Direct determination of the neutron skin thicknesses in $^{40,48}$Ca from proton elastic scattering at $E_p = 295$ MeV

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The neutron density distributions and neutron skin thicknesses in $^{40,48}$Ca are determined from the angular distributions of the cross sections and analyzing powers of polarized proton elastic scattering at $E_p = 295$ MeV. Based on the framework of the relativistic impulse approximation with the density-dependent effective NN interaction, the experimental data is successfully analyzed, providing precise information of neutron and proton density profiles of $^{40,48}$Ca with small uncertainties. The extracted neutron and proton density distributions give neutron skin thicknesses in $^{40,48}$Ca for $-0.010^{+0.022}_{-0.020}$ fm and $0.168^{+0.025}_{-0.028}$ fm, respectively. The results of the density profiles and the neutron skin thickness in $^{48}$Ca are directly compared with the ab initio coupled-cluster calculations with interactions derived from chiral effective field theory, as well as relativistic and non-relativistic energy density functional theories.

Protons and neutrons in a nucleus tend to be distributed so that their density sum does not exceed the saturation density $\rho_{\text{sat}} \sim 0.17$ fm$^{-3}$. The proton and neutron distributions are almost identical; they have a plateau of density $\sim 0.5\rho_{\text{sat}}$ at the center in symmetric nuclei where the neutron number and the proton number are almost the same ($N \sim Z$). On the other hand, excess neutrons in neutron-rich nuclei are pushed to the nuclear surface, forming a region where only neutrons exist. This region is called a “neutron skin”.

Theoretical studies indicate that the thickness of the neutron skin $\Delta r_{np}$, which is defined as the difference of the neutron and proton root-mean-square (rms) radii ($\Delta r_{np} \equiv r_n - r_p$), embodies the stability of pure neutron matter. The quantity that characterizes the stability of neutron matter is called “symmetry energy”. The neutron matter equation of state (EOS) is a sum of well-known EOS of the symmetric nuclear matter and the symmetry energy. EOS governs not only the formation of nuclei but also astrophysical phenomena like neutron stars and super nova explosions. Consequently, the neutron matter EOS has been intensively studied in both nuclear physics and astrophysics [1–5]. The experimentally-measured $\Delta r_{np}$ can help elucidate the nature of high-density neutron matter occurring at neutron stars and binary neutron star mergers in the universe [6].

In previous studies, the doubly magic $^{208}$Pb has been used as a benchmark nucleus because the double magicity removes the effects from a complicated nuclear structure. This enables reliable comparisons between the experimental results and theoretical predictions. $\Delta r_{np}$ in $^{208}$Pb is theoretically predicted to have a strong correlation with the coefficient $L$ of the first density-derivative of the symmetry energy [7–9]. Many facilities have made experimental efforts to determine $\Delta r_{np}$ in $^{208}$Pb by measuring proton elastic scattering [10, 11], coherent pion-photoproduction [12], antiprotonic atom X-ray [13], and electric dipole polarizability [14]. Their results are in the range of $0.15–0.21$ fm with the error of approximately $\pm 0.03$ fm. The PREX experiment using parity-violating (PV) electron scattering resulted in $\Delta r_{np} = 0.33^{+0.16}_{-0.18}$ fm [15], which is consistent with other results within its large statistical error. The results have been compared with theoretical predictions based on the relativistic and non-relativistic energy density functional (EDF) theories [1, 3, 16, 17].

Recently, $\Delta r_{np}$ in $^{48}$Ca has been investigated both theoretically and experimentally. One merit of $^{48}$Ca is that the nucleus is within the range of the state-of-the-art ab initio calculations [18–22]. An interesting physics case is the direct assessment of the three nucleon force (3NF) effects. The 3NF plays an important role in high-density nuclear matter [23]. Ab initio coupled-cluster (CC) calculations based on the chiral effective field theory (EFT) interactions including the three-nucleon force, have been successfully performed for $^{48}$Ca [20, 22, 24]. $\Delta r_{np}$ in $^{48}$Ca should exhibit a new aspect of the neutron matter EOS, which cannot be seen in $^{208}$Pb because an ab initio calculations cannot be applied at present to $^{208}$Pb. In this Letter, we present the results of the direct determination of the neutron density distribution and $\Delta r_{np}$ in $^{40,48}$Ca by proton elastic scattering at 295 MeV. The extracted neutron density distribution and $\Delta r_{np}$ in $^{48}$Ca are compared with recent ab initio CC calculations [22, 25] and predictions of relativistic and non-relativistic EDF theories.

