B01 : Study of neutron matter EOS via the measurement of neutron skin thickness of ^{132}Sn

Juzo ZENIHIRO, RNC

for the **ESPRI** collaboration

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 $\mathsf{E}(\rho,\delta)$: the energy per nucleon

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

- EOS of symmetric nuclear matter $\mathsf{E}(\rho,0)$:

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

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

- The symmetry energy $\mathsf{S}(\rho)$:

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

→ Still less certain !

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

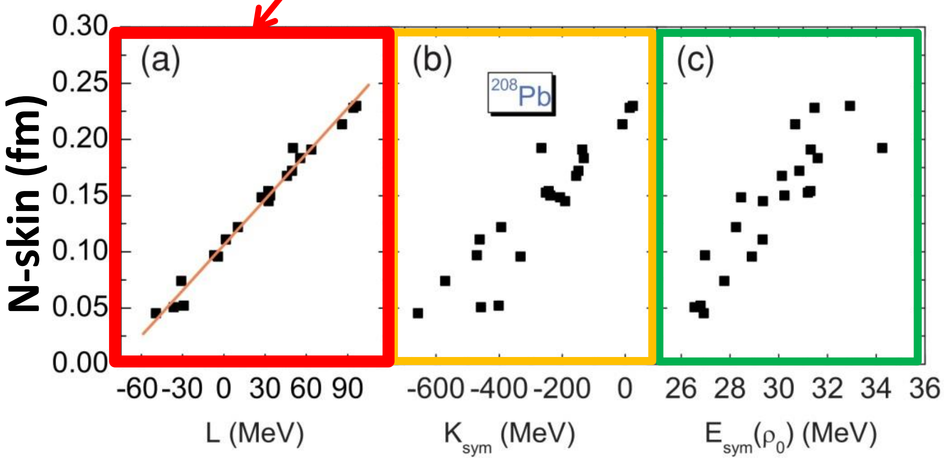
Symmetry energy vs. Neutron skin

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

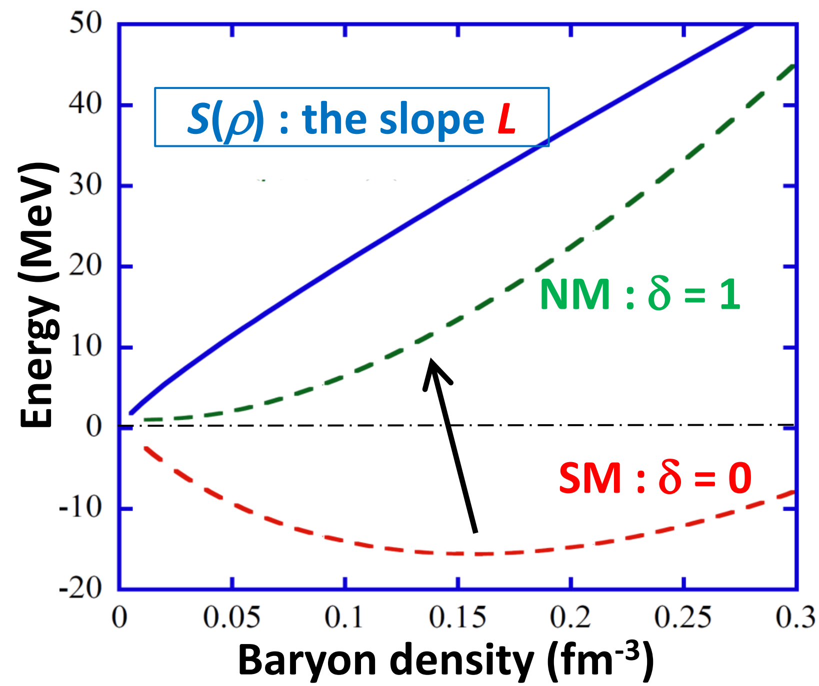
$$S(\rho) = S(\rho_{sat}) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + O(\varepsilon^3)$$

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

Strong correlation!



L.-W. Chen et al., PRC82, 054314.



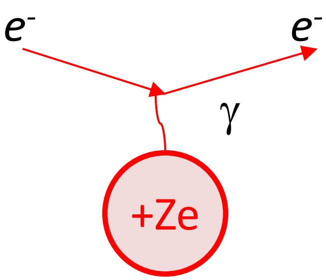
Determine the slope coefficient ***L*** ***of S(ρ)*** → **neutron matter EOS**

Impact on **neutron star** structure

- Radius, cooling system, etc.

Proton elastic scattering
–nuclear form factors–

Electron scattering ; Nuclear charge $\frac{d\sigma}{d\Omega} = \left| F_{ch}^{A}(q) \right|^2 \frac{d\sigma}{d\Omega}_{Mott}$



$$F_{ch}^{A}(q) \Leftrightarrow \rho_{ch}^{A}(r)$$
$$F_{ch}^{p}(q) \cdot F_{p}(q) \Leftrightarrow \rho_{p}(r)$$

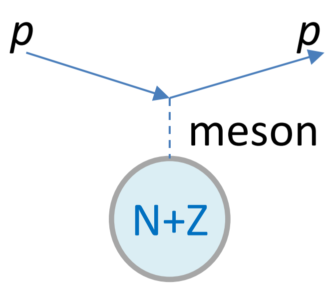
: well established in 1980s

$$\rho_p(r), \rho_n(r)$$

$$\Delta r_{np} = r_n - r_p$$

Similarly...

Proton scattering ; Nuclear matter



$$F_{p+n}(q) \Leftrightarrow \rho_{p+n}(r)$$

: our work

Extraction of density distributions in nuclei

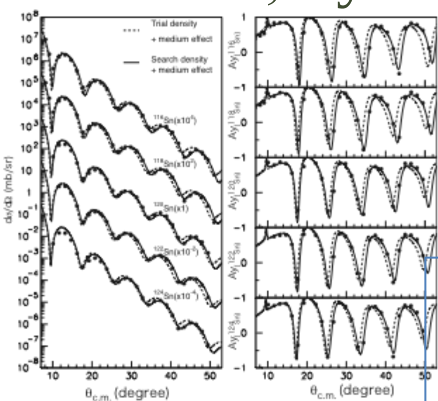
Polarized proton elastic scattering at 300MeV (RCNP, Osaka University)
⇒We have succeeded in extracting neutron density distributions of Sn, Pb isotopes systematically.

