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Improvement of charge resolution for trans-iron nuclei ($Z \geq 30$) in CR-39 plastic nuclear track detectors using trajectory tracing technique

S. Ota[2,1], N. Yasuda[3], L. Sihver[4,5,6], S. Kodaira[3], S. Naka[1], Y. Ideguchi[1], and N. Hasebe[1]

[1]Research Institute for Science and Engineering, Waseda University, Tokyo, Japan
[2]Advanced Science Research Center, Japan Atomic Energy Agency, Ibaraki, Japan
[3]National Institute of Radiological Sciences, Chiba, Japan
[4]Chalmers University of Technology, Goteborg, Sweden
[5]Roanoke College, Salem, Virginia, USA
[6]Texas A & M University, Texas, USA

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Abstract. Charge identification of trans-iron nuclei (nuclear charge: $Z \geqq 30$) using CR-39 plastic nuclear track detector (PNTD) is essential as a part of an effort to our future measurements of the projectile charge changing cross sections for galactic cosmic ray nuclei, but extremely hard. Therefore, an improvement method of the charge resolution (δZ) for 350 MeV/n Ge in CR-39 PNTD using the trajectory tracing technique with averaging the signals of nuclear tracks for each ion was studied. Eight sheets of CR-39 PNTDs were aligned and exposed to Ge beam behind a graphite target to produce projectile fragments. Average of the nuclear track data was taken over 16 detector surfaces for each ion, then the δZ of Ge was successfully improved from 0.31 charge unit on single surface to 0.15 charge unit in rms, which is good enough for making the precise cross section measurements and no other experiments using CR-39 PNTDs or the other passive detectors have achieved such a good δZ for the trans-iron nuclei with $Z/\beta < 50$ (β: relativistic velocity). This method will be very important for our future cross section measurements toward the study of galactic cosmic ray origin.

1 Introduction

Projectile charge changing cross sections for cosmic ray nuclei on hydrogen and He targets play essentially important roles for the study of galactic cosmic ray (GCR) origin and its source composition (Shapiro and Silberberg, 1970). Some experimental and theoretical works on those cross sections were previously made (Ferrando et al., 1988; Webber et al., 1990a,b,c, 2003; Silberberg and Tsao, 1990). However, there still have been uncertainties in much of the cross section data, and therefore the present knowledge of cross section has not led to successful determination of the GCR source composition. There are considerably inconsistent results between some experiments which measured the same reactions in different methods, and also between the experiments and prediction by some theoretical models (e.g. Westfall et al., 1979; Canton et al., 2007; Golovchenko et al., 2010). In addition, for the trans-iron nuclei (nuclear charge: $Z \geqq 30$) in GCR, those cross section data are much fewer and limited in spite of their importance (Binns et al., 2007; Kodaira et al., 2009). To solve these problems, we plan to carry out systematic measurements of the projectile charge changing cross sections at intermediate energy range ($0.1-1$ GeV/n) for some important GCR components on hydrogen using a single method, and make drastic comparison with previous data (Ota et al., 2009).

We have developed the measurement system for cross section using CR-39 plastic nuclear detector (PNTD). CR-39 PNTD is one of the most suitable detectors for measurements of projectile charge changing cross sections. By using multiple layers of CR-39 PNTD interspersed with layers of target materials in a stack configuration and tracing nuclear tracks through individual layers, it is possible to reproduce the trajectories of projectiles and the fragments in the target with extremely high position resolution (~ 1 µm) with larger angular acceptance. The system consists of a high speed imaging optical microscope (HSP-1000) and a sophisticated track analyzing software (Pit Fit) (Yasuda et al., 2005, 2009). They made it extremely easier to earn statistics such as using 10^{4-5} projectiles in a few days, and greatly improved the statistics of the CR-39 PNTD methods to a level comparable

Correspondence to: S. Ota
(ota.shuya@jaea.go.jp)

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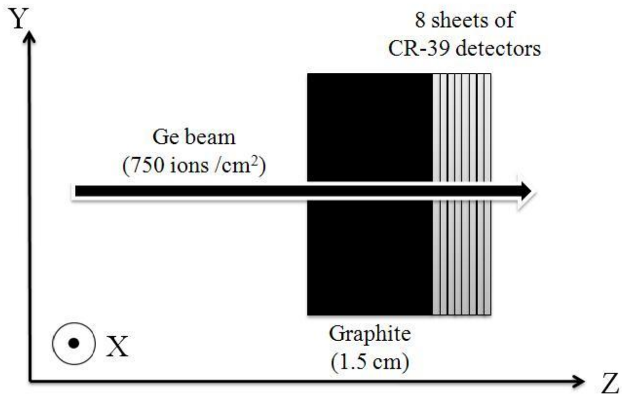

Fig. 1. Schematic view of the experimental set up.

to results obtained previously using active detectors (Webber et al., 1990a,b,c). Thus our project to determine the projectile charge changing cross sections is ongoing and some results will be reported in elsewhere.

