Neutron dose measurement in carbon ion radiation therapy at HIRFL (IMP) *

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Abstract For radiation protection purposes, the neutron dose in carbon ion radiation therapy at the HIRFL (Heavy Ion Research Facility in Lanzhou) was investigated. The neutron dose from primary ^{12}C ions with a specific energy of 100 MeV/u delivered from SSC was roughly measured with a standard Anderson-Broun rem-meter using a polyethylene target at various distances. The result shows that a maximum neutron dose contribution of 19 mSv in a typically surface tumor treatment was obtained, which is less than 1% of the planed heavy ion dose and is in reasonable agreement with other reports. Also the γ-ray dose was measured in this experiment using a thermo luminescent detector.

Key words heavy ion therapy, HIRFL, neutron dose

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1 Introduction

Carbon ions are very suitable for radiation therapy due to their physical and biological properties. Different to photons, the energy loss of heavy ions is proportional to the $1/E$, which means that the heavy ions have an inverted energy deposition along the track; at the end of the particle ranges a maximum energy deposition, i.e., dose deposition is obtained which is the so called “Bragg peak”. Since the range of heavy ions in a certain material is exactly related to the ion energy, adjusting the ion energy one can easily change the maximum dose deposition point. In addition, the relative biological effectiveness (RBE) of heavy ions is much larger than that of photons or light particles. But the nuclear reactions along the penetration path cause a significant alteration of the radiation field, which leads to an attenuation of the primary particles and a build-up of lower-Z fragments with increasing penetration depth. As the range of particles scales with A/Z^2, the depth-dose profile of the heavy ion beam shows a characteristic fragment tail beyond the Bragg peak as shown in Fig. 1 [1]. Neutrons, although having a smaller contribution to the total dose as compared with charged particles, can affect a much broader region, especially in healthy tissue, so they must be treated carefully.

At energies of several hundreds MeV/u which are required for radiotherapy, the peripheral collisions in which the beam particles lose one or several nucleons becomes important. Neutrons produced in this process have the following characteristics: they have very broad energy distributions, the maximum energy can even reach twice of the incident ion energy per nucleon. Neutron spectra at small angles show a broad peak at about two-thirds of the incident ion energy per nucleon, i.e. about 60 MeV for 100 MeV/u ^{12}C ions. The total neutron yields vary drastically with the ions energy, the impact of target materials is not so significant.

Studies of the fragmentation of light ions in water or tissue-substitute materials dedicated to biomedical applications can be traced back to the work of W. Schimmerling et al. [2] at Princeton. Detailed measurements on the fragmentation of 670 MeV/u ^{20}N in water were performed by W. Schimmerling et al. [3]. These kind of ions have been used at that time in patient treatment at BEVALAC (LBL); other reports on nuclear fragmentation of heavy ions in biomedical application can be found until very recently [4–6].

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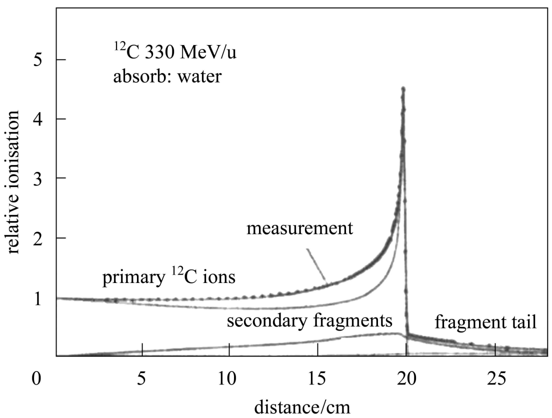

Fig. 1. Bragg curve for 330 MeV/u ^{12}C ions in water measured at GSI.

Some researches are aimed at the measurement of neutron yields, spectra and angular distributions from mid-energy heavy-ion bombarding of thick targets. G. Li et al measured at HIRFL IMP neutrons from 50–100 MeV/u ions on thick targets using the activation method [7] and T. Kurosawa et al. performed a systematic study on neutron yields, spectra and angular distributions of various ions on thick targets with the TOF method at HIMAC (Heavy Ion Medical Accelerator in Chiba) [8, 9]. The experimental results have been compared with calculations using the HIC code. The original purpose of these studies was a use for radiation protection such as neutron field investigations, shielding design, etc., but the data obtained can be used for biomedical purposes also.

Neutron detectors widely used for dose monitoring are the so called A-B rem-meter [10], which in fact are the Bonner Ball with a thermal neutron absorber inside. That kind of detectors has a good energy response from thermal energies up to about 20 MeV, but they may badly underestimate the neutron dose at higher energy regions. Thus some modification of the moderator of the standard A-B rem-meter had to be done. Calculations show that a modification can increase the neutron response at high energy while keeping the response curve unchanged in the lower energy region [11–13]. However, because of lack of a mono-energetic neutron source, the calibration at high energy region is still a problem and the experimental data are not satisfactory.