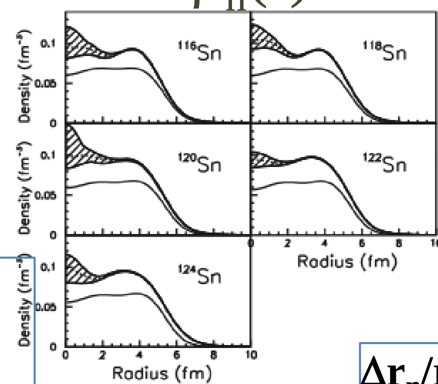
Stable nuclei

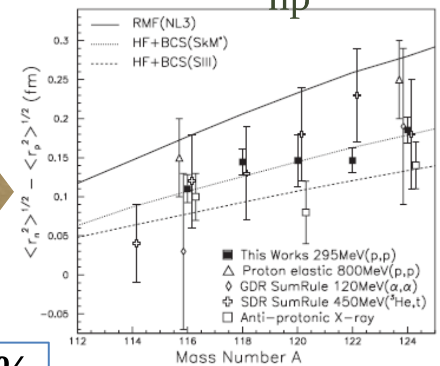
$d\sigma/d\Omega$, Ay $\rho_n(r)$ Δr_{np}

Sn

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





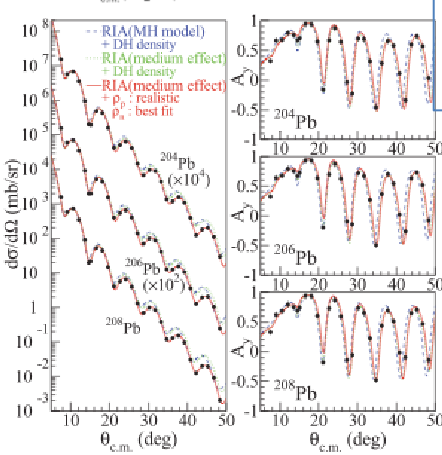


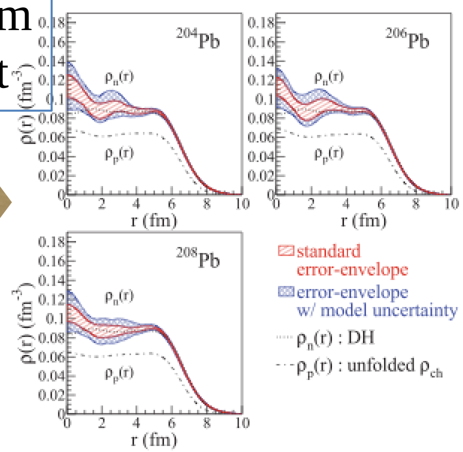
RIA + Medium Effect

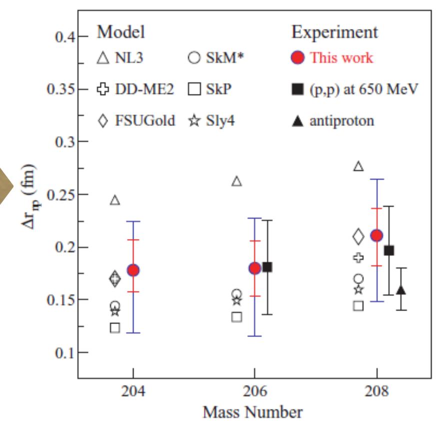
$\Delta r_n/r_n < 0.5\%$

Pb

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



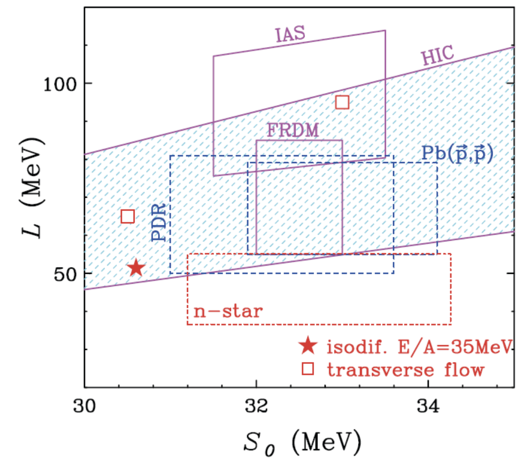


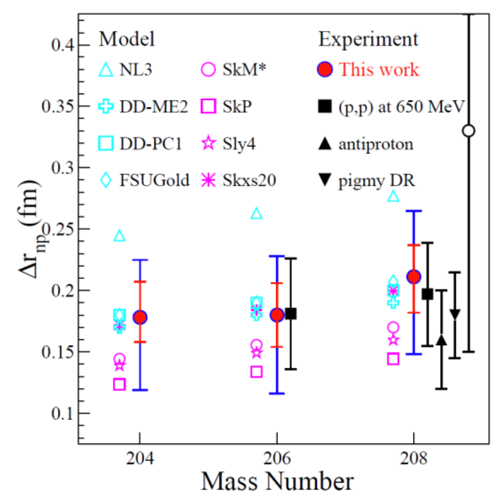


Unstable nuclei such as ^{132}Sn → ESPRI project

Symmetry energy experiments

- SAMURAI-TPC (SPiRIT) : π+/π- ratio
  - HI collision
- (p, p’) at 0 degree : dipole polarizability
  - proton inelastic scattering
- PREX-II, CREX : neutron radius & skin thickness
  - parity-violating electron elastic scattering
  - Stable nuclei : ^{208}Pb, ^{48}Ca (2015, 2016)
- ESPRI : neutron radius & skin thickness
  - proton elastic scattering
  - Stable & unstable nuclei





2. Unstable nuclei -ESPRI project-

Application to exotic nuclei with large isospin asymmetry

-toward ^{132}**Sn** -

ESPRI project

Unstable nuclei →experimental data itself is rare !

