Nucleon density distributions extracted from proton elastic scattering at intermediate energies

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1. Nucleon density distribution

protons & neutrons in a nucleus

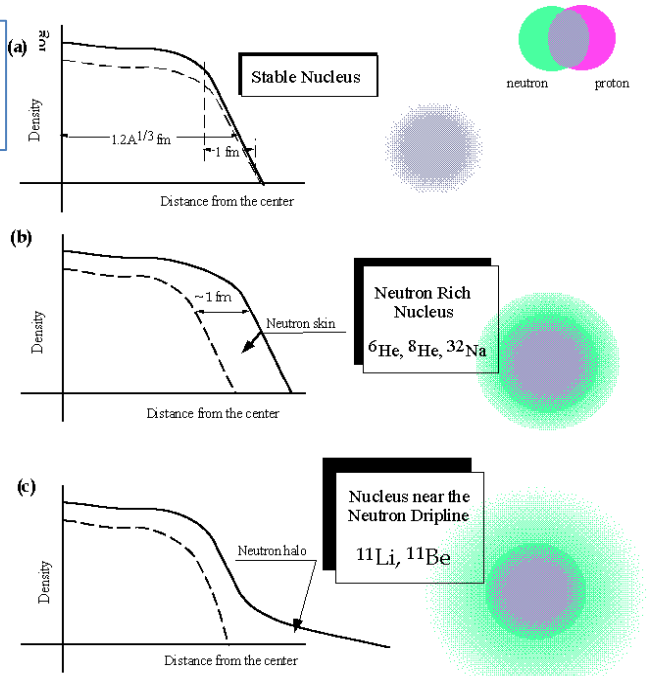
Nucleus is finite quantum many-body system made from 2 different fermions, p & n.

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

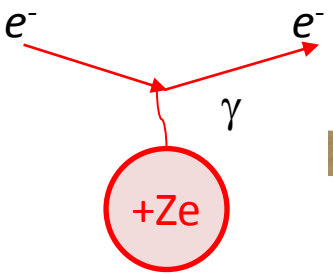
Neutron skin thickness vs. Symmetry energy



2. How to see nucleons?

Start from Hofstadter's experiments –nuclear form factors–

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



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

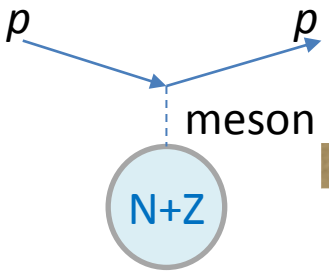
$$F_{ch}^{p}(q) \cdot F_{p}(q) \Leftrightarrow \rho_{p}(r)$$

R. Hofstadter
(Nobel prize in 1961)

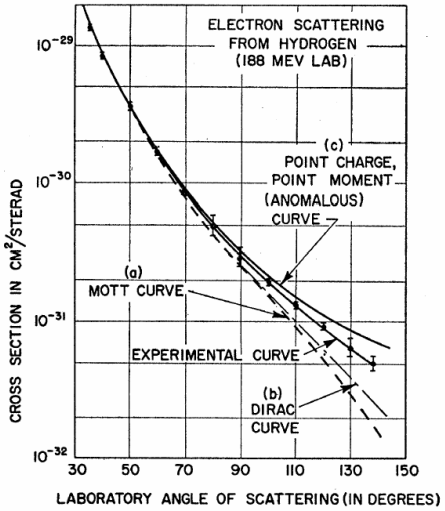
$$\rho_p(r), \rho_n(r)$$

Similarly…

Proton scattering ; Nuclear matter



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



$\rho_{ch}(r)$, $\rho_p(r)$, $\rho_n(r)$

- Stable nuclei
  - ✓ Nuclear charge distribution $\rho_{ch}(r)$
    - ✓ EM probe (very simple)
    - ✓ For example, r_{ch} = ^{208}Pb : 5.5010(9) fm (0.02% accuracy)
  - ✓ Proton density distribution $\rho_p(r)$: derived from $\rho_{ch}(r)$
  - ☐ Neutron density distribution $\rho_n(r)$
    - ☐ Hadronic probe (very complicated)
    - ☐ Suffering from large uncertainties (~1% accuracy) Incomplete knowledge of *NN* interaction inside nucleus
    - → Our work

- Unstable nuclei
  - ☐ Little information about $\rho_{ch}(r)$, $\rho_p(r)$, $\rho_n(r)$!
  - → SCRIT for $\rho_{ch}(r)$: e-RI collision
  - → ESPRI for $\rho_p(r)$, $\rho_n(r)$: Our work

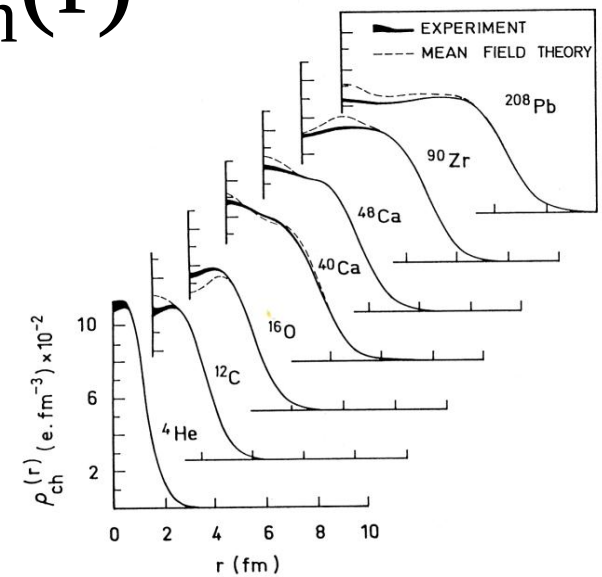
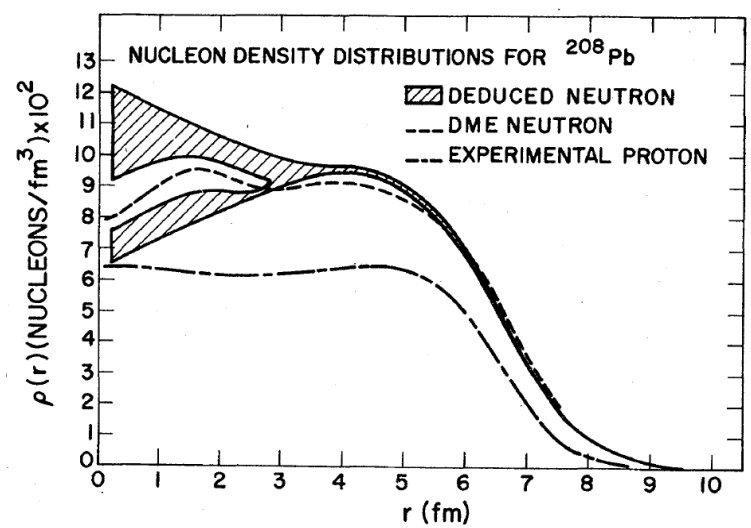


Figure 8 Charge density distributions of doubly closed-shell nuclei. The thickness of the solid line depicts the experimental uncertainty. The mean field calculations are from (53).



3. Proton elastic scattering and some results

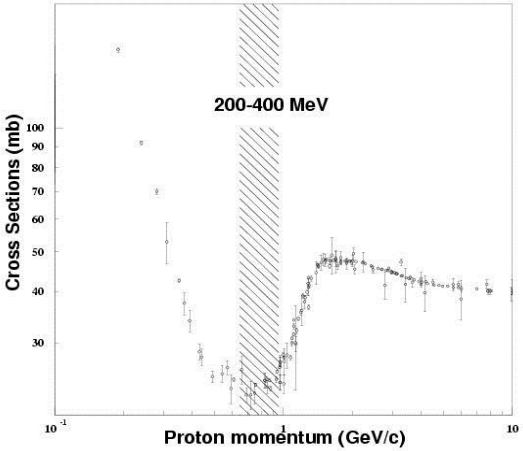
The case of Pb isotopes

300 MeV proton

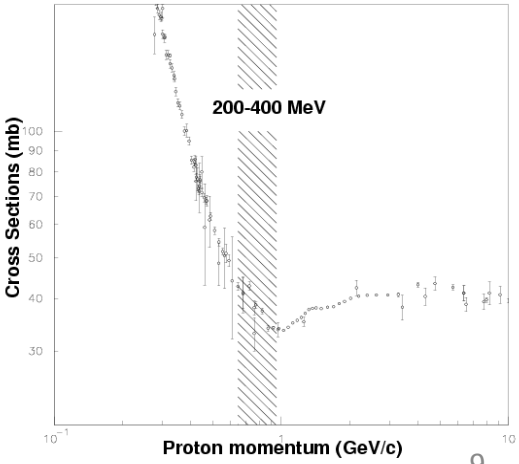
Good probe to extract interior information of nucleus

- Interact with both neutrons and protons
- long mean free path (~2fm)
  - →interior structure (→ surface structure)
- one-step reaction is dominant
  - →simple description ; <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)

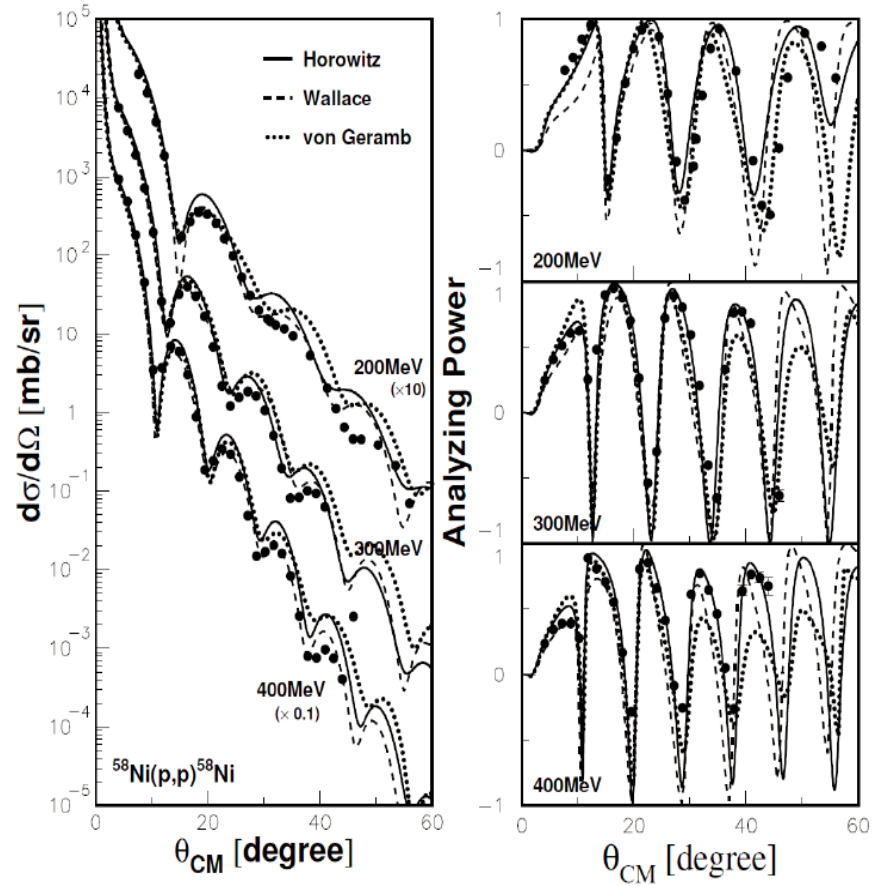
$$F = F^S + F^V \gamma^\mu_{(0)} \gamma_{(1)\mu} + F^{PS} \gamma^5_{(0)} \gamma^5_{(1)}$$
$$+ F^T \sigma^{\mu\nu}_{(0)} \sigma_{(1)\mu\nu} + F^A \gamma^5_{(0)} \gamma^\mu_{(0)} \gamma^5_{(1)} \gamma_{(1)\mu}$$

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

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

→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.

How to extract neutron densities from proton elastic scattering?

RIA ($t\rho$ optical potential)

Effective NN interaction

+ folding

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

input

Modify the RLF interaction to explain real data (^{58}Ni) 3

Fixed 1

- $\rho_p^V(r)$: unfolding $\rho_{ch}(r)$
- $\rho^S = 0.96\ \rho^V$ 2

Free parameter

- $\rho_n^V(r)$: minimize the χ^2

output

Calculation

$ds/d\Omega$, A_y, Q

χ^2 method

Experimental data

$ds/d\Omega$, A_y, Q

1. Realistic proton density distributions

Unfolding $\rho_{ch}(r)$

Neutron charge contribution

$$\rho_{ch}(r) = \int \rho_p(r)\rho_{ch}^p(|\mathbf{r}-\mathbf{r}'|)d\mathbf{r}' + \int \rho_n(r)\rho_{ch}^n(|\mathbf{r}-\mathbf{r}'|)d\mathbf{r}'$$
$$+ \text{spin-orbit term}$$
$$= \int \rho_p(r)\tilde{G}_E^p(|\mathbf{r}-\mathbf{r}'|)d\mathbf{r}' + \int \rho_n(r)\tilde{G}_E^n(|\mathbf{r}-\mathbf{r}'|)d\mathbf{r}'$$
$$+ \text{spin-orbit and Darwin-Foldy term}$$

negligible (~ 0.01 fm)

Fourier transform

$$\tilde{\rho}_{ch}(q) \cong \tilde{\rho}_p(q)G_E^p(q) + \tilde{\rho}_n(q)G_E^n(q)$$

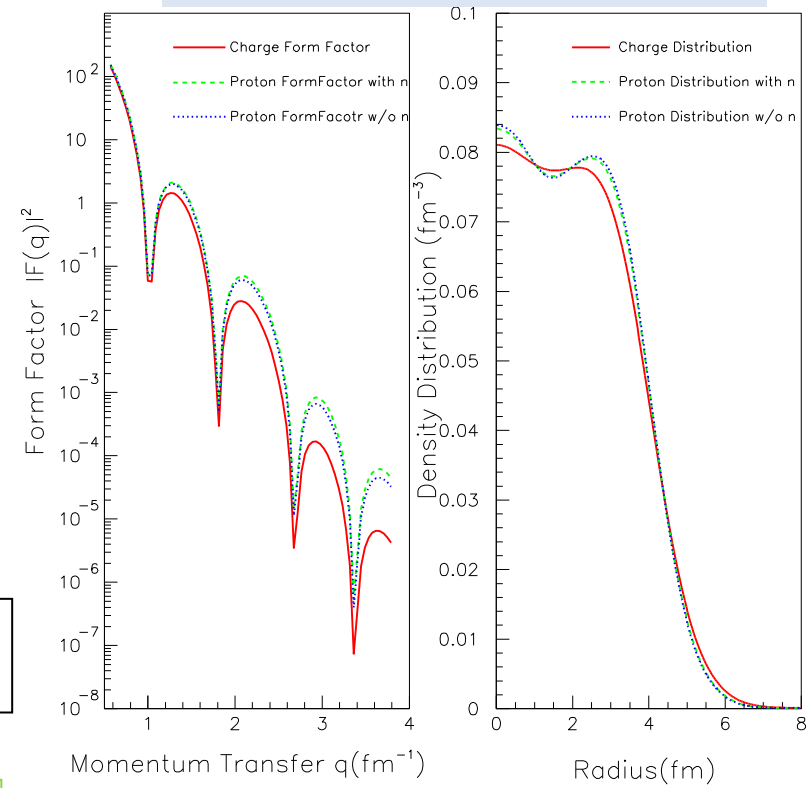
Sachs form factors

$$\langle r^2 \rangle_{ch} = \langle r^2 \rangle_p + \langle r^2 \rangle_{ch}^p + \frac{N}{Z}\langle r^2 \rangle_{ch}^n$$

~(0.89)^2 fm^2

~ -0.11 fm^2

H. de Vries, et al, ADNDT36, 495, and so on.



Sum of Gaussians

$$\rho^{SOG}(r) = \sum A_i (e^{-(r-Ri)^2/\gamma^2} + e^{-(r+Ri)^2/\gamma^2}),$$
$$A_i = \frac{ZQ_i}{2\pi^{3/2}\gamma^3(1+2R_i^2/\gamma^2)}, \sum Q_i = 1$$

