Charge-Changing Cross Sections of 736 A MeV ^{28}Si on Carbon Targets *

Jun-Sheng Li(李俊生)[1**], Ying-Hua Dang(党英华)[1], Dong-Hai Zhang(张东海)[1], Jin-Xia Cheng(程锦霞)[2], S. Kodaira[3], N. Yasuda[4]

[1]*Institute of Modern Physics, Shanxi Normal University, Linfen 041004*
[2]*College of Electric and Information Engineering, Beifang Ethnic University, Yinchuan 750021*
[3]*Radiation Measurement Research Section, National Institute of Radiological Sciences, Chiba 263-8555, Japan*
[4]*Research Institute of Nuclear Engineering, University of Fukui, Fukui 914-0055, Japan*

(Received 4 May 2017)

The total and partial charge-changing cross sections of ^{28}Si on carbon targets at 736 and 723 A MeV are studied by CR-39 plastic nuclear track detectors using the HSP-1000 microscope system and the PitFit track measurement software. The values of the total charge-changing cross section are $\sigma_{\rm tot} = (1179\pm50)$ mb and $\sigma_{\rm tot} = (1186\pm42)$ mb at 736 and 723 A MeV, respectively. The result is compared with the ones obtained by other experimental and theoretical results. The odd–even effect of the partial charge-changing cross section is observed.

PACS: 25.70.Mn, 25.75.−q, 25.70.−z DOI: 10.1088/0256-307X/34/10/102501

The knowledge of heavy ion fragmentation at intermediate and high energies from several hundreds of A MeV to several A GeV is very necessary in nuclear physics, astrophysics, radiobiology and applied physics, etc. Understanding the interaction mechanism at intermediate and high energy nuclear collisions is very important to estimate the radiation damage to the equipment of space vehicles, to calculate the transport of the heavy ions in the galactic cosmic rays (GCR) through the interstellar medium, and to understand the effects of these components of cosmic rays.[1−3] Hence, it is necessary to have accurate knowledge of fragmentation cross section of heavy ions at different energies in various target media. The charge-changing cross section provides a way to clarify the reaction mechanisms in heavy ion collisions and the distribution of valence protons, particularly for neutron-rich projectiles. Until now, the projectile fragmentation charge-changing cross section has been explored by many research groups at relativistic energy with various targets.[4−32] Yamaguchi *et al.* introduced a phenomenological way to relate point proton distribution radii ($r_{\rm p}$) to charge-changing cross sections($\sigma_{\rm cc}$) in carbon target.[4] Recently, the charge-changing cross section has been measured to obtain the information on the $r_{\rm p}$ of some unstable nuclei.[15−21]

When free-space doses from GCR heavy ions are plotted as a function of atomic number, the contribution of silicon to dose equivalent in free space is second only to that of iron.[8] Therefore the fragmentation cross sections of silicon ions on various targets are of considerable importance. At present, the results of the total and partial charge-changing cross sections of ^{28}Si ion beam in different targets using the CR-39 detector are relatively less, and the results of different research groups do not agree well with each other.[4−14] In this study, using CR-39 detectors, the total and partial charge-changing cross sections of 736 and 723 A MeV ^{28}Si on carbon targets are calculated, aiming at filling the gap in the profile of experimental cross sections of fragmentation productions and giving a further study on the dependence of the charge-changing cross sections on the energies. The experimental results are compared with other experimental results and theoretical models.