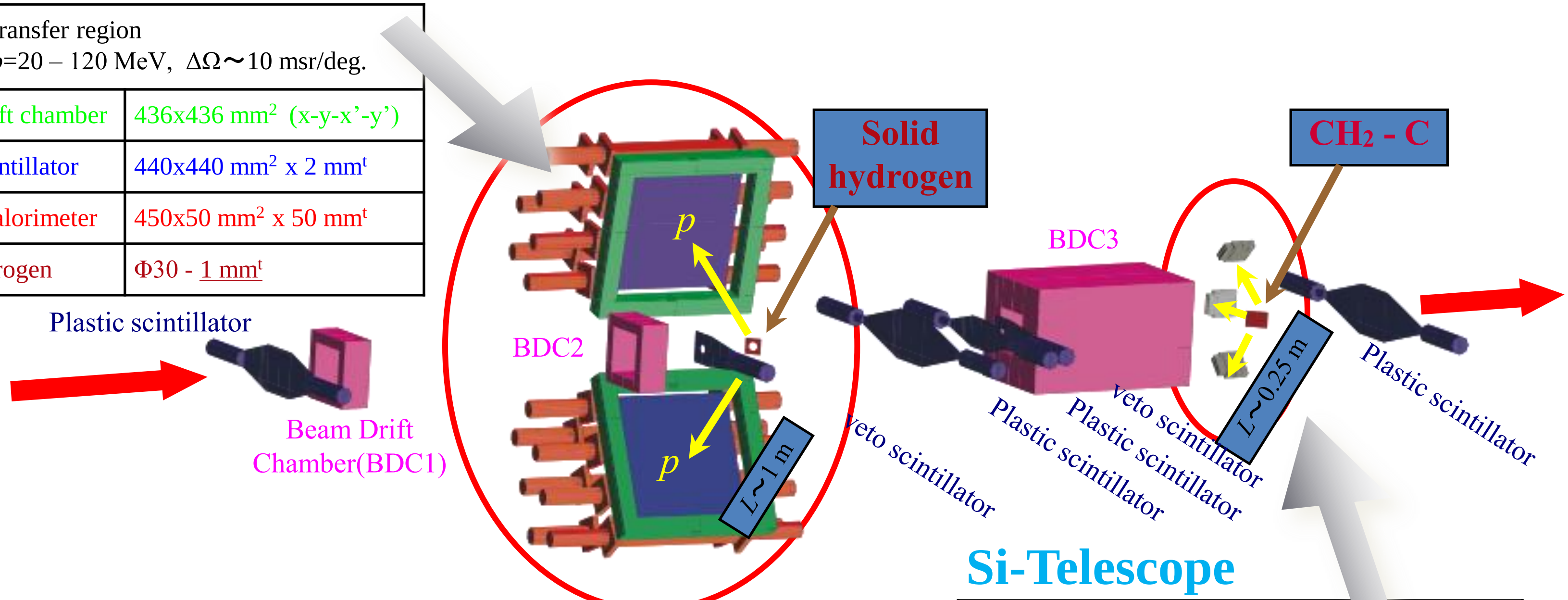
→ Elastic Scattering of Protons with **RI** beam (**ESPRI**) project

- ✓ To measure angular distributions of differential cross sections
- ✓ To deduce the proton & neutron densities of unstable nuclei

Recoil Proton Spectrometer (RPS)

Large momentum transfer region
θ_{lab} = 66 - 80°, Ep=20 – 120 MeV, ΔΩ∼10 msr/deg.

RPS	Recoil drift chamber	436x436 mm^2 (x-y-x'-y')
	plastic scintillator	440x440 mm^2 x 2 mm^t
	NaI(Tl) calorimeter	450x50 mm^2 x 50 mm^t
Target	Solid hydrogen	Φ30 - 1 mm^t



Si-Telescope

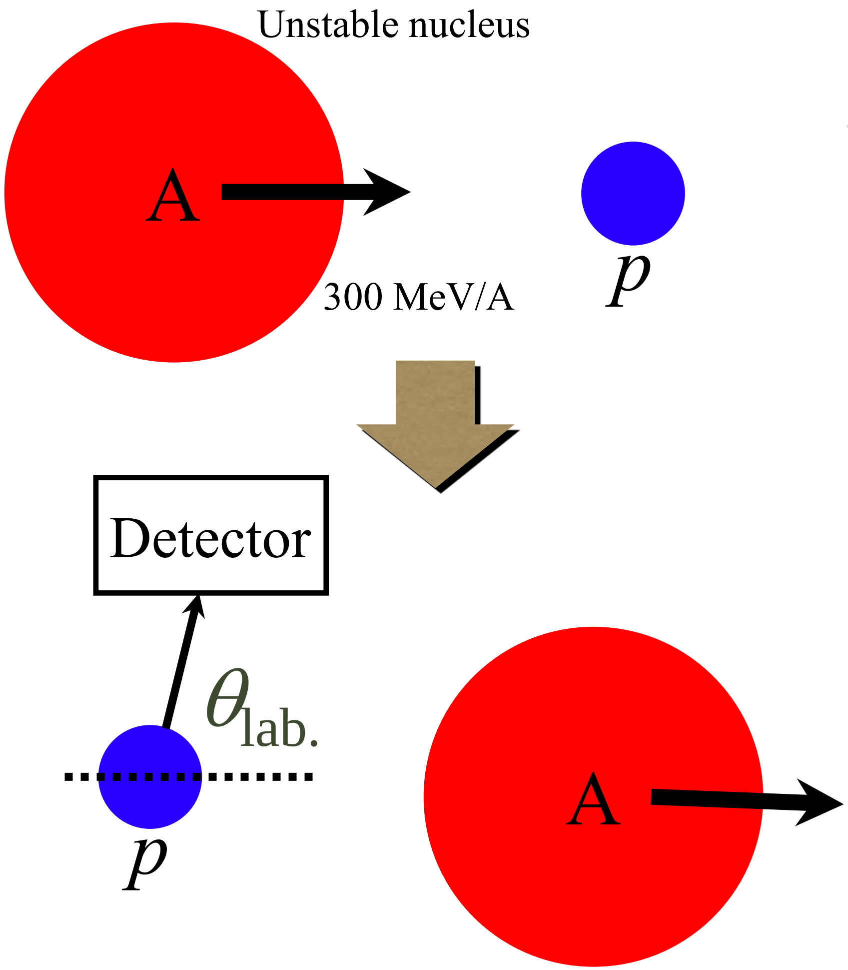
Small momentum transfer region
θ_{lab} = 75 - 85°, Ep=5 – 50 MeV ΔΩ∼14 msr/deg.