$G_E^{p,n}$ from *e-p* or *-d* elastic data

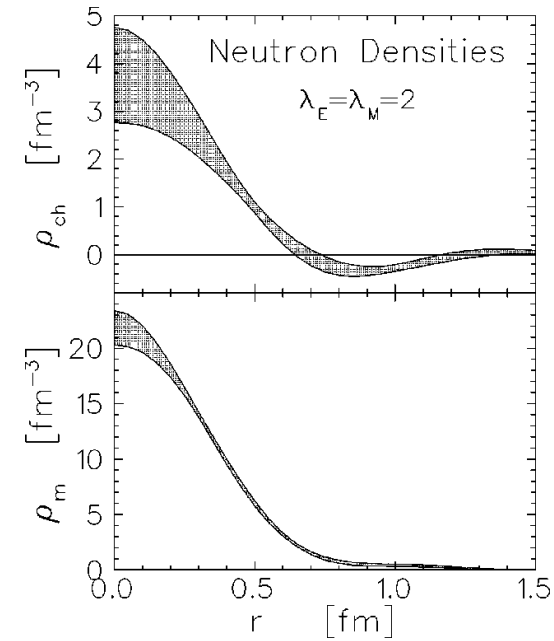
- low-Q^2(<1GeV) analysis by I. Sick [PLB576, 62(2003)]
  - Continued-fraction expansions
  - Model independent nucleon charge radius :

    r_{ch}^p = 0.895(18) fm

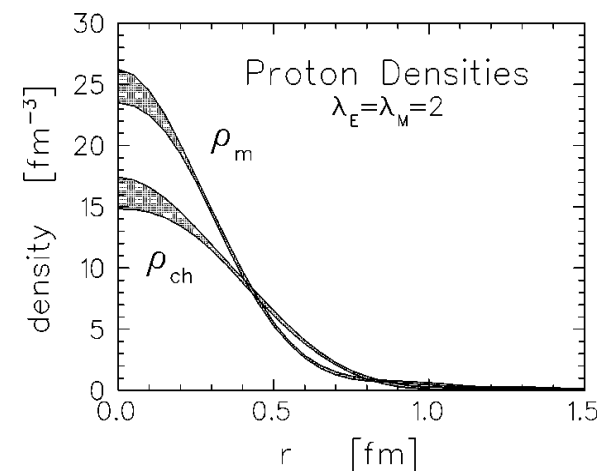
    $(r_{ch}^n)^2$ = -0.113 fm^2

$$G_E^p(Q^2) \propto \cfrac{1}{1+\cfrac{b_1 Q^2}{1+\cfrac{b_2 Q^2}{1+\cdots}}}$$

This work



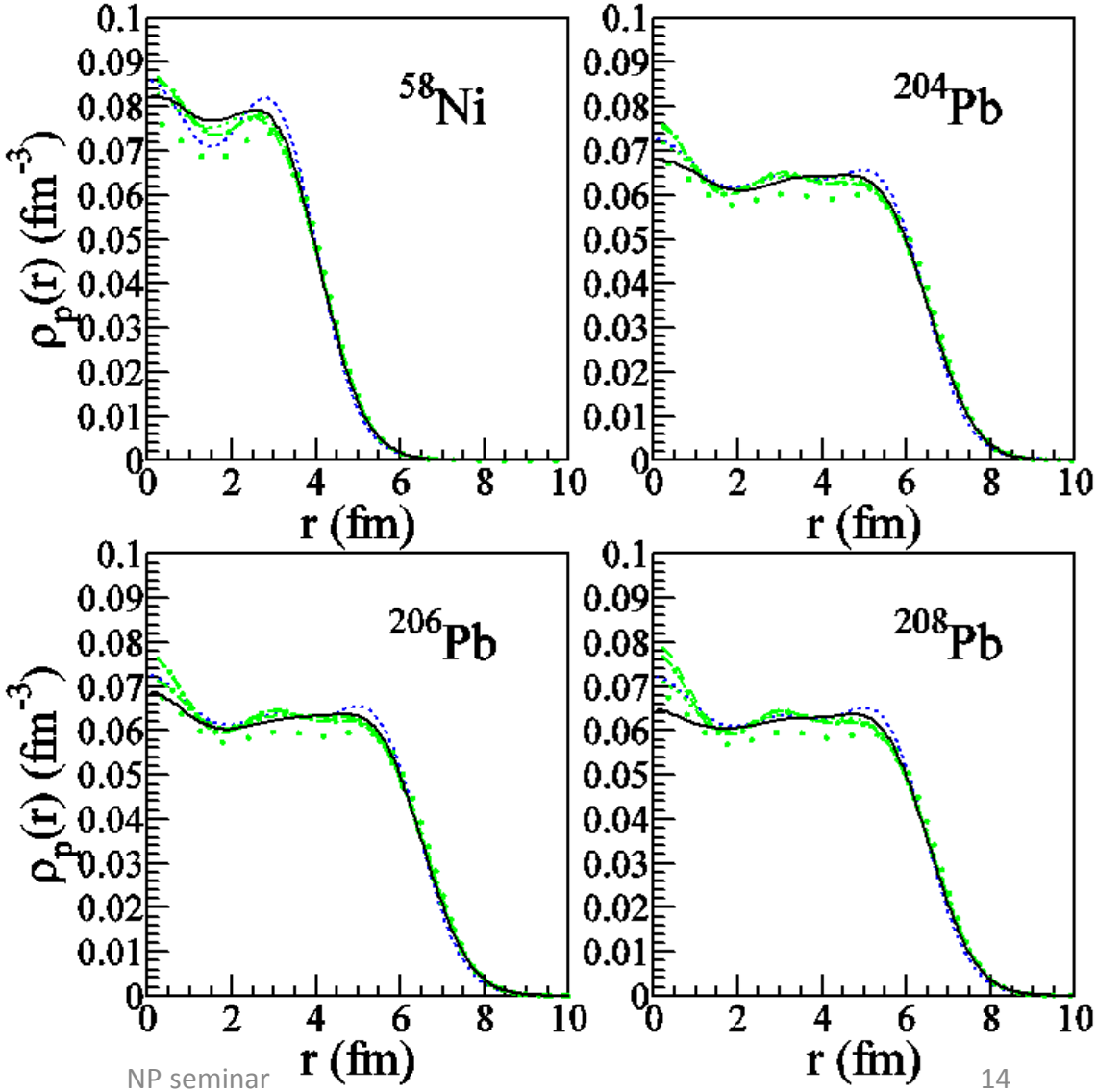
- However, recent study by muonic-hydrogen Lamb shift says r_{ch}^p = 0.84184(67) fm… still under discussion. [Nature 466,213(2010)]



Extracted proton density distributions

- Solid : extracted $\rho_p(r)$
- Blue dotted : Relativistic Hartree calculation
- Green : Skyrme-Hartree-Fock calculations

Nucleus	r_{ch} (fm)	r_p (fm)
^{58}Ni	3.772(4)	3.680
^{204}Pb	5.479(2)	5.420
^{206}Pb	5.490(2)	5.433
^{208}Pb	5,503(2)	5.442



2. Scalar density distributions

$$\rho^S(r) \approx \left\{1 - \frac{3}{10}\frac{k_F^2}{M^{*2}}\right\}\rho^V(r).$$ (RMF by Serot and Waleck)

0.93(interior)~0.98(surface)
kF~1.3fm-1, M*~0.6M at saturation

For medium or heavy nuclei (A>56)

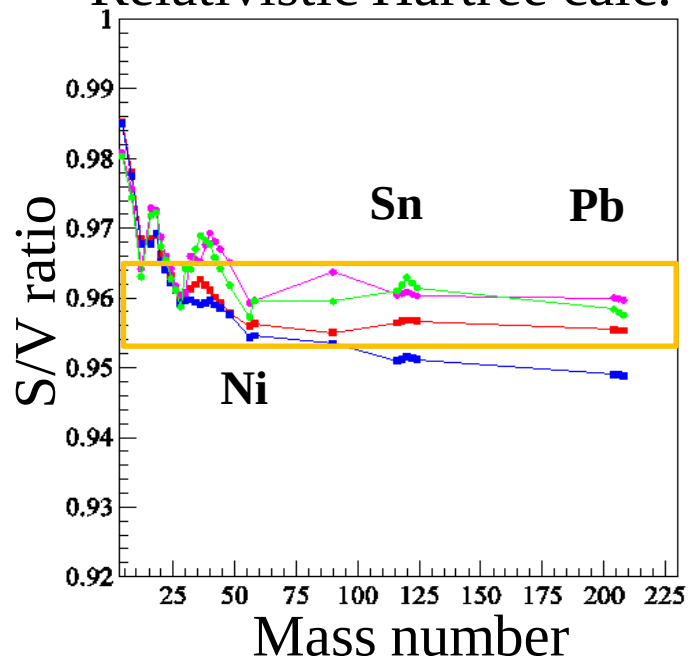
- 0th moment (volume) : proton, neutron

$$\int \rho^S(r)d\mathbf{r} \approx 0.95 \sim 0.96 \int \rho^V(r)d\mathbf{r}.$$

- 2nd moment (size) : proton, neutron

$$\int r^2\rho^S(r)d\mathbf{r} \approx 0.96 \int r^2\rho^V(r)d\mathbf{r}.$$

Relativistic Hartree calc.



3. Medium modification of RLF *NN* interaction

Medium effect

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

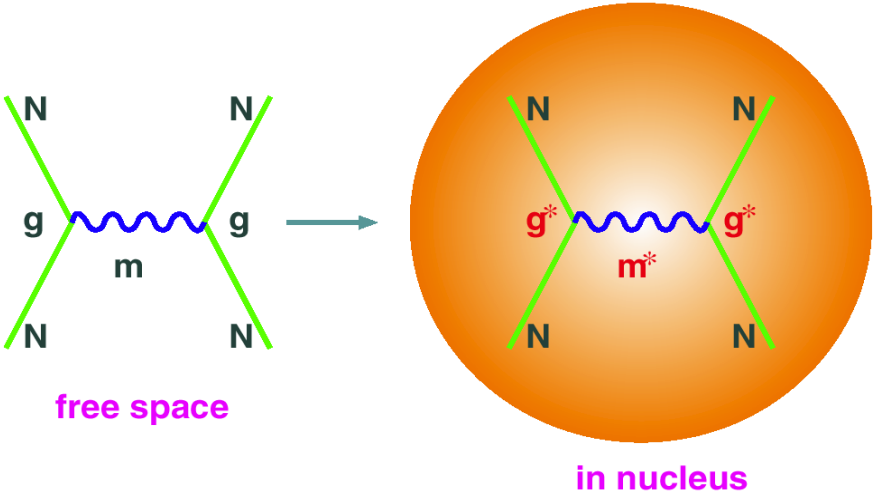
$$m_j \rightarrow m_j^* \equiv m_j\left(1+b_j\rho(r)/\rho_0\right)$$

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

→ Phenomenological parameters; a_j, b_j
→ Universal form of density-dependent terms
→ At ρ=0, same as free *NN* interaction

Need to calibrate with real data

NN interaction



H. Sakaguchi et al., PRC57, 1749.

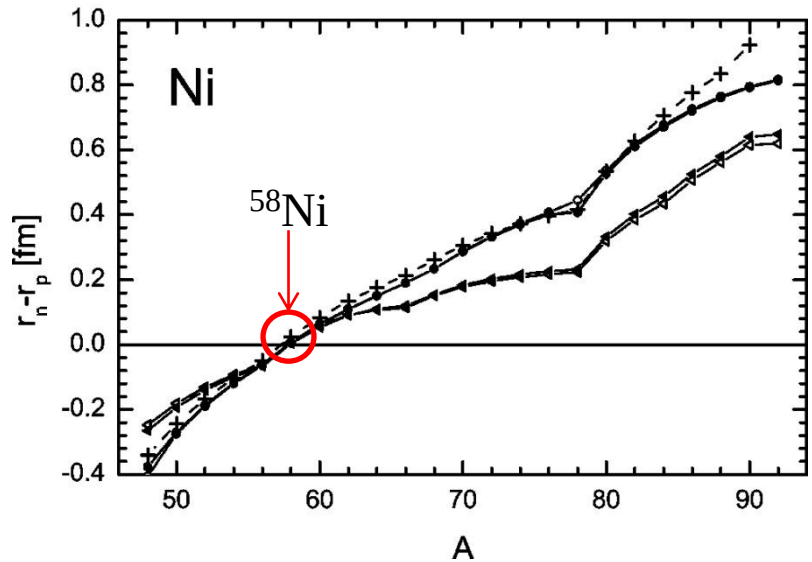
Calibration of medium effect by ^{58}Ni

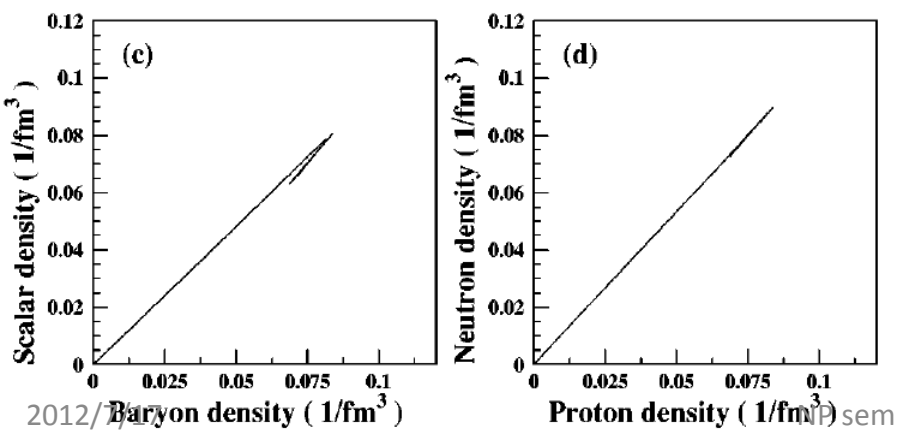
^{58}Ni

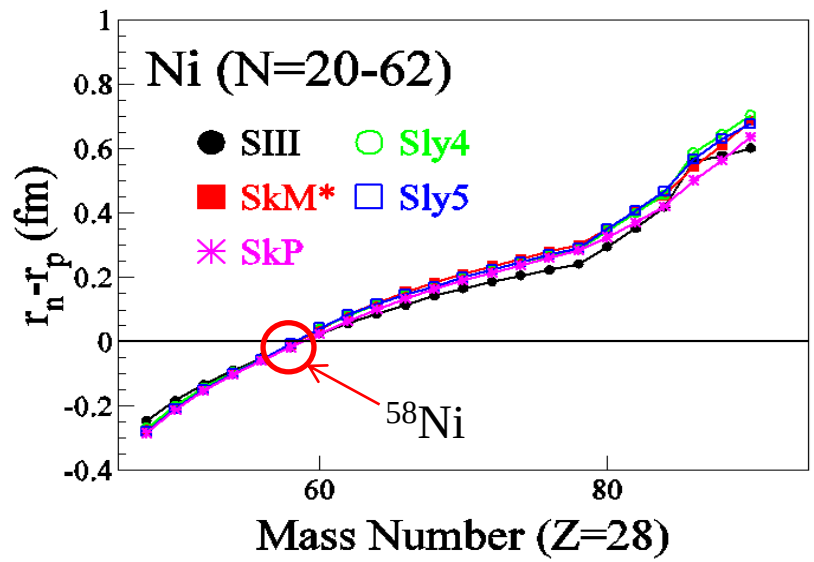
Various experimental & theoretical results say :

$r_n \cong r_p$: almost the same size

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





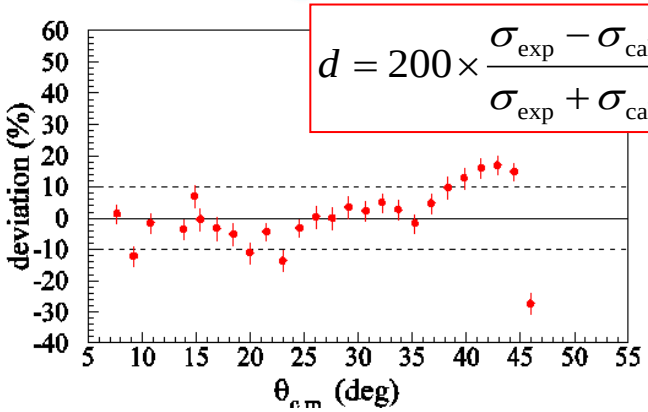


Calibration of medium effect by ^{58}Ni

- 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 $\chi 2$ search

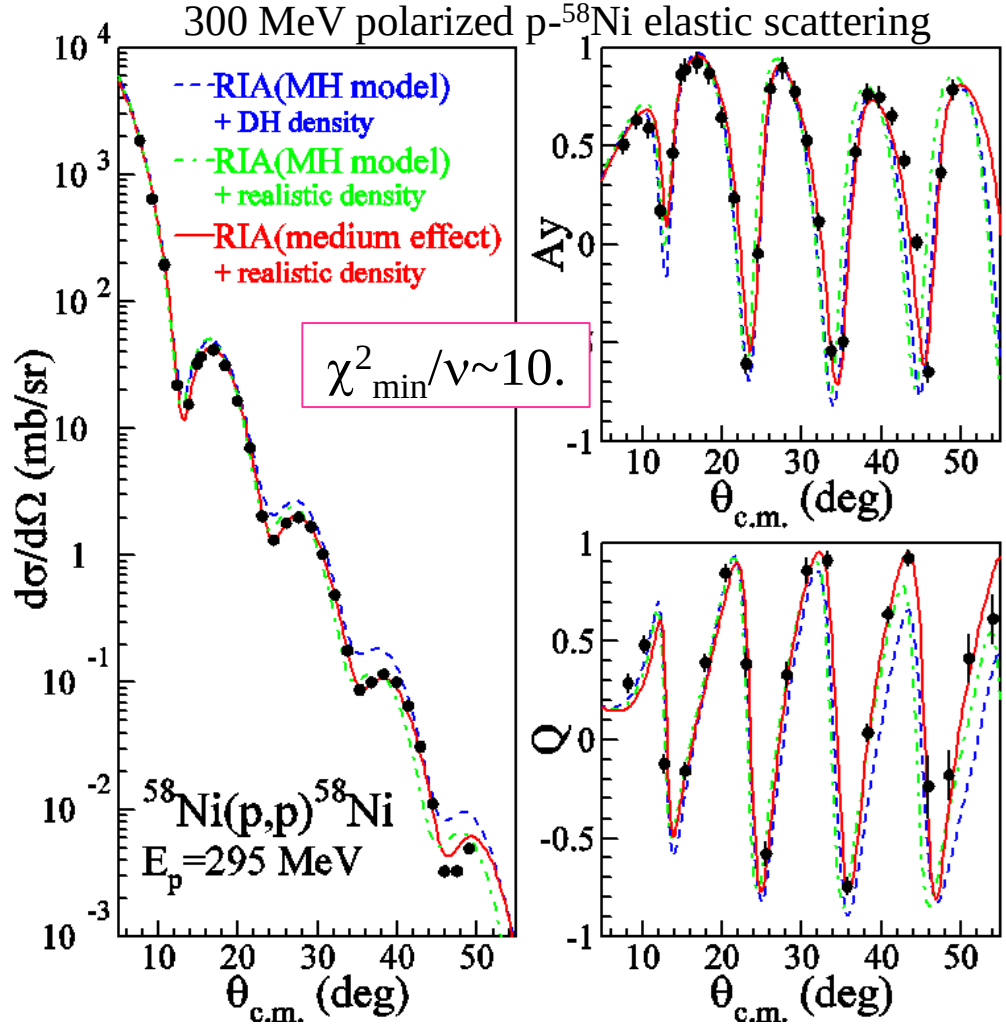
$$d = 200 \times \frac{\sigma_{\exp} - \sigma_{\mathrm{calc}}}{\sigma_{\exp} + \sigma_{\mathrm{calc}}}$$



