Symposium on Nuclear Structure, Reaction, and Astrophysics
(NuSRAP2026)

Proton elastic scattering from ^{132}Sn at intermediate energy for deducing the density distribution

Yuto Hijikata
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July 15, 2026

Paper and collaborators

Paper

YH, J. Zenihiro, et al., Prog. Theor. Exp. Phys. **2026**, 013D02 (2026).

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Outline

- Introduction
  - Nuclear matter EoS and Neutron skin thickness
  - Measurements of neutron skin thickness
  - Proton elastic scattering at intermediate energy
- Experiment, data reduction, and result
  - Proton elastic scattering from ^{132}Sn at 200 MeV/u in inverse kinematics @ RIBF
- Structure analysis with reaction model
  - Relativistic impulse approximation
- Compare the experimental result with structure calculation
  - Ab-initio calculation using χ-EFT interactions
- Summary

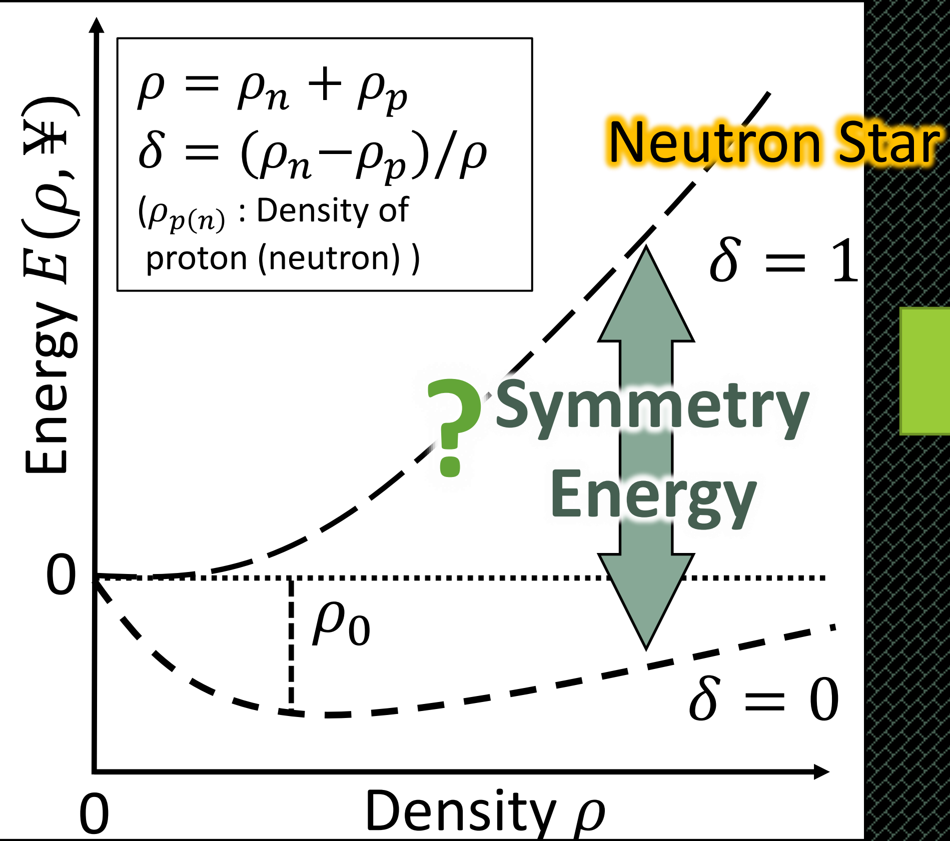
Symmetry Energy and Neutron skin

Infinite system : Nuclear matter Equation of State (EOS)

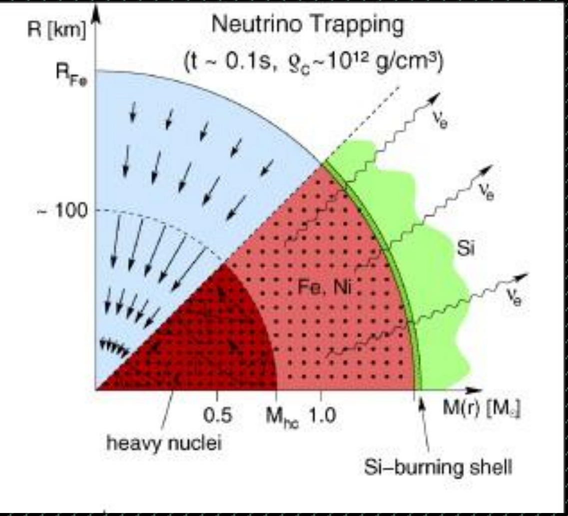
$E(\rho,\delta) = E(\rho,0) + S(\rho)\delta^2 + O(\delta^4)$

Symmetry Energy $S(\rho)$ <- Not determined precisely

$S(\rho) = J + L * \varepsilon + \frac{K_{\mathrm{sym}}}{2} * \varepsilon^2 + \cdots \quad (\varepsilon = \frac{\rho-\rho_0}{3\rho_0})$

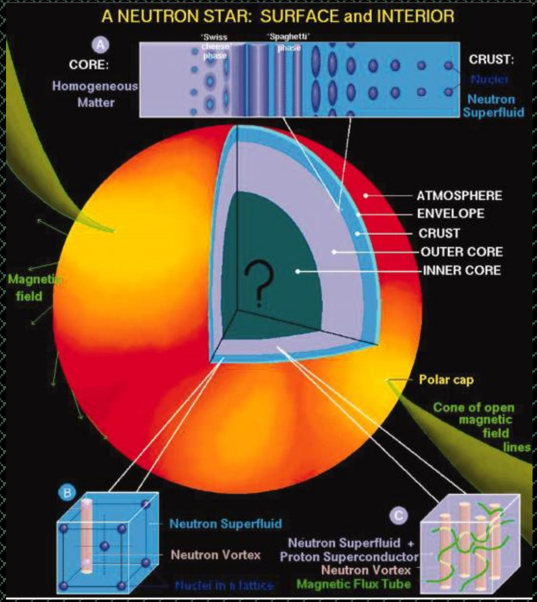


Supernova



H.Th. Janka, et al., Phys. Rep., 442, 1, (2007).

Neutron star



J. M. Lattimer and M. Prakash, Science 304, 536 (2004).

Neutron star merger

LIGO and Virgo Collaboration, PRL 119, 161101 (2017)

Symmetry Energy and Neutron skin

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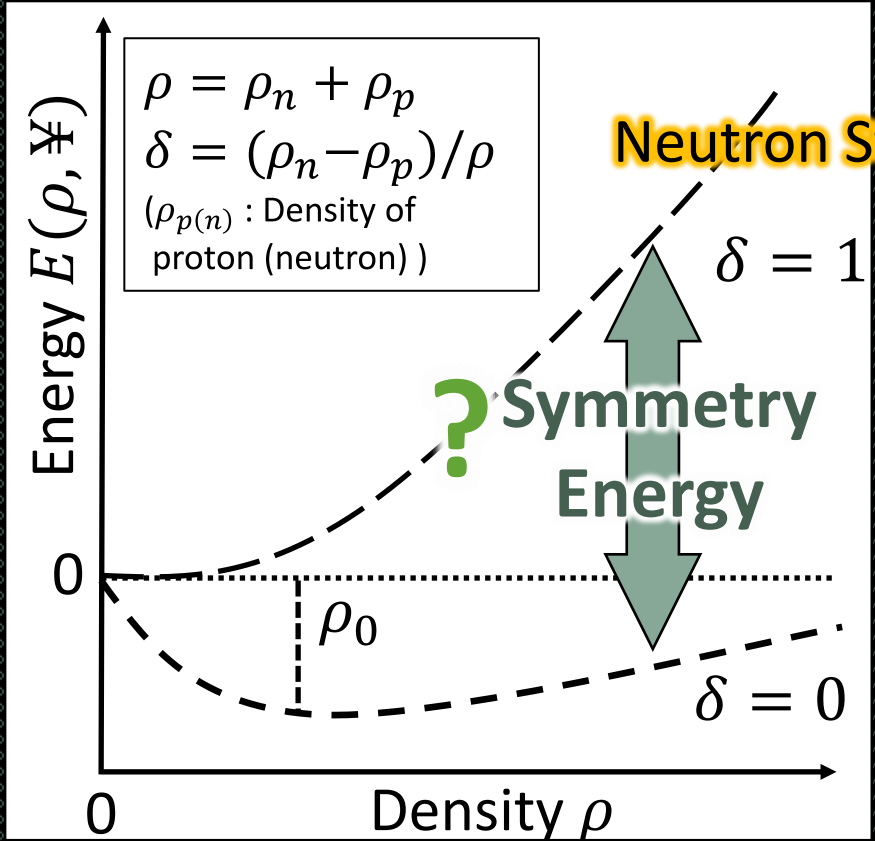
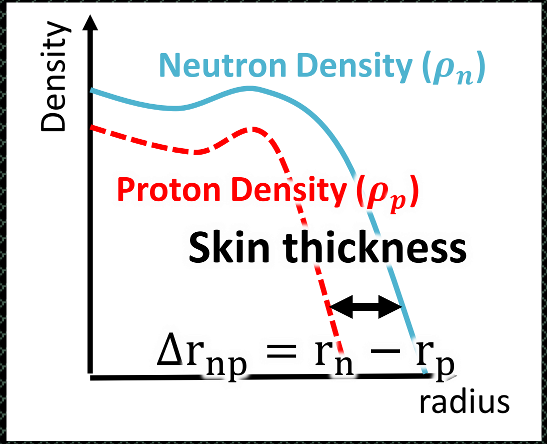


