Article

A new approach for deducing rms proton radii from charge-changing reactions of neutron-rich nuclei and the reaction-target dependence

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ABSTRACT

We report the charge-changing cross sections (σ_{cc}) of 24 p-shell nuclides on both hydrogen and carbon at about 900A MeV, of which ^{8,9}Li, $^{10-12}$Be, ^{10,14,15}B, $^{14,15,17-22}$N and ^{16}O on hydrogen and ^{8,9}Li on carbon are for the first time. Benefiting from the data set, we found a new and robust relationship between the scaling factor of the Glauber model calculations and the separation energies of the nuclei of interest on both targets. This allows us to deduce proton radii (R_p) for the first time from the cross sections on hydrogen. Nearly identical R_p values are deduced from both target data for the neutron-rich carbon isotopes; however, the R_p from the hydrogen target is systematically smaller in the neutron-rich nitrogen isotopes. This calls for further experimental and theoretical investigations.

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1. Introduction

Uncovering how protons and neutrons distribute in atomic nuclei is one of the keys to understanding the strong force that binds nucleons together, the nature of new phenomena occurring in exotic nuclei, and the equation of state (EOS) of nuclear matter that determines the properties of astronomical objects. Two of the most quoted static properties for nuclear extension in space are the root-mean-square (rms) point-matter radius (R_m) and rms point-proton radii (R_p), reflecting the distribution of nucleons and protons in space, respectively. Methods using the electroweak probe *via.*, e.g., electron scattering and isotopic shift, and the hadronic probe *via.*, e.g., proton elastic scattering, interaction or charge-changing reactions, have been developed to determine the nuclear size [1–4]. In the last decades, the advancement of radioactive ion beams allows studying nuclear reactions in inverse kinematics involving short-lived nuclei with good precision. This makes the hadronic probe increasingly important to study nuclear sizes up to the most exotic nuclei.

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Nuclear collisions at hundreds to thousands of MeV/nucleon represent a major application scenario for hadronic probes. Precise measurements of interaction, charge-changing, and neutron-removal cross sections, especially for the very short-lived and weak-intensity nuclides close to the neutron drip line, have contributed significantly to our understanding of halo nuclei [5], neutron skin [6–8], shell structure [9–11], and the EOS of nuclear matter [12,13]. In particular, the proton radii (or charge radii) of a significant fraction of these exotic nuclides cannot be determined by electron scattering and isotope shift due to the inherent limitations of these methods.

In contrast to the electroweak probe, where the electroweak interaction is accurately known, the hadronic probe, however, may suffer from uncertainties due to the complex nature of strong nuclear force, which affects both the structure of collided nuclei and the reaction dynamics. The Glauber model, which describes the charge-changing reaction by considering the interactions of protons of the projectile nuclide with protons and neutrons of the target nuclide, has been used to deduce the rms proton radius of the projectile nuclide from the charge-changing cross section. In this approach, one often needs to introduce a sort of normalization to reproduce the cross sections of stable nuclei on the relevant target since the calculations are systematically smaller than the experimental data [7,14–16]. The reason behind this is not clear yet, but possible mechanisms have been proposed, including the proton evaporation (PE) process after neutron(s) removal [17,18] and the "p–n exchange" [19]. Moreover, the data on carbon and hydrogen targets may require different considerations [20,21]. Therefore, determining the fact responsible for the systematic difference between the experimental data and Glauber model interpretation is crucial for computing the proton radius of nuclides, especially exotic ones.

In the present paper, we report the charge-changing cross sections of 24 p-shell nuclei from Li to O isotopes at about 900A MeV on carbon ($\sigma_{cc,C}$) and hydrogen targets ($\sigma_{cc,H}$) together, where ^{8,9}Li, $^{10-12}$Be, ^{10,14,15}B, $^{14,15,17-22}$N and ^{16}O on hydrogen and ^{8,9}Li on carbon target are reported for the first time. Other data have been published already in Refs. [7,10,11,19,22,23] but we reanalyzed independently here. A novel systematic behavior of the scaling factors that include isotope dependence is presented. Proton radii determined with the new method at both two targets are presented together with matter radii.

