Identification of nuclear fragments formed during fragmentation reaction with heavy ion beam using hybrid system of silver halide photography and plastic track detector CR-39

Ken'ichi KUGE*, Kentaro HAYASHI*, Yusuke ENDO*, Nakahiro YASUDA**, Chika FUKUSHIMA, Hiroshi SHIBUYA***, Akira HASEGAWA*, Hiroshi KUMAGAI****;***
****Faculty of Engineering, Chiba University, Chiba, ** National Institute of Radiological Sciences, Chiba, ***Faculty of Science, Toho University, Funabashi, ****Radio Isotope Center, Chiba University, Chiba, Japan.***

Abstract

This is a feasibility study to measure nuclear fragment reactions in tissue equivalent materials to estimate absorbed dose for carbon ion cancer therapy. A hybrid system was developed for identifying the nuclear charge of high energy ions from Z=1 to Z=6 by combining a silver halide photographic film and the CR-39 plastic track detector. The photographic film (the nuclear emulsion) is able to record the minimum ionizing particles such as high energy protons, while CR-39 records the tracks of heavier ions. Lines of silver clusters on the photographic films were analyzed using the ultra track selector (UTS), and this provided the peak height volumes (PHV) considered as the volumes of the lines. The etch pits on the surface of CR-39 were analyzed with the scanning optical microscope and this provided the minor axes of the etch pits. The mapping image of the etch pits was superimposed with that of the silver clusters, and the correspondence of the positions was analyzed. Three peaks were detected on the minor axis, and they were due to the ions of C, B, and Be. Similar three peaks were observed on the PHV, but the position correspondence suggested that the largest peak was due to the ions of C, B, and Be. Peak analysis of the other peaks indicated two peaks and one shoulder, which must be due to the ions of H, He, and Li.

Introduction

A heavy ion beam is a stream of high energy ions that comprise atomic nuclei whose masses are greater than those of protons. When the ions pass through some materials, a fragmentation reaction occasionally occurs in which an atomic nucleus is divided into fragments of smaller nuclei. However, we do not have a large stock of knowledge about the fragmentation reaction.

This beam, especially carbon, is used for the cancer therapy because the dose arises dramatically at the end of range of ions (in the tumor). As consequence, it decreases the surface (skin) dose administered to the patient[1] in contrast to X-ray cancer therapy. On the other hand, the carbon beam will be fragmented by nuclear reactions in material (tissue) into lighter ions. Detailed information such as nuclear charge and emission angle of the fragmented ions is also indispensable for the accurate dose measurements, because the influence of each ion is different. It is required that the detecting method to identify the nuclear charge of fragmented ions from nuclear reactions with higher special resolution.

The linear energy transfer (LET) is the amount of energy supplied to a certain material par unit length in the material. Because LET is proportional to the square of particle charge (Z) and to the inverse of square of velocity β= v/c, c is the velocity of light. The energy of therapeutic carbon beam is about several hundred MeV/u, and is corresponding to β= 0.6 – 0.7. The projectile fragmentation reaction is dominated in this energy region, means that the produced lighter ions having similar velocity of projectile will be emitted from reaction point. Therefore, the identification must be possible by detecting the difference of LET[2].

CR-39 plastic nuclear track detector (PNTD) is a thermoset polymer sensitive to charged particles of LET between 5 and 1500 keV/µm. The passage of a charged particle through the detector breaks the chemical bonds of the material and leaves what is known as a latent damage trail. Following exposure, the PNTD is chemically etched in a solution of NaOH at high temperature (50°C - 90°C). The etching solution preferentially attacks the latent damage trail, leaving a conical pit along the trajectory of the charged particle. The dimensions of the elliptical intersection of the conical track and the detector surface are proportional to the LET of the original charged particle. It is well known that the CR-39 PNTD has high charge resolution, but is has no sensitivity for lower LET ions. For instance, the CR-39 PNTD is able to detect the ions having nuclear charge down to Z=3 or Z=4 at this energy.

On the other hand, the photographic film (nuclear emulsion) is able to record the minimum ionizing particles such as high energy electrons. It forms lines of latent image specks along the nuclear track in an emulsion layer, when the ions pass through the emulsion. Silver clusters appear during development treatment and form visible lines of silver clusters. At this energy, the photographic film can detect all types of ions and δ-electrons which associate with ions. Difference of nuclear charge can be observed as the difference of the width of track (line). However the width might be saturated when the ions having higher nuclear charge, means that we can distinguish only the nuclear charge Z=1 and Z=2 from the track width information.