The carbon targets were exposed by an 800 A MeV ^{28}Si ion beam at the heavy ion medical accelerator in Chiba (HIMAC) at the Japanese national institute of radiological sciences (NIRS). The beam fluence is about 1250 ions/cm^2. A type of HARZLAS TD-1 CR-39 sheet manufactured by Fukuvi Chemical Industry Co., LTD. is placed before and after the targets. The typical configuration of the stack for this experiment is shown in Fig. 1. Using this configuration, we can obtain the charge-changing cross sections of ^{28}Si on carbon targets at different energies. In this work, we focus on the interactions of ^{28}Si on carbon targets at 736 and 723 A MeV because of the lack of the charge-changing cross sections of ^{28}Si on carbon targets at energies of 550–750 A MeV. The thickness of the targets and CR-39 detectors were about 5 mm and 0.783 mm, respectively. The beam energy at the first target upper surface is 788 A MeV. The total and partial charge-changing cross sections of ^{28}Si in the first target have been calculated in our previous work.[12] The CR-39 detectors were etched in 7N NaOH aqueous solution at 70℃. The etching time is 15 h. Then, the beam ions and their fragments in the CR-39 manifest as etch-pit cones (tracks) on both sides of CR-39 sheets. After etching, the tracks were scanned and analyzed using the HSP-1000 microscope system and the PitFit track measurement software.[33] Figure 2 shows the images of ion tracks scanned by the HSP-1000 microscope sys-

*Supported by the National Natural Science Foundation of China under Grant Nos 11075100, 11347198 and 11565001, and the Shanxi Provincial Science Foundation under Grant No 2011011001-2.
**Corresponding author. Email: lijs@sxnu.edu.cn

tem. The spot A is the track of ^{28}Si, the spots B and C are the tracks of projectile fragments (PFs). Using PitFit software, we can obtain the geometric information of the tracks, such as the area of etched track spot on CR-39 surfaces, the position coordinates and other information. Figure 3 shows the base-area distribution of etched tracks of 736 A MeV ^{28}Si and their fragments in CR-39 detector after carbon target. The charge of PFs is identified by the base area distribution. Multi Gaussian fittings are made in the base-area distribution. It is clear that the base-area distribution of ^{28}Si ions and their fragments with charge from 5 to 13 manifests a better and more resolution capability of the CR-39 detector. The trajectories of ^{28}Si and the ones of PFs are reconstructed in the scanned stack. Details of track tracing and reconstruction, identification of charge of PFs can be found in our recent works.[24–26]

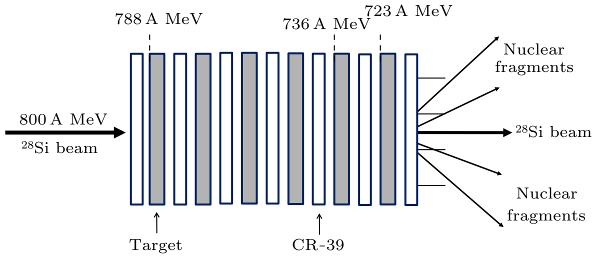

Fig. 1. The typical configuration of the stacks for this experiment.

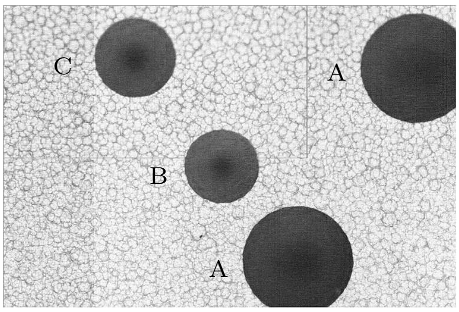

Fig. 2. Tracks of charged particles on CR-39.

The total charge-changing cross section is calculated by using the following relation[11]

$$\sigma_{\rm tot} = \frac{A_{\rm T}\ln(N_{\rm in}/N_{\rm out})}{\rho_{\rm T} t N_{\rm AV}}, \tag{1}$$

where $A_{\rm T}$, $\rho_{\rm T}$, t and $N_{\rm AV}$ are the nuclear mass of the target, target density, thickness of the target, and the Avogadro number, respectively, $N_{\rm in}$ is the number of ^{28}Si ions before the target, and $N_{\rm out}$ is the number of ^{28}Si ions after the target. The systematic error in counting the number of ^{28}Si ions after the target and the PFs is less than 2%.

