Measurement of the very-forward-angle neutron elastic scattering and PHITS simulation for neutron shielding

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1. Introduction

$\rho = \rho_n + \rho_p \qquad \delta = \dfrac{\rho_n - \rho_p}{\rho}$

◆ Nuclear matter EoS

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

δ: Isospin asymmetry degree of ρ_p and ρ_n

◆ Symmetry energy $S(\rho)$

$$S(\rho) = S_0 + \frac{L}{3\rho_0}(\rho - \rho_0) + \mathcal{O}((\rho - \rho_0)^2)$$

Neutron matter ($\delta = 1$) e.g., neutron star

➢ ***S(ρ)* is less certain than symmetric nuclear matter ($\boldsymbol{\delta = 0}$)**

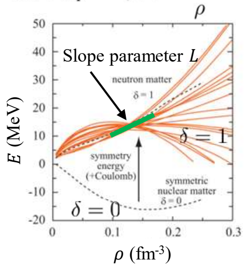

Figure: The EoS of neutron matter calculated by theoretical models [1]

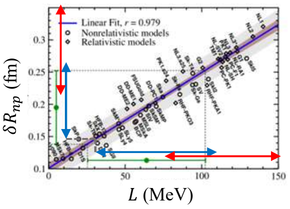

Figure: Linear correlation between slope parameter and neutron skin thickness [2]

Linear correlation b/w L and δR_{np} in ^{208}Pb

Neutron skin thickness $\delta R_{np} = R_n - R_p$

- ■ Proton distribution radius
  - ➢ Precisely determined
- ■ Neutron distribution radius
  - ➢ **Still less certain**

2. Our approach

2.1 Determination of neutron density distribution

Measure the cross section at forward angles

- ■ Proton elastic scattering (PES)
  - ➢ Mainly Coulomb scattering occurs
- ■ Neutron elastic scattering (NES)
  - ➢ Contribution of nuclear force only

We adopted Neutron elastic scattering as probe

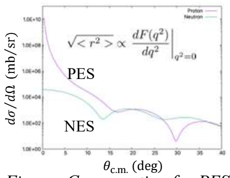

Figure: Cross section for PES and NES

2.2 Theoretical model – RIA

Developed folding model for NES

- ■ Based on Relativistic Impulse Approximation (RIA) for PES
- ■ Assuming charge symmetry
- ➢ New RIA model for NES

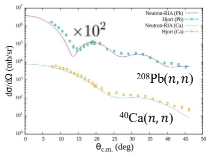

Figure: New RIA for NES with previous data

We tried to determine the neutron skin thickness δR_{np} in ^{208}Pb with measurement of neutron elastic scattering at RCNP N0 course in Mar. 2023

3. Experimental Method

1st Exp. at RCNP N0 course in Mar. 2023

- ☐ (n, n) scatt. with proton beam at 65 MeV
- ☐ Targets : ^{208}Pb and ^{40}Ca
- ☐ Very forward angles ($\theta_{\mathrm{lab.}} = 4, 7$ deg)

Photograph of ^{208}Pb target, collimators and shielding blocks

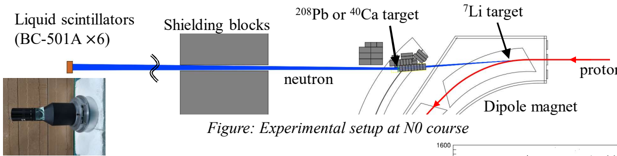

Figure: Experimental setup at N0 course

Incident neutrons ($E_n \cong 63.4$ MeV)

- ➢ Generated by the reaction ^{7}Li$(p, n)^{7}$Be

Identification of scattered neutrons

- ➢ Time of Flight (ToF)
  - Measured energy of neutrons
- ➢ Pulse Shape Discrimination (PSD)
  - Distinguished neutrons from photons

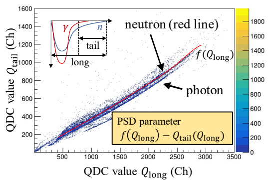

Figure: 2-D histogram of QDC values measured over two different gates

4. Result of 1st Exp.

Angular distribution

Table: Cross section for ^{208}Pb(n, n) and ^{40}Ca(n, n)

