B01 : ESPRI experiment and the neutron skin of ^{132}Sn

proton elastic scattering of
unstable nuclei

Juzo ZENIHIRO, RNC

Contents

1. Symmetry energy and neutron skin thicknesses

Extraction of proton & neutron density distributions from proton elastic scattering

Nuclear matter EOS with isospin asymmetry δ

- EOS of nuclear matter E(ρ,δ) : the energy per nucleon

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

- EOS of symmetric nuclear matter E(ρ,0) :

$$E(\rho,0) = E(\rho_{sat},0) + \frac{K_0}{2}\varepsilon^2 + O(\varepsilon^3)$$

→ $E(\rho_{sat},0) \sim -16$ MeV, $K_0 \sim 240$ MeV

- The symmetry energy S(ρ) :

$$S(\rho) = S(\rho_{sat}) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + O(\varepsilon^3)$$

→ Still less certain !

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p},\ \varepsilon = \frac{\rho - \rho_{sat}}{3\rho_{sat}}$$

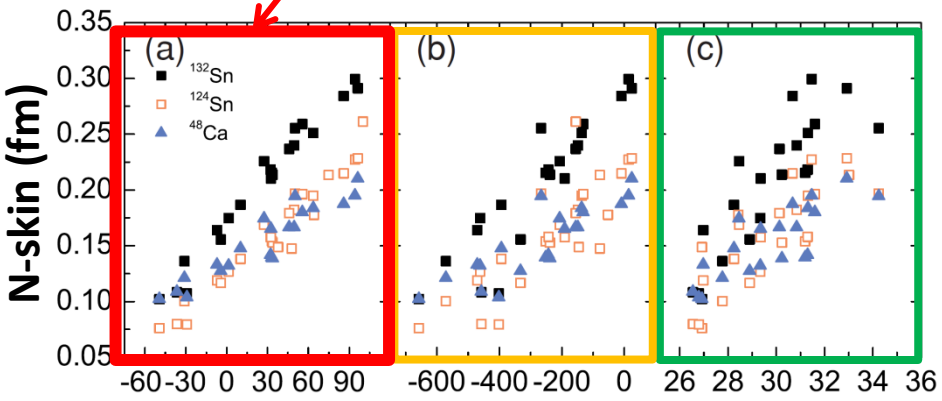
Symmetry energy vs. Neutron skin

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

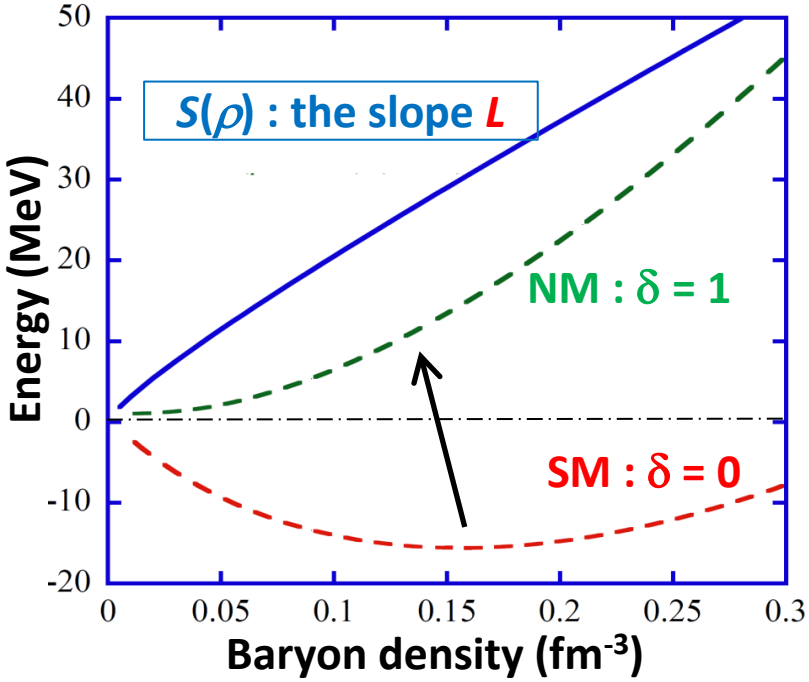
$$S(\rho) = S(\rho_{sat}) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + O(\varepsilon^3)$$

$$\varepsilon = \frac{\rho - \rho_{sat}}{3\rho_{sat}}$$

Strong correlation!



Taken from L.-W. Chen et al., PRC72, 064309.



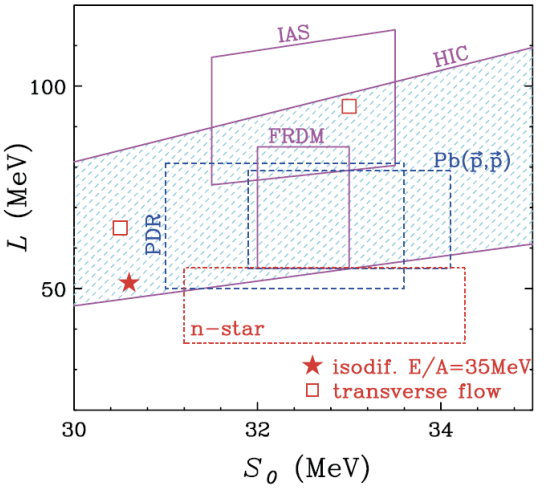
Determine the slope coefficient ***L*** *of* ***S(ρ)*** → **neutron matter EOS**

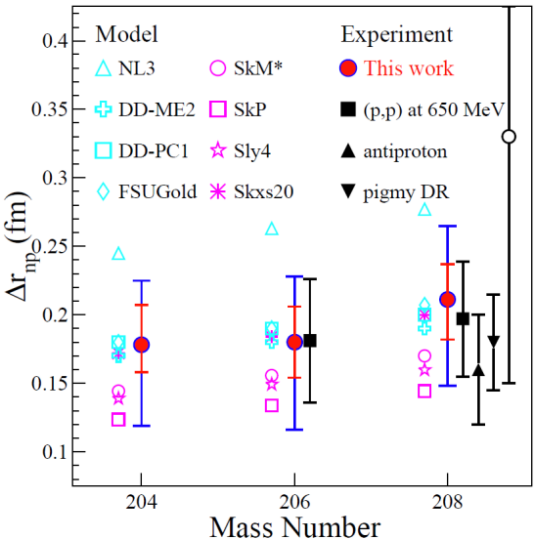
Impact on **neutron star** structure

- Radius, cooling system, etc.