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

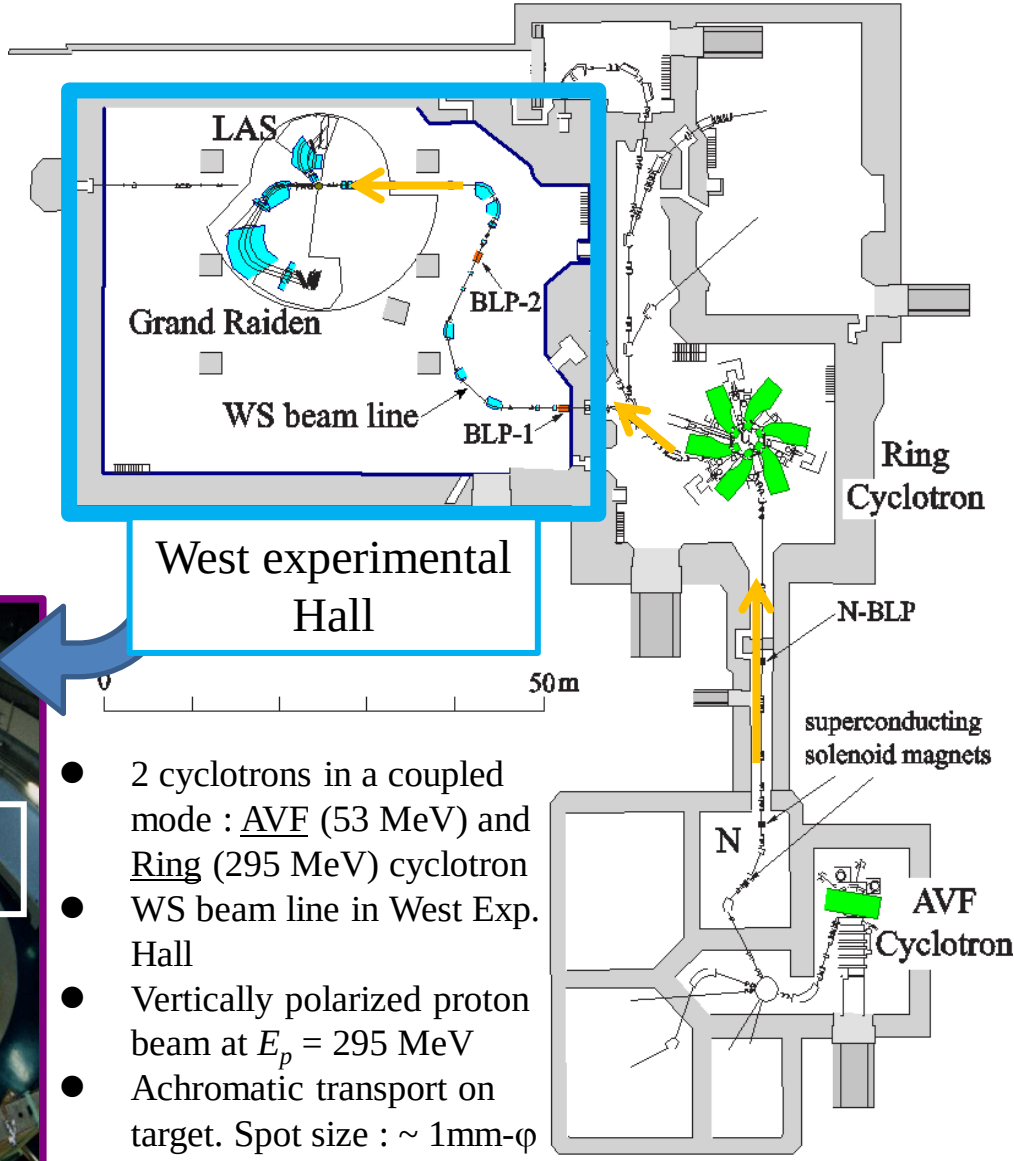


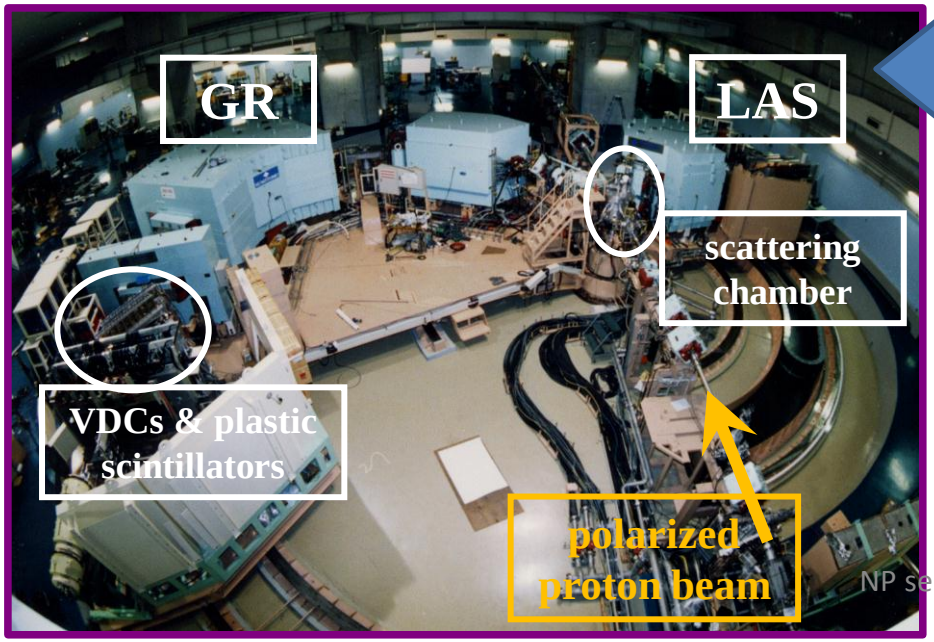
-Pb case-

Experiment @RCNP

Conditions (RCNP-E248)

- Scattering observables : $d\sigma/d\Omega$, A_y
- Beam energy : 295MeV
- Beam polarization : 70~80%
- Energy resolution : ~100keV
- Angular & momentum transfer range : 9~45deg., 0.5~3.5fm^{-1}
- Targets : ^{204,206,208}Pb, ^{58}Ni



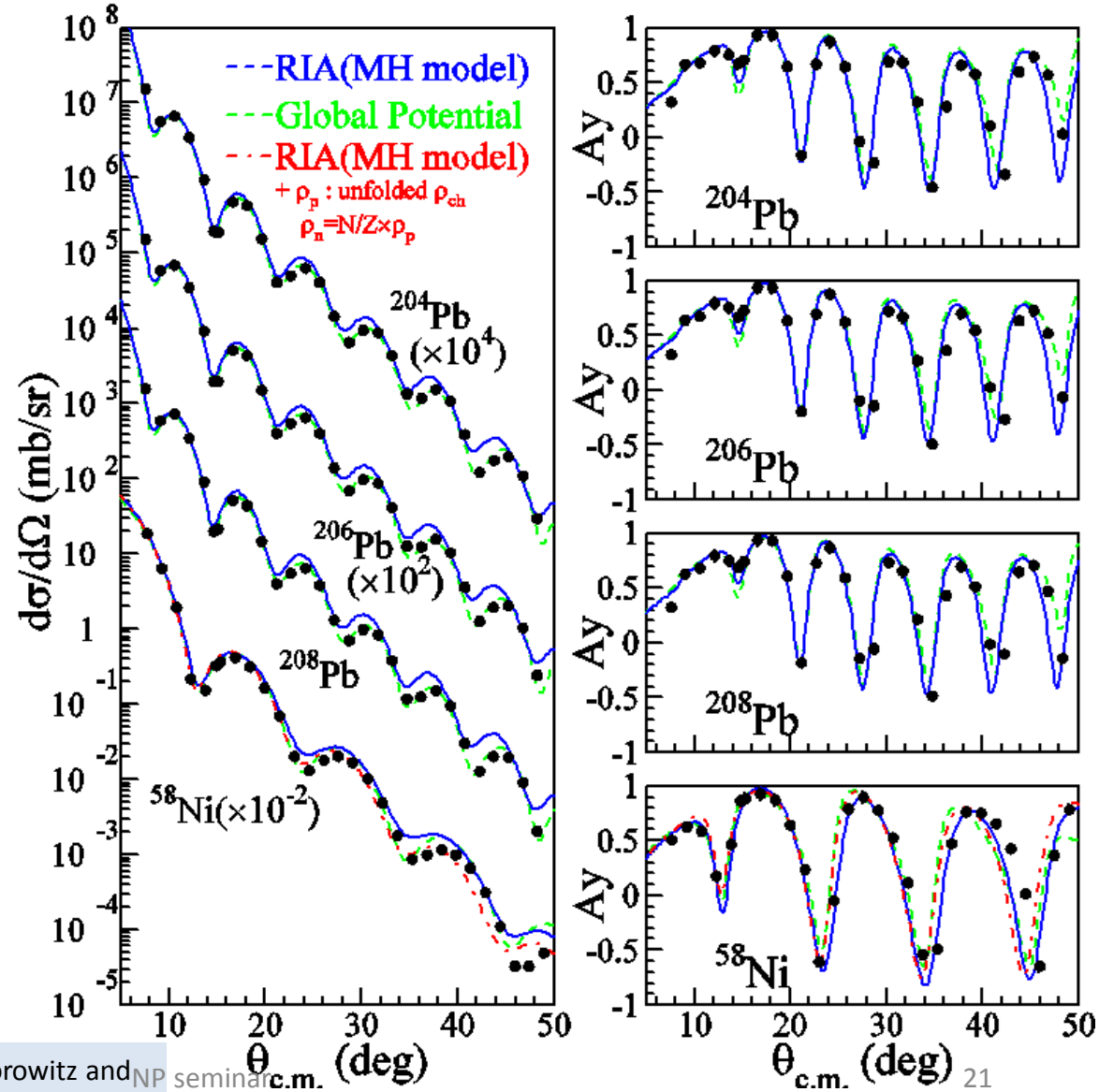


- 2 cyclotrons in a coupled mode : AVF (53 MeV) and Ring (295 MeV) cyclotron
- WS beam line in West Exp. Hall
- Vertically polarized proton beam at E_p = 295 MeV
- Achromatic transport on target. Spot size : ~ 1mm-φ

Comparison with theoretical predictions

- Relativistic impulse approximation by Murdock and Horowitz (IA1):
  → $t\rho$ optical potential
  - relativistic Love-Franey *NN* interaction
  - Relativistic Hartree densities
- RIA for ^{58}Ni case by MH model, but
  → realistic nucleon densities
- Global optical potential

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



D. P. Murdock and C. J. Horowitz, PRC35, 1442. C. J. Horowitz and B. D. Serot, NPA368, 503.

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

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

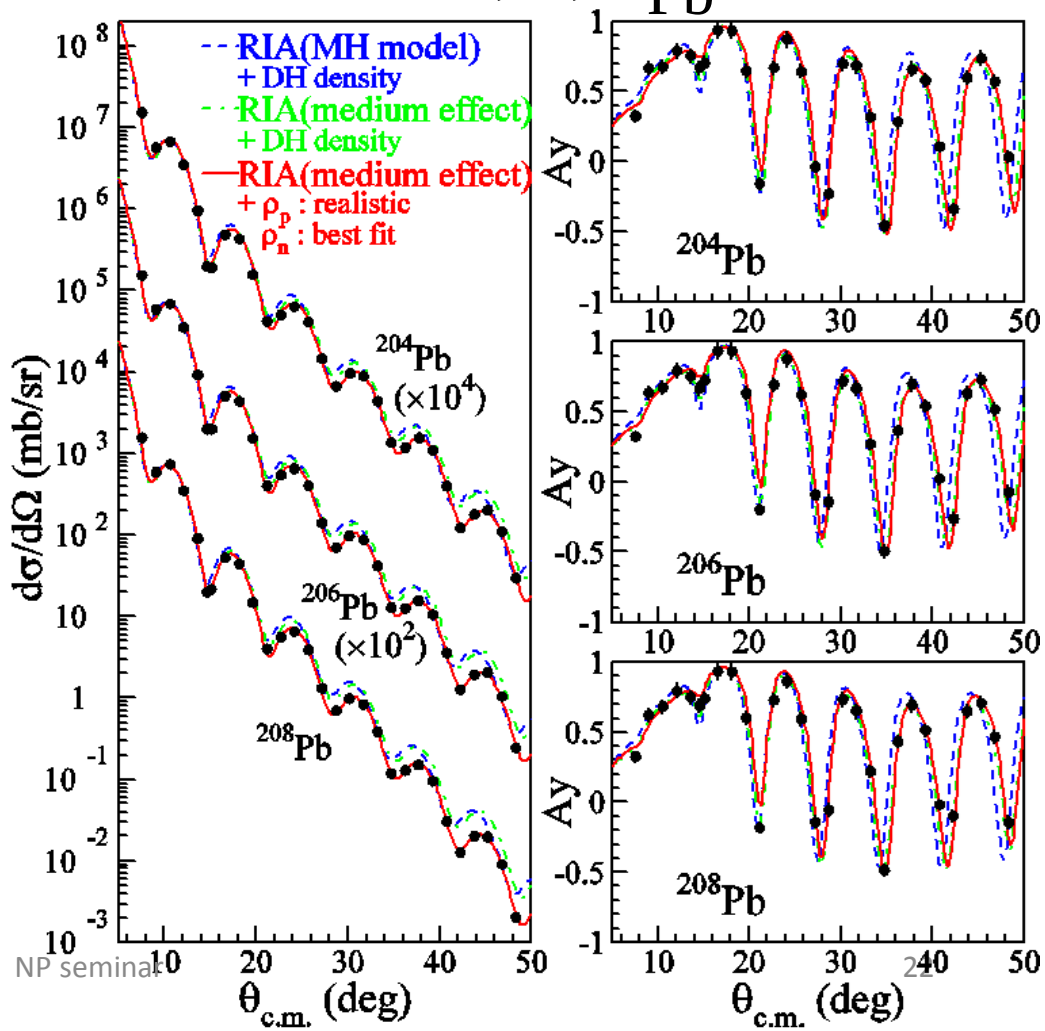
$$A_i = \frac{NQ_i}{2\pi^{3/2}\gamma^3(1+2R_i^2/\gamma^2)}, \sum Q_i = 1$$

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

minimum $\chi 2$ search

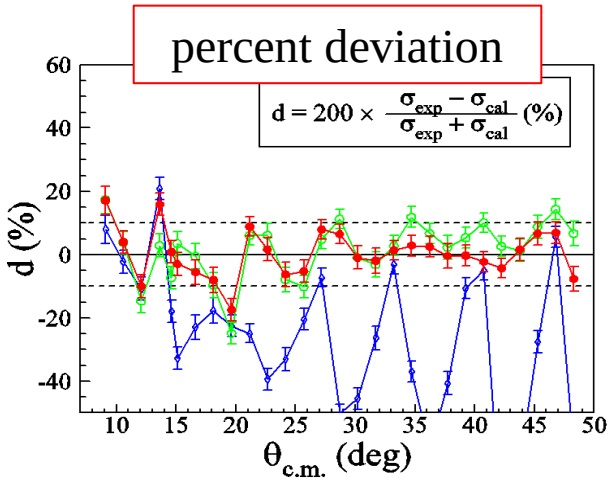
reduced $\chi^2_{min} \sim 4$.