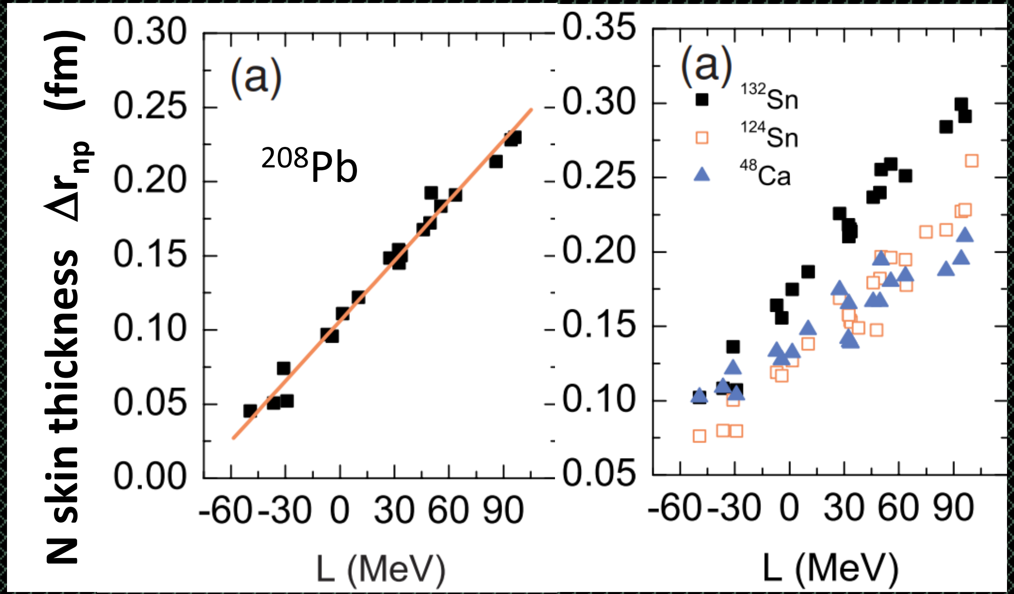
Strong correlation

Finite system : Nucleus

Neutron Skin structure of heavy neutron-rich nuclei, especially doubly magic nuclei (^{208}Pb, ^{48}Ca, ^{132}Sn, etc)

- Balance between small ρ <-> small δ

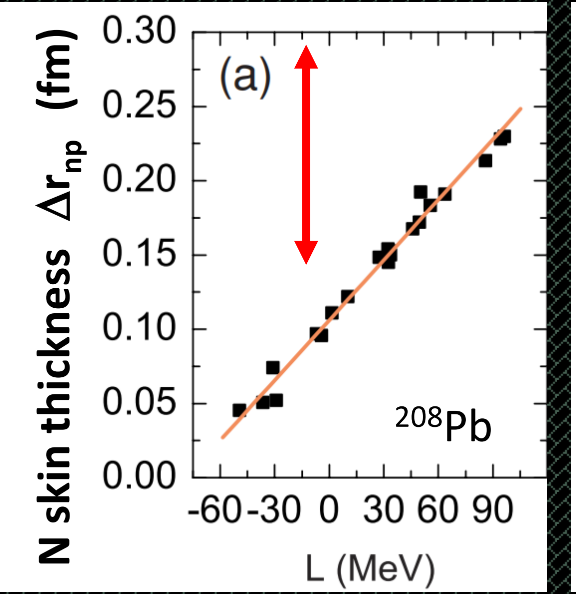




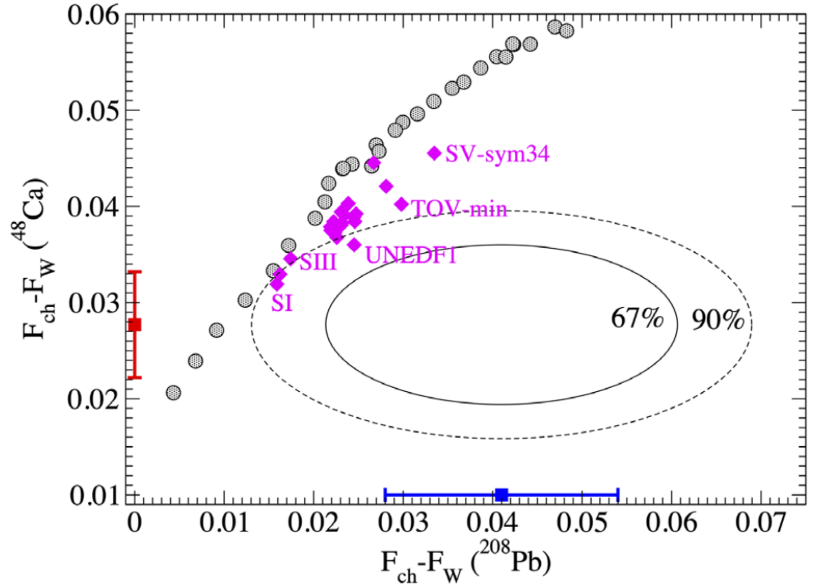
L.-W. Chen et al., PRC 72, 064309 (2005).

Methods of measuring N skin thickness

- Hadronic probe
  - Proton elastic scattering (This work)
  - Reaction・Interaction cross sections
    - A few cps beam
      -> RI, Systematic measurement
- Parity-violating electron scattering
  - PREX (^{208}Pb), CREX (^{48}Ca) @J-Lab
  - Clean reaction frameworks
  - Very small statistics, only one momentum-transfer point
  - PREX-CREX puzzle
- Coulomb excitation
  - Electric dipole polarizability (α_D)
  - Pygmy dipole resonance (PDR)
  - Model dependence



PREX-CREX puzzle



Adhikari, at al., Phys. Rev. Lett. 129, 042501 (2022).

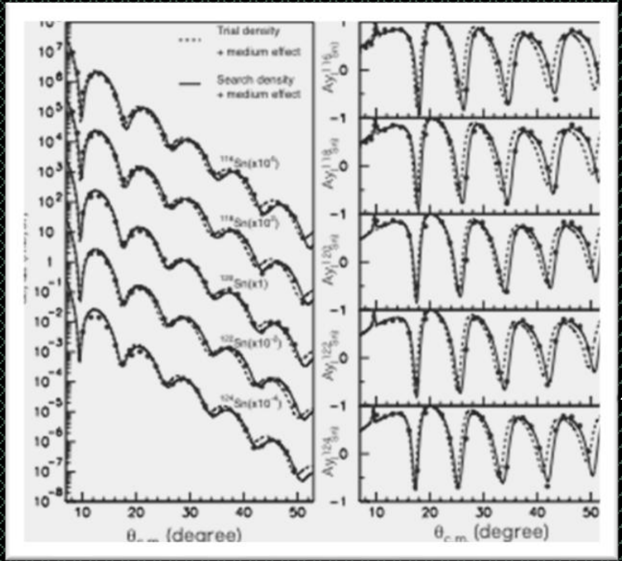
^{208}Pb neutron skin

Experiment	Δr_{np} of ^{208}Pb [fm]	model error
^{208}Pb(p,p) [18]	$0.211^{+0.054}_{-0.063}$	○
PREX-II [8]	0.283(71)	○
α_D [10]	$0.156^{+0.025}_{-0.021}$	×
PDR [11]	0.180(35)	×
$\bar{p}$-atom X-ray I [13]	$0.16(2)_{\rm stat}(4)_{\rm syst}$	○
$\bar{p}$-atom X-ray II [14]	$0.20(4)_{\rm exp}(5)_{\rm mdl}$	○
Coherent π^0 photoprodocution [15]	$0.15^{+0.03}_{-0.04}$	×

Proton elastic scattering at 300 MeV

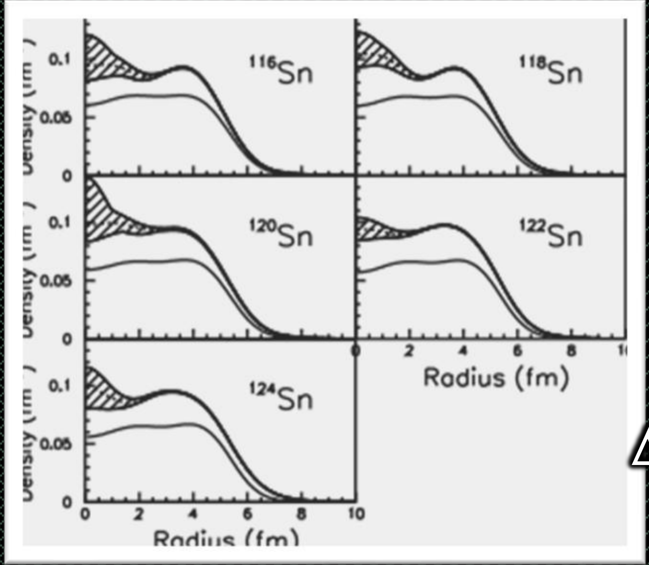
- (2000's) Our groups have deduced (neutron) density distributions for stable Ca, Sn, Pb isotopes by performing proton elastic scattering at intermediate energy (300 MeV).
- For stable nuclei, charge density distribution can be determined precisely by elastic electron scattering.

$d\sigma/d\Omega$, Ay (Momentum-transfer $q = 0.5 \sim 3.5$ fm^{-1})



χ^2 fitting
RIA +
Medium Effect
(MM-RIA)

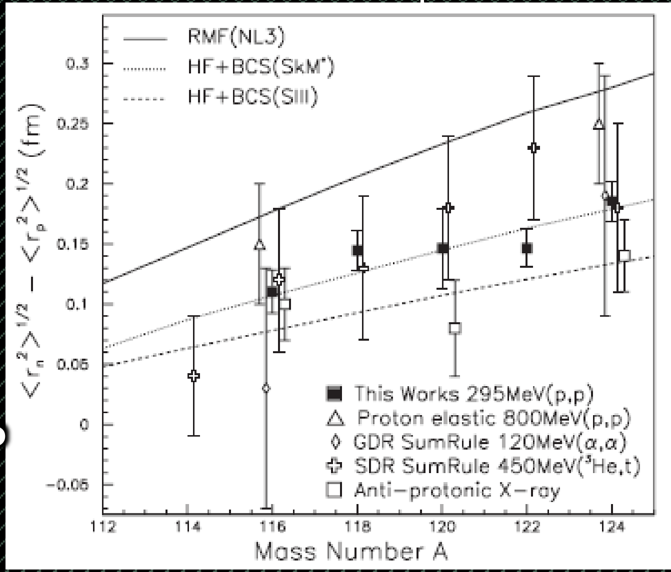
$\rho_n(r)$



S. Terashima et al., Phys. Rev. C 77, 024317 (2008).

$\Delta r_n / r_n < 0.5\%$

Δr_{np}



- 300MeV : Longest mean-free path in nuclei -> not only surface but also interior.
- Angular distributions can be reasonably reproduced by RIA (Relativistic impulse approximation). Incorporating medium effect improves the reproducibility.
- Densities were deduced in model-independent form (Sum of Gaussian).
- We evaluated the uncertainty caused by reaction model.

