Measurement of the Fragmentation of 400 MeV/nucleon Carbon Nuclei Used in Hadron-Therapy by the Nuclear Emulsion Technology

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Abstract In the cancer treatment by the hadron-therapy, beams of Carbon nuclei present therapeutic advantages over proton beams. The knowledge of the fragmentation of Carbon nuclei when they interact with human tissues is important to evaluate the spatial profile of the energy deposition in the human body, hence maximizing the effectiveness in hitting the cancer with minimal damage to the neighbouring tissues. The measurement is also of interest for the evaluation of the biological damage by cosmic rays to astronauts in space missions.

Nuclear emulsions allow to measure particle trajectories with space resolution at the micrometric level. In the Emulsion Cloud Chamber (ECC) technique, nuclear emulsion films are interleaved with plates of passive material in a multiple sandwich structure. This allows to integrate the target and the fragment detector in a very compact structure. The development of techniques of controlled fading of particle tracks in nuclear emulsions has opened the way to measurements of the specific ionisation over a very broad dynamic range.

The data presented in this paper have been obtained by exposing an ECC to a beam of Carbon nuclei with 400 MeV/nucleon at the Heavy Ion Medical Accelerator in Chiba, Japan. The ECC consisted of emulsion films and, as passive material, of polycarbonate with a density similar to that of the human body.

We report on the identification of nuclear fragments through the measurement of their specific ionisation, linked to the electrical charge. The results provide also features of the interactions such as the scattering angles for the different ions. We finally report the measurement of the partial charge-changing cross-sections, and in particular the production cross-section of low charge fragments, which is poorly known. The cross-sections obtained in this work are compared to those available from other experiments.

Key words: hadrontherapy, carbon beams, cross-sections

1. Introduction

Unlike the electromagnetic radiation conventionally used for cancer treatment, charged hadrons deposit most of their energy in a restricted domain around the end of their ionization range. This leads to a high therapeutic effectiveness with minimal damage to neighbouring tissues. This is the merit of the so-called hadron-therapy. The tissue thickness traversed before depositing their energy can be tuned by changing the energy of the nuclei, which is typically of a few hundreds MeV/nucleon. Among hadrons, the use of nuclei heavier than protons is expected to improve the therapeutic effectiveness. Light nuclei and in particular Carbon nuclei are now used or planned to be used for cancer therapy in a number of dedicated facilities around the world. The nuclear fragments generated in the interaction of the projectile nuclei inside the patient body go, however, beyond their ionization range thus producing some damage in the tissues downstream of the tumor. The study of the fragmentation of the projectile nuclei is therefore important to improve the precision achievable in hitting the tumor with minimal effects on the neighbouring tissues. Moreover, the data obtained in fragmentation studies contribute to define the parameters of nuclear interaction models entering in computer programs which simulate the biological effects for the optimization of their effectiveness. Studies of the nuclear fragmentation are currently carried out using a target which, from the point of view of nuclear interactions, has properties close to those of the human body. The nuclear fragments are conventionally observed by detectors external to the target. Their identification can be achieved by comparing the energy loss in a plastic scintillator and the total residual energy in a BGO scintillator. The total charge-changing and partial cross-section of $^{12}$C in carbon, paraffin and water was reported by using etched track detectors. The Emulsion Cloud Chamber (ECC) technique consists of using a sequence of nuclear emulsion films interleaved with passive material and thus allows to integrate the target and the fragment detector in a very compact set-up. Nuclear emulsions allow the measurement of the fragments' emission angles event by event with granularity and space resolution at the micrometric level. The development of techniques of controlled fading of particle tracks has opened the way to measurements of the specific ionization over a very broad dynamic range. This work is devoted to the detailed study of the fragmentation of a Carbon beam.

2. The Emulsion Cloud Chamber and the beam exposure

We have built an ECC made of a sequence of nuclear emulsion films interleaved, as passive material, with 1 mm thick plates of
polycarbonate in a multiple sandwich structure. The polycarbonate has a density of 1.15 g/cm$^3$ and an electron density of $3.6 \times 10^{23}$ cm$^{-3}$. For comparison, the electron density of water (the main constituent of the human body) is $3.3 \times 10^{22}$ cm$^{-3}$. Thus the target has similar characteristics to water as far as nuclear interactions are concerned. The ECC consisted of 73 consecutive modules, each made of three emulsion films interleaved with polycarbonate plates. Its structure is shown in Fig. 1. The chamber length allows the study of the Bragg peak too. The 3 emulsion films, denoted as $R_0$, $R_1$, and $R_2$, were treated differently after the exposure and before their chemical development. $R_0$ was not refreshed and was developed soon after the exposure. $R_1$ and $R_2$ underwent a 3 day refreshing at 98% relative humidity with 30°C and 38°C temperature, respectively. The pile of emulsions and polycarbonate plates was vacuum packed. A light-tight aluminum tape was used to protect the pile from light. The ECC was exposed to a beam of $^{12}$C nuclei with an energy of 400 MeV/nucleon at the Heavy Ion Medical Accelerator (HIMAC) in Chiba (Japan). The beam flux was monitored by a scintillator counter. On the emulsion films, an integrated flux of about 10 $^{12}$ nuclei/mm$^2$ was obtained. The ECC was placed in three positions: with emulsion films perpendicular to the beam and inclined of $\pm 150$ mrad. The tilted exposures were meant to improve the film to film alignment.

