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Reaction Cross Section Of The Two-neutron Halo Nucleus ^{22}C At 235 MeV/nucleon

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The reaction cross section (σ_R) of the very neutron-rich carbon isotope ^{22}C has been measured on a carbon target at 235 MeV/nucleon. A σ_R of 1.280 ± 0.023 b was obtained for ^{22}C, significantly larger than those for the neighboring isotopes, supporting the halo character of ^{22}C. A ^{22}C root-mean-squared matter radius of 3.44 ± 0.08 fm was deduced using a four-body Glauber reaction model. This value is smaller than an earlier estimate of 5.4 ± 0.9 fm derived from a σ_R measurement on a hydrogen target at 40 MeV/nucleon.

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1. Introduction

The nuclear halo is a characteristic structure of nuclei far from stability, which is a dilute matter distribution extending far beyond the core of the nucleus [1]. Borromean two-neutron halo systems, such as ^{11}Li, are of particular interest for the study of many-body effects, such as possible strong neutron-neutron (*nn*) correlations [2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

Recently, the most neutron-rich carbon isotope ^{22}C (two-neutron separation energy $S_{2n} = -0.14 \pm 0.46$ MeV [12]) has been paid sizable attention, due to a possible extended two-neutron halo structure - as suggested by a large root-mean-squared (rms) matter radius $\tilde{r}_m$ of 5.4 ± 0.9 fm deduced from the large reaction cross section ($\sigma_R = 1.338 \pm 0.274$ b) measured on a proton target at 40 MeV/nucleon [13]. This value is significantly larger than those for well-known halo nuclei such as ^{11}Li. The nucleus ^{22}C is also significant in terms of the shell closure at $N = 16$, as was recently established for ^{24}O [14, 15]. Importantly, if the $N = 16$ shell closure in ^{22}C is confirmed, the two-neutron valence configuration would be $[2s_{1/2}]^2$. Experimentally, evidence for $N = 16$ closure has been found by using the neutron removal reaction on ^{22}C [16].

The large uncertainties on the earlier measurement of σ_R and the deduced $\tilde{r}_m$ [13] do not constrain the theoretical models. A mean-field model, using an adjusted Skyrme interaction, predicted $\tilde{r}_m = 3.89$ fm [17]. Three-body model calculations for ^{22}C, with dominant $[2s_{1/2}]^2$ valence neutron configurations [18, 19], derive $\tilde{r}_m$ in the range 3.50-3.70 fm. Due to the increased mass of ^{22}C and the resulting smaller fractional contribution of the two valence nucleons to $\tilde{r}_m$, all three-body model calculations [18, 19, 20, 21] require extremely weak two-valence-neutron binding to produce an enhanced $\tilde{r}_m$. Given the significant error on the experimental estimate of Ref. [13] and that the theoretical values are within $\sim 2\sigma$ of this value, more definitive conclusions require data of significantly higher precision.

In this spirit, the present paper reports a precise ^{22}C reaction cross section (σ_R) measurement on a carbon target at 235 MeV/nucleon. A more detailed description on the ^{22}C σ_R can be found in Ref. [22]. At this energy, unlike the earlier 40 MeV/nucleon proton target measurement, the assumed forward scattering dominance of the core and valence particles, that underpins the Glauber (eikonal) model description, is well satisfied. In addition, it has been shown that the optical limit (OL) approximation to Glauber theory provides an excellent description of the (reasonably well-bound) core-target systems without the need to consider additional corrections [23, 24] - a result of the highly absorptive nature of the core-target interactions in the case of a carbon target.

2. Experiment

The experiment was performed at the Radioactive Isotope Beam Factory (RIBF) accelerator complex operated by the RIKEN Nishina Center and Center for Nuclear Study, University of Tokyo. A beam of ^{22}C was produced via projectile fragmentation of a 345 MeV/nucleon ^{48}Ca beam from the Superconducting Ring Cyclotron incident on a 20 mm thick Be target. The ^{22}C fragments were separated using BigRIPS [25]. The momentum acceptance was set to be $\pm 3\%$. The secondary beams were identified event-by-event by measuring the time-of-flight (TOF), magnetic rigidity ($B\rho$), and energy loss (ΔE) with plastic scintillators, a multi-wire proportional counter, and an ionization chamber located at the focal planes of BigRIPS. The ^{22}C beam was transported to

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SAMURAI [26], and impinged on a carbon target with a thickness of 1.789 g/cm^2. ^{19,20}C were also transported to SAMURAI as contaminants of ^{22}C beams. The mean energies of the ^{22}C beams at the middle of the target were 235 MeV/nucleon.

