Nuclear matter Equation of State Studied by Polarized Proton Inelastic Scattering

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For RCNP-E282, E316 Collaborations

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Table of Contents

1. Physics motivation and Strategy
2. Experimental method
3. Results
4. Discussion
5. Work in progress
6. Summary
Physics Motivation and Strategy

Symmetry energy of Nuclear EoS is important in nuclear physics as well as nuclear astrophysics

Structure of neutron star

http://www.astro.umd.edu/~miller/nstar.html

Core collapse supernova


Accreting neutron star

X-ray bursts

Neutron star mass vs radius


Physics Motivation and Strategy

**EoS for Energy per nucleon at zero temperature**

\[
\frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho, 0) + S(\rho) \delta^2 + \ldots
\]

\[
\rho(r) \equiv \rho_n(r) + \rho_p(r)
\]

\[
\delta(r) \equiv \frac{\rho_n(r) - \rho_p(r)}{\rho_n(r) + \rho_p(r)}
\]

**Symmetry energy**

\[
S(\rho) = J + \frac{L}{3\rho_0}(\rho - \rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho - \rho_0)^2 + \ldots
\]

\(J\): Symmetry energy at the saturation density

\(L\): Slope parameter

Salutation density
\(\rho_o = \sim 0.16\) fm\(^{-3}\)

\[L \mu P \mu R_n^{4\ star}\]

\(P\): baryonic pressure

Determination of \(J\) and \(L\) is important for nuclear astrophysics related to neutron star
Physics Motivation and Strategy

Prediction of the neutron matter EOS is much parameter dependent.
Physics Motivation and Strategy

Slope parameter (L) and Neutron Skin thickness

Large L ⇔ Small $E_{\text{sym}}$ in low $\rho$ ⇔ Thick neutron skin
Small L ⇔ Large $E_{\text{sym}}$ in low $\rho$ ⇔ Thin neutron skin

![Graph showing the relationship between $E_{\text{sym}}$ and $\rho$, with data points and linear fit indicating neutron skin thickness.]

Lie-Wen Chen et al., PRL94(032701)

X. Roca-Maza et al., PRL106, 252501 (2011)
Physics Motivation and Strategy

Correlation between Neutron Skin Thickness and Dipole Polarizability ($\alpha_D$)

Strong correlation between the dipole polarizability and the neutron skin thickness of $^{208}$Pb


Physics Motivation and Strategy

Electric Dipole Polarizability ($\alpha_D$)

Inversely energy weighted sum-rule of $B(E1)$

$$\alpha_D = \frac{8\pi}{9} \int \frac{dB(E1)}{E_x}$$

Key of experimental issue:
precise measurement of E1 strength in wide energy region including PDR and GDR. (Especially, low excitation energy region is important)
Physics Motivation and Strategy

How to measure electric dipole response of nuclei, precisely?

The $(\gamma, \gamma')$ reaction has been used to measure the PDR region.

$\rightarrow$ There is difficulty to measure at around $S_n$ due to the threshold problem.

The $(\gamma, xn)$ reaction has been used to measure the GDR region.

$\rightarrow$ Extraction of the E1 strength is quite model-dependent.

Polarized proton inelastic scattering can measure the total strength in wide excitation energy region.
In the present experimental condition, both of E1 and spin-M1 mode are observed.

E1/spin-M1 decomposition
1. Multipole decomposition
2. Polarization transfer analysis at 0°

spin flip/non-flip separation
Model independent
T. Suzuki PTP 104(2000)859

Total Spin Transfer ($\Sigma$)

$$
3 \frac{(2D_{SS} + D_{LL})}{4} = \begin{cases} 
1 & \text{for } \Delta S = 1 \text{ spin-M1} \\
0 & \text{for } \Delta S = 0 \text{ E1}
\end{cases}
$$

$D_{SS}$ and $D_{LL}$: Spin transfer observable
Experimental Method

High-resolution polarized (p, p’) measurement at zero degrees and forward angles
Experimental method
Experimental method

- High-resolution WS beam-line (dispersion matching technique)
- RING cyclotron
- Large angle spectrometer
- AVF cyclotron
- High-resolution spectrometer Grand RAIDEN