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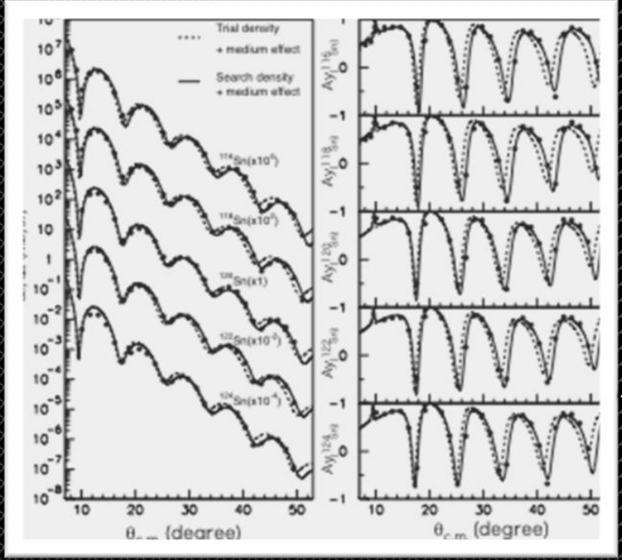

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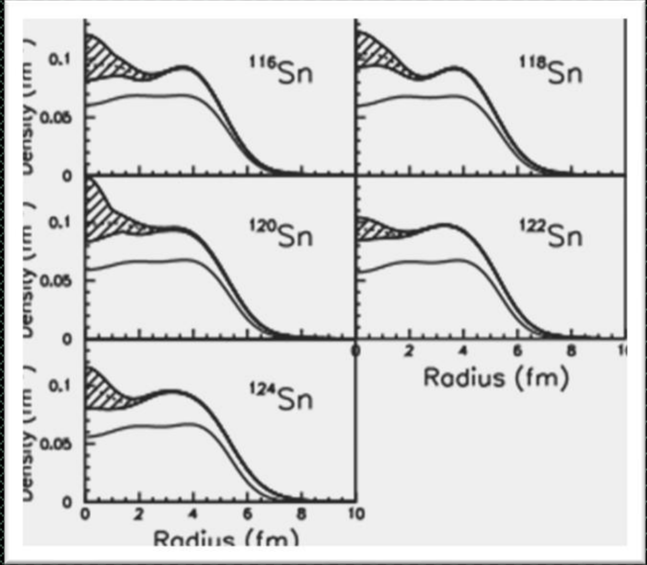

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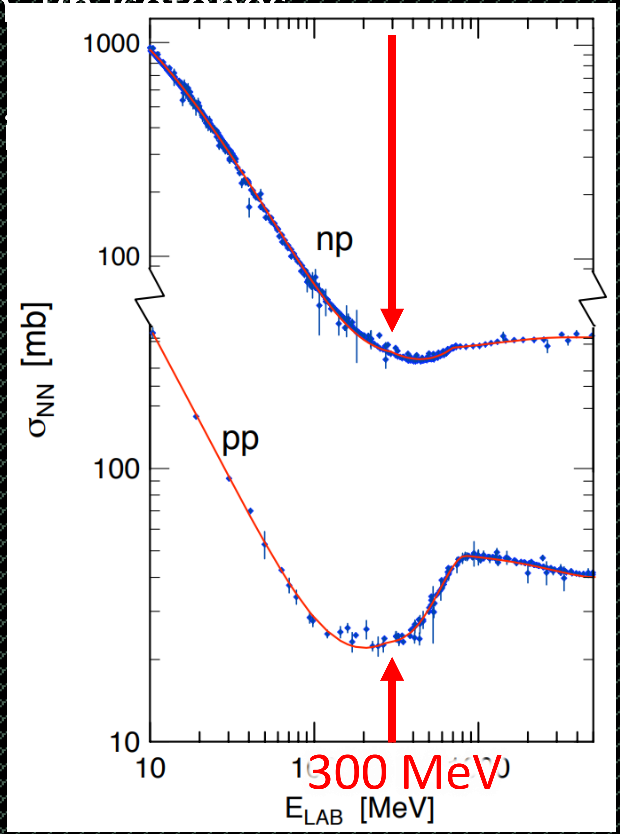

C. A. Bertulani and C. De Conti, Phys. Rev. C, 81, 064603 (2010).

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For improving the precision of N skin

- The experimental values of the neutron skin thickness of ^{208}Pb are widely scattered.
- Neutron skin thicknesses of the stable nuclei are small.

- Neutron skin thickness of neutron rich RI with large isospin asymmetry.
- ESPRI (Elastic Scattering of Proton with RI beams)
  - Since they correlates more strongly with EOS parameters, we can impose stricter constraints if achieving the same precision for the radius
  - In this work, we focus on doubly magic nuclei ^{132}Sn.

^{208}Pb neutron skin

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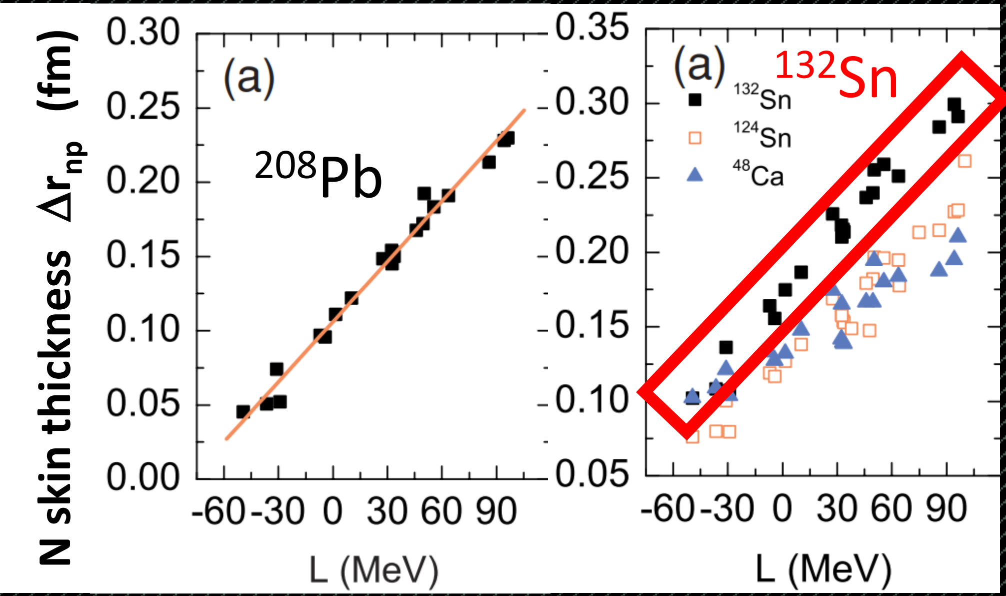


PES for unstable nuclei

- Stable nuclei (conventional method)
  $\rho_{ch}(r)$: measurable by electron scattering
  PES @ 300 MeV : $F_{p+n}(q)$

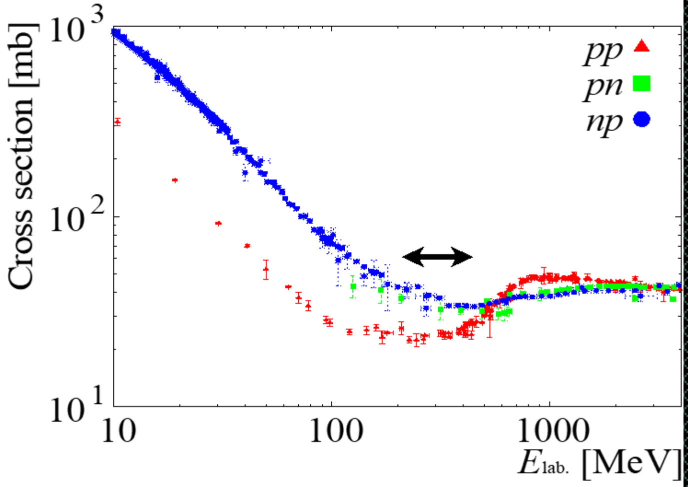
$\rho(r)$: Density
$F(q)$: Form Factor, $\tilde{\rho}$

- Unstable nuclei (new method)
  (ESPRI : Elastic Scattering of Proton with RI beams)
  × electron scattering (c.f. SCRIT at RIKEN RIBF)
  PES @300MeV : $t_{pp}^{300}F_p(q) + t_{pn}^{300}F_n(q)$
  + PES @200MeV : $t_{pp}^{200}F_p(q) + t_{pn}^{200}F_n(q)$

$\Rightarrow \rho_p(r) + \rho_n(r)$

$$\frac{t_{pp}^{300}}{t_{pn}^{300}} \neq \frac{t_{pp}^{200}}{t_{pn}^{200}}$$

  - Using a difference of the energy dependence of the *pp* & *pn* interactions we can independently deduce $\rho_p(r), \rho_n(r)$ from the two-energy measurement.
  - Confirmed by the PES experiment for ^{90}Zr.



Result of test exp. of ^{90}Zr

	Type 1 Single energy 300 MeV	Type 2 Single energy 200 MeV	Type 3 Double energy 200MeV+300 MeV
χ^2/ν	262/45	218/53	488/98
$\langle r^2\rangle_n^{1/2}$	4.285(16) fm	4.300(22) fm	4.300(17) fm
$\langle r^2\rangle_p^{1/2}$	4.200 fm	4.200 fm	4.21(2) fm
Δr_{np}	0.85(16) fm	0.100(22) fm	0.090(26) fm

Conventional method — New method

H. Sakaguchi, J. Zenihiro / Progress in Particle and Nuclear Physics 97 (2017) 1–52

- We successfully performed the PES for ^{132}Sn at 200 & 300 MeV/u in inverse kinematics at RIKEN RIBF.
- Analysis for 200 MeV/u data was finished.

- Charge radius (r_{ch}) for ^{132}Sn was measured at ISOLDE.
  (F. Le Blanc et al., Phys. Rev. C 72, 034305 (2005).)

This talk
Extraction of matter density distribution and radius by the result of the PES at 200 MeV/u and r_{ch}.

