Polarized proton elastic scattering and Nucleon density distributions

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outline

1. Nucleon density distributions
2. Polarized proton elastic scattering
3. How to extract
4. Effective *NN* interaction
5. Extraction of $\rho_n(r)$
6. New method of simultaneous extraction of $\rho_p(r)$, $\rho_n(r)$
7. Summary and future perspective

Point-nucleon density distributions

Fundamental information of nuclei; $\rho_p(r), \rho_n(r)$

→ Nuclear size & shape are helpful for comprehensive understanding of nuclear structure & reaction model,

→ <u>**Neutron skin thickness → the nuclear matter EOS**</u>

➢ Stable nuclei

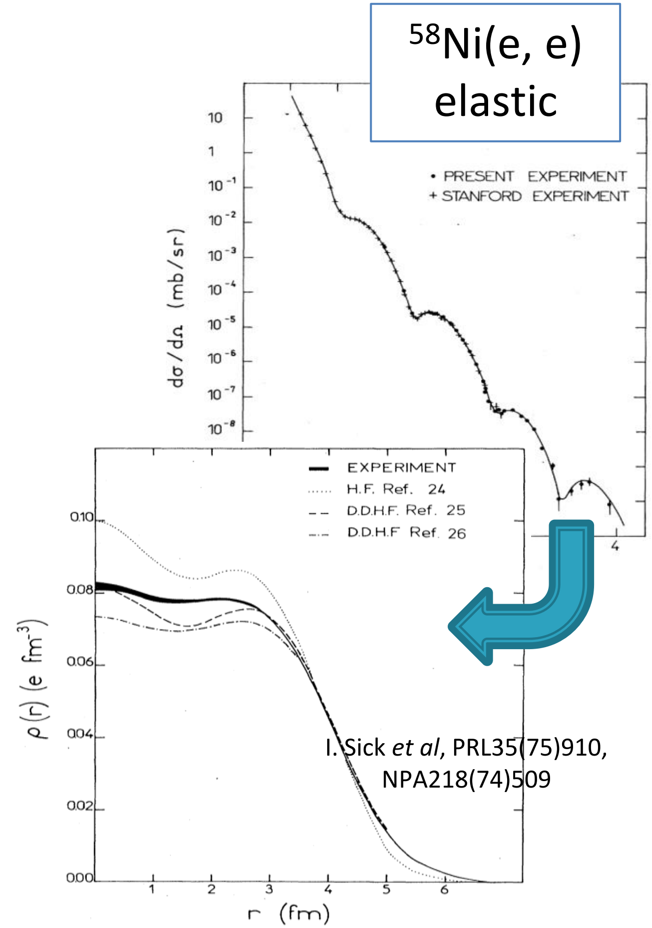
- Proton density distribution $\rho_p(r)$: derived from $\rho_{ch}(r)$
  - Charge distribution $\rho_{ch}(r)$: EM probe (simple)
  - For example, r_{ch} = ^{208}Pb : 5.5010(9) fm (0.02% accuracy)
- <u>Neutron density distribution $\rho_n(r)$</u> : Our work
  - Hadronic probe (very complicated)
  - Suffering from large uncertainties

  ← Incomplete knowledge of *NN* interaction inside nucleus

➢ Unstable nuclei

- Little information about $\rho_p(r)$, $\rho_n(r)$, $\rho_{ch}(r)$!

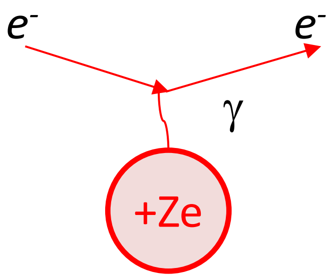
→ <u>Investigate a new method of simultaneous extraction of $\rho_p(r)$, $\rho_n(r)$: Our work</u>



H. de Vries, et al, ADANDT36, 495, and so on.

Polarized proton elastic scattering

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



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

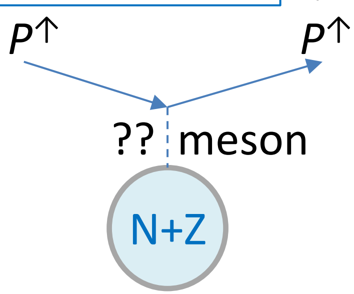
$$F_{ch}^{p}(q) \cdot F_{p}(q) \Leftrightarrow \rho_{p}(r)$$

: well established in 1980s

$$\rho_{p}(r), \rho_{n}(r)$$

$$\Delta r_{np} = r_{n} - r_{p}$$

Proton scattering @ 300 MeV ; Nuclear matter



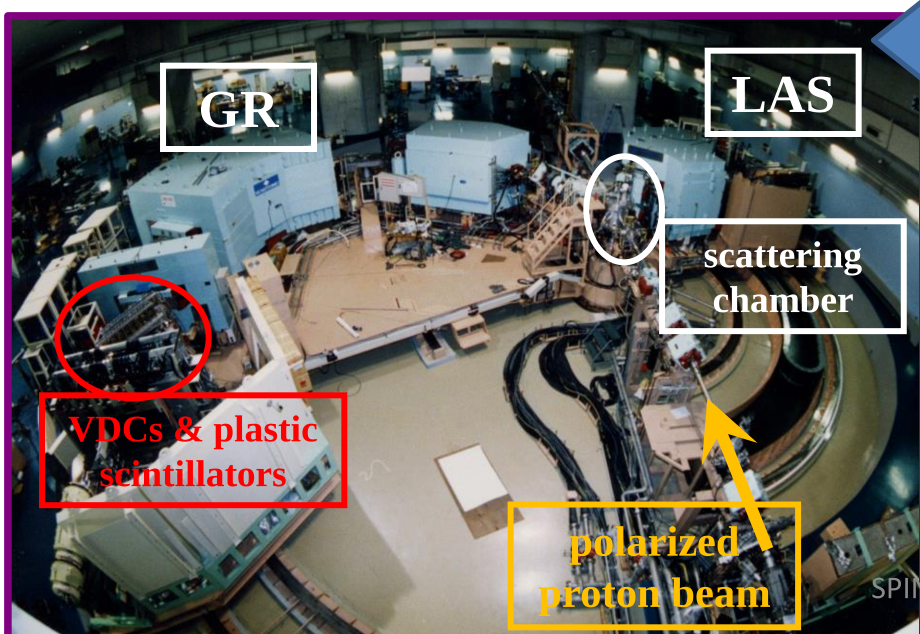
$$F_{p+n}(q) \Leftrightarrow \rho_{p+n}(r)$$

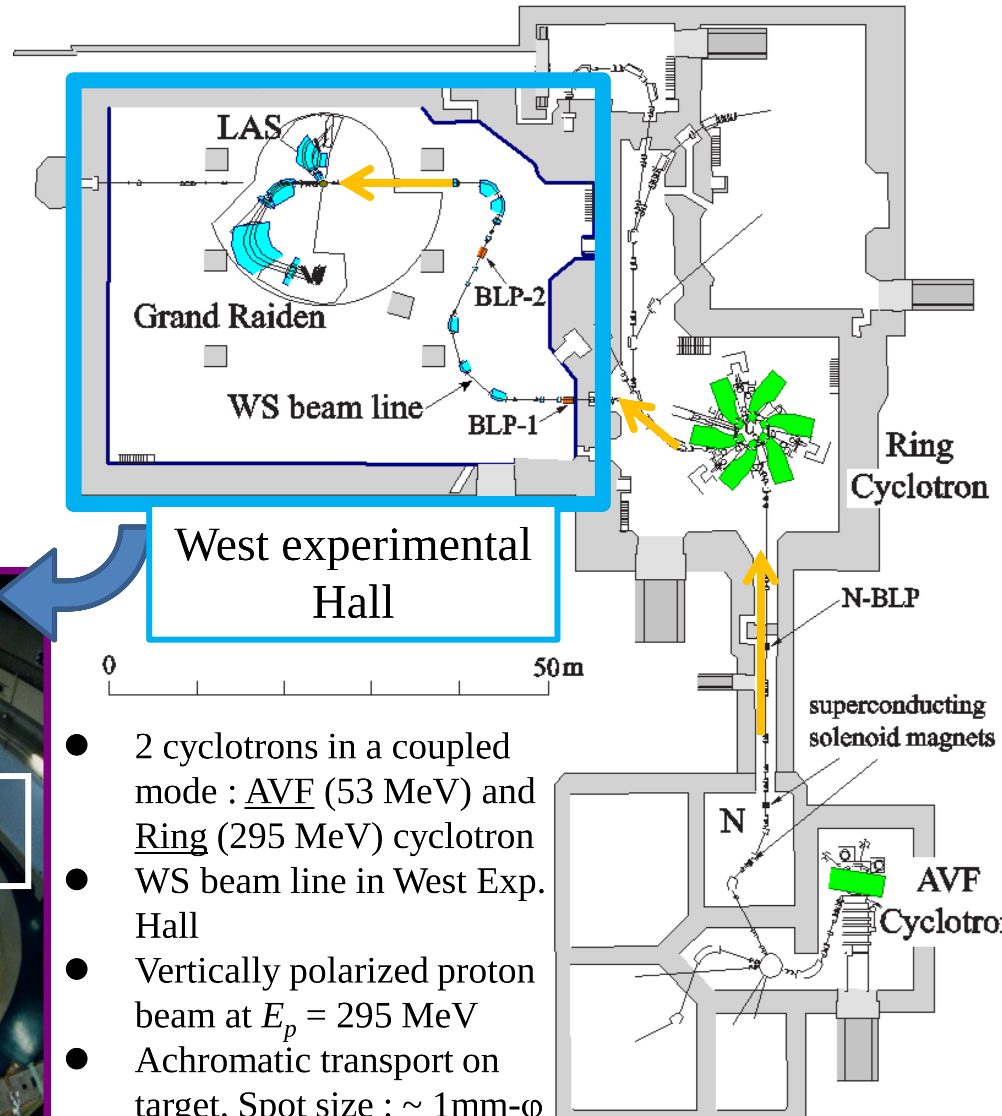
: our work

Ring cyclotron facility @RCNP

Experimental conditions

- Scattering observables : $d\sigma/d\Omega$, A_y, Q
- Beam energy : 295MeV
- Beam polarization : 70~80%
- Energy resolution : <200keV
- Angular & momentum transfer range : 8~50deg., 0.5~3.5fm^{-1}
- Target : $^{40\text{-}48}$Ca, ^{58}Ni, ^{90,92,94}Zr, $^{116\text{-}124}$Sn, $^{204\text{-}208}$Pb





- 2 cyclotrons in a coupled mode : AVF (53 MeV) and Ring (295 MeV) cyclotron
- WS beam line in West Exp. Hall
- Vertically polarized proton beam at E_p = 295 MeV
- Achromatic transport on target. Spot size : ~ 1mm-φ

How to extract neutron densities from proton elastic scattering?

