Nucleon density distributions extracted from proton elastic scattering at intermediate energies

Juzo ZENIHIRO, RIKEN Nishina Center
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   - Neutron skin vs EOS
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1. Nucleon density distribution
How are nucleons ($p$, $n$) distributed in a nucleus? : $\rho_p$, $\rho_n$

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

\[ \frac{d\sigma}{d\Omega} = \left| F^{A}_{ch}(q) \right|^2 \frac{d\sigma}{d\Omega} \text{ Mott} \]

\[ F^{A}_{ch}(q) \Leftrightarrow \rho^{A}_{ch}(r) \]

\[ F^{p}_{ch}(q) \cdot F^{p}_{p}(q) \Leftrightarrow \rho^{p}_{p}(r) \]

R. Hofstadter
(Nobel prize in 1961)

Proton scattering

\[ \rho^{p}_{p}(r), \rho^{n}_{n}(r) \]

Similarly...

Nuclear matter

\[ F^{p+n}_{p+n}(q) \Leftrightarrow \rho^{p+n}_{p+n}(r) \]
\( \rho_{\text{ch}}(r), \rho_p(r), \rho_n(r) \)

- **Stable nuclei**
  - Nuclear charge distribution \( \rho_{\text{ch}}(r) \)
    - EM probe (very simple)
    - For example, \( r_{\text{ch}} =^{208}\text{Pb} : 5.5010(9) \text{ fm} \) (0.02\% accuracy)
  - Proton density distribution \( \rho_p(r) \) : derived from \( \rho_{\text{ch}}(r) \)
  - 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 \( \rho_{\text{ch}}(r), \rho_p(r), \rho_n(r) \)!
  - SCRIT for \( \rho_{\text{ch}}(r) \) : e-RI collision
  - ESPRI for \( \rho_p(r), \rho_n(r) \) : Our work
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; Relativistic Impulse Approximation (RIA)
RIA framework

- Dirac $t\rho$-optical potential: single folding of $NN$ amplitude ($t$) & densities ($\rho$)
  - $NN$ amplitude; 10 mesons’ coupling including both direct & exchange terms are tuned by free $NN$ phase shift analysis (RLF model by C. J. Horowitz)
    \[ F = F^S + F^V \gamma^\mu_{(0)}\gamma_{(1)\mu} + F^{PS} \gamma_{(0)}^5 \gamma_{(1)}^5 \]
    \[ + F^T \sigma^\mu_{(0)}\sigma_{(1)\mu\nu} + F^A \gamma_{(0)}^\mu \gamma_{(0)}^\nu \gamma_{(1)}^5 \gamma_{(1)}^\mu \]
  - For spin-0 nucleus only Scalar & Vector component remain
    \[ U = \frac{-4\pi i\text{lab}}{M} [F_{S0}\rho_S + \gamma_0 F_{V0}\rho_V] \]
  - 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
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 ($^{58}\text{Ni}$)

Fixed

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

Free parameter

- $\rho_n^V(r)$: minimize the $\chi^2$

output

Calculation

$ds/d\Omega, A_y, Q$

$\chi^2$ method

Experimental data

$ds/d\Omega, A_y, Q$
1. Realistic proton density distributions

Unfolding $\rho_{ch}(r)$

$$\rho_{ch}(r) = \int \rho_p(r)\rho_{ch}^p(|r-r'|)dr' + \int \rho_n(r)\rho_{ch}^n(|r-r'|)dr'$$

+ spin - orbit term

$$= \int \rho_p(r)\tilde{G}_E^p(|r-r'|)dr' + \int \rho_n(r)\tilde{G}_E^n(|r-r'|)dr'$$

+ spin - orbit and Darwin - Foldy term

negligible ($\sim 0.01$ fm)