Recently, we succeeded in discovering that the capability of charge identification using CR-39 PNTD is mainly limited for $4 \leq Z \leq 30$ at intermediate energy range (Ota et al., 2011). Since other passive detectors have no sensitivity for particles of $Z/\beta < 50$ with good resolution (Westphal et al., 1994), it is essential to improve the charge resolution of CR-39 PNTD for the trans-iron nuclei ($Z \geqq 30$) with $Z/\beta < 50$ for their cross section measurements. Therefore, in this paper, we studied an improvement method of charge resolution for 350 MeV/n Ge ($Z/\beta = 46.4$) nuclei using CR-39 PNTD. The trajectory tracing technique with averaging the signals of nuclear tracks for each ion was employed to improve the charge resolution, and limitation of averaging was verified.

2 Principle of the improvement

2.1 Charge identification using CR-39 plastic nuclear track detector

An energetic heavy ion creates a latent nuclear track along its trajectory by ionization loss when it passes through the detector. By chemical etching with such as NaOH solution, the latent track is developed to an elliptical nuclear track with the measurable size by means of optical microscopy. The response of the CR-39 PNTD to a projectile particle is frequently defined by the area of elliptical opening of the nuclear track (Benton and Nix, 1969; Fleisher et al., 1975; Benton, 1978; Fowler et al., 1979), and it is utilized for charge identification in especially accelerator experiments since Z and β of the projectile are specified in advance (Flesch et al., 1999; Cecchini et al., 2008). The size of nuclear track area is proportional to Z/β of projectile since it correlates with the energy loss in the detector, and the projectile fragments have nearly the same β as the projectiles at intermediate energy (Heckman et al., 2002; Westfall et al., 1976). Therefore it is possible to identify Z of projectile and fragments from the area distribution of all the measured tracks on a given sheet of CR-39 PNTD.

The charge resolution (δZ) in CR-39 detector can be defined as

$$\delta Z = \frac{\delta A_Z}{(A_Z - A_{Z-1})} \, , \tag{1}$$

where A_Z, A_{Z-1} and δA_Z denote the mean nuclear track areas of particles with Z (projectile) and $Z-1$, and the standard deviation of A_Z, respectively (Ota et al., 2011). Each value of A_Z, A_{Z-1} and δA_Z can be measured by fitting the charge distribution with multi Gaussian. Typically, $\delta Z \leq 0.15$ charge unit (c. u.) is necessary for identification in the experimental condition such as the large ratio of the numbers of projectiles and fragments, i.e. cross section measurements (Webber et al., 1990a,b; Westphal and He, 1993). In our former study, we revealed that projectiles with $Z \geqq 30$ are almost hard to identify at intermediate energy range using the CR-39 PNTD (Ota et al., 2011).

2.2 Multiple measurements with the trajectory tracing technique

The trajectory tracing technique with averaging the signals of nuclear tracks for each ion by use of multiple detectors to improve the charge resolution have been traditionally employed with several kinds of radiation detectors (e.g. Price et al., 1988; Webber et al., 1990b; Cecchini et al., 1993; Zeitlin et al., 1997; Toshito et al., 2004; Weaver et al., 2006). The effectiveness is often explained by statistics and rejection of background events (Toshito et al., 2004; Webber et al., 1990b). Especially, passive detectors such as CR-39 PNTD and nuclear emulsion are suitable for improvement by this method because the thinness of detector allows us to use the more detectors to make measurements (Toshito et al., 2006). Improvements of δZ using the method with passive detectors have been proven in some experiments (Flesch et al., 1999; Toshito et al., 2006; Cecchini et al., 2008). In there, the trajectory tracing techniques were applied to improve the δZ of Fe, C, and Si projectiles, respectively at intermediate energy.