Several experimental studies on $\Delta r_{np}$ in $^{48}$Ca have been performed and planned [26, 27]. The electric dipole polariz-
ability $\alpha_D$ of $^{48}$Ca has been precisely determined by combining proton inelastic scattering data with photoabsorption data [26]. $\Delta r_{np}$ in $^{48}$Ca has been deduced by comparing the data with several EDF and ab initio theories. However, a direct determination of $\Delta r_{np}$ in $^{48}$Ca independent from a specific nuclear structure model is very important to examine the theory. One possibility is a CREX experiment using PV electron scattering which is a clean probe compared with hadronic probes [27]. The electro-weak interaction mediated by a photon and the $Z^0$ boson is used to probe neutrons inside a nucleus. The experiment is quite difficult because the precision of ppb level is required for the measurement of the PV asymmetry.

Proton elastic scattering is another approach to directly extract the neutron density distributions. Compared to PV electron scattering, the advantages are a high sensitivity to the neutron density and a highly attainable statistics due to a large cross section. The cost for the high efficiency is more complicated reaction mechanism than that in electron scattering. An accurate determination of the neutron density distribution requires an established reaction model and a reliable calibration using nuclei with a well-known density distribution.

Herein we use proton elastic scattering at $\sim 300$ MeV and analysis in the framework of the relativistic impulse approximation (RIA). The weakest nucleon-nucleon ($NN$) interaction appears around 300 MeV and the nucleus is the most transparent to an incident proton. This allows the impulse approximation to be used for the reaction analysis, providing the opportunity to determine the density distribution at the nuclear interior.

The angular distributions of the cross sections and analyzing powers for polarized proton elastic scattering from $^{40,48}$Ca were measured with a high-resolution magnetic spectrometer, “Grand Raiden” [29] at Research Center for Nuclear Physics, Osaka University, over an angular range of $7^\circ$–$48^\circ$. Polarized protons accelerated to 295 MeV were scattered by a natural Ca foil (abundance of $^{40}$Ca 96.9\%) and an enriched $^{48}$Ca foil (enrichment 97.7\%) with thicknesses of 3.50 and 1.06 mg/cm$^2$, respectively. Beam polarization was kept above 70\% during the measurements. Beam intensity was adjusted in the range of 1–400 nA, depending on the scattering angle. The momenta of scattered protons, which were analyzed by the Grand Raiden spectrometer, were determined by the focal plane detectors. The typical energy resolution was about 100 keV in the full width at half maximum. As shown in Fig. 1, the measured data-sets of the differential cross sections and analyzing powers of $^{40,48}$Ca($\beta$, $p$) (black dots) cover the wide momentum transfer range of 0.5–3.5 fm$^{-1}$.

The neutron density distributions are determined by the method employed in Refs [11, 30]. The method is based on the RIA model developed by Murdock and Horowitz (MH model) [31], which is among the most successful models for proton elastic scattering in the intermediate energy region ($\geq$ 200 MeV) [30]. The present analysis modified the relativistic Love-Franey (RLF) $NN$ interaction employed in the original MH model [32] to take the effects of the nuclear medium into account, e.g. Pauli blocking, multi-step processes, and vacuum polarization effects. The modification was introduced in a form of density-dependent coupling constants and masses of mesons used in the RLF interaction [33]. As reported in Ref. [11], the density-dependent parameters in the modification were well determined so that the medium-modified RIA calculation reproduces the proton elastic scattering data on $^{58}$Ni at the same incident energy as the present work. Previous studies [11, 28] have demonstrated that the analysis method successfully works in different regions of nuclei like tin and lead. The parameters determined for $^{58}$Ni work well for $A = 116$–208. Thus, these parameters should be reasonable in the case of the calcium isotopes with masses closer to $A = 58$.