Symmetry energy experiments

- SAMURAI-TPC (SPiRIT) : π+/π- ratio
  - HI collision (Sn isotope?)
- (p, p') at 0 degree : dipole polarizability
  - proton inelastic scattering (^{208}Pb, ^{90}Zr, etc.)
- PREX-II, CREX : neutron radius & skin thickness (^{208}Pb, ^{48}Ca)
  - parity-violating electron elastic scattering
  - Stable nuclei : ^{208}Pb, ^{48}Ca (2015, 2016)
- ESPRI : neutron radius & skin thickness
  - proton elastic scattering
  - Stable & unstable nuclei
  - Pb, Sn, Zr, Ca, ^{132}Sn, ^{66,70}Ni





2. pre-ESPRI

Polarized proton elastic scattering at **300MeV** (Ring cyclotron facility at RCNP, Osaka University)
⇒We have succeeded in extracting neutron density distributions of Sn, Pb isotopes systematically.

Stable nuclei : ρ_p is known.

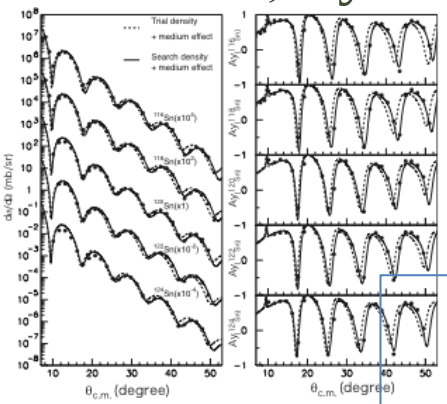
dσ/dΩ, Ay

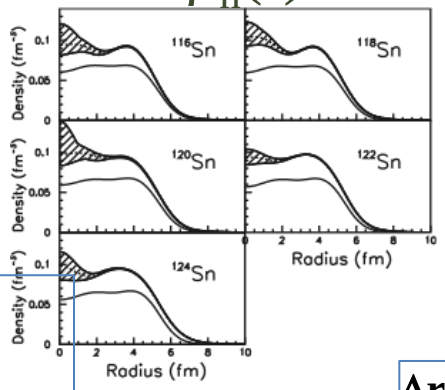
$\rho_n(r)$

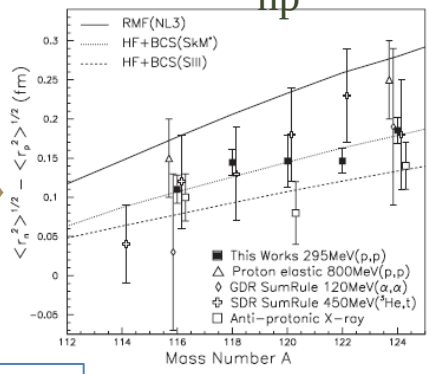
Δr_{np}

Sn

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



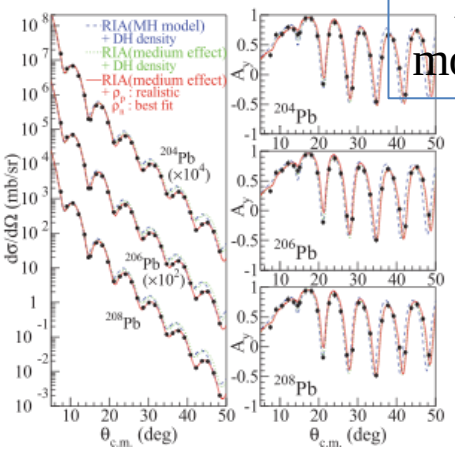


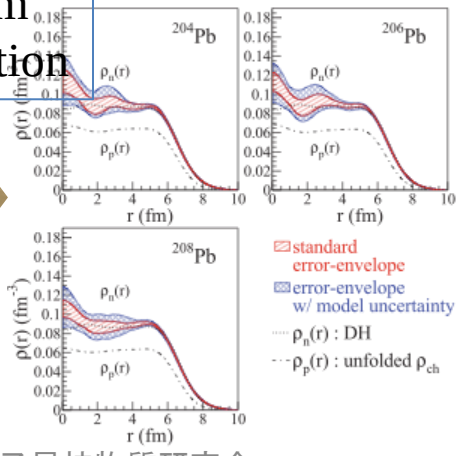


RIA
+
Medium modification

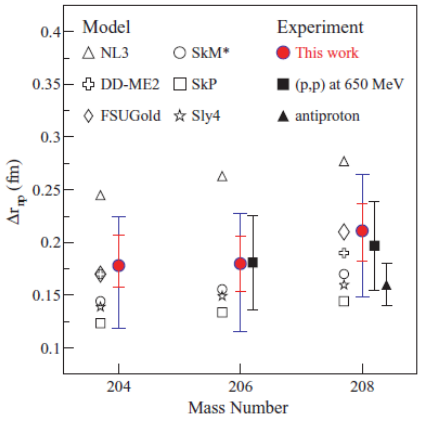
Pb

J.Zenihiro et al., Phys. Rev. C 82, 044611 (2010)





$\Delta r_n/r_n < 0.5\%$



3. ESPRI

ESPRI : Elastic Scattering of Protons from RI beam

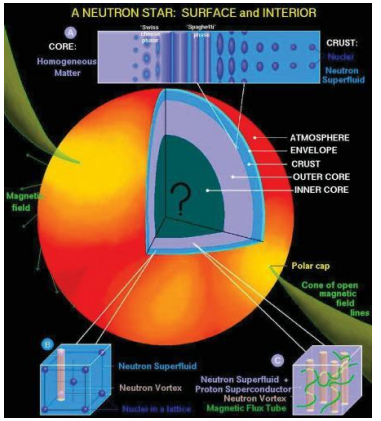
Physics motivations:

Extraction of p & n densities of unstable nuclei from *p*-RI elastic scattering measurements