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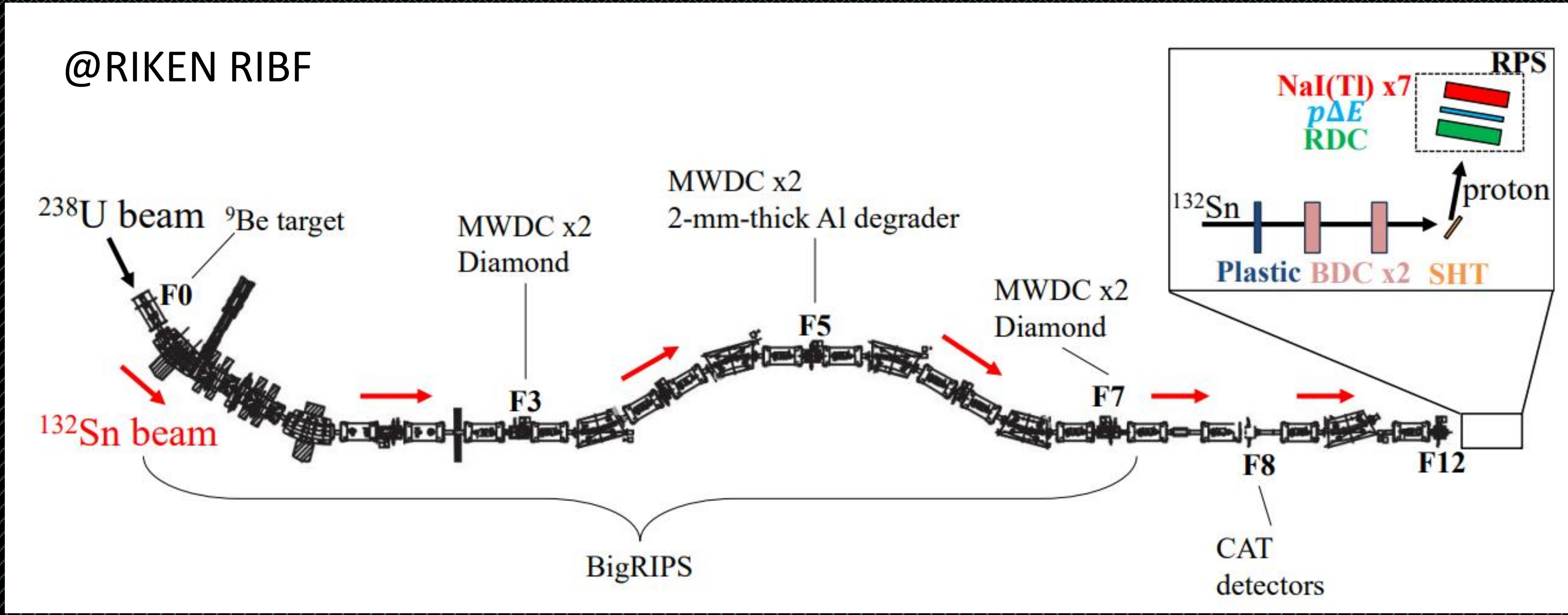
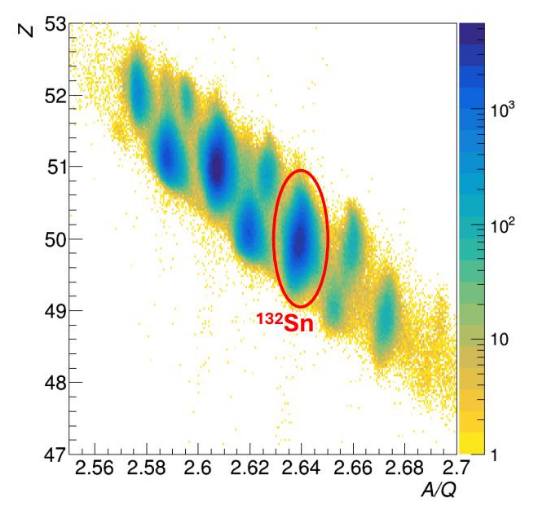
Experimental setup



- The secondary beam was separated and identified in the BigRIPS spectrometer.
- Elastics events were selected by missing mass spectroscopy.
  -> Beam angle θ_b・Energy T_b, Recoil proton angle θ_p, EnergyT_p should be measured precisely.
- High-statistics measurement
  - High-intensity secondary beam (≈200 kcps)
    -> LP-MWDC, diamond detectors (developed at CNS, The Univ. of Tokyo) and New PID method (TOF-$B\rho$-$B\rho$)
  - Solid hydrogen target (SHT)

BigRIPS analysis

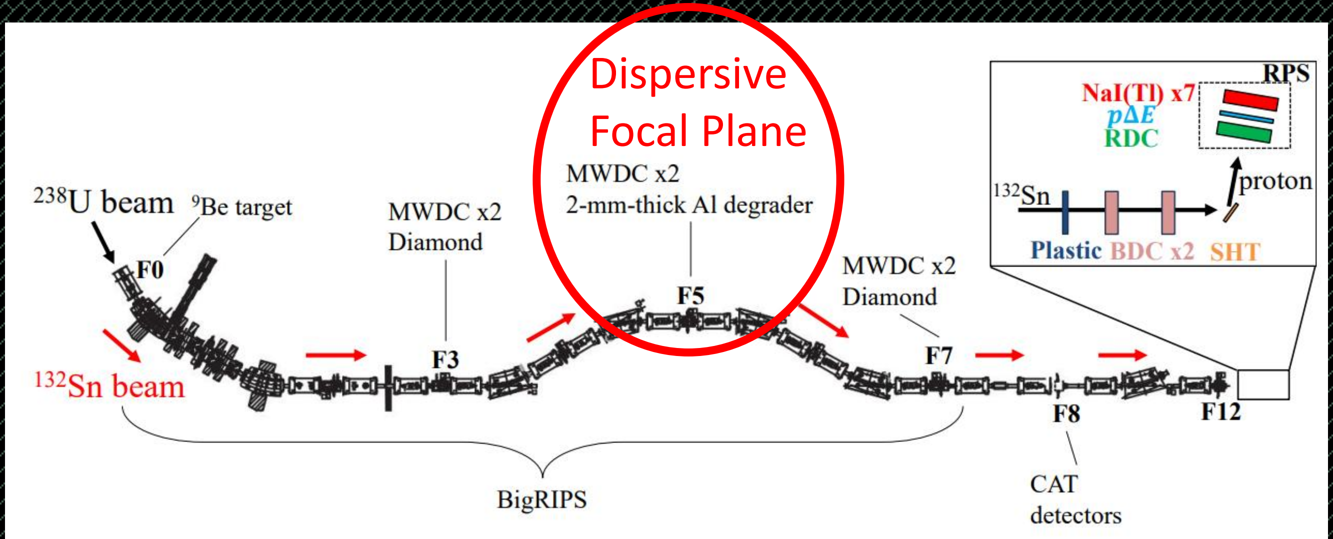
Beam : PID, T_b, θ_b
Recoil : PID, T_p, θ_p
→ Excitation Energy E_x
Scattering angle θ
→ Yield y_i
Beam# I_{beam}, Target # N_{tgt}
Efficiency ϵ
→ Cross section $\frac{d\sigma}{d\Omega}$



Beam PID Method

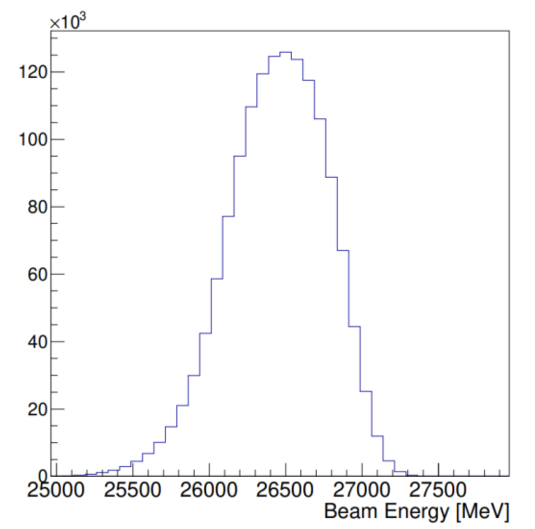
TOF-$B\rho$-$B\rho$ method w/ diamond, LP-MWDC, Thick Al degrader@F5

- Time of Flight (TOF), position -> A/Q
- In the standard method, ΔE is directly measured by the detector such as Ion chamber. In this work, it was indirectly deduced by the change of $B\rho$ in the degrader @F5.
  - $\Delta E = (\gamma_{35} - 1)Am_u - (\gamma_{57} - 1)Am_u$
  - We used the relatively thicker degrader to achieve enough resolution.



Beam energy

- By the position@F5
- 196—210 MeV/u



ESPRI devices

Beam : PID, T_b, θ_b
Recoil : PID, T_p, θ_p
→ Excitation Energy E_x
Scattering angle θ
→ Yield y_i
Beam# I_{beam}, Target # N_{tgt}
Efficiency ϵ
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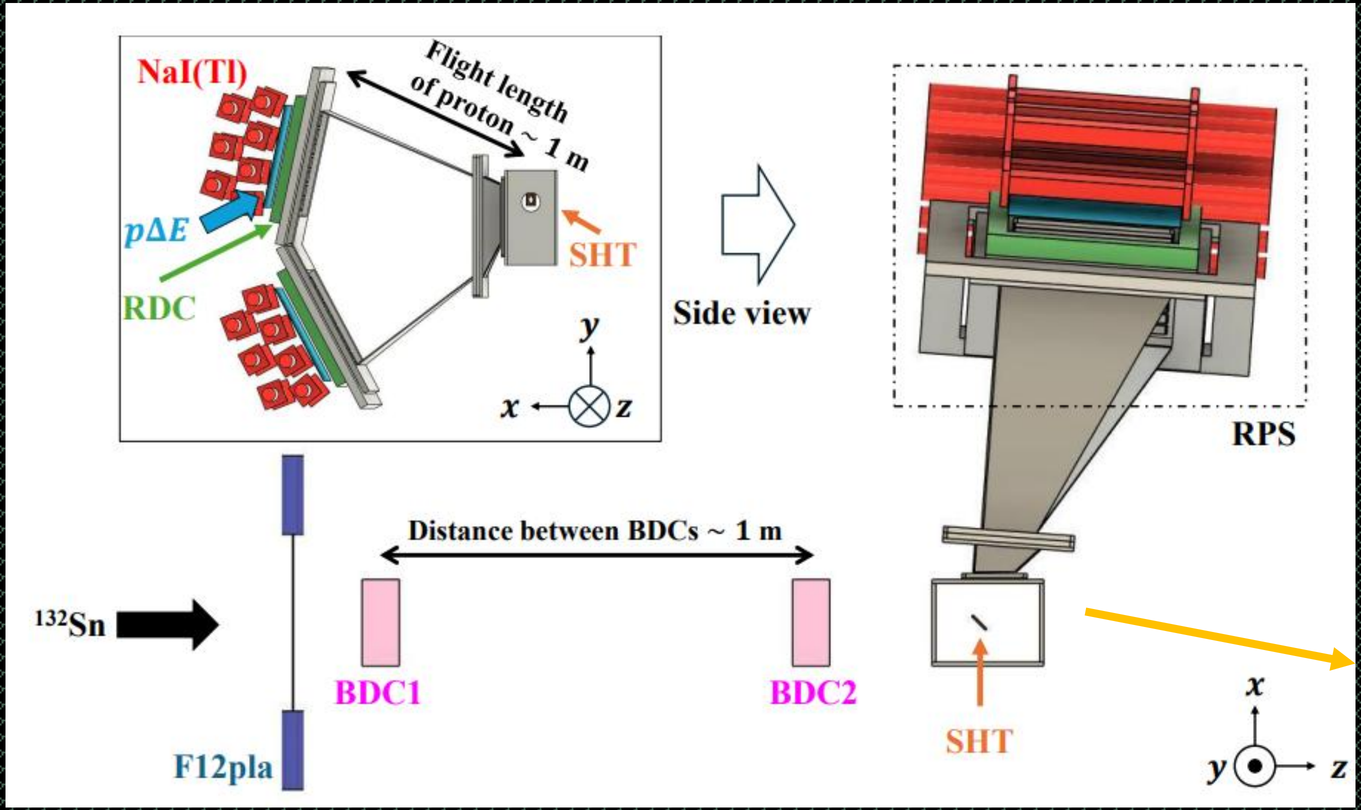


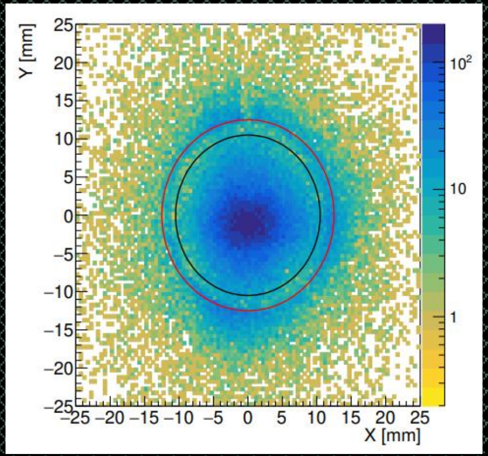
Beam incident angle θ_b

- By the two beamline drift chamber (BDC)
- Selected the target region for removing backgrounds.