2 Experiment

The experiment was carried out at the biomedical terminal of HIRFL. ^{12}C ions were accelerated to 100 MeV/u by the SSC and delivered vertically down to a basement and through a stainless steel window with a thickness of 50 μm to a treatment bed which was placed at about 1.0 m from the floor. The distance from the window to the bed is 1.5 m. An organic glass energy attenuator was placed close to the window. For different depth treatments, its thickness can be adjusted from 0 to 2 cm. In our experiment, the standard Anderson-Braun neutron rem-meter, NM2, was placed transversely on the bed at different distances from the beam axis (see Fig. 2). Because the volume of NM2 is big (21 cm in diameter and 35.5 cm in length, the length of the polyethylene moderator is 25 cm), the moderator acts at a small distance as a target. The NM2 was directly irradiated by the ^{12}C beam. At a larger distance, a cylinder polyethylene target with a diameter of 10 cm and a length of 12 cm was placed in the beam line as a target. The beam intensity was the same as in a real treatment, i.e., about 3×10^6 particles per second.

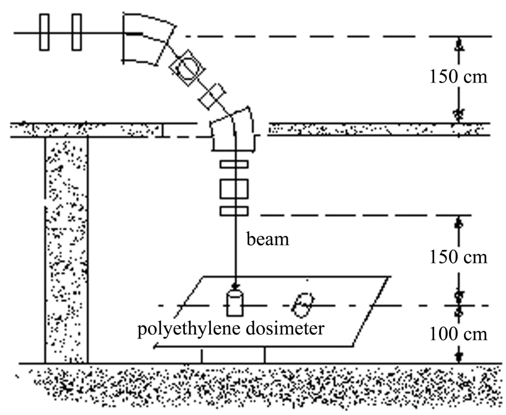

Fig. 2. Experimental arrangement.

To investigate the impact of the γ-ray dose on the patient during the treatment, a set of thermo luminescent detectors were placed on the treatment bed at different distances. The detectors were previously calibrated by a standard γ-radiation field.

3 Results and discussion

Fig. 3 shows the measured results, the data have been normalized with the beam intensity. Since the ^{12}C ion energy is 100 MeV/u, many neutrons are emitted with energies higher than 20 MeV, especially in the forward direction. Therefore the measured results may not represent the real neutron dose and some corrections might be necessary. LI Gui-Sheng [14] reported a theoretical correction coefficient for neutrons emitted from the intermediate energy heavy ion reaction 100 MeV/u ^{12}C+C, measured with a 25.4 cm single-sphere rem-meter, a condition that is quiet similar to that in our experiment, so we can use his results in our work. The correction coefficients for 100 MeV/u ^{12}C+C are 13.38, 6.55, 3.04, 1.39 and 1.15 in the angle region of 0°–15°, 15°–30°, 30°–60°, 60°–120° and 120°–180° respectively. Thus for a typical treatment (divided into 10 irradiation) with a beam intensity of about 3×10^6 particles per second and an irradiation time period of about 6 minutes each, a maximum neutron dose of 19 and 6 mSv for the cases with/without a 20 mm organic glass energy attenuator respectively was obtained. These values are less than 1% of the treatment dose.

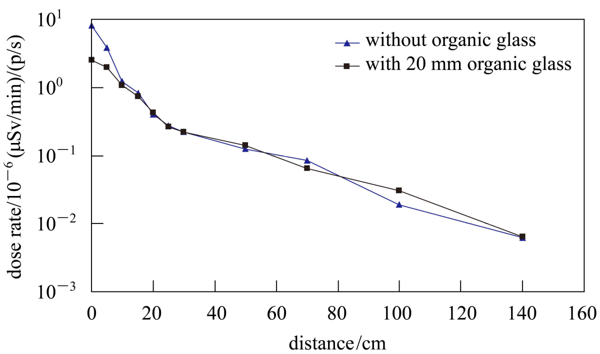

Fig. 3. Measured neutron dose rate in carbon ion radiation therapy.

The results of the γ-ray dose measurements are shown in Fig. 4. The maximum γ-ray dose during the treatment is about 0.79 mSv, which is an order of magnitude lower than that of the neutron dose.

Although the neutron and γ-ray dose is much smaller than the treatment dose of the present work, they can nevertheless affect a much larger region in the tissue. The present work aimed at a surface tumour therapy, where the ion energy was only 100 MeV/u. This energy region should be extended to about 400 MeV/u for a deep tumour therapy. Under such a condition more neutrons will be generated and it seems to be necessary to reconsider the problem of the dose contribution of neutrons and gamma-rays. To analyze the neutron dose accurately, neutron spectrum measurements, especially in the very low energy region (∼keV) are very important.

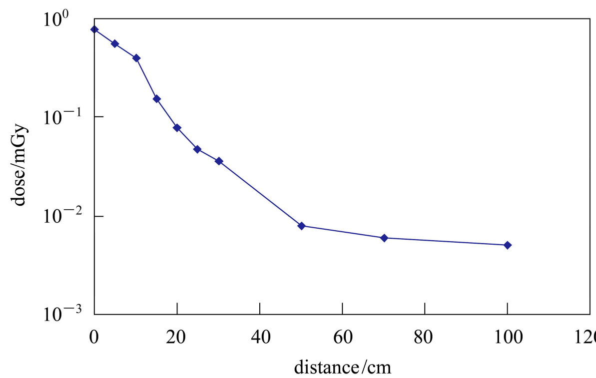

Fig. 4. Measured gamma dose in carbon ion radiation therapy.

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