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Charge resolution of CR-39 plastic nuclear track detectors for intermediate energy heavy ions

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ABSTRACT

The charge resolution (δZ) for heavy ions (nuclear charge: $Z < 40$) of 0.1–1 GeV/n energy in CR-39 plastic nuclear track detector (PNTD) and its dependence on etching time, and on projectile Z and energy were investigated and optimized as part of an effort to make precise measurements of projectile charge-changing cross sections. Two types of CR-39 PNTD, HARZLAS TD-1 and BARYOTRAK, were exposed to heavy ion beams with seven values of Z behind thick targets to produce projectile fragments. Following chemical etching (7 N NaOH at 70 °C) for varying etch times, δZ of the projectiles was determined for each detector type. A strong dependence of δZ on the amount of bulk etch (B) was seen. It was also observed that δZ can be remarkably improved with longer etching time as a function of $B^{-1/2}$, in accordance with the trend seen in other types of track detector such as glass nuclear track detector. However, for $B \geqslant 60$ μm (30 h etching), saturation occurs and there is no further improvement in δZ. Analysis of the correlations between projectile Z, energy, detector response, and fluctuation of the response make it possible to develop a model to predict the δZ for projectiles of given Z and energy. The predicted and measured values of δZ show good agreement within 10%. We conclude that $4 \leqslant Z \leqslant 30$ at intermediate energy can be identified with good δZ in these detectors. The predictive model will be used in designing future cross section measurement experiments.

1. Introduction

Uncertainties in projectile charge-changing cross section for heavy ions of intermediate energy (between a few hundred MeV/n and a few GeV/n) on interstellar medium (ISM) targets consisting mainly of hydrogen are a longstanding problem for determination of the chemical composition at galactic cosmic ray (GCR) sources [1–3]. In order to accurately determine the GCR composition at its source, the chemical composition of the GCR spectrum observed near the Earth must be corrected for nuclear interactions with interstellar hydrogen [4,5]. Although large scale, systematic experiments to determine the cross sections of the main GCR heavy ion component ($4 \leqslant Z \leqslant 28$) were performed in the 1980s–90s [6–8], these results have not led to successful determination of the GCR source composition due to remaining uncertainties in the cross section data and some discrepancies in the data of various groups using different methods [9–12]. Cross section data for trans-iron nuclei ($Z \geqslant 30$) are also important in establishing some crucial constraints on nucleosynthesis processes and acceleration mechanisms occurring at the GCR sources [13], but currently there is insufficient cross section data for these nuclei [14,15]. To solve this problem, systematic measurements for a wide range projectiles and energies using a single method, and comparison of the results from this method with data obtained by other methods and with model calculations are needed. Our project aims to measure the charge-changing cross section of C–Xe projectiles on hydrogen targets using CR-39 plastic nuclear track detector (PNTD) [16].

CR-39 PNTD is one of the most suitable detectors for the determination of heavy ion charge-changing cross sections in target materials. By using multiple layers of CR-39 PNTD interspersed with layers of target material in a stack configuration and by tracing nuclear tracks through individual layers, it is possible to reproduce the trajectories of primary particles in the target and

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determine the angular dependence of the projectile fragments. Because there is little change in the kinetic energy of the projectile fragments emitted from a nuclear reaction relative to the kinetic energy of the primary projectile, fragment charge can be accurately determined. Thus it is possible to reconstruct the individual nuclear interaction and precisely determine the charge-changing cross section using CR-39 PNTD by trajectory tracing techniques [17,18]. We have adopted the "CH_2–C subtraction method" to determine the cross section for hydrogen targets by subtracting the results obtained for C (graphite) targets from results obtained for CH_2 (polyethylene) targets [7]. The use of thin solid targets with CR-39 PNTDs minimizes the number of secondary reactions in the target and maximizes the coverage of the angular acceptance for fragments.

A high speed imaging microscope (HSP-1000) and sophisticated track analysis software (Pit Fit) have been developed to analyze 10^5–10^6 nuclear tracks in the CR-39 PNTDs within a few days [19,20]. This imaging system has greatly improved the statistics of CR-39 PNTD methods to a level comparable to results obtained previously using active detectors [6–12]. In this work, characteristics of the charge resolution of CR-39 PNTDs for various heavy ion projectiles, such as the dependence on etching time, and projectile Z and energy were investigated through a study of detector response to heavy ions and experimental accuracy to optimize detector performance for charge identification. This work is useful for further systematic measurements of total/partial projectile charge-changing cross sections over a wide range of Z using the combination of the new microscope and analysis software.

2. Principle of heavy ion detection in CR-39 PNTDs

2.1. Detector response

A charged particle produces a latent track along its trajectory by ionization, when it passes through a layer of CR-39 PNTD. The latent track can be enlarged by chemical etching, where upon it becomes an elliptical nuclear track that can be analyzed by means of optical microscopy. The response of CR-39 PNTD to a projectile particle of given Z and projectile velocity (Z/β) is frequently defined by the area of elliptical opening of the nuclear track ($A = (\pi D_A D_B)/4$), where D_A and D_B denote major and minor axes of the ellipse [21–24]. The quantity A is generally utilized for particle identification in accelerator experiments, since Z and β of the projectile are specified in advance [25,26]. A is a function of Z, since projectile fragments produced in nuclear interactions have nearly the same velocities as the primary projectile ($\beta_{\mathrm{frag}} \approx \beta_{\mathrm{proj}}$) in the intermediate energy range (0.1–1 GeV/n) [27,28]. This makes it possible to identify the Z from the distribution of the areas of all the measured tracks on a given layer of CR-39 PNTD.