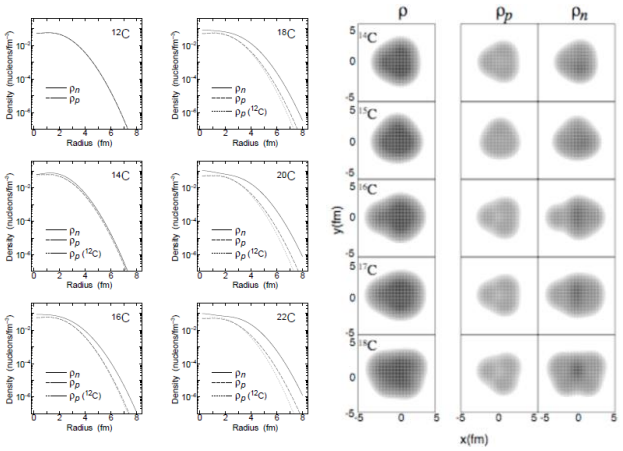
1. Asymmetric nuclear matter EOS study through neutron skin measurements
   → medium-heavy nuclei
2. Structure study (cluster, skin, halo, etc.)
   → light nuclei

Achievements :

1. Development of the detector system for inverse kinematics.
2. Measurements of angular distributions of cross sections of unstable nuclei.
3. Extraction method of both p & n densities from proton elastic scattering data only.



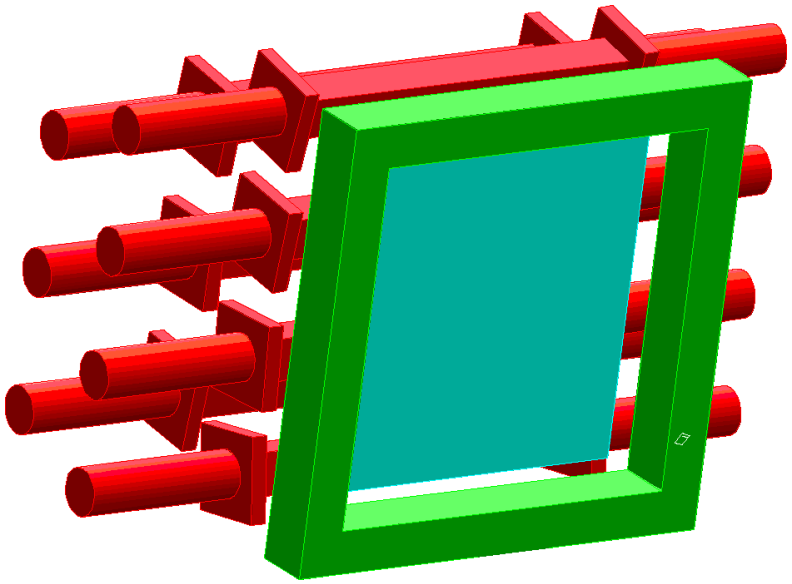
Neutron star structure

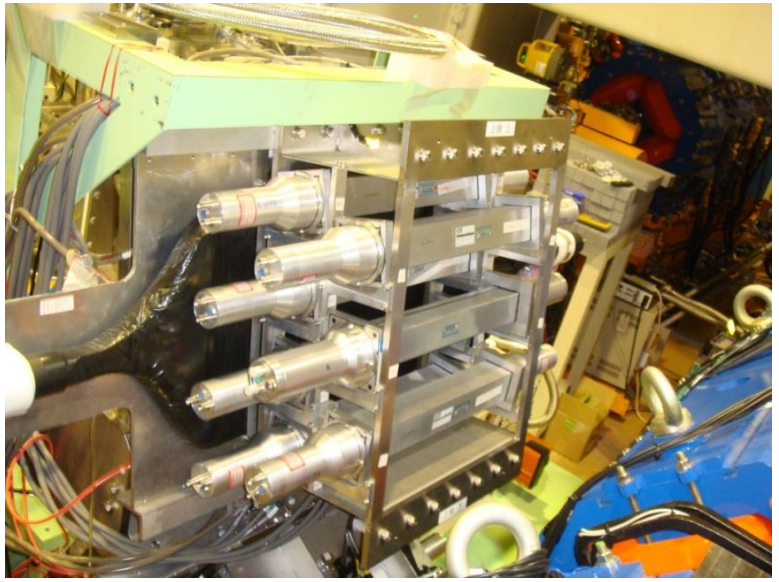


AMD calculations of C isotopes taken from Yoshiko Kanada-En'yo and Hisashi Horiuchi, Progress of Theor. Phys. Suppl. No142, (2001)

4. ESPRI detectors

Recoil Proton Spectrometer (RPS)