Therefore, we developed a hybrid detector based on the combination of the photographic film and CR-39, which is expected to be able to identify all types of ions. This type of hybrid detector must be capable of obtaining a large amount of data for statistical treatments. We stacked the photograph films and CR-39 plates and tested the hybrid detector by analyzing the tracks formed on them.

Experimental

The CR-39 plates used were HARZLAS TD-1 (FUKUVI), and the photographic films were OPERA films (Fuji Photo Film) developed for the OPERA experiment[3]. The films and plates were stacked by superposing one of their corners. These stacks were vacuum packed using a light-shielded laminate film to fix all plates and films. The stacks were vertically exposed to 290 MeV/u C ions at an exposure density of 3000 ions/cm^2 by using the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences. An acrylic plate was set in front of the stack. The energy of ions decreased to about 160 MeV after passing through this filter. At the same time, a small number of fragmentation reaction occurred in the filter by few C ions. This produced five types of fragments from H to B ions. The CR-39 plate was etched in a sodium hydroxide solution of 7 mol/l at 70 ^{o}C for 16 h. The OPERA film was developed in an amidol developer, which is generally used for track detection, at 20 ^{o}C for 25 min.

The size of the etch pits on the CR-39 plate was measured with a scanning optical microscope connected to a personal computer to obtain a large amount of data[4]. Mapping data of the etch pits was obtained simultaneously. This data provided positional information; the superposed corner of each plate was regarded as the origin of the coordinate system. We measured the track volumes of silver clusters on the photograph film by using the ultra track selector (UTS)[5] at Toho University. An emulsion layer was divided into 16 thin layers, and the area of the silver clusters in each layer was measured. The peak height volume (PHV) was calculated by adding the areas in each layer. The PHV was considered as the relative volume of the silver clusters in the emulsion layer, and it correlated to the LET[5]. Mapping data of the silver clusters was also obtained.

Because some ions did not enter vertically and both the CR-39 plate and the photograph film have some thickness, positions of the etch pits and the silver clusters are not always at the same location. In order to consider the correspondence of the etch pits and the silver clusters formed by the same ion, the affine transformation was used to obtain the best fit. The etch pit image on CR-39 was superimposed on the silver cluster image on the photographic film. All distances from a silver cluster to the etch pits on CR-39 were measured, and the most suitable translation to be superimposed the both images was obtained by analyzing the distance distribution. Thus, the tracks on the photographic film that did not have the correspondence to the tracks on the CR-39 plate were picked up.

Results and Discussion

Figure 1 shows the distribution along the minor axes of the etch pits on CR-39 in a square of 1.4 cm. Three peaks were obtained, and the peak for the largest minor axis was significantly higher than the others; it increased beyond the upper boundary of the figure. Those three peaks were identified from the left to be due to Be, B and C ions from the data of previous measurements, respectively. Therefore, the identification of these three ions was achieved distinctly, while the ions of H, He, and Li were not detected.

Figure 2 shows the distribution of the PHV on the OPERA films in a square of 1 cm and the result of the correspondence with the tracks on CR-39 and the OPERA film. Both figures are the same; however, the dark areas in figures (b) and (a) indicate tracks that did and did not correspond to the etch pits on CR-39, respectively. Three peaks are observed, and the peak for the largest PHV value is significantly higher than the others. The correspondence of the peaks in figure (a) and in figure 1 indicates that the largest peak is not only due to C ions but also due to Be and B ions. Thus, the dark area in figure (b) should be due to the other ions of H, He, and Li because they cannot form tracks on CR-39. Only two peaks appear in this area, while three types of ions form tracks.

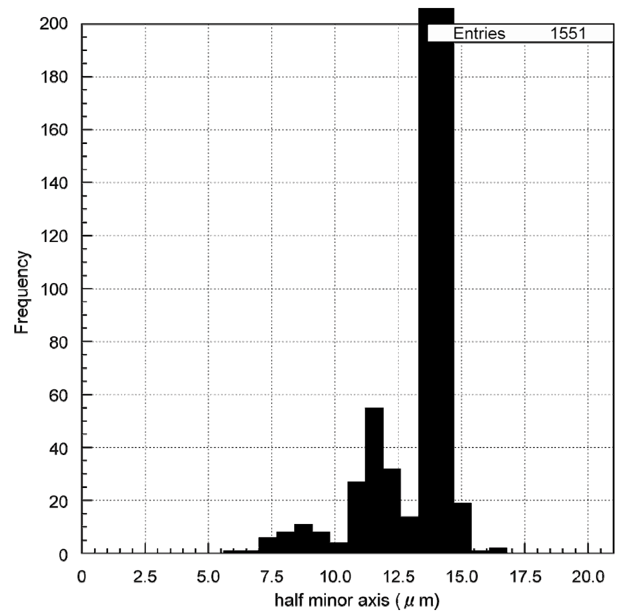

Figure 1.
Histogram in half minor axis of etch pits on CR39 in a 1.4 cm square.