3 Experimental procedure

3.1 Beam exposure

Two types of CR-39 detectors ($5 \times 5\,\mathrm{cm}^2$ with 0.9 mm thickness), HARZLAS TD-1 and BARYOTRAK (Fukuvi Chemical Industry, Japan), are being used selectively in our project to measure charge changing cross sections owing to the difference of detector response as a function of Z/β (Yasuda et al., 2008). Our previous study made it possible to predict δZ for projectiles with given Z/β (Ota et al., 2011). In our

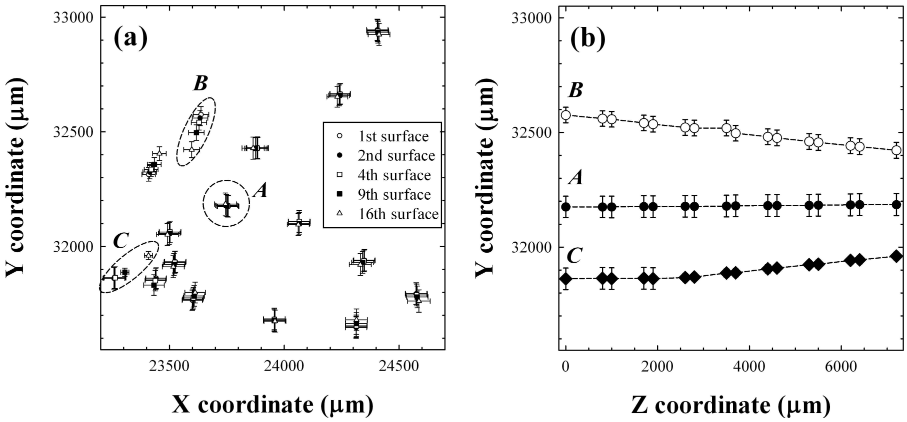

Fig. 2. **(a)** Positions of some nuclear tracks on 1st, 2nd, 4th, 9th, and 16th surfaces aligned to the coordinate of 1st surface. X and Y error bars represent the nuclear track size (major and minor axes of nuclear track), respectively. **(b)** Projection of three typical trajectories from the Fig. **(a)** on $Z-Y$-plane. Trajectory A: incident Ge ion, B: fragmented ion from the target, and C: fragmented ion in the CR-39 PNTD.

model, value of nuclear track area can be predicted as functions of Z/β and bulk etch according to the response function of detector. The standard deviation of the given nuclear track area is empirically given. Thus values of A_Z, A_{Z-1}, and δA_Z are calculated, and then δZ is estimated using Eq. (1). For this experiment using 500 MeV/n Ge ($Z=32$) beam, we chose BARYOTRAK since the δZ is estimated to be 0.32 c. u. which is better than the δZ in TD-1.

A schematic view of the experimental set up is shown in Fig. 1. Eight sheets of CR-39 detectors were put together along Z direction behind a graphite target with 1.5 cm thickness as a stack in a plastic case. The stack was exposed to 500 MeV/n Ge ($Z=32$) beam with the density of about 750 ions/cm^2 using HIMAC accelerator at National Institute of Radiological Sciences, Japan. The energies of Ge passed through the target at the front (just behind the target) and back detectors in the stack were calculated using the SRIM code (Ziegler et al., 1985) to be about 375 and 335 MeV/n, respectively.

3.2 Reconstruction of beam trajectories

The detectors were etched by 7 normal NaOH solution at the temperature of 70°C in a thermostat for 25 h (equivalent to 51.6 μm in bulk etch). The range of temperature in the thermostat was controlled to be < 0.1°C. The area of 4.5×4.5 cm^2 in the front and back surfaces of the detectors were scanned by HSP-1000 and the position and size of nuclear tracks were measured by Pit Fit. Thus nuclear track data from total of 16 detector surfaces are acquired from the stack and utilized for the following trajectory tracing. As a demonstration of the trajectory tracing, the 3 dimensional coordinates of some reconstructed trajectories in the stack were shown in Fig. 2. Positions of nuclear tracks on each measured surface (X and Y) were aligned to the corrdinate of the first surace as shown in Fig. 2**(a)**, and the track trajectories were traced for each ion using a semi-automatic routine developped by Ota et al. (2008, 2011). In the routine, neighbouring nuclear tracks on adjacent surfaces are automatically matched according to the distance of the tracks at first, and then manually checked and corrected for the case any corresponding track cannot be found. Finally, total of 12 000 track trajectories were reconstructed in the stack. Three typical trajectories are shown in Fig. 2**(b)**. Trajectory A shows an incident Ge ion and B has rather sharp angle to Z axis with smaller track area than the trajectories A and C run parallel to Z axis for first several layers, but suddenly inflected with smaller track area. Trajectories B and C are recognized as fragmented ions from the target and in the detector, respectively. Trajectories like C ($\sim 15\%$ of total trajectories) were rejected to average the signals (areas) for further analysis.