1-mm-thick Solid Hydrogen Target (SHT)

- Low background because of pure hydrogen.
- Suppressing multiple scattering

Beam profile of recoil trigger



Recoil particle PID

Beam : PID, T_b, θ_b
Recoil : PID, T_p, θ_p
→ Excitation Energy E_x
Scattering angle θ
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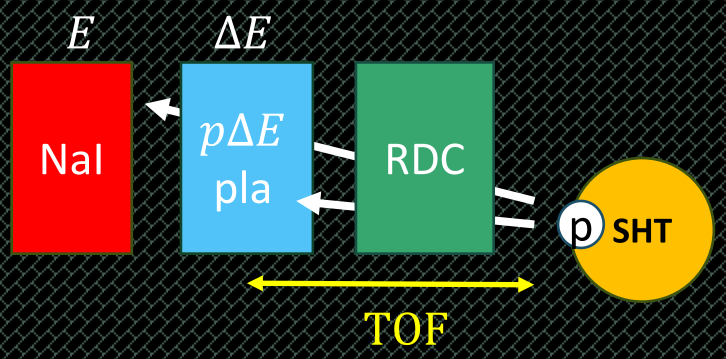
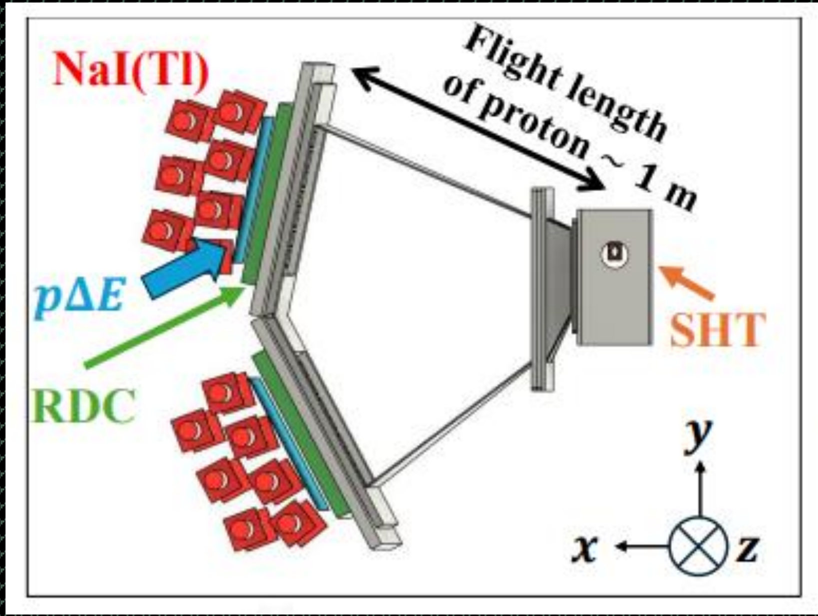
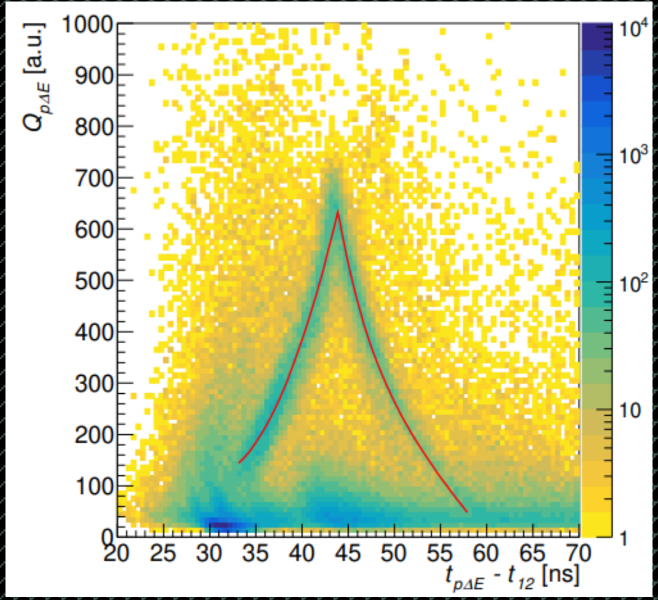


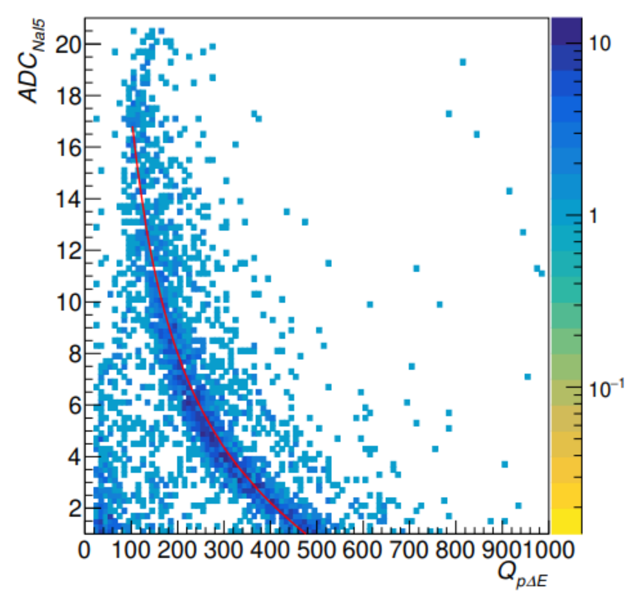
Recoil Proton spectrometer (RPS)



- Recoil proton angle θ_p : By Recoil Drift Chamber (RDC)
- PID and T_p determination methods depend on the energy

	Stopping at $p\Delta E$	Penetrating $p\Delta E$
Proton energy	Time of Flight (TOF)	NaI calorimeter
PID method	Q ($p\Delta E$) vs TOF	E-ΔE method





Kinematical correlation

Beam : PID, T_b, θ_b
Recoil : PID, T_p, θ_p
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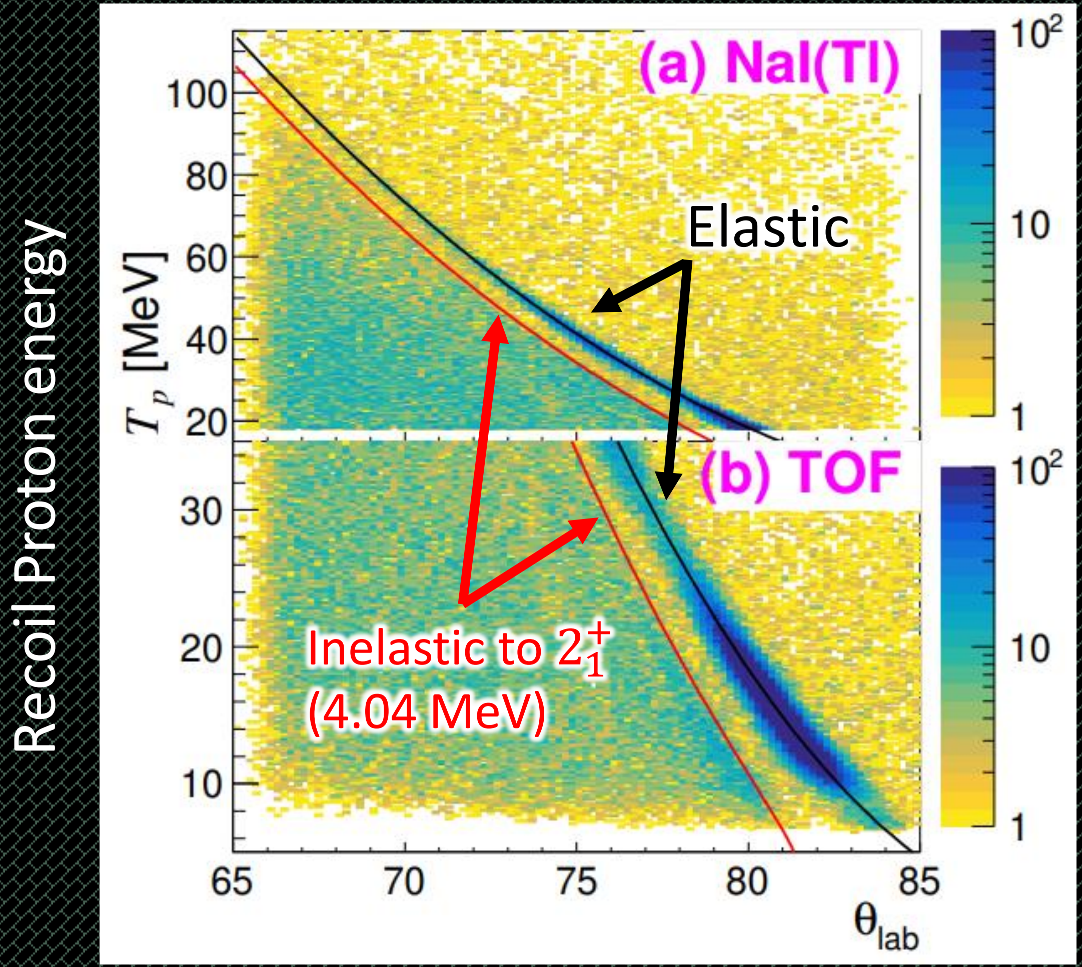
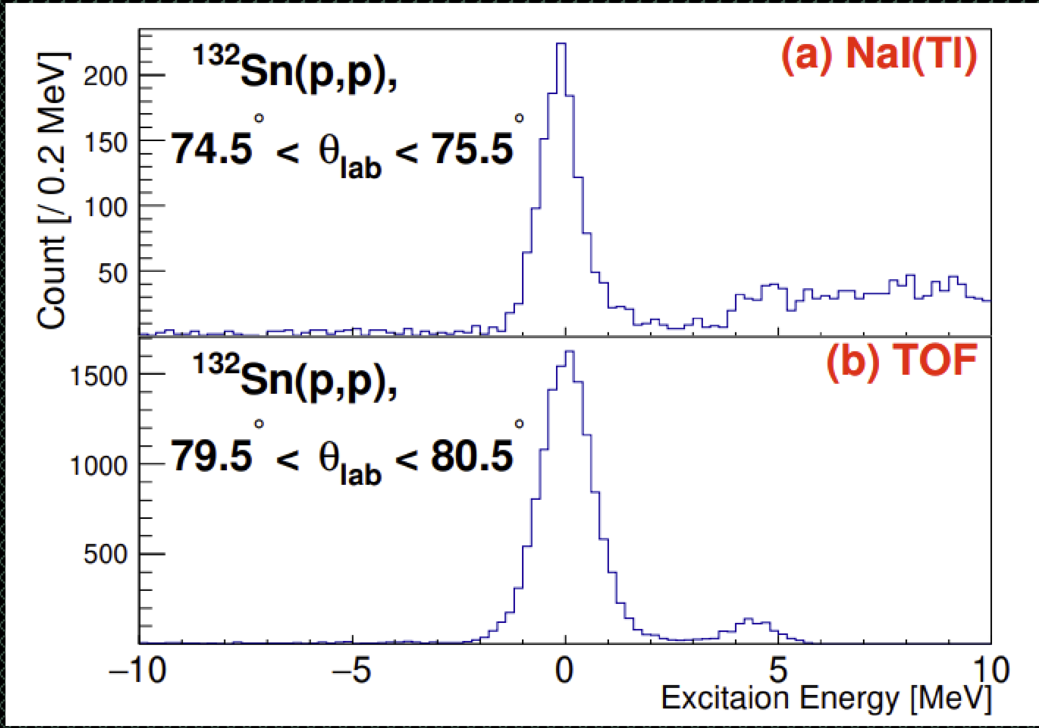


