EPJ Web of Conferences 66, 03099 (2014)
DOI: 10.1051/epjconf/20146603099


# Charge-changing interactions probing point-proton radii of nuclei

S. Yamaki[1], J. Kouno[1], D. Nishimura[2], M. Nagashima[3], M. Takechi[4], K. Sato[1], K. Abe[3], Y. Abe[5], M. Fukuda[6], H. Furuki[1], I. Hachiuma[1], A. Homma[3], N. Ichihashi[1], C. Ichikawa[1], N. Inaba[5], T. Ito[3], K. Iwamoto[6], T. Izumikawa[8], Y. Kamisho[6], N. Kikuchi[3], S. Kinno[2], A. Kitagawa[7], T. Kojima[2], T. Kuboki[1], M. Mihara[6], S. Miyazawa[1], S. Momota[9], Y. Morita[6], D. Nagae[5], Y. Nakamura[3], K. Namihira[1], R. Nishikiori[5], I. Nishizuka[1], T. Niwa[5], M. Ogura[3], Y. Ohkuma[3], T. Ohtsubo[3], S. Okada[5], J. Ohno[6], A. Ozawa[5], Y. Saito[5], T. Sakai[3], S. Sato[7], D. Sera[3], F. Suzaki[1], S. Suzuki[1], S. Suzuki[3], T. Suzuki[1], M. Taguchi[2], H. Uenishi[6], M. Wakabayashi[6], D. Watanabe[2], M. Yaguchi[6], S. Yasumoto[1], and T. Yamaguchi[1,a]

[1] *Department of Physics, Saitama University, Saitama 338-8570, Japan*
[2] *Department of Physics, Tokyo University of Science, Noda 278-8510, Japan*
[3] *Department of Physics, Niigata University, Niigata 950-2181, Japan*
[4] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[5] *Institute of Physics, University of Tsukuba, Ibaraki 305-8571, Japan*
[6] *Department of Physics, Osaka University, Toyonaka 560-0043, Japan*
[7] *National Institute of Radiological Sciences, Chiba 263-8555, Japan*
[8] *RI Center, Niigata University, Niigata 951-8510, Japan*
[9] *School of Environmental Science and Engineering, Kochi University of Technology, Kochi 782-8502, Japan*

**Abstract.** The question of whether charge-changing interactions can be used to probe point-proton radii of nuclei remains unanswered. Charge-changing cross sections, $\sigma_{cc}$, were systematically investigated using stable and unstable nuclear beams of intermediate-energy. The ratios of the experimental $\sigma_{cc}$ values to the calculated ones obtained from a phenomenological Glauber-type model analysis are found to be nearly constant in a broad range of $Z/N$ for light neutron-rich nuclei. This enables the determination of density distributions, i.e., the radii of protons tightly bound in nuclei. To test the applicability of the present method to all nuclei in the nuclear chart, extensive measurements were performed for medium-mass nuclei ranging from $Z = 18$ to 32. The present study suggests the potential capability of a new experimental approach for exploring exotic nuclei.

## 1 Nuclear radii – introduction

Charge radii are the basic ground-state properties of nuclides, reflecting a variety of structures of point-proton distributions in nuclei. Today, nuclear shell evolution far from the stability line is considered an intriguing and challenging topic in radioactive-isotope (RI) beam science. Protons and neutrons develop differently in a neutron-rich region, resulting in a large difference between the proton-distribution and neutron-distribution radii, also known as the neutron skin [1]. Such studies have so

[a] e-mail: yamaguti@phy.saitama-u.ac.jp

far been performed on the interaction ($\sigma_I$) and/or reaction ($\sigma_R$) cross sections using relativistic-energy RI beams, owing to the development of radioactive nuclear beam facilities worldwide. Nuclear matter radii have been determined through the Glauber model analysis of the measured cross sections, while charge radii have predominantly been obtained from precision isotope-shift measurements. The systematics of matter radii has led to, for example, the discovery of a typical neutron-halo nucleus $^{11}$Li [2] and a new magic number $N = 16$ in light neutron-rich nuclei [3]. Recent highlights of $\sigma_I$ measurements can be found in Ref. [4].

In order to experimentally determine the neutron skin of exotic nuclei, a new methodology to distinguish point-proton and neutron radii is required. Isotope-shift and electron-scattering experiments have so far provided the highest precision in charge radius measurements; however, they suffer from a certain limitation with regard to the luminosity of rare species close to the drip line. Since the charge-changing cross sections, $\sigma_{cc}$, of intermediate-energy heavy ions are sensitive to their proton distributions, the point-proton radii could feasibly be extracted [5], facilitating the fastest access to the drip line. Thus, point-proton radii are determined from $\sigma_{cc}$ measurements, whereas matter radii are determined from $\sigma_R$ measurements. Both measurements can be simultaneously performed in a single experiment, and the same theoretical framework, namely, the Glauber-type model analysis, can be reliably employed for both reaction channels.