4 Results

Charge distributions obtained at the 1st surface of stack is shown in Fig. 3**(a)**. The charge peaks corresponding to $Z=32$ down to 15 can be seen in the figure, respectively. However, each charge peak is not clear at all. The Ga ($Z=31$) peak was completely contaminated with the Ge peak and cannot be found from the figure. The δZ of Ge are measured to be 0.31 c. u. and, which is in good agreement with the value given by our prediction model (Ota et al., 2011) mentioned in Sect. 3.1.

We took an average ($A_{\rm ave}$) of the track areas over 16 surfaces for each of trajectory, i.e. $A_{\rm ave}=\left(\sum_{i=1}^{N}A_i\right)/N$. The improved charge distribution is shown in Fig. 3**(b)**. Each nuclear charge peak becomes sharp and the Ga peak becomes apparent apart from the Ge peak. The δZ were finally about 50% improved from 0.31 c. u. to 0.15 c. u., respectively, which is good enough for making the precise cross section measurements. No other experiments using CR-39 PNTDs or the other passive detectors have achieved such a good δZ for trans-iron nuclei ($Z\geq30$) with $Z/\beta<50$ by a single sheet. Therefore, we conclude that the trajectory tracing method using CR-39 PNTDs can be the essential way for charge identification of the trans-iron nuclei with $Z/\beta<50$.

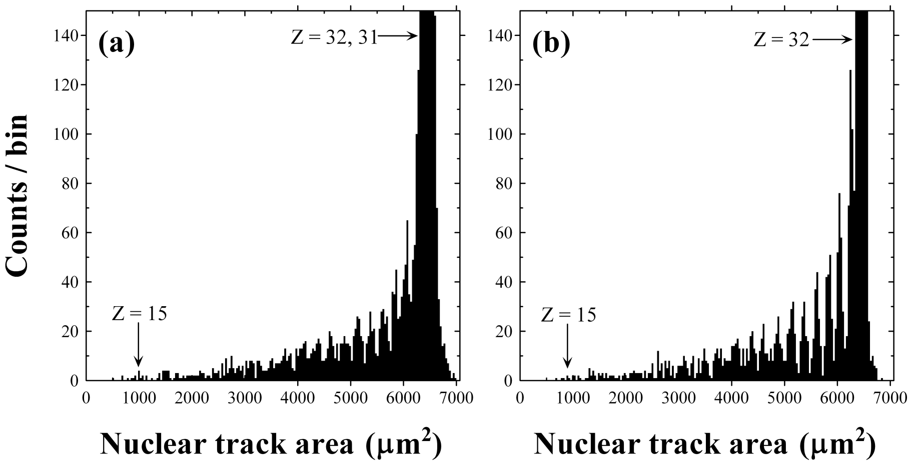

Fig. 3. Charge distributions of Ge projectiles and their fragments acquired **(a)** on 1st surface of the stack, and **(b)** by averaging the signals from 16 surfaces.

Table 1. Mean values of Ge charge (nuclear track area) distribution (A_Z) with a standard deviation (δA_Z), difference from means of Ga distribution ($A_Z - A_{Z-1}$) and charge resolution (δZ) for the number of sampled detector surfaces.

Number of surfaces	A_Z (δA_Z)*	$A_Z - A^*_{Z-1}$	δZ (c. u.)
1	6449.5 (54.9)	176.3**	0.31
2	6382.9 (48.6)	174.5	0.28
4	6387.2 (40.8)	181.8	0.22
9	6410.2 (29.8)	180.9	0.16
16	6437.8 (28.0)	186.6	0.15

*unit is μm^2.
**deduced from the ratio of $A_Z - A_{Z-1}$ and A_Z in the results of two sampled surfaces since Ga peak was not clearly identified.

5 Discussion

Dependence of the standard deviation of A_Z (δA_Z) for Ge track on the number of sampled surfaces (N) was shown in Fig. 4. The δA_Z are rapidly improved up to first $8-9$ surfaces, and they finally saturated after that ($N \geqq 10$). Corresponding numerical data to the mean values of Ge nuclear track area distribution (A_Z), its standard deviation (δA_Z), and differences from the mean value of Ga distribution ($A_Z - A_{Z-1}$) at $N = 1, 2, 4, 9$ and 16 are summarized in Table 1.

