STUDIES OF ELECTRIC DIPOLE RESPONSE IN NUCLEI USING THE SCATTERING OF POLARIZED PROTONS*

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The electric dipole ($E1$) response of ^{208}Pb has been precisely determined by proton inelastic scattering measurement at very forward angles. The electric dipole polarizability, which is an inversely energy-weighted sum-rule of the electric dipole strength, has been extracted as $20.1\pm0.6\,\mathrm{fm}^3$. The data has been used to constrain the neutron skin thickness of ^{208}Pb as $0.168 \pm 0.22\,\mathrm{fm}$ and the slope parameter of the symmetry energy as $L = 46 \pm 15$ MeV. The determination of the slope parameter is important for nuclear physics as well as for astrophysical simulations related to neutron stars.

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1. Introduction

Determination of the nuclear equation of state (EOS) is one of the fundamental goals of the nuclear physics. The EOS represents the bulk properties of nucleonic matter such as finite nuclei, infinite nuclear matter and neutron stars. Since the nucleonic matter is composed of two kinds of particles, *i.e.* neutrons and protons, the EOS has a term which depends on the density difference between neutrons and protons. Recently the term, symmetry energy, has been drawing much attention from both theoretical and experimental works. Accurate determination of the symmetry energy leads to precise prediction of the properties of neutron rich nuclei, neutron deficient nuclei, and super heavy nuclei. It is also a basic input of the calculation of heavy ion collision process. In astrophysics the symmetry energy is relevant

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to the study of the mass, radius and internal structure of neutron stars, dynamical process of supernova explosion, neutron star cooling, evolution of a neutron star binary, X-ray burst, and nucleosynthesis. Thus determination of symmetry energy is quite important.

Basic approach to determine the nuclear EOS is to obtain experimental data which are sensitive to the EOS for nuclear ground states and excited states, and to construct theoretical models which well describe the data. In this article, we will report on a precise determination of the dipole polarizability of ^{208}Pb by measuring Coulomb excitation with proton inelastic scattering at forward angles. The dipole polarizability is closely related to the neutron skin thickness of ^{208}Pb and to the density dependence of the symmetry energy.

2. Symmetry energy, neutron skin thickness and dipole polarizability

The nuclear equation of state can be expressed by an equation of energy per particle (E/A) as a function of nucleon density (ρ) and asymmetry parameter (δ) [1].

$$E/A(\rho,\delta) = E/A(\rho,0) + S(\rho)\delta^2 + \cdots\,, \tag{1}$$

$$S(\rho) = J + \frac{L}{3\rho_0}(\rho-\rho_0) + \frac{K_{\mathrm{sym}}}{18\rho_0^2}(\rho-\rho_0)^2 + \cdots\,, \tag{2}$$

$$\rho \equiv \rho_n + \rho_p\,, \tag{3}$$

$$\delta \equiv \frac{\rho_n - \rho_p}{\rho_n + \rho_p}\,, \tag{4}$$

where ρ_n and ρ_p stand for neutron and proton densities, respectively, and $\rho_0(\sim 0.16\ \mathrm{fm}^{-3})$ is the saturation density of the symmetric ($\delta = 0$) nuclear matter. The term $S(\rho)$ is called symmetry energy. It represents the asymmetry dependence of the energy. The first order density dependence of $S(\rho)$ is parametrized with the *slope parameter* L. The slope parameter is proportional to the baryonic pressure in a neutron star [2] and to the fourth of the neutron star radius [3].

Strong linear correlation between the slope parameter and the neutron skin thickness of ^{208}Pb is predicted in self-consistent mean field model calculations with various sets of interaction parameters. Here the neutron skin thickness δR_{np} is defined as the difference of the root mean square radii of the density distributions between neutrons and protons. For example, Roca-Maza *et al.* have extracted a linear relation of $\delta R_{np}\,(\mathrm{fm}) = 0.101 + 0.00147L\,(\mathrm{MeV})$ [4]. Thus the experimental data on the neutron skin thickness gives strong constraint on the slope parameter.

Parity-violating asymmetry measurement of electron elastic scattering at Jefferson Laboratory [5] is one of promising model-independent determinations of the neutron skin thickness of ^{208}Pb. They have used weak interaction to probe the from factor of the neutron density distribution at a momentum transfer of $q = 0.475$ fm^{-1}. The latest result has, however, large uncertainty as $\delta R_{np} = 0.302 \pm 0.175(\text{exp}) \pm 0.026(\text{model}) \pm 0.005(\text{strange})$ fm [6]. An improved measurement with better statistics is highly desired.