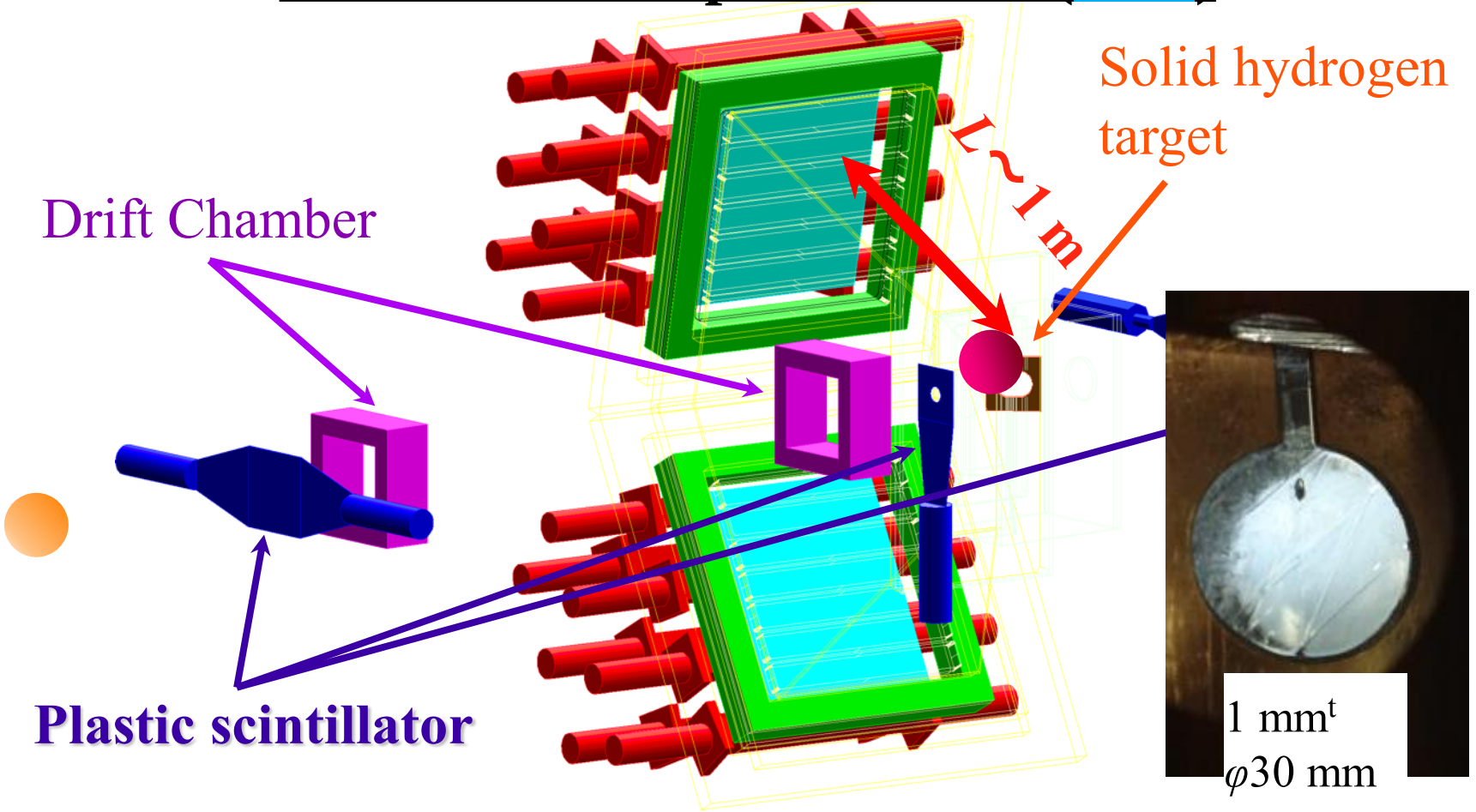




θ_{lab} = 66° - 80° , Ep=20-120 MeV, $\Delta\Omega$～10 msr/deg. q=1-2.2 fm^{-1}, ΔEx = 400-500 keV	
Recoil drift chamber	436x436 mm^2 (x-y-x'-y'-x'-y)