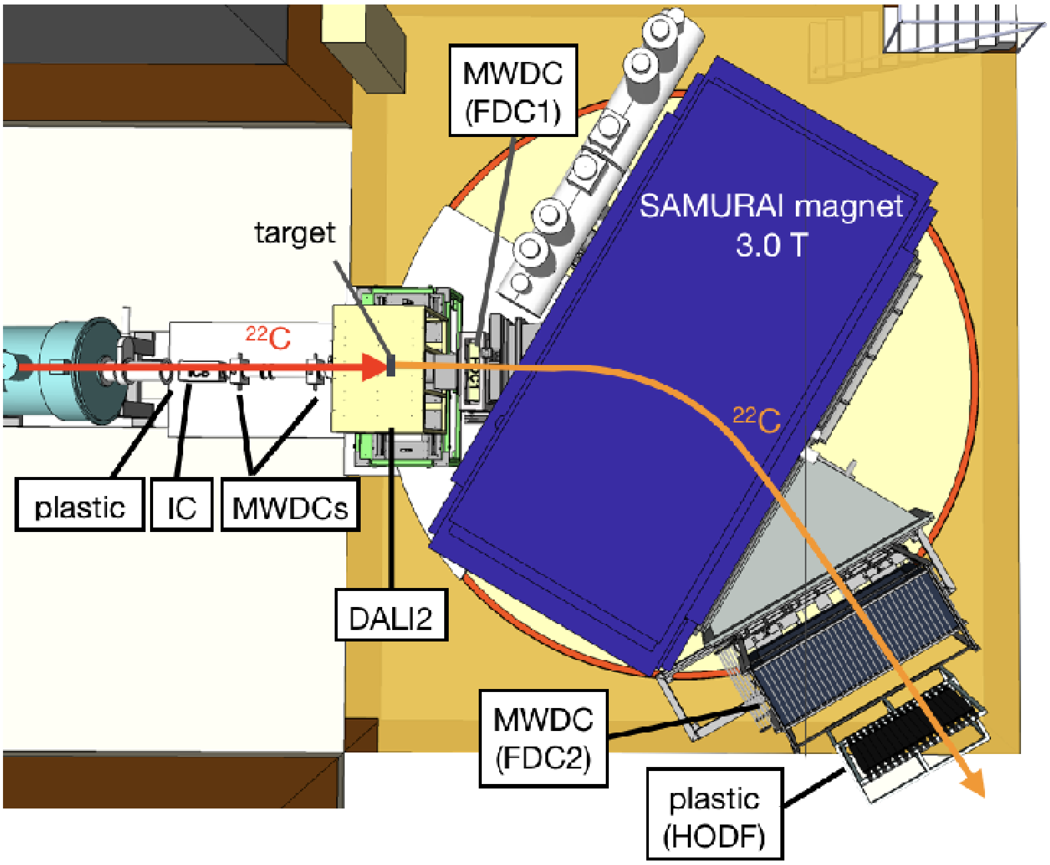

Figure 1: Schematic view of the experimental setup of SAMURAI.

The schematic view of the experimental setup at SAMURAI is shown in Fig. 1. The incoming beams were detected by a plastic scintillator and ionization chamber located upstream of the target. The incident angle and the position on the target were monitored by using two MWDCs just before the target. The target was surrounded by the DALI2 array [27] to detect de-excitation γ rays from excited outgoing fragments, which were used to estimate the inelastic cross section to bound excited states in target and projectile, as shown elsewhere [22].

The residues from the ^{22}C + C reactions were identified using detectors located at the entrance and exit of the SAMURAI magnet - the detailed detector setup can be found in Ref. [26]. The $B\rho$ values of the charged particles were reconstructed using the positions and angles at two multi-wire drift chambers FDC1 and FDC2 [26]. The TOF was obtained from the plastic scintillator hodoscope HODF located downstream of FDC2 with respect to the plastic scintillator upstream of the target. The ΔE measured using FDC1 was also employed for the identification.