Recently, Reinhard and Nazarewicz have reported a very strong correlation between the dipole polarizability of ^{208}Pb and its neutron skin thickness in the framework of a self-consistent mean field calculation based on the energy-density functional method with the SV$_{\text{min}}$ Skyrme interaction [7]. Since the dipole polarizability corresponds to the static dipole polarization of a nucleus in a uniform external electric field, it is sensitive to the difference of the density distribution between neutrons and protons as well as the density dependence of the symmetry energy which acts as the restoring force of the polarization. The dipole polarizability α_{D} is related to the inversely energy-weighted sum-rule of the electric dipole reduced transition probability $B(E1)$ as

$$\alpha_{\text{D}} = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{S(\omega)}{\omega} d\omega \,, \tag{5}$$

where ω stands for the excitation energy, σ_{abs} for the photo-absorption cross section, and $S(\omega) = dB(E1)/d\omega$ for $B(E1)$ per unit excitation energy. Therefore, the dipole polarizability can experimentally be determined by measuring $B(E1)$ distribution. We have applied proton inelastic scattering measurement at forward angles for studying the $B(E1)$ distribution of ^{208}Pb.

3. Experimental method

The experiment has been performed at the cyclotron facility of the Research Center for Nuclear Physics (RCNP), Osaka University. Details of the experimental setup, conditions, and analysis procedures can be found in references [8–11]. A polarized proton beam at 295 MeV has been accelerated with a beam intensity of 2–10 nA and a polarization of 0.7. An isotopically enriched ^{208}Pb foil with a thickness of 5.2 mg/cm^2 has been used as a target. The excitation energy resolution was 30 keV. The experimental setup is shown in Fig. 1. The primary beam which passed through the target was transported in the Grand Raiden spectrometer, extracted at the focal plane, and stopped in the beam dump. Polarization axis of the beam was controlled by using two superconducting solenoids which were placed in the beam line between the injector and the main cyclotrons. In the polarization transfer

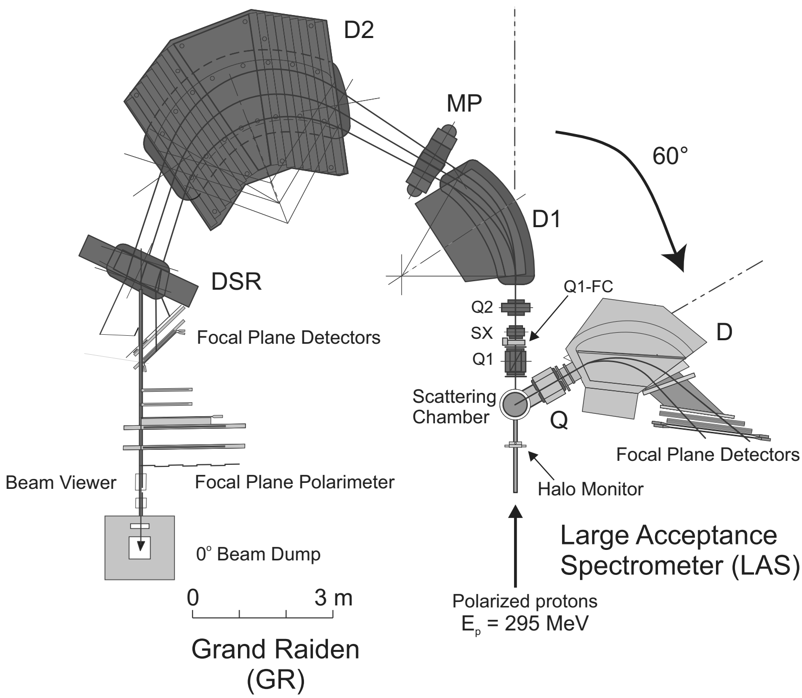

Fig. 1. The experimental setup of the Grand Raiden spectrometer in the zero degree measurement for the *DSR plus* mode. See the text for details.

measurement, two different focal planes [12] of the Grand Raiden spectrometer [13] were used. The first one is the standard focal plane for which the magnetic field of the third dipole magnet (DSR) was not used. The second one is the focal plane of the *DSR plus* mode in which the DSR magnetic field was used to bend scattered protons by 18 degrees in addition to the bending by the D1 and D2 dipoles as shown in Fig. 1. A sideway polarized beam and the standard focal plane were used for measuring the polarization transfer coefficient $D_{\mathrm{SS}'}$. A longitudinally polarized beam and the *DSR plus* mode were used for measuring $D_{\mathrm{LL}'}$. Polarization transfer coefficients were measured in an angular range of 0–2.5 degrees. Differential cross sections were measured in an angular range of 0–6 degrees. The measured excitation energy range was 5–25 MeV. Further information can be found in Ref. [11].