RIA ($t\rho$ optical potential)

Effective *NN* interaction

+ folding

Nucleon density distribution : $\rho_p^V(r)$, $\rho_n^V(r)$, $\rho_p^S(r)$, $\rho_n^S(r)$

C. J. Horowitz, PRC31, 1340(1985).
D. P. Murdock et al., PRC35, 1442(1987).

Modify the RLF interaction to explain real data (^{58}Ni)

input

Fixed

- $\rho_p^V(r)$: unfolding $\rho_{ch}(r)$
- $\rho^S = 0.96\ \rho^V$

Free parameter

- $\rho_n^V(r)$: minimize the χ^2

output

Calculation

ds/dΩ, A_y, Q

χ^2 method

Experimental data

ds/dΩ, A_y, Q

Effective *NN* interaction

Medium modification of RLF *NN* interaction

Medium effect

$$g_j^2 \to g_j^{*2} \equiv \frac{g_j^2}{1 + a_j \rho(r)/\rho_0},$$

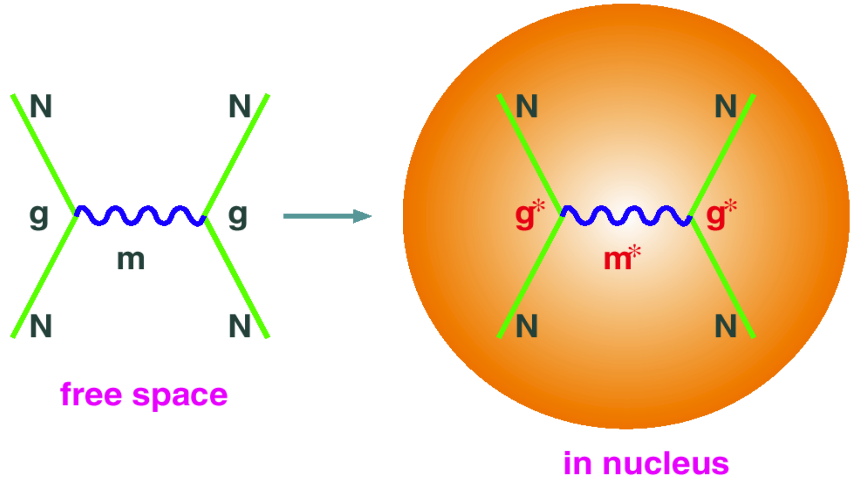
$$m_j \to m_j^* \equiv m_j \left(1 + b_j \rho(r)/\rho_0\right)$$

$$j = \sigma, \omega.$$

→ Universal form of density-dependent terms

→ At ρ=0, same as free *NN* interaction

NN interaction

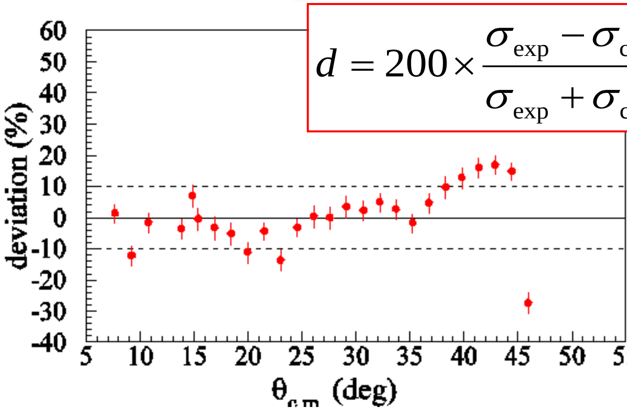


H. Sakaguchi et al., PRC57, 1749.
S. Terashima et al., PRC77, 024317.

Calibration of medium effect by ^{58}Ni

- Four free parameters: a_j, b_j ($j=\sigma, \omega$)
- $\rho_p(r)$: unfolding $\rho_{ch}(r)$
- $\rho_n(r) = (N/Z)\rho_p(r)$

minimum χ2 search

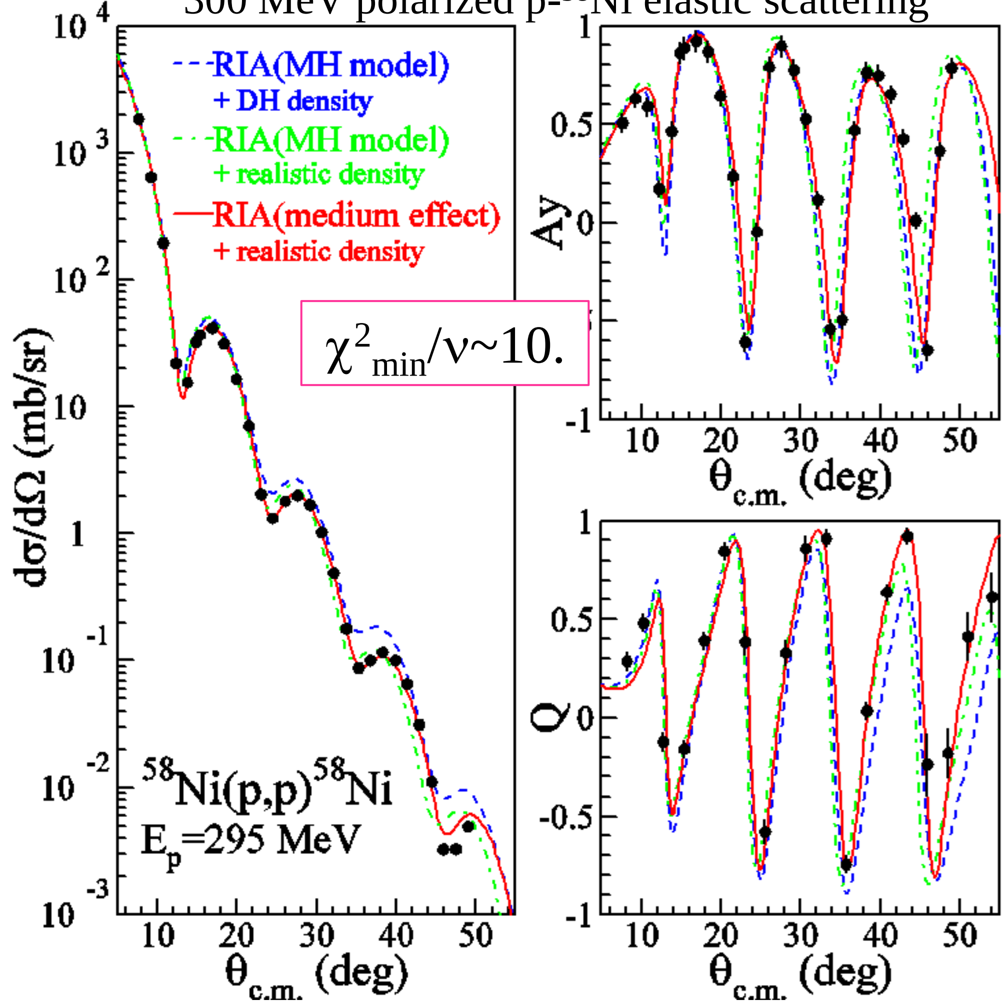


$$d = 200 \times \frac{\sigma_{exp} - \sigma_{calc}}{\sigma_{exp} + \sigma_{calc}}$$

Calibrated medium effect parameters

j	σ	ω
a_j	-0.044(26)	0.037(40)
b_j	0.097(13)	0.075(21)

Differential cross sections & analyzing powers of 300 MeV polarized p-^{58}Ni elastic scattering



$\chi^2_{min}/\nu \sim 10.$

Extraction of neutron densities of Pb isotopes

- Fixed medium effect parameters by ^{58}Ni data: a_j, b_j ($j=\sigma, \omega$)
- $\rho_p(r)$: unfolding $\rho_{ch}(r)$
- $\rho_n(r)$: SOG model independent function

$$\rho_n^{\mathrm{SOG}}(r) = \sum A_i \left(e^{-(r-Ri)^2/\gamma^2} + e^{-(r+Ri)^2/\gamma^2}\right),$$

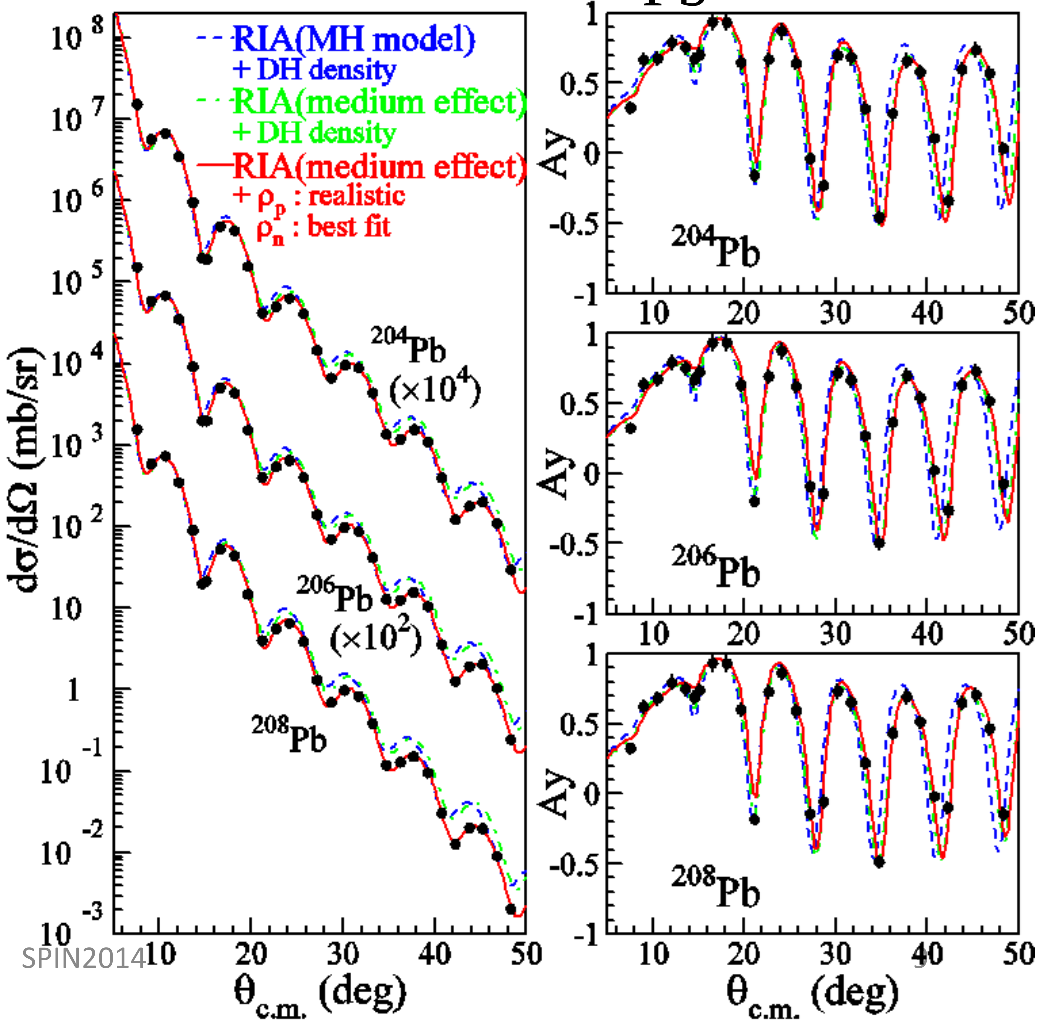
$$A_i = \frac{NQ_i}{2\pi^{3/2}\gamma^3(1+2R_i^2/\gamma^2)}, \sum Q_i = 1$$

Fixed : γ, R_i (same as $\rho_{ch}(r)$)
Free parameters : Q_i (i=1~12)

minimum $\chi 2$ search

reduced χ^2_{min} ~ 4.