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3. Results and discussions

The reaction cross section σ_R is related to the interaction cross section σ_I as,

$$\sigma_R = \sigma_I + \sigma_{inel}, \tag{3.1}$$

where σ_{inel} corresponds to the inelastic cross section to the bound excited states of projectile and target. Since σ_{inel} is small relative to σ_I at the present beam energy, as is shown in elsewhere [22], the σ_I is regarded as σ_R in the following discussions. The σ_R were derived using the transmission method [28], where σ_R can be written as,

$$\sigma_R = -\frac{1}{N_t}\log\left(\frac{\Gamma}{\Gamma_0}\right). \tag{3.2}$$

Here, N_t is the number of target nuclei per unit area, while Γ is the ratio of the number of non-interacting outgoing particles to the number of incoming particles. Γ_0 corresponds to Γ for an empty target, to take into account reactions in the detectors.

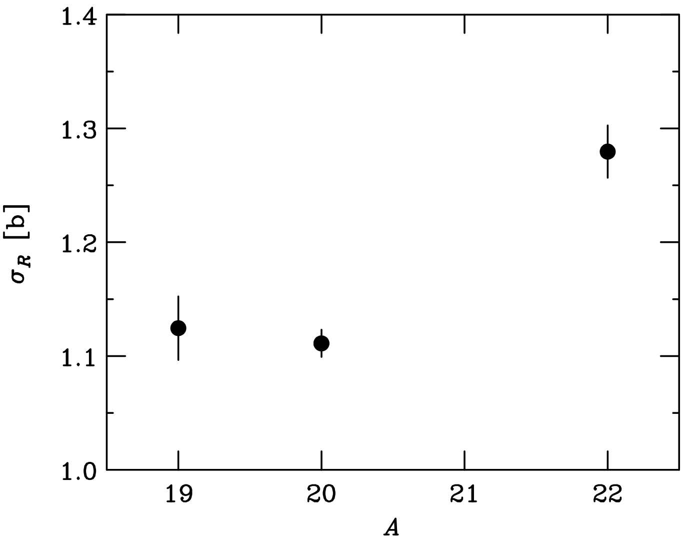

Figure 2: Mass number dependence of the reaction cross section for the carbon isotopes obtained in the present study.

Figure 2 shows the measured σ_R of the carbon isotopes in the present study. The σ_R values of ^{19,20}C were extracted by using the ^{19,20}C beams mixed in the main ^{22}C beam. As seen from Fig. 2, the σ_R value for ^{22}C is enhanced relative to those of ^{19,20}C, consistent with a two-neutron halo character of ^{22}C.

For the ^{22}C + C system, a four-body (three-body projectile plus target) Glauber reaction model analysis [29, 30], previously applied to ^{22}C, is employed. Full details of the physical inputs and the construction of the three-body model ^{22}C ground-state wave functions can be found in Ref. [19]. In these calculations [19], the additional pair of valence neutrons in ^{22}C are found to occupy the $2s_{1/2}$ orbital, with minimal $1d_{3/2}$ orbital occupancy. In this case, the ^{20}C core has a filled $1d_{5/2}$ sub-shell. With the $1d_{5/2}$ orbital bound by $S_n(^{20}\text{C}) = 2.93$ MeV, the ^{20}C core rms radius is then

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2.89 fm from a Hartree-Fock calculation with the SkX interaction [31]. This value is used when computing $\tilde{r}_m$ of ^{22}C.

Solutions of the ^{22}C three-body wave functions use the Gogny, Pires and De Tourreil (GPT) *nn* interaction. The n-^{20}C interactions are described by Woods-Saxon potentials with a spin-orbit term. The parameters of these potentials in the $2s_{1/2}$ and $1d_{5/2,3/2}$ orbitals can be found in Ref. [19]. To provide a family of ^{22}C three-body wave functions with different ground-state eigenstates (i.e. binding energies E_{3B} $(= -S_{2n})$) and hence different sizes (rms hyperradii) we use a family of three-body Hamiltonians. These Hamiltonians differ in the choice of (i) the (unbound) $2s_{1/2}$ state potential depth (and their s-wave n-^{20}C scattering length) and (ii) the strength V_{3B} of an added attractive central hyperradial three-body force, $V_{3B}(\rho) = -V_{3B}/(1+[\rho/5]^3)$, where ρ is the hyperradius. Having fixed the Hamiltonian by choosing the above interaction strengths, the three-body wave function, its $\tilde{r}_m$, and $S_{2n}(^{22}\mathrm{C})$ are determined from the lowest eigenstate of the eigenvalue problem.

