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Development of a method to deduce point-proton radii from charge changing cross sections

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Charge changing cross sections (σ_{CC}) for $^{40-48}$K and $^{42-51}$Ca have been measured using BigRIPS at RIBF, RIKEN. The σ_{CC} obtained along the long isotopic chain of K and Ca revealed the fact that σ_{CC} have strong proton separation energy (S_p) dependence. The data are compared with the calculation based on the Glauber model and also with the proton evaporation model. It is found that the σ_{CC} data are well reproduced when the proton evaporation effect is taken into account.

KEYWORDS: charge changing cross section, point proton radii

1. Introduction

The nuclear charge radius is a fundamental property of atomic nucleus. Recent systematic studies of charge radii along the isotopic chain lead to the discovery of new phenomena reflecting the shell evolution in neutron-rich nuclei. The precise study of charge radii for Ca isotopes by Isotope-Shift (IS) measurements elucidated unexpectedly large enhancement of charge radii in Ca isotopes beyond the neutron number $N = 28$ [1]. The recent charge changing cross section (σ_{CC}) measurements allow one to study point-proton radii of light exotic nuclei which are rather difficult to be investigated by the IS measurement and to observe proton sub-shell closure in neutron-rich nuclei [2]. The extraction of point-proton radius from σ_{CC} is based on the extensive studies of the correlation between point-proton radii and σ_{CC} for the light nuclei and the modification of the Glauber model. In this work, we try to extend the applicability of this method to heavier mass region ($A > 40$). In order to study the correlation between point-proton radii and σ_{CC} for nuclei $A > 40$, we measured σ_{CC} for $^{40-48}$K, and $^{42-51}$Ca of which the charge radii are known from IS measurements [1, 3].

2. Experiment

Experiments were performed at RIBF operated by RIKEN Nishina Center and Center for Nuclear study, University of Tokyo. Secondary beams of K and Ca isotopes were produced with a 345 MeV/nucleon ^{238}U primary beam bombarding a rotating beryllium production target installed at the F0 focal plane of the BigRIPS superconducting fragment separator [4]. The transmission method was employed to measure σ_{CC}. In the transmission method, σ_{CC} is obtained from the relation $\sigma_{CC} = -\frac{1}{t}\ln(\frac{\Gamma}{\Gamma_0})$. The Γ is the ratio of the number of non-charge-changing outgoing particles to the number of incoming particles, Γ_0 is the same ratio for an empty-target measurement to correct for nuclear reactions in the detectors, and t denotes the thickness of the reaction target. The schematic view of the BigRIPS beam line and the experimental setup is shown in Fig.1. A wedge-shaped natural carbon target was set at the F5 momentum dispersive focal plane as a reaction target. The target thickness is 1.803(3) g/cm^2 at the center and the wedge angle is 9.61 mrad. Incoming particles were pre-separated and identified using the beam line between the F3 and F5 focal planes with $B\rho - \Delta E - TOF$ method [5]. TOF (Time Of Flight) and the $B\rho$ (magnetic rigidity) of the particles were determined by the timing and position information from plastic scintillation counters at F3, and F5. For the measurements of ΔE (energy loss of the particles), the ion chamber located at F3 was used. The atomic number of outgoing particles was identified using ion chambers set at the F5 and F7 focal planes.

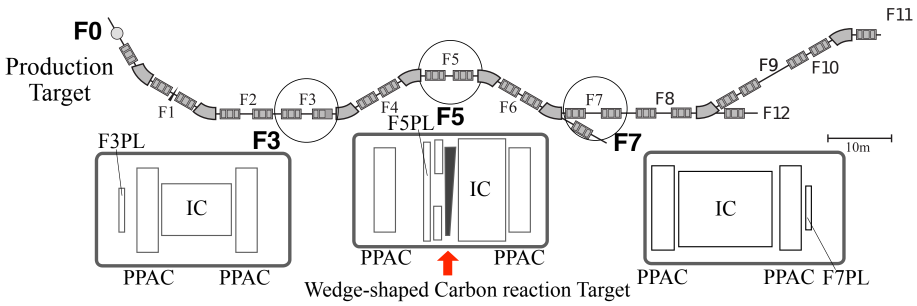

Fig. 1. The schematic view of the experimental setup based on the BigRIPS fragment separator.