proton elastic scattering from ^{204,206,208}Pb

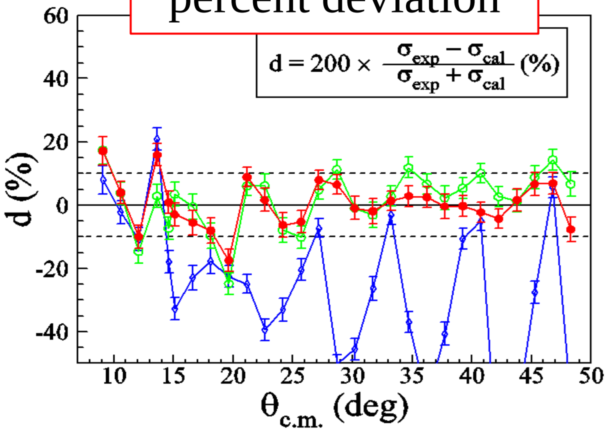


Error-envelope of $\rho_n(r)$

^{208}Pb case

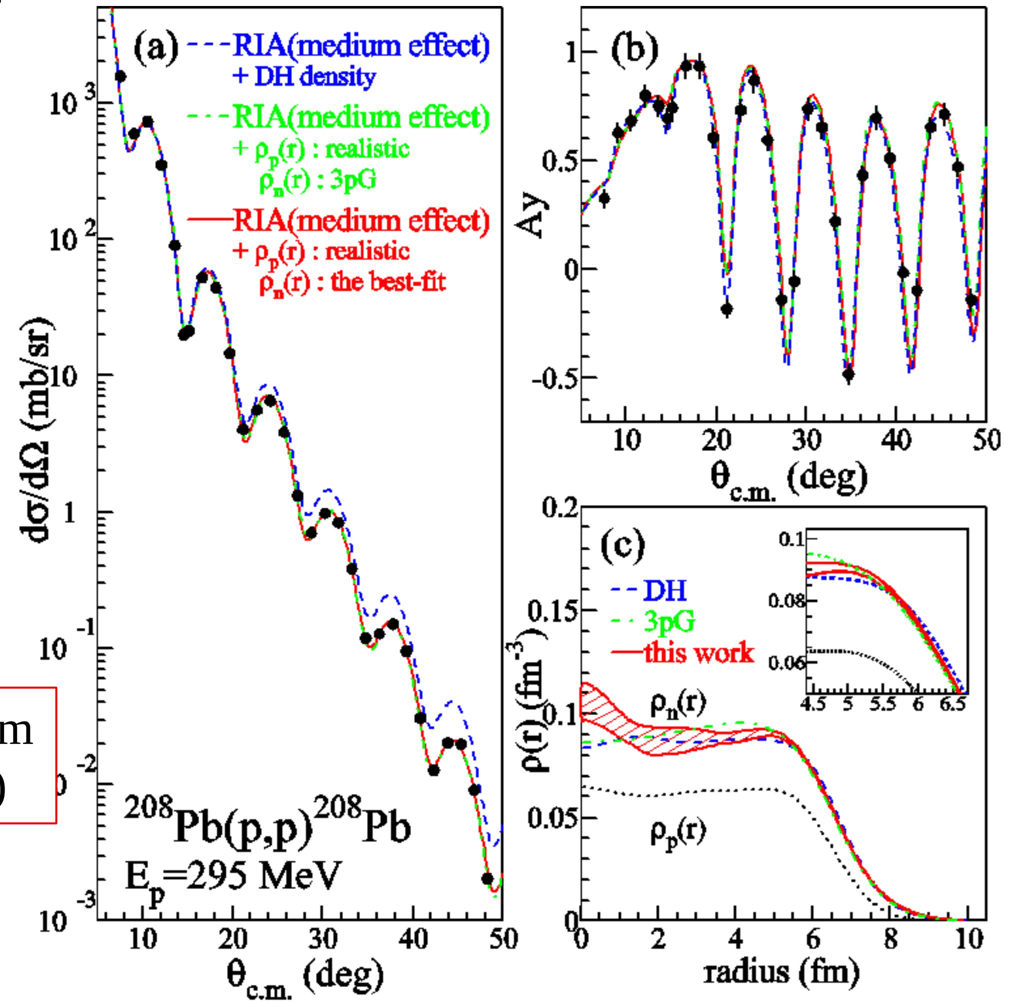
- Error-envelopes due to exp. errors :
  $\chi^2 \leqq \chi^2_{min} + \Delta\chi^2$. ← ~11
- Comparison with previous $\rho_n(r)$:
  3-parameter-Gaussian (3pG) by L. Ray (Ref.[58])

percent deviation



0.06 fm (1%)

ρ_n type	χ^2/ν (ν=47)	r_n (fm)
3pG	255/47=5.4	5.593
SOG	192/47=4.1	$5.653(30)_{stat.}$



Extraction of $\rho_n(r)$

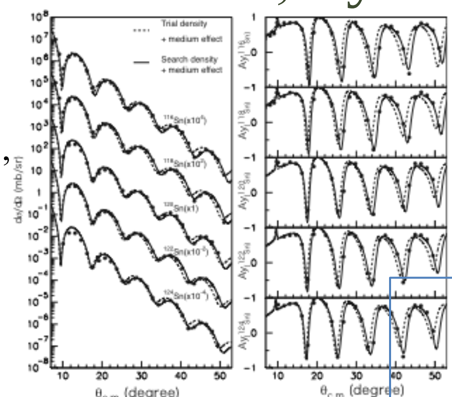
Polarized proton elastic scattering at **300MeV** (Ring cyclotron facility at RCNP, Osaka University)
⇒We have succeeded in extracting neutron density distributions of Sn, Pb isotopes systematically.

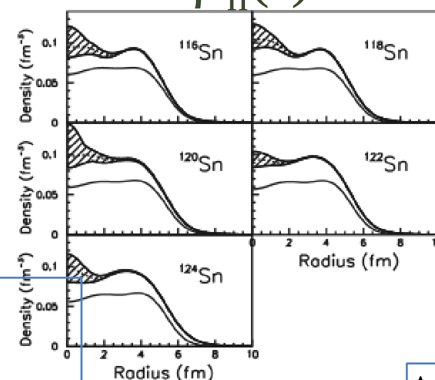
<u>Stable nuclei</u> : ρ_p is known.

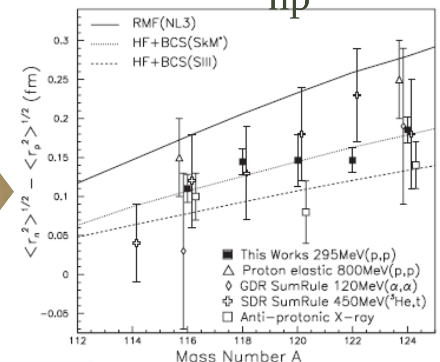
$d\sigma/d\Omega$, Ay — $\rho_n(r)$ — Δr_{np}

Sn

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





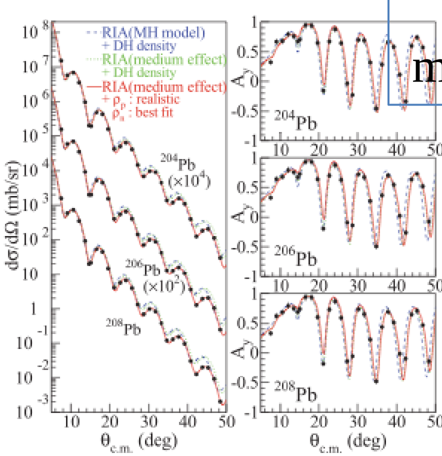


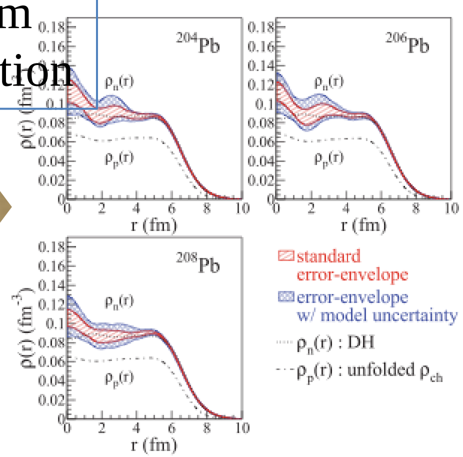
RIA
+
Medium modification

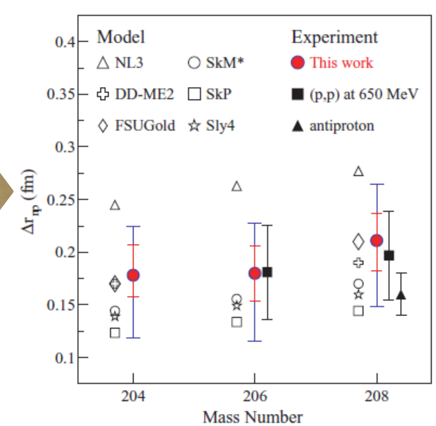
$\Delta r_n/r_n < 0.5\%$

Pb

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



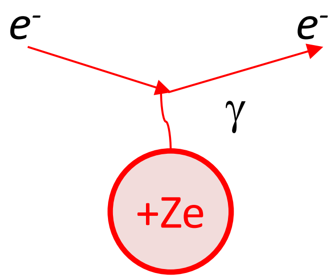




Simultaneous extraction from two-energy p-elastic data

For stable nuclei

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



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

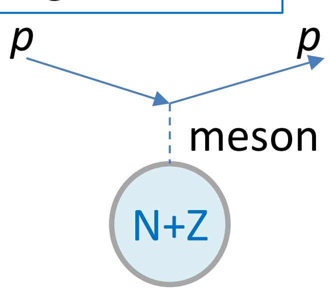
$$F_{ch}^{p}(q) \cdot F_{p}(q) \Leftrightarrow \rho_{p}(r)$$

: well established in 1980s

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

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

Proton scattering @ 300 MeV ; Nuclear matter



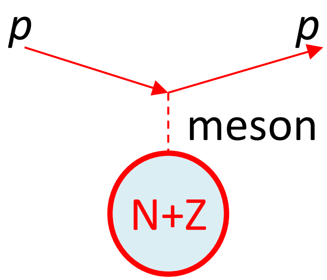
$$F_{p+n}(q) \Leftrightarrow \rho_{p+n}(r)$$

: our work

Simultaneous extraction from two-energy p-elastic data

For unstable nuclei

Proton scattering @200MeV

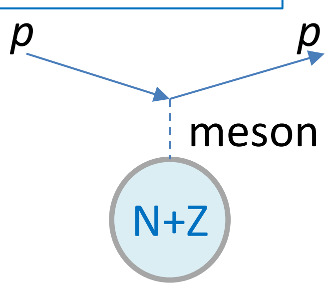


$$t_{pp}^{200} F_p(q) + t_{pn}^{200} F_n(q) \Leftrightarrow \rho_p(r) + \rho_n(r)$$

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

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

Proton scattering @ 300 MeV



$$t_{pp}^{300} F_p(q) + t_{pn}^{300} F_n(q) \Leftrightarrow \rho_p(r) + \rho_n(r)$$

Energy dependence of NN interaction and Nuclear potential

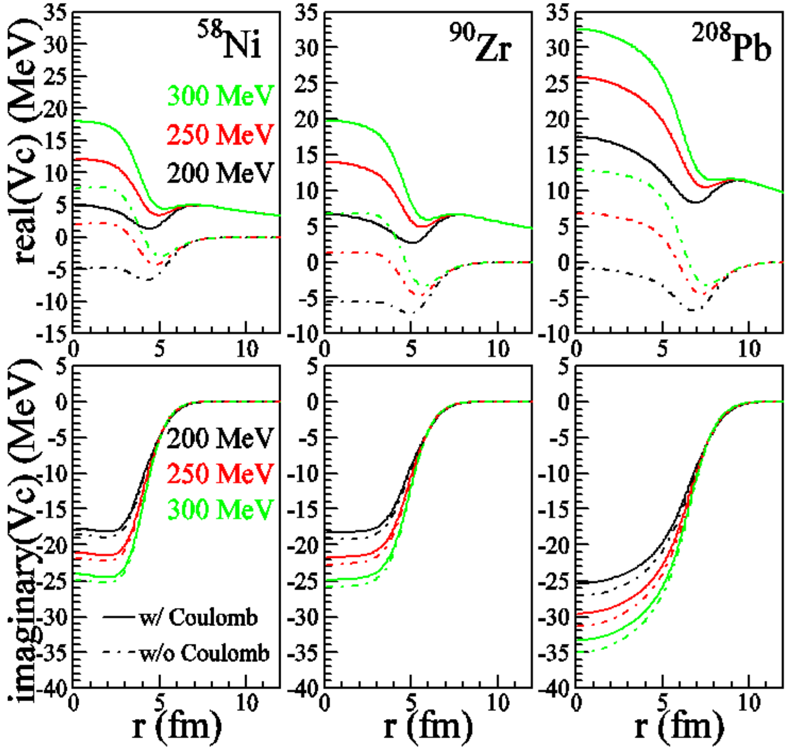
Expecting…

1. *pp* & *pn* interactions are different and have different energy-dependences from each other.

