Radiation Protection Dosimetry (2006), Vol. 122, No. 1–4, pp. 485–487
Advance Access publication 4 December 2006
doi:10.1093/rpd/ncl402

EXPERIMENTAL FRAGMENTATION STUDIES WITH ^{12}C THERAPY BEAMS

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High-energy beams of ^{12}C ions in the range of 80-430 MeV u^{-1} delivered by the heavy-ion synchrotron SIS-18 are used for radiotherapy of deep-seated localized tumors at the treatment unit at GSI Darmstadt. In order to improve the physical database, the fragmentation characteristics along the penetration path in tissue were investigated experimentally by using a water phantom as tissue-equivalent absorber. Measurements were performed at specific energies of 200 and 400 MeV u^{-1} of the incident ^{12}C ions and at six different depths before and behind the Bragg peak. Secondary fragments with nuclear charges $Z_f = 1$–5 were identified by scintillation detectors using ΔE–E and time-of-flight techniques. The preliminary results include energy- and angular distributions, fragment yields, build-up curves and attenuation of the primary carbon projectiles.

INTRODUCTION

High-energy fragmentation reactions occurring along the beam penetration path in tissue leads to attenuation of the primary beam flux and build-up of secondary lower-charge fragments which give rise to the characteristic dose tail behind the Bragg peak. These effects become most significant at large initial energy and correspondingly large penetration depth of the primary beam.

Pioneering experiments on fragmentation in tissue-equivalent materials started in the 1970s at Princeton University and LBL Berkeley(1) (using mainly ^{20}Ne beams). More recently, various fragmentation studies, especially for ^{12}C ions and water targets, were performed by the GSI Biophysics group(2,3) and by the HIMAC group at NIRS Chiba(4). In order to expand and improve the existing database for the physical models used for treatment planning(5) at the heavy-ion tumour therapy unit at GSI Darmstadt a new series of fragmentation measurements was recently started (Figure 1).

EXPERIMENTAL SET-UP

Primary ^{12}C ions with specific energies of 200 or 400 MeV u^{-1} delivered by the heavy-ion synchrotron SIS-18 were detected by a thin scintillation paddle located in air behind a thin vacuum exit window. This detector served as a beam counter and as start detector for time-of-flight (tof) measurements. The beam then entered through an air-filled pipe and a thin plexiglass window into a water absorber. Incident on the target, the beam spot size (full width at half maximum) is about 5 mm and the beam divergence is in the order of a few mrad. The thickness of the water absorber was adjustable over a wide range with by moving the position of the tube in the water with a linear axis driven by a stepping motor. The absolute water thickness was determined with an accuracy of 0.5 mm and a specific position could be repeated with an accuracy of 10 μm.

Secondary fragments emerging from the water absorber into the forward hemisphere were detected at about 3 m distance by a 5 or 10 mm thick plastic scintillator (4×4 cm^2 area) which delivered an energy loss signal and the stop signal for the tof measurement. The signals were recorded in coincidence event-by-event by a VME data acquisition system. All charged fragments from carbon down to protons were identified and separated by the analysis of two-dimensional ΔE-tof-plots.

Angular distributions were measured by moving the stop detector on a linear drive perpendicular to the beam axis, covering forward angles up to 10°. Alternatively, for measurements of the primary beam attenuation a ΔE–E telescope detector consisting of a 9 mm thick scintillation detector (ΔE) and a 14 cm thick BaF_2-detector (E) was positioned at a short distance behind the exit window of the water phantom.

RESULTS

The analysis of the data obtained in two beam times in February and July 2005 is still in progress. In the following, preliminary results at the present stage of the analysis are presented.

Attenuation of primary carbon beam

In Figure 2, the fraction of primary ^{12}C ions surviving the passage through the water absorber is shown as a function of water depth, together with the corresponding measured Bragg curves. The beam attenuation is well described by an exponential function with a mean free path $\lambda = 259(16)$ mm.

