Fragmentation studies of high energy ions using CR39 nuclear track detectors

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Abstract

We report on the measurements of the total charge changing fragmentation cross sections in high-energy nucleus-nucleus collisions using Fe, Si and Pb incident ions. Several stacks of CR39 nuclear track detectors with different target combinations were exposed at normal incidence to high energy accelerator beams to integrated densities of about 2000 ions/cm\textsuperscript{2}. The nuclear track detector foils were chemically etched, and ion tracks were measured using an automatic image analyser system. The cross section determination is based on the charge identification of beam ions and their fragments and on the reconstruction of their path through the stacks.

Keywords: CR39; nuclear track detector; chemical etching; charge identification; total charge changing cross section

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1 Introduction

Fragmentation studies of high energy ions are relevant for nuclear physics, cosmic ray physics, astrophysics and applied physics [1]. High energy heavy ion fragmentation cross-sections are also useful to describe the effects of primary cosmic radiation hitting spacecraft walls. Important applications of the propagation of fast heavy ion beams through matter are given in space radiation protection and in the field of cancer therapy [2].

In this paper we present experimental results on the fragmentation of 158 A GeV lead ions, 1 A GeV and 0.41 A GeV iron ions and 1 A GeV silicon ions. These measurements are part of a series of exposures at CERN, Brookhaven National Laboratory and CHIBA aimed to study the response of the CR39 nuclear detector and to determine the fragmentation cross sections of Pb, Fe and Si ions projectiles. Targets of C, CR39, CH\textsubscript{2}, Al, Cu and Pb were used; they were chosen to be thin enough to minimise multiple interactions and thick enough to produce a sufficient number of fragments.

2 Experimental procedure

We exposed several stacks made of CR39 nuclear track detectors and different targets to different energy beams at: CERN-SPS, 158 A GeV Pb\textsuperscript{82+}; BNL-NSRL, 1 A GeV Fe\textsuperscript{26+} and

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Si$^{14+}$; CHIBA, 0.41 A GeV Fe$^{26+}$. Each stack has CR39 sheets upstream and downstream of the target. The exposures were performed at normal incidence. The charged fragments produced by projectile interactions with target nuclei keep most of the projectile longitudinal velocity. They can be detected after the target in CR39 detectors. Our CR39 sheets were manufactured by the Intercast Europe Co. of Parma, Italy, using a specially designed line of production [3].

The detection principle of the CR39 [4] is based on the fact that a through-going heavily ionising particle produces a cylindrical radiation-damaged region along the ion trajectory creating a “latent track”. This damaged region is chemically reactive and can be etched by an appropriate chemical treatment. As a result, an etched cone is formed on both sides of each detector sheet, see Fig. 1. The cones are visible under a microscope. After exposure, the CR39 detectors were etched for 30 h in a 6N NaOH water solution at a temperature of 70 °C.

![Figure 1: Left: Tracks of Pb$^{82+}$ ions and their fragments in a CR39 detector; for this photomicrography the detector was inclined to show both sides. Right: Sketch of an “etched track” in one side of the detector for a normally incident ion.](image)

An automatic image analyser system [5] was used to scan the detector surfaces and measure the etch-pit cone areas. For each etch-pit cone the base area, the eccentricity, the central brightness and the coordinates were measured.

A tracking procedure was used to reconstruct the path of the beam and of the fragments. To better identify the projectile and fragment charges we performed an average of the measured etch-pit areas for each track in 3 or more sheets. Distributions of the etched cone base areas for CR39 detectors located after the fragmentation targets are shown in Fig. 2. Well separated peaks for the primary ions and for fragments are observed and a charge can be assigned to individual peaks; for a given $z/\beta$ value, we have the same cone base area for different energies (Fig. 2).

The reduced etch rate $p = v_T/v_B$, where $v_T$ and $v_B$ are the track and bulk etch velocities, respectively, was used to characterise the detector response [6,7]. It was determined on the basis of the surface area measurements of the etch-pits. The response of the detector is...
given by the relation p vs REL (Restricted Energy Loss); the REL was computed using the Bethe-Block formula (Particle Data Group). Fig. 3 shows the measured calibration curves (p vs REL) for relativistic Pb, Fe and Si ions.

Figure 2: Distributions of the etched cone areas (average areas for each track over 3 sheets) for CR39 detectors located after the fragmentation targets. Peaks for incident ions and their fragments are well separated and charges can be assigned to each peak. For a given z/β value, we have the same cone base area for different beam energies.

3 Total charge-changing cross sections

For the determination of the total charge-changing cross sections, σtot, the number of beam ions before the target (incident ions) and the number of beam ions after the targets were measured [8-11]. The target thicknesses were chosen to optimise the fragmentation process.

Our measured σtot for the collisions of 158 A GeV Pb ions, 1 A GeV Fe26+ and Si14+ and 0.41 A GeV Fe26+ on different targets are given in the sixth column of Table 1. The fragmentation charge-changing cross section for beam ions was evaluated using the formula

\[ \sigma_{\text{tot}}(\exp) = X_T \cdot \ln\left( \frac{N_i}{N_s} \right) \] (1)

where \( X_T = \frac{A_T}{\rho_T} \cdot t_T \cdot N_A \) for each target; \( N_i \) is the number of primary ions, \( N_s \) the number of beam ions surviving after the target, \( \rho_T \) the target density, \( A_T \) the atomic mass of the target, \( t_T \) the target thickness and \( N_A \) is the Avogadro number. In this procedure, successive fragmentation processes are neglected. Hydrogen cross sections were obtained from the measured cross sections on carbon and on CH₂ using the formula:
\[ \sigma_H = \frac{1}{2}(3\sigma_{CH_2} - \sigma_C) \quad (2) \]

We compare our experimental cross-sections with the geometric collision cross section for a projectile of mass number \( A_p \) on a target of mass number \( A_T \):

\[ \sigma_{\text{tot(\text{theo})}} = \pi r_0^2 (A_p^{1/3} + A_T^{1/3} - b)^2 \quad (3) \]

assuming \( r_0 = 1.35 \text{ fm} \) and \( b = 0.83 \) [12]. These theoretical cross sections are given in the 7th column of Table 1.

Figure 3: \( p \) vs REL calibration curves for CR39 exposed to Lead, Iron and Silicon ions of different energies.

4 Conclusions

The total charge-changing cross sections in different targets were measured using beams of Pb nuclei of 158 A GeV, 1 A GeV Fe\(^{26+}\) and Si\(^{14+}\), 0.41 A GeV Fe\(^{26+}\) with CR39 nuclear track detectors placed before and after the targets, Table 1. Our results are in agreement with the theoretical values given by Eq. (3).

The calibration of the CR39 was determined by the relation \( p \) vs REL (Restricted Energy Loss) that shows that a unique curve gives the response of the detector at different energies.

We also exposed different stacks of CR39 to 3, 5 and 10 A GeV for both Fe and Si ions at the BNL AGS. These studies are in progress and should become available in the near future.

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Table 1: The total charge-changing cross sections for Pb, Fe and Si ion projectiles on different targets. The cross sections on CH\(_2\) and CR39 are averages, as indicated in column 2. The data given in the last 3 rows are preliminary. The quoted uncertainties on \(\sigma_{\text{tot}}^{(\text{exp.})}\) are only statistical.

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