The Bradt–Peters cross section is also calculated using the relation[34]

$$\sigma_{\rm tot} = \pi r_0^2 (A_{\rm T}^{1/3} + A_{\rm p}^{1/3} - b_0)^2, \tag{2}$$

where r_0 = 1.35 fm, b_0 = 0.94, $A_{\rm p}$ is the projectile mass number, and $A_{\rm T}$ is the target mass number. The experimental total charge-changing cross sections and theoretical prediction are listed in Table 1. Figure 4 presents the dependence of the total charge-changing cross sections of ^{28}Si on carbon targets on the energy. It is found that our experimental data are in agreement with the results of other ones and theoretical prediction within experimental uncertainties and do not show any obvious energy dependence.

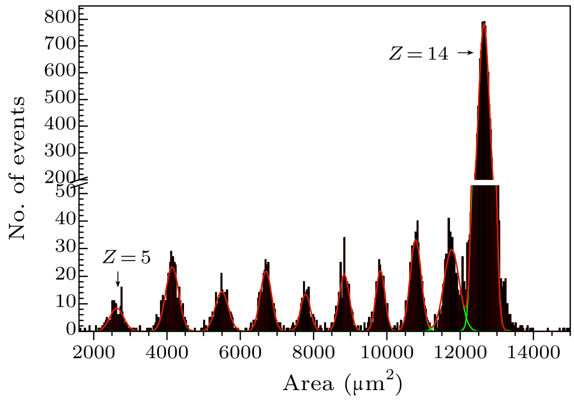

Fig. 3. Base-area distribution of etched tracks of 736 A MeV ^{28}Si and their fragments in CR-39 detector after C target.

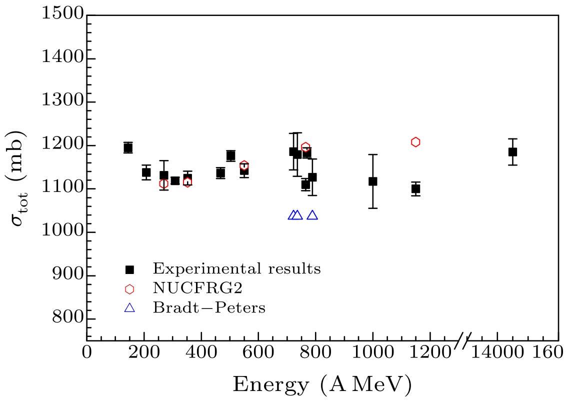

Fig. 4. Dependence of the total charge-changing cross sections on the energy.

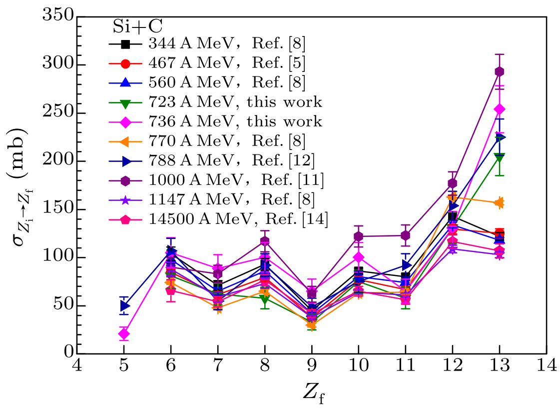

Fig. 5. The dependence of the partial cross sections of fragment production on the charge of fragment in interactions of ^{28}Si in C targets.

For calculating the partial charge-changing cross section of the fragment with charge $Z_{\rm f}$, we can use the following relation[11]

$$\sigma_{Z_{\rm i}\to Z_{\rm f}} = \frac{A_{\rm T}}{\rho_{\rm T} t N_{\rm AV}}\Big(\frac{N^{\rm f}_{\rm out}}{N^{\rm p}_{\rm out}} - \frac{N^{\rm f}_{\rm in}}{N^{\rm p}_{\rm in}}\Big), \tag{3}$$

where $\sigma_{Z_{\rm i}\to Z_{\rm f}}$ is the partial charge-changing cross section of a beam ion $Z_{\rm i}$ into $Z_{\rm f}$, $N^{\rm f}_{\rm in}$ and $N^{\rm f}_{\rm out}$ are the numbers of PFs with charge $Z_{\rm f}$ before and after the target, $N^{\rm p}_{\rm in}$ and $N^{\rm p}_{\rm out}$ are the numbers of beam ions before and after the target, $A_{\rm T}$, $\rho_{\rm T}$, t and $N_{\rm AV}$ are the nuclear mass of the target, target density, thickness of the target, and the Avogadro number, respectively. The formula is valid if the thickness of the target is smaller compared with the mean free path of the fragments in that material.