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



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

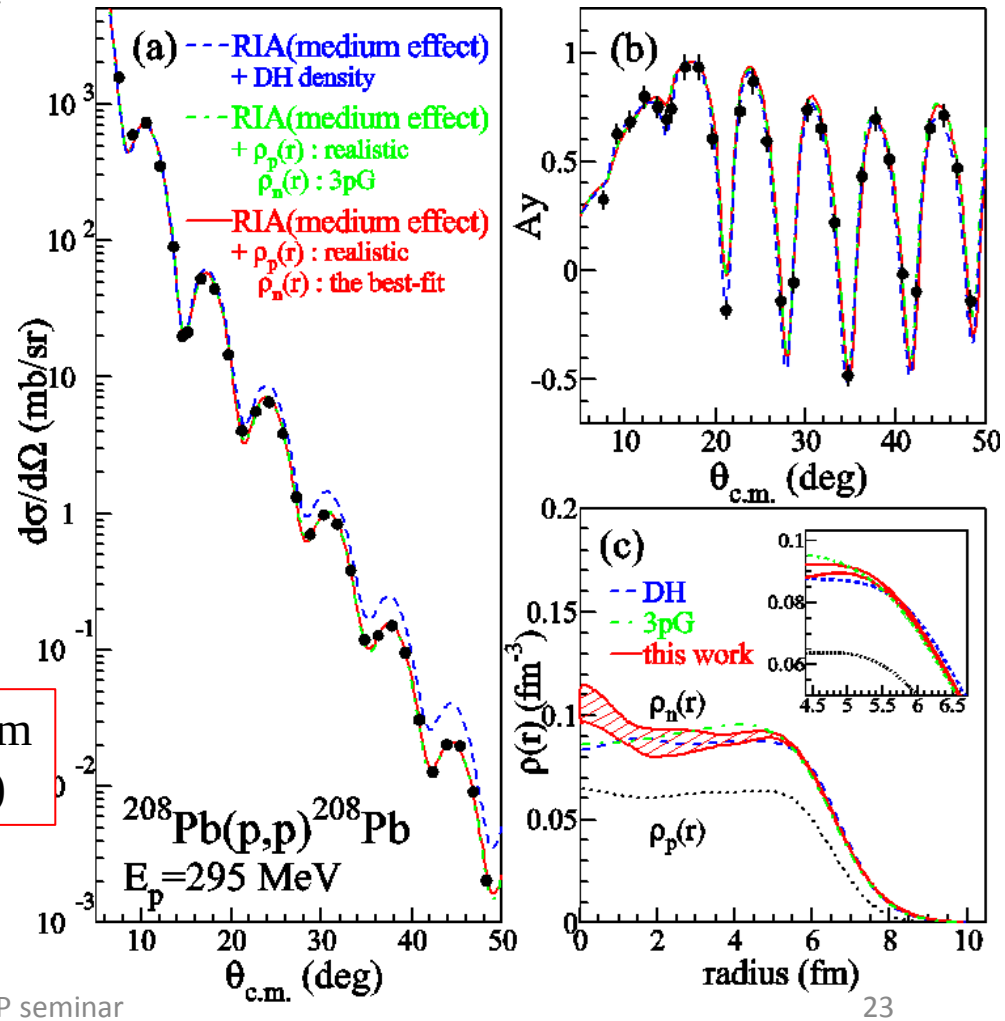
- Error-envelopes due to exp. errors :
  $\chi^2 \leqq \chi^2_{min} + \Delta\chi^2$ ← ~11
- Comparison with previous $\rho_n(r)$: 3-parameter-Gaussian (3pG) by L. Ray (Ref.[58])



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)$_{stat.}$

0.06 fm (1%)

^{208}Pb case



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>

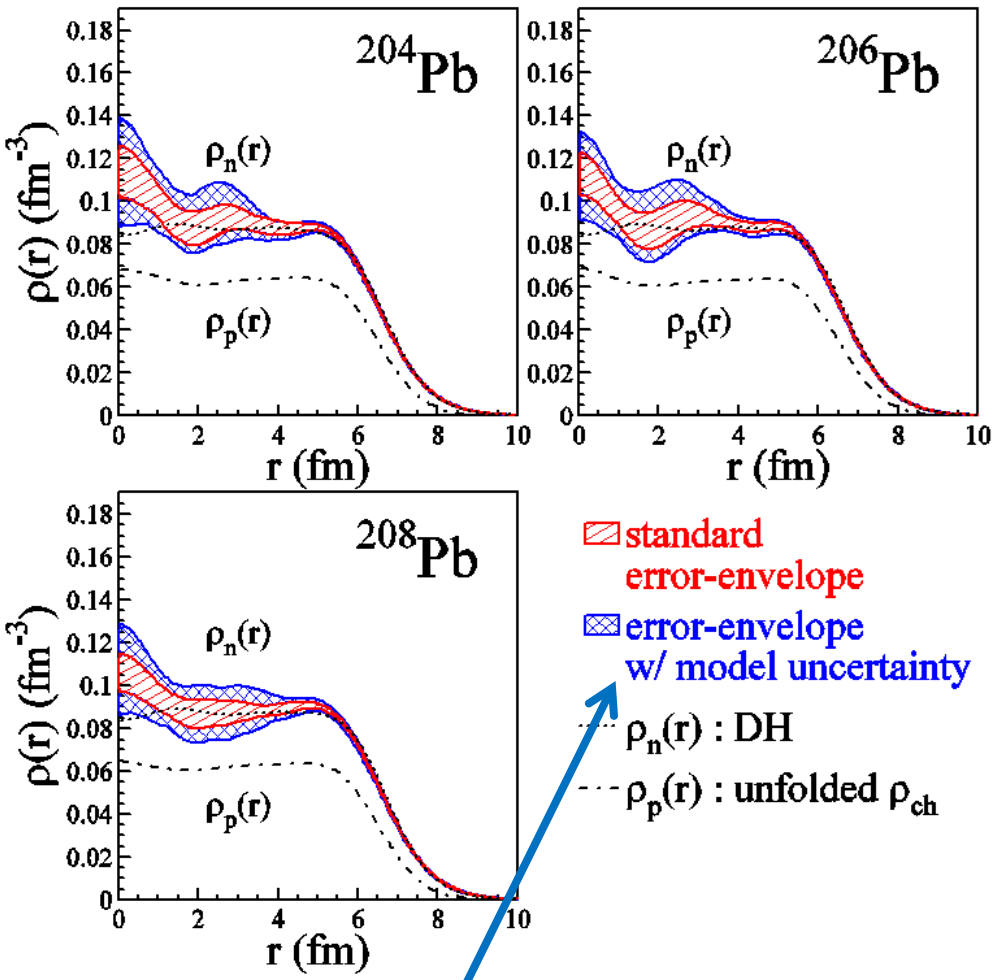
$$\begin{cases} \tilde{\chi}^2 \equiv \chi^2 / S^2 = \sum \left(\dfrac{y^{exp} - y^{calc}}{\boxed{S \cdot \delta y^{exp}}} \right)^2, \\ \tilde{\chi}^2_{min} \equiv \chi^2_{min} / S^2 = \nu \Leftrightarrow S = \sqrt{\chi^2_{min} / \nu}. \end{cases}$$

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

$$\Updownarrow$$

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

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



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

Neutron skin thicknesses Δr_{np}

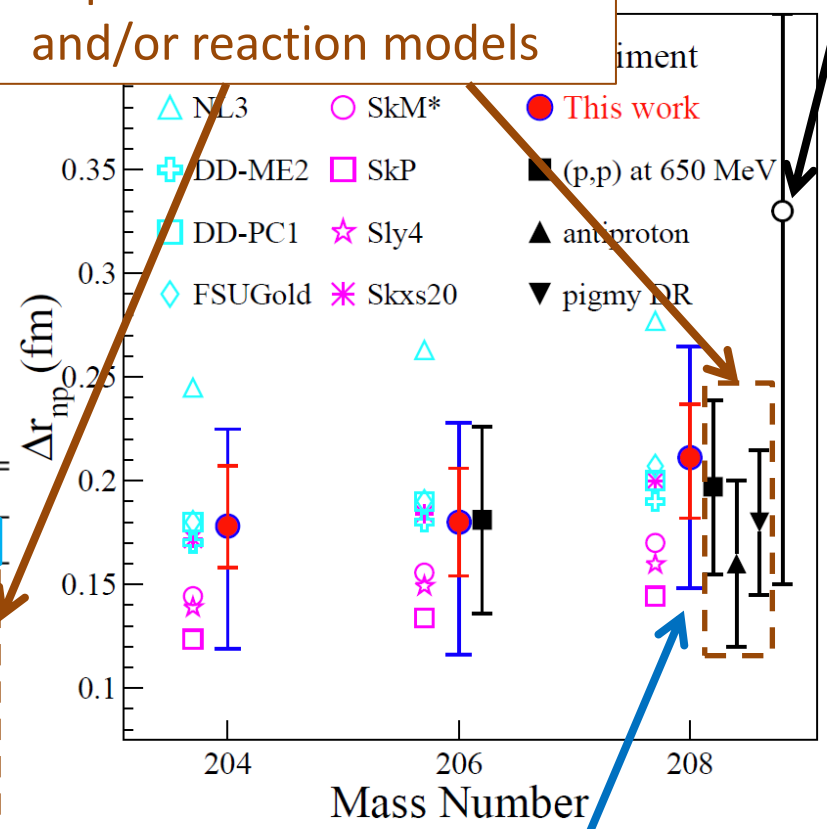
- Comparison with previous experimental results
- Comparison with several mean-field models
  - ✓ relativistic : NL3, DD-ME2, DD-PC1, FSUGold
  - ✓ non-relativistic : SkM*, SkP, Sly4, Skxs20

208Pb

Experiment	r_p	r_n	Δr_{np}
This work from Table. 5.1	5.442(2)	$5.653^{+0.026}_{-0.029}{}^{+0.054}_{-0.063}$	$0.211^{+0.026}_{-0.029}{}^{+0.054}_{-0.063}$
^{208}Pb(p,p) at 800 MeV [58]*	5.45	5.59(4)	0.14(4)
^{208}Pb(p,p) at 650 MeV [62]†	5.46	5.66(4)	0.20(4)
Isospin diffusion data in Sn + Sn at 50 MeV/u [51]‡	-	-	0.22(4)
GDR from (α,α') at 120 MeV[61]	-	-	0.19(9)
PDR from $^{129-132}$Sn(γ,γ') [68]¶	-	-	0.18(4)
PDR in ^{68}Ni and ^{132}Sn [72]‖	-	-	0.194(24)
X-ray cascade from $\bar{p}$-atom (1)[67]**	5.44	5.60	$0.16(2)_{stat}(4)_{syst}$
X-ray cascade from $\bar{p}$-atom (2)[73]††	5.45	$5.65(5)_{mdl}$	$0.20(4)_{exp}(5)_{mdl}$

Dependent on structure and/or reaction models

PREX



Evaluate reaction model ambiguity

Nuclear matter EOS with isospin asymmetry δ

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

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

→ E(ρ_{sat},0) ~ -16 MeV, K_0 ~ 240 MeV

- The symmetry energy S(ρ) :

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

→ Still less certain !

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

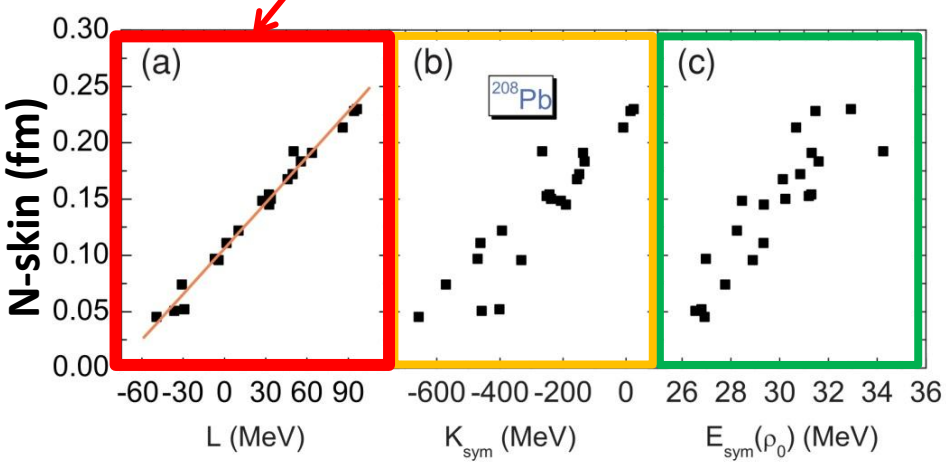
Δr_{np} for ^{208}Pb vs. Symmetry energy

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

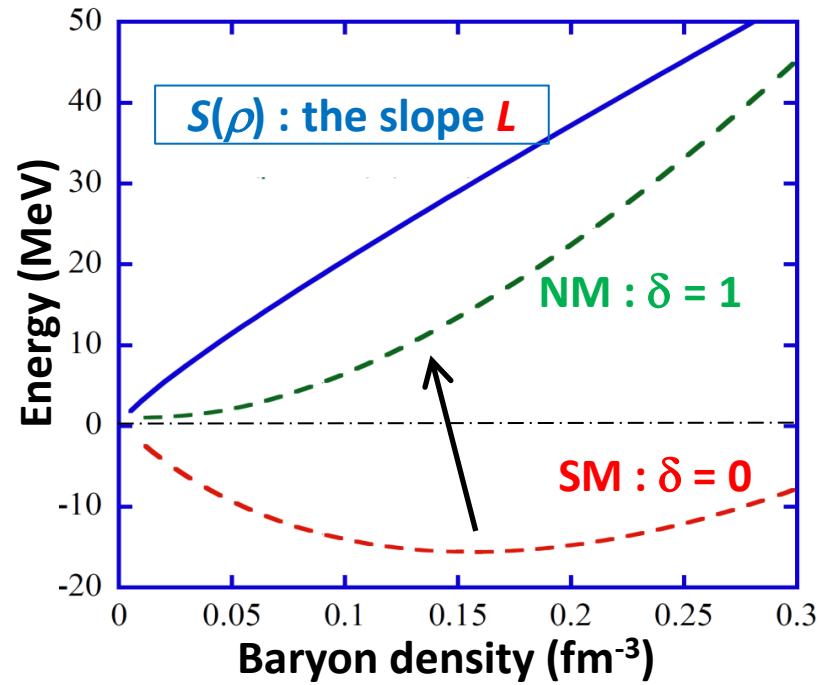
$$S(\rho) = S(\rho_{sat}) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + O(\varepsilon^3)$$

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

Strong correlation!



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



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

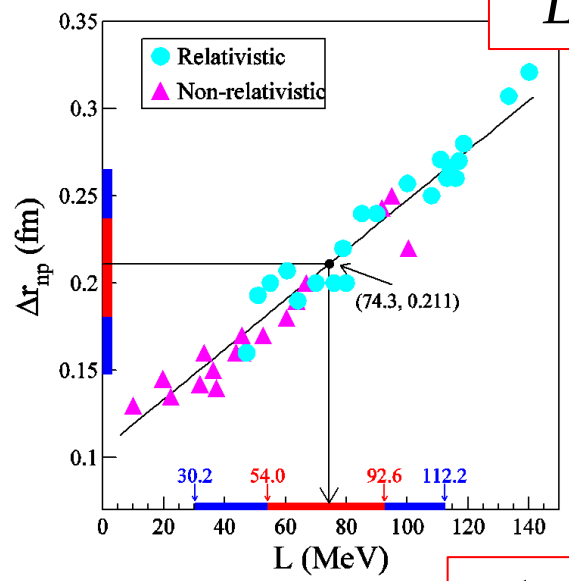
Impact on **neutron star** structure

- Radius, cooling system, etc.

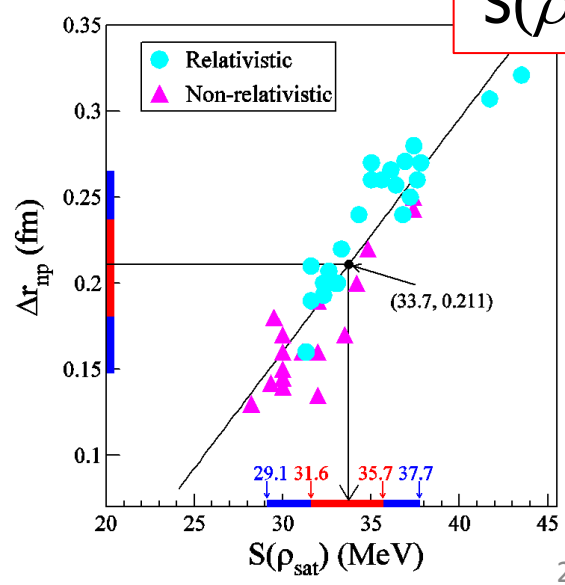
Δr_{np} for ^{208}Pb vs the symmetry energy coefficients

- Plot many mean-field predictions
- The incompressibility and symmetry energy coefficients :
  K_0, $S(\rho_{sat})$, L, K_{sym}
- Strong correlation :
  Δr_{np} vs $S(\rho_{sat})$, Δr_{np} vs L
- Perform linear fitting and deduce the constraint range of $S(\rho_{sat})$ and L.