2. Central part of nuclear optical potential changes shallow attractive to shallow repulsive from 200 to 300 MeV (-5 ~ 10 MeV), while the nuclear Coulomb potential does not change and relatively large (> 10 MeV)

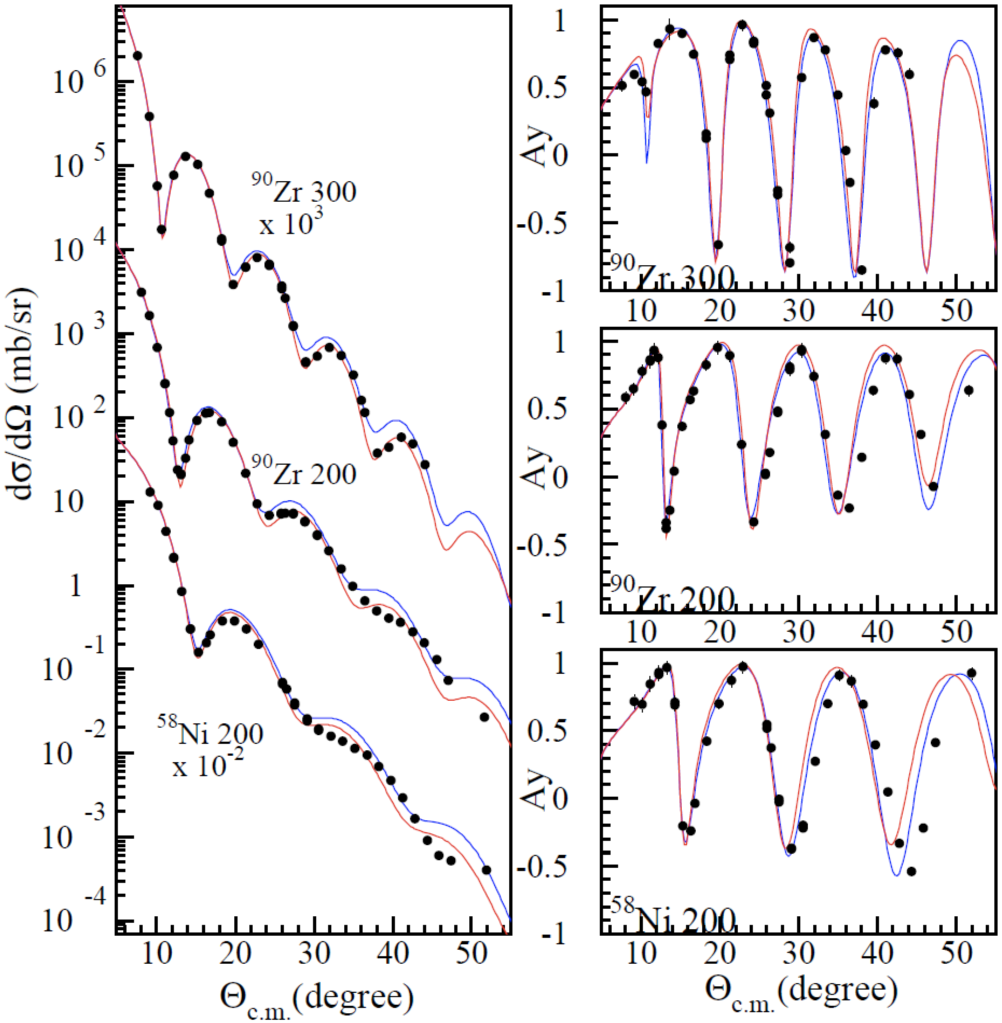
→ Scattering observables are really sensitive to both densities?

Central part (Vc) of optical potentials



Test experiment at RCNP (E366)

Obtained data of 90Zr, 58Ni
@ 200, 300 MeV

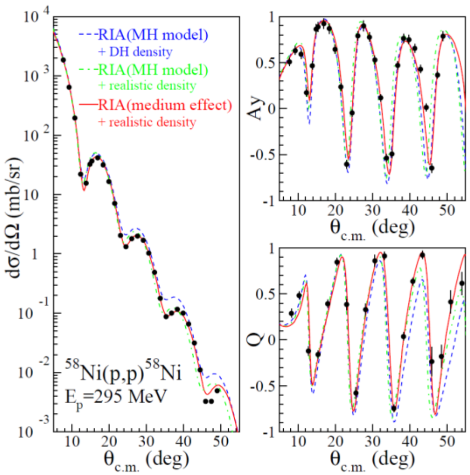


Blue : original RIA

Red : RIA with realistic ρ_p
& $\rho_n = \rho_p * N/Z$

→ Calibrate effective NN interaction @ 200MeV

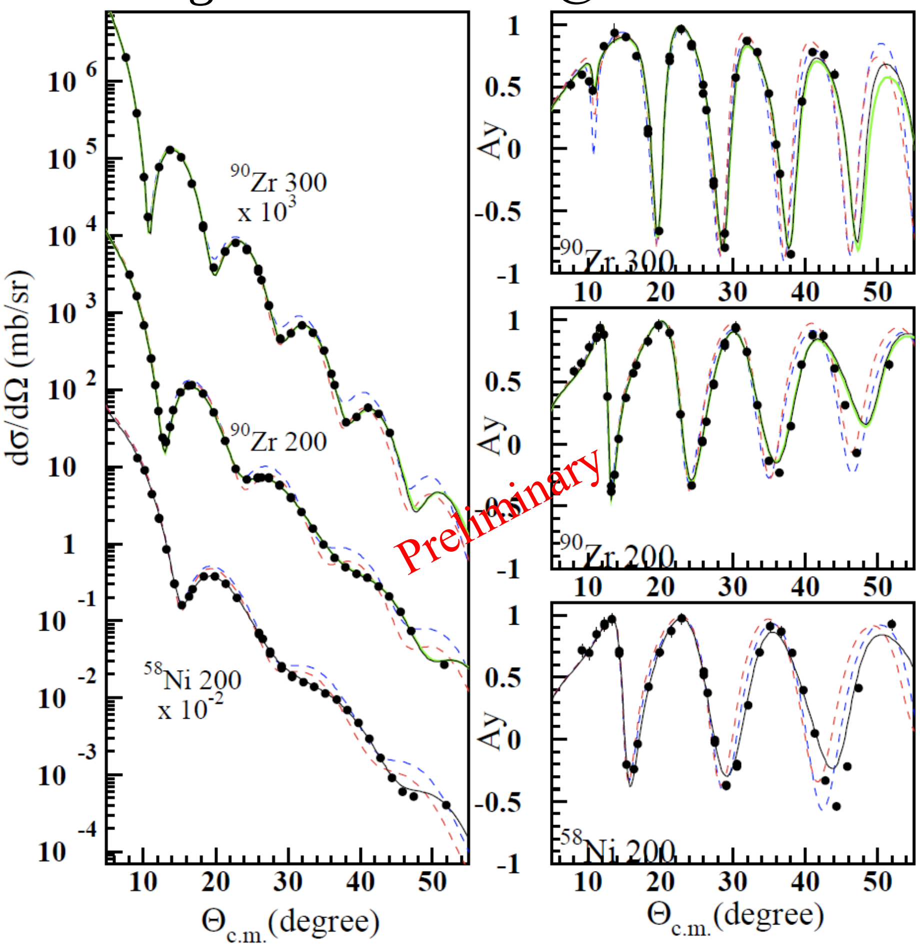
→ For 300MeV already calibrated by previous work ↓



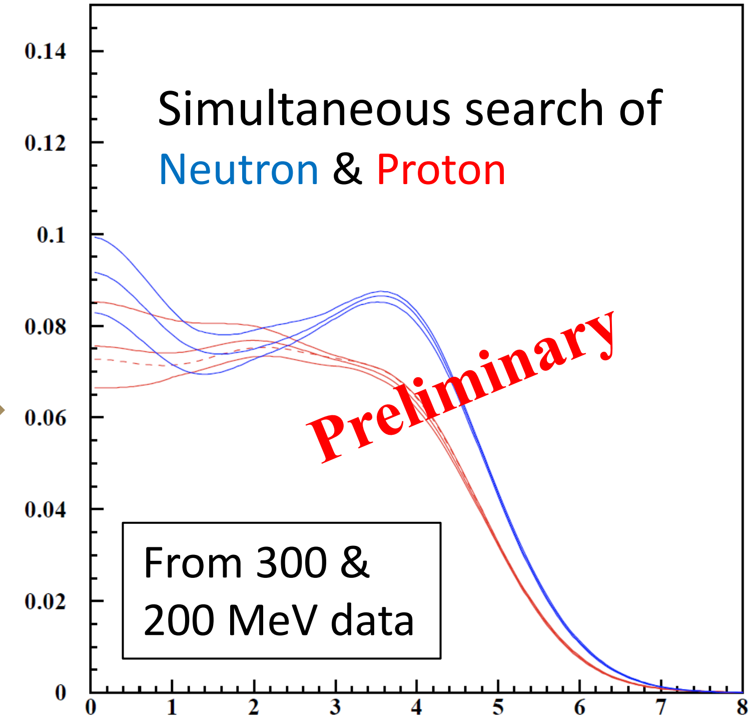
J.Zenihiro et al.,Phys. Rev. C 82, 044611 (2010)

Some results

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)**

Summary

- For stable nuclei
  - We developed a new description of effective interaction in the framework of RIA, and which is very successful.
  - Proton density distributions can be derived from nuclear charge distributions
  - We succeeded in extracting $\rho_n(r)$ of Pb, Sn isotopes from polarized proton elastic scattering

- For unstable nuclei
  - New method has been developed to extract both $\rho_p(r)$, $\rho_n(r)$ from two-energy proton elastic scattering data.
  - Feasibility test experiment has been done and the preliminary result shows that this method works very well!