Plastic scintillator	440x440 mm^2 x 2 mm^t
NaI(Tl) caorimeter	431.8x45.72 mm^2 x 50.8 mm^t

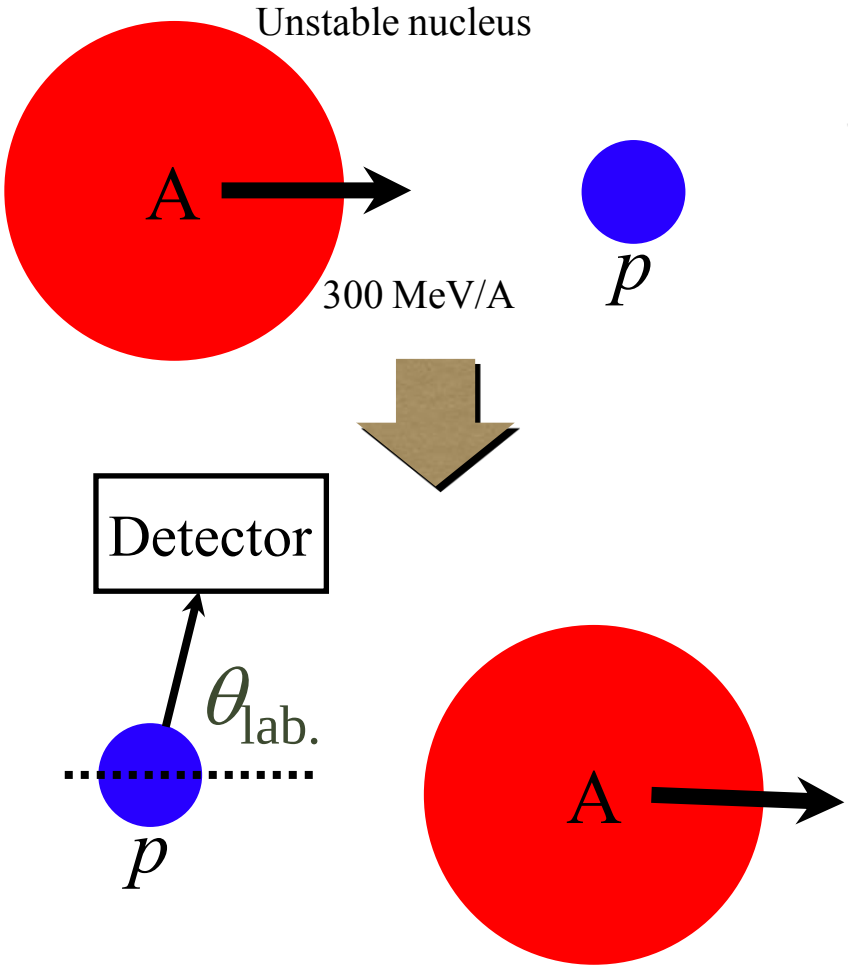
4. ESPRI detectors

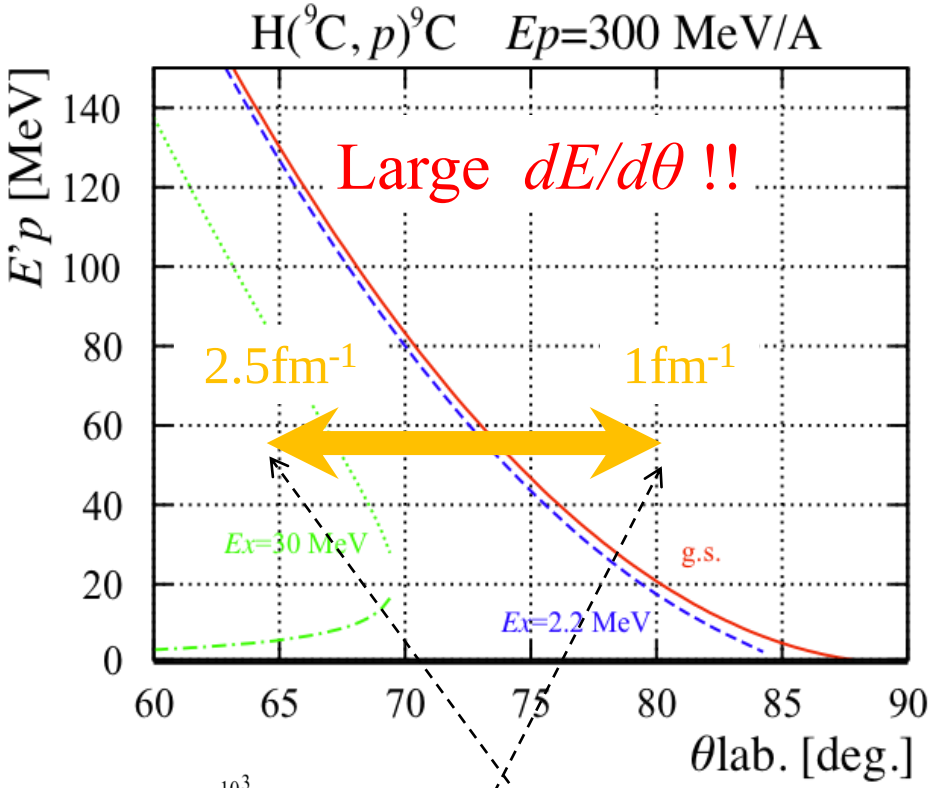
Recoil Proton Spectrometer (RPS)

