Measurements of total reaction cross sections for $^{17}$Ne using a solid hydrogen target

T. Moriguchi$^1$, M. Amano$^1$, A. Ozawa$^1$, W. Horiuchi$^2$, Y. Abe$^3$, T. Fujii$^4$, R. Kagesawa$^1$, D. Kamioka$^1$, A. Kitagawa$^3$, M. Mukai$^1$, D. Nagae$^5$, M. Sakaue$^4$, S. Sato$^3$, S. Suzuki$^6$, T. Suzuki$^4$, T. Yamaguchi$^1$ and K. Yokota$^4$

$^1$ Institute of Physics, University of Tsukuba, Ibaraki 305-8571, Japan
$^2$ Department of Physics, Hokkaido University, Sapporo 060-0810, Japan
$^3$ National Institute of Radiological Sciences, Chiba 263-8555, Japan
$^4$ Department of Physics, Saitama University, Saitama 338-8570, Japan
$^5$ Research Center for SuperHeavy Elements, Kyushu University, Fukuoka 819-0395, Japan
$^6$ Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

E-mail: moriguchi@tac.tsukuba.ac.jp

Abstract. We measured the energy dependence of the total reaction cross sections ($\sigma_R$) for the proton-drip-line nucleus, $^{17}$Ne, using a solid hydrogen target. We compared the experimental data with theoretical calculations using the Glauber model. We found that the theoretical cross sections overestimate the experimental ones in the low-energy region ($\sim 100$ A MeV), whereas they significantly underestimate the experimental data in the intermediate-energy region ($\sim 300$-500 A MeV). These trends are the same as those for $\sigma_R$ for carbon–proton collisions, which were measured previously. We discuss several possibilities for resolving this discrepancy. This work demonstrates the necessity of additional careful investigations of the energy dependence of $\sigma_R$ for various nuclei on proton targets in order to determine nuclear size properties precisely.

1. Introduction

Skin structure is one of the representative phenomena of unstable nuclei. The skin thickness is defined as the difference between the proton and neutron root-mean-square (RMS) radii ($r_p$ and $r_n$) of a nucleus. Since this quantity is closely related to the nuclear symmetry energy in the nuclear matter equation of state (EOS) [1], studies of the skin structure contribute not only to nuclear physics but also to elucidating of the mechanism of supernova explosions and the internal structures of neutron stars.

The energy dependence of the total reaction cross section ($\sigma_R$) has been used to deduce the nucleon density distributions. In particular, measurements of $\sigma_R$ on a proton target allow the possibility of separating the proton and neutron density distributions ($\rho_p$ and $\rho_n$) by using the asymmetry of the nucleon–nucleon total cross sections ($\sigma_{NN}^{tot}$) [2]. This separation enables the extraction of the skin thickness. The $\rho_p$ and $\rho_n$ for $^{11}$Li, $^{11}$Be, and $^8$B have been separated successfully by measuring $\sigma_R$ at several tens of A MeV with a proton target [3, 4]. Theoretical investigations suggest that the energy dependence of $\sigma_R$ on a proton target is useful for separating $r_p$ and $r_n$ together with the practical prescriptions [5, 6]. However, only a few experimental values of $\sigma_R$ for unstable nuclei on a proton target are available; in particular, measurements at
intermediate energies from 200 to 600 A MeV have not been reported previously. Consequently, the energy dependence of $\sigma_R$ for unstable nuclei on a proton target has not been investigated adequately to date.

In the present study, we investigate the energy dependence of $\sigma_R$ on a proton target over a wide energy range for the proton-drip-line nucleus $^{17}$Ne ($T_{1/2} = 109.2(6)$ ms [7], $S_{2p} = 933.10(61)$ keV [8]). The $^{17}$Ne isotope is known to be a candidate of two-proton halo nucleus, and its radii and densities are well known experimentally [9, 10, 11]. Thus, $^{17}$Ne offers an ideal example for studying unstable nuclei on a proton target.

2. Experiment and analysis

To measure $\sigma_R$ for $^{17}$Ne, we adopted the transmission method, using the equation

$$\sigma_R = -\frac{1}{N_t} \ln \left( \frac{R_{\text{in}}}{R_{\text{out}}} \right),$$

where $R_{\text{in}}$ is the ratio of the number of non-interacting particles ($N_o$) to the number of incoming particles ($N_i$) for a target-in measurement, and $R_{\text{out}}$ is the same ratio for a target-out measurement. Target-out measurements are necessary in order to subtract the contributions of reactions with materials other than the reaction target. The number of target nuclei per unit area is denoted by $N_t$.

