P,T): p-p, p-n, n-p, n-n

$$\rho_{Pi}^z(\mathbf{s}) = \int_{-\infty}^{\infty} \rho_{Pi}\left(\sqrt{\mathbf{s}^2 + z^2}\right) dz$$

$$\Gamma_{ik}(\mathbf{b}) = \frac{1 - i\alpha_{ik}}{4\pi\beta_{ik}^2}\sigma_{ik} \exp\left(-\frac{\mathbf{b}^2}{2\beta_{ik}^2}\right)$$

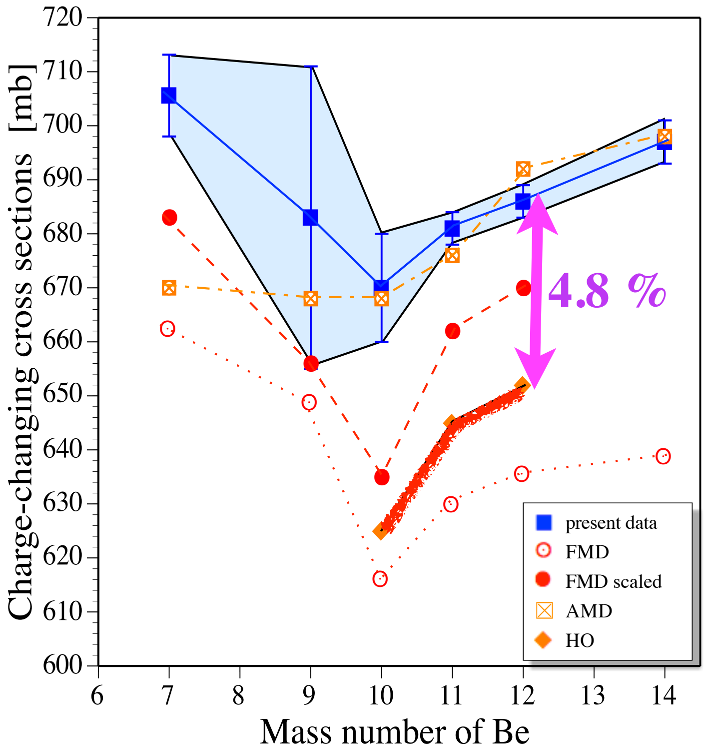
$$\sigma_{cc} = \iint \left[1 - T_c(\mathbf{b})\right] d\mathbf{b}$$

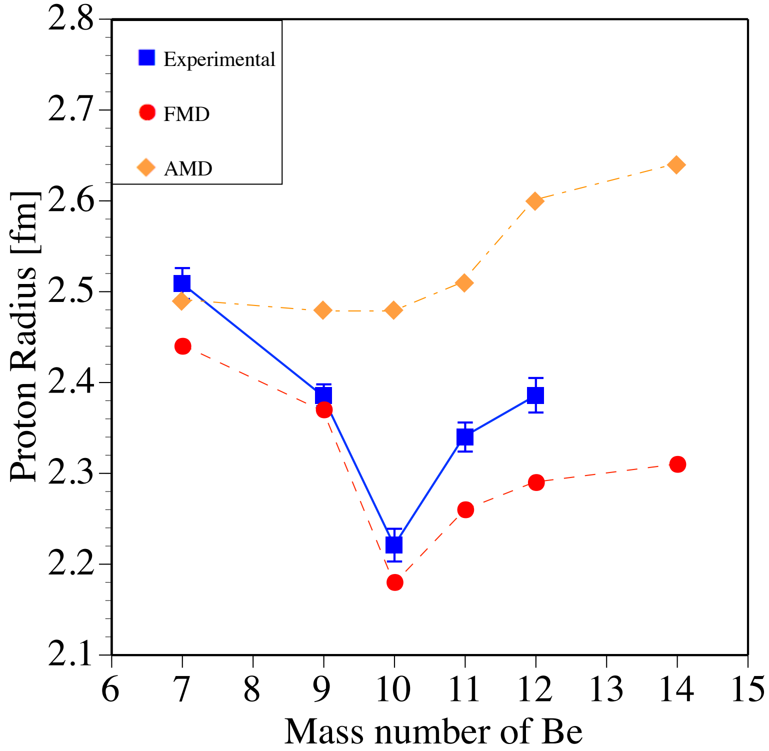
$$T_c(\mathbf{b}) = \left|\exp[i\chi_c(\mathbf{b})]\right|^2$$