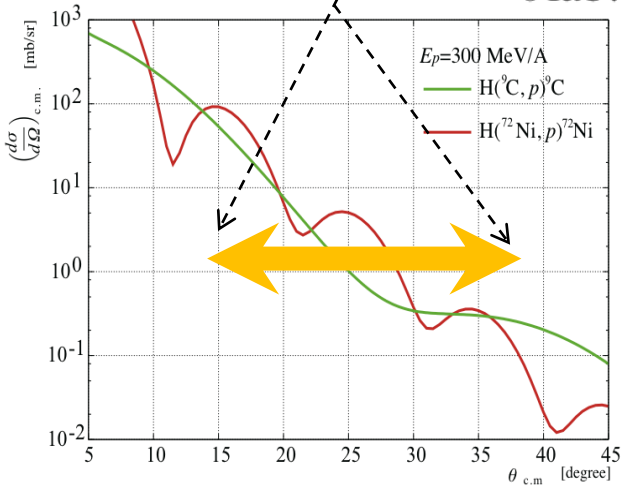


Kinematics of ESPRI

Inverse kinematics : fixed probe

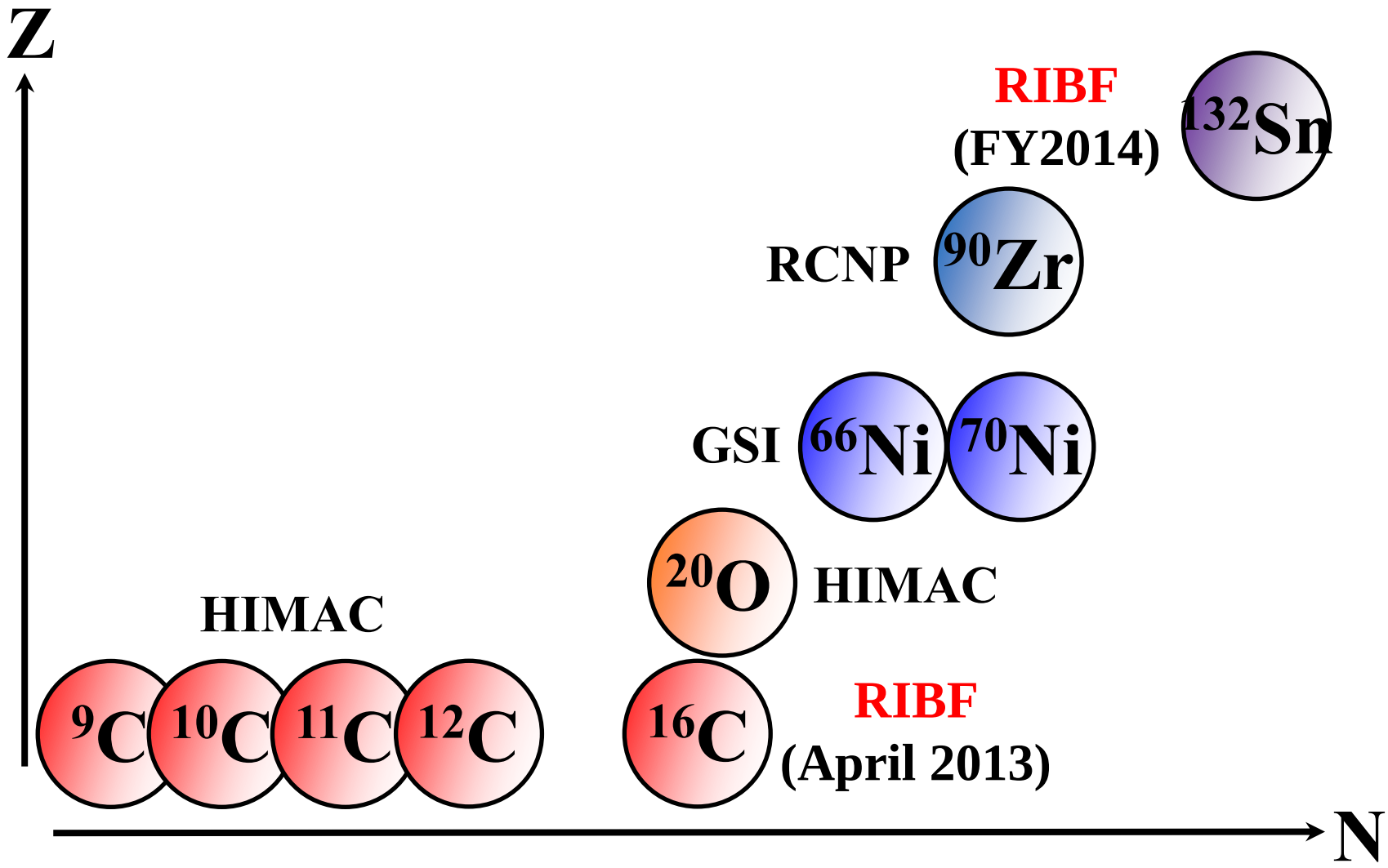






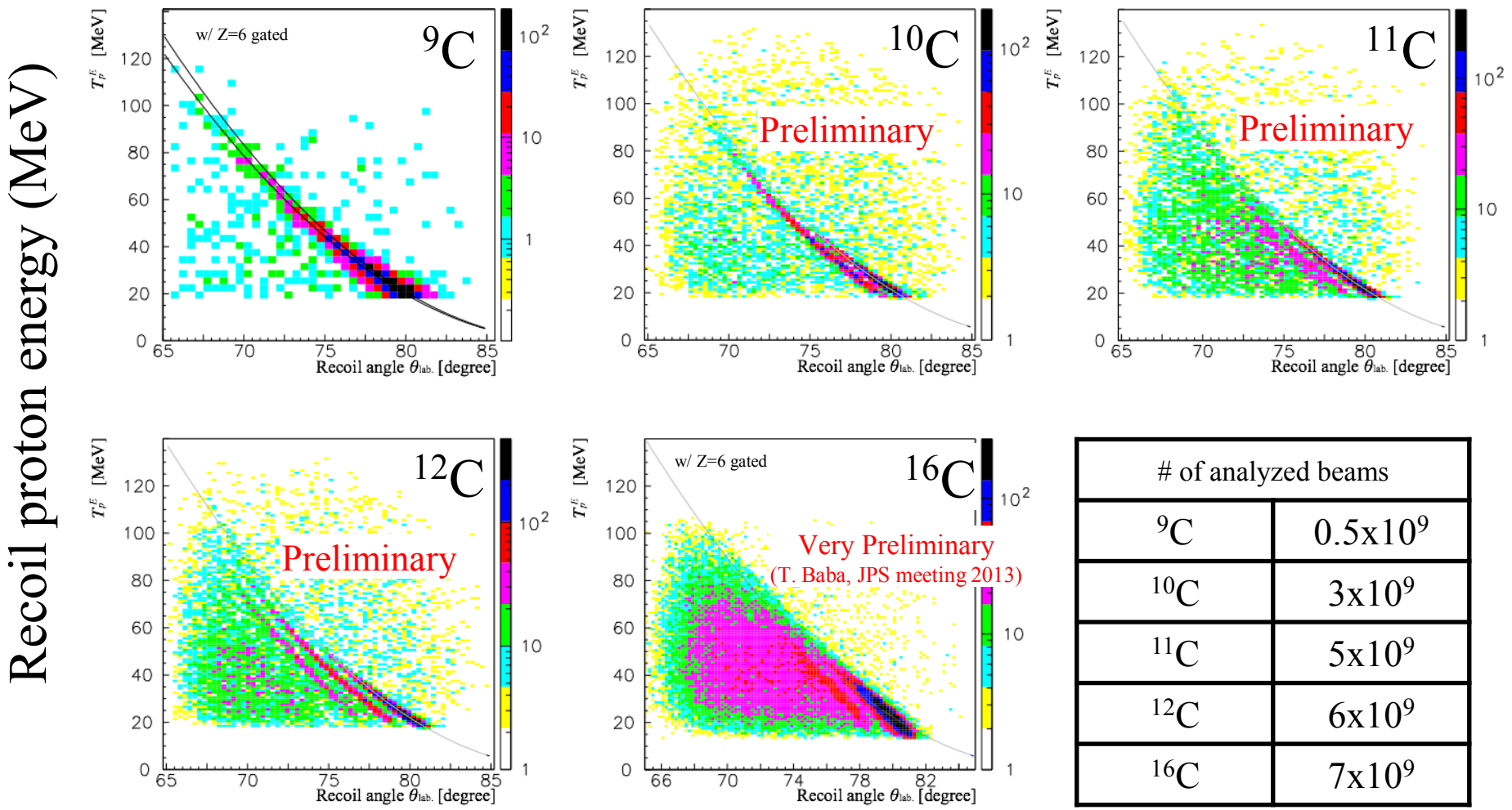
It has been difficult to measure in a wide momentum transfer region.
Experiments in the lower momentum transfer region (<1 fm^{-1}) have been done so far.
- RIKEN, GANIL,MSU : <100 MeV/A
- GSI (He, Li isotope) : 700 MeV/A