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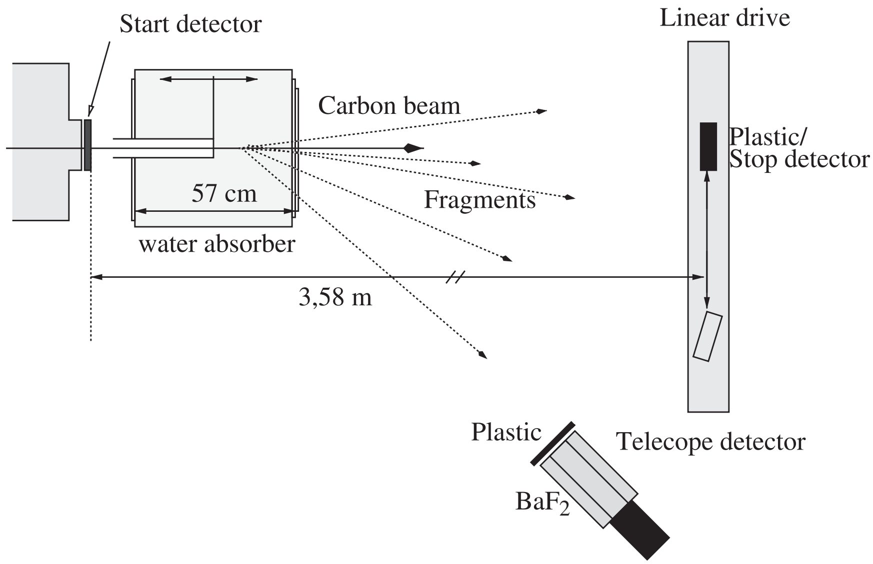

Figure 1. Scheme of the experimental setup used for fragmentation measurements at GSI. Nuclear fragments produced by primary ^{12}C ions in a water target are identified by their energy loss, total energy and time-of-flight measured with various scintillation detectors.

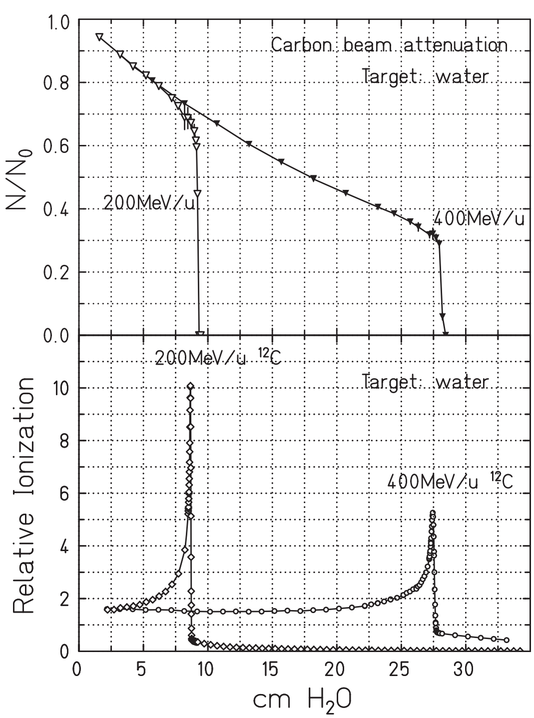

Figure 2. Attenuation of primary ^{12}C beams and corresponding Bragg curves. The surviving fraction of carbon nuclei as a function of depth was measured with a ΔE–E telescope. The lines are shown to guide the eyes.

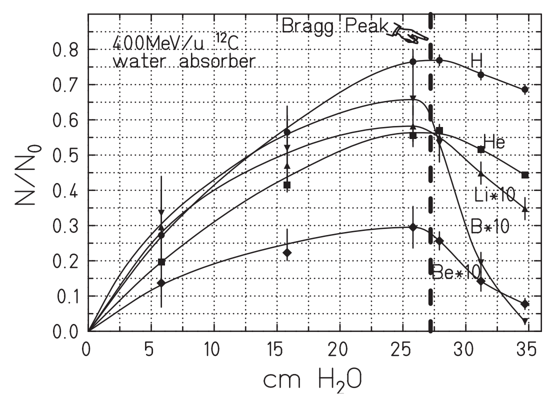

Figure 3. Build-up of secondary fragments produced by 400 MeV u^{-1} carbon ion beam in a water phantom. The lines are shown to guide the eyes.

At 200 MeV u^{-1} still 70% of the primary ^{12}C ions are present at Bragg peak position, while this fraction decreases to 30% at 400 MeV u^{-1}.

Fragment characteristics at 400 MeV u^{-1}

At six different depths of the water absorber before and behind the Bragg peak, the energy distributions and angular distributions of the emitted secondary fragments were investigated. At a depth of 31.2 cm (i.e. 4 cm behind the Bragg peak) the fragment spectrum is dominated by protons and alpha-particles. Their energy spectra are broad and peak at about 220 MeV u^{-1} and they also show the broadest angular distributions, while the heavier fragments (B, Be, Li) are emitted in a rather cone of about 0°–5°.

The build-up curves shown in Figure 3 were obtained by integration of the angular distributions from 0° to 10°.

In this work the fragmentation characteristics of ^{12}C ions were studied at an energy of 400 MeV u^{-1}. This is about the highest energy required for carbon ion therapy and here the fragmentation effects are most significant. As the nuclear reaction cross sections vary only slightly in the range of 100–400 MeV u^{-1}, the comparison of these data with model calculations (e.g. Monte-Carlo simulations) will result in reliable predictions of fragmentation characteristics also at lower energies.

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