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Recent measurements for hadrontherapy and space radiation: nuclear physics

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Abstract

The particles and energies commonly used for hadron therapy overlap the low end of the charge and energy range of greatest interest for space radiation applications, Z=1-26 and approximately 100-1000 MeV/nucleon. It has been known for some time that the nuclear interactions of the incident ions must be taken into account both in treatment planning and in understanding and addressing the effects of galactic cosmic ray ions on humans in space. Until relatively recently, most of the studies of nuclear fragmentation and transport in matter were driven by the interests of the nuclear physics and later, the hadron therapy communities. However, the experimental and theoretical methods and the accelerator facilities developed for use in heavy ion nuclear physics are directly applicable to radiotherapy and space radiation studies. I will briefly review relevant data taken recently at various accelerators, and discuss the implications of the measurements for radiotherapy, radiobiology and space radiation research.

KEYWORDS: Space radiation protection.

1. Introduction

Nuclear fragmentation complicates both spacecraft shielding design and treatment planning for radiotherapy. Measurements at particle accelerators can be used to evaluate fragmentation effects with well-defined beams and high statistics. While they cannot simulate the complex radiation fields found in space, they can be used to test fragmentation and radiation transport model performance for selected critical parameter sets, *e.g.* for specific projectile charges, masses and energies and target materials and thicknesses.

The data required are of two general types: *cross sections*, which are probabilities that an ion with a given charge, mass and energy incident on a given target nucleus will produce a fragment with a given set of properties (charge, mass, energy, angle); *fluences*, which are numbers of fragments produced at depth in shielding. The measurements involved in the two cases are similar, the principal difference being the target thickness. A cross section is the probability for a particular interaction to take place, and therefore must be measured with as thin a target as practical, in order to minimize the likelihood of secondary or higher order interactions affecting the final state of the measured fragment. Cross sections as a function of fragment energy are particularly critical for heavy ion transport model development. A fragment fluence measurement can be made, in principle, behind any target thickness, and is designed to measure the cumulative effects of all the nuclear and electromagnetic interactions which can affect the final state radiation field observed in the laboratory. Cross sections more directly reflect the dynamics of high energy nucleus-nucleus interactions, and are fundamental information which must be incorporated into transport models. Fluence measurements are used to test how well a model accounts for the many different interactions which can occur in thick targets.

The peak energy range of the heavy ions in the galactic cosmic radiation (GCR), roughly 0.1-1 GeV/nucleon, is fortuitously close to what has been available for over 25 years at high energy heavy ion accelerators (Fig. 1), and a number of heavy ion reaction cross sections have been measured. Since the choice of projectiles, targets, energies and parameters in these measurements has been motivated for the most part by basic questions in nuclear physics, the fragmentation cross section database is still sparse in some regions of particular interest for space radiation, for example for iron ions.

What follows is a brief, non-exhaustive survey of data from some recent accelerator experiments relevant to space radiation research and radiotherapy. Space limitations preclude a detailed discussion here; the interested reader is urged to consult the references or in the case of unpublished data, the individual experimenters whose work is cited. A good introduction to the subject can be found in the proceedings of a recent workshop on spacecraft and planetary habitat shielding [1]. A review somewhat more detailed than this one can be found in Ref. [2], from which some of this paper is adapted.

Nuclear interactions can be divided into three classes: projectile fragmentation; target fragmentation and mid-rapidity, or intermediate in velocity between target and projectile. Projectile fragments are the fastest and therefore the most penetrating, and are concentrated in the forward direction. Mid-rapidity fragments tend to be light fragments emitted at large angles in the laboratory, and are detected using the same techniques as projectile fragments, but with the detector designed or positioned to cover angles well away from the projectile direction. Target fragments are slow and highly ionizing. Because of their short range they are a challenge to measure. Other divisions are between charged fragments and neutrons and between ‘light’ and ‘heavy’ projectiles. The latter distinction is somewhat arbitrary. In this paper, ‘heavy’ refers primarily to iron (Z = 26).

2. Heavy ion projectile fragmentation

Iron is the heaviest significantly abundant ion in the galactic cosmic radiation, and as such is the heaviest ion typically studied with regard to shielding effectiveness. Heinrich et al. [3] and Zeitlin et al. [4] have made recent measurements of the iron fragmentation cross section near the beam axis in a variety of targets at 700 and 1050 MeV/nucleon, respectively. Heinrich et al. used CR-39 plastic nuclear track detectors and Zeitlin et al., silicon solid state detectors. The data show that the iron fragmentation cross section depends rather weakly on beam energy in this energy regime. Comparisons (Fig. 2) of the 1050 MeV/nucleon data to model calculations [5-7] show that none of the models successfully reproduce the data in every respect, indicating that further model development is warranted. At HIMAC (NIRS, Chiba, Japan) Kanai et al. [8] have studied the fragmentation of iron (90 and 500 MeV/nucleon) and krypton (400 MeV/nucleon) beams in tissue equivalent material.