$$i\chi_c(\mathbf{b}) = \iint_P \iint_T \sum_{i} \left[\rho_{Pp}^z(\mathbf{s})\rho_{Ti}^z(\mathbf{t})\Gamma_{pi}(\mathbf{b}+\mathbf{s}-\mathbf{t})\right] d\mathbf{s}d\mathbf{t}$$

(P,T): p-p, p-n~~, n-p, n-n~~

Comparison with models



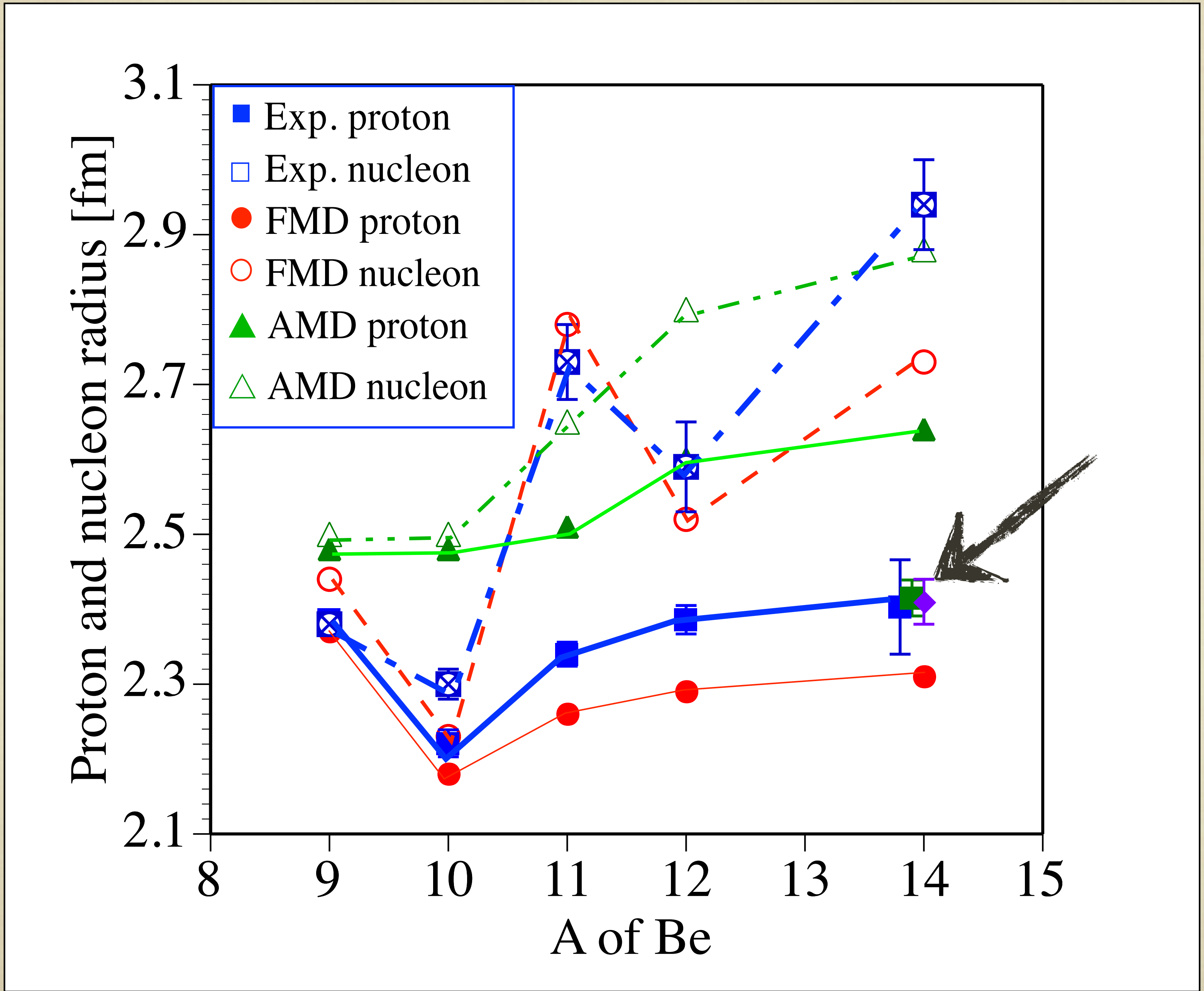


σ_I can be reproduced by the Glauber model if we know the proton radii within 5 % discrepancies.
All isotopes σ_I can be reproduced introducing one common factor ~1.05.

Proton radius of ^{14}Be

- The Glauber model provide the σ_{cc} with known proton radii.
- Assume harmonic oscillator density distribution as model density.
- Fit the observed σ_{cc} by adjusting the size parameter of the density distribution.

^{14}Be proton radius (Results)



Effect of neutrons in the projectile

(P,T): p-p, p-n~~, n-p, n-n~~

$$\sigma_{cc} = \iint \left[1 - T_c(\mathbf{b})\right] d\mathbf{b}$$

