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MEASUREMENT OF INTERACTION CROSS-SECTIONS FOR NEUTRON-RICH Na ISOTOPES*

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The interaction cross-sections ($\sigma_{\rm I}$) of neutron-rich Na isotopes, $^{23-35}$Na, on C target have been measured at $250A$ MeV using the RI beam factory (RIBF) at RIKEN. Mass dependence of $\sigma_{\rm I}$ for $^{27-35}$Na suggests monotonic growth of the skin thickness. The root-mean-square nuclear matter radii ($\tilde{r}_{\rm m}$) of $^{23-35}$Na were deduced from observed $\sigma_{\rm I}$ via a Glauber-type calculation. These $\tilde{r}_{\rm m}$ are in a good agreement with the theoretical prediction by relativistic mean field model (RMF). $\tilde{r}_{\rm m}$ of $^{33-35}$Na were determined for the first time.

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1. Introduction

Since the middle of the 1980s, nuclear radii of exotic nuclei have been studied via measurements of interaction cross-sections (σ_I) at relativistic energies [1]. Measurements of σ_I allow us to determine root-mean-square nuclear matter radii ($\tilde{r}_\mathrm{m}$) for unstable nuclei via Glauber-type calculation. From these measurements, unusual nuclear structures, such as skin and halo structures, have been found and discussed. Particularly on Na isotopes, their σ_I were measured at GSI up to mass number $A = 32$, and the existence of neutron skin structure was found [2]. However, above $A = 32$ near the drip-line, no measurement of σ_I had been done so far due to their low production rate. The combination of superconducting ring cyclotron (SRC) and superconducting fragment separator (BigRIPS) in the RI beam factory (RIBF) at RIKEN has now opened to access such drip-line nuclei [3, 4]. In this work, we have measured σ_I of Na isotopes, $^{23-35}$Na at 250A MeV at RIBF and determined $\tilde{r}_\mathrm{m}$ of these nuclei.

2. Experimental details

Measurements were performed at BigRIPS beam-line in the RIBF, operated by the RIKEN Nishina Center and the Center for Nuclear Study, University of Tokyo. The interaction cross-section σ_I was experimentally determined by the transmission method. The cross-section is described as $\sigma_\mathrm{I} = -\frac{1}{t}\ln(\frac{R}{R_0})$, where t denotes the number of nuclei per unit area in the reaction target. R is the ratio of number of non-interacting outgoing particles and that of the incoming particles, and R_0 is the same ratio on a measurement without a reaction target to account for the effect of nuclear reactions in the detectors. Fig. 1 shows the experimental setup. Secondary beams of $^{23-35}$Na were produced via projectile fragmentation. A primary beam of 345A MeV ^{48}Ca with a typical intensity of 100 pnA was used. Produced fragments were pre-separated at the 1st stage of BigRIPS. The Al wedge-shaped degrader was placed at the first focal plane (F1). Carbon reaction targets of 3.60 and 1.80 g/cm^2 thickness were used to measure σ_I of $^{30-35}$Na and $^{23-29}$Na, respectively. They were located at the intermediate focal plane of BigRIPS (F5). The 1st and 2nd stages of BigRIPS were used to separate and identify the incoming and outgoing particles, respectively. Particles were identified by $B\rho$–ΔE–TOF method using ion chambers and plastic scintillation counters. The parallel plate avalanche counters (PPACs) located at F3 were used to observe the beam position and angle, which were used to apply an appropriate emittance-cut for the incoming secondary beams to count accurately all the non-interacting particles without missing them after the reaction target.

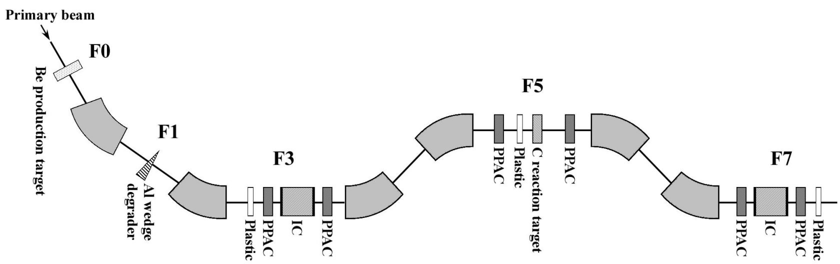

Fig. 1. Schematic view of the experimental setup for $\sigma_{\rm I}$ measurements at BigRIPS.