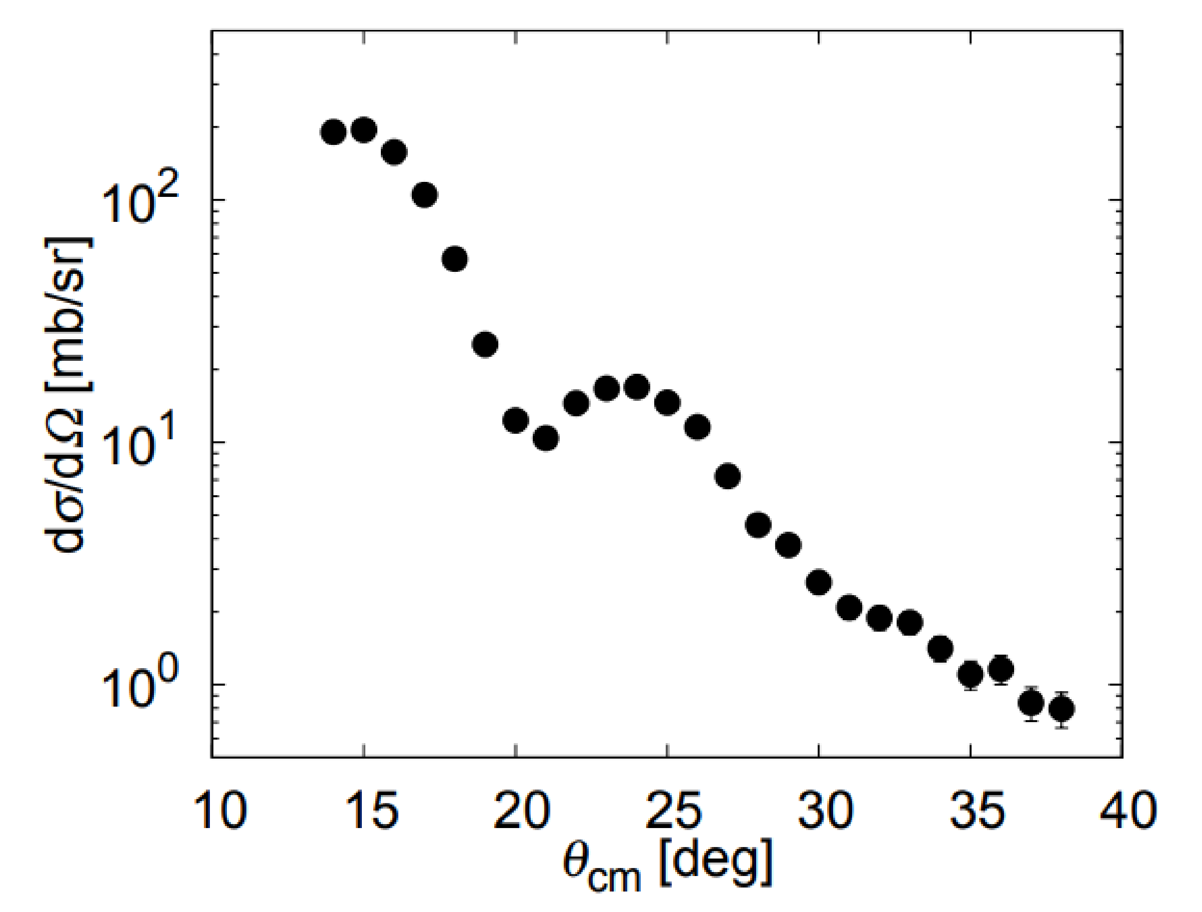
- Typical resolution : 700 keV(σ)
- Good signal-to-noise ratio.



Result : Differential cross sections

Beam : PID, T_b, θ_b
Recoil : PID, T_p, θ_p
→ Excitation Energy E_x
Scattering angle θ
→ Yield y_i
Beam# I_{beam}, Target # N_{tgt}
Efficiency ϵ
→ Cross section $\frac{d\sigma}{d\Omega}$

- We successfully measured the differential cross sections of elastic scattering from heavy RI of $A \geq 100$ for the first time.
- Covering wide region
  θ_{cm}=14—38 deg ⇔ momentum-transfer q=0.8—2.1 fm^{-1}
- Main component of uncertainties
  - Uncertainty of the target thickness @ forward angle
  - Statistical error @ backward angle



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Relativistic impulse approximation

<u>Relativistic Impulse approximation (RIA)</u>

PES at intermediate energy is well described by folding the nucleon-nucleon interaction with nuclear density.

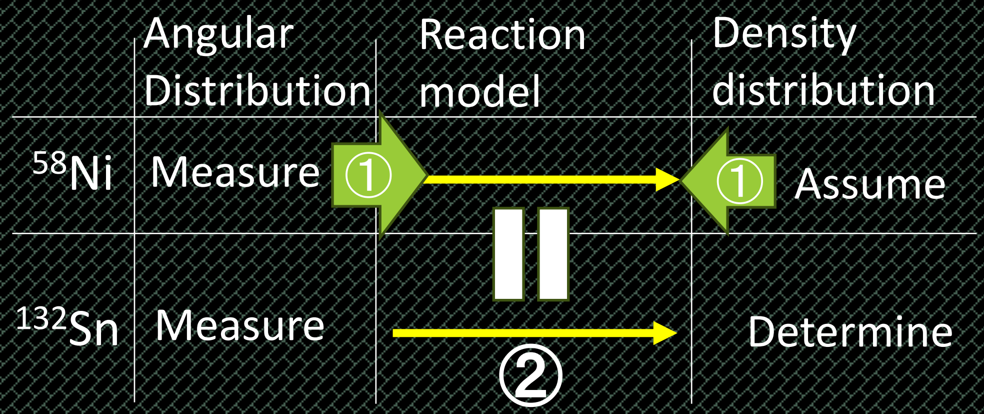
<u>Medium-modified-RIA (mm-RIA)</u>

To describe more accurately, medium-effect parameters are incorporated phenomenologically.

- Density-dependent correction terms are included in the coupling constant g_i and mass m_i of σ and ω mesons.
- Because of describing them in universal forms,
  we can apply parameters determined by PES from one nuclide to other nuclides.

$$
\begin{aligned}
g_i^2, \bar{g}_i^2 \quad & \rightarrow \frac{g_i^2}{1 + a_i \rho(r)/\rho_0}, \frac{\bar{g}_i^2}{1 + \bar{a}_i \rho(r)/\rho_0}, \\
m_i, \overline{m}_i \quad & \rightarrow m_i \left[1 + b_i \frac{\rho(r)}{\rho_0} \right], \overline{m}_i \left[1 + \bar{b}_i \frac{\rho(r)}{\rho_0} \right], \\
i \quad & = \sigma, \omega,
\end{aligned}
$$