To single out the precise neutron density distribution $\rho_n(r)$, the point-proton density distribution $\rho_p(r)$ is necessary. The nuclear charge distribution $\rho_{ch}(r)$ was precisely determined from the electron scattering data [34]. Thus, $\rho_p(r)$ can be derived by unfolding $\rho_{ch}(r)$ with the intrinsic proton and neutron electromagnetic distributions. Using the Fourier transforms of the distributions in the momentum space $q (\vec{F}_q(r) \equiv \int \rho(r) \exp(i \vec{q} \cdot \vec{r}) d\vec{r})$, the relation can be written as

$$F_{ch}(q) = F_p(q)G^p_E(q^2) + F_n(q)G^n_E(q^2) + F_{SO}(q).$$

FIG. 1. Differential cross sections and analyzing powers for polarized proton elastic scattering from $^{40,48}$Ca at 295 MeV. Blue and red lines are from the MH model and the result of the best-fit in this analysis, respectively.

where $F_{ch}$, $F_{p(n)}$, and $G^{p(n)}_E$ are the nuclear charge, the point-proton (neutron), and the Sachs single-nucleon electric form factors, respectively. The value of $r^2_{\rho_{ch}} = 0.769$ fm$^2$ ($0.116$ fm$^2$) in Ref. [36] is employed for the mean-square single-proton (neutron) charge radius of $G^{p(n)}_E$. The nuclear charge distributions of $^{40,48}$Ca were taken from Ref. [34].
The spin-orbit contribution $F_{SO}$ is mainly attributed to the nucleons in an open $l$ shell. Although its contribution to the entire proton density is quite small and neglected in many cases, it has a non-negligible effect in the determination of $\Delta r_{np}$. If $(2j+1)$ neutrons are filled in the $j = l + 1/2$ sub-shell and the proton shell is closed like $^{48}$Ca, $F_{SO}$ can be approximated as

$$F_{SO}(q) \approx \frac{l(2j+1)(G^p_M(q^2) - 2G^n_M(q^2))}{4m^2} \cdot \frac{\partial r_p^n(r)}{r^2 \partial r},$$

where $G^p_M$ is the single-neutron magnetic form factor, $r_p^n(r)$ is the density of each neutron in the $j = l + 1/2$ sub-shell, and $m$ is the nucleon mass. (The relativistic description of $F_{SO}$ is presented in Refs. [37, 38].) The spin-orbit contribution is sizable in $^{40}$Ca due to the eight neutrons in the $2f_{7/2}$ subshell. The increase of $r_p$ in $^{40}$Ca due to the $F_{SO}$ term is evaluated to be $\approx 0.02$ fm [38, 39], which is compatible with the typical uncertainty of $\Delta r_{np}$ [11]. Hence, the spin-orbit contribution should be included to determine $r_p$ in $^{48}$Ca. The $F_{SO}$ contribution in $^{40}$Ca can be neglected because the nucleons in the $LS$-closed shells do not contribute to the $F_{SO}$ term, as shown in Ref. [39] for the non-relativistic limit.

The extraction of $r_p$ in $^{40,48}$Ca was carried out by a $\chi^2$ fitting to the proton elastic scattering data with $r_p$ determined by solving Eqs. (1) and (2) iteratively. $r_p$ is modeled with a sum-of-Gaussian (SOG) function with 11 free parameters. There is no $a$ priori assumption on the form factor and the extracted density distributions are independent of specific nuclear structure models. $r_p$ is derived by applying $r_n$ determined from the proton scattering data to the second and third terms in Eq. (1) and the $p'_n$ term in Eq. (2). The $(2j+1)p'_n$ is approximated with $r_n - r_p$. The error of $r_p$ is not considered in this fitting procedure since it is much smaller than that of $r_n$. The $\chi^2$ fitting procedure started with initial values of $r_n = (N/Z)p_p$, and $F_{SO} = 0$ and continued until the self-consistent solution was obtained.