The upper panel of Fig. 2 shows the excitation energy spectrum of the $^{208}\mathrm{Pb}(p,p')$ reaction at 0.0–2.5 degrees. The giant dipole resonance (GDR) is clearly seen as a bump structure centered at 13 MeV with fine structures in the lower energy tail. Discrete states were observed below the neutron separation energy ($S_n = 7.368$ MeV). As shown in Fig. 3, all the known $E1$ states from nuclear resonance fluorescence (NRF) measurements have been

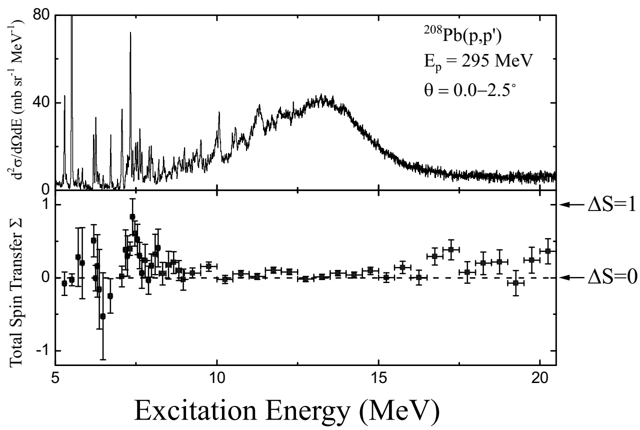

Fig. 2. Measured double differential cross sections (upper panel) and total spin transfer (lower panel) of the $^{208}\mathrm{Pb}(p, p')$ reaction at $E_p = 295$ MeV and at 0–2.5 degrees.

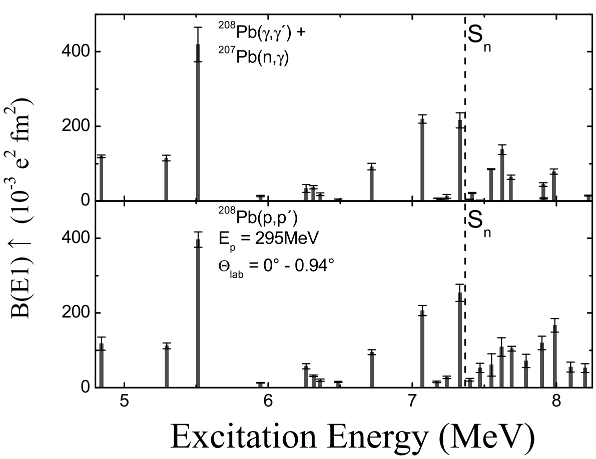

Fig. 3. Electric dipole reduced transition probability, $B(E1)$, of low lying states determined by the (p, p') experiment (lower panel) and real-photon measurements (upper panel).

observed. For low lying $E1$ transitions, $B(E1)$ has been extracted from the (p, p') cross section at 0.0–0.94 degrees. Note that absolute value of $B(E1)$ can be accurately determined by the proton inelastic scattering data since $E1$ excitations are dominantly mediated by Coulomb interaction which has essentially no model uncertainty. The extracted $B(E1)$ is excellently consistent with the data of NRF below S_n. At above S_n more strength than known from earlier studies has been observed.

4. Determination of the $E1$ strength distribution

For extracting $B(E1)$ strength in the continuum region, decomposition of $E1$ and $M1$ strengths is necessary. We have applied two independent methods. The first method uses polarization transfer data. A quantity named total spin transfer (Σ) is defined as

$$\Sigma(0^\circ) = \frac{3 - (2D_{\mathrm{SS}'}(0^\circ) + D_{\mathrm{LL}'}(0^\circ))}{4}\,. \tag{6}$$

The total spin transfer takes a value of unity for spin-$M1$ excitation by nuclear interaction, and zero for $E1$ excitation by Coulomb interaction. The relation holds model-independently at zero degrees provided the parity conservation [14]. The measured total spin transfer is shown in the lower panel of Fig. 2. The GDR bump region is dominantly composed of $E1$ strengths. A concentration of spin-$M1$ strengths is observed in the 7–8 MeV region as is reported in polarized real-photon studies [15, 16].