## 2 Charge-changing cross sections – a new approach

To describe charge-changing cross sections using the Glauber-type approach, we modified the zero-range optical-limit Glauber model formula (see Ref. [5] in detail). Figures 1(a–f) show the applicability of the present method for stable nuclei with known charge radii. The experimental data for $^{12}$C, $^{20}$Ne, $^{27}$Al, $^{24}$Mg, $^{36,40}$Ar, and $^{56}$Fe on C were taken from Refs. [6–10], and the curves were calculated with the developed formula. The calculated cross sections are mostly greater than the experimental

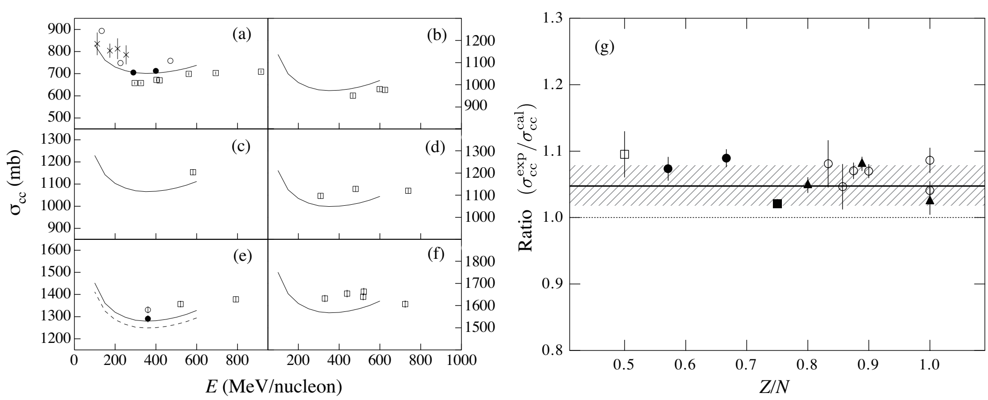


**Figure 1.** Left panel: Comparison of the calculated and experimental values of $\sigma_{cc}$ taken from [5]: (a) $^{12}$C on C (open squares [6], crosses [7], open circles [8], and solid circles [9]); (b) $^{20}$Ne on C [6]; (c) $^{27}$Al on C [6]; (d) $^{24}$Mg on C [6]; (e) $^{36}$Ar (solid circle [10]) and $^{40}$Ar (open circle [10] and open squares [6]) on C, where corresponding calculations are indicated by the dashed and solid curves, respectively; and (f) $^{56}$Fe on C [6]. Right panel: (g) The ratios of experimental to calculated values of $\sigma_{cc}$ as a function of $Z/N$ for stable and unstable light nuclei with known charge radii. The solid line and the shaded band show the results of the least-squares fitting of the experimental data and the corresponding standard deviations, respectively (taken from [11]).

$\sigma_{cc}$ obtained for $^{12}$C and $^{20}$Ne in the present energy range, but the calculations underestimate the data for $^{27}$Al, $^{24}$Mg, $^{36,40}$Ar, and $^{56}$Fe. A typical difference between the experimental and predicted $\sigma_{cc}$ values is ~4%.

To extend the present method to unstable nuclei, $\sigma_{cc}$ values of neutron-rich Be, C, and O isotopes on a carbon target were measured at 300 MeV/nucleon [11]. A series of experiments were carried out using the fragment separator at the Heavy Ion Medical Accelerator in Chiba (HIMAC) synchrotron facility at the National Institute of Radiological Sciences (NIRS) [12]. Since the charge radii of some of these unstable nuclei are precisely known already, the ratios of the experimental $\sigma_{cc}$ values to the calculated ones are obtained as a function of $Z/N$, as shown in Fig. 1(g) (see also Fig. 2 of Ref. [11]) in which the data measured at high energies are also included [13]. We find that the ratios are nearly constant, over a broad range of $Z/N$, with a standard deviation of ±3%, as shown by the shaded area in Fig. 1(g). The constant ratio suggests that the direct proton removal channel dominates the charge-changing process at intermediate energies. This fact enables the determination of the density distributions, i.e., the radii of protons bound in neutron-rich nuclei. A successful application is seen in $^{15,16}$C [11].

## 3 Towards medium-mass nuclei

As an extension of previous studies on light nuclei, we systematically measured $\sigma_{cc}$ of medium-mass nuclei on a carbon target at 300 MeV/nucleon. The measured nuclei ranged from $Z = 18$ to 32, and their partial charge-changing cross sections were also measured [14]. Figure 2 shows preliminary results for the measurements of the $\sigma_{cc}$ values of Ca, Ti, Cr, and Fe isotopes as a function of the neutron number $N$. For comparison, $\sigma_{cc}$ values of light neutron-rich nuclei, B, C, N, O, and F isotopes measured at approximately 1 GeV/nucleon are plotted as well [13].