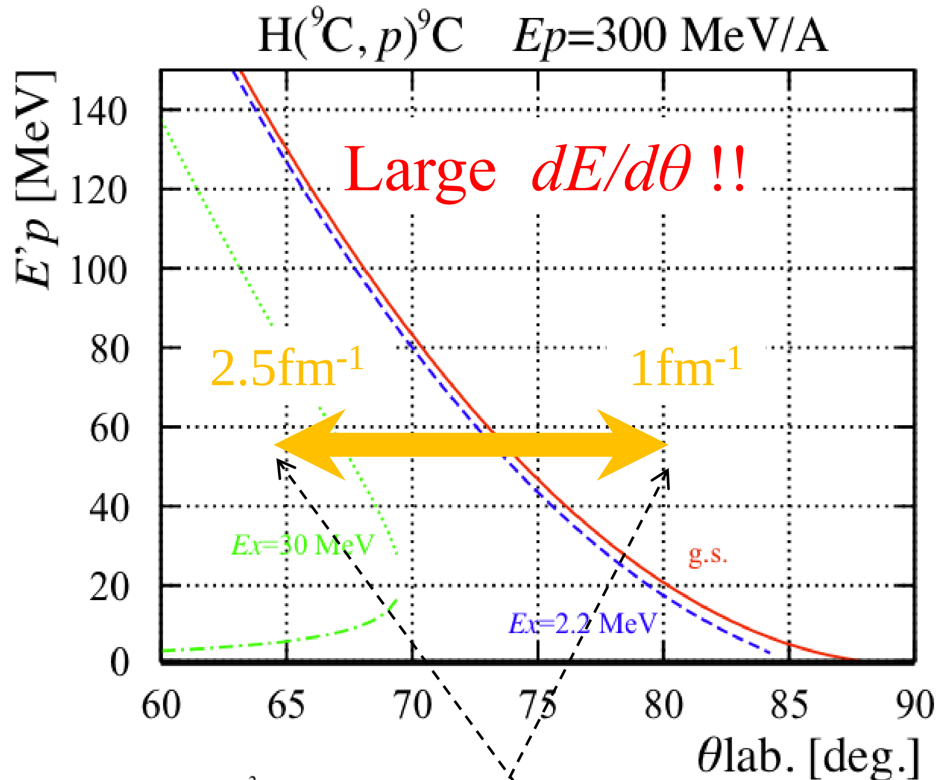
Telescope	Si strip	70x50 mm^2 x 300 μm^t
	CsI(Tl)	70x50 mm^2 x 25.5 mm^t
Target	CH_2 - C	70x50 mm^2 x 0.01—0.1mm^t

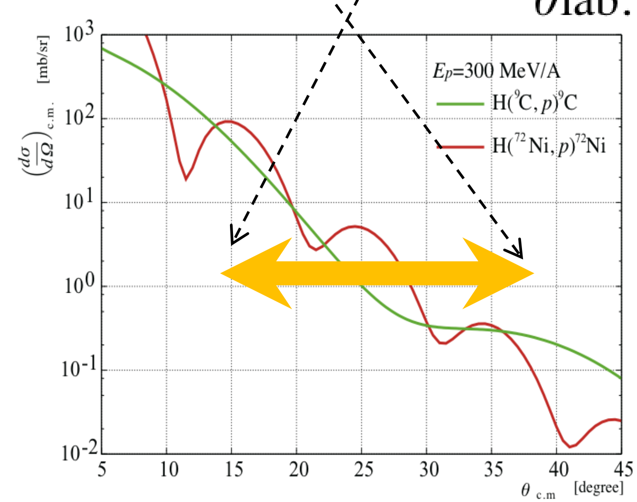
- ◆ Missing mass spectrometer : $P^{\mu}_{beam}+P^{\mu}_{p} \Rightarrow E_x$ (ΔEx~400 keV)
- ◆ Cover extensive momentum transfer region : up to ∼2.5 fm^{-1}

Kinematics of ESPRI

Inverse kinematics : fixed probe





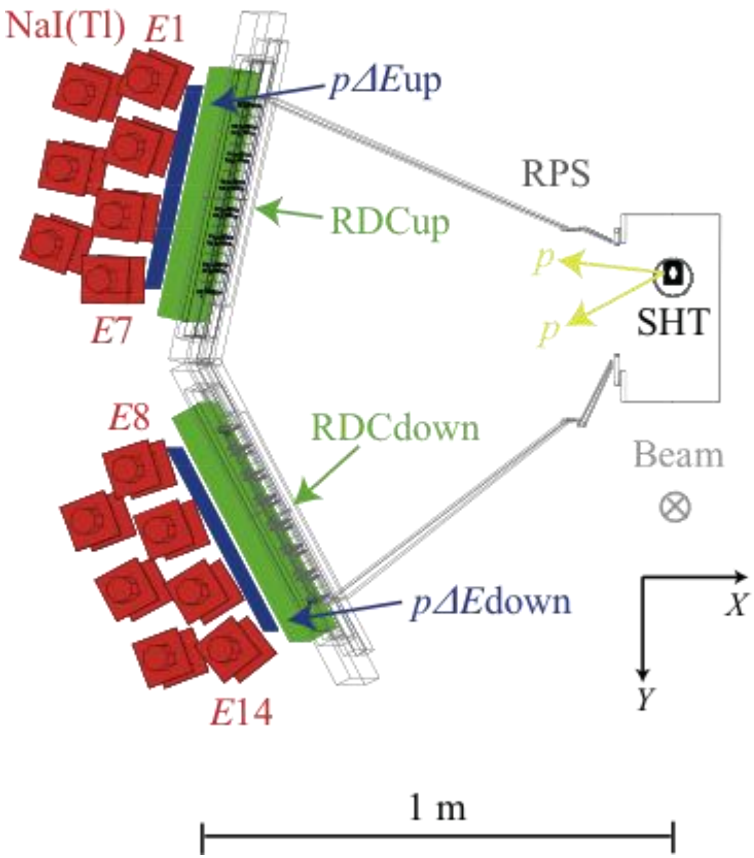


It has been difficult to measure in a wide momentum transfer region.

