Fragmentation of High-Energy ^{12}C Ions in Tissue-Equivalent Targets

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A detailed knowledge of the fragmentation properties of primary beam particles penetrating tissue is a major prerequisite for treatment planning in heavy-ion therapy. Projectile fragments are abundantly produced in peripheral nuclear collisions and have in general longer penetration ranges than the primary ions. This leads to a characteristic dose tail beyond the Bragg maximum. Furthermore, the lower-Z fragments have a different relative biological effectiveness as compared to the primary ions. Therefore, the composition of the particle field as a function of depth has to be included into the calculation of the biological effect.

Our earlier fragmentation studies concentrated on the measurement of production rates and angular and momentum distributions of charged particles produced by light ion beams (in particular ^{12}C) penetrating water and other tissue-equivalent targets [1,2,3]. These experiments were continued last year with the investigation of the fast neutron component.

A detector telescope consisting of a 15 cm long, 9 cm in diameter BaF_2 crystal and a 9 mm thin NE102 plastic scintillator in front of it was set up to measure yields, angular distributions and energy spectra of fast neutrons and of charged fragments generated by 100 to 400 MeV ^{12}C ions stopped in thick water, iron and lead targets. The thickness of the targets corresponded to 1.3 times the primary ion range. Operating the NE102 as a veto detector, neutrons can be discriminated from charged particles (mainly protons and α-particles). The neutron energies were measured by time-of-flight (3 m flight path) using a thin start detector (1 mm NE102) in front of the target. The neutron efficiency of the BaF_2 scintillator increases with neutron energy and is nearly constant (about 15%) in the range of 100 to 400 MeV. In collaboration with PTB Braunschweig (V. Dangendorf) the response of the BaF_2 detector was measured in the neutron beams available at Louvain-la-Neuve (Belgium) and Faure (South Africa) with energies of 45 MeV and 100 and 150 MeV respectively.

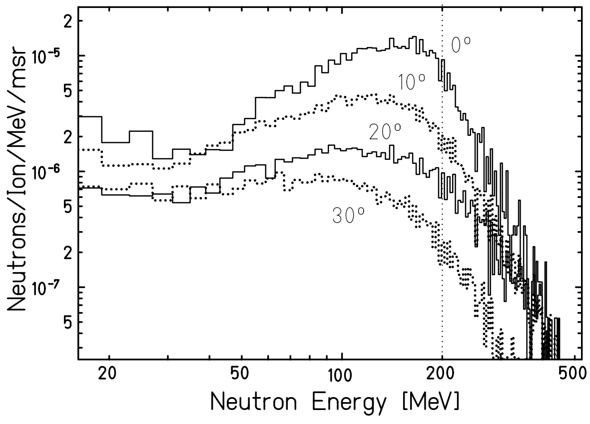

Figure 1: Neutron energy spectra from 200 AMeV ^{12}C ions in a 12.78 g/cm^2 thick water target at different angles.

The neutron energy spectra (Fig.1) show a broad peak at approximately 60% of the initial primary ion energy. This peak becomes more prominent in forward direction and signifies the production of fast neutrons in a breakup process while slower neutrons coming from evaporation processes are isotropically emitted. The fact that neutron energies up to about twice the energy of the incident particle are observed is due to the Fermi energy. These results were found to be in qualitative agreement with similar studies using ^{4}He ions stopped in various thick targets [4]. More recent results with heavier ions were reported in [5,6]. The angular distributions of energy-integrated spectra shown in figure 2 are forward peaked and gaussian shaped. The distributions of the neutrons and hydrogen (inclusive p, d, t) fragments are much broader than that for helium fragments.

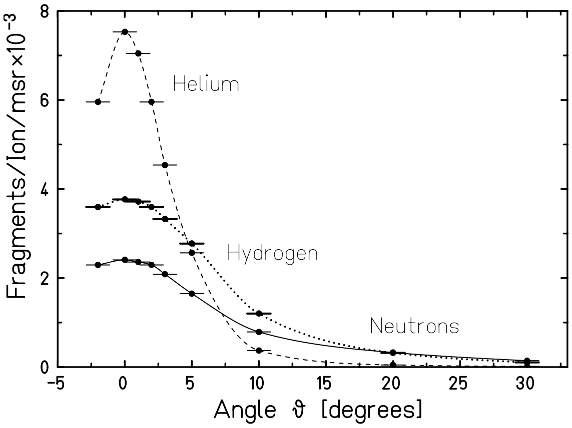

Figure 2: Angular distribution of neutrons, hydrogen and helium fragments produced by a 200 AMeV ^{12}C ion beam in a 12.78 g/cm^2 thick water target.

Besides these studies with phantom targets the characteristic of light particle production in actual patient treatments in Cave M was investigated. The telescope detector was placed 3 m downstream from the patient under polar angles of -5° to +90° degrees. Details of the observed spectra and fragment yields depend on the individual treatment plan, the location of the tumor and the patients anatomy. The aim of these studies is to compare the measured yields of light particles (n, H, He, Li) with those assumed by the physical model which was used for treatment planning.

References

[1] Schardt, D. *et al.*, Adv. Space Res. Vol.17, N^o 2, 87(1996)

[2] Schall, I. *et al.*, NIM B 117,221(1996)

[3] Golovkov, M. *et al.*, Adv. in Hadrontherapy, Elsevier 1997, 316-324

[4] Cecil, R.A. *et al.*, Phys. Rev. C 21, 6, 2471-2484(1980)

[5] Kurosawa, T. *et al.*, Nucl. Sci. Eng. 132, 30-57(1999)

[6] Heilbronn, L. *et al.*, Nucl. Sci. Eng. 132, 2-15(1999)