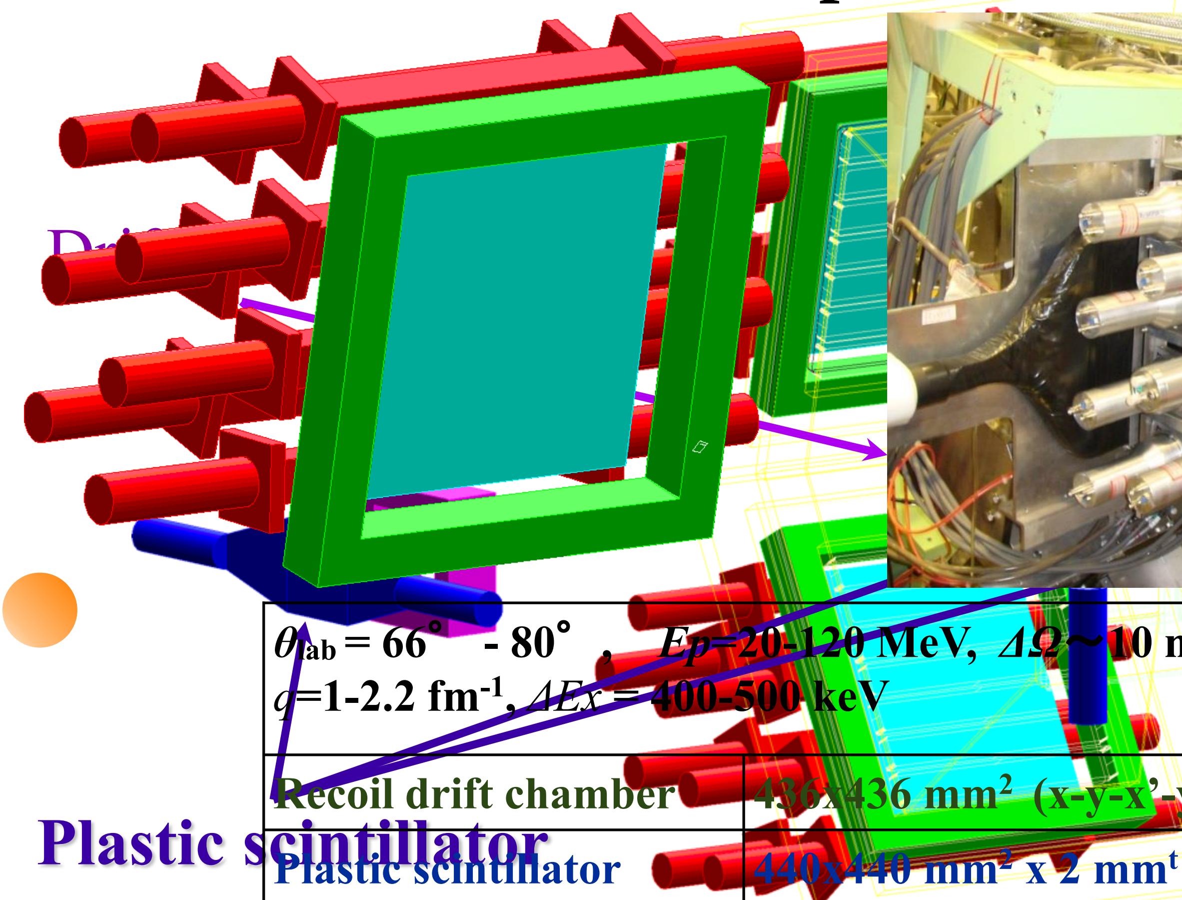
Ongoing & future

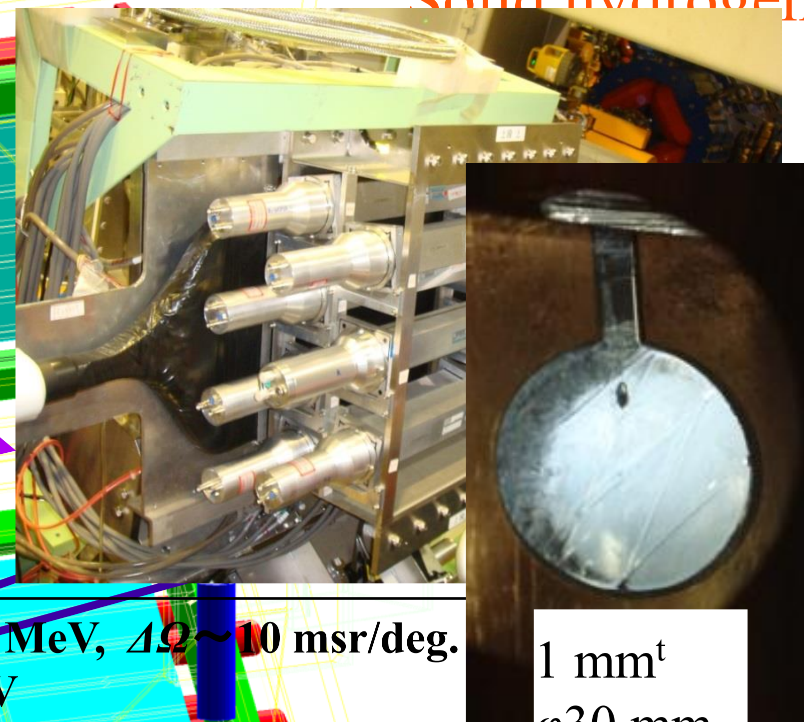
- ESPRI project (**E**lastic **S**cattering of **P**rotons with **RI** beam) has been already launched.
  - Detector development and test using RI beam has been done at HIMAC, Chiba and GSI, Germany.
  - 1mm-t & 30mm-ϕ *p*SHT [Y. Matsuda, et al., NIMA643, 6(2011)]
  - Excitation energy resolution ~ 500 keV(σ)

- ESPRI experiments @RIBF, RIKEN, Japan
  - NP0709-RIBF40 : ^{16}C at 300MeV/u (light unstable nuclei) → Successfully done in FY2013!
  - NP1112-RIBF79 : ^{132}Sn at 200&300MeV/u → Approved.
    - Experiment will be performed in FY2015
    - The new method will be adopted.
    - → neutron skin thickness of ^{132}Sn will constrains the symmetry energy.

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) calorimeter	431.8x45.72 mm^2 x 50.8 mm^t

Elastic Scattering of Protons with RI beams (ESPRI) project

Collaborators

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RCNP
I.Tanihata
H.Jin Ong

GSI
S272 collaborators

NIRS
E.Takada
M.Kanazawa

Thank you!

protons & neutrons in a nucleus

Nucleus is finite quantum many-body system made from 2 different fermions, p & n.

How are nucleons (p, n) distributed in a nucleus? : ρ_p, ρ_n

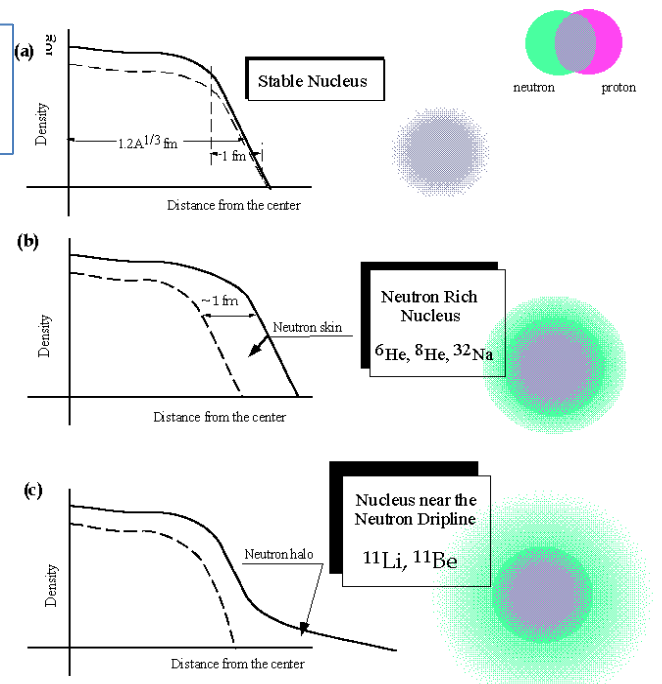
⬇

fundamental and direct information to constrain nuclear structure or reaction models

→ Shell structure
→ Saturation property
→ Halo, skin structure → nuclear matter EOS with isospin asymmetry

⬇

Neutron skin thickness vs. Symmetry energy

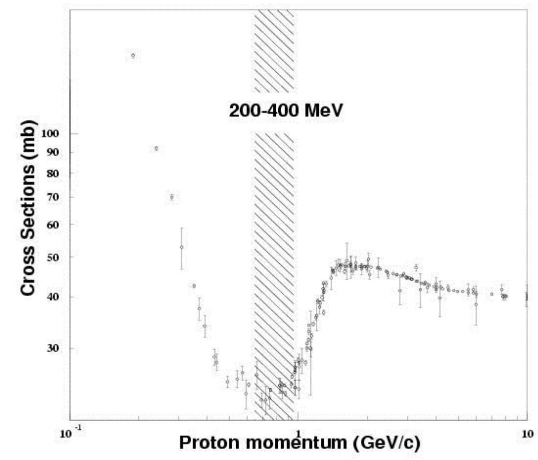


300 MeV proton

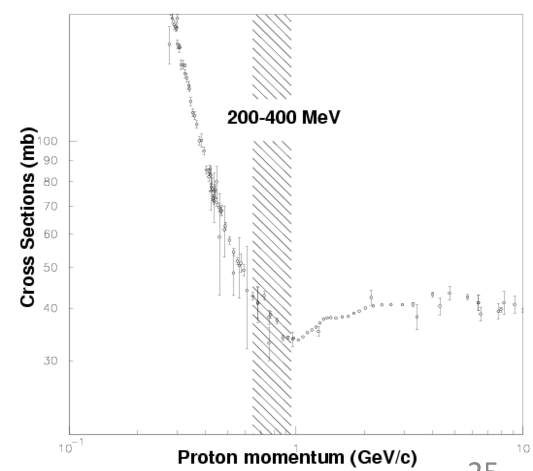
Good probe to extract interior information of nucleus

- Interact with both neutrons and protons
- long mean free path (~2fm)
  - →interior structure (→ surface structure)
- one-step reaction is dominant
  - →simple description ; successful <u>Relativistic Impulse Approximation (RIA)</u>

pp total cross section



np total cross section



RIA framework

- Dirac ***tρ***-optical potential : single folding of *NN* amplitude (***t***) & densities (*ρ*)
  - *NN* amplitude; 10 mesons' coupling including both direct & exchange terms are tuned by free NN phase shift analysis(RLF model by C. J. Horowitz)

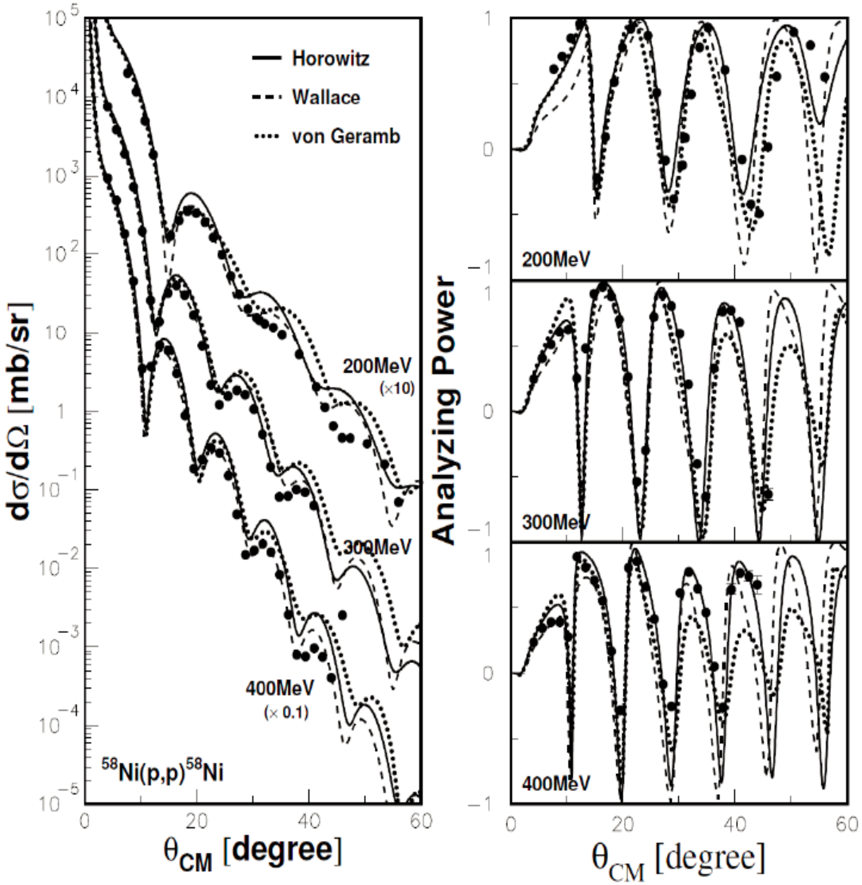
$$F = F^S + F^V \gamma^{\mu}_{(0)} \gamma_{(1)\mu} + F^{PS} \gamma^5_{(0)} \gamma^5_{(1)} + F^T \sigma^{\mu\nu}_{(0)} \sigma_{(1)\mu\nu} + F^A \gamma^5_{(0)} \gamma^{\mu}_{(0)} \gamma^5_{(1)} \gamma_{(1)\mu}$$

  - For spin-0 nucleus only Scalar & Vector component remain

$$U = \frac{-4\pi i p_{\mathrm{lab}}}{M} [F_{S0}\rho_S + \gamma_0 F_{V0}\rho_V]$$

→Relatively good agreement with p-A scattering data, particularly, analyzing powers above 100 MeV

- Not enough to extract densities
  → Need effective NN interaction inside nuclear medium



D. P. Murdock and C. J. Horowitz, PRC35, 1442. C. J. Horowitz and B. D. Serot, NPA368, 503.
H. Sakaguchi et al., PRC57, 1749.

