Nuclear Data for Radiotherapy

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The production of projectile fragments is one of the most important, but not yet perfectly understood, problems to be considered when planning for the utilization of high-energy heavy charged particles for radiotherapy. The charge-changing cross section is one of the most fundamental values when describing the extent of fragmentation. Simulation codes reproduce experimental cross-section data with good precision for carbon ions. Energy and spatial distributions of fragment particle species are needed for a precise estimation of the biological effect. Microdosimetric energy-deposition information has been investigated to understand the nature of radiation effectiveness to cell nucleus. The role of neutrons has recently drawn considerable attentions to estimate the late effect of therapeutic irradiation.

1. Introduction

Projectile and target nuclei are broken up into fragment particles when colliding with each other. The projectile fragments reach a further region beyond the range of the primary particles, and cause unwanted exposure, known as a 'fragment tail'. It is considered that the biological effect to a cell by a charged particle is due to its ionization formed around a track of the particle. Because the track structure is characterized by the deposited energy and velocity of the particle, the resultant biological effect depends not only on LET, but also the

particle species. This fact makes it indispensable to know the *"radiation quality"*, *i.e.,* the fluence and LET on each element for a precise estimation of the biological effect of any therapeutic beam that we use.

2. Macroscopic effect: cross section and depth-dose distribution

The dose, quantity of radiation, is the most fundamental parameter to be controlled in radiotherapy. Fig. 1 indicates the total charge-changing cross section measured at some institutes. The solid line in the figure depicts the calculated cross section by HIBRAC[1]. HIBRAC is a simulation code of the fragment reaction, and is widely used among many particle-therapy facilities. As shown in the figure, the experimental results agree well with each other within the error bars. A slight systematic discrepancy is found between the measurements and the calculations at an energy below 150 MeV/n; however, the difference has only a small effect on the depth-dose calculation. The calculated depth-dose curve of a 290 and 400MeV/n of ^{12}C beam in water with HIBRAC[2] agrees well with the dose measured with an ionization chamber at NIRS, as shown in fig. 2. This clinically sufficient simulation accuracy is one of the bases for successful ongoing particle therapy.
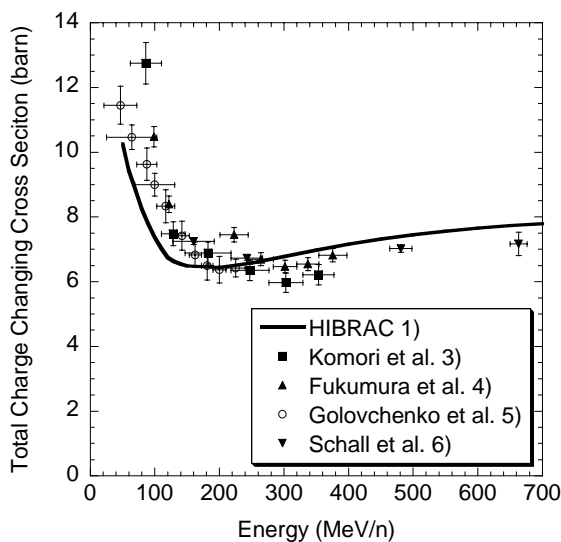

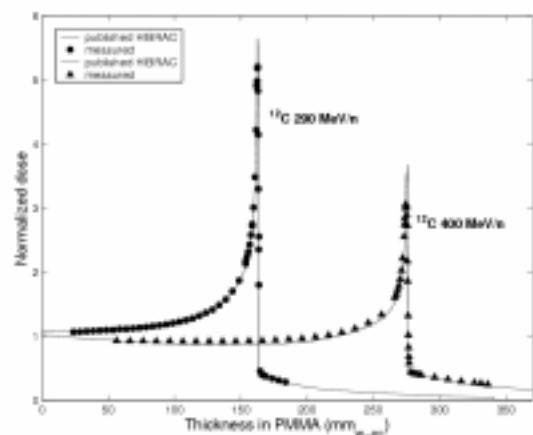Fig.1 Total charge-changing cross section of ^{12}C ions in PMMA.

Fig.2 Depth-dose distribution of 290 and 400 MeV/n of ^{12}C beam in water.

3. Microscopic effect: fluence, LET and spatial distribution

Fig. 3 shows a normalized fluence distribution of fragments emitted from the incidence of a 290 MeV/n ^{12}C beam as a function of the PMMA thickness. The closed symbols and lines denote the experimental values measured at HIMAC (Heavy Ion Medical Accelerator in Chiba) of NIRS[7] and the calculational results by HIBRAC[2], respectively. For the sake of a comparison, the experimental results taken with CR-39 track detectors are plotted together as open symbols. Slight discrepancy is found on the light elements; however, HIBRAC reproduces well the experimental observations.
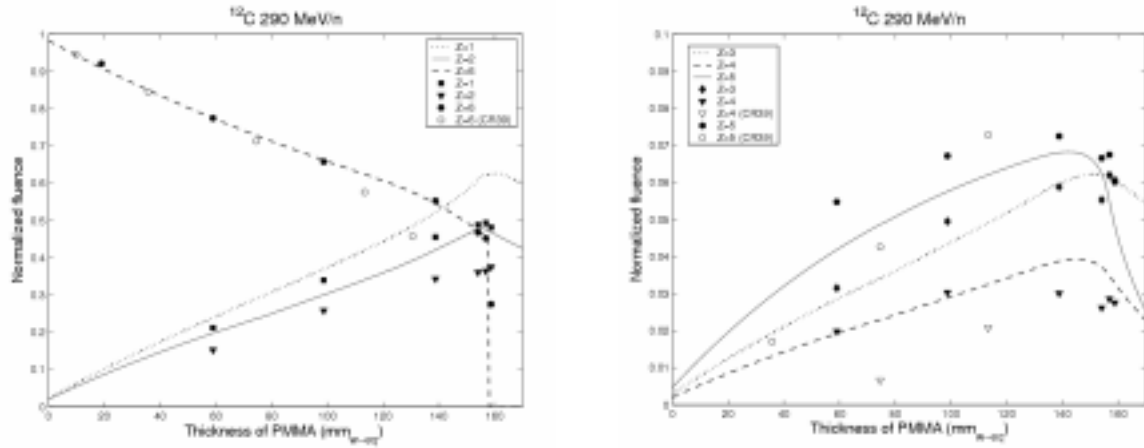