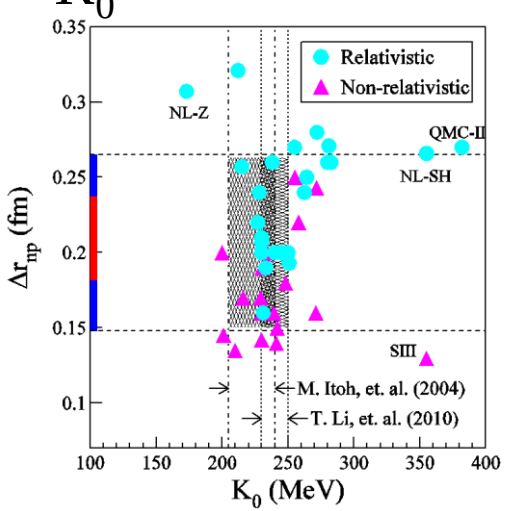
L



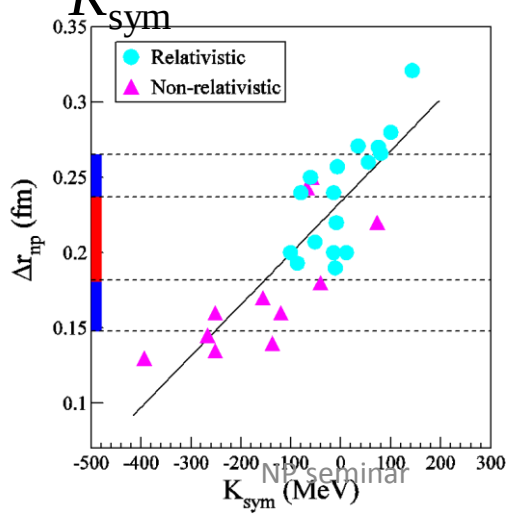
$S(\rho_{sat})$



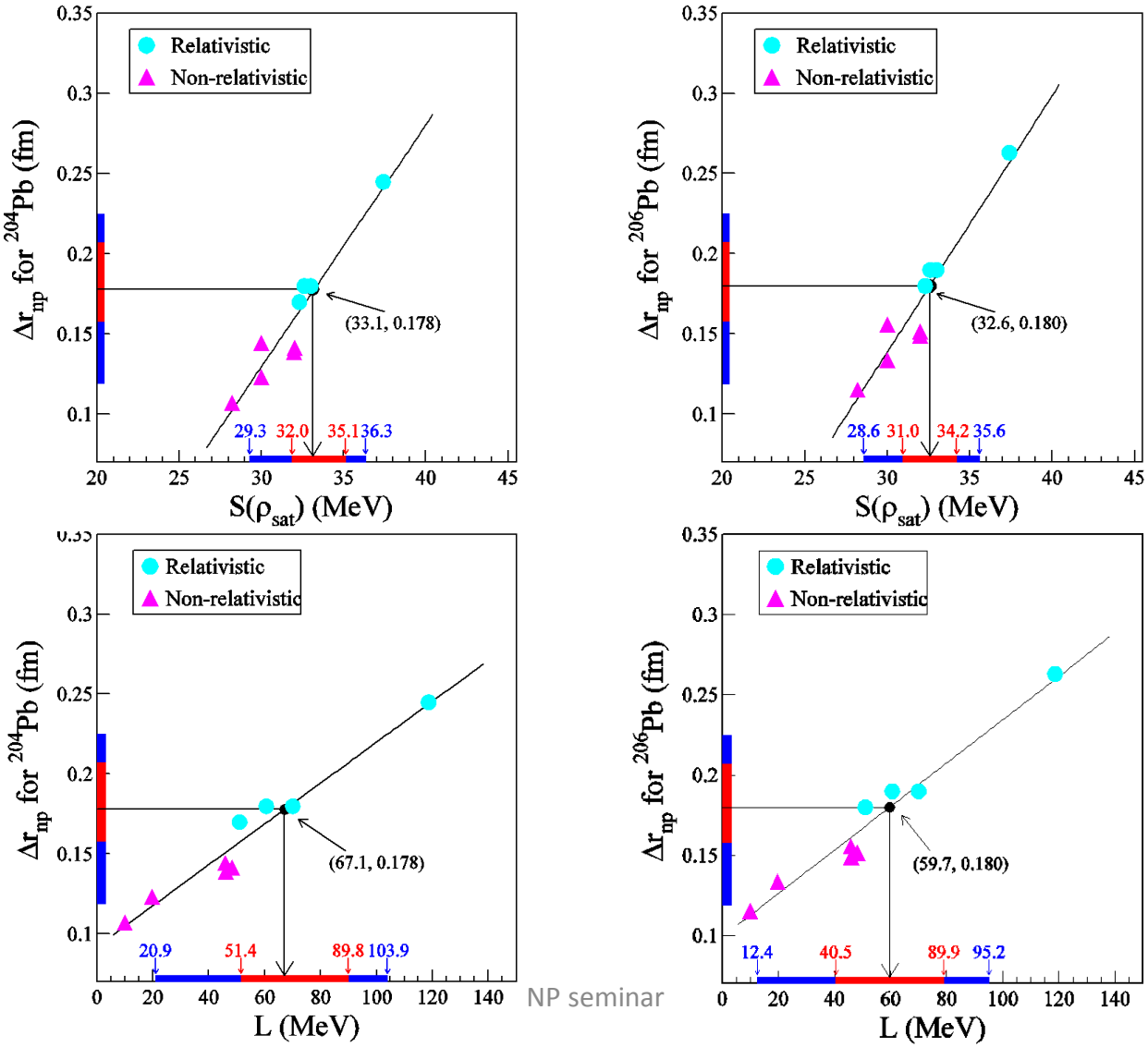
K_0



K_{sym}



Δr_{np} for ^{204,206}Pb vs the symmetry energy coefficients

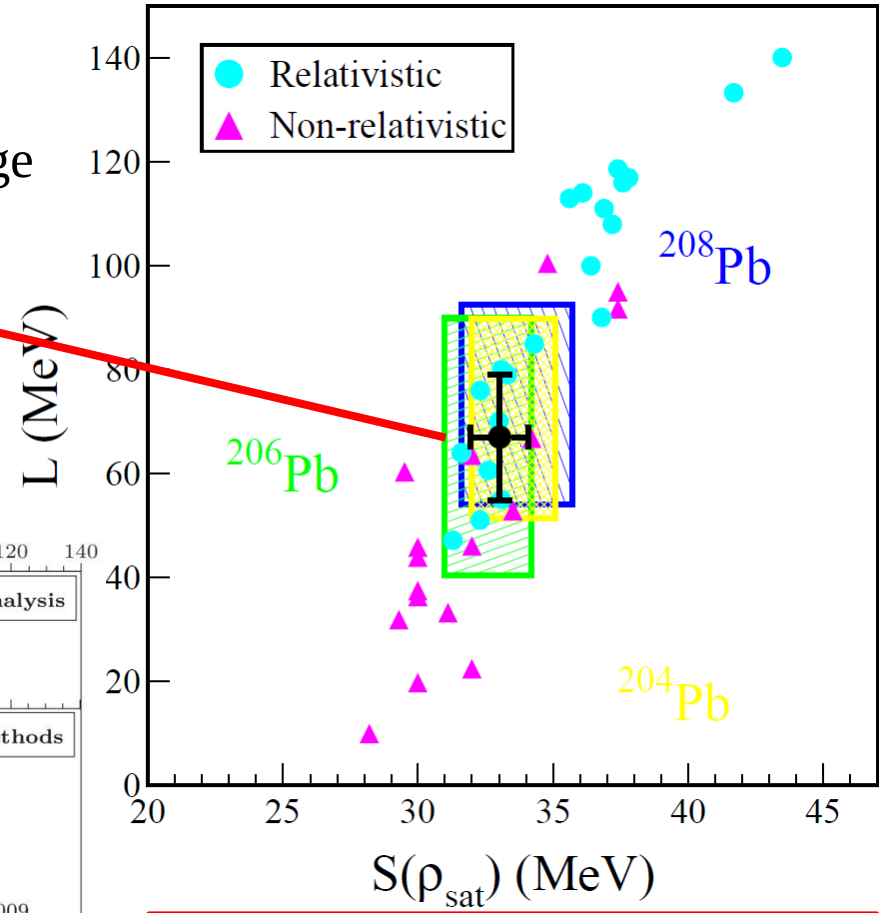


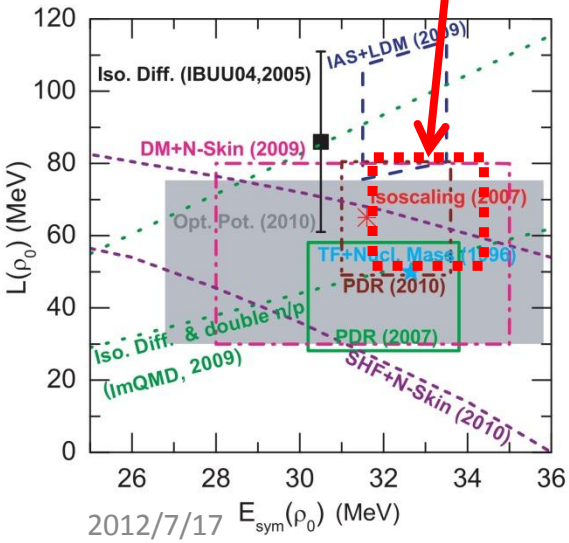
The symmetry energy coefficients deduced from Δr_{np} for ^{204,206,208}Pb

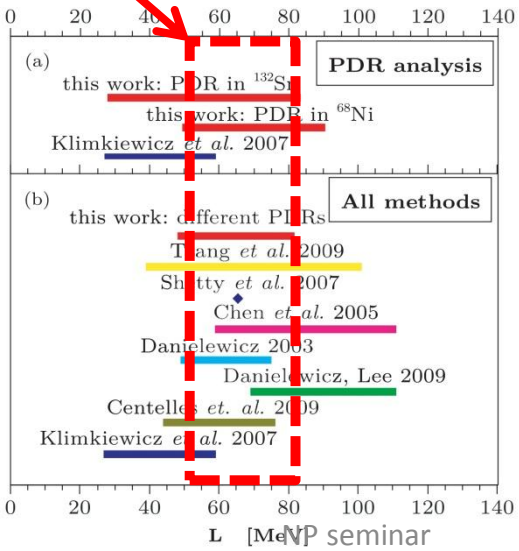
- Deduced region of the symmetry energy coefficients : weighted average

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

→ comparable with previous studies but still large







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

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

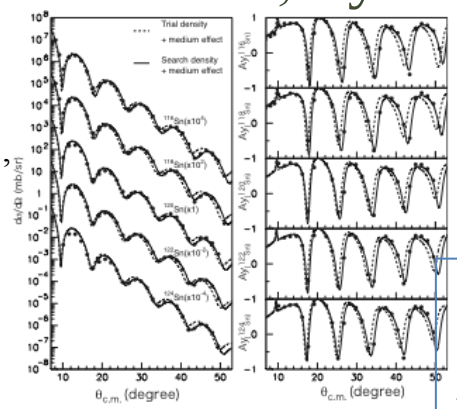
$d\sigma/d\Omega$, Ay

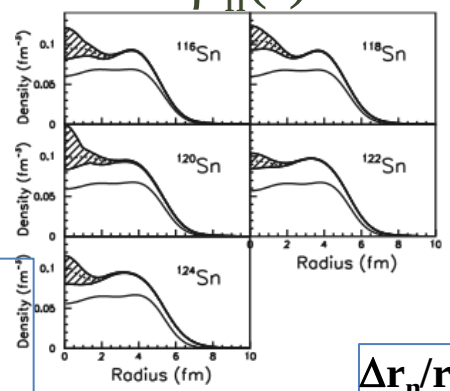
$\rho_n(r)$

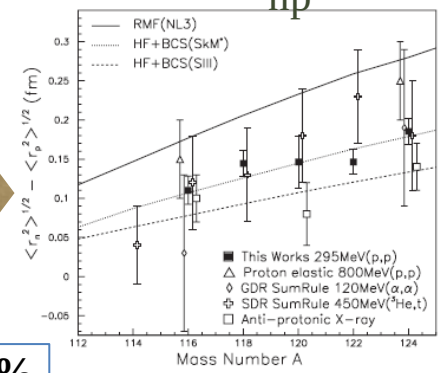
Δr_{np}

Sn

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





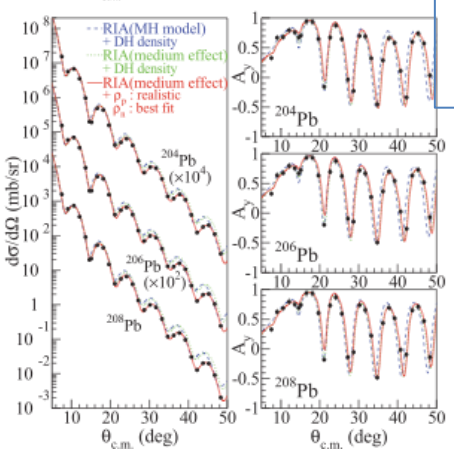


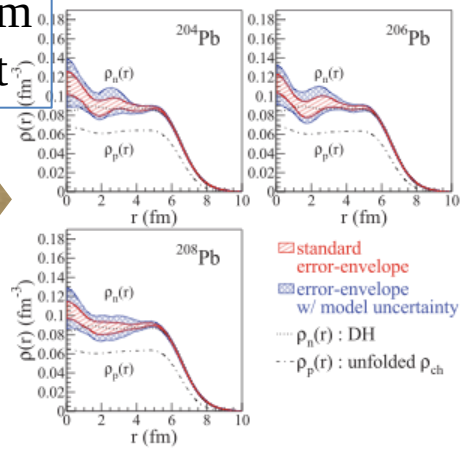
RIA + Medium Effect

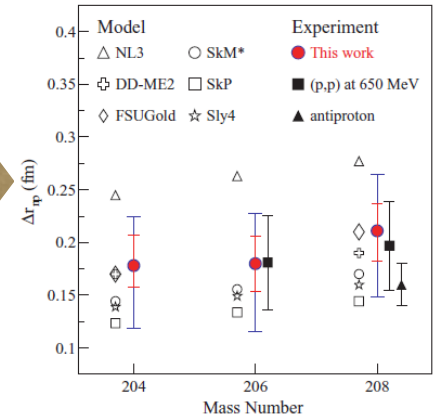
$\Delta r_n/r_n < 0.5\%$

Pb

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







Unstable nuclei → ESPRI project

4. Unstable nuclei -ESPRI project-

Application to nuclei with large isospin asymmetry

ESPRI project

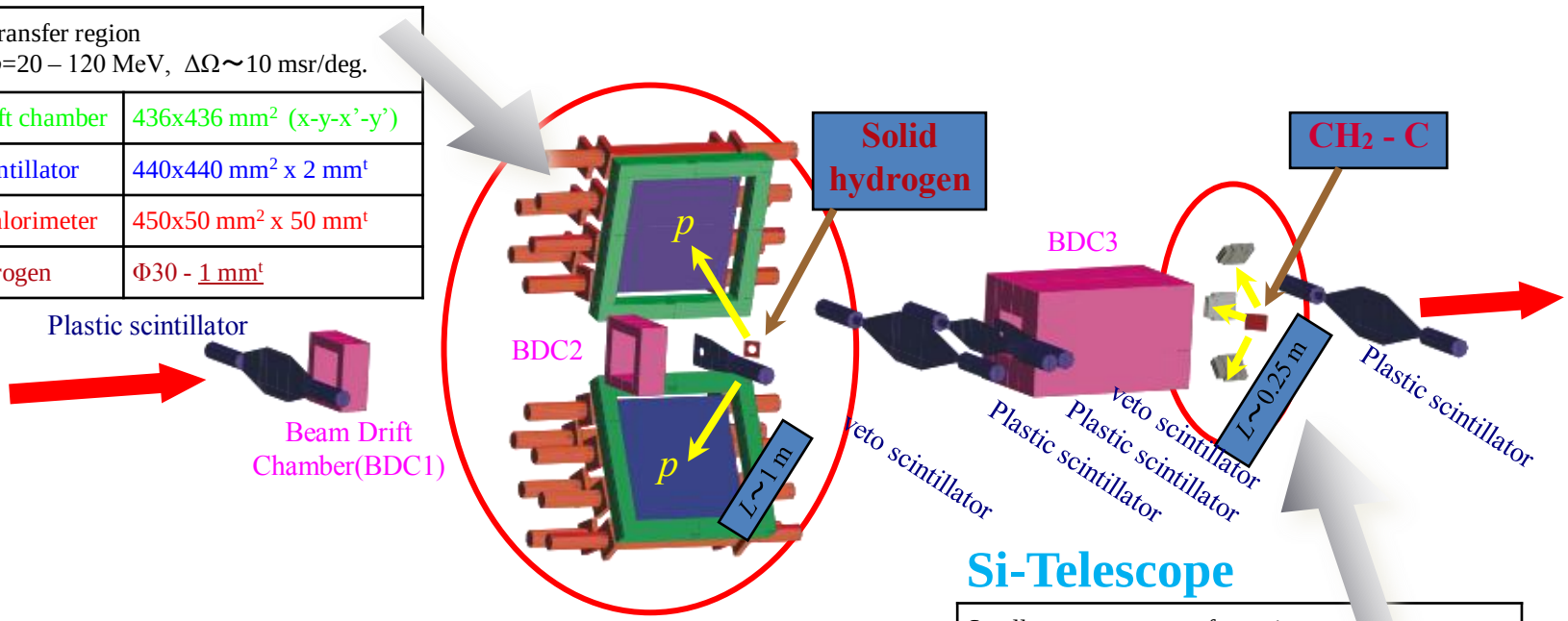
Unstable nuclei →experimental data itself is rare !

→ **E**lastic **S**cattering of **P**rotons 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



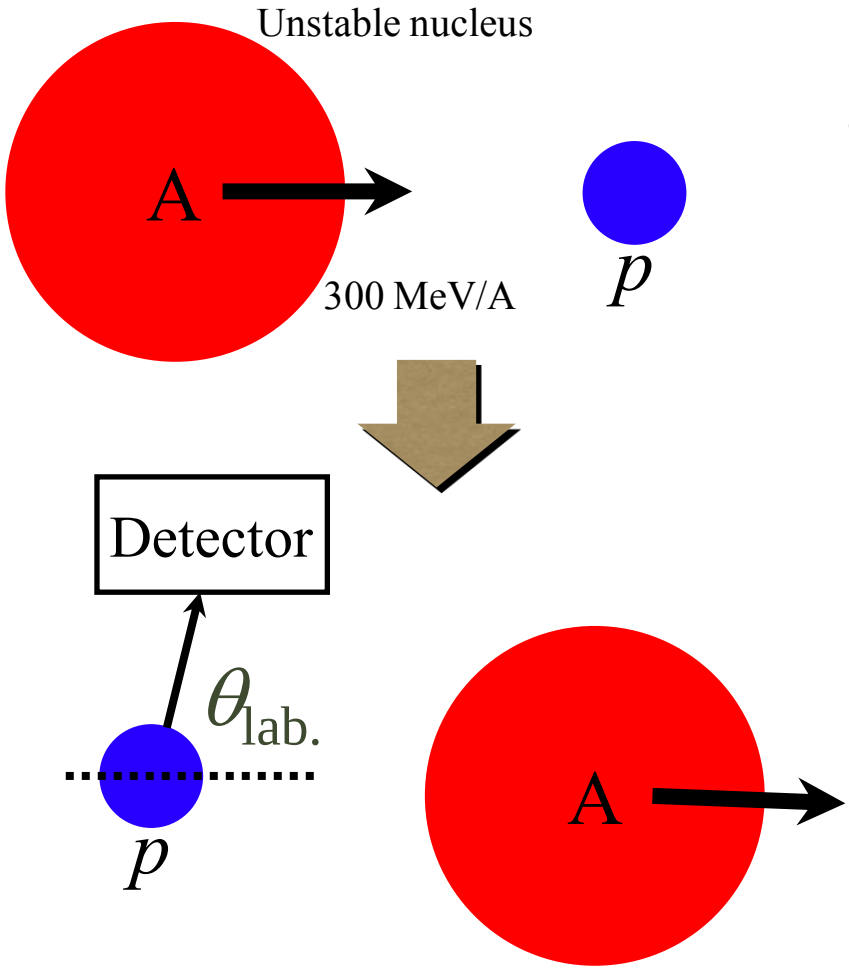
Si-Telescope

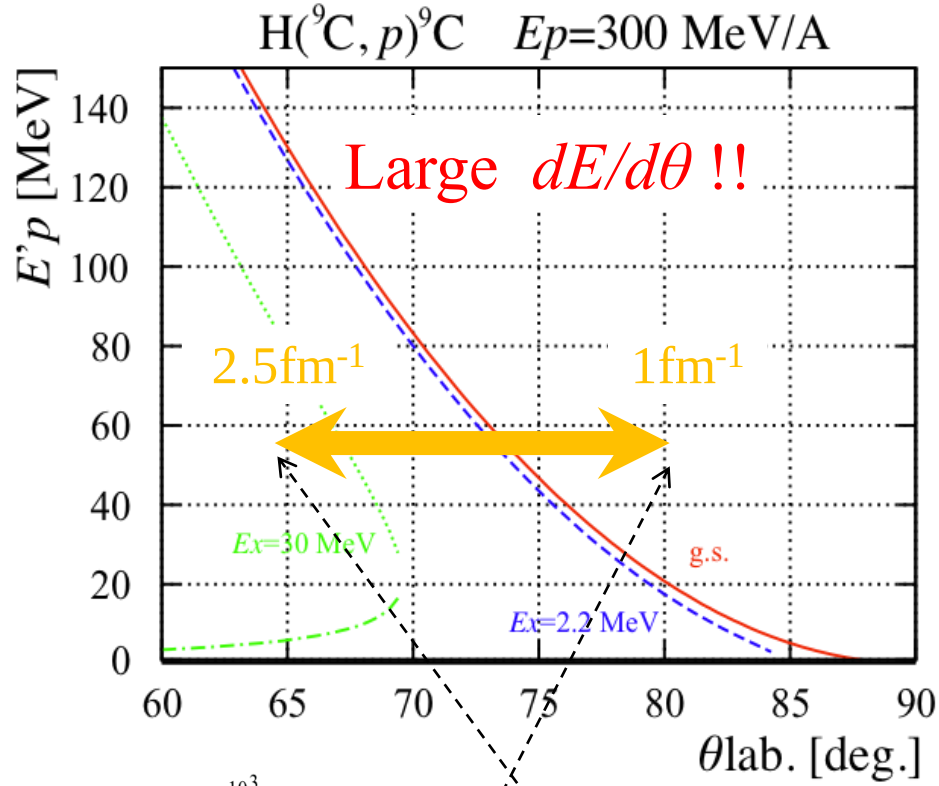
Small momentum transfer region **θ_{lab} = 75 - 85°** , *Ep*=5 – 50 MeV ΔΩ∼14 msr/deg.		
Telescope	Si strip	70x50 mm^2 x 300 μm^t
	CsI(Tl)	70x50 mm^2 x 25.5 mm^t
Target	CH_2 - C	70x50 mm^2 x 0.01—0.1mm^t