Fourier transform

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

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

Sachs form factors

$$\sim (0.89)^2 \text{ fm}^2$$

$$\sim -0.11 \text{ fm}^2$$

Neutron charge contribution

Sum of Gaussians

$$\rho_{SOG}(r) = \sum A_i (e^{-(r-R_i)^2/\gamma^2} + e^{-(r+R_i)^2/\gamma^2})$$

$$A_i = \frac{ZQ_i}{2\pi^{3/2}\gamma^3(1+2R_i^2/\gamma^2)}$$

$$\sum Q_i = 1$$
$G_E^{p,n}$ from $e-p$ or $-d$ elastic data

- low-$Q^2(<1\text{GeV})$ analysis by I. Sick [PLB576, 62(2003)]
  - Continued-fraction expansions
  - Model independent nucleon charge radius:
    \[
    r_{ch}^p = 0.895(18) \text{ fm} \\
    (r_{ch}^n)^2 = -0.113 \text{ fm}^2
    \]

\[
G_E^p(Q^2) \propto \frac{1}{1 + \frac{b_1 Q^2}{1 + \frac{b_2 Q^2}{1 + \ldots}}}
\]

However, recent study by muonic-hydrogen Lamb shift says $r_{ch}^p = 0.84184(67) \text{ fm}$... 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

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$r_{ch}$ (fm)</th>
<th>$r_p$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{58}$Ni</td>
<td>3.772(4)</td>
<td>3.680</td>
</tr>
<tr>
<td>$^{204}$Pb</td>
<td>5.479(2)</td>
<td>5.420</td>
</tr>
<tr>
<td>$^{206}$Pb</td>
<td>5.490(2)</td>
<td>5.433</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>5.503(2)</td>
<td>5.442</td>
</tr>
</tbody>
</table>

2012/7/17
2. Scalar density distributions

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

- 0.93 (interior) \(-\) 0.98 (surface)
- \(k_F\) \(-\) 1.3 fm\(^{-1}\), \(M^*\) \(-\) 0.6M at saturation

For medium or heavy nuclei (\(A>56\))

- 0\(^\text{th}\) moment (volume): proton, neutron

\[ \int \rho^S(r) \, dr \approx 0.95 \sim 0.96 \int \rho^V(r) \, dr. \]

- 2\(^\text{nd}\) moment (size): proton, neutron

\[ \int r^2 \rho^S(r) \, dr \approx 0.96 \int r^2 \rho^V(r) \, dr. \]
3. Medium modification of RLF $NN$ interaction

Medium effect

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

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

$j = \sigma, \omega$.

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

Need to calibrate with real data

H. Sakaguchi et al., PRC57, 1749.
Calibration of medium effect by $^{58}\text{Ni}$

$^{58}\text{Ni}$

Various experimental & theoretical results say:

$r_n \cong r_p$ : almost the same size

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

Ni (N=20-62)

- SIII
- Sly4
- SkM*
- Sly5
- SkP

58Ni
Calibration of medium effect by $^{58}\text{Ni}$

- 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

Calibrated medium effect parameters

<table>
<thead>
<tr>
<th>$j$</th>
<th>$\sigma$</th>
<th>$\omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_j$</td>
<td>-0.044(26)</td>
<td>0.037(40)</td>
</tr>
<tr>
<td>$b_j$</td>
<td>0.097(13)</td>
<td>0.075(21)</td>
</tr>
</tbody>
</table>

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

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

- RIA(MH model) + DH density
- RIA(MH model) + realistic density
- RIA(medium effect) + realistic density

$\frac{d}{d\Omega}\left(\text{mb/st}\right)$

$\frac{d}{d\Omega}\left(\text{mb/st}\right)$

$58\text{Ni}(p,p)^{58}\text{Ni}$

$E_p = 295$ MeV
-Pb case-
Experiment @RCNP

Conditions (RCNP-E248)
- Scattering observables: $d\sigma/d\Omega, A_y$
- Beam energy: 295 MeV
- Beam polarization: 70~80%
- Energy resolution: ~100 keV
- Angular & momentum transfer range: 9~45°, 0.5~3.5 fm$^{-1}$
- 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: ~ 1 mm-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

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

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

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

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

Fixed: \(\gamma, R_i\) (same as \(\rho_{ch}(r)\))
Free parameters: \(Q_i \ (i=1\sim12)\)

minimum \(\chi^2\) search

reduced \(\chi^2_{\text{min}} \approx 4.\)
Estimation of error-envelopes of $\rho_n(r)$