Fig. 3   Normalized fluence of fragments produced from ^{12}C-290MeV/n in PMMA.
          Symbols: experimental data   lines: HIBRAC calculation

The next step for a microscopic understanding of fragmentation is to take spatial information into account. Scanning beam irradiation is materialized at some facilities according to a recent trend toward highly localized beam delivery. The usage of smaller (several mm in diameter) beam size than that of the conventionally used at broad beam (100~200 mm in diameter) enhances the importance of the information on the spatial distribution of fragments.

Multiple scattering is the most dominant factor affecting beam divergence. Because the extent of multiple scattering can be calculated by Moliele's formula to good precision, the

divergence of primary particles in a matter can be well estimated. For fragment particles, however, one cannot overlook the effect of a momentum transfer at the reaction point.

Fig. 4 shows an example of the lateral fluence distribution of fragments for the incidence of a ^{12}C-290 MeV/n beam to water. The development of σ of each element is reproduced well by combining multiple scattering and Fermi momentum transfer.[8]
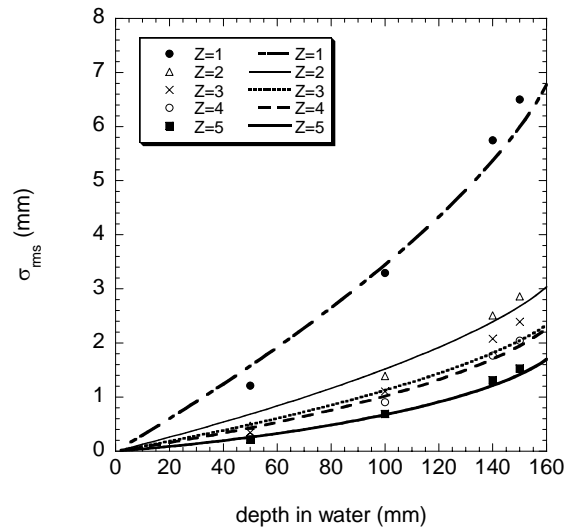

Fig. 4 Lateral spread of fragments for the incidence of ^{12}C-290MeV/n in water.

4. Microdosimetry

Biological effect caused by radiations is considered to be originated from lesions caused in DNA strands. The DNA has a diameter of about 2nm and enclosed in a cell nucleus that is about 10 μm in diameter. The energy deposition in such minute size is governed by randomness. Due to large fluctuations of energy deposition, LET, a macroscopic averaged value, has little meaning to the life and death of a cell. To understand the nature of radiation effect to the biological system, such microscopic energy distribution has been investigated as microdosimetry. Microdosimetric-kinetic model[9] is one of the attempts to explain the biological effect of radiations with microdosimetric information. Damage to a cell is characterized with specific energy (corresponds to dose in macroscopic view) in domains assumed inside a cell nucleus and parameters that reflect radiation sensitivity of the cell to X-ray. For HSG cell, its biological response to various kind and energy of ions is successfully reproduced independent of particle species with experimental specific energy spectra when assuming the domain diameter as 700 nm[10]. The approach will make it possible to determine clinical or biological dose by physical measurement. Further investigation is required to

verify the adoptability of the model and understand the relationship between domain size and actual biological structure.

5. Neutrons

Unlike other charged fragment particles, produced neutrons are largely scattered out in space. As a result, neutrons show wide spatial and energetic distributions at the isocenter. Primal energy-deposition process of neutron in a matter is to collide with proton(s) and makes them recoil. The recoiled proton deposits all of its received kinetic energy around the neighbor of the collision point. The resultant high energy density deposition may locally cause significant biological damage. Their contribution to the target region is included in the measured depth-dose distribution of the therapeutic beam; however, there is little estimation at off-axis. Even the extent of energy delivered by neutrons is small compared to those by therapeutic (charged-particle) beam and affects little to the success of the tumor control, it may cause long-term side effect such as secondary cancer.[11] From the point of view, it is required to understand the spatial neutron distribution in the therapy room and estimate the risk for the induction of the secondary cancer. The information will be utilized as one of the standards when considering the optimal heavy-charged particle therapy modality.

6. Conclusion

10 years have passed since the beginning of clinical trials for carbon therapy at HIMAC. As the first stage, good clinical results have been derived for most cases. That is, in part, due to well understandings to the macroscopic nuclear reaction cross section. To brush up the ongoing therapy modality and establish the optimal *"heavy-ion therapy"* in the coming second stage, both theoretical and experimental efforts must be paid on the microscopic interactions of particles including neutrons with a matter. Nuclear data for the purpose has significant importance from the viewpoint.

References
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