ρ_0 : standard density, a_i, b_i : parameter



Calibration of Medium effect parameters

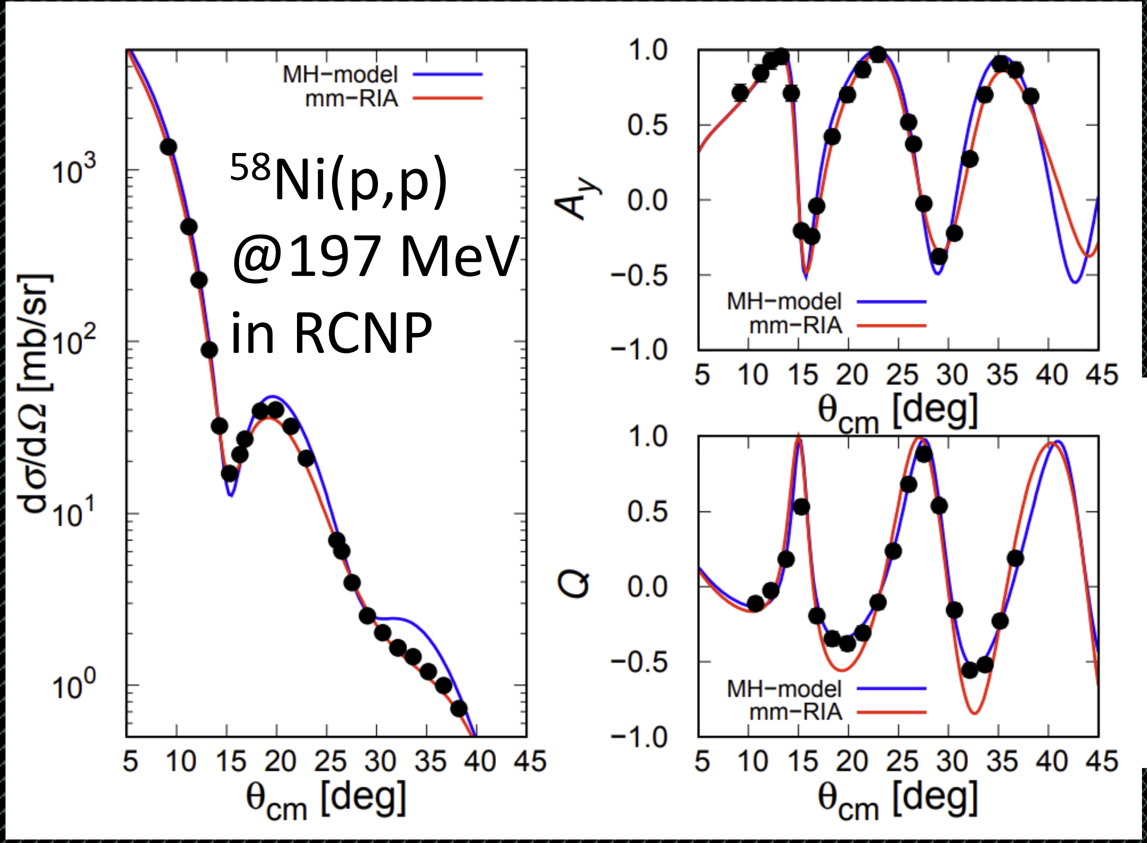
We calibrated the a_i, b_i by PES from <u>^{58}Ni</u>

- Experimental and theoretical results indicate that the radii and density distributions of the proton and neutron are similar.
  -> Both density can be determined from the charge density deduced by the electron scattering.
- Fitted the angular distributions of the proton elastic scattering.

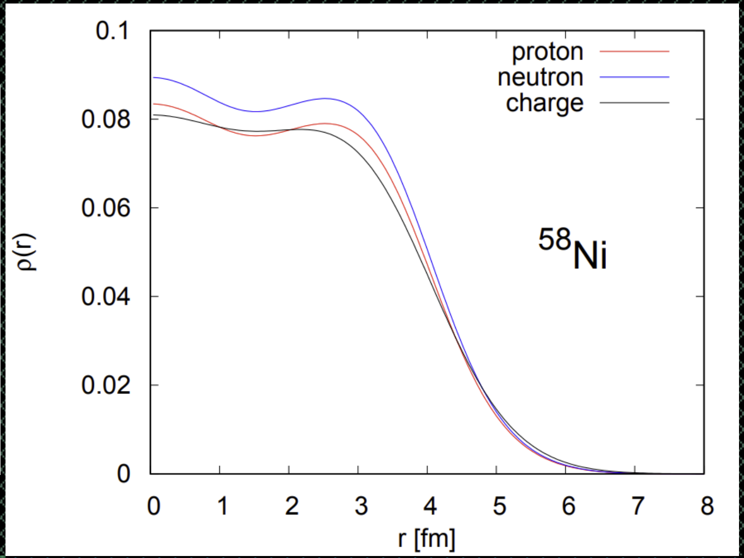
$$g_i^2, \bar{g}_i^2 \rightarrow \frac{g_i^2}{1+a_i\rho(r)/\rho_0}, \frac{\bar{g}_i^2}{1+\bar{a}_i\rho(r)/\rho_0},$$

$$m_i, \overline{m}_i \rightarrow m_i\left[1+b_i\frac{\rho(r)}{\rho_0}\right], \overline{m}_i\left[1+\bar{b}_i\frac{\rho(r)}{\rho_0}\right],$$

$$i = \sigma, \omega,$$



i	σ	ω
a_i	0.0210	0.1965
$\bar{a}_i$	2.0467	1.1549
b_i	0.0326	−0.0224
$\bar{b}_i$	−0.0799	−0.0501



Result

Extracted the matter radius by performing χ^2 fitting for the obtained CS by using the RIA calculation.

- The proton & neutron density distributions
  : 2pF distributions; $\rho_i(r) = \frac{n_i}{1+\exp\{(r-c_i)/a_i\}}$.
- $\rho_m(r) = \rho_p(r) + \rho_n(r)$
- The proton radius was constrained by charge radius measured at ISOLDE.

- Reduced $\chi^2 \approx 1.3$.
- The matter radius of ^{132}Sn is determined for the first time :
  $\sqrt{< r_m^2 >} = 4.758^{+0.023}_{-0.024}$ fm.

$\sqrt{< r_{ch}^2 >} = 4.7093 \pm 0.076$ fm

(F. Le Blanc et al., Phys. Rev. C 72, 034305 (2005).)

$\sqrt{< r_p^2 >} \approx \sqrt{< r_{ch}^2 > + R_p^2 + \frac{N}{Z} R_n^2}$

($R_{p(n)}$: intrinsic proton radius)

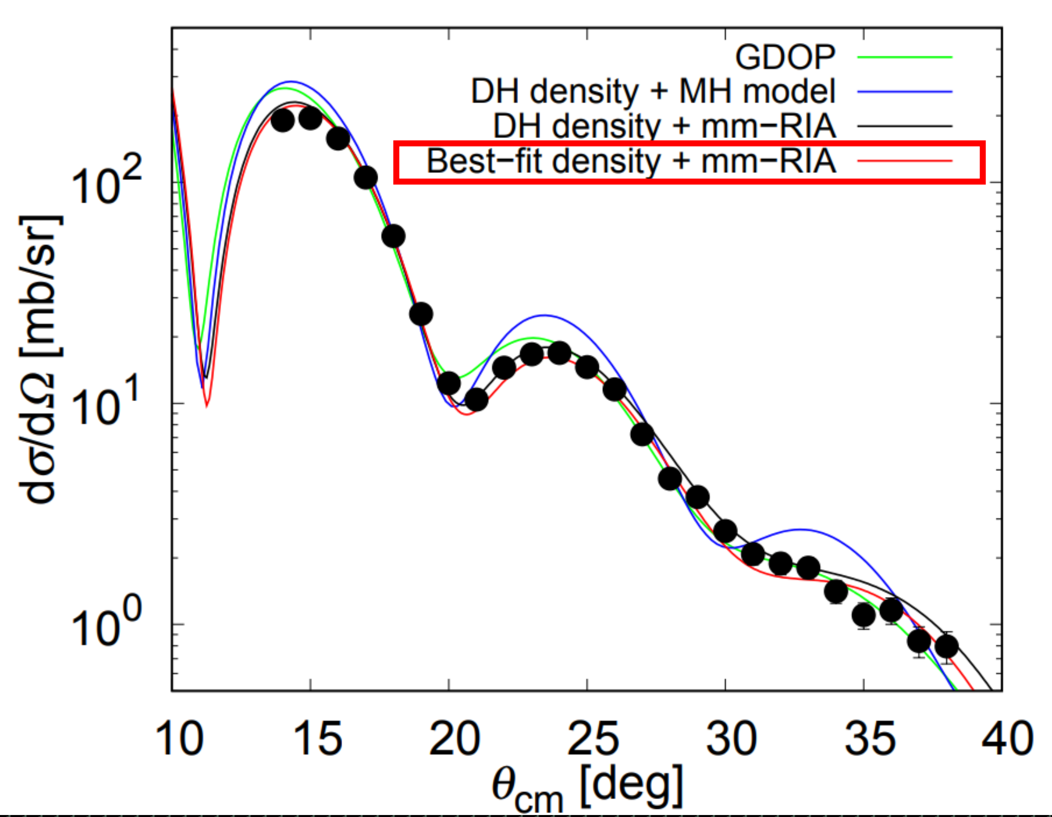


Table 2 Minimum χ^2 value and best-fit 2pF parameters.

$\chi^2_{\min}/ndf$	c_p	a_p	c_n	a_n
38.0/22	$5.632^{+0.076}_{-0.119}$	$0.430^{+0.063}_{-0.044}$	$5.581^{+0.066}_{-0.068}$	$0.576^{+0.033}_{-0.037}$

Outline

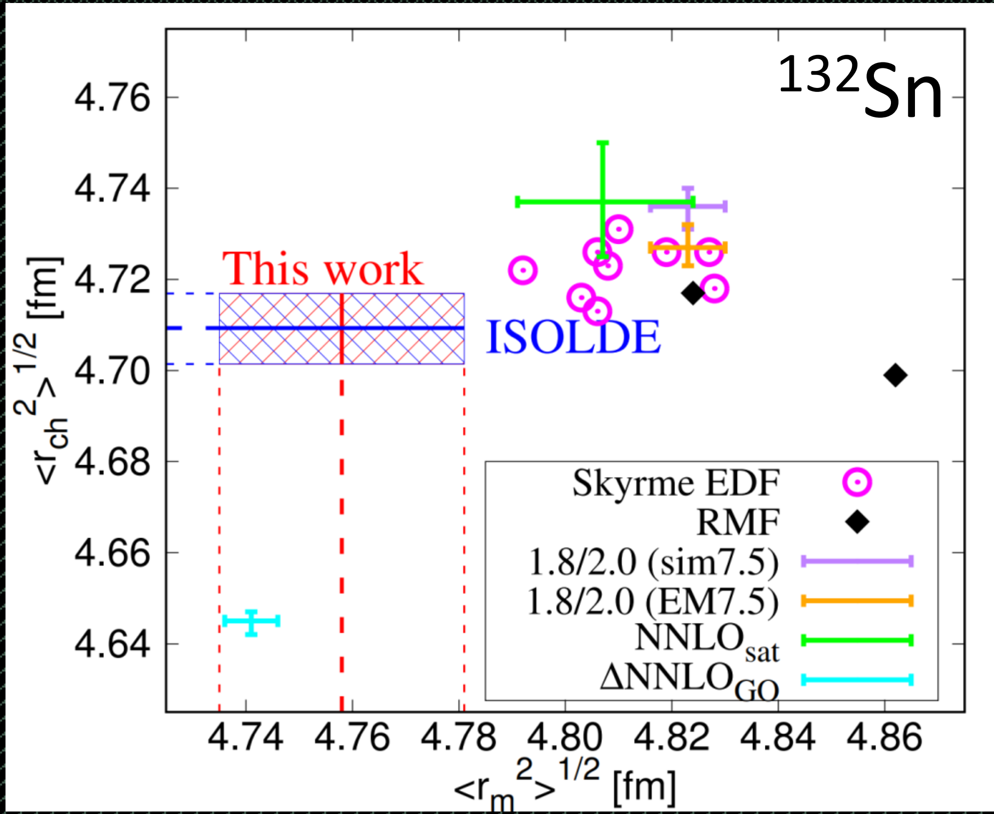
- Introduction
  - Nuclear matter EoS and Neutron skin thickness
  - Measurements of matter radius, charge radius, and neutron skin thickness
  - Proton elastic scattering at intermediate energy
- Experiment, data reduction, and result
  - Proton elastic scattering from ^{132}Sn at 200 MeV/u in inverse kinematics @ RIBF
- Structure analysis with reaction model
  - Relativistic impulse approximation
- Compare the experimental result with structure calculation
  - Ab-initio calculation using χ-EFT interactions
- Summary