5. Experiments



5-1. Light unstable nuclei : ^{9,10,11,12,16}C

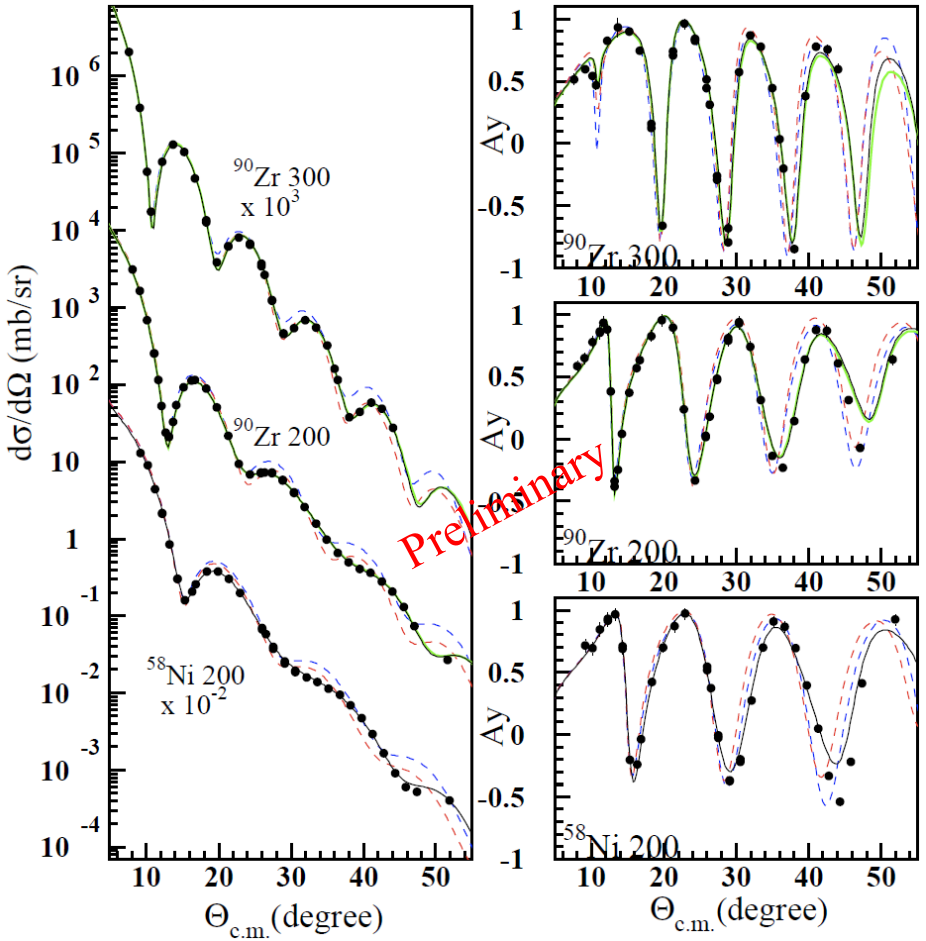
Kinematical correlation : T_p vs θ_p



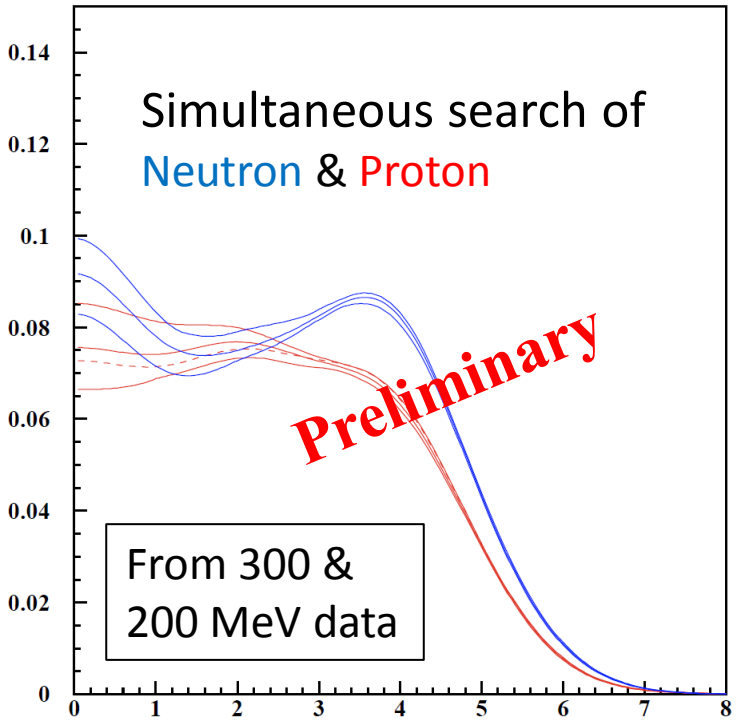
# of analyzed beams	
^{9}C	0.5x10^{9}
^{10}C	3x10^{9}
^{11}C	5x10^{9}
^{12}C	6x10^{9}
^{16}C	7x10^{9}

5-3. simultaneous extraction from two-energy p-elastic data of ^{90}Zr

Fitting results for ^{90}Zr @ **200** & **300** MeV



Extracted densities of ^{90}Zr



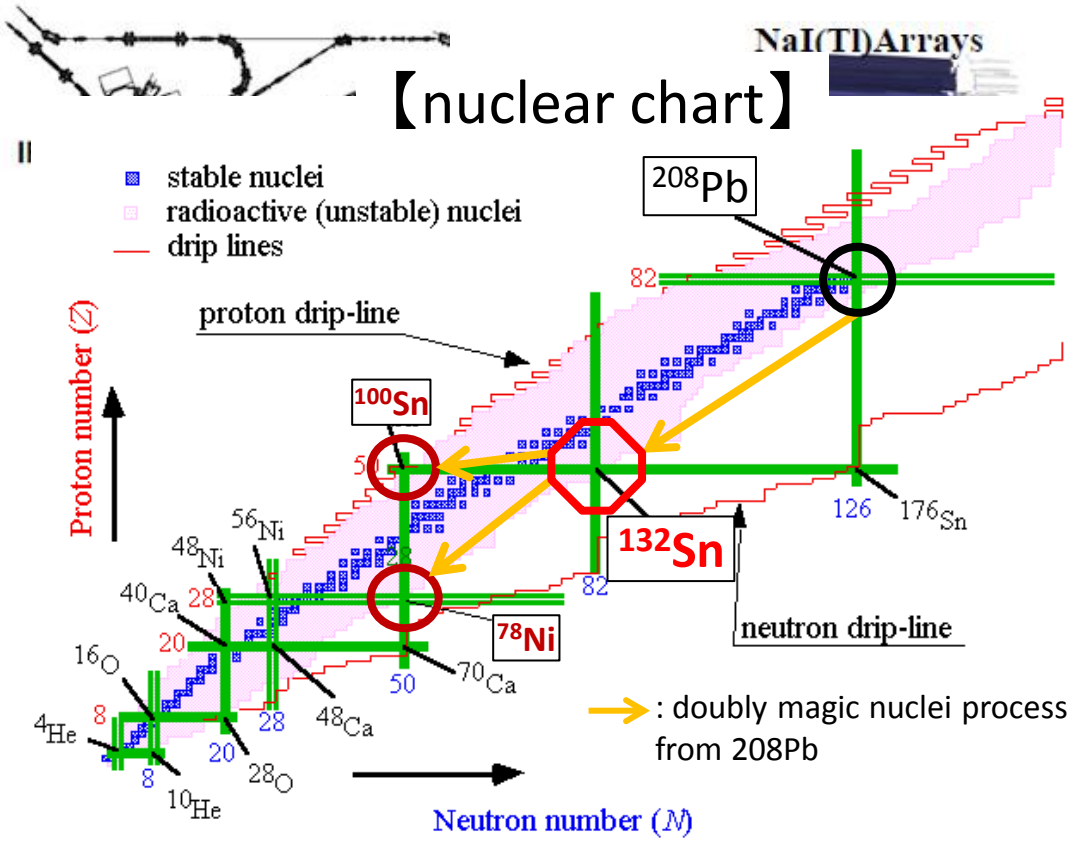
r_n	r_p	Δr_{np}
4.300(17)	4.210(20)	**0.090(26)**