2. Experiment and result

The experiment was performed with the fragment separator FRS at GSI [24], Germany. The isotopes of interest were produced by fragmentation of 1A GeV ^{22}Ne and ^{40}Ar ions in a 6.3 g/cm^2 Be target, then separated and identified in flight on the event-by-event basis by the magnetic rigidity ($B\rho$), time of flight (TOF), and energy loss (ΔE) measurements. The σ_{cc} measurements were carried out with the transmission method on a 4.01 g/cm^2 carbon target and a 3.375 g/cm^2 polyethylene target. The cross sections on hydrogen were derived by subtracting the cross section on the C target from those for the polyethylene target. The method of extracting cross sections is described in the previous paper [10]. One important difference of the cross section treatment has to be noted. A veto counter with a central square was placed just in front of the reaction target primarily to remove multi-hit and scattered light particles from upstream. With the C target data, the cross sections deduced using the veto information are systematically smaller than those without by about 6%, but this induces a minor effect in the extraction of the published R_p value [7]. Moreover, the relevant cross sections on the H target do not change with the veto information. This effect occurs because the veto likely detects some

light particle events from the back-scattering of the target fragmentation, and simulations validate this impact. We use here the cross section data without considering the veto.

Newly determined cross sections in the H target are shown in Table 1 together with some related quantities. To extract R_p from σ_{cc}, we apply the zero-range optical-limit approximation (ZROLA) Glauber model. It employs the Eikonal approximation, which is valid in the experimental energy domain and is able to accurately represent the interaction cross sections [2]. In this approach, only the collisions of the projectile protons with the target nuclide contribute to σ_{cc}, while the projectile neutrons are treated as spectators. The only inputs to the model are the known nucleon-nucleon (NN) cross sections, the proton density distribution of projectile nuclide, and the proton and neutron density of target nuclide. We also performed the finite-range (FROLA) model [25,26] and eventually achieved the identical radius results. This indicates that our approach is robust and independent of both models.

3. New approach for deducing rms proton radii

We computed σ_{cc}^{calc} for ten nuclei (^{8,9}Li, ^{10,11}Be, ^{10}B, ^{12,14}C, ^{14,15}N, and ^{16}O) at 900A MeV on C and H targets with ZROLA. The ten nuclei have well-determined charge radii R_c [1], from which one can deduce R_p and the harmonic oscillator (HO) density distributions. The density in the Dirac delta form is utilized for the hydrogen target, while the HO density distribution is for the carbon target.

The ratios of the measured charge-changing cross sections to the ZROLA calculations are shown in Table 1. The ZROLA values at 900A MeV are systematically lower than our data on carbon by 10%–20% and than the hydrogen data by 20%–50%. Such underestimation in cross sections, which was also observed at 300A MeV [15–18,21], is considered to be due to the fact that the Glauber model only reflects the direct proton removal process of the projectile, $\sigma_{cc,Direct}$. In reality, there is a possibility that charged particle(s), mostly protons, can be emitted following the direct neutron removals, where the pre-fragment is highly excited. This process can contribute to the final σ_{cc}^{exp} [17,18], but is beyond the current reaction model.

To better account for the PE process following the projectile neutron removal, we introduce a new quantity, $S_1(_N^A Z) \equiv S_n(_N^A Z) + S_p(_{N-1}^{A-1} Z)$. $S_n(_N^A Z)$ is the neutron separation energy from the projectile nucleus, and the $S_p(_{N-1}^{A-1} Z)$ is the proton separation energy from the one-neutron removed nucleus. We sort the $\sigma_{cc}^{exp}/\sigma_{cc}^{calc}$ values of stable nuclei according to $S_1(_N^A Z)$ in Fig. 1. It is interesting to see that the ratios on each target show a linear dependence on $S_1(_N^A Z)$, except ^{10}Be. The linearly fitted lines for the hydrogen and carbon data are $f(\text{H}) = -0.0132(10)S_1 + 1.596(23)$ and $f(\text{C}) = -0.0047(8)S_1 + 1.209(16)$, respectively. The H target data are more sensitive on $S_1(_N^A Z)$ than the relevant C target data. Such correlation cannot be seen when plotting $\sigma_{cc}^{exp}/\sigma_{cc}^{calc}$ versus Z/N [15] or other parameters. Deviation of ^{10}Be from this line is easily understood because the neutron-removed nucleus ^{8}Be decays immediately into a pair of α particles after direct or cascade two neutron removal [22,27,28]. This will result in a sizable charge change but is not included in S_1. It should be noted, however, that there are rare nuclei with the α-evaporation probability after neutron removals, like ^{10}Be. In the dominant cases, the proton-evaporation process occurs after neutron removals in high-energy heavy-ion collisions.