- Error-envelopes due to exp. errors:
  \[ \chi^2 \leq \chi^2_{\text{min}} + \Delta\chi^2 \approx 11 \]

- Comparison with previous $\rho_n(r)$:
  3-parameter-Gaussian (3pG) by L. Ray (Ref.[58])

<table>
<thead>
<tr>
<th>$\rho_n$ type</th>
<th>$\chi^2/\nu$ (v=47)</th>
<th>$r_n$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3pG</td>
<td>255/47=5.4</td>
<td>5.593</td>
</tr>
<tr>
<td>SOG</td>
<td>192/47=4.1</td>
<td>5.653(30)</td>
</tr>
</tbody>
</table>

$208$Pb case

- Figure (a): Comparison with previous $\rho_n(r)$
  - 3-parameter-Gaussian (3pG) by L. Ray (Ref.[58])
  - Percent deviation:
    \[ d = 200 \times \frac{\sigma_{\text{exp}} - \sigma_{\text{cal}}}{\sigma_{\text{exp}} + \sigma_{\text{cal}}} \] (\%)
  - $0.06$ fm (1%)

- Figure (b): Comparison of $\rho_n(r)$ at $E_p=295$ MeV
  - DH
  - 3pG
  - this work

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

- $\chi^2_{\text{min}}/\nu \sim 4$: incompleteness of the theoretical model as well as unknown experimental systematics
- Error-envelopes due to model uncertainties:
  - $S$ realizes $\chi^2_{\text{min}}/\nu = 1$.
  
\[
\tilde{\chi}^2 = \frac{\chi^2}{S^2} = \sum \left( \frac{y_{\text{exp}} - y_{\text{calc}}}{S \cdot \delta y_{\text{exp}}} \right)^2,
\]

\[
\tilde{\chi}^2_{\text{min}} = \frac{\chi^2_{\text{min}}}{S^2} = \nu \Leftrightarrow S = \sqrt{\frac{\chi^2_{\text{min}}}{\nu}}.
\]

\[
\tilde{\chi}^2 \leq \tilde{\chi}^2_{\text{min}} + \Delta \chi^2 \\
\chi^2 \leq \chi^2_{\text{min}} + \Delta \chi^2 \times S
\]

$\chi^2 = \chi^2_{\text{min}} + \Delta \chi^2 \times \left( \frac{\chi^2_{\text{min}}}{\nu} \right)$.
Neutron root-mean-square radii

- 2 types of errors of $r_n$: due to experimental errors only ($\delta r_n^{\text{std}}$) $\rightarrow$ ~0.5 %
- total errors including model & unknown systematic uncertainties ($\delta r_n^{\text{mdl}}$) $\rightarrow$ ~1 %

(Extracted $r_n$, $\delta r_n$)

<table>
<thead>
<tr>
<th></th>
<th>$r_{\text{ch}}$</th>
<th>$r_p^{\text{unfold}}$</th>
<th>$r_n$</th>
<th>$\delta r_n^{\text{std}}$</th>
<th>$\delta r_n^{\text{mdl}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{204}\text{Pb}$</td>
<td>5.479(2)</td>
<td>5.420(2)</td>
<td>5.598</td>
<td>+0.029</td>
<td>+0.047</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.020</td>
<td>-0.059</td>
</tr>
<tr>
<td>$^{206}\text{Pb}$</td>
<td>5.490(2)</td>
<td>5.433(2)</td>
<td>5.613</td>
<td>+0.026</td>
<td>+0.048</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.026</td>
<td>-0.064</td>
</tr>
<tr>
<td>$^{208}\text{Pb}$</td>
<td>5.503(2)</td>
<td>5.442(2)</td>
<td>5.653</td>
<td>+0.026</td>
<td>+0.054</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.029</td>
<td>-0.063</td>
</tr>
</tbody>
</table>
Neutron skin thicknesses $\Delta r_{np}$

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

Dependent on structure and/or reaction models

Evaluate reaction model ambiguity
Nuclear matter EOS with isospin asymmetry $\delta$