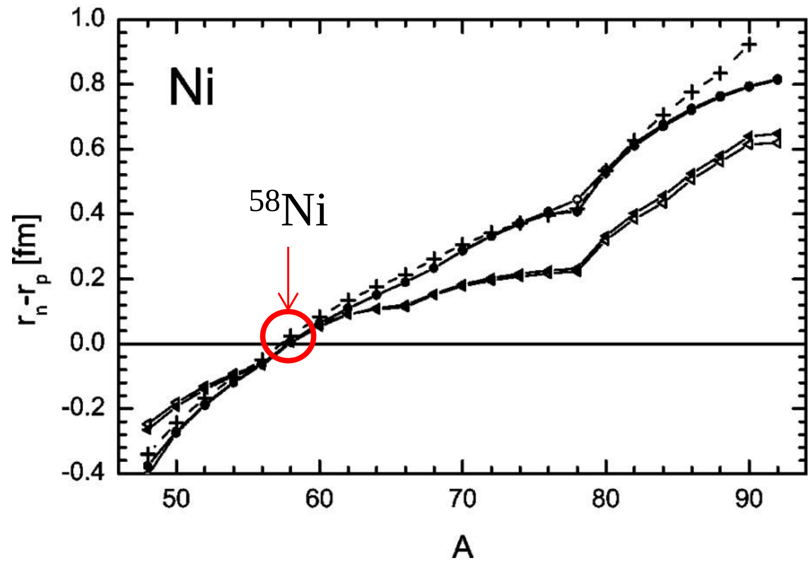
Calibration of medium effect by ^{58}Ni

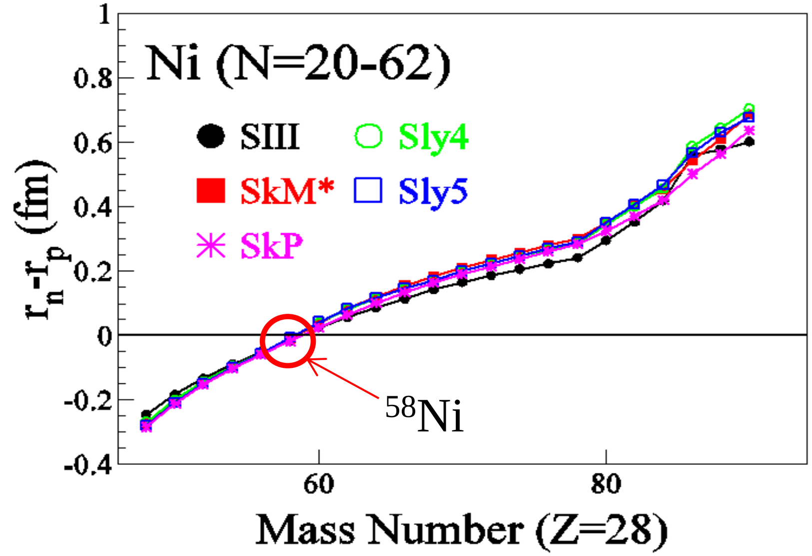
^{58}Ni

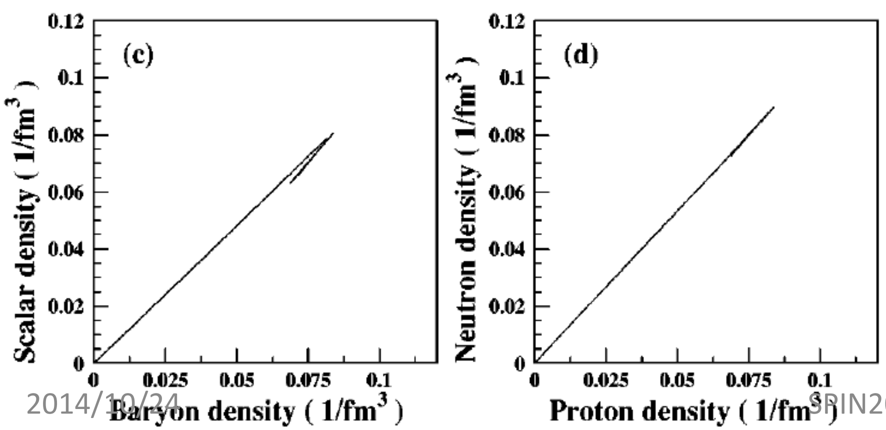
Various experimental & theoretical results say :

$r_n \cong r_p$: almost the same size

$$\rho_n(r) = \frac{N}{Z}\rho_p(r)$$







^{58}Ni	r_p	r_n	Δr_{np}	Ref.
DME+D1	3.68	3.67	-0.01	PRC21, 1568(1980)
HF-BCS+SIII	3.738	3.732	-0.006	NPA603, 23(1996)
HF-BCS+SkM*	3.722	3.720	-0.002	PRC33, 335(1986)
HF-BCS+SGII	3.719	3.697	-0.012	PRC72, 044307(05)
RMF+NL3	3.652	3.691	0.040	ADNDT71, 1(1999)
RMH+RH	3.652	3.691	0.039	NPA368, 503(1981)
Glauber	3.763(50)	3.72(5)	-0.043(70)	PLB67, 402(1977)
Glauber	3.67(5)	3.60(5)	-0.07(7)	PLB72, 33(1977)
Glauber	3.763(50)	3.75(10)	-0.01(7)	NPA360, 233(1981)
1st KMT	3.688	3.652(74)	-0.035(74)	PRC18, 2641(1978)
2nd KMT	3.686	3.700(50)	0.014(50)	PRC19, 1855(1979)
p atom	-	-	$-0.09^{+0.09}_{-0.16}$	PRL87, 082501(01)
This work	3.680	3.680	0.000	

Estimation of error-envelopes of $\rho_n(r)$

- $\chi^2_{min}/\nu \sim 4$: incompleteness of the theoretical model as well as unknown experimental systematics
- Error-envelopes <u>due to model uncertainties</u> :

  S realizes <u>$\chi^2_{min}/\nu = 1$.</u>

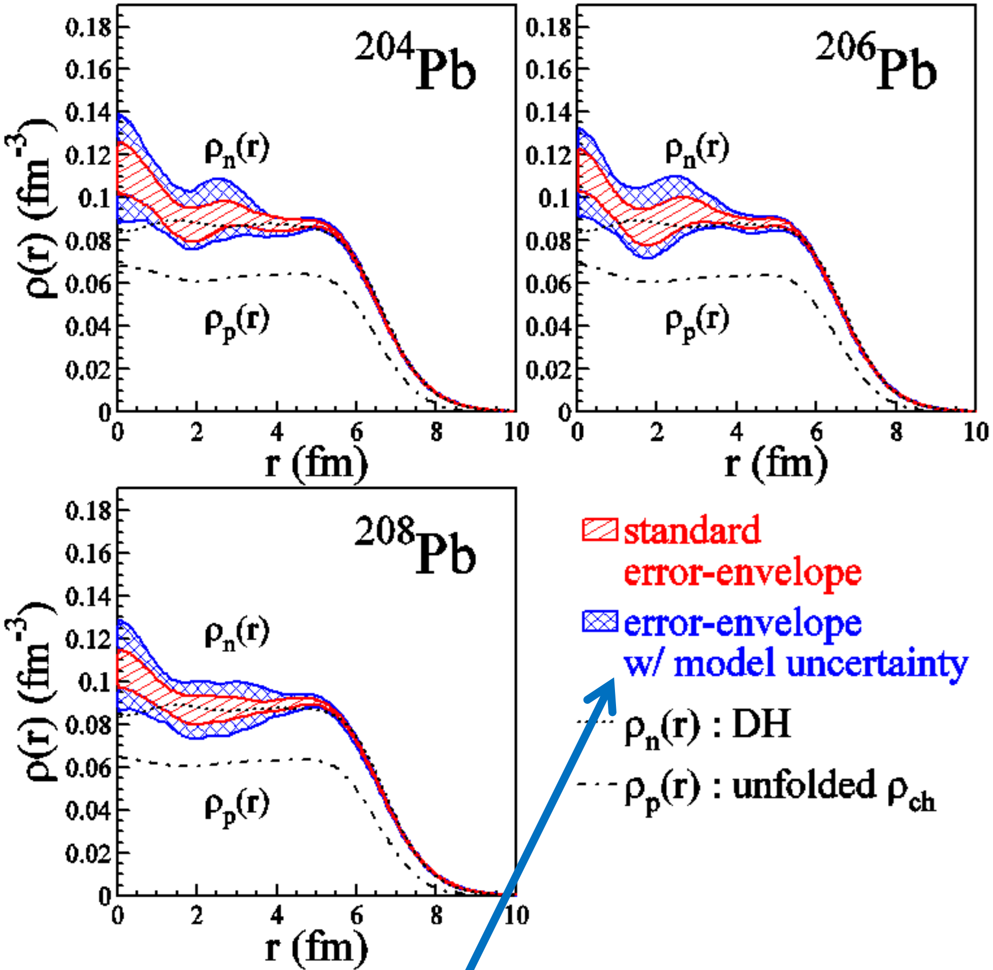
$$\begin{cases} \tilde{\chi}^2 \equiv \chi^2 / S^2 = \sum \left(\dfrac{y^{exp} - y^{calc}}{S \cdot \delta y^{exp}} \right)^2, \\ \tilde{\chi}^2_{min} \equiv \chi^2_{min} / S^2 = \nu \Leftrightarrow S = \sqrt{\chi^2_{min} / \nu}. \end{cases}$$

$$\tilde{\chi}^2 \leq \tilde{\chi}^2_{min} + \Delta\chi^2$$

$$\Updownarrow$$

$$\chi^2 \leq \chi^2_{min} + \Delta\chi^2 \times S$$

$$= \chi^2_{min} + \Delta\chi^2 \times (\chi^2_{min} / \nu)$$



Total error-envelope

Neutron root-mean-square radii

- 2 types of errors of r_n : due to
  experimental errors only (δr_n^{std}) → **~ 0.5 %**
  total errors including model &
  unknown systematic uncertainties (δr_n^{mdl}) → **~1 %**

(all in fm)