In general, the charge-changing cross section is, by definition, sensitive to the $Z$ number of the projectile. Figure 2 clearly shows that the measured $\sigma_{cc}$ values increase with $Z$ but are less sensitive to $N$. The data stay constant within a relative variance of approximately ±5%. A careful observation of the variance of the present data reveals that the $\sigma_{cc}$ values often increase toward the neutron-deficient side. Here, it should be noted that the high-energy data lie in the neutron-rich unstable region, whereas the present data, some of which are even located at the neutron-deficient side, lie in the stable region. For such nuclei, there might be a correlation between the $\sigma_{cc}$ values and the proton separation energies, $S_p$, which monotonically decrease toward the neutron-deficient side.

Figure 3 shows correlations between the values of $\sigma_{cc}$ and $S_p$ for (a) Ca, Ti, (b) Cr, and Fe isotopes. The $\sigma_{cc}$ values of Ca and Ti isotopes mostly increase as $S_p$ decreases, as shown in Fig. 3(a), while $\sigma_{cc}$

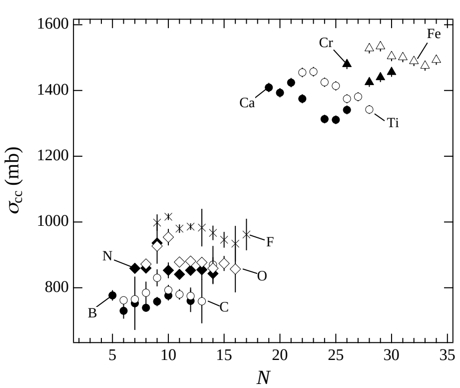


**Figure 2.** Preliminary results for the $\sigma_{cc}$ values of Ca (solid circles), Ti (open circles), Cr (solid triangles), and Fe (open triangles) isotopes as a function of $N$. The data for B, C, N, O, and F isotopes measured at high energies are taken from Ref. [13].

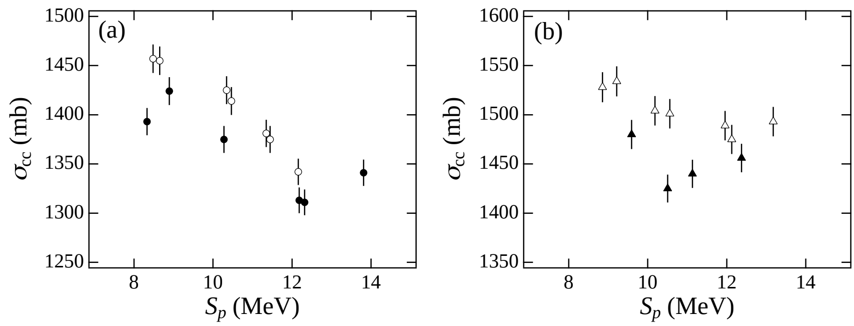


**Figure 3.** Correlations of preliminary $\sigma_{\rm cc}$ versus proton separation energy, $S_p$, for (a) Ca (solid circles), Ti (open circles), (b) Cr (solid triangles), and Fe isotopes (open triangles).

of Cr and Fe isotopes stay nearly constant as shown in Fig. 3(b). The present behavior in the stable and neutron-deficient region is apparently different from that in the light neutron-rich region. Using nuclei with known charge radii, the systematic behavior of the ratios of the experimental $\sigma_{\rm cc}$ values to the calculated ones should be carefully calibrated. The modified Glauber-type approach would then provide the point-proton radii of medium-mass unstable nuclei for which charge radii are yet to be determined. The results will be presented in a forthcoming publication.

## Acknowledgments

These experiments were supported by the Research Project with Heavy Ions at NIRS-HIMAC. The present study was partly supported by JSPS KAKENHI Grant Numbers 23600002 and 24244024.

## References

[1] T. Suzuki et al., Phys. Rev. Lett. **75**, 3241 (1995).
[2] I. Tanihata et al., Phys. Rev. Lett. **55**, 2676 (1985).
[3] A. Ozawa et al., Phys. Rev. Lett. **84**, 5493 (2000).
[4] M. Takechi et al., Phys. Lett. B **707**, 357 (2012).
[5] T. Yamaguchi et al., Phys. Rev. C **82**, 014609 (2010).
[6] W.R. Webber, J.C. Kish, and D.A. Schrier, Phys. Rev. C **41**, 520 (1990).
[7] A. N. Golovchenko et al., Phys. Rev. C **66**, 014609 (2002).
[8] I. Schall et al., Nucl. Instrum. Methods Phys. Res. B **117**, 221 (1996).
[9] C. Zeitlin at al., Phys. Rev. C **76**, 014911 (2007).
[10] G. Iancu, F. Flesch, and W. Heinrich, Radiat. Meas. **39**, 525 (2005).
[11] T. Yamaguchi et al., Phys. Rev. Lett. **107**, 032502 (2011).
[12] M. Kanazawa et al., Nucl. Phys. A **746**, 393c (2004).
[13] L.V. Chulkov et al., Nucl. Phys. A **674**, 330 (2000).
[14] S. Yamaki et al., Nucl. Instrum. Methods Phys. Res. B, (2013) in press. doi:10.1016/j.nimb.2013.05.057