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

Recoil Proton Spectrometer (RPS)



	Solid H_2 (SHT)	RDC	$p\Delta E$	E
material	Para H_2	Ar+C_2H_6	Plastic	NaI(Tl)
effective area	φ 30 mm	436 x 436 mm^2	440 x 440 mm^2	431.8 x 45.72 mm^2
thickness	1 mm	69.4 mm	2.53 / 3.09 mm	50.8 mm
Resolution		500 μm	TOF : 0.1 nsec	0.3 %(80 MeV)

Para Solid Hydrogen Target (*p*-SHT)

Normal hydrogen at 300 K

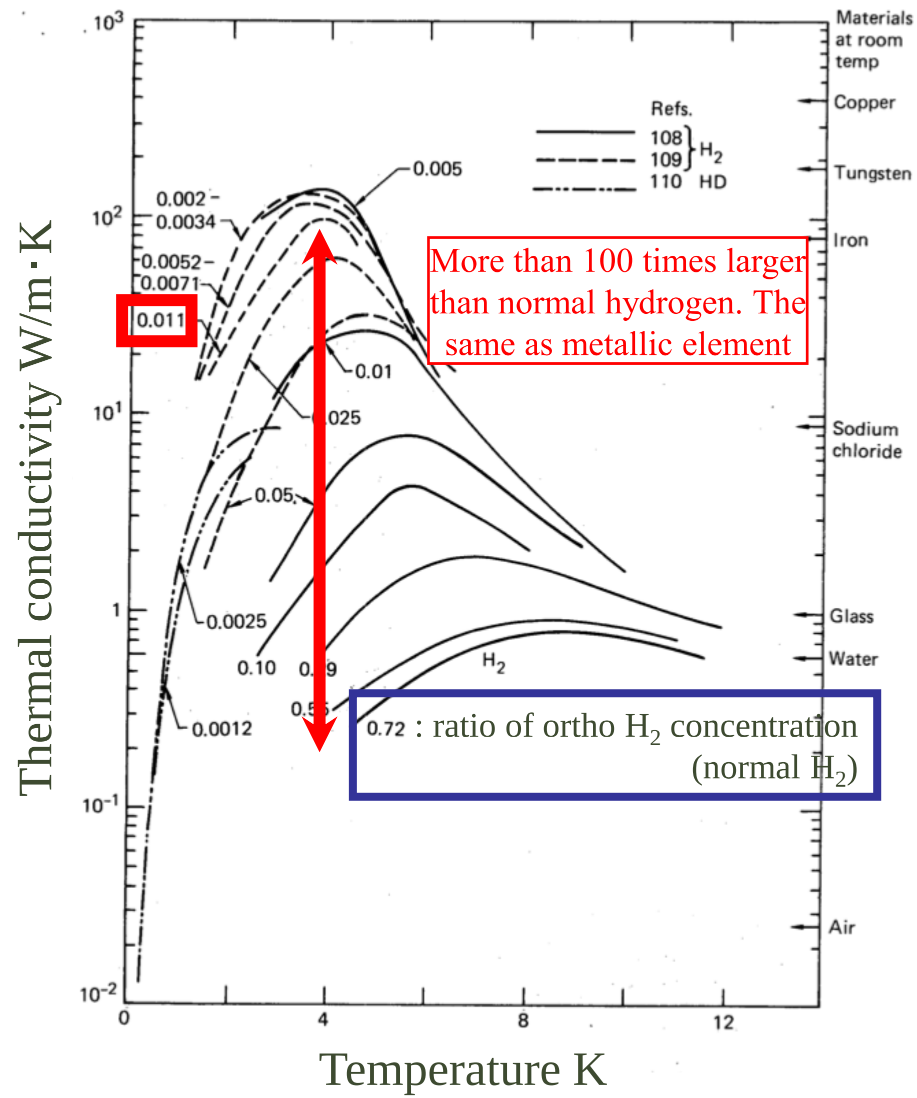
•*para*-H_2 : *ortho*-H_2 = 1: 3

Ortho-para converter (FeO(OH) catalysis)

achieve ~100% *para*-H_2 !!

Y. Matsuda *et al.*

Success of 1-mm-thick 30-mm-ϕ SHT !!!



P.C.Souers, CRYOGENIC HYDROGEN DATA PERTINENT TO MAGNETIC FUSION ENERGY, Lawrence Livermore Laboratory Report UCRL-52628 (1979) Livermore California.

108 : R.W.Hill and B.Schneidmesser, Z.Physik. Chem. Neue Folge 16 (1958).

109 : R.G.Bohn and C.F.Mate, Phys. Rev. B 2 (1970) 2121.