Extracted r_n, δr_n

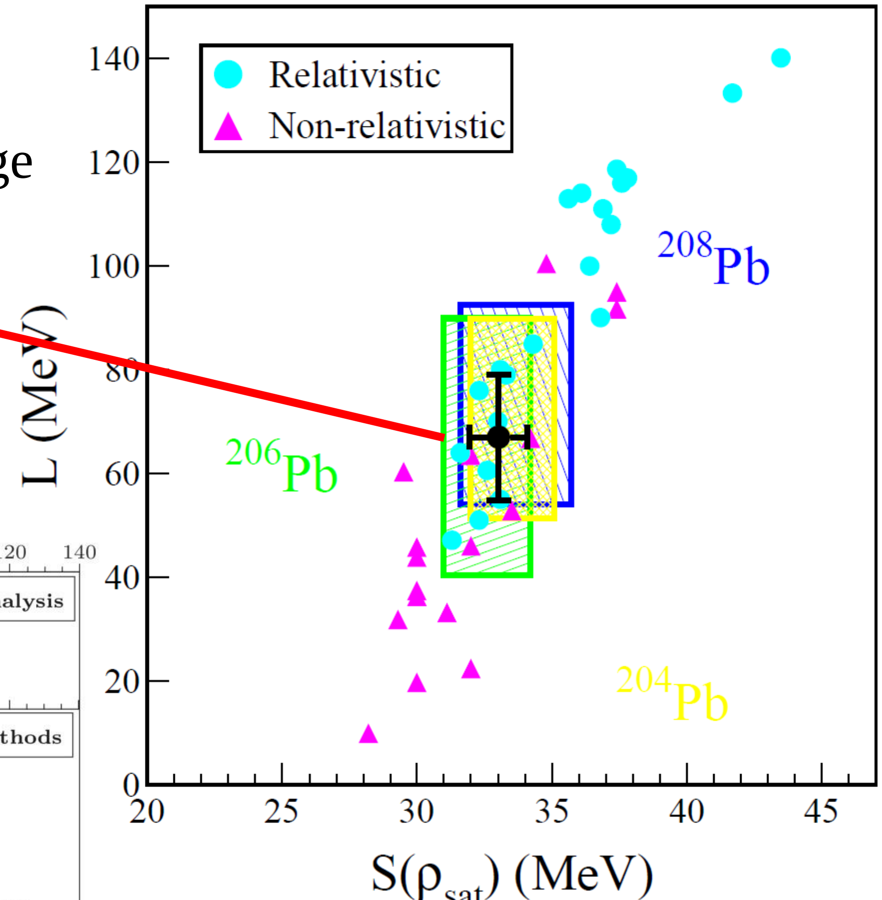
	r_{ch}	r_p^{unfold}	r_n	δr_n^{std}	δr_n^{mdl}
^{204}Pb	5.479(2)	5.420(2)	5.598	+0.029	+0.047
				-0.020	-0.059
^{206}Pb	5.490(2)	5.433(2)	5.613	+0.026	+0.048
				-0.026	-0.064
^{208}Pb	5.503(2)	5.442(2)	5.653	+0.026	+0.054
				-0.029	-0.063

The symmetry energy coefficients deduced from Δr_{np} for ^{204,206,208}Pb

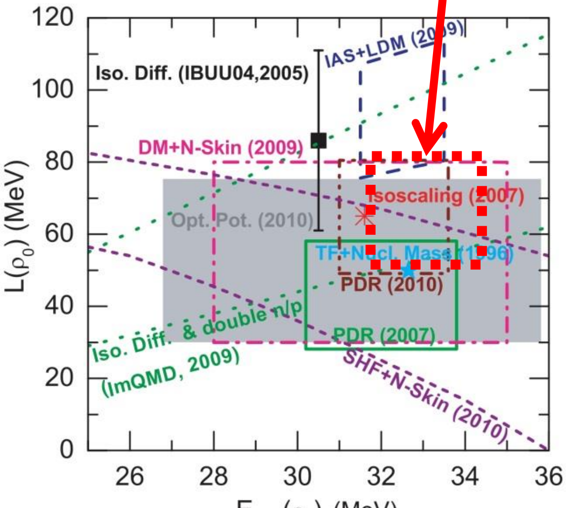
- Deduced region of the symmetry energy coefficients : weighted average

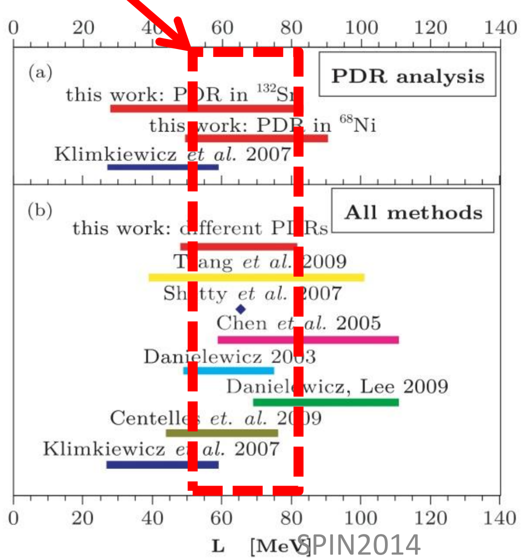
$S(\rho_{sat}) = 33.0 \pm 1.1$ MeV
$L = 67.0 \pm 12.1$ MeV

→ <u>comparable with previous studies but still large</u>



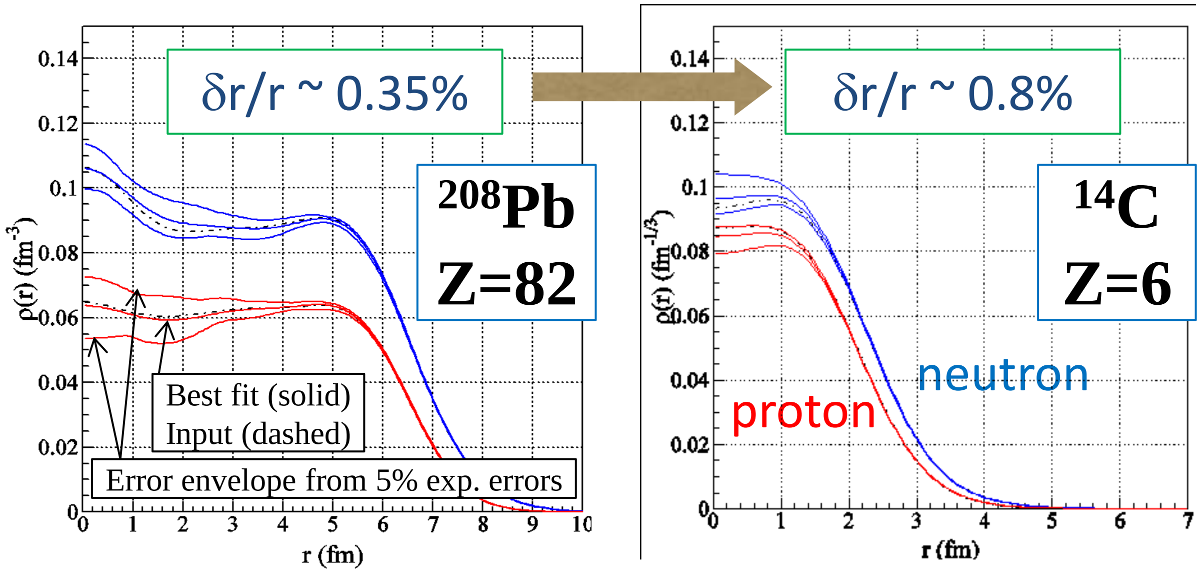
!!Note that 3 ranges in plot are due to experimental errors only!!





Simulation results 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 ~5% experimental errors.



$$\rho_n^{SOG}(r) = \sum A_i \left(e^{-(r-Ri)^2/\gamma^2} + e^{-(r+Ri)^2/\gamma^2}\right),$$

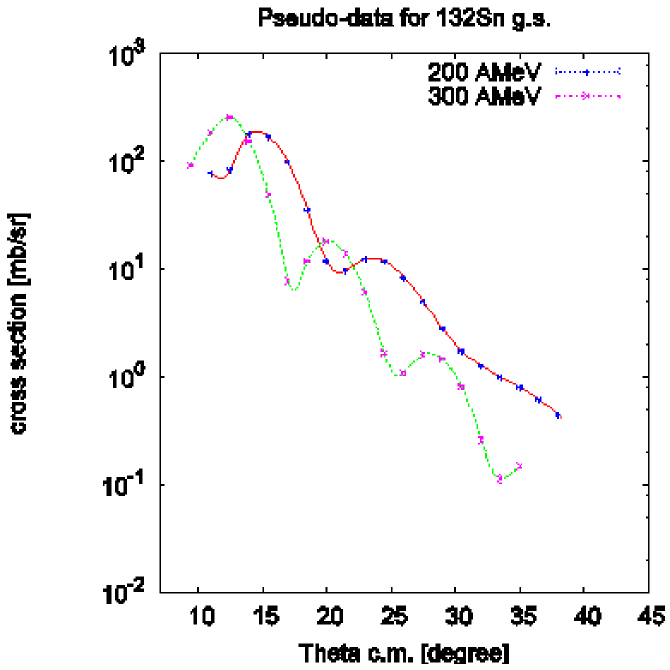
$$A_i = \frac{NQ_i}{2\pi^{3/2}\gamma^3(1+2R_i^2/\gamma^2)}, \sum Q_i = 1$$

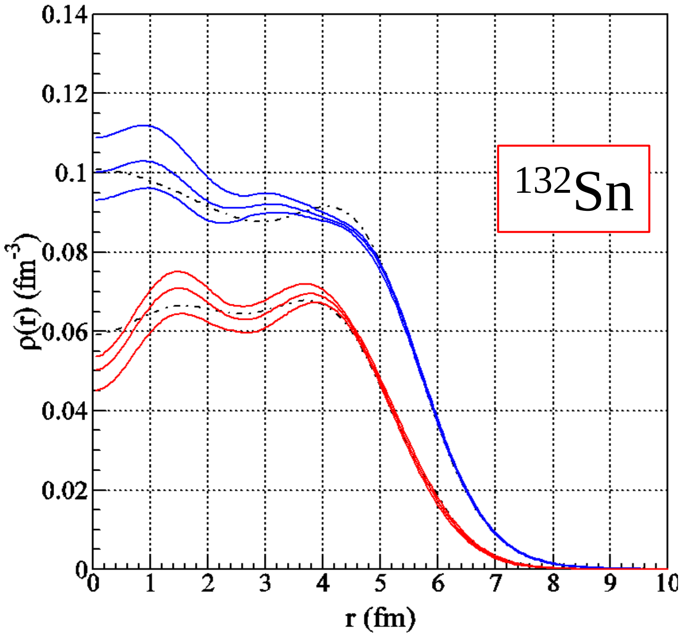
Fixed : γ, R_i (same as $\rho_{ch}(r)$)
Free parameters : Q_i (i=1~12)

The case of unstable nucleus; ^{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.