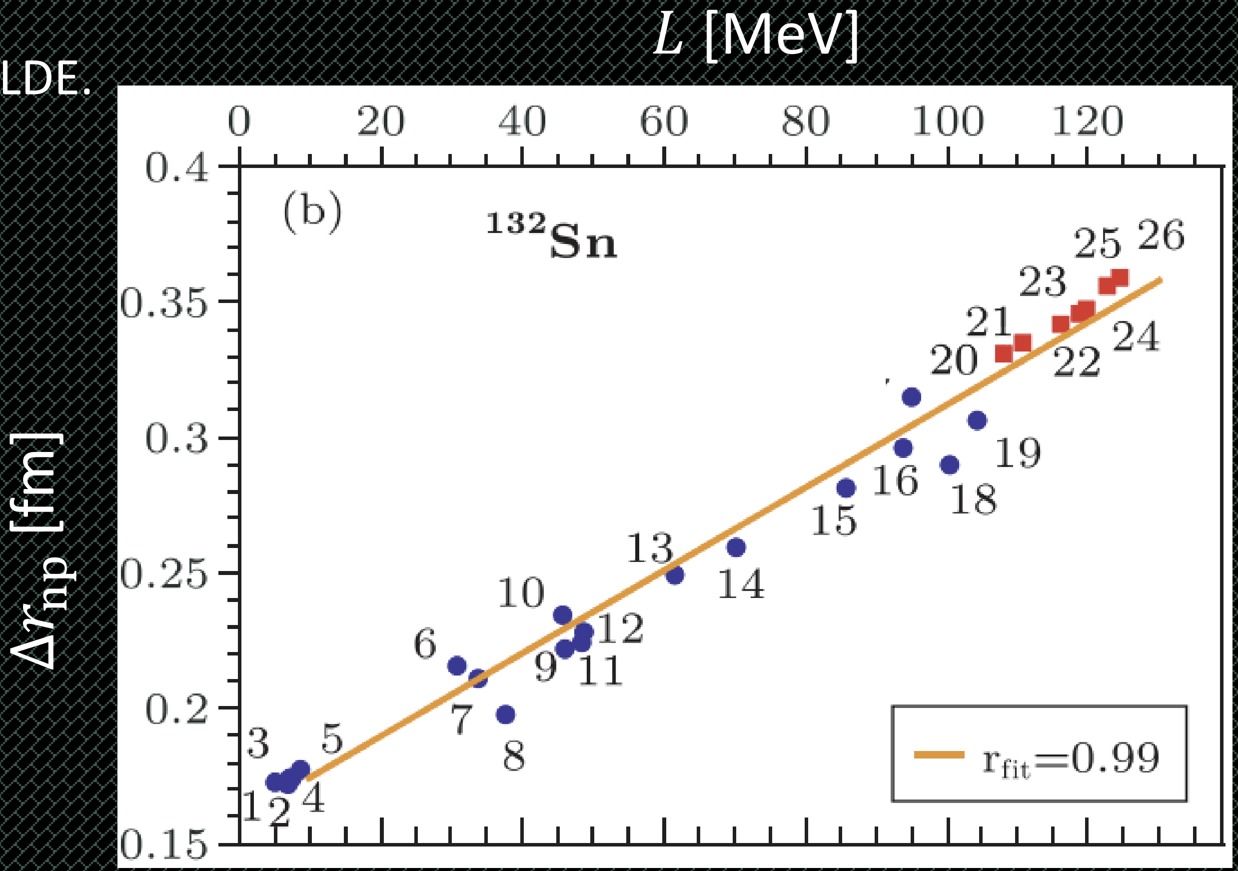
Matter radius vs Charge radius of ^{132}Sn

- Even including some Skyrme-Hartree-Fock calculations, only ab-initio (IMSRG) calculation using $\Delta NNLO_{GO}$ interaction reproduces the matter radius of this work.
- However, the charge radius of $\Delta NNLO_{GO}$ density is smaller than the experimental value measured at ISOLDE.

$\Delta r_{np} \approx 0.18$ fm

-> It favor the CREX result in the PREX-CREX puzzle.

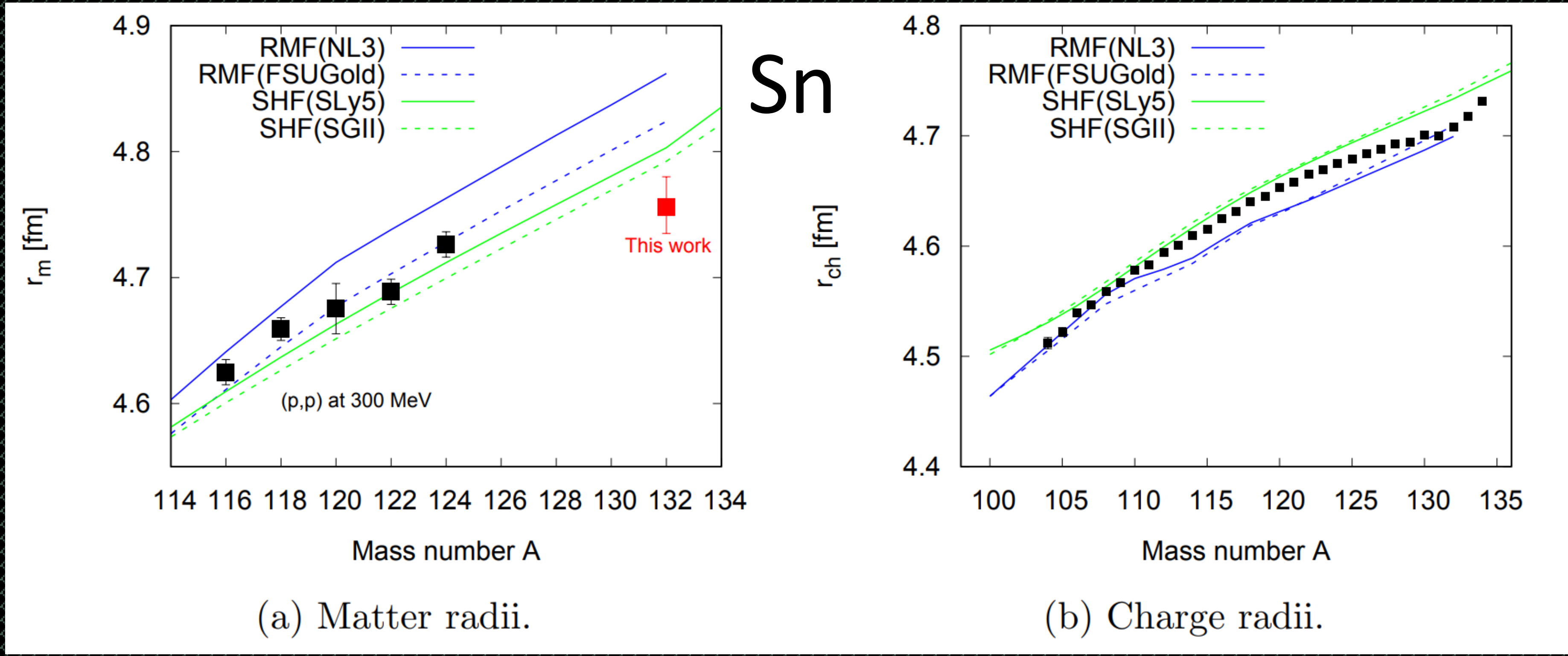




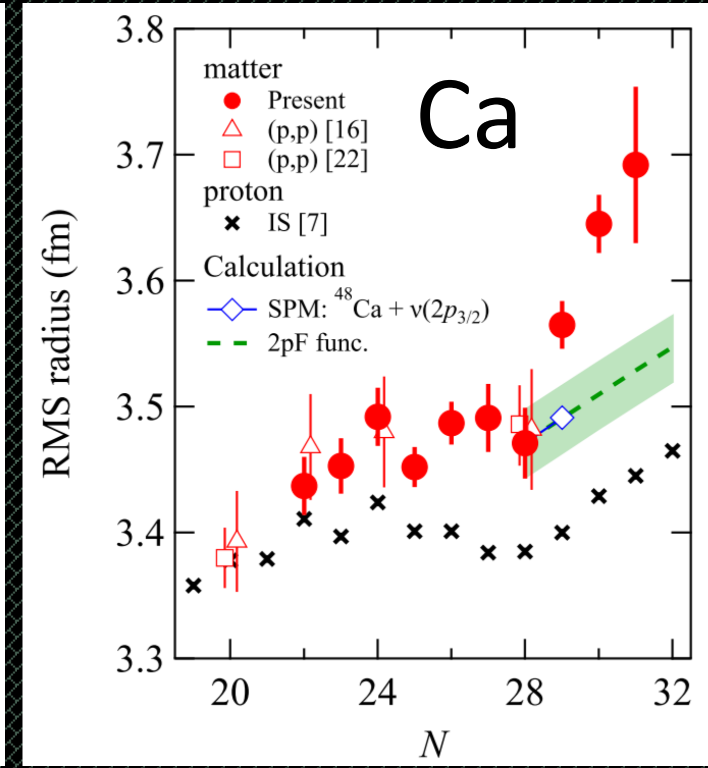
A. Carbone, et al., PRC 81, 041301(R) (2010).

Systematics in the isotopes

- Compared with the conventional calculations, both charge and matter radii shrink at ^{132}Sn.
- This trend also appears in the Ca isotopic chain.



(a) Matter radii. (b) Charge radii.



Summary and Outlook

Summary

- We performed PES measurements from ^{132}Sn at 200 & 300 MeV/u in inverse kinematics.
- We completed the analysis of the 200 MeV experiment.
- For the first time, the matter radius of ^{132}Sn was determined, namely $\sqrt{< r_m^2 >} = 4.758^{+0.023}_{-0.024}$ fm.
- Currently, no theoretical calculations predict the experimental matter and charge radii simultaneously.

Outlook

- Data reduction of the 300 MeV experiment and
  combined analysis of 200 & 300 MeV for separate determination of p and n density distributions.
- We have developed a new system to measure PES of rare isotopes, such as ^{52}Ca.