The distinct correlation identified in Fig. 1 is the first evidence of the widespread presence of the PE process in charge-changing reactions. This demonstrates that it is a universal process, occurring not only in (near-) stable isotopes but also in neutron-rich iso-

Table 1
Separation energy S_1, secondary beam energies at the middle of the target, measured $\sigma_{cc,C}$, $\sigma_{cc,H}$ and the ratios of the measured CCCS to the ZROLA calculation.

| Isotope	S_1	E/A	$\sigma_{cc,C}^{exp}$	$\sigma_{cc,H}^{exp}$	$\sigma_{cc}^{exp}/\sigma_{cc}^{calc}$	
	(MeV)	(MeV)	(mb)	(mb)	Carbon	Hydrogen
^{8}Li	12.0	901	642(16)	149(14)	1.184(29)	1.418(133)
^{9}Li	16.5	958	608(14)	141(8)	1.151(27)	1.434(88)
^{10}Be	23.7	994	713(11)	206(10)	1.185(18)	1.596(77)
^{11}Be	20.1	928	713(15)	179(13)	1.147(24)	1.343(98)
^{12}Be	23.3	959	741(11)	186(7)		
^{10}B	8.2	930	784(10)	233(8)	1.190(15)	1.526(52)
^{14}B	16.8	990	751(14)	223(9)		
^{15}B	20.0	963	773(3)	206(2)		
^{12}C	27.4	928	764(5)	217(4)	1.080(7)	1.246(23)
^{14}C	25.7	991	797(9)	220(8)	1.111(13)	1.246(45)
^{15}C	22.0	893	791(3)	233(3)		
^{16}C	25.2	808	809(17)	231(16)		
^{17}C	23.2	962	800(9)	232(7)		
^{18}C	27.5	955	813(5)	226(4)		
^{19}C	26.6	880	807(8)	224(6)		
^{14}N	12.5	924	868(6)	280(5)	1.142(8)	1.421(25)
^{15}N	18.4	762	861(19)	277(30)	1.117(25)	1.395(151)
^{17}N	17.4	927	874(6)	269(6)		
^{18}N	15.9	848	869(14)	265(19)		
^{19}N	20.6	949	860(4)	256(4)		
^{20}N	18.5	877	866(3)	257(3)		
^{21}N	22.5	874	846(9)	245(9)		
^{22}N	20.9	882	858(15)	244(12)		
^{16}O	23.0	920	898(7)	284(7)	1.088(8)	1.269(31)
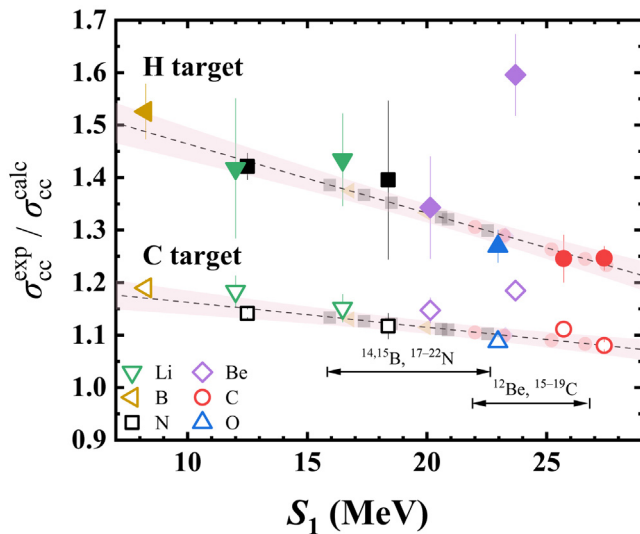
Fig. 1. (Color online) Ratios of experimental charge-changing cross sections to theoretical ones, $\sigma_{cc}^{exp}/\sigma_{cc}^{calc}$, as a function of the separation energy, S_1 for ten nuclei with well known R_p. The data on the H target and C target are indicated with filled and open marks, respectively. The dashed line and shaded band represent the best linear fit to the data but excluding ^{10}Be, and the 95% confidence interval. Indicated along the lines are also the positions of the remaining 14 neutron-rich isotopes by translucent symbols.