The second method is called multipole-decomposition analysis (MDA). Angular distribution of the cross section in each excitation energy bin has been fitted as a sum of angular distributions of several multipolarities. Angular distribution shapes were calculated by distorted wave impulse approximation (DWIA) by using the code DWBA07 [17] and Franey and Love effective interaction [18]. Several RPA amplitudes and single particle wave functions were taken from a calculation by quasi-particle phonon model (QPM) [19]. For each energy bin, mixture of multipolarities and target wave functions were determined by the least-square fit method so as to reproduce the experimental angular distribution. The results of the two methods agreed well to each other [9].

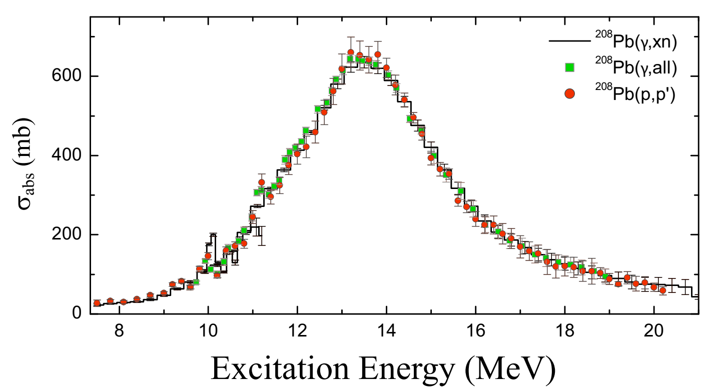

Fig. 4. Comparison of photo-absorption cross sections determined by (p,p') (circle), (γ,xn) [20] (solid line) and tagged gamma-absorption [21] (square) measurements in the GDR region for ^{208}Pb.

The photo-absorption cross section in the GDR region extracted by MDA is shown in Fig. 4. The result is consistent with the data of (γ, xn) measurement [20] and total photo-nuclear cross sections by using tagged-photon method [21].

The overall $B(E1)$ distribution determined by the (p, p') is shown in Fig. 5. The bump centered at ∼13 MeV corresponds to the GDR. and the strength concentration at around 7–9 MeV corresponds to the pygmy dipole resonance (PDR). Accurate $B(E1)$ strength distribution of ^{208}Pb has been determined from 5 to 20 MeV which fully covers PDR and GDR.

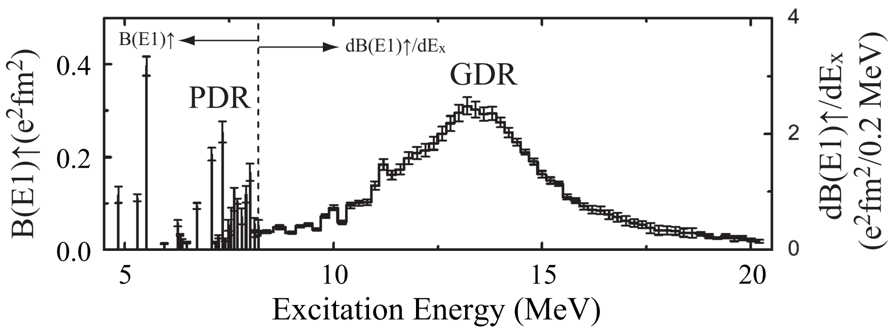

Fig. 5. The measured $B(E1)$ distribution of ^{208}Pb. The bump centered at $\sim$ 13 MeV corresponds to the giant dipole resonance, and the strength concentration at around 7–9 MeV corresponds to the pygmy dipole resonance.

5. Results

The dipole polarizability of ^{208}Pb has been determined up to 20 MeV from the measured $B(E1)$ distribution as $\alpha_{\rm D} = 18.9 \pm 1.3$ fm^3. By taking the average of the independent data including the gamma absorption at higher energies [21] the dipole polarizability of ^{208}Pb up to 130 MeV has been determined as 20.1 ± 0.6 fm^3.

Based on the model calculation by Reinhard and Nazarewicz [7] the measured dipole polarizability has been converted to the neutron skin thickness of ^{208}Pb as $\delta R_{np} = 0.156 + 0.025 - 0.021$ fm [9]. Model dependence of the correlation has been studied for various sets of model parameters [22]. The neutron skin thickness of ^{208}Pb has been determined as 0.168 ± 0.22 fm by taking average of theoretical predictions which predict dipole polarizability in the experimental uncertainty.