$$T_p(\mathbf{b}) \equiv T_c(\mathbf{b}) = \left|\exp[i\chi_c(\mathbf{b})]\right|^2$$ **:Probability of protons are intact.**

$$i\chi_c(\mathbf{b}) = \iint_P \iint_T \sum_i \left[\rho_{Pp}^z(\mathbf{s})\rho_{Ti}^z(\mathbf{t})\Gamma_{pi}(\mathbf{b}+\mathbf{s}-\mathbf{t})\right] d\mathbf{s}d\mathbf{t}$$

$$T_n(\mathbf{b}) = \left|\exp[i\chi_n(\mathbf{b})]\right|^2 \qquad i\chi_n(\mathbf{b}) = \iint_P \iint_T \sum_i \left[\rho_{Pn}^z(\mathbf{s})\rho_{Ti}^z(\mathbf{t})\Gamma_{ni}(\mathbf{b}+\mathbf{s}-\mathbf{t})\right] d\mathbf{s}d\mathbf{t}$$

$$T_I(\mathbf{b}) = T_p(\mathbf{b}) \bullet T_n(\mathbf{b})$$

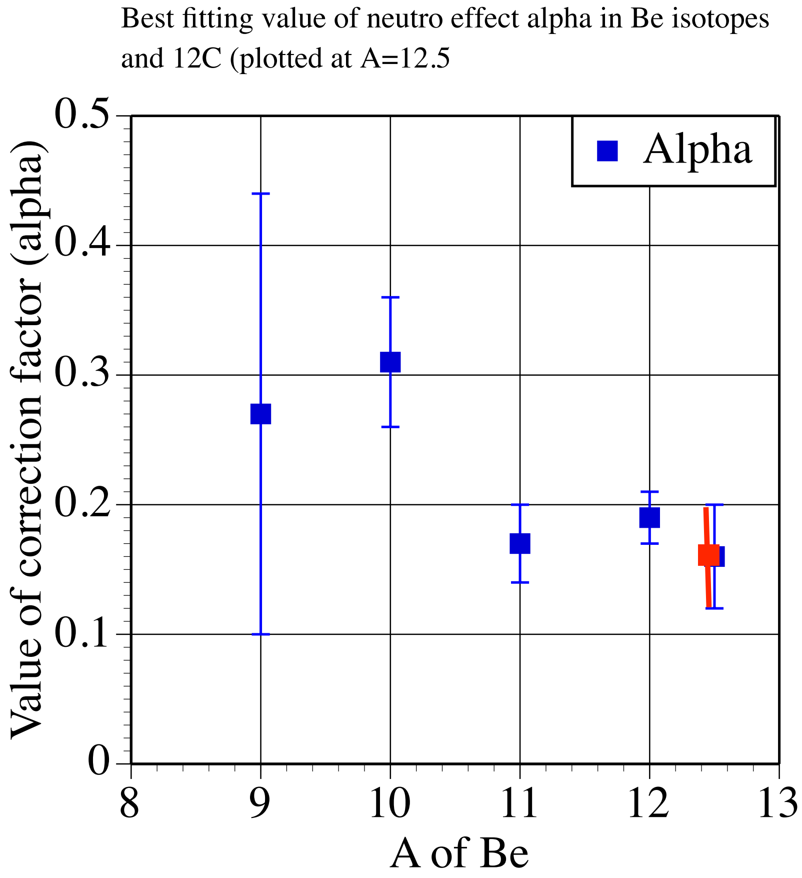
$$T_{no}(\mathbf{b}) = \left[1 - T_n(\mathbf{b})\right] \bullet T_p(\mathbf{b})$$:Probability hitting projectile neutron(s) without hitting proton(s)

