Recent progress in emulsion technology to study fragmentation reactions of high energetic ion beams

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Abstract

The R&D project to study nuclear fragmentation using emulsion in attempt to improve the accuracy of dose calculation in carbon ion radiotherapy has been carried out at NIRS-HIMAC since 2003. Based on the developed techniques, we are accumulating experimental data of fragmentation reactions for various beams and target

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combinations. In this programme we are also developing the practical application of hybrid apparatus of emulsion and CR-39, and performing basic study of gold deposition development in order to improve measurement of ionization.

Key words: nuclear emulsion, charge identification, heavy ion

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1 Introduction

Knowledge of the nuclear fragmentation reactions is very important for many different applications including heavy ion radiotherapy [1] and shielding against Galactic Cosmic Rays during manned missions outside the earth magnetic field [2]. For example, carbon ions of several hundred MeV/u are currently used for radiotherapy at several facilities in the world because of their therapeutic advantages over conventional photon radiation or proton beams. Radiotherapy with beams of heavy ions provides highly localized dose distributions at the end of the range (called Bragg peak). However, the projectile fragmentation products can cause an undesired dose beyond the Bragg peak. Though this effect can be estimated if the charge-changing cross sections of carbon ions in tissue equivalent materials, e.g., water, is known and the cross sections were measured in several experiments [3], yet the current knowledge of fragmentation of carbon ion is not satisfactory and experimental studies have been carried out in recent years [4].

Emulsion is one of the most suitable devices to study the fragmentation of heavy ions in high energetic nucleus-nucleus interactions, since it has the capability of spatial resolution of micron-order and excellent multi-particle separation in nearly 4π solid angle. Despite these advantages, this technology has not been applied in the past to a high statistic experiment because the track recognition is quite time-consuming due to the manual scanning of emulsion. However, the automatic image processing system called Ultra Track Selector (UTS) developed in Japan [5] improved the scanning procedure drastically. In the DONUT experiment, the first observation of tau neutrino interaction was accomplished by NETSCAN method [6,7]: a combination of UTS and the off-line program treating a vast amount of read-out track data. Presently, more than 50 times higher speed system called Super-UTS, whose scanning speed is several 10 cm^2/hour, is in practical use and used for OPERA experiment [8] which is ongoing long baseline neutrino oscillation experiment. Another key device in the recent emulsion technology is an OPERA film [9] which is a mass-produced emulsion film developed for the OPERA experiment. Motivated by these remarkable progress in the nuclear emulsion technology, we launched a project to apply it to study the interactions of relativistic heavy ions in matter at HIMAC (Heavy Ion Medical Accelerator in Chiba) at NIRS (National Institute of Radiological Sciences), Chiba, Japan in 2003.

In this paper we review the recent progress in emulsion technology to study fragmentation reactions of high energetic ion beams and report the current status of our ongoing experiment.

2 Charge identification by refreshing method

Charge identification of ions in nuclear emulsion is essential for the study of fragmentation, though its automated procedure has not been established yet.

The UTS system records a pulse hight for each track. The pulse hight is in proportion to dE/dx for relativistic singly charged particles [10]. However, we found the saturation of pulse hight for highly ionizing particles like ions. Therefore the key technology we needed to develop was a realization of non-saturating OPERA films for highly ionizing particles. To realize a emulsion film of above mentioned quality, we studied a possibility to utilize the so-called refreshing technique. Refreshing is a technology to erase tracks in emulsion film by means of forced fading. It is caused by destruction of latent image center in a silver bromide crystal by oxidation. OPERA film has capability of refreshing [9]. This implies that, adjusting the amount of forced fading of track images in the film by controlling temperature and humidity, the saturation of grain density by passage of ions can be resolved.

We conducted an experiment to study charge identification by refreshing method using HIMAC synchrotron and demonstrated that the charge of He, Li, Be, B and C, whose energies were around 290 MeV/u, were well discriminated [11]. Also this method was studied by using an emulsion scanning system developed in Italy [12].

3 Measurements of charge-changing cross section and production cross sections of ^{8}Be and ^{9}B

After establishing the charge identification, we developed the Emulsion Cloud Chamber (ECC) to measure the fragmentation reaction of carbon interacting with tissue equivalent material of water and polycarbonate. The ECC was designed so that it can store information about all fragmentation reactions over the whole region where primary carbons penetrate the chamber (Fig. 1). Each emulsion module has four emulsion sheets reinforced with a polycarbonate plate and is vacuum-packed with an aluminum-coated film for light and water shielding. The OPERA film was used as the emulsion sheet. All emulsion sheets in the chamber were inspected using UTS. Reconstruction of tracks and vertices was performed by off-line program in the NETSCAN framework. The charge of each individual track was identified by using the combination of pulse heights measured in several emulsion sheets having undergone different refreshing treatments. We measured total and partial charge-changing cross sections for the productions of B, Be and Li fragments for 200- to 400-MeV/u ^{12}C on water and polycarbonate [13]. This measurement is important to evaluate the spatial profile of their energy deposition in the human body.