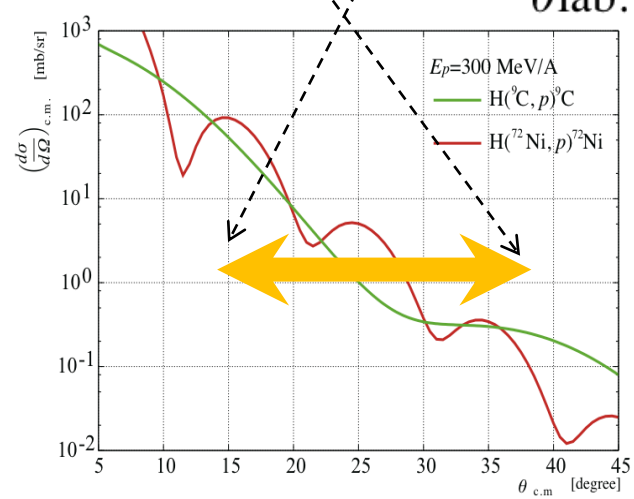
- ◆ Missing mass spectrometer : $P^{\mu}_{beam}+P^{\mu}_{p} \Rightarrow E_x$ (ΔEx~400 keV)
- ◆ Cover extensive momentum transfer region : up to ∼2.5 fm^{-1}

Kinematics of ESPRI

Inverse kinematics : fixed probe





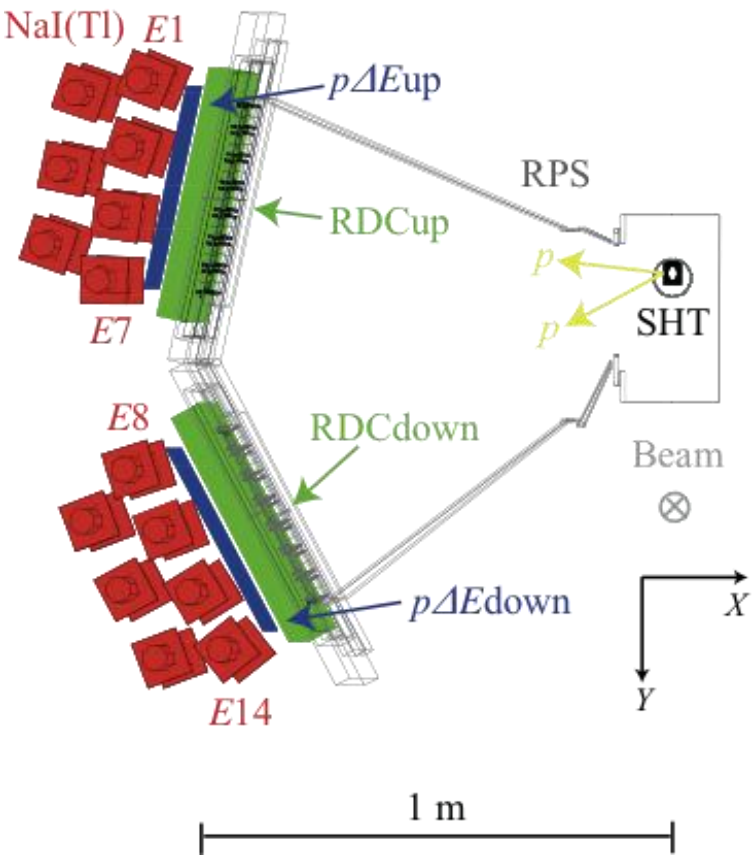


It has been difficult to measure in a wide momentum transfer region.

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

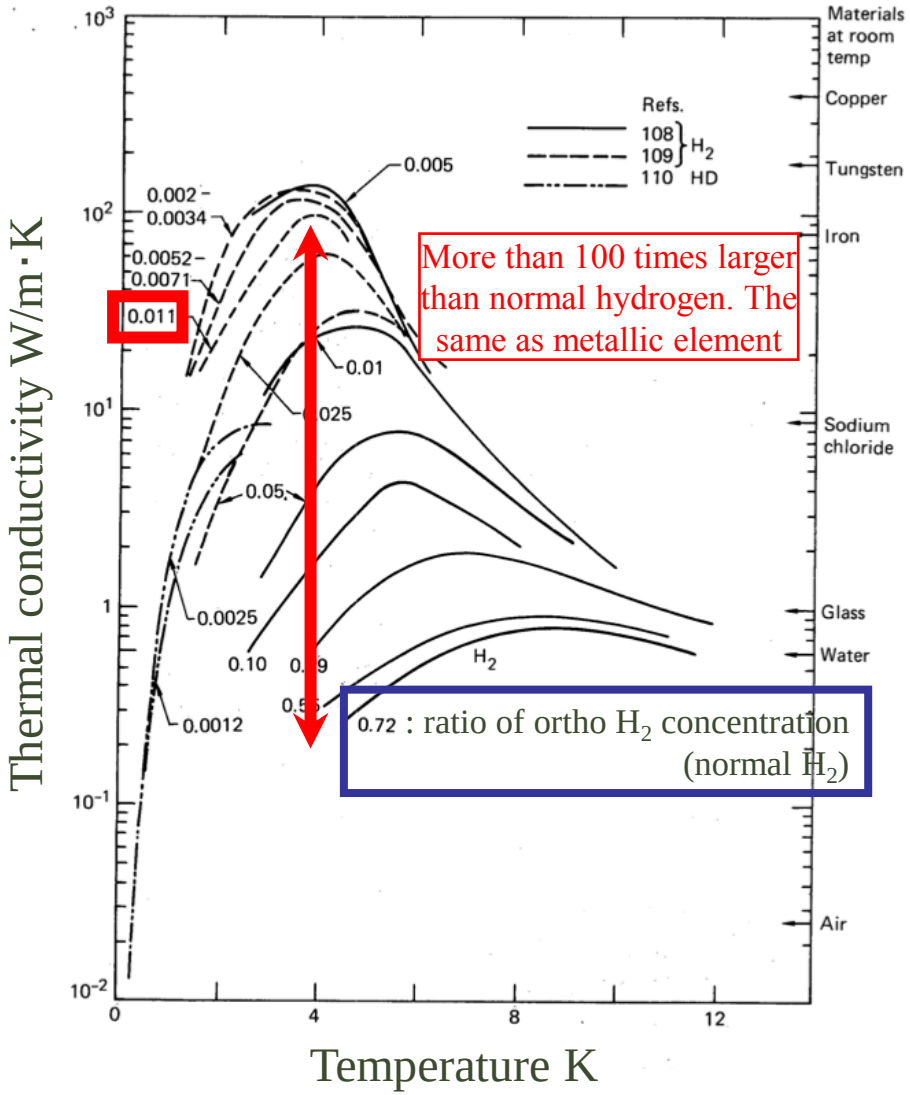
•*para*-H_2 : *ortho*-H_2 = 1: 3

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.

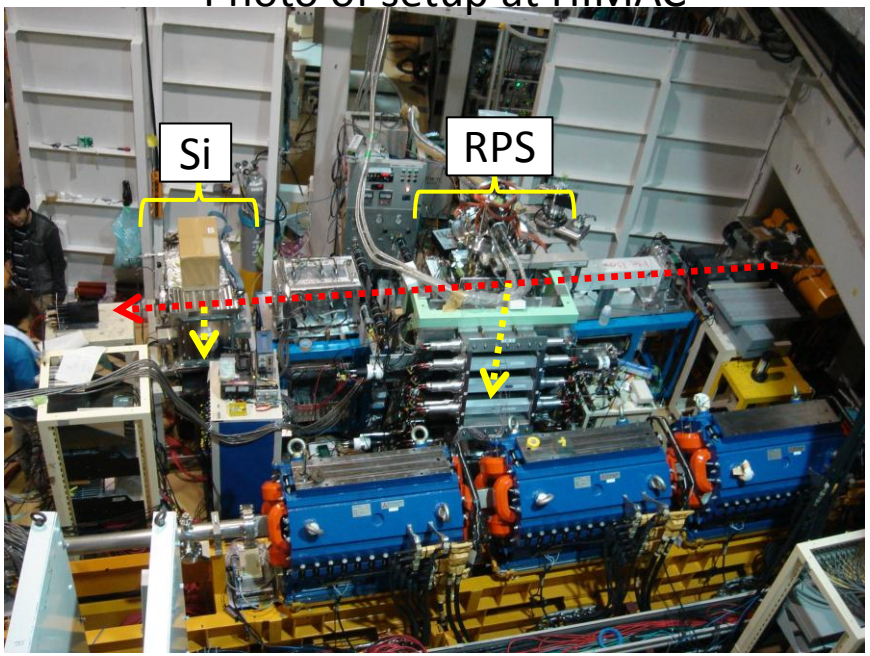
R & D at HIMAC

◆Test of the detector system

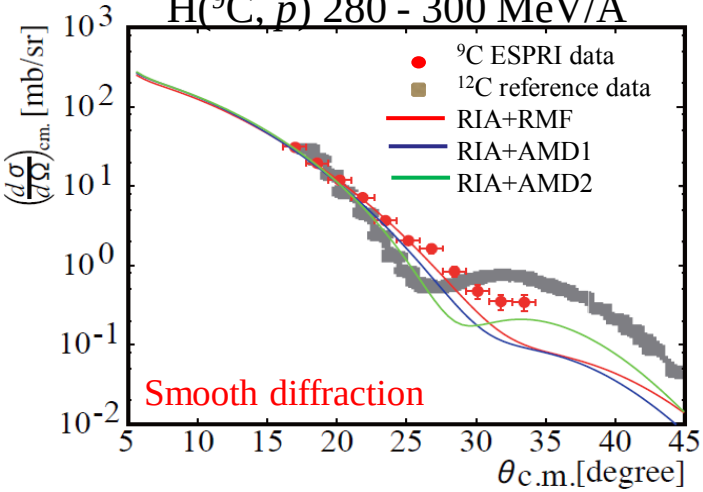
- ✓ Each detectors were developed at several accelerator facilities.
- ✓ Total setup was tested using $^{9,10,11}C$, ^{20}O at HIMAC