- EOS of nuclear matter $E(\rho,\delta)$: the energy per nucleon

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

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

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

\[ \rightarrow E(\rho_{\text{sat}}, 0) \sim -16 \text{ MeV}, \quad K_0 \sim 240 \text{ MeV} \]

- The symmetry energy $S(\rho)$:

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

\[ \rightarrow \text{Still less certain!} \]

\[ \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}, \quad \varepsilon = \frac{\rho - \rho_{\text{sat}}}{3\rho_{\text{sat}}} \]
**Δr_{np} for 208Pb vs. Symmetry energy**

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

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

- **Strong correlation!**

\[ \varepsilon = \frac{\rho - \rho_{\text{sat}}}{3\rho_{\text{sat}}} \]

Determine the slope coefficient \( L \) of \( S(\rho) \) → neutron matter EOS

**Impact on neutron star structure**
- Radius, cooling system, etc.

L.-W. Chen et al., PRC82, 054314.
$\Delta r_{np}$ for $^{208}\text{Pb}$ vs the symmetry energy coefficients

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

\[ K_0 \]
\[ K_{\text{sym}} \]
$\Delta r_{np}$ for $^{204,206}$Pb vs the symmetry energy coefficients

![Graphs showing the relationship between $\Delta r_{np}$ and the symmetry energy coefficients for $^{204,206}$Pb.](image)
The symmetry energy coefficients deduced from $\Delta r_{np}$ for $^{204,206,208}$Pb

- Deduced region of the symmetry energy coefficients: weighted average

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

→ 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

Sn

Pb

Unstable nuclei ➔ ESPRI project

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4. Unstable nuclei - ESPRI project -

Application to nuclei with large isospin asymmetry
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)

<table>
<thead>
<tr>
<th>RPS</th>
<th>Recoil drift chamber</th>
<th>436x436 mm² (x-y-x’-y’)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>plastic scintillator</td>
<td>440x440 mm² x 2 mm¹</td>
</tr>
<tr>
<td></td>
<td>Nal(Tl) calorimeter</td>
<td>450x50 mm² x 50 mm¹</td>
</tr>
</tbody>
</table>

Target: Solid hydrogen, Φ30 - 1 mm¹

Large momentum transfer region

θ_lab = 66 - 80°, Ep=20 – 120 MeV, ΔΩ~10 msr/deg.

Small momentum transfer region

θ_lab = 75 - 85°, Ep=5 – 50 MeV ΔΩ~14 msr/deg.

- Missing mass spectrometer: \( P^\mu_{\text{beam}} + P^\mu_p \rightarrow E_x \) (\( \Delta E_x \sim 400 \text{ keV} \))
- Cover extensive momentum transfer region: up to \( \sim 2.5 \text{ fm}^{-1} \)

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Kinematics of ESPRI

Inverse kinematics: fixed probe

Unstable nucleus

A

300 MeV/A

p

Detector

θ_{lab.}

A

p

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

H(⁹C, p)⁹C  Ep=300 MeV/A

Large dE/dθ!!

2.5fm⁻¹  1fm⁻¹

Ex=30 MeV  g.s.

Ex=2.2 MeV

E_p=300 MeV/A

H(²⁷Ni, p)²⁷Ni
## Recoil Proton Spectrometer (RPS)

<table>
<thead>
<tr>
<th>Material</th>
<th>Para H₂</th>
<th>RDC</th>
<th>pΔE</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effective area</strong></td>
<td>φ 30 mm</td>
<td>436 x 436 mm²</td>
<td>440 x 440 mm²</td>
<td>431.8 x 45.72 mm²</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>1 mm</td>
<td>69.4 mm</td>
<td>2.53 / 3.09 mm</td>
<td>50.8 mm</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>500 μm</td>
<td>TOF : 0.1 nsec</td>
<td>0.3 % (80 MeV)</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- RPS: Recoil Proton Spectrometer
- SHT: Solid H₂ Target
- NaI(Tl): Sodium Iodide with Thallium activator
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% $para-H_2$!!

Success of 1-mm-thick 30-mm-$\phi$ SHT !!!