topes. Theoretical calculations of (p, pn) reactions suggest that decreasing separation energies S_n lead to increasing neutron removal cross sections [29–31]. S_n, the first term of S_1, thus is expected to be positively correlated with the one-neutron removal process, the leading part in the total neutron-removals. In addition, a larger $S_n(^A_N Z)$ may lead to a lower excitation energy for the pre-fragment $^{A-1}_{N-1}Z$ produced right after the one-neutron removal. As a result, it becomes less probable for the hot pre-fragment to de-excite via charged particles. When extended to the collision systems with different projectiles and beam energies, the orbital of

the removed neutron and the beam energy may also affect the excitation of pre-fragments. Protons are most favorable among charged particles to be emitted due to the Coulomb barrier, and their emission probability depends on the excitation energy and the proton emission threshold $S_p(^{A-1}_{N-1}Z)$, the second term of S_1. The observed trend in Fig. 1 shows consistent behavior with the PE process. One can further extend S_1 by including multiple-nucleon removal and evaporation processes, but we do not see significant improvement in the fit. This is mainly due to the cross sections for removing two or more neutrons being much smaller than those for one neutron [32] and the experimental uncertainties.

The well-defined correlation of $\sigma_{cc}^{exp}/\sigma_{cc}^{calc}$ with S_1 offers an empirical way to calibrate the model and deduce R_p for the 14 nuclides (^{12}Be, $^{14-15}$B, $^{15-19}$C, $^{17-22}$N), whose radii were not determined by the electroweak interaction probe. The important thing is that the systematic obtained by the R_p known nuclei spread in a wide range of S_1 so that the scaling value for the exotic nuclei can be obtained by the interpolation of the systematic, instead of the extrapolation. We incorporate this phenomenological scaling factor $f(S_1, \text{Targ})$ into the ZR Glauber model, where f is determined by the S_1 of the projectile and the type of target. This scaling factor introduces uncertainty by typically 1.3% and 2.4% for σ_{cc}^{calc} on C and H targets, respectively. The HO type proton density distribution and proton radius R_p of the projectile nucleus are determined when matching σ_{cc}^{calc} to σ_{cc}^{exp}. Once R_p is determined, we can calculate the neutron radius R_n as well as the matter radius R_m in a similar manner but by reproducing instead the interaction cross sections at similar beam energies (σ_I) [6].

We extracted the proton and matter radius of all nuclides from the C target (R_p^C, R_m^C) and the H target (R_p^H, R_m^H), where radii are extracted for the first time from H target. For $^{12,14-19}$C and $^{14,15,17-22}$N isotopes, the R_p^C and R_m^C agree well with the results of previous publications ($R_p^{C,Ref}$, $R_m^{C,Ref}$), within errors [7,10]. In Fig. 2, we compare the radii on the H target with those on the C target that have been published.