Target	Angle (deg) (c.m.)	$d\sigma/d\Omega$ (mb/sr)	± (statistics) (mb/sr)
^{208}Pb	4.03	35720	5508(15.4%)
	4.52	37144	5413(**14.6%**)
	7.22	19449	6491(33.4%)
	7.71	23453	5125(21.9%)
^{40}Ca	4.12	8673	2802(32.3%)
	4.62	7592	2746(36.2%)
	7.37	5672	4657(82.1%)
	7.88	9275	3702(39.9%)

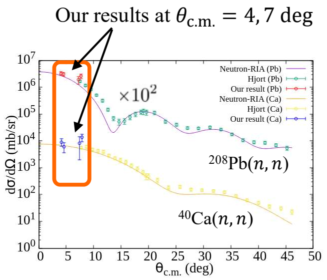

Figure: Angular distribution for ^{208}Pb(n, n) and ^{40}Ca(n, n) with RIA calculation and the previous data by E. L. Hjort et al. [3]

Consistent with theoretical calculation

However, the result is **NOT** precise

- Theoretical demand : $\varepsilon \sim 5\%$
- Our result (at best) : $\varepsilon \geq 14.6\%$
  - ■ Large statistical error
  - ■ Systematic error may exist

We need to discussion on feasibility

- Low SNR: $S/N \approx 10^{-1}$
- **Background neutrons shielding ($\boldsymbol{E_n \leq}$ 63MeV)**

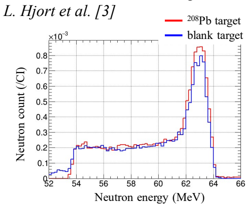

Figure: Energy spectra in ^{208}Pb and blank target

Evaluation of background neutrons is essential for next experiment

➢ **PHITS[4] simulation (version 3.31)**

5. PHITS for High energy neutron shielding

What is the major factor in the background neutrons?

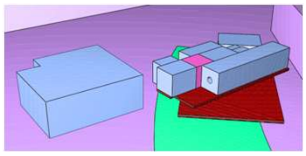

Figure: Perspective drawing plotted by ANGEL-4.50

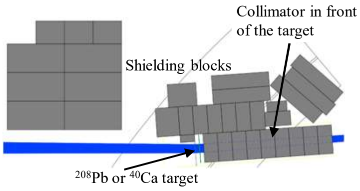

Figure: Enlarged top view of setup near the target

Table: Origin of the background neutrons in the 4-degree setup

	All	Scattered at CO	Scattered at CO and SB	Scattered at SB	Scattered at SD	Other
Forward current ($\times 10^{-10}$/cm^2/source)	5.28	3.69	0.63	0.32	0.21	0.42
Percentage	100%	**70.0%**	**12.1%**	6.0%	3.9%	8.0%

CO: collimator, SB: shielding blocks

SD: shielding door

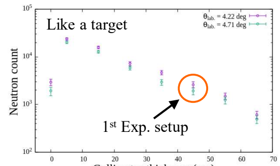

Figure: Simulation of neutron count for different collimator thickness

Source of background neutrons

- ☐ Scattering at collimator in front of the ^{208}Pb or ^{40}Ca target
  - ➢ Collimator as a **"scattering target"**

Effect of collimator

- ☐ Thicker collimator is effective for neutron shielding

6. Summary and Next for 2nd Exp.

- ☐ ^{208}Pb(n, n) and ^{40}Ca(n, n) scattering at very forward angles was measured at RCNP N0 course
- ☐ New RIA model for neutron elastic scattering has been developed
- ☐ Angular distribution for ^{208}Pb(n, n) and ^{40}Ca(n, n) was measured
- ☐ However, the result is NOT precise because it has low signal-to-noise ratio
- ☐ PHITS simulation for neutron shielding was performed
  - ➢ Scattering at collimator is the major factor in background neutrons
  - ➢ Improvement of feasibility is in progress for **2nd Exp. in Feb. 2024!**

References

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