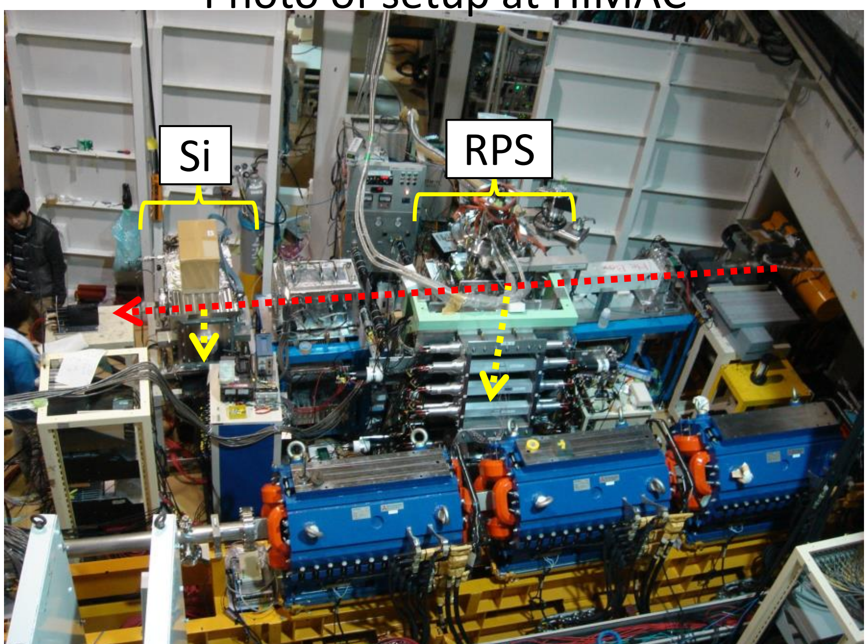
R & D at HIMAC

◆Test of the detector system

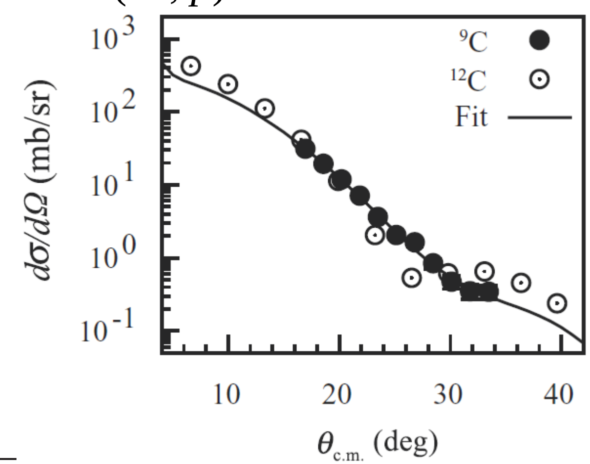
- ✓ Each detectors were developed at several accelerator facilities.
- ✓ Total setup was tested using ^{9,10,11}C, ^{20}O at HIMAC