Improvement of the signal (δA_Z) by statistics is generally expected as:

$$\delta A_Z(N) = \frac{\delta A_Z(1)}{\sqrt{N}} \qquad (2)$$

(Toshito et al., 2004), or

$$\delta A_Z(N) = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(\delta A_{Z,i}\right)^2} \qquad (3)$$

(Weaver et al., 2006), where $\delta A_Z(N)$ denotes the δA_Z averaged over N surfaces of detector and $\delta A_Z, i$ denotes the δA_Z on the ith surface. The Eq. (3) is the case for that δA_Z is not constant between each surface. The estimation by Eq. (2) gave good agreement with the improvement of δA_Z for 1.2 GeV/c π^+ and proton distributions in the measurements using 29 sheets of emulsion chambers by Toshito et al. (2004). The estimation by Eq. (3) was discussed to give good agreement with the improvement of mass resolution for 310 MeV/n ^{84}Kr in the experiment using 16 sheets of BP-1 glass detectors by Weaver et al. (2006). Estimated signals ($\delta A_Z(N)$) by Eqs. (2) and (3) for our experiment are shown as curves in Fig. 4. It is obvious experimental result is improved slowly compared to the estimations and the differences from the estimations become larger as N increases.

One of the reasons for the saturation may be due to the differences of deposited energies (dE/dx) between the detectors in the stack (Ge projectile energies are 375 MeV/n and 335 MeV/n, i.e. $Z/\beta = 45.6$ and 47.2 on the front and back detectors in the stack, respectively). Such energy difference varies the response of the detector because that of CR-39 PNTD depends on Z/β. Besides, some non charge-changed but mass-changed events (Ge isotopes) are included in the Ge distribution in the Fig. 3 (estimated to 5% of total Ge using PHITS simulation code (Niita et al., 1995; Iwase et al., 2002)). Those mass-changed events have larger energy fluctuation (estimated $dE/E \sim$ a few percentage) compared to non interacted particles (estimated $dE/E \sim 0.2\%$), and the larger dE/dx leads to the larger δA_Z. Running average of the data contaminated with such events disrupt the improvement. Further study on the causes of the saturation is needed to determine the optimal number of CR-39 PNTD for our future measurement of projectile charge-changing cross sections.

6 Conclusions

Improvement of charge resolution (δZ) for 350 MeV/n Ge ($Z = 32,\ Z/\beta = 46.4$) in CR-39 plastic nuclear track detector (PNTD) using the trajectory tracing technique with averaging the signals of nuclear tracks for each ion was studied as a part of systematic project to measure the projectile charge changing cross sections. The δZ was finally improved from 0.31 c. u. on single surface of CR-39 PNTD to 0.15 c. u. by average of 16 surface measurements. The δZ are good enough for making the precise cross section measurements and no other experiments using CR-39 PNTDs or the other passive detectors have achieved such a good δZ for trans-iron nuclei with $Z/\beta < 50$. Therefore, we conclude that the trajectory tracing method using CR-39 PNTDs can be the essential way for charge identification of trans-iron nuclei. However, it was observed that the improvement of δZ was almost saturated over ~ 10 surfaces. We considered that the reasons mainly come from the large energy difference of projectiles from the 1st to 16th surfaces of stack, and the contamination in the sampled data with mass-changed events produced in the detectors/target. Further study on the causes of the saturation is needed to determine the optimal number of CR-39 PNTD for our future measurement of projectile charge-changing cross sections.

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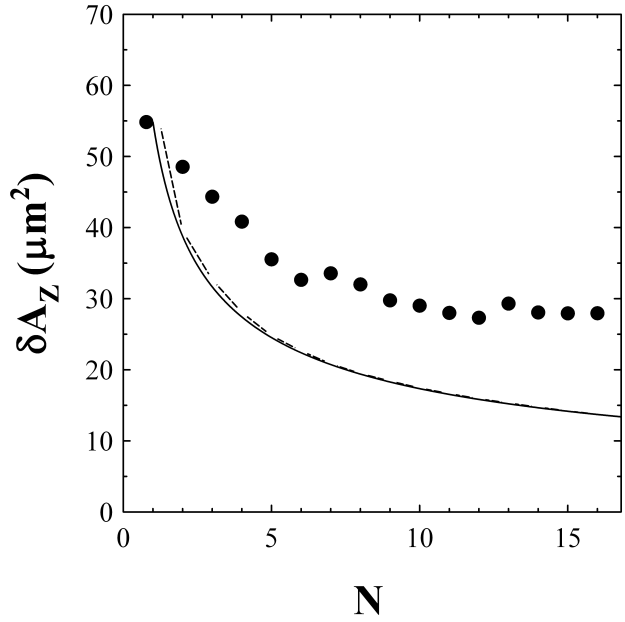

Fig. 4. Dependence of standard deviation of Ge charge (nuclear track area) distribution and the number of sampled surfaces. Measurement errors are included in the plot. Black line and dashed line denote the estimations by Eqs. (2) and (3), respectively.

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