2.2. Charge resolution

The charge resolution (δZ) of CR-39 PNTD for projectiles with given Z and β is defined as

$$\delta Z(Z,\beta) = \frac{\delta A_z}{A_z - A_{z-1}} \quad (1)$$

Here, A_Z and $A_{Z\text{-}1}$ correspond to the average track areas of the projectiles (with the charge of Z) and fragments (Z-1), respectively. The quantity δA_Z denotes the standard deviation of A_Z. Previous cross section measurements were performed with $\delta Z < 0.2$ charge units (c. u.), e. g., using the CR-39 PNTD (0.1–0.2 c. u.) [25,26,29,30], using silicon semiconductor detectors (0.1–0.2 c. u.) [31,32], and using scintillation counters (0.13–0.14 c. u.) [6]. A charge resolution <0.15 c. u. is required for precise measurements [33], especially when the ratio of the number of projectile tracks to fragment tracks is large as is the case for thin targets. Therefore, in this work we regard $\delta Z < 0.15$ c. u. as the criterion required for the precise measurement of charge-changing cross section.

3. Experimental procedure

Two types of CR-39 PNTD (5×5 cm^2 with 0.9 mm thick), HARZLAS TD-1 and BARYOTRAK, are being used in our project to measure charge-changing cross sections owing to wide detection range in Z of TD-1 and the surface clarity of BARYOTRAK [34]. The stacks consisted of C (graphite) or CH_2 (Polyethylene) target, varying in thickness between 2 and 5 cm, sandwiched between layers of HARZLAS TD-1 or BARYOTRAK CR-39 PNTD. Each detector/target stack was exposed to beams of C, O, Si, Ar, Fe, Kr, or Xe at energies of 0.1–1 GeV/n, at the NIRS (National Institute of Radiological Science) HIMAC or BNL (Brookhaven National Laboratory) NSRL. Detector/target stacks were each exposed to particle densities of about 1000 ions/cm^2. The CR-39 PNTD layers were then etched in 7 N NaOH solution at 70 °C for between 5 and 60 h. The resulting nuclear tracks were imaged using an HSP-1000 microscope with a $20\times$ objective lens (corresponding to 0.35 μm/pixel). The size and position of the imaged tracks were analyzed using the PitFit software [19].

4. Results

4.1. Response function

Correlations between nuclear track area and Z/β were obtained for the both of TD-1 and BARYOTRAK CR-39 PNTD as shown in Fig. 1a to assess the differences in charge resolution in both detectors. Here, the mean track area (A) of about 40 tracks in a 2×2 mm region of the detector was measured for each beam and normalized to 1 by the mean area of 200 MeV/n Xe ($Z/\beta = 96$) tracks to obtain A_{relative} for both detector types. Response functions were obtained by fitting the measured values with a polynomial function of the form:

$$A_{\mathrm{relative}}(Z,\beta) = a(Z/\beta)^3 + b(Z/\beta)^2 + c(Z/\beta) + d \quad (2)$$

where the coefficients a, b, c, and d are defined in Table 1. The normalization points in Fig. 1a were scaled as A_{real} (μm^2) = $3.12B^2 + 0.30B$ and A_{real} (μm^2) = $3.02B^2 - 0.70B$ for TD-1 and BARYOTRAK, respectively, where B (μm) is the amount of bulk etch for a given etching time. Using these relations, the vertical axis in the figure reproduces the values of nuclear track area for any value of bulk etch (i.e. for any etch time).

The minimum detection limits of Z/β in CR-39 PNTD analyzed using the HSP-1000/PitFit system were $Z/\beta = 5$ in TD-1 and $Z/\beta = 16$ in BARYOTRAK, respectively. In Fig. 1a, the slope for BARYOTRAK is substantially steeper than that for TD-1 in the lower Z/β region. The slope of the response function is closely connected with δZ, since the steeper slope enlarges a difference of A_Z and $A_{Z\text{-}1}$ (A_Z–$A_{Z\text{-}1}$), which is the denominator of Eq. (1), for a given $\delta(Z/\beta)$ (=Z/β–(Z-1)/β), leading to better charge resolution. The derivatives of response functions ($dA_{\mathrm{relative}}/d(Z/\beta)$) for both detectors were calculated from Eq. (2) as shown in Fig. 1b in order to see the Z/β dependence on the steepness of their slopes. These derivatives show that it is easier to distinguish individual nuclear charge for lower Z/β particles than for higher Z/β particles in both detector types. Also, BARYOTRAK has superior charge resolution for $16 < Z/\beta < 53$ than does TD-1, while TD-1 has superior charge resolution than BARYOTRAK for the other Z/β ranges ($5 < Z/\beta < 16$ and $53 < Z/\beta < 100$). Thus one can easily recognize how to use the two types of detectors selectively according to the demand of the experiment. However, the shape of the response function will