The accuracy of the determined neutron skin thickness is remarkably good comparing with experimental works as shown in Fig. 6. Each experimental data has its own model uncertainty, which is often difficult to

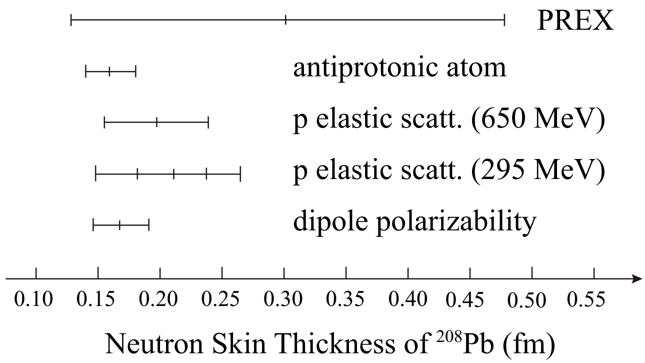

Fig. 6. The neutron skin thickness of ^{208}Pb measured by parity-violating electron scattering (PREX) [5, 6], analysis of the systematic of the X-ray detection data of anti-protonic atoms [24], proton elastic scattering at 650 MeV [25] and 295 MeV [23], and the dipole polarizability (this work) [9, 22].

estimate. In our case, high accuracy data of $B(E1)$ could be extracted by an electro-magnetic probe, for which the reaction mechanism is accurately known, and by applying a well-defined sum-rule value which can reduce the model uncertainty.

The slope parameter of the symmetry energy has been determined as $L = 46 \pm 15$ MeV from the neutron skin thickness of ^{208}Pb by using the theoretical correlation between the slope parameter and the neutron skin thickness [4].

The result is plotted in Fig. 7 as well as the constraints from other studies shown in Ref. [1]: heavy ion collision (HIC), pygmy dipole resonance (PDR), isobaric analog states (IAS), nuclear mass formula with finite range droplet model (FRSM), estimation from neutron star observations (n-star). The results from different methods look reasonably consistent to each other The allowed region of J and L is now becoming much limited.

For making further constraints on model parameters, dipole polarizability data for other nuclei are also important. One of good candidates is ^{48}Ca, for which theoretical predictions of the neutron skin thickness are scattered and are relatively uncorrelated with that of ^{208}Pb. Proton inelastic scattering data on ^{48}Ca [26] is already measured. Analysis and extraction of the dipole polarizability is in progress for ^{48}Ca as well as for ^{90}Zr [26], ^{96}Mo, ^{120}Sn, ^{144,154}Sm.

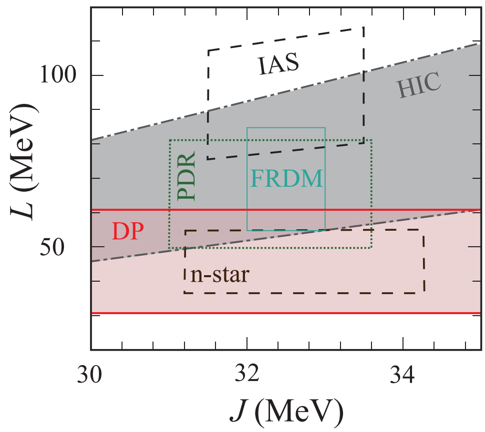

Fig. 7. Constraint of the symmetry energy parameters of J and L by various methods. The present dipole polarizability data and those in Ref. [1] are plotted. See the text for details.

6. Summary

The complete electric dipole ($E1$) strength distribution in ^{208}Pb has been determined up to 20 MeV by high-resolution proton inelastic scattering measurement at very forward angles. Multipole components in the differential cross section data have been decomposed by two independent methods: polarization transfer analysis and multipole decomposition analysis. The full $E1$ strength distribution has been obtained over a broad excitation energy range covering the pygmy dipole resonance and the giant dipole resonance. The developed experimental technique is suitable to study the systematics of electric dipole polarizability as well as pygmy dipole resonance of stable nuclei. The electric dipole polarizability of ^{208}Pb up to 130 MeV was determined as 20.1 ± 0.6 fm^3 by combining the present data and other available data. The precise data constrain the neutron skin thickness of ^{208}Pb as 0.168 ± 0.022 and the slope parameter of the symmetry energy as $L = 46 \pm 15$ MeV with a help of theoretical model calculations. The accuracy is quite good and would make a strong constraint on model parameters and the prediction of neutron star properties, supernova explosion dynamics, and many other interesting astrophysical predictions. Beyond these results we note that the experimental data can also be applied for pygmy dipole resonance strength distribution [10, 26], spin-$M1$ strength distribution [27], fine-structure and level density of the $E1$ strength by using statistical methods [28], and for gamma-ray strength function.

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