The chemical development was carried out at the Nagoya University. After the development, the films were brought to Naples University where they were analyzed by fast automated microscopes operating at a speed of 20 cm$^2$/hour with tracking efficiency larger than 90% and high purity ($\sim$2 fake tracks/cm$^2$).

3. Analysis methods

The automated microscopes have a focal depth of a few $\mu$m. By varying the focal plane over 20 levels along the depth of the emulsion layers, they gather a series of tomographic images which are read by a CMOS camera. A track is seen as a sequence of grains at different depths, each grain consisting of a cluster of pixels. Apart from saturation effects, the grain density along the particle path is proportional to the specific ionization. Therefore as a variable sensitive to the specific ionization, hence to the particle charge, we take the sum of the pixels of all the grains belonging to the track normalized to a given track length in the emulsions. This sum is called track volume. In the data acquisition, the automated microscope reconstructs the so-called micro-tracks, a micro-track being a sequence of aligned grains in a 44 $\mu$m emulsion layer. The alignment, within errors, of two micro-tracks in a film gives a so-called base-track. Base-tracks are characterized by a higher angular precision than micro-tracks, because of the lever arm given by the thickness of the plastic base and because the grains close to the base do not suffer the distortions resulting from the chemical development. After the alignment, base-tracks are associated to form tracks of particles. Each track is characterized by three track volume variables ($VR_0$, $VR_1$, and $VR_2$), one for each refreshing condition of the films traversed by the track. By averaging over the base-tracks in the emulsions having undergone the same refreshing, the statistical error on the track volume is reduced thus providing a better charge discrimination.

The $R_2$ refreshing procedure produces the complete erasing of all tracks of particle with charge equal to 1. Therefore, for proton identification only $VR_0$ and $VR_1$ are used. For Helium and heavier nuclei only $VR_1$ and $VR_2$ are effective, since $VR_0$ shows saturation. The charge separation is obtained by looking at correlations between appropriate pairs of track volume variables.

4. Results

We have scanned an emulsion surface $S=2.325$ cm$^2$ of 79 consecutive emulsion films. This corresponds to an ECC volume of 24 cm$^3$, including 78 Lexan plates. About 2300 interaction vertices have been reconstructed. All the fragments have been analyzed. Fig. 2a shows the scatter plot of $VR_0$ versus $VR_1$ for the fragmentation products. We see two distinct peaks corresponding to H and He. Heavier ions are not clearly identified. By projecting the scatter plot onto an axis passing through the centres of the two peaks, we obtain the distribution of the variable $VR_{12}$ shown in Fig. 2b. A good separation between H and He is visible. Fig. 3a shows the scatter plot of $VR_1$ versus $VR_2$ for the fragmentation products. The separation of Helium, Lithium, Beryllium, Boron and Carbon becomes clear. By projecting the scatter plot onto an axis passing through the centres of the peaks, we obtain the distribution of the variable $VR_{12}$ shown in Fig. 3b. These results have been published.

Fig. 4 shows the production angle (with respect to the Carbon parent angle) for $Z=1$ (a) and $Z=2$ (b) secondary tracks connected to multi-prong vertices. The $Z=1$ particles are the lightest fragmentation products and are produced at larger angles. The fragments produced by Carbon primary interactions show in turn secondary interactions: the distribution of the path length for $Z=1$ (a) and $Z=2$ (b) particles are shown in Fig. 5. The interaction length for $Z=1$ particles is $\lambda_1=14.0 \pm 1.2$ mm while for $Z=2$ particles is $\lambda_2=19.3 \pm 2.3$ mm.

With the overall collected statistics of interactions we have measured the charge changing cross-sections. We call $\Delta z$ the difference between the charge of the Carbon incident beam and the maximum charge of the produced fragments so that, for instance, $\sigma(\Delta z=3)$ denotes the cross-section of the Carbon interacting with lexan and producing Lithium and lighter fragments. The obtained results are:

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\sigma(\Delta z=3) = (1650 \pm 120) \text{ mbar.n.}
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\[
\sigma(\Delta z=2) = (1060 \pm 100) \text{ mbar.n.}
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\[
\sigma(\Delta z=1) = (2330 \pm 150) \text{ mbar.n.}
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These results are consistent with the ones obtained in Ref. 7.)
Fig. 2 Scatter plot of $VR_0$ versus $VR_1$, providing the separation of H from He and heavier nuclei (a). The distribution of $VR_{01}$, providing the H and He separation (b). The tracks originate from the fragmentation of carbon nuclei all along the chamber.

Fig. 3 Scatter plot of $VR_1$ versus $VR_2$ (a). The distribution of $VR_{12}$, showing the separation between He, Li, Be, B and C (b). The tracks originate from the fragmentation of carbon nuclei all along the chamber.

Fig. 4 Scattering angle of H (a) and He (b) fragments.
Fig. 5  Path length for $Z=1$ (a) and $Z=2$ (b) particles showing a secondary interaction in ECC cell units (1 cell corresponds to one polycarbonate plate and one emulsion film and has a total length of 1.3 mm)

References

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