Polarized proton beam
Energy: 295 MeV
Energy resolution: ~25 keV
Intensity: 2 nA
Averaged polarization: ~ 0.7
(both of longitudinal and sideway)
Experimental method

Grand RAIDEN Spectrometer

Large Angle Spectrometer
Experimental method

Spectrometers in 0°  Experiment setup at RCNP, Osaka

\[ \Sigma \equiv \frac{3 - (2D_{SS} + D_{LL})}{4} \]

Total Spin Transfer (\(\Sigma\))

\(D_{SS}\) and \(D_{LL}\): Spin transfer observable

\(208\text{Pb target: } 5.2 \text{ mg/cm}^2\)

\(120\text{Sn target: } 6.5 \text{ mg/cm}^2\)

Dispersion matched beam: 1 – 10 nA

Averaged polarization ~ 0.7
Results
Results

Excitation energy spectrum

\( ^{208}\text{Pb}(\vec{p}, \vec{p}') \)  
\( E_p = 295 \text{ MeV} \)  
\( \theta = 0^\circ - 2.5^\circ \)

\( ^{120}\text{Sn}(\vec{p}, \vec{p}') \)  
\( E_p = 295 \text{ MeV} \)  
\( \theta = 0^\circ - 2.5^\circ \)

\( ^{208}\text{Pb}: \text{A. Tamii et. al. PRL 107(2011)06250} \)

\( ^{120}\text{Sn}: \text{T. Hashimoto et al., PRC92(2015)031305(R)} \)
Results

E1 and spin-M1 decomposition
Polarization observable at 0 degs

Spin flip/non-spin flip separation

$^{208}\text{Pb}(p, p')$
$E_p = 295$ MeV
$\theta = 0^\circ - 2.5^\circ$

$^{120}\text{Sn}(\vec{p}, \vec{p'})$
$E_p = 295$ MeV
$\theta = 0^\circ - 2.5^\circ$

Total Spin Transfer

$$\Sigma \equiv \frac{3 - (2D_{ss} + D_{LL})}{4} = \begin{cases} 1 & \text{for } \Delta S = 1 \text{ (Spin M1)} \\ 0 & \text{for } \Delta S = 0 \text{ (E1)} \end{cases}$$
Results

E1 and spin-M1 decomposition
Comparison with Multi-pole Decomposition Analysis

$^{208}\text{Pb} (\vec{p}, \vec{p}')$
$E_p = 295$ MeV
$\theta_{\text{lab}} = 0^\circ - 2.5^\circ$

$^{120}\text{Sn} (\vec{p}, \vec{p}')$
$E_p = 295$ MeV
$\theta = 0^\circ - 2.5^\circ$
$\Delta S = 0$

$\Delta S = 1$

$\Delta S = 0$

good agreement within respective error bars

$^{208}\text{Pb}$: A. Tamii et al. PRL 107(2011)06250
$^{120}\text{Sn}$: T. Hashimoto et al., PRC92(2015)031305(R)
MDA of $^{120}\text{Sn}$ was performed by A. M. Krumbholtz
PLB 744(2015)7
Results

The B(E1) strength distribution

Comparison with $(\gamma, xn)$ results

$^{208}$Pb: A. Tamii et al. PRL 107(2011)062502

$^{120}$Sn: T. Hashimoto et al., PRC92(2015)031305(R)

All data are excellent agree with each other

Refs. of $^{208}$b$(\gamma, \gamma')$, $^{207}$Pb(n, $\gamma$), $^{208}$Pb($\gamma$, xn)
N. Ryezayeva et. al. PRL 89(2002)272502
J. Enders et. al. NPA 724(2003)243
T. Shizuma et. al., PRC 78(2008)061303
R. Schwengner et. al., PRC81(2010)054315
A. Veyssiere et. al., NPA 159(1970) 561

$^{208}$Pb: A. Tamii et. al. PRL 107(2011)062502

$^{120}$Sn: T. Hashimoto et al., PRC92(2015)031305(R)
Results

Electric Dipole Polarizability

\[ \alpha_D = \begin{array}{c} 2.7 \text{ fm}^3 \\
16.2 \text{ fm}^3 \\
1.2 \text{ fm}^3 \end{array} \]

Total: 20.1 ± 0.6 fm³

\[ ^{208}\text{Pb}: \text{A. Tamii et. al. PRL 107}(2011)06250 \]

\[ ^{120}\text{Sn}: \text{T. Hashimoto et al., PRC92}(2015)031305(R) \]
Results

Running sum of Electric Dipole Polarizability

- $\alpha_D$ in $^{208}$Pb
- DP is saturating at around $\sim$40 MeV.