While the blue solid lines in Fig. 1 represent the predictions by the original MH model with Dirac-Hartree (DH) nucleon densities [35], the red solid lines are the best-fit results with the reduced $\chi^2$ minima 4.6 and 4.0 for $^{40,48}$Ca, respectively. Figure 2 shows the extracted $r_n$ in $^{40,48}$Ca (red solid) together with $r_p$ used in the search after the iteration (black dash-dotted). The upper panels in Fig. 2 show the density distributions, whereas the lower panels are those multiplied by the phase space factor $4\pi r^2$. The red hatched areas show the standard error envelopes due to the experimental statistical and systematic errors only. The blue cross-hatched areas are shown to visualize the maximum uncertainty of the present method as well as the experimental errors. The uncertainty is attributed to any effect that makes the reduced $\chi^2$ larger than unity and is evaluated by determining the density distributions for the same data set but with artificially increased errors so that the reduced $\chi^2$ becomes unity. The blue cross-hatched areas are comparable to the red hatched areas. The results show that the present method is well established for the accurate determination of density distributions. More details of the analysis method are reported in Refs. [11, 30]. In $^{40}$Ca, $r_n$ has almost the same shape as $r_p$. On the other hand, $r_n$ in $^{48}$Ca is clearly enhanced over $r_p$ and exhibits the characteristic nose structure around 3 fm, as shown in the top-right panel of Fig. 2. This structure is attributed to the radial distribution of the $1f_{7/2}$ orbit in which the excess eight neutrons are filled.

| $^{40}$Ca | $^{48}$Ca |
|---|---|
| $r_n$ | $r_p$ | $r_n$ | $r_p$ | $\Delta r_{np}$ | $\delta_{exp}$ | $\delta_{exp+\text{mod}}$ |
| This work | 3.460 | 3.387 | 3.555 | 0.168 | +0.028 | +0.055 |
| DD-ME2 | 3.39 | 3.57 | 0.18 | - | - |
| SAMi-J28 | 3.44 | 3.60 | 0.16 | - | - |
| NNLO$_{ud}$ | 3.41 | 3.54 | 0.13 | - | - |
| $\Delta$NNLO | 3.47 | 3.62 | 0.15 | - | - |

Table I. Table of the rms radii and the skin thicknesses. $r_n$ and $r_p$ used in this work, and the extracted $r_n$ and $\Delta r_{np}$ in $^{40,48}$Ca are listed. $\delta_{exp}$ and $\delta_{exp+\text{mod}}$ are the two types of errors of $r_n$ and $\Delta r_{np}$ due to the experimental errors only and the errors including model uncertainties, respectively. For $^{48}$Ca, some EDF and $ab$ initio predictions are compared. All values are in fm.
experimental results: the \textit{ab initio} CC method with NNLO\textsubscript{sat} and \textDelta NNLO interactions [20, 22], as well as, a relativistic and a Skyrme EDF parameterization (DD-MEb, SAMi-J28) of the Ref. [40]. \textDelta NNLO is the chiral EFT interaction recently proposed by explicitly including \textDelta-isobar [22]. NNLO\textsubscript{sat} and DD-MEb give reasonable \(r_0\) values while \textDelta NNLO and SAMi-J28 predict larger \(r_p\) and \(r_n\). However, for the skin thickness of \(^{48}\text{Ca}\), all the predictions give consistent values with our result considering the error.

Figure 3 compares the experimentally-determined density distributions in \(^{48}\text{Ca}\) (red solid and hatched lines) with the predictions by NNLO\textsubscript{sat} (blue short-dash), \textDelta NNLO (magenta long-dash), DD-MEb (green dash-dotted), and SAMi-J28 (black dotted). The lower panel (b) of Fig. 3 shows the deviations of each prediction from our work multiplied by \(4\pi r^2\) \((\Delta = 4\pi r^2(\rho^{\text{cal}} - \rho^{\text{exp}}))\). For clarity, \(\rho_n\) and \(\Delta_n\) are shifted by +0.02 fm\(^{-3}\) and +1.0 fm\(^{-3}\), respectively. The NNLO\textsubscript{sat} and DD-MEb predictions surprisingly agree with our result. \textDelta NNLO and SAMi-J28 predict large diffusenesses of \(\rho_p\) and \(\rho_n\). Consequently, they give larger \(r_p\) and \(r_n\), compared to our work. It is thus demonstrated that comparison with the experimentally obtained \(\rho_p\) and \(\rho_n\) enables the assessment of the theoretical predictions which is not possible only with the neutron skin thickness. This is an advantage in the proton elastic scattering method over other methods that determine only the radii or skin thicknesses.