3. Experimental results

In Fig. 2(a) preliminary interaction cross-sections $\sigma_{\rm I}$ measured at $250A$ MeV are plotted as a function of the mass number of Na isotopes. Previous results measured at $950A$ MeV are also plotted in the figure. They are scaled with the help of Glauber-type calculations, described later, which account for the incident-energy dependence of $\sigma_{\rm I}$. The dotted line in the figure shows simple mass dependence of $\sigma_{\rm I}$ calculated by the equation $\sigma_{\rm I} = \pi[R_{\rm I}({\rm C}) + r_0 A^{1/3}]^2$, where $R_{\rm I}({\rm C})$ is the interaction radius of ^{12}C and r_0 is determined so as to reproduce the $\sigma_{\rm I}$ of ^{23}Na measured at $250A$MeV. As shown in Fig. 2(a) present results are consistent with previous ones within the errors. The data deviate from the dotted line more significantly at larger mass numbers, suggesting monotonic growth of the neutron-skin thickness.

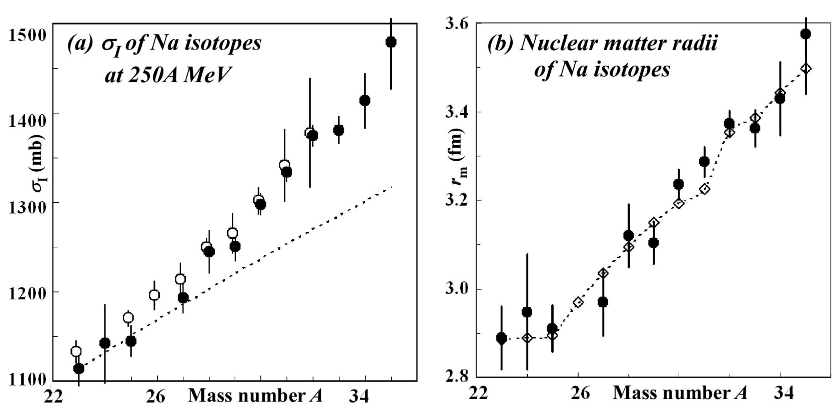

Fig. 2. (a) Preliminary results of $\sigma_{\rm I}$ of $^{23-35}$Na. Solid symbols indicate the present results, open symbols are the scaled ones from the previous measurement at GSI, and the dotted line shows the $\sigma_{\rm I}$ calculated by $\sigma_{\rm I} = \pi[R_{\rm I}({\rm C}) + r_0 A^{1/3}]^2$. (b) Results of Glauber analysis for $^{23-35}$Na. Solid circles indicate $\tilde{r}_{\rm m}$ deduced from observed $\sigma_{\rm I}$, open rhombi show the predictions from RMF. The lines connect the open rhombi.

4. Glauber analysis

We deduced the nuclear matter radii $\tilde{r}_{\rm m}$ from the measured $\sigma_{\rm I}$ using the Glauber calculation. We employed the finite-range modified optical-limit calculation taking into account the Fermi-motion effect [5], which agrees well with experimental total reaction cross-section ($\sigma_{\rm R}$) for ^{12}C on C target at 250A MeV. We assumed that $\sigma_{\rm I}$ is nearly equal to $\sigma_{\rm R}$. As for the density distribution of the target, we used the harmonic oscillator function, which reproduces $\sigma_{\rm R}$ of ^{12}C+^{12}C [5]. We assumed that projectile density distribution is Fermi-type for both protons and neutrons. Namely, the density $\rho_{\rm m}(r)$ at a distance r is given by $\rho_{\rm m}(r) = \rho_{\rm m}(0)/\left[1+\exp\{(r-R_{\rm m})/d_{\rm m}\}\right]$, where $R_{\rm m}$ and $d_{\rm m}$ denote the half-density radius and the surface diffuseness, respectively. We used fixed diffuseness parameter $d_{\rm m} = 0.564$ fm which agrees with nuclear charge radius ($\tilde{r}_{\rm c}$) of ^{23}Na from elastic electron scattering [6]. We determined $R_{\rm m}$ so as to reproduce observed $\sigma_{\rm I}$. Once the distribution has been determined, root-mean-square nuclear matter radius $\tilde{r}_{\rm m}$ is calculated by the equation $\tilde{r}_{\rm m} = \left\langle r_{\rm m}^2\right\rangle^{1/2} = \left[\int r^2\rho_{\rm m}(r)d\vec{r}/\int \rho_{\rm m}(r)d\vec{r}\right]^{1/2}$. In Fig. 2(b) $\tilde{r}_{\rm m}$ of Na isotopes are plotted as a function of its mass number. Present results agree with the prediction of the calculation, based on the RMF model [7].

5. Summary

The interaction cross-sections for $^{23-35}$Na on C have been measured at 250A MeV at the RIKEN RIBF. The root-mean-square nuclear-matter radius $\tilde{r}_{\rm m}$ was from measured $\sigma_{\rm I}$ for $^{23-35}$Na using Glauber-type calculation. A monotonic growth of skin thickness is indicated in the mass number range 27–35. A relativistic mean-field calculation reproduces well the extracted $\tilde{r}_{\rm m}$ values.

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