- $\alpha_D$ in $^{120}$Sn
- DP is saturating at around 40 MeV.
Discussion

Constraints on J-L and neutron-skin thickness from DP data
Discussion

Quasi-Deuteron Excitation Contribution

Photon absorption by a virtual deuteron in the nucleus

Needs to be subtracted for comparison with EDF calculations.

$^{208}$Pb

$\alpha_D(^{208}$Pb): $20.1 \pm 0.6$ fm$^3$

quasi-\textit{d}: $0.51 \pm 0.15$ fm$^3$

w/o quasi-\textit{d}: $19.6 \pm 0.6$ fm$^3$

$\sim 2.5\%$

$^{120}$Sn

$\alpha_D(^{120}$Sn): $8.93 \pm 0.36$ fm$^3$

quasi-\textit{d}: $0.34 \pm 0.08$ fm$^3$

w/o quasi-\textit{d}: $8.59 \pm 0.37$ fm$^3$

$\sim 4\%$
Discussion

Constraints on J-L from DP data

These $\alpha$ data give essentially one constraint on the symmetry energy in the $J-L$ plane.

$^{208}\text{Pb}$: A. Tamii et al., PRL 107(2011)06250

$^{120}\text{Sn}$: T. Hashimoto et al., PRC92(2015)031305(R)

$^{68}\text{Ni}$: D. Rossi et al., PRL 111 (2013) 242503

Data taken from C.J. Horowitz et al., JPG41, 093001 (2014)

X. Roca-Maza et al., PRC92, 064304(2015)
Work in progress

- Measurements on $^{112}\text{Sn}$, $^{124}\text{Sn}$ and on $^{92}\text{Zr}$, $^{94}\text{Zr}$, $^{96}\text{Zr}$ have been measured in 2015.
- Data analysis on $^{90}\text{Zr}$, $^{96}\text{Mo}$, $^{154}\text{Sm}$ (deformed nucleus)
- The result of $^{48}\text{Ca}$ experiment is publication in preparation

Uncertainty dominate by parameterization of nuclear background in MDA

New measurements including $^{40, 44}\text{Ca}$ for a smaller uncertainty are approved at RCNP

Theory: Darmstadt-Tennessee-TRIUMF
The electric dipole polarizability is a well-defined observable which is sensitive to the symmetry energy parameters of the nuclear EOS.

Proton inelastic scattering at very forward angles was employed as an electromagnetic probe for extracting the full electric dipole response of nuclei.

IV properties of the effective interaction:

Electric dipole response of $^{208}$Pb, $^{120}$Sn and $^{48}$Ca measured precisely by proton inelastic scattering.

Constraints on the symmetry energy and Neutron skin thickness

Pygmy dipole resonance distribution and Nuclear structure etc..

Isotope dependence on Sn and Zr have been measured and on Ca will be measured
208Pb

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Thank you for your attention
Backup Slides
Physics Motivation and Strategy

Probes of the Electric Dipole Response

1. Real photon absorption
   - $(\gamma,\gamma')$ Nuclear Resonance Fluorescence
   - $(\gamma,n)$, $(\gamma,2n)$, ...

2. Virtual photon excitations
   (Coulomb excitation)
   - Invariant mass method
     with an unstable nucleus beam
   - Missing mass method
     with proton inelastic scattering