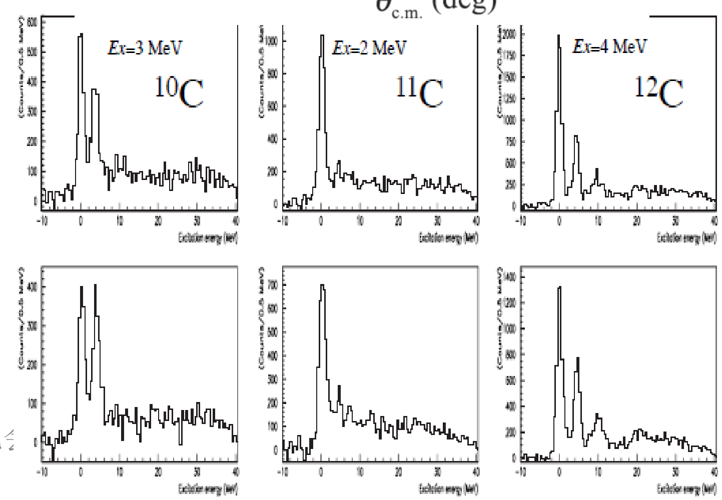
→ Successfully performed

Photo of setup at HIMAC

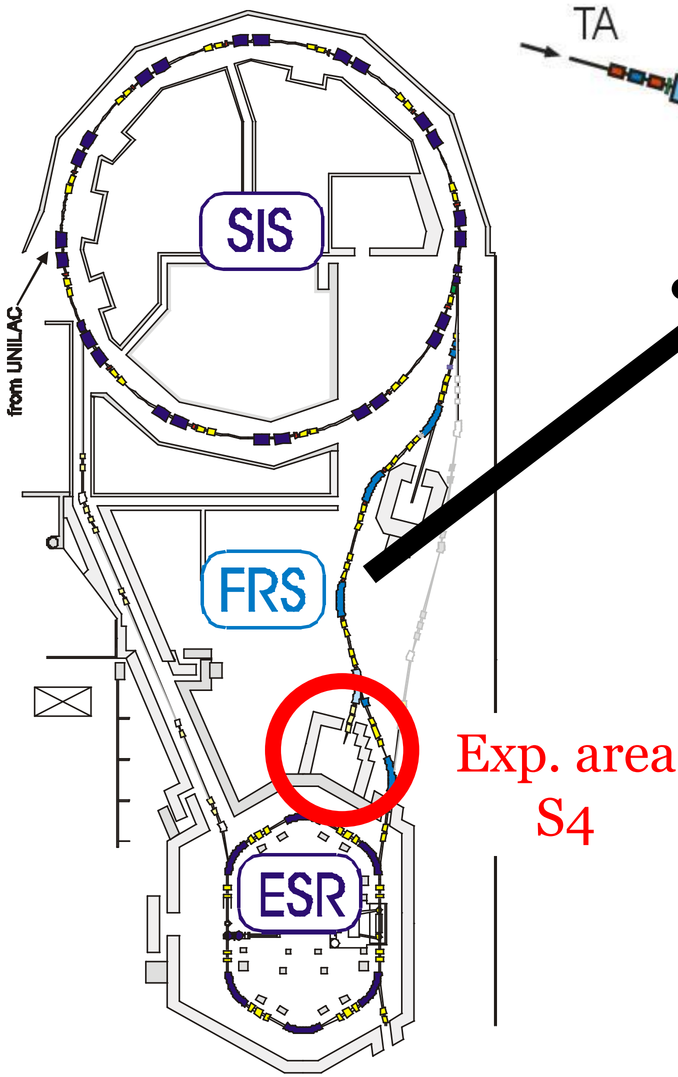


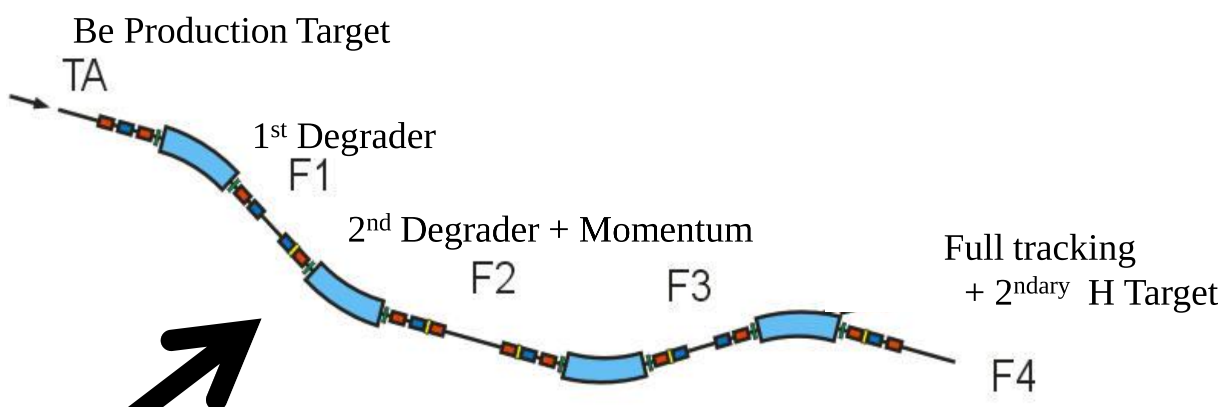
H(^{9}C, *p*) 280 - 300 MeV/A





R & D at GSI

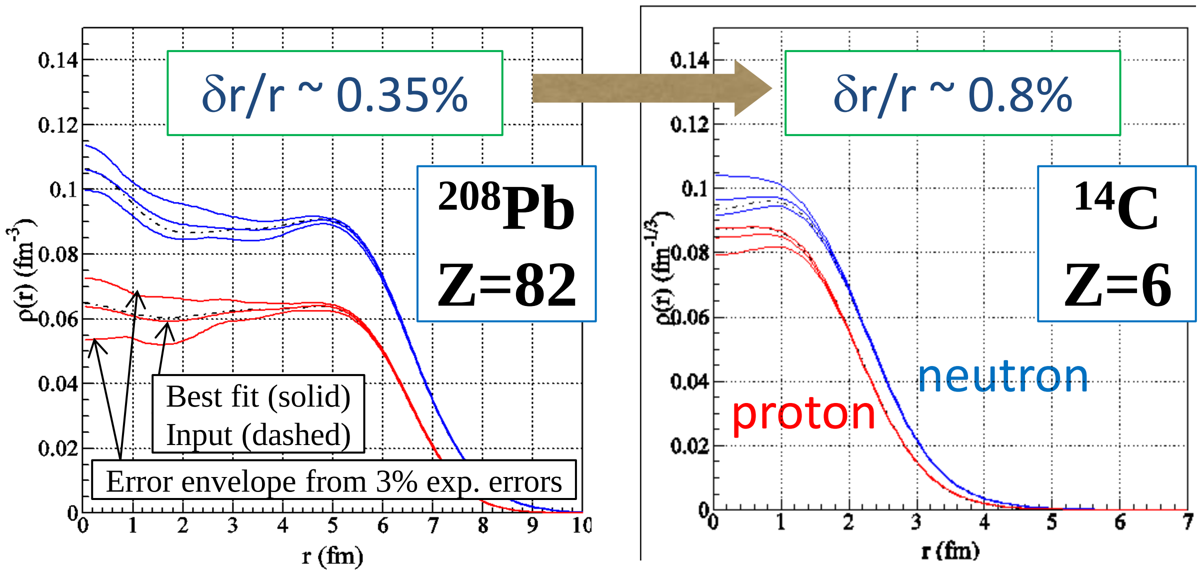




Secondary beam	^{66,70}Ni	
	300 MeV/u	
	3x10^{3} (^{70}Ni), 2x10^{4} (^{66}Ni)/spill	
Target	SHT 1 mm^{t} (8.6 mg/cm^{2})	
Primary beam	^{86}Kr (34+)	
	520 (^{70}Ni), 540 (^{66}Ni) MeV/u	
	2-3x10^{10} counts/spill	
Spill structure	3 seconds(duty factor 33%)	
Measurement time	8+1 (^{70}Ni), 2+1 (^{66}Ni) days	

Feasibility test of simultaneous extraction of $\rho_p(r)$, $\rho_n(r)$

Simulation results from ***pseudo*-data** (**ds/dΩ, A$_y$**) of ^{208}Pb, ^{14}C(p,p) at 200, 300 MeV with 3% experimental errors.



A proposal of test of this method using real data of two-energy proton elastic scattering from Zr isotopes was approved and the experiment has been performed at 2012!

→ Data analysis is now ongoing.