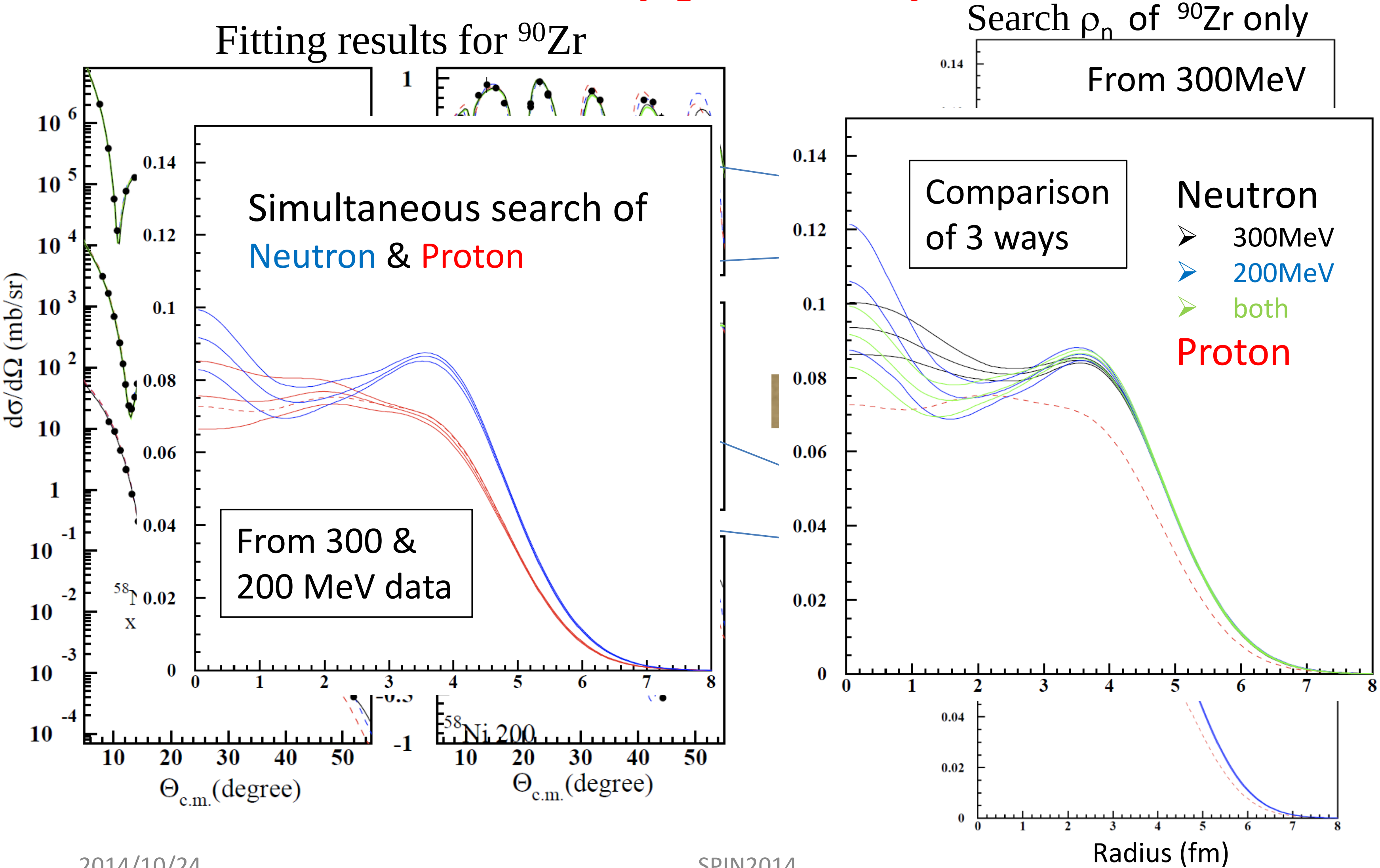
	g.s. (input)	g.s. (extracted)	δr/r
r_n	4.916	**4.907(23)**	**0.46%**
r_p	4.650	**4.612(49)**	**1.0%**
Δr_{np}	0.266	**0.295(54)**	--





Extraction of densities of ^{90}Zr

Very preliminary !!



Extracted radii and skin of ^{90}Zr

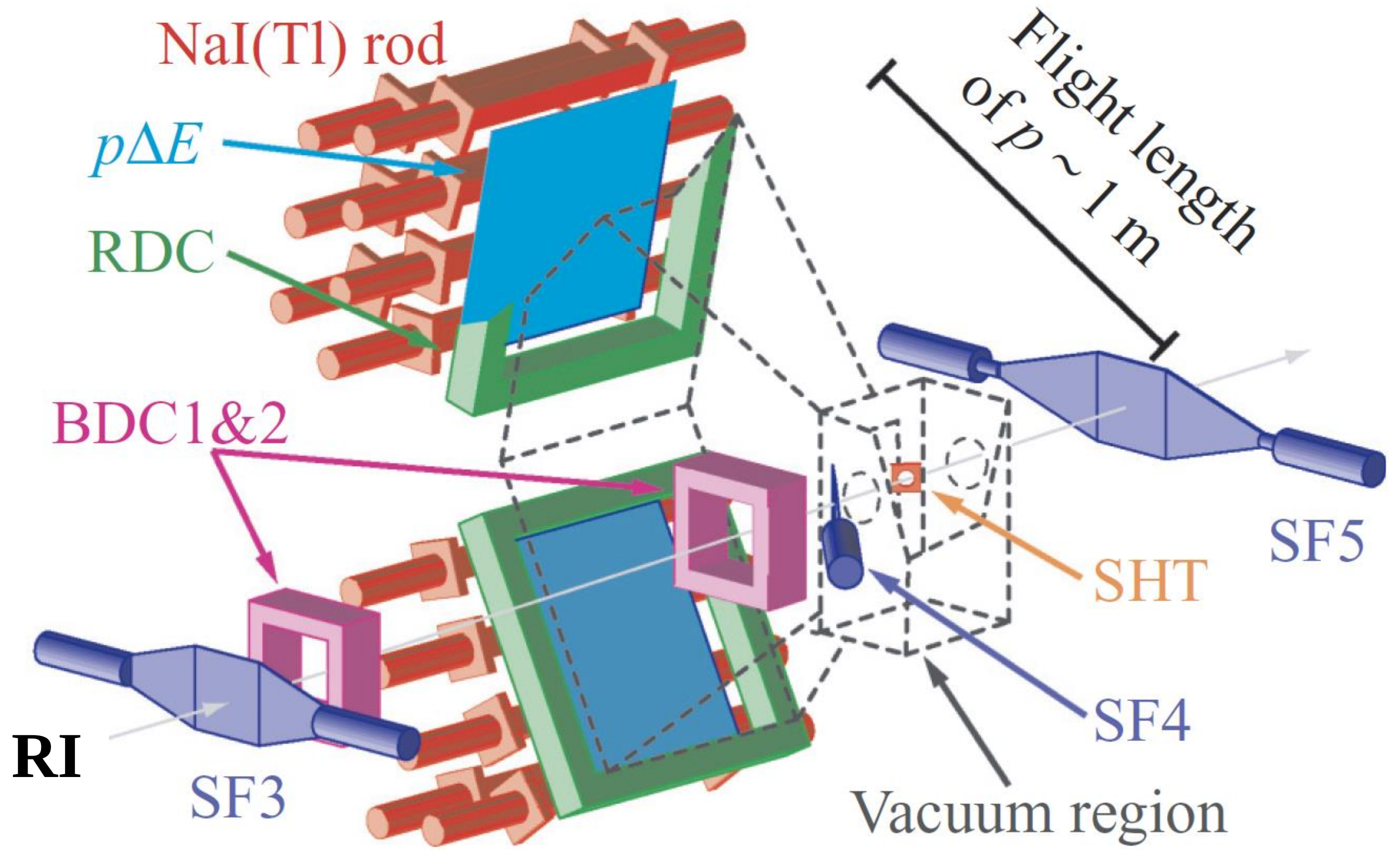
Very preliminary !!

	Type I	**Type II**	**Type III**
χ^2/ν	262/45	218/53	**488/98**
r_n	4.285(16)	4.300(22)	**4.300(17)**
r_p	4.200	4.200	**4.21(2)**
Δr_{np}	0.085(16)	0.100(22)	**0.090(26)**

(all in fm)

Type I : 300MeV data only
Type II : 200 MeV data only
Type III : 200 & 300 MeV data
* Errors are experimental only!

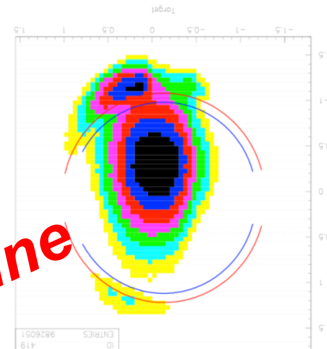
Recoil proton spectrometer (RPS)



ESPRI measurement for ^{16}C

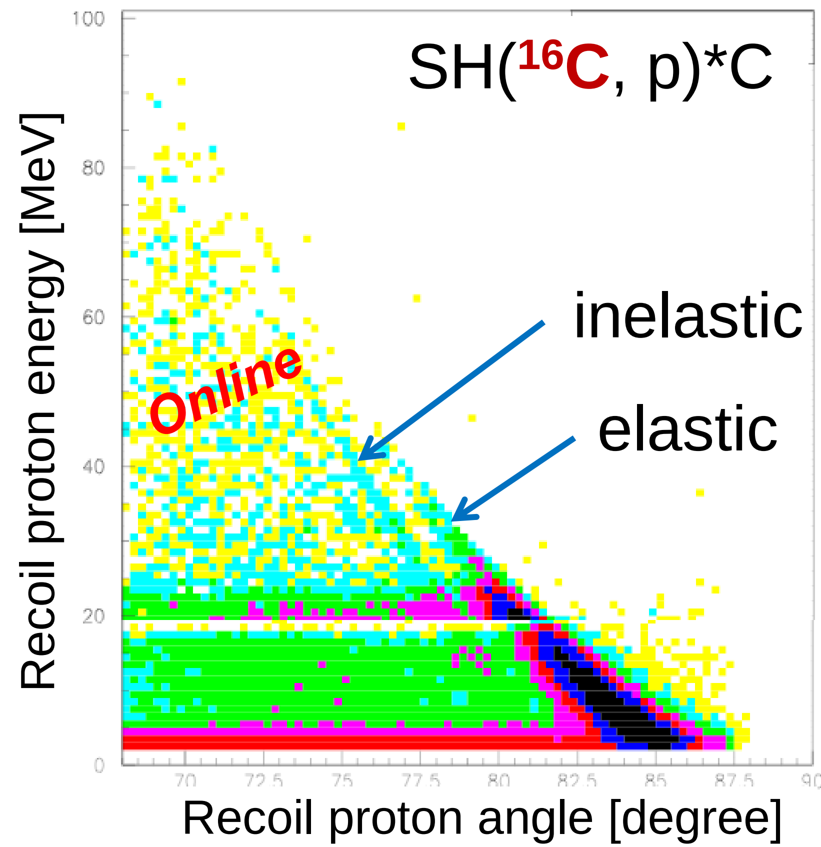
^{16}C beam profile on SHT

[Photo]

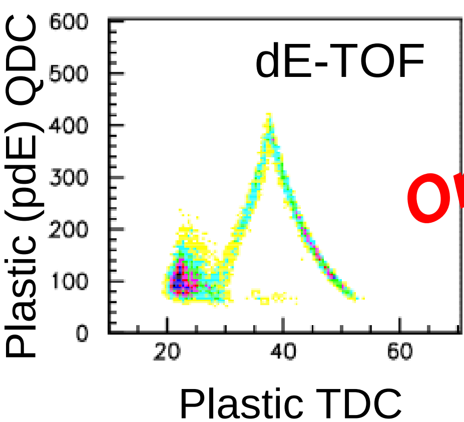


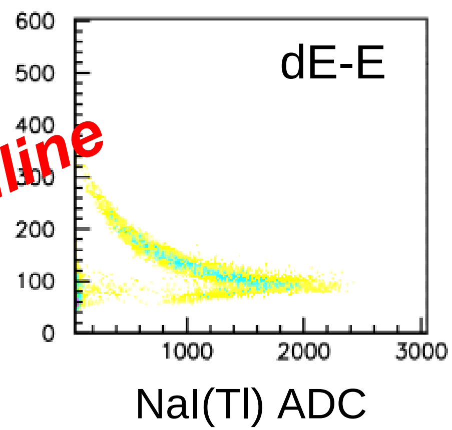
[Data]

Kinematical correlation plot



Clear identification of recoil protons





Analysis is ongoing.

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)