The fragmentation reaction of the C ion beam forms the fragments from H to B ions. Among those ions, the ions of Be, B, and C were identified with CR-39 distinctly. The ions of H, He, and Li were detected only as the PHV peaks on the photographic film. They were separated from the other heavy ions, although only two peaks were observed. However, the peak analysis revealed the shoulder on the right side of the center peak. Therefore, the peaks consisted of three components, which could be corresponded to H, He, and Li ions.

The conditions of emulsion and development in this study could not provide distinct separation of the peaks. The separation might be achieved by improving these conditions. We have proposed a method for the gold deposition development[6] and this method was also useful for the detection of nuclear tracks[7] because it improved the spatial resolution of the PHV. Effective separation can be achieved by employing this method.

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Author Biography

Ken’ichi KUGE received his D. degree in Engineering from Kyoto University in 1984. Since 1979 he has worked in the Department of Imaging Science (the present name ; Department of Information and Imaging Sciences) at Chiba University in Chiba. His work has primarily focused on the silver halide photographic science, including photosensitivity and sensitization. Recently his focus has been expanded to novel imaging systems based on silver halide technology. He is a member of the IS&T and the JSPST.

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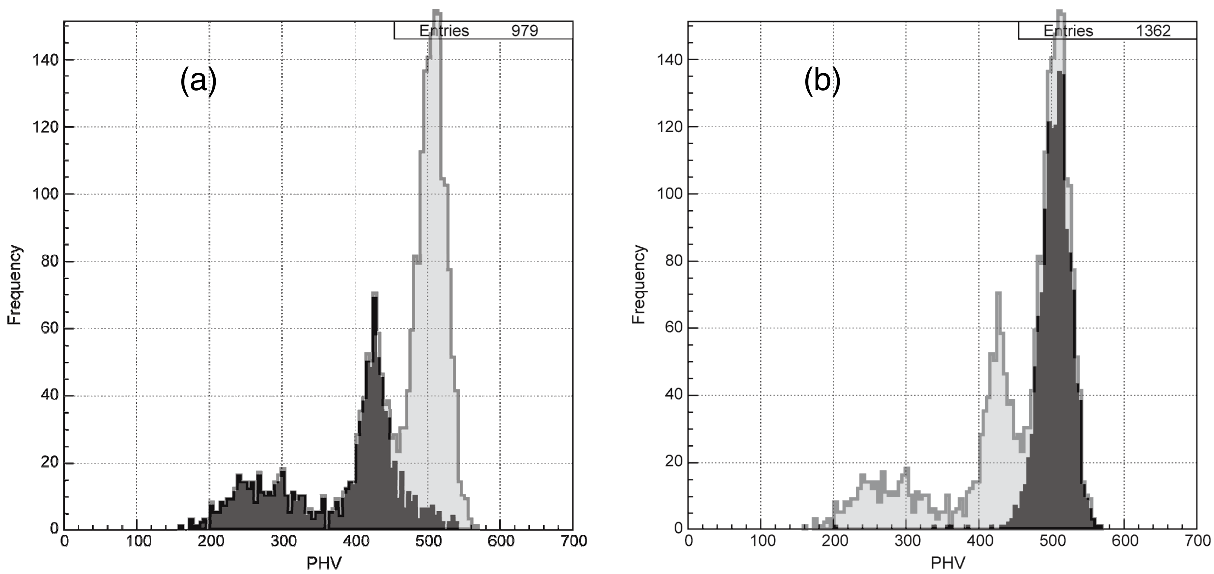

***Figure 2**.*
Histogram in PHV on OPERA film in a 1 cm square. Both figures are the same histogram except that the dark area in (a) indicates the tracks without a correspondence to the etch pits on CR-39, and the dark area in the right figure (b) indicates the tracks having the correspondence.