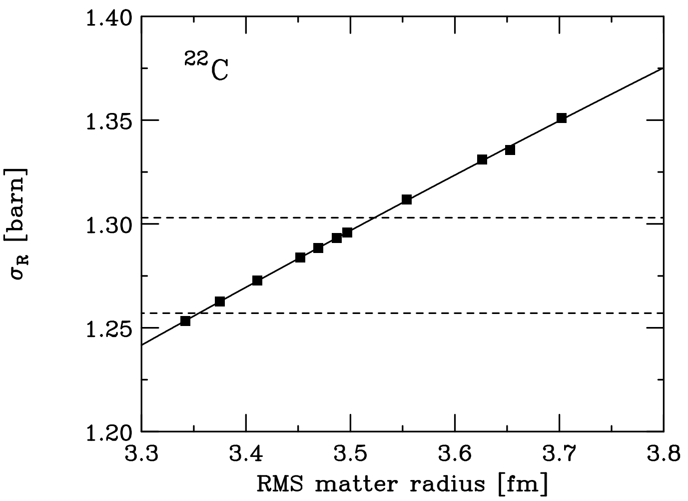

Figure 3: RMS matter radius dependence of the reaction cross section calculated by the four body Glauber model. The dashed lines represent the range of 1σ error of the present experiment.

The filled squares in Fig. 3 show the dependence of the four-body Glauber calculations of σ_R on the $\tilde{r}_m$ of the calculated three-body ground-state wave functions. All of the wave functions have dominant $(92-94\%)$ $[2s_{1/2}]^2$ and smaller $(2-4\%)$ $[1d_{3/2}]^2$ two-neutron configurations. The solid curve through the calculated results is a second order polynomial fit while the dashed horizontal lines correspond to the 1σ error on σ_R from the present experiment. From the model calculations of the figure we can estimate $\tilde{r}_m$ from the present data of 3.44 ± 0.08 fm.

Consistent with our earlier discussion, this deduced $\tilde{r}_m$ from the present few-body-model analysis is smaller, by about 2σ, than the previously reported value (5.4 ± 0.9 fm [13]) with its large uncertainty. As was noted earlier, the present higher precision and more absorptive and surface dominated higher beam energy measurement on a nuclear (carbon) target, places the underpinning Glauber (eikonal) dynamical model description of the reaction used here on a much stronger footing regarding the magnitudes of multiple-scattering and other corrections [23, 24].

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Our deduced $\tilde{r}_m$ is also in agreement with values: (i) ranging from 3.6–3.75 fm for S_{2n} values between 400-600 keV, of the three-body model calculation of Ref. [18], and (ii) $\tilde{r}_m = 3.4$ and 3.6 fm, with S_{2n} of 400 and 200 keV, of Ref. [20]. These models, like the present one, calculate an *s*-wave configuration of the two valence neutrons with probability $\geq 90\%$, in line with a picture in which the $N = 16$ magicity persists at ^{22}C – as suggested by other more fundamental approaches [32, 33]. However, the reaction cross section alone is somewhat insensitive to details of the microscopic structure and more precise, more exclusive reaction experiments and mass measurements are required.

4. Summary

In summary, we have measured the reaction cross sections of ^{22}C on a C target at 235 MeV/nucleon. The ^{22}C reaction cross section was found to be much larger than that of ^{20}C, supporting the two neutron halo nature of ^{22}C. The deduced ^{22}C rms matter radius, 3.44 ± 0.08 fm, from the four-body Glauber reaction model analysis, is consistent with other theoretical predictions based on ^{22}C three-body model wave functions [18, 20]. The present rms radius is smaller and has a much reduced uncertainty than that of Ref. [13]. More exclusive measurements, such as Coulomb dissociation and fast neutron-knockout reactions, will allow for a more detailed study of the structure of ^{22}C, including the potential role of core excitations on the $N = 16$ magicity [34, 35].

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