Y. Matsuda et al.

More than 100 times larger than normal hydrogen. The same as metallic element

0.72: ratio of ortho $H_2$ concentration (normal $H_2$)

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
R & D at GSI

Be Production Target

1st Degrader

2nd Degrader + Momentum

Full tracking + 2ndary H Target

Exp. area S4

### Secondary beam
- $^{66,70}\text{Ni}$
- 300 MeV/u
- $3 \times 10^3 (^{70}\text{Ni}), 2 \times 10^4 (^{66}\text{Ni})$/spill

### Target
- SHT 1 mm$^2$ (8.6 mg/cm$^2$)

### Primary beam
- $^{86}\text{Kr}$ (34+)
- 520 ($^{70}\text{Ni}$), 540 ($^{66}\text{Ni}$) MeV/u
- 2-3x10$^{10}$ counts/spill

### Spill structure
- 3 seconds (duty factor 33%)

### Measurement time
- 8+1 ($^{70}\text{Ni}$), 2+1 ($^{66}\text{Ni}$) days
Setup at S4(S2)
Wedge Degrader
Lycca chamber

MUSIC
Isomer Tagging System:
Wedge degrader + PL. Scinti. + stopper + HPGe + PL. Scinti.

Lycca chamber: Total energy calorimeter
Establish the experimental method

First measurements!!

Preliminary results of GSI exp.
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 two-energy analysis method to extract both proton and neutron density simultaneously from 200 & 300 MeV proton elastic scattering.
Feasibility test of simultaneous extraction of $\rho_p(r)$, $\rho_n(r)$

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

\[ \delta r/r \sim 0.35\% \]

208\text{Pb}  
\[ Z=82 \]

\[ \delta r/r \sim 0.8\% \]

14\text{C}  
\[ Z=6 \]

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
- $^{16}\text{C}$: first ESPRI measurement with high statistics at RIBF (NP0709-RIBF40)
- $^{132}\text{Sn}$: flag-ship nuclei as a next step from $^{208}\text{Pb}$ (NP1112-RIBF79)
  - $n$-skin thickness to constrain the symmetry energy of nuclear EOS
  - Test of the measurement of isomer-$^{132}\text{Sn}$(p,p) reaction
  - High-rate tolerance of beam-line detector is required (~1MHz)

Future perspective...
- ESPRI Combined with Rare RI Ring or polarized proton target
  - Cross sections or analyzing powers of p-$^{78}\text{Ni}$, $^{100}\text{Sn}$
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.

<table>
<thead>
<tr>
<th></th>
<th>g.s. (input)</th>
<th>g.s. (extracted)</th>
<th>$\delta r/r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_n$</td>
<td>4.916</td>
<td>4.907(23)</td>
<td>0.46%</td>
</tr>
<tr>
<td>$r_p$</td>
<td>4.650</td>
<td>4.612(49)</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\Delta r_{np}$</td>
<td>0.266</td>
<td>0.295(54)</td>
<td>--</td>
</tr>
</tbody>
</table>
Summary of ESPRI

1. R & D at HIMAC, Chiba and GSI, Germany.
   ✓ HIMAC-P213: $^9\text{C}$, $^{10,11}\text{C}$, $^{20}\text{O}$ (FY2006-2008) → Y. Matsuda to be submitted
   ✓ GSI-S272: $^{66,70}\text{Ni}$ (FY2009-2010) → analysis is ongoing by S. Terashima
   → 1mm-t & 30mm-Ø $p$SHT (NIMA643,6(2011)), energy resolution of ~500keV($\sigma$)
   → 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: $^{90,92,94,96}\text{Zr}$ (FY2011-2012)
   □ RCNP-E375: $^{12,13,14}\text{C}$ (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: $^{16,18}\text{C}$ (light unstable nuclei; already approved & ready)
   □ NP1112-RIBF79: $^{132}\text{Sn}$ (heavy unstable nuclei; approved by 2011 NP-PAC)
Elastic Scattering of Protons with RI beams (ESPRI) project

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2012/7/17
NP seminar
Thank you for your attention.