Further analysis to detect ^{8}Be and ^{9}B productions has been performed. These nuclides are unstable and promptly decay into α particles or proton. Production of projectile-like ^{8}Be fragments in reactions of relativistic nuclei has been studied previously using emulsion [14]. We observed ^{8}Be production in a few 100 MeV/u ^{12}C on water as a prominent peak in opening angle between two α particles around 10 mrad. Our high statistic data made it possible to investigate correlations of three secondary particles (α-α -p) and detect two-stage decay of ^{9}B: $^{9}\mathrm{B} \rightarrow \mathrm{p} + {}^{8}\mathrm{Be} \rightarrow \mathrm{p} + (\alpha+\alpha)$. It was observed as a prominent peak in opening angle between ^{8}Be and proton around 20 mrad . Detail of analysis including measurements of cross sections will be the subject of a forthcoming paper. Detection of peaks at small opening angle requires very high precision measurement of track angle and multi-particle separation. Emulsion has an unique capability to study the production of these nuclides in the energy region over 100 MeV/u.

In addition, emulsion detector has a potential to identify the mass of each fragment if we install it in magnetic field [15]. Mass of the fragments can be derived from magnetic rigidity and energy loss. The identification of exclusive reaction mode such as p + ^{12}C leading to d + ^{11}C will be feasible in the future.

4 Hybrid chamber with CR-39

A CR-39 plastic nuclear track detector has been used to measure the fragmentation reactions. The tracks can be observed as pits after etching process, and its radius is correlated with the energy loss. CR-39 has been used as a device to identify the charge of particles whose charges are more than approximately four. However, this device is not sensitive to low charge particles such as proton, helium and lithium. We considered hybrid detector of emulsion and CR-39, expecting complementary capability for charge identification.

We developed the hybrid chamber of emulsion and CR-39 to measure the fragments produced in the reactions of $\sim$ 400 MeV/u carbon beams interacting with carbon targets (Fig. 2). Each module is consists of three OPERA films for different refreshing treatments. CR-39 is installed every five layer of detector modules. A high speed imaging microscope with track analysis software for CR-39 [16] was used to obtain the charge information. An area of 4 cm $\times$ 4 cm was scanned in each OPERA film and CR-39. Tracks detected in the two devices in the same module were connected. Fig. 3 shows the distribution of pulse heights and radius of etch pits for the connected tracks measured in the modules located at approximately 64 mm far from upstream surface of the chamber (21st module from upstream). Tracks detected in the OPERA film with higher pulse heights are detected also in CR-39, and charge of Be, B and C nuclei are well discriminated by the radius of etch pits. On the contrary, tracks detected in the OPERA film with lower pulse heights are not connected to CR-39. Li and Be nuclei will be identified with the refreshing method. We will use this technique to study the fragmentation of higher charge beams like O, Ca and Fe.

5 Gold deposition development

To improve the ionization measurement greatly we are studying a possibility to use the so-called gold deposition development [17]. When charged particles pass through the emulsion, a latent image is recorded on the silver bromide crystal due to ionization. After normal development, silver bromide crystals having at least one latent image speck change into silver grains. On the other hand, gold deposition development is a kind of physical development in which gold grains are formed by the reduction of gold ions in the developer. The gold grain is created from each latent image speck and form a spherical structure. This gold deposition development is known as a method to observe a latent image speck in the crystal. This implies that, counting the number of latent image specks along tracks, finer geometrical structure of energy deposit can be observed. We have developed the way to observe latent image specks along track [18]. Fig. 4 shows electron micrographs of 388 MeV/u carbon beam and 5 MeV α particle in OPERA film visualized with gold deposition development. More detailed study such as relationships between dE/dx and liner density of the latent image specks along tracks will be the subject of a forthcoming paper. This method will be useful for high precision ionization measurement, and study of production mechanism of latent image specks in the silver bromide crystals.

6 Conclusion

We have pursued a unique capability of newly developed emulsion technology to study nuclear fragmentation. We are now accumulating heavy ion interactions with light nuclei (like C, O, H, Ca and P) in the energy range up to 400 MeV/u to establish a database of the reactions which are important for the dose calculation of the heavy ion radiotherapy and advancing R&D for improving particle identification. In the future, we will attack more challenging studies, for example, identification of the mass of the fragments by using magnetic spectrometer [15], and precise measurement of the production cross section of neutron. Because these measurements require high statistic and high resolution measurement, the emulsion will be very suitable device for these studies.