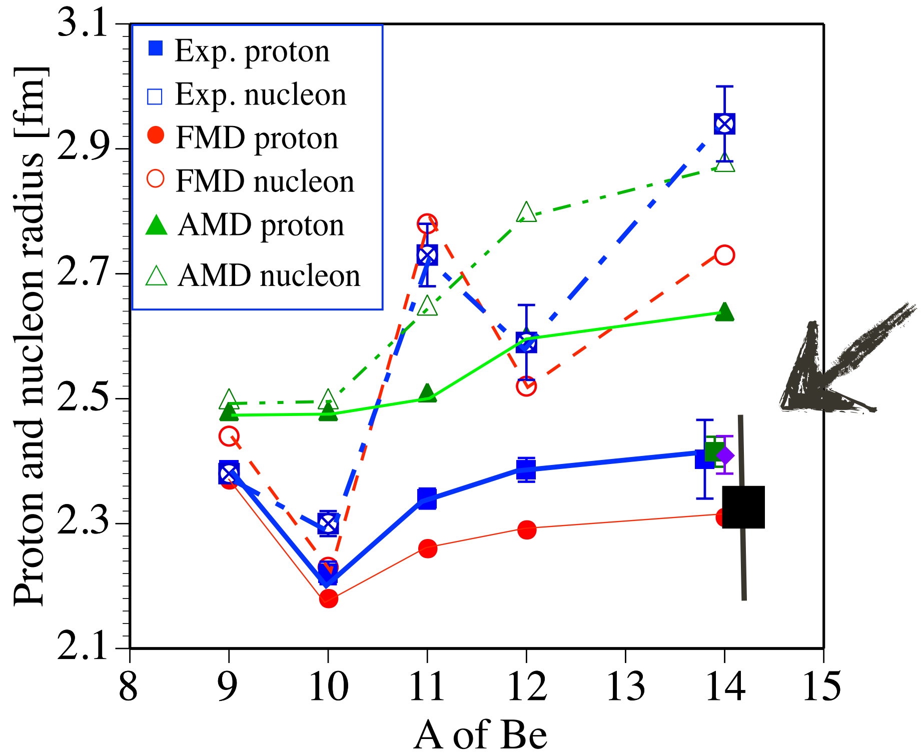
$$1 - T_I(\mathbf{b}) = \left[1 - T_p(\mathbf{b})\right] + \left[1 - T_n(\mathbf{b})\right] \bullet T_p(\mathbf{b})$$

Proton removal — "Neutron only" removal

$$\sigma_{cc}^{improved} = \iint \left[1 - T_p(\mathbf{b})\right] + \alpha\left[1 - T_n(\mathbf{b})\right] \bullet T_p(\mathbf{b}) d\mathbf{b}$$

Alpha does not change for different isotopes





SUMMARY

- Proton radius of ^{14}Be has been determined from measurement of charge changing cross sections at 900*A* MeV
- With a Glauber model analysis applying the scaling of the cross section, $<r_p^2>^{1/2}$ = 2.41±0.04 fm has been obtained.
- With another Glauber model that include a influence of neutron scatterings, $<<r_p^2>^{1/2}$ = 2.32±0.14 has been obtained.