3. Results

Preliminary results of σ_{CC} for K and Ca isotopes are plotted as a function of mass number in Fig.2 (a) and (b). In Fig.2 (c), existing σ_{CC} data for Ti and Cr isotopes [6] are also plotted. It can be clearly seen that the σ_{CC} decreases as the neutron number increases. The results of calculations using Glauber model are shown with dashed lines. Here, we performed the zero-range optical-limit Glauber-type calculations [7] without correcting factor. The point proton density distributions of nuclei are assumed to be the two-parameter Fermi distributions. The half-density radius and diffuseness of the densities are determined to reproduce the experimental charge radii [1, 3, 8], and the central densities of those isotopes estimated from the available electron scattering data [9, 10]. It can be seen that the Glauber calculations agree with the data at neutron-rich region and underestimate the data at around $N = Z$ region.

In Fig.2(d), the ratio of σ_{CC} data for K, Ca, Ti, and Cr isotopes to the Glauber calculations are shown as a function of proton separation energies S_p. It is shown that the ratios are close to

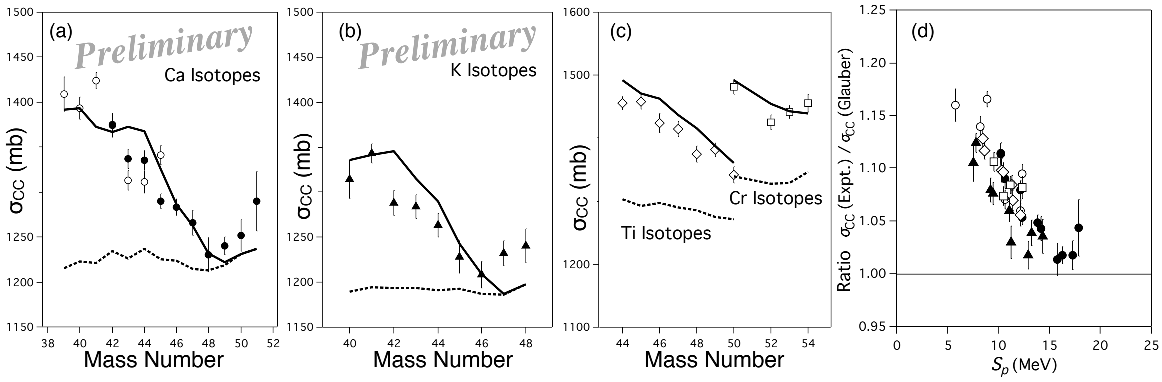

Fig. 2. (a),(b),(c); The preliminary results for $\sigma_{\rm CC}$ data for Ca (solid circles) and K (solid triangles) and existing data for Ca (open circles), Ti (open diamonds), and Cr (open squares) are plotted as a function of mass number. The zero-range optical-limit Glauber-type calculations are shown with dashed lines and the calculations which take into account the proton evaporation effect are shown with solid lines (See also text for the details.). (d); The ratios of those data to the Glauber calculations are plotted as a function of S_p.

the unity in the higher S_p region. It seems that the Glauber model better reproduces the data for nuclei in which protons are well bound. At the lower S_p region, the Glauber model considerably underestimates the data. It is interesting that the Glauber model, which calculates only direct process of charge-changing reaction where protons are directly scattered out by target nucleons, can reproduce the data for proton-well-bound nuclei but not the data for nuclei with low S_p. The indirect charge-changing process may contribute more significantly to the reaction of nuclei with low S_p. Using the proton evaporation model [11], we calculated the $\sigma_{\rm CC}$ through the indirect charge-changing process, where the abrasion of neutrons occurs first and then protons evaporate from the excited residual prefragment. Proton evaporation cross sections after the neutron abrasion from the projectile can be described $\sigma_{\rm ev} = \sum_{a=1}^{N} \int dE\ \sigma_{-an} w_a(E)$, where N is the neutron number of projectile, σ_{-an} is a neutron removal cross sections and $w_a(E)$ is the probability distribution to obtain the excitation energy E by removal of a nucleons. σ_{-an} are determined using EPAX3 [12] and normalized so that the total neutron removal cross section is equal to the difference of total reaction cross section and $\sigma_{\rm CC}$ values. $w_a(E)$ is calculated following the distribution given by the Gaimard - Schmidt formula [13] and the proton evaporation is assumed to occur only when the excitation energy of the prefragment exceeds the S_p. The E_{max} parameter in the Gaimard - Schmidt formula should be related to the potential depth of the projectile nucleus and here we assume that $E_{max} = S_{4n}(\alpha + \beta\frac{N-Z}{A})$, where S_{4n} is the experimental 4 neutron separation energy of the projectile and α and β were determined to reproduce the data of ^{40}Ca and ^{48}Ca. The calculation results are shown in Fig.2 with solid lines. The $\sigma_{\rm CC}$ data are well reproduced by considering the proton evaporation process. Further study of this model and the applicability to other nuclei is undergoing.

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