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Figure captions

Fig.1

(a) A schematic view of the whole structure of the water target Emulsion Cloud Chamber (ECC). (b) Detailed structure of emulsion modules.

Fig.2

A schematic view of the whole structure of the carbon target Emulsion Cloud Chamber (ECC).

Fig.3

(left) Distribution of pulse height measured in an OPERA film which is not refreshed. Solid line: only tracks connected to CR-39. Dashed line: all tracks. (right) Distribution of radius of etch pits measured in CR-39. An OPERA film and a CR-39 were in the same module. Distance from upstream surface of the chamber to this module was approximately 64 mm.

Fig.4

Electron micrographs of tracks visualized with gold deposition development. (left) 388 MeV/u ^{12}C. (right) 5 MeV α particle.

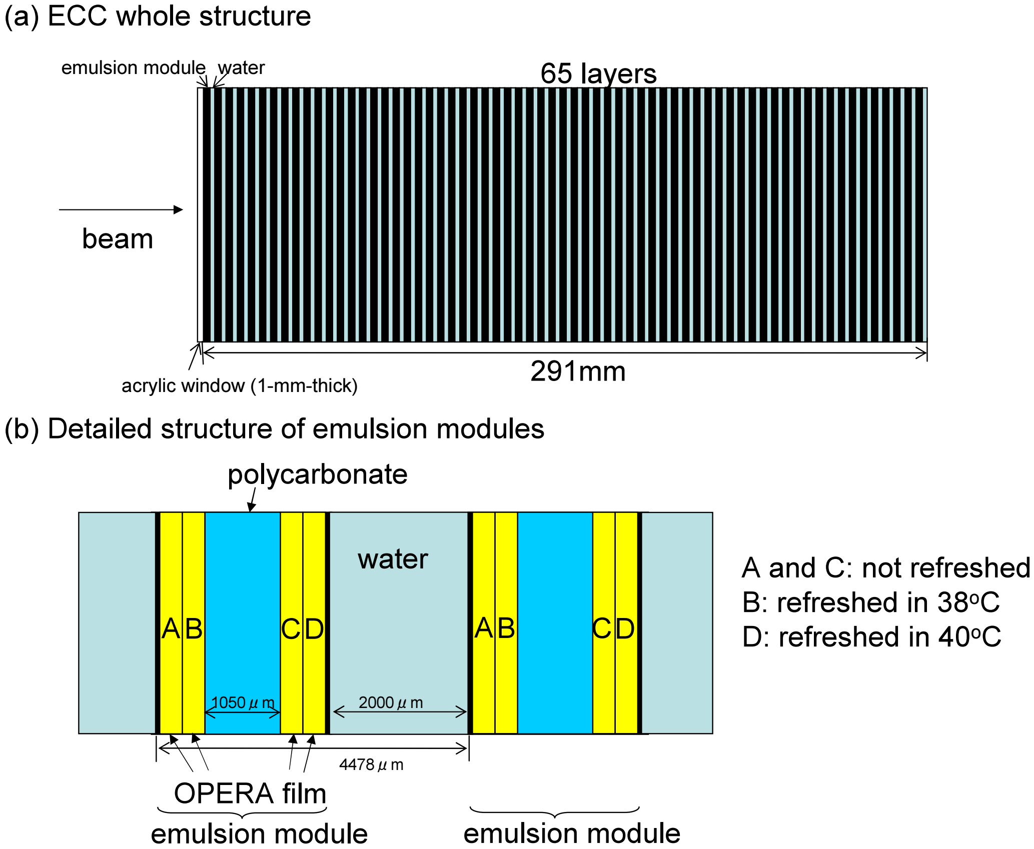
(a) ECC whole structure
emulsion module
water
65 layers
beam
acrylic window (1-mm-thick)
291mm
(b) Detailed structure of emulsion modules
polycarbonate
water
A
B
C
D
A
B
C
D
1050 μ m
2000 μ m
4478 μ m
A and C: not refreshed
B: refreshed in 38°C
D: refreshed in 40°C
OPERA film
emulsion module
emulsion module

Fig. 1.

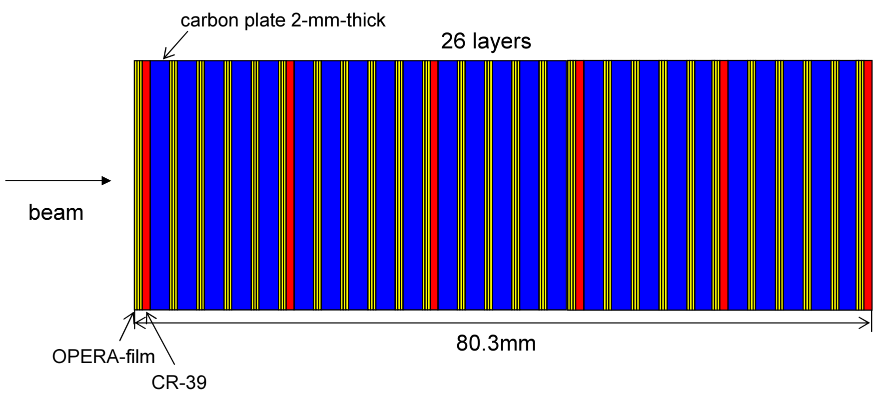
carbon plate 2-mm-thick
26 layers
beam
80.3mm
OPERA-film
CR-39

Fig. 2.