3. Excitation by nuclear force
   with $\alpha$ or $^{17}$O inelastic scattering
Physics Motivation and Strategy

[Periodic Table]
Experimental method

Grand Raiden spectrometer @ RCNP
Focal plane detectors

Focal plane
Polarimeter

Total Spin Transfer ($\Sigma$)

$$\Sigma \equiv \frac{3 - (2D_{SS} + D_{LL})}{4}$$

$D_{SS}$ and $D_{LL}$: Spin transfer observable

Polarized Proton beam $E_p = 295$ MeV

$D_{SS}$ Measurement

$D_{LL}$ Measurement

$^{120}$Sn target
Thickness: 6.5 mg/cm$^2$
Purity 98.4 %
B(E1): continuum and GDR region
Method 1: Multipole Decomposition

Neglect of data for $\Theta > 4$: $(p,p')$ response too complex

Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg
Discussion

Constraints on J-L from DP data

\[
\begin{align*}
\alpha_D^{208}\text{Pb} &\approx 24 \\
\alpha_D^{120}\text{Sn} &\approx 120 \\
\alpha_D^{68}\text{Ni} &\approx 208
\end{align*}
\]
\[ \Delta r_{np} = 0.165 \pm (0.009)_{\text{expt}} \pm (0.013)_{\text{theor}} \pm (0.021)_{\text{est}} \text{ fm} \]

for the estimated \( J = 31 \pm (2)_{\text{est}} \)

All results agree with error bars and limit the range of neutron skin thickness to 0.15-0.20 fm
Discussion

Skyrme interaction

Relativistic mean field model

Theoretical calculations:
P.-G. Reinhard
J. Piekarewicz (FSU series)

P. Reinhard et al., PRL94(2005)142501
T. Hashimoto et al., PRC92(2015)031305(R)
The result is in good agree with error bars except for the result of antiproton annihilation

T. Hashimoto et al., PRC92(2015)031305(R)
Discussion

Electric Dipole Polarizability of $^{68}$Ni

Invariant mass spectroscopy by Coulomb Excitation

\[ \alpha_D = 3.40 \pm 0.23 \text{ fm}^3 \]
Structure of the PDR via the \((p, p' \gamma)\) and \((\alpha,\alpha'\gamma)\) reaction for inelastic \(\nu\)-nucleus response Noji et al. 5

Super-deformed states in \(^{28}\text{Si}\) via \(\gamma\)-particle coinc. Jenkins et al. 6

high-spin states population by light-ion reactions, Ideguchi et al. 3

*1 A. Bracco, F. Crespi, V. Derya, M.N. Harakeh, T. Hashimoto, P. von Neumann-Cosel, N. Pietralla, D. Savran, A. Tamii, V. Werner, and A. Zilges et al.

CAGRA(Clover Ge Array)

E. Ideguchi and M. Carpenter

Clovers: ANL+Tohoku+IMP

Preparation in progress

Collaboration

RCNP, Tohoku, ANL, LBNL, Milano, TU-Darmstadt, GSI, Köln, KVI, IFJ-PAN, IMP, ...

Aug. 2016
Excess Neutron Oscillation of the PDR

Predictions of the transition densities.

In both the IS and IV response

Signature of the neutron excess oscillation
- sensitivity to the surface transition
- IS excitation
- characteristic q-dependence

Out of phase $n$-$p$ oscillation

Only in the IV response

D. Bianco et al., PRC 86 (2012) 044327

Equation of Motion  Phonon Method

Courtesy of A. Zilges
Structure of the PDR

(p,p'γ) and (α,α'γ) for PDR in $^{64}\text{Ni}$, $^{90,94}\text{Zr}$, $^{120,124}\text{Sn}$, $^{206,208}\text{Pb}$

Collaboration

RCNP, Tohoku, ANL, Berkley, Milano, TU-Darmstadt, GSI, Köln, KVI, IFJ-PAN

Transition densities by QPM calc.

$q$-dep. of the PDR excitation for $^{208}\text{Pb}$
Electric Dipole Polarizability ($\alpha_D$)

Electric Dipole Polarization

$$\vec{P} = N \vec{E}$$

$\alpha$: dipole polarizability of an atom

Restoring force: symmetry energy
Experiment: Darmstadt-Osaka
Theory: Darmstadt-Tennessee-TRIUMF

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