The obtained values of \(\Delta r_{np}\) in \(^{40,48}\text{Ca}\) with the experimental errors are \(-0.010^{+0.022}_{-0.025}\) fm and \(0.168^{+0.025}_{-0.028}\) fm, respectively. The \(^{40}\text{Ca}\) result is consistent with almost all the theoretical calculations, which predict a small proton skin in \(^{48}\text{Ca}\). The small proton skin is a result of the repulsive Coulomb force that pushes protons outwards. The result of \(\Delta r_{np}\) in \(^{48}\text{Ca}\) is consistent in the range of 0.14–0.20 fm, which was recently obtained by interpreting the dipole polarizability (DP) of \(^{48}\text{Ca}\) [26]. However, the value of \(\Delta r_{np} = 0.249(23)\) fm reported by the dispersive optical model (DOM) analysis [41] differs from our work and the DP result. The left panel of Fig. 4 plots the correlation between \(\Delta r_{np}\) in \(^{48}\text{Ca}\) and the slope parameter \(L\) of the symmetry energy predicted by the \textit{ab initio} and EDF models, while the right panel compares the \(\Delta r_{np}\) values of \(^{48}\text{Ca}\) and \(^{208}\text{Pb}\) predicted by the relativistic and Skyrme EDF models. Black squares, green triangles, and magenta circles represent the predictions of the \textit{ab initio} method, the relativistic EDF models (NL3 [42], DD-ME2 [43] DD-ME\textdelta [44], DD-PC1 [45], FSU [46], FSU2 [47] IUFSU [48]) and Skyrme EDF models (SkM* [49], Sk255, Sk272 [50], SeaLL1 [51], UNEDF0 [52]), respectively. Open triangles and circles are sets of the DD-ME and SAMi-J families in Ref. [40], respectively. Open squares are the \textit{ab initio} results by newly developed NNLO\textsubscript{sat} and \textDelta NNLO interactions. The blue rectangle represents the region estimated from several chiral EFT interactions by G. Hagen et al. in Ref. [25]. The red hatched area shows the result of our work while the arrows are the ranges by DP and DOM analyses. Compared to the recent EDF theories, \textit{ab initio} theories predict a slightly smaller neutron skin thickness. Our result for \(^{48}\text{Ca}\) implies that \(L\) is in the range of 20–70 MeV. The right panel of Fig. 4 plots the correlation between the \(^{48}\text{Ca}\) and \(^{208}\text{Pb}\) skin thicknesses. A difference between the results from the proton elastic scattering and from the dipole polarizability is noticeable. The arrow denotes the PREX result of \(^{208}\text{Pb}\) [15].

In summary, we performed a direct determination of the neutron density distributions and the skin thicknesses of \(^{40,48}\text{Ca}\) from proton elastic scattering at 295 MeV. The obtained value of \(\Delta r_{np} = 0.168^{+0.025}_{-0.028}\) fm for \(^{48}\text{Ca}\) is consistent with the DP analysis, while the DOM analysis provides a large skin thickness. The recent \textit{ab initio} and EDF predictions give consistent values of \(\Delta r_{np}\) with this work. In particular, the calculations of the \textit{ab initio} CC model using the NNLO\textsubscript{sat} interaction and the DD-MEb model provide density distributions that are consistent with our result.

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FIG. 4. (Left) ∆r_{np} in 48Ca versus the slope parameter L. (Right) ∆r_{np} in 48Ca versus 208Pb. Squares, triangles, and circles are predictions by "ab initio" CC method with chiral EFT interactions, relativistic and Skyrme EDFs, respectively. In the left panel, the arrows indicate the result of DP and DOM analyses, while the present result is shown by a red dash line with the hatched area. The blue rectangle shows the region evaluated in Ref. [25]. In the right panel, the red hatched region shows the overlap between this work for 48Ca and the previous work for 208Pb of Ref. [11]. The arrow is due to the PREX experiment, while the black hatched region is obtained by the DP analyses.

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