The experiment was performed using a fragment separator in the Heavy Ion Medical Accelerator in Chiba (HIMAC, Japan) [12]. $^{20}$Ne was used as the primary beam, with three energies: 180, 400, and 600 A MeV. The secondary beam was produced by bombarding a beryllium target located at the entrance of the separator with the $^{20}$Ne beam. $^{17}$Ne particles were identified by using the magnetic rigidity (B$\rho$), the time-of-flight (TOF) between two plastic scintillation counters, and the energy loss ($\Delta E$) detected by a silicon detector. Figure 1 shows a schematic view of the experimental setup at the final focal plane. The plastic scintillation counter shown in Fig. 1 was used for the stop signal of the TOF. Two parallel-plate avalanche counters (PPACs) [13] were placed for beam tracking. Figure 2 (a) shows a two-dimensional TOF-$\Delta E$ plot before the reaction target in the case of $^{17}$Ne at 289A MeV. We obtained this plot after selecting the beam position and angle ranges for good transmission, using beam tracking provided by the position information from the two PPACs. As shown in Fig. 2 (a), the $^{17}$Ne particles are clearly separated from other nuclei. In order to determine $N_i$, we performed Gaussian fits after projecting the main peak of $^{17}$Ne separately onto the TOF and $\Delta E$ axes. In the present analysis, we counted the number of $^{17}$Ne within $\pm 2$ sigma as $N_i$.

A solid hydrogen target (SHT) was used as the reaction target [14]. In the present experiment, we used two different thicknesses of SHTs: $50 \times 30$ mm$^3$ (1.58 $\times 10^{23}$/cm$^2$) and $50 \times 100$ mm$^3$ (5.21 $\times 10^{23}$/cm$^2$). The thickness of the SHT we employed depended on the positions of the incident particles, since the surfaces of the thin entrance and exit windows of the SHT swell because of the internal pressure. This expansion was approximated by a second-order polynomial function [14]. For this study, we determined the value of $N_t$ by using the effective thickness obtained by considering the statistical weight of the beam position at the exit of the SHT.

Downstream from the SHT, an ionization chamber (IC) [15] was placed to provide the $\Delta E$ for determining the atomic number ($Z$) of the particles ejected from the SHT. For 600 A MeV primary beam, we installed a copper energy degrader before the NaI(Tl) so that the particles stopped in the NaI(Tl). Figure 2 (b) shows a two-dimensional $\Delta E$-$E$ particle identification (PID) plot after the SHT. This plot was obtained by selecting $^{17}$Ne before the SHT, as mentioned above. Non-interacting $^{17}$Ne events form the main peak in Fig. 2 (b). The tail from the main peak towards low $E$ corresponds to events from nuclear reactions inside the NaI(Tl) scintillation counter and should be counted as non-interacting $^{17}$Ne. Fluorine isotopes are not observed since
the $^{16}$F produced by one-proton removal reactions is an unbound nucleus. In order to determine $N_o$, we projected the non-interacting $^{17}$Ne events shown in Fig. 2 (b) onto the $\Delta E$ axis, and we obtained the width of the peak from a Gaussian fit. In the present analysis, we counted the number of events in the gate from $-3.5$ to $+5$ sigma as $N_o$ in order to prevent contamination by the oxygen isotopes.

We applied this analysis procedure to all the data, including the target-out measurements, to obtain $\sigma_R$ for $^{17}$Ne. The experimental errors take into account both the statistical errors and the uncertainty in the target thickness.

**Figure 1.** Schematic view of the experimental setup at the final focal plane of the fragment separator. See text for definitions of abbreviations.

**Figure 2.** Particle identification (PID) plots from the target-in measurement in the case of $^{17}$Ne at 289.4 MeV (a) two-dimensional TOF-$\Delta E$ PID plot before the SHT, (b) two-dimensional $\Delta E$-$E$ PID plot after the SHT.

### 3. Results and discussions

Figure 3 (a) shows the energy dependence of $\sigma_R$ for $^{17}$Ne on the proton target. Closed circles and open squares represent the present and previous [16] experimental results, respectively. As shown in Fig. 3 (a), $\sigma_R$ for $^{17}$Ne on the proton target over the wide energy range from 73 to 432.4 MeV were obtained in the present study.