Table 2 lists the experimental partial charge-changing cross sections for PFs with charges of $5 \le Z \le 13$ produced in the interactions of ^{28}Si projectiles in C targets at various energies. Figure 5 presents the variation of the partial cross sections with the charge of PFs for the interactions of ^{28}Si with the C target. An obvious odd–even effect is observed in the PFs production in all interactions. The odd–even effect is mainly affected by the pairing energy and the Wigner energy in the statistical decay process.[35−37] The partial cross section for $Z = 5$ is relatively small because of the low statistics. The partial cross section for $Z = 13$ is relatively large due to the fact that there are mixed events in the statistical distinction.[9,25,26]

Table 1. The total charge-changing cross sections for interactions of ^{28}Si on C targets.

Energy (A MeV)	$\sigma_{\rm tot}$ (mb)	NUCFRG2	Bradt–Peters	References
144	1195±12			Ref. [4]
208	1138±17			Ref. [4]
270	1131±34	1112		Ref. [8]
309	1119±8			Ref. [4]
352	1125±16	1115		Ref. [8]
467	1136.4±12.8			Ref. [5]
503	1176±12			Ref. [13]
550	1142±16	1154		Ref. [8]
723	1186±42			This work
736	1179±50		1037	This work
765	1110±14	1196		Ref. [8]
770	1183±12			Ref. [13]
788	1127±42		1037	Ref. [12]
1000	1117±62			Ref. [11]
1150	1100±16	1208		Ref. [8]
14500	1185.0±30.0			Ref. [14]

Table 2. Experimental partial charge-changing cross sections for the production of ^{28}Si projectiles for C targets.

	Beam energy (A MeV)									
$Z_{\rm f}$	344[8]	467[5]	560[8]	723 (This work)	736 (This work)	770[8]	788[12]	1000[11]	1147[8]	14500[14]
13	122±4	125.3±4.7	118±3	205±20	254±24	157±2	225±19	293±18	103±3	107.0±7.4
12	143±4	129.5±4.8	134±3	131±16	131±17	163±2	154±15	177±12	109±4	116.7±6.9
11	80±3	66.7±3.4	74±2	58±11	65±12	64±2	92±12	123±11	61±2	56.2±4.7
10	86±3	77.1±3.5	80±2	75±12	100±15	63±2	75±11	122±11	64±2	65.1±5.1
9	45±2	37.8±2.4	42±1	33±8	65±12	30±2	49±9	62±8	38±2	42.0±4.1
8	93±6	79.4±3.5	86±5	58±11	100±15	65±2	92±12	117±11	73±5	76.8±5.6
7	71±5	61.5±3.1	65±4	62±11	89±14	48±1	55±9	83±9	59±5	54.2±5.2
6	104±7	84.6±3.6	98±6	81±13	104±16	74±2	107±13	90±10	88±7	65.7±11.4
5					21±7		50±9			

In conclusion, the total and partial charge-changing cross sections for 736 and 723 A MeV ^{28}Si ion beams on the C target have been measured using CR-39 detectors. The total charge-changing cross sections of our experimental result are in agreement with other experimental data and the theoretical predictions. The total charge-changing cross sections in the present work do not show any obvious energy dependence. The partial cross sections show an obvious odd–even effect for the fragments with charges of $5 \le Z \le 12$.

We gratefully acknowledge the staff of the HIMAC for providing the beam to expose the stacks.

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