Fig. 2a displays the rms matter and the proton radii of carbon isotopes determined by the C target and H target. Excellent agreement is seen for both R_p and R_m. Fig. 2b shows the radii of nitrogen
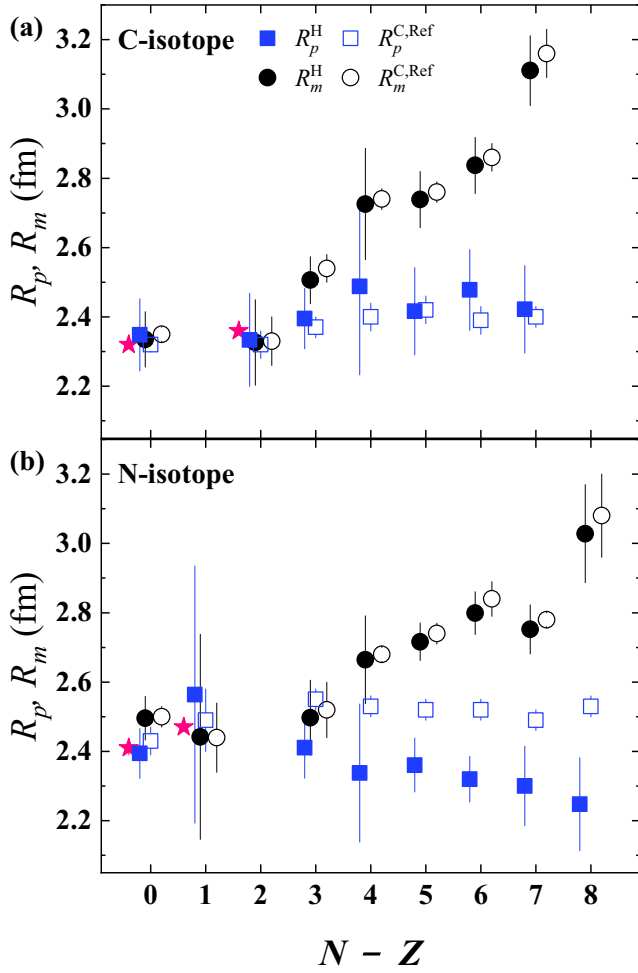
Fig. 2. (Color online) R_p extracted from $\sigma_{cc,H}$ (R_p^H, filled squares) and R_m from σ_I [6] (R_m^H, filled circles), compared with the published radii [10,7] on the C target ($R_p^{C,Ref}$, open squares, $R_m^{C,Ref}$, open circles) for C (a) and N isotopes (b). The tabulated R_p values for ^{12,14}C and ^{14,15}N [1] are shown by stars. The $N - Z$ values for the data have been slightly shifted for better visibility.

Fig. 3. (Color online) Difference of the proton radii extracted from the carbon and hydrogen data, $R_p^C - R_p^H$, as a function of $N - Z$ for odd-Z (a) and even-Z (b) isotopes. The dashed line shows the best linear fit to the data, while the shaded band indicates the 95% confidence interval. The $N - Z$ values for the data are slightly shifted. Note the combined standard uncertainties of $R_p^C - R_p^H$ are shown for each point.

isotopes. The R_m determined from both again agree very well. However, the R_p values determined by the C target tend to be systematically larger than the according H target ones when moving to the neutron-rich side.

We would like to emphasize the new scaling identified in Fig. 1 is also presented when using the FROLA models instead. In fact, the FROLA calculations are systematically larger than the ZROLA by about 3% and 7% for the C and H targets, respectively. However, this systematic difference can be incorporated into the scaling factor function when compared to the same experimental data. In the FROLA case, the relevant fits for the C and H target data are $f(C) = -0.0127(9)S_1 + 1.542(18)$ and $f(H) = -0.0045(7)S_1 + 1.169(16)$, respectively. Employing FROLA will give almost identical slopes but lower intercepts than employing ZROLA. Eventually, one obtains consistent R_p values which are independent of the Glauber models.