We investigated the energy dependence of $\sigma_R$ for $^{17}$Ne on the proton target using the Glauber model [17], which is a widely accepted method for extracting nuclear size properties from $\sigma_R$. In this paper, we take a standard approximation, the optical limit approximation (OLA) [17] for the nucleus-proton scattering. The basic inputs to the OLA are $\rho_0$, $\rho_s$, and the profile function $\Gamma_{NN}$, which is responsible for describing nucleon-nucleon collision. The latter is often given in parameterized form [18], and the parameter set we used in the present study is listed in Ref. [19].
\[ \rho_p \text{ and } \rho_n \text{ for } ^{17}\text{Ne} \text{ are needed to calculate } \sigma_R \text{ using the Glauber model. The matter density distribution } (\rho_m) \text{ and the RMS matter radius } (r_m) \text{ for } ^{17}\text{Ne} \text{ are experimentally known from the previous } \sigma_R \text{ measurements [10]. The RMS charge radius } (r_{ch}) \text{ of } ^{17}\text{Ne} \text{ is also known experimentally from optical isotope shift measurements [20]. It can be converted into an RMS point–proton radius } (r_p) \text{ using } r_p^2 = r_m^2 - \langle R^2_p \rangle - \frac{\hbar^2}{4m_p^2c^2}, \text{ where } \langle R^2_p \rangle \text{ and } \langle R^2_n \rangle \text{ are the RMS charge radius of the proton [21] and the neutron [22], respectively, and the last term is the Darwin-Foldy correction [23]. The RMS point–neutron radius } (r_n) \text{ can be obtained by substituting } r_m \text{ and } r_p \text{ into } r_n^2 = \left( \frac{2}{3} \right) r_p^2 + \left( \frac{4}{3} \right) r_n^2. \text{ In a previous study [10], the same core width parameters were assumed for } \rho_p \text{ and } \rho_n \text{ to deduce } \rho_m \text{ for } ^{17}\text{Ne}. \text{ In the present study, those of } \rho_p \text{ and } \rho_n \text{ were modified independently so as to reproduce the values of } r_p \text{ and } r_n \text{ determined as discussed above, keeping the value of } r_m \text{ fixed. The deduced values of } \rho_p \text{ and } \rho_n \text{ for } ^{17}\text{Ne} \text{ were used as the input densities for the Glauber-model calculations.}

The solid lines in Figs. 3 (a) and (b) show the results of OLA calculations for ^{17}\text{Ne}-proton and ^{12}\text{C}-proton collisions [19], respectively, along with the experimental cross sections. As shown in Fig. 3 (a), the calculated } \sigma_R \text{ slightly overestimates the experimental cross sections for } ^{17}\text{Ne} \text{ at 73 and 100 A MeV, whereas it significantly underestimates those at 289 and 432 A MeV. In particular, the difference between the experimental results and the theoretical calculations is greatest around 430 A MeV, and this difference is approximately 18 times larger than the experimental error in } \sigma_R \text{ at that energy. Even with the uncertainties in the RMS radii taken into account, it is difficult to reproduce the experimental values of } \sigma_R \text{ simultaneously at low and intermediate energies. This trend in the } ^{17}\text{Ne}-\text{proton collisions is also seen in the } ^{12}\text{C}-\text{proton cross sections. That is, the calculated } \sigma_R \text{ is larger (smaller) than the experimental cross sections at low (intermediate) energies, as shown in Fig. 3 (b). In the present calculations, we use the nucleon-nucleon total reaction cross section } (\sigma_{N_N}^{tot}) \text{ in free space, which is included in the } \Gamma_{N_N}. \text{ However, it can be modified in the nuclear medium owing to, e.g., Fermi motion and Pauli blocking. These in-medium effects affect } \sigma_{N_N}^{tot} \text{ at low energies (several tens } A \text{ MeV), but not at intermediate and high energies. Therefore, it is difficult to explain the experimental } \sigma_R \text{ for the nucleus-proton collisions simultaneously at low and intermediate energies with in-medium effects. Another possibility is the uncertainties of the } \Gamma_{N_N} \text{ in the Glauber model we used. We attempted to calculate } \sigma_R \text{ by varying a part of the parameters in } \Gamma_{N_N} \text{ from their original values [19]. However, the calculated } \sigma_R \text{ on the proton target showed little variation with modifications of } \Gamma_{N_N}, \text{ and it is difficult to reproduce the experimental data. At present, the discrepancy between the experimental results and the Glauber-model calculations for } \sigma_R \text{ for the nucleus–proton collisions remains an open question. To understand the energy dependence of } \sigma_R \text{ for nucleus–proton collisions, we need to measure additional values of } \sigma_R \text{ not only for unstable nuclei but also for stable nuclei and to verify them with theoretical calculations in order to establish a method for determining nuclear size properties precisely. Details of the results and additional discussions are provided in Ref. [25].}