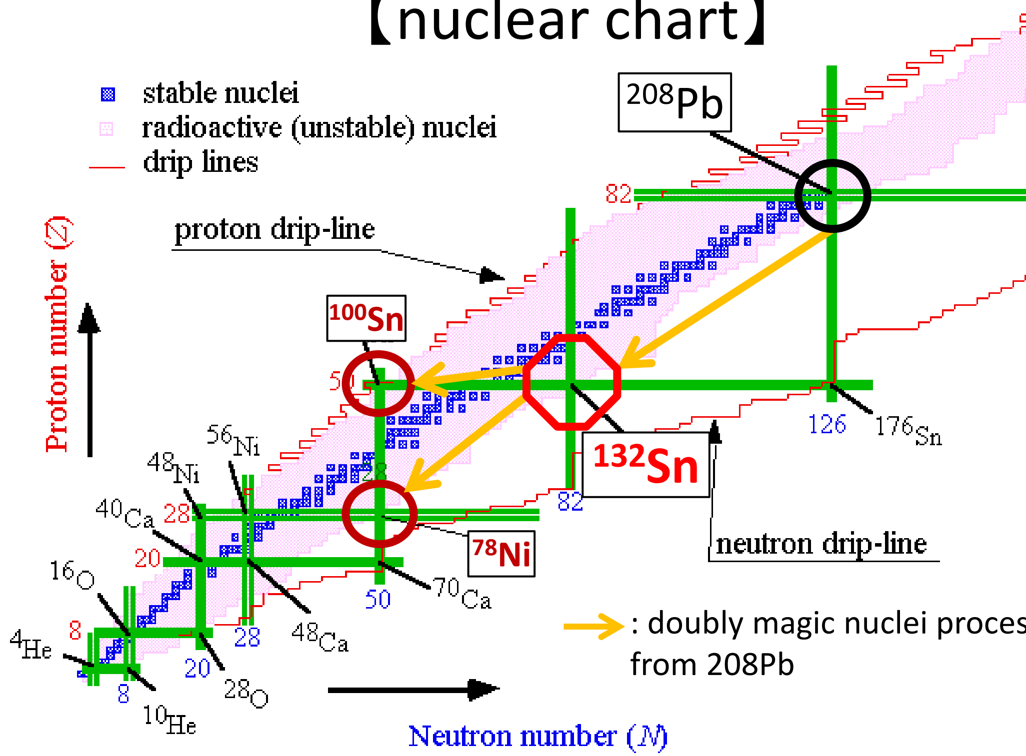
ESPRI at RIBF

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)**
   - → **n-skin thickness to constrain the symmetry energy of nuclear EOS**
   - → **Test of the measurement of isomer-132Sn(p,p) reaction**
   - → **High-rate tolerance of beam-line detector is required (~1MHz)**

【nuclear chart】

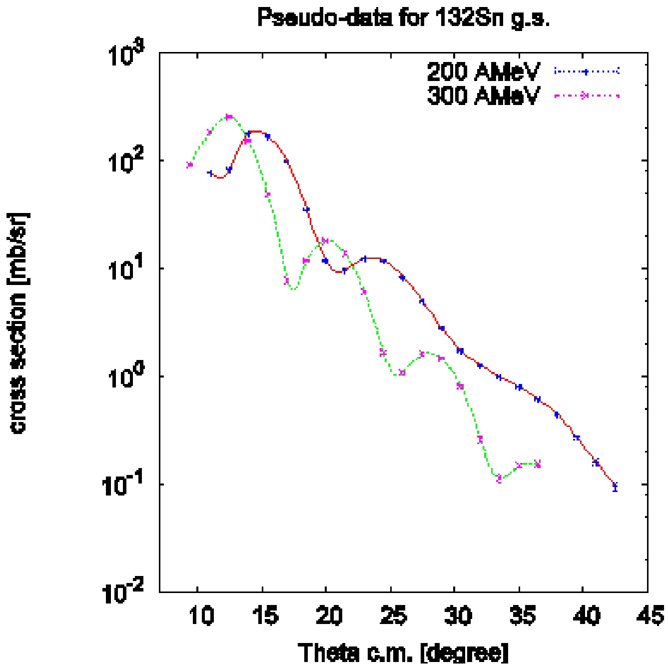


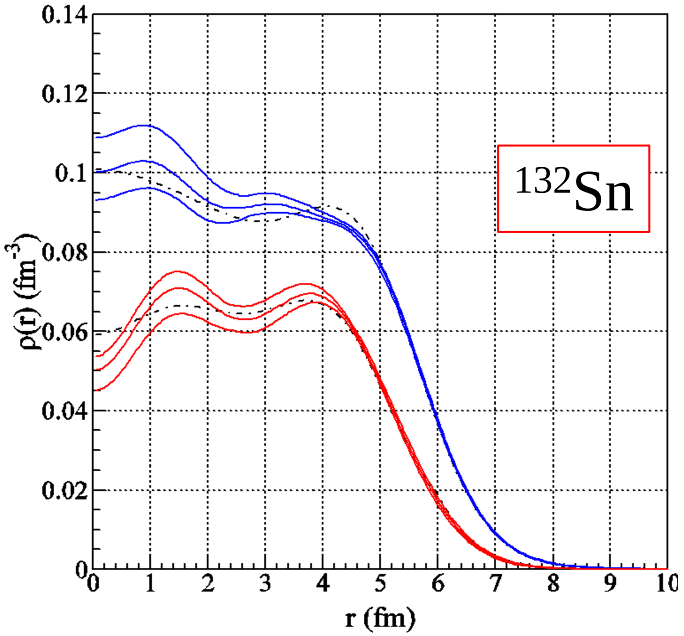
→ : doubly magic nuclei process from 208Pb

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)**	**1.0%**
Δr_{np}	0.266	**0.295(54)**	**--**





Summary of ESPRI

1. R & D at HIMAC, Chiba and GSI, Germany. → Successfully done!
   - ✓ HIMAC-P213 : ^{9}C, ^{10,11}C, ^{20}O (FY2006-2008) [Y. Matsuda, et al., Phys. Rev. C87, 034614(2013)]
   - ✓ GSI-S272 : ^{66,70}Ni (FY2009-2010)

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

   →still large experimental errors by low statistics →**ESPRI@RIBF**

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 developed with stable nuclei.
   - ✓ RCNP-E366 : $^{90,92,94(,96)}$Zr (FY2012)
   - ☐ RCNP-E375 : ^{12,13,14}C (FY2012-2013)

   →feasibility test by generating pseudo-data shows good results. →**ESPRI@RIBF**

3. ESPRI @ RIBF with high-intensity RI beam for more precise data
   - ✓ NP0709-RIBF40 : ^{16}C (light unstable nuclei; successfully done in April 2013)
   - ☐ NP1112-RIBF79 : **^{132}Sn** (heavy unstable nuclei; approved by 2011 NP-PAC)
     - ☐ Detectors are now being developed.
     - ☐ Will be performed in FY2014-2015 (14 days).

4. Stable nuclei
   - ☐ Neutron skin of **^{48}Ca, ^{90}Zr**

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
M. Dozono

Miyazaki Univ.
Y.Maeda

Tohoku Univ.
T.Kobayashi

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

RCNP
I.Tanihata
O.H.Jin

GSI
S272 collaborators

NIRS
E.Takada
M.Kanazawa