6. ESPRI at RIBF

Toward extraction of proton & neutron densities of unstable nuclei

■ Suitable energy & high intensity

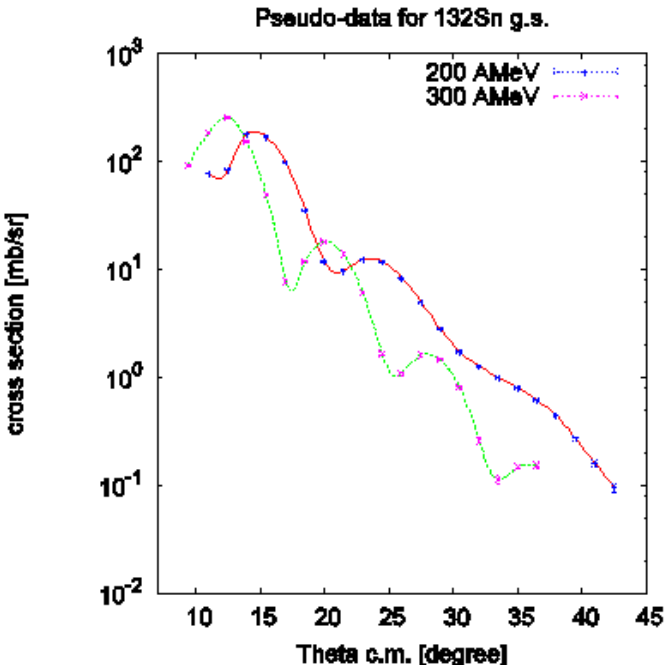
1. **^{16}C** : the first ESPRI measurement with high-intensity RI beams at RIBF **(NP0709-RIBF40)** has been done in this April.
2. **^{132}Sn : flag-ship nuclei as a next step from ^{208}Pb (NP1112-RIBF79)**
   - → **At 200 & 300 MeV/u**
   - → **n-skin thickness to constrain the symmetry energy of asymmetric nuclear matter EOS**
   - → **High-rate & high-Z tolerance of beam-line detector is required (up to ~1MHz & Z~50)**
     MWDC, Solid Ar(Xe), etc. will be tested at HIMAC in 2014

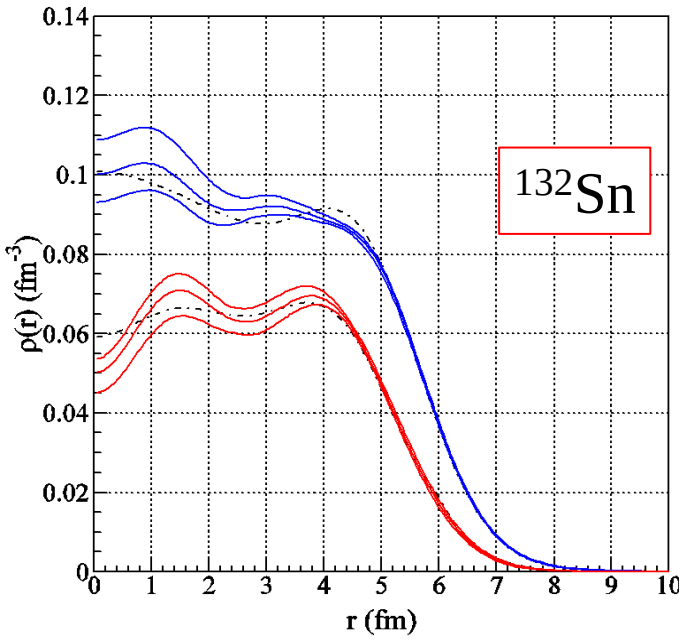


Expected results of ^{132}Sn

- Test of simultaneous extraction of $\rho_p(r)$, $\rho_n(r)$ of ^{132}Sn from pseudo-data of differential cross sections
- Using RIA and relativistic-Hartree calculations as nucleon density distributions.

	g.s. (input)	g.s. (extracted)	δr/r
r_n	4.916	**4.907(23)**	**0.46%**
r_p	4.650	**4.612(49)**	**1.1%**
Δr_{np}	0.266	**0.295(54)**	--





7. Summary

1. ESPRI @ HIMAC, Chiba and GSI, Germany. → Successfully done!
   - ✓ **HIMAC-P179&P213** : **^{9}C**, ^{10,11}C, ^{20}O (FY2007-2009) [Y. Matsuda, et al., Phys. Rev. C87, 034614(2013)]
   - ✓ **GSI-S272** : ^{66,70}Ni (FY2009-2010)

   →1mm-t & 30mm-ϕ *p*SHT [Y. Matsuda, et al.,NIMA643,6(2011)], energy resolution of ~500keV(σ)

   →still large experimental errors due to low statistics

2. Test of the simultaneous extraction of $\rho_p(r)$ & $\rho_n(r)$ from proton elastic scattering data at 200, 300 MeV/u
   - ✓ *two-energy* analysis method is now being developed with stable nuclei.
   - ✓ **RCNP-E366** : ^{90,92,94}Zr (FY2012)
   - ☐ **RCNP-E375** : ^{12,13,14}C (FY2013-2014)

   →feasibility test experiment (E366) shows good results.

3. ESPRI @ RIBF with high-intensity RI beam
   - ✓ **NP0709-RIBF40** : ^{16}C at 300 MeV/u (light unstable nuclei; successfully done in April 2013!)
   - ☐ **NP1112-RIBF79** : **^{132}Sn** at 200&300 MeV/u (heavy unstable nuclei; approved by 2011 NP-PAC)
     - ☐ Detectors are now being developed.
     - ☐ Will be performed in 2015 (14 days).

4. Stable nuclei
   - ✓ Neutron densities of Sn & Pb isotopes, neutron skin of ^{208}Pb
   - ☐ Neutron skin of **^{48}Ca, ^{90}Zr**

5. Future work?
   - ☐ HI+HI elastic scattering → $\rho \sim 2\rho_0$: T. Furumoto, et. al,. PrC85,044607(2012)

Elastic Scattering of Protons with RI beams (ESPRI) project

Collaborators

S.Terashima (Beihang Univ.)
Y.Matsuda (RCNP)
H.Sakaguchi (RCNP)
H.Otsu (RIKEN)
T.Baba (Kyoto Univ.)

RIKEN
H.Takeda
K.Ozeki
K.Yoneda

Tohoku Univ.
T.Kobayashi

Kyoto Univ.
T.Kawabata
T.Murakami
M.Tsumura
T.Furuno

Miyazaki Univ.
Y.Maeda

RCNP
I.Tanihata
H.Jin Ong

GSI
S272 collaborators

NIRS
E.Takada
M.Kanazawa

Thank you for your attention.