4. Summary

We have studied the energy dependence of the total reaction cross sections } (\sigma_R) \text{ for } ^{17}\text{Ne using a SHT and have compared the new } \sigma_R \text{ data with a standard theoretical calculation, the Glauber model. We found that the Glauber-model calculations slightly overestimate } \sigma_R \text{ at low energies (73 and 100 A MeV) and significantly underestimate it at intermediate energies (289 and 432 A MeV). We have discussed several possibilities for resolving this discrepancy, but we have been unable to obtain a clear explanation for it. At present, the discrepancy between the experimental results and the Glauber-model calculations for } \sigma_R \text{ for nucleus–proton collisions remains an open question. More experimental measurements of } \sigma_R \text{ on proton targets for various nuclei are needed in order to understand the behavior of } \sigma_R \text{ for nucleus–proton collisions over}
Figure 3. Energy dependence of the reaction cross section ($\sigma_R$) for (a) $^{17}$Ne-proton and (b) $^{12}$C-proton collisions. Note that the energy per mass number $A$ of an incident nucleus ($A$ MeV) in the proton-fixed frame corresponds to that of an incident proton (MeV) in the nucleus-fixed frame. Closed circles and open squares in (a) represent the present and previous experimental results [16], respectively. The open circles in (b) are the experimental results taken from previous studies [24]. The solid curves in both panels represent Glauber-model calculations in the optical limit approximation (OLA) [17, 19].

the whole energy range.

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References
[1] Roca-Maza X, Centelles M, Vinàs X and Warda M 2011 Phys. Rev. Lett. 106 252501
[2] Particle data group 2018 http://pdg.lbl.gov/ssect/contents.html
[3] Nishimura D et al. 2010 Nucl. Phys. A 834 470c
[4] Moriguchi T et al. 2013 Phys. Rev. C 88 024610
[5] Horiuchi W, Suzuki Y and Inakura T 2014 Phys. Rev. C 89 011601(R)
[6] Horiuchi W. Hatakeyama S, Ebata S and Suzuki Y 2016 Phys. Rev. C 93 044611
[7] Tilley D R, Weller H R and Cheves C M 1993 Nucl. Phys. A 565 1
[8] Wang M, Audi G, Kondev F G, Huang W J, Naimi S and Xu X 2017 Chin. Phys. C 41 030003
[9] Ozawa A et al. 1994 Phys. Lett. B 334 18
[10] Tanaka K et al. 2010 Phys. Rev. C 82 044309
[11] Kanungo R et al. 2003 Phys. Lett. B 571 21
[12] Kanazawa M et al. 2004 Nucl. Phys. A 746 393c
[13] Kumagai H, Ozawa A, Fukuda N, Stimmer K and Tanihata I 2001 Nucl. Instrum. Methods Phys. Res. A 470 562
[14] Moriguchi T et al. 2010 Nucl. Instrum. Methods Phys. Res. A 624 27
[15] Kimura K et al. 2005 Nucl. Instrum. Methods Phys. Res. A 538 608
[16] Nishimura D, Fukuda M et al. 2019 private communication
[17] Glauber R J 1959 Lectures in Theoretical Physics vol 1 p 315 (New York: Interscience)
[18] Ray L 1979 Phys. Rev. C 20 1857
[19] Abu-Ibrahim B, Horiuchi W, Kohama A and Suzuki Y 2008 Phys. Rev. C 77 034607
[20] Angelí I and Marinova K 2013 At. Data Nucl. Data Tables 99 69
[21] Sick I 2003 Phys. Lett. B 576 62
[22] Kopecky S, Harvey J A, Hill N W, Krenn M, Pernicka M, Riehs P and Steiner S 1997 Phys. Rev. C 56 2229
[23] Friar J L, Martorell J and Sprung D W L 1997 Phys. Rev. A 56 4579
[24] Carlson R F 1996 At. Data Nucl. Data Tables 63 93
[25] Moriguchi T et al. 2019 Nucl. Phys. A 994 121663