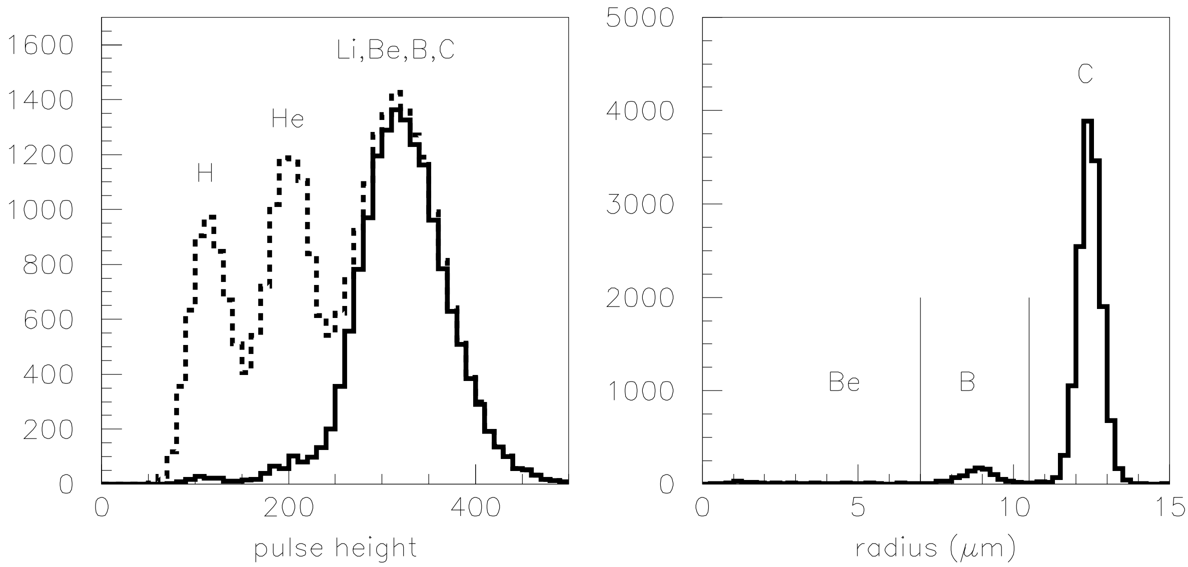
1600
1400
1200
1000
800
600
400
200
0
0
200
400
pulse height
H
He
Li,Be,B,C
5000
4000
3000
2000
1000
0
0
5
10
15
radius (μm)
Be
B
C

Fig. 3.

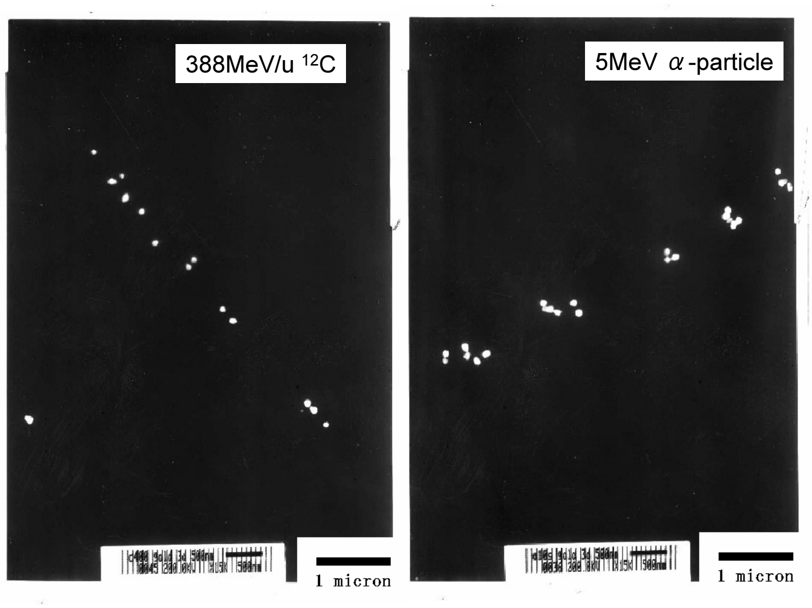
388MeV/u 12C
5MeV α-particle
1 micron
1 micron

Fig. 4.