A conclusive explanation for the observed difference in the deduced R_p for neutron-rich N isotopes remains open. Knockout reactions have indicated that a proton as a target can observe both the inside and surface of the projectile, whereas a carbon as a target is more sensitive to the surface [29,30]. In this sense, the shape of the projectile's proton density distribution can play a role since the tail of the proton density distribution displays greater sensitivity to the C target than to the H target. It thus could enhance the
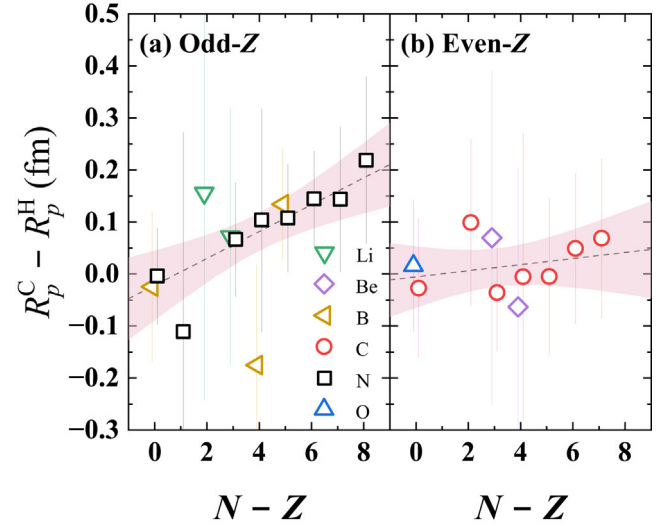
effect for the N isotopes having an odd number of protons. In Fig. 3, we summarize the $R_p^C - R_p^H$ for all the isotopes in this work as a function of neutron excess. Note that the nuclei with $N - Z = 0, 1, 2$ and part of 3 have been used to calibrate our approach to deduce proton radii. Overall, the differences follow approximately a linear trend with neutron excess. For odd-Z data, the best-fit straight line has a slope of 0.025(6), which is significantly larger than 0.006(6) for the even-Z data. This may indicate that employing the HO type to characterize the proton density distribution of neutron-rich isotopes of odd-Z nuclides is insufficient.

4. Summary

In summary, we report here the analysis of data on the σ_{cc} of 24 p-shell nuclides on carbon and hydrogen at around 900A MeV. We found a new correlation of σ_{cc} with S_1, an index for the proton-evaporation process after neutron removals in charge-changing reactions. With this correlation, we can determine the isotope-dependent scaling factor empirically. This provides a new insight to determine R_p from σ_{cc} on either a proton or any heavy-ion targets to study nuclei far from the stability line in experiments using inverse kinematics.

We are aware that the correlation with S_1 is empirical. It remains a challenge for the theory to quantify the link between the PE process with S_1. Other mechanisms, such as the excitation of giant resonances *via* the nuclear interaction [33,34] and the "p–n exchange" process [19], may also partially affect the charge-changing reaction. Dedicated theoretical calculations of light nuclei densities and momentum distributions [35–37] will be very interesting. This will help to pin down the factors responsible for the difference observed by the two probes and to understand how protons distribute inside the neutron skin. Furthermore, extending the S_1 scaling method beyond the p-shell nuclei will need further evaluation by a large data set composed of different projectiles, incident energies, and targets. In the forthcoming experiments [38], we will attempt to identify the PE process and to what extent its contribution to the σ_{cc}. Nevertheless, this empirical correlation hints at a deeper understanding. The present analysis shows that

there are excellent agreements in the deduced R_p values of C isotopes or even-Z isotopes from C-target and H-target data, but there seem to be systematic discrepancies in the case of N isotopes or odd-Z isotopes. This may related to the basic concept of how to characterize the nuclear size and the possible effect of the heavy-ion probes.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

Author contributions

Baohua Sun and Isao Tanihata supervised the project. Jichao Zhang, Feng Wang, Satoru Terashima, Baohua Sun, and Isao Tanihata processed the data. Jichao Zhang and Baohua Sun performed calculations. Jichao Zhang, Baohua Sun, and Isao Tanihata wrote the manuscript with input from all authors, and Rituparna Kanungo and Christoph Scheidenberger were deeply involved in the discussion and writing process. Rituparna Kanungo and Isao Tanihata proposed and led the experiment. All authors participated in the experiments, data processing, and manuscript revision.

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