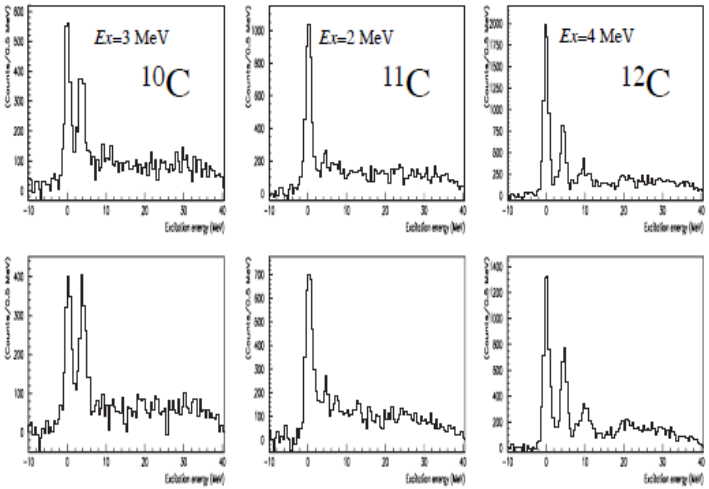
→ Successfully performed

Photo of setup at HIMAC

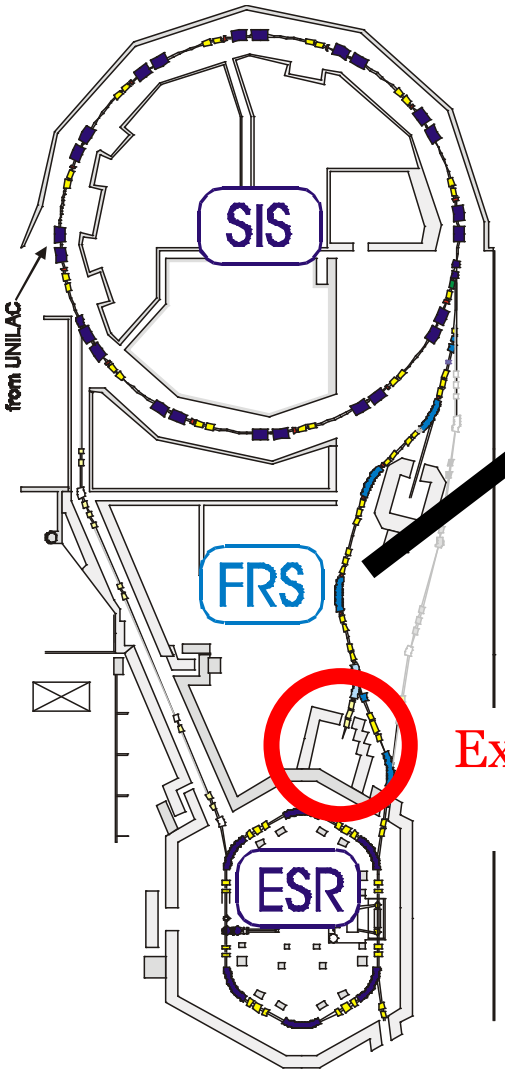


H(^{9}C, p) 280 - 300 MeV/A

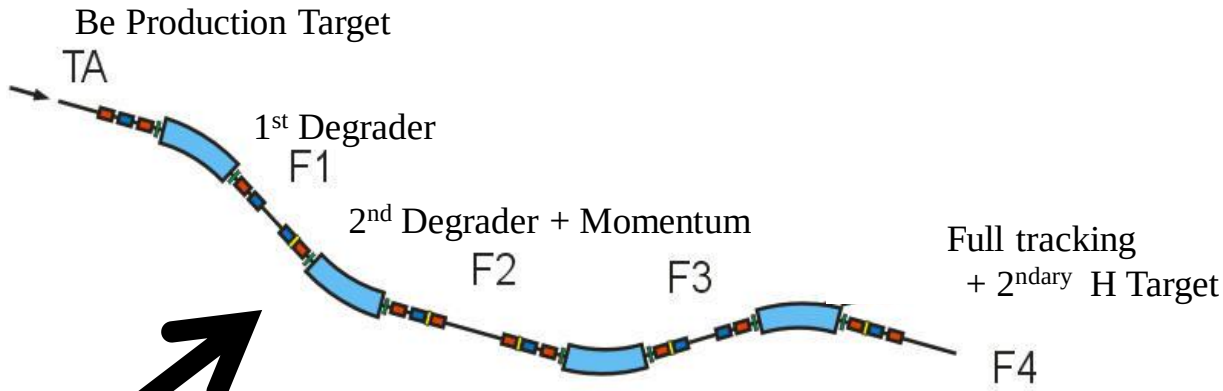




R & D at GSI

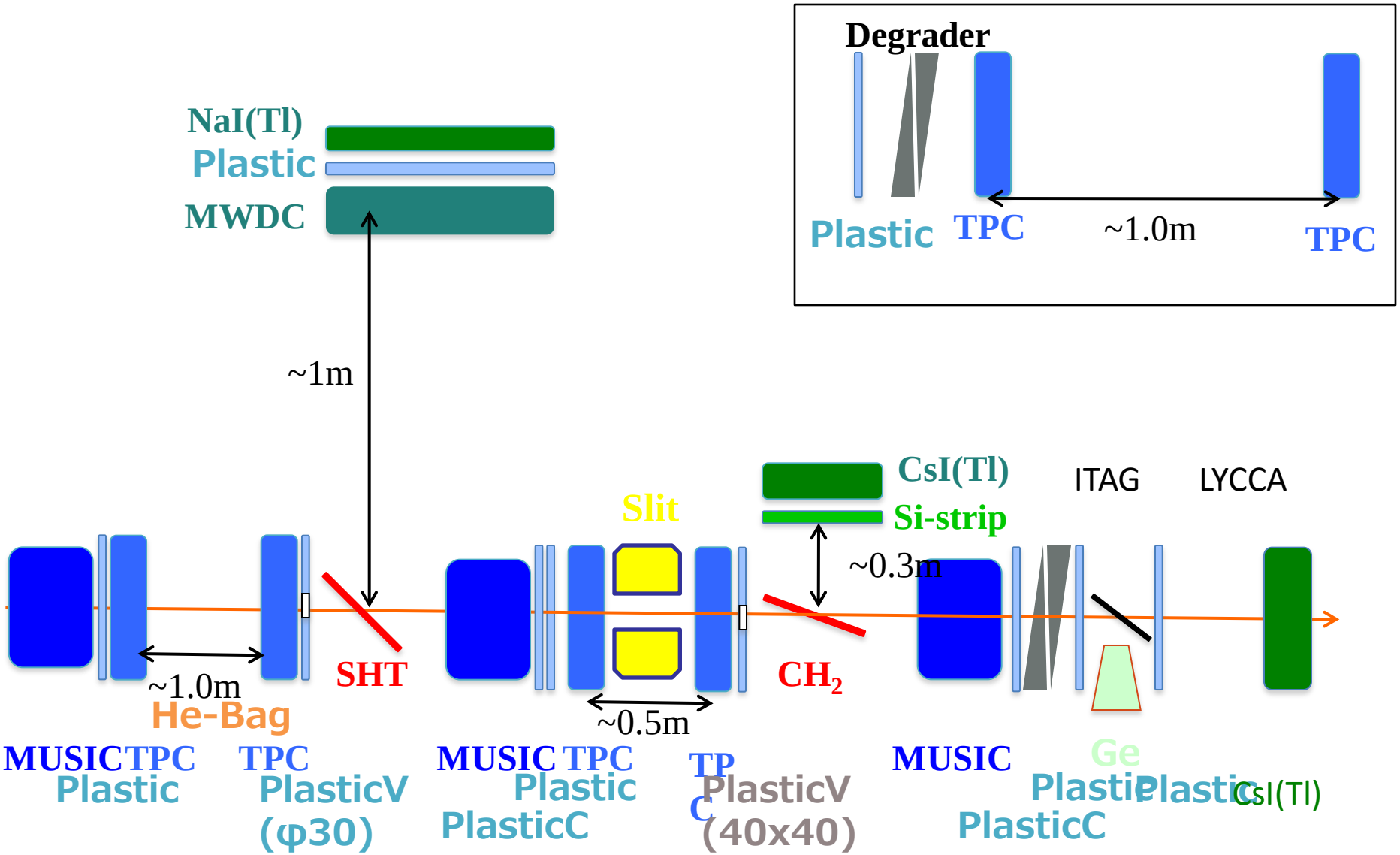


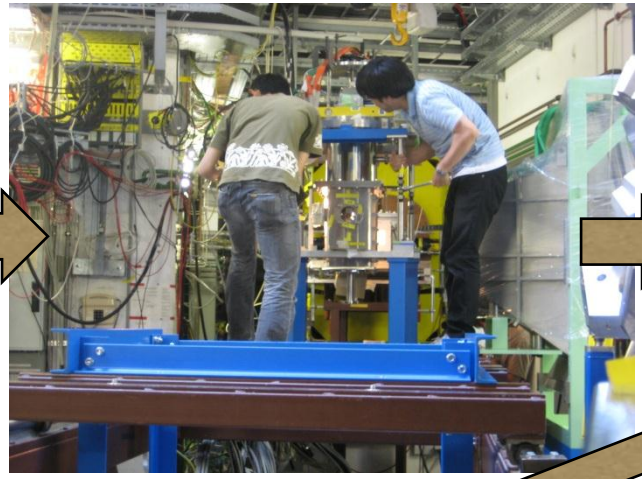
Exp. area
S4

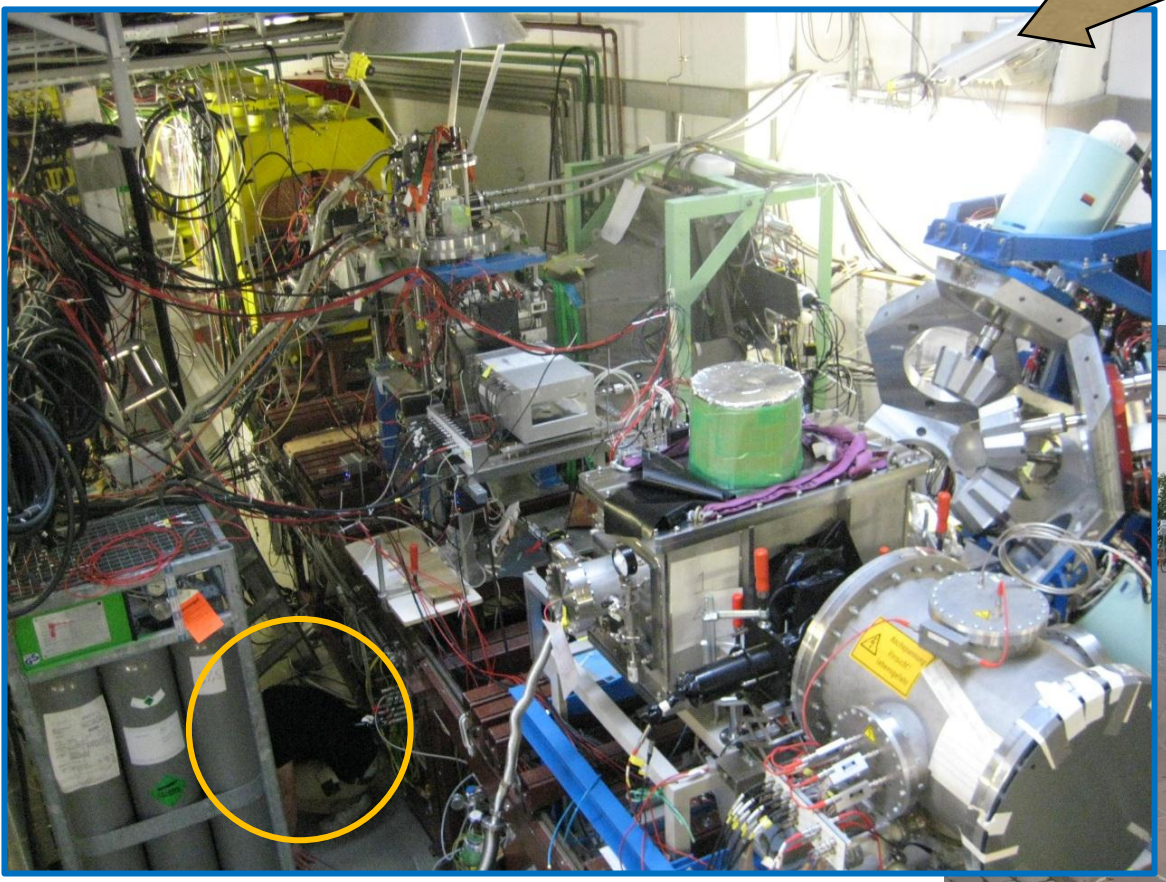


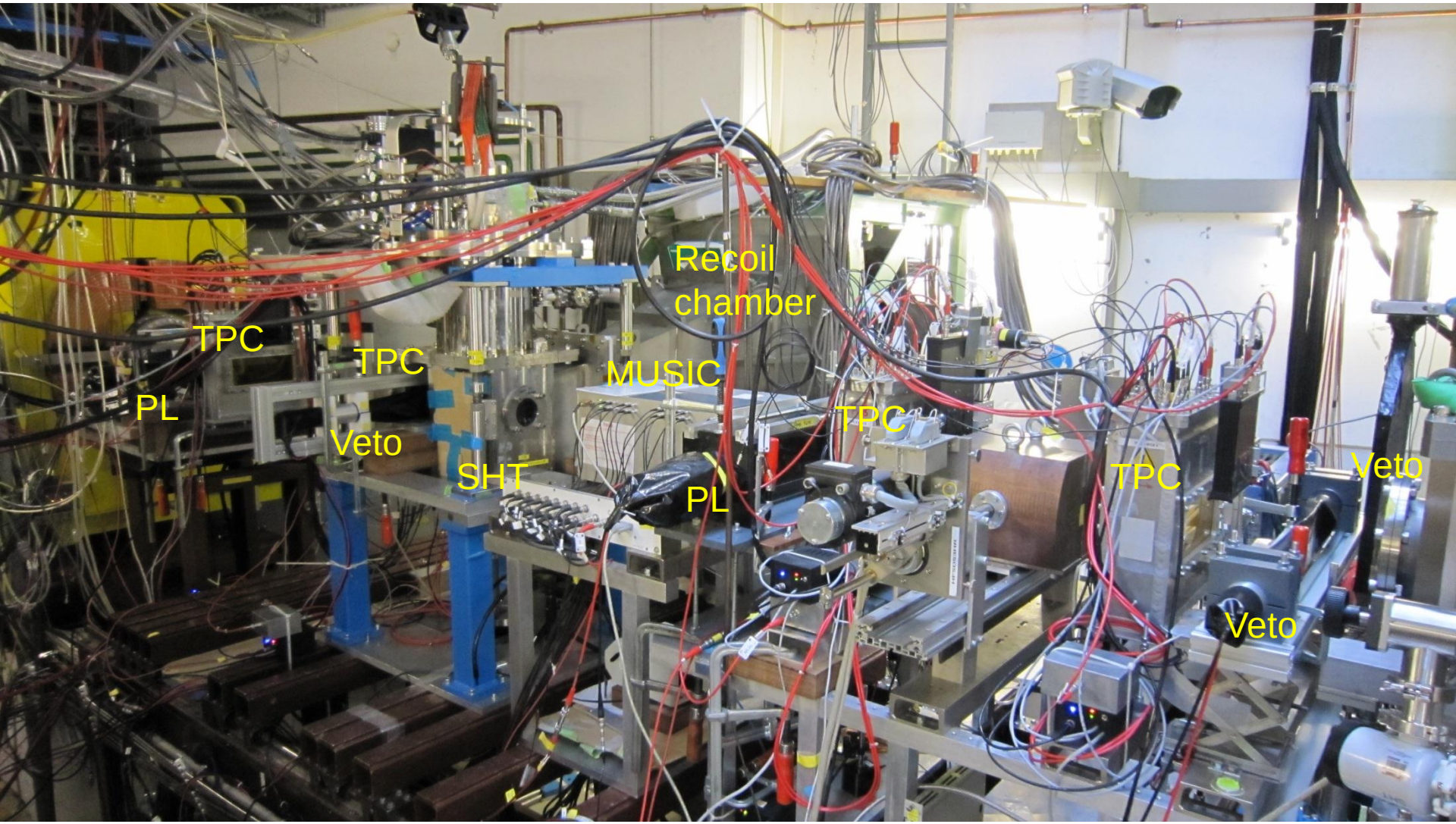
Secondary beam	^{66,70}Ni
	300 MeV/u
	3x10^{3} (^{70}Ni), 2x10^{4} (^{66}Ni)/spill
Target	SHT 1 mm^{t} (8.6 mg/cm^{2})
Primary beam	^{86}Kr (34+)
	520 (^{70}Ni), 540 (^{66}Ni) MeV/u
	2-3x10^{10} counts/spill
Spill structure	3 seconds(duty factor 33%)
Measurement time	8+1 (^{70}Ni), 2+1 (^{66}Ni) days

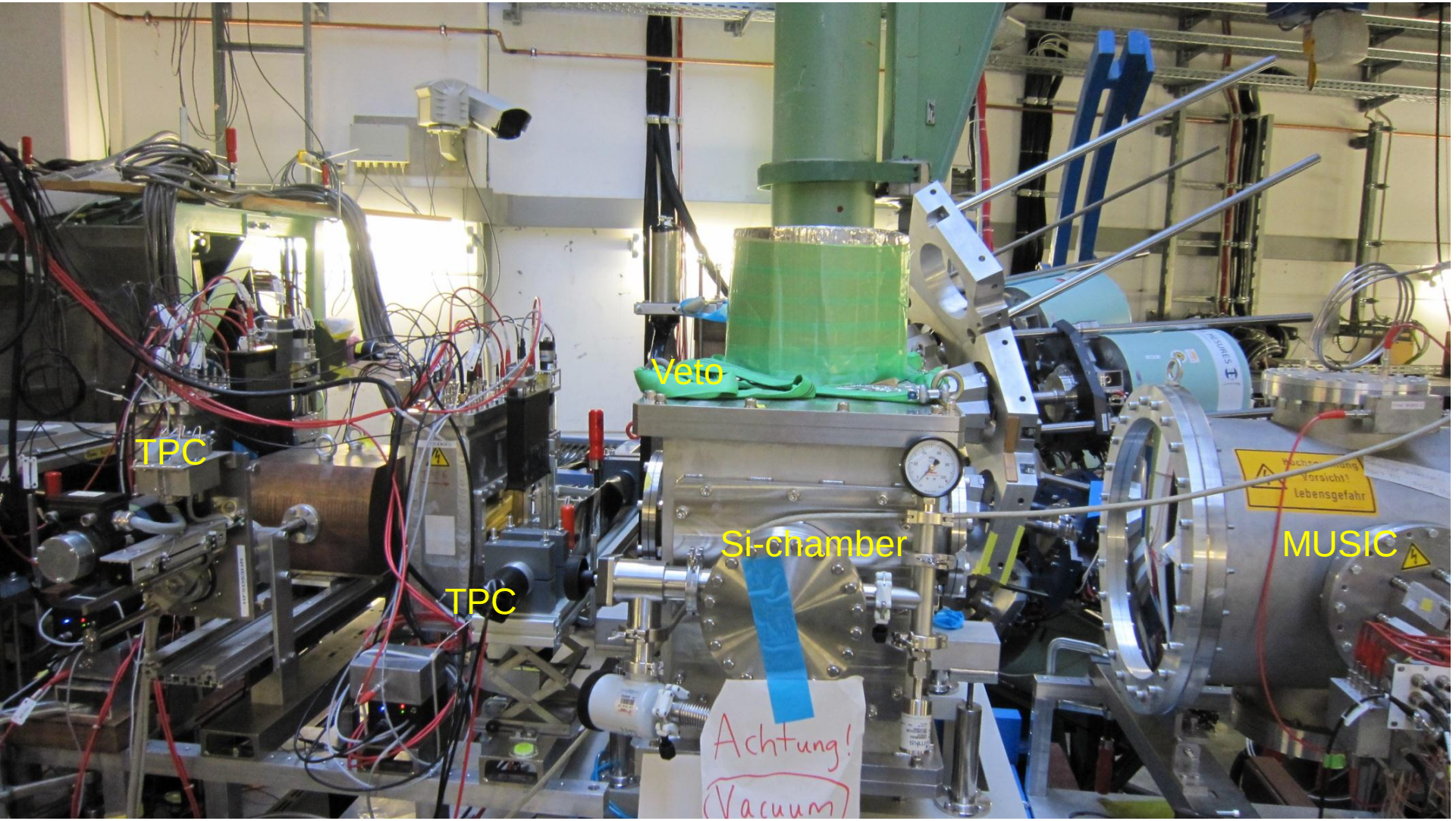
Setup at S4(S2)

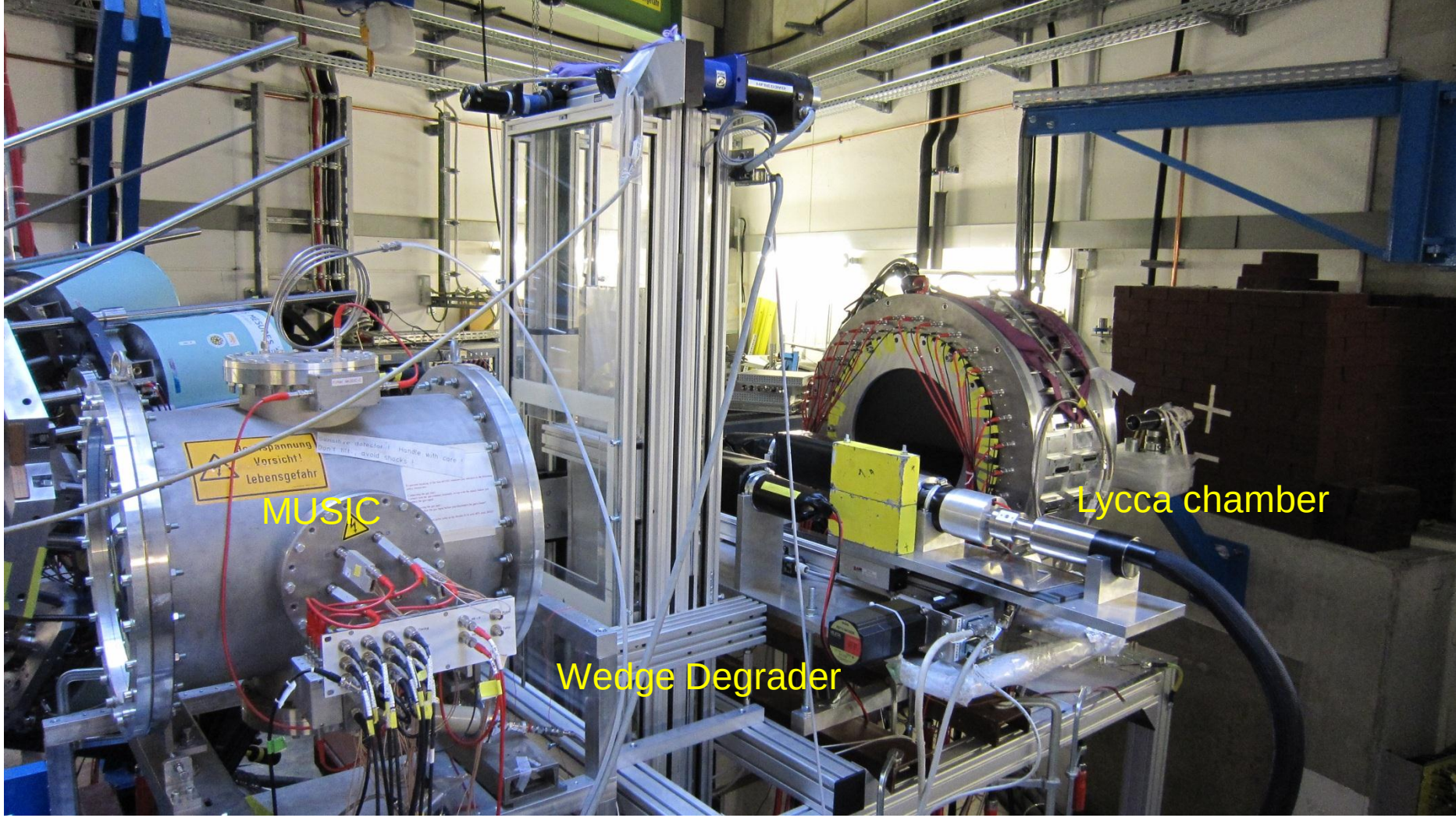







Recoil
chamber
TPC
TPC
PL
Veto
MUSIC
TPC
SHT
PL
TPC
Veto
Veto


Veto
TPC
TPC
Si-chamber
MUSIC
Achtung!
Vacuum
Vorsicht!
Lebensgefahr



MUSIC:

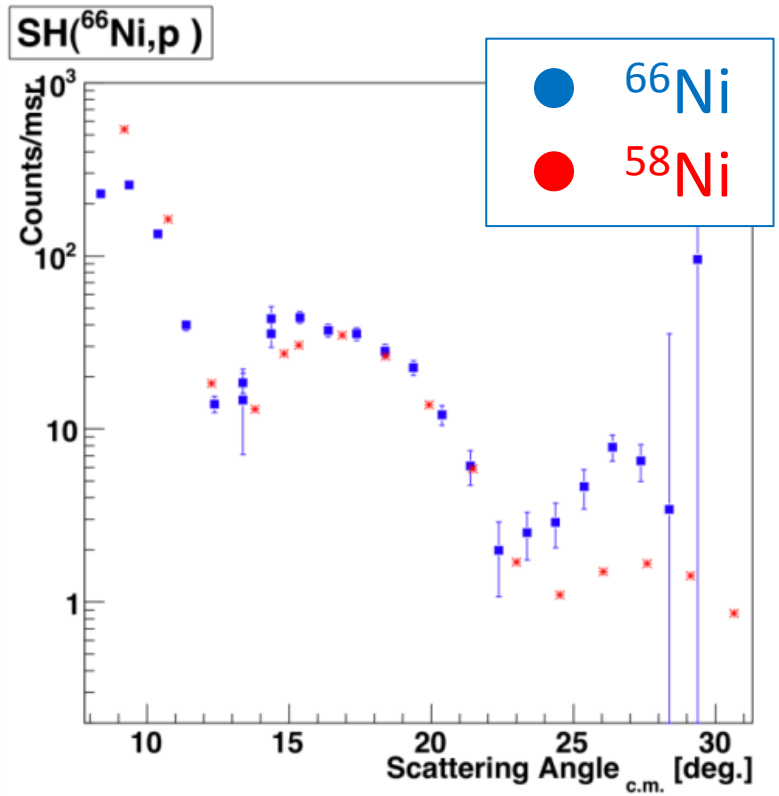
Paricle identification

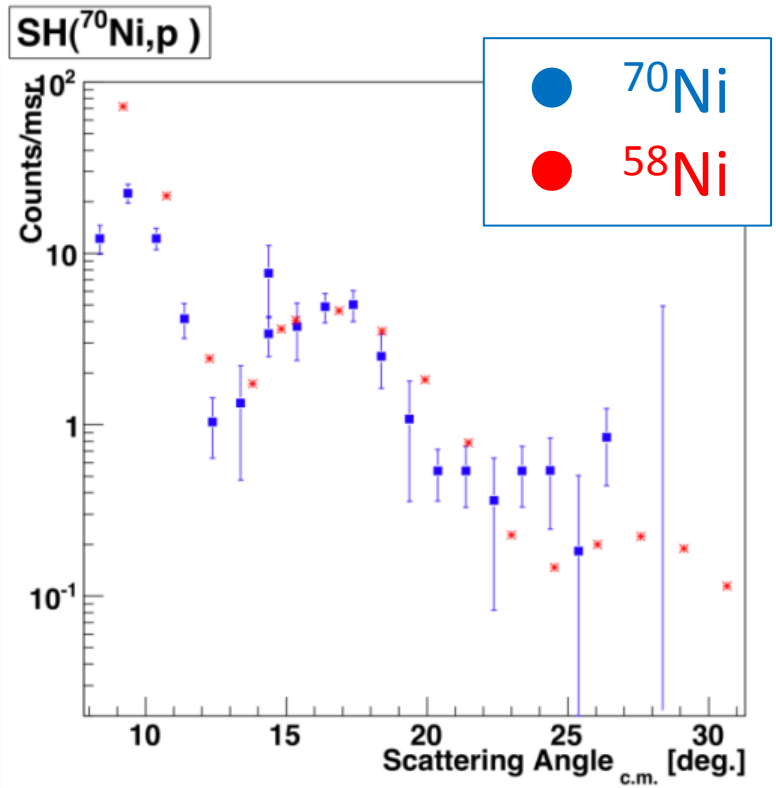
Isomer Tagging System :

Wedge degrader+PL. Scinti. +
stopper + HPGe +PL.Scinti.

Lycca chamber: Total energy calorimeter

Preliminary results of GSI exp.





First measurements !!

Establish the experimental method

Simultaneous extraction of proton and neutron density distributions

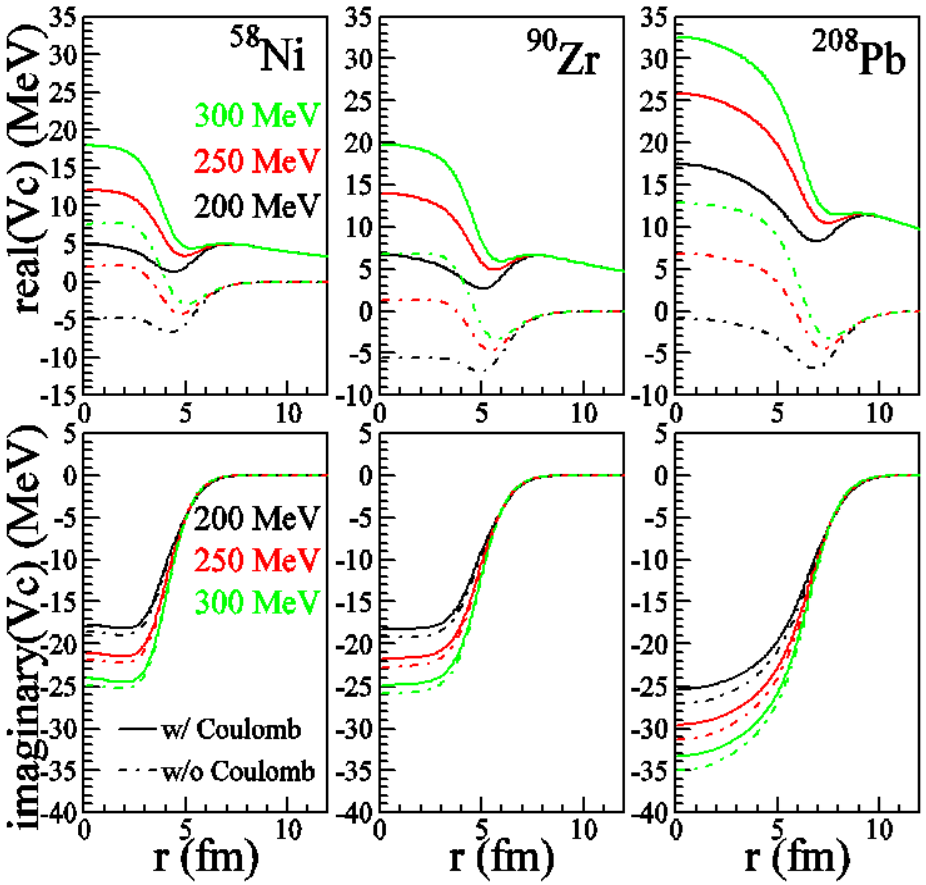
- For unstable nuclei, no nuclear charge information.
- Is it possible to extract both $\rho_p(r)$ & $\rho_n(r)$ from proton elastic scattering?

→ Maybe possible

1. pp & pn interactions are different and have different energy-dependences from each other. (isospin dependence)→ sensitive to light nuclei
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) → sensitive to heavy nuclei

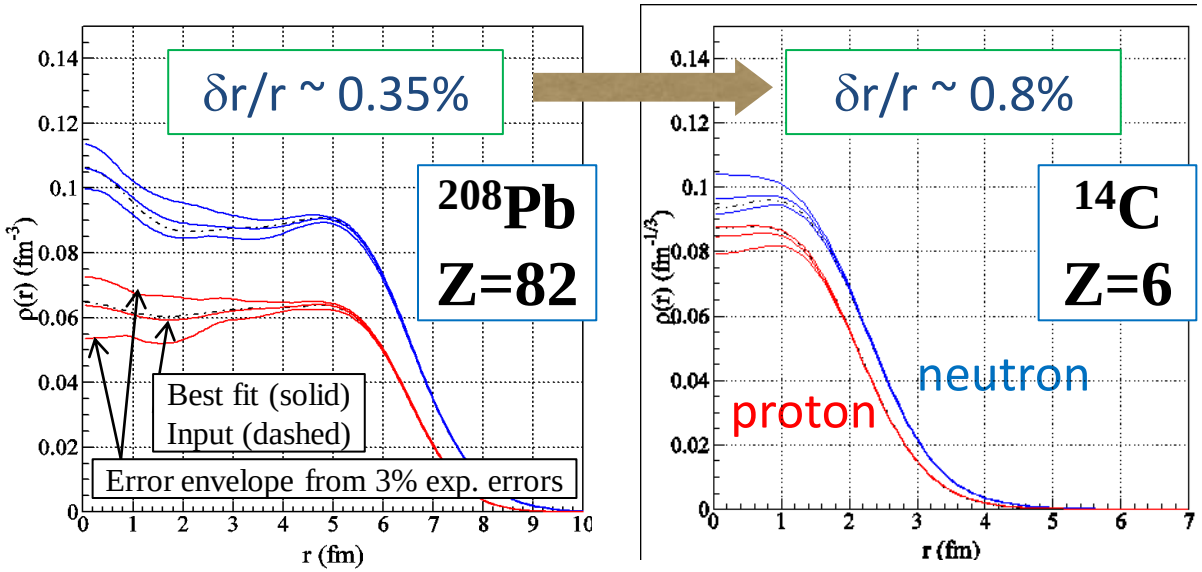
→ We propose <u>two-energy analysis method</u> to extract both proton and neutron density simultaneously from 200 & 300 MeV proton elastic scattering.

Central part (Vc) of optical potentials



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 April 2012!

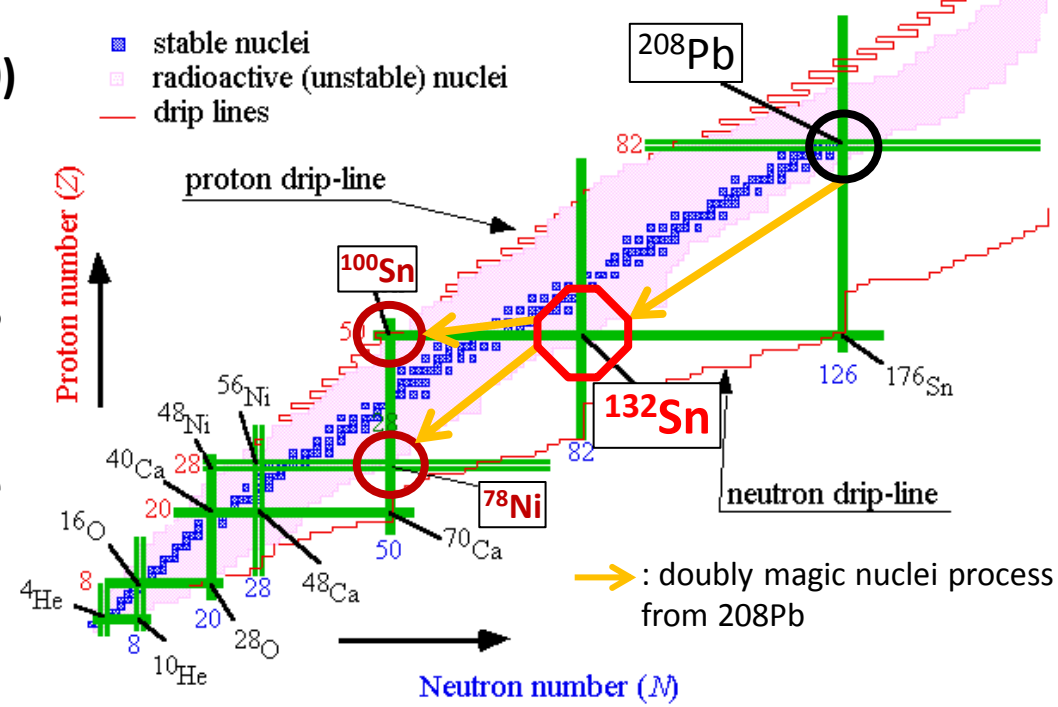
→ Data reduction is now ongoing.

ESPRI at RIBF

Toward extraction of proton & neutron densities of unstable nuclei

- Most suitable energy & high intensity
- **^{16}C** : first ESPRI measurement with high statistics at RIBF **(NP0709-RIBF40)**
- **^{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】



Future perspective…

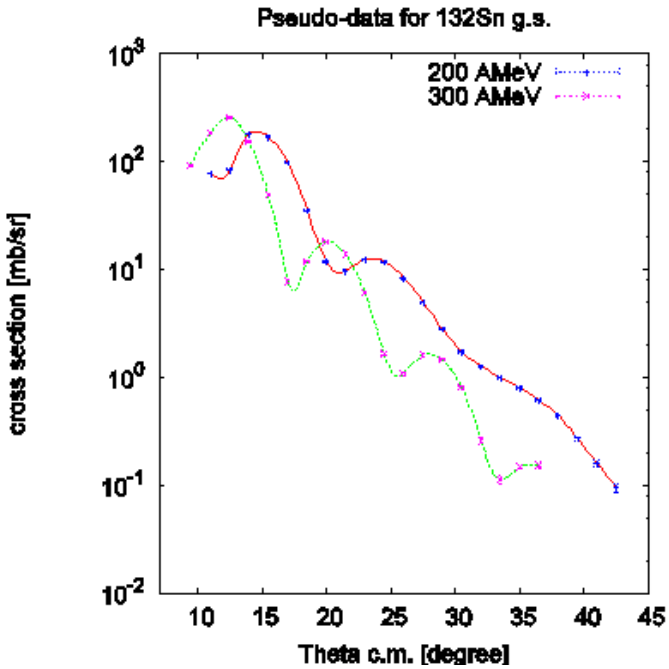
- **ESPRI Combined with Rare RI Ring** or **polarized proton target**
  - → Cross sections or analyzing powers of p-^{78}Ni, ^{100}Sn

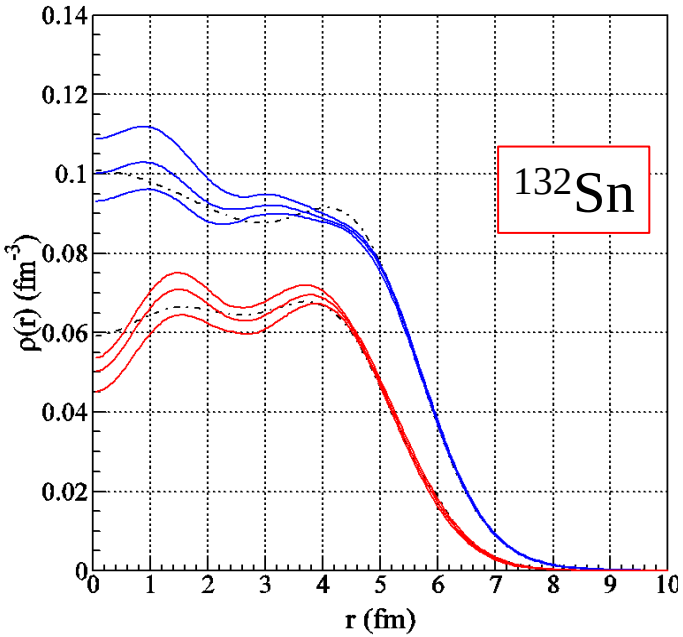
Develop the ESPRI measurements at larger isospin asymmetry system

Expected results of 132Sn

- 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.
   - ✓ HIMAC-P213 : ^{9}C, ^{10,11}C, ^{20}O (FY2006-2008) → Y. Matsuda to be submitted
   - ✓ GSI-S272 : ^{66,70}Ni (FY2009-2010) → analysis is ongoing by S. Terashima

   →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 now developed with stable nuclei.
   - ✓ RCNP-E366 : $^{90,92,94(,96)}$Zr (FY2011-2012)
   - ☐ RCNP-E375 : ^{12,13,14}C (FY2012-2013)

   →feasibility test by generating pseudo-data shows good results.

   → Data reduction is ongoing **→ESPRI@RIBF**

3. ESPRI @ RIBF with high-intensity RI beam for more precise data
   - ☐ NP0709-RIBF40 : $^{16(,18)}$C (light unstable nuclei; already approved & ready)
   - ☐ NP1112-RIBF79 : **^{132}Sn** (heavy unstable nuclei; approved by 2011 NP-PAC)

Elastic Scattering of Protons with RI beams (ESPRI) project

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Thank you for your attention.