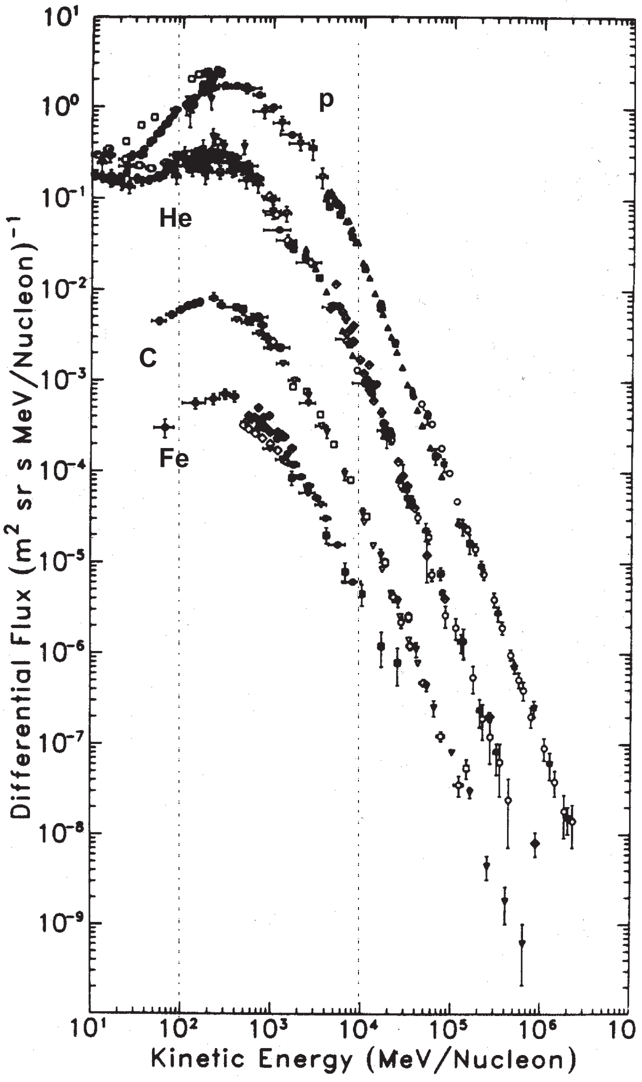

Fig. 1 – Flux of selected nuclei in the galactic cosmic radiation as a function of kinetic energy per nucleon. The dashed lines denote the approximate energy range of heavy ion particle accelerators. (Original plot from Simpson, JA. Elemental and isotopic composition of the galactic cosmic rays. Ann Rev Nucl Part Sci 1983: 33; 323-81).

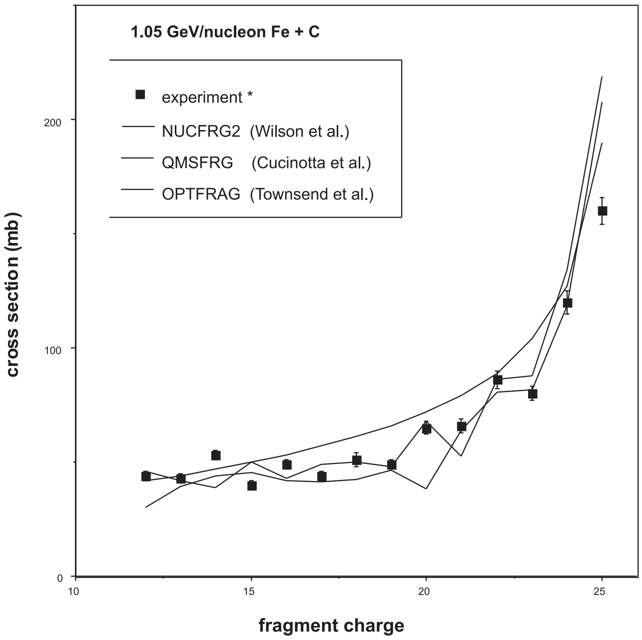

Fig. 2 – Charge changing cross sections for $\Delta Z = -1$ to -14 for 1.05 GeV/nucleon ^{56}Fe ions incident on H, C, Al and Cu targets. The lines represent the predictions of several different nuclear fragmentation models .

3. Light ion projectile fragmentation

Carbon ions are now being used for radiotherapy at GSI and NIRS, which makes information on carbon fragmentation in tissue-like materials of great interest. For shielding applications, relatively light ions such as helium, carbon, neon and silicon are worth studying both in their own right and because they are produced as secondary fragments by interactions of heavier primary ions in spacecraft shielding and in the human body. For purposes of improving models, nuclear physics effects which might be obscured in the complicated final states of heavier ion collisions may be easier to sort out in the simpler final states of light ion collisions.

Schardt et al. [9, 10] have used the FRS fragment separator at the SIS-18 accelerator (GSI, Darmstadt, Germany) to study the beam attenuation and fragment build-up along the beam axis of ^{16}O, ^{14}N, ^{12}C (Fig. 3) and ^{10}B fragmenting in water. They have also measured angular and momentum distributions of light fragments-p, d, t, α, n-out to 30°.

In support of the HIMAC radiotherapy program, Kanai et al. [8, 11] have measured fragmentation with a 100 mm diameter beam in the HIMAC biology beam line, using the following beams on a PMMA ($C_5H_8O_2$) target: ^{4}He (150 MeV/nucleon); ^{12}C (290 and 400 MeV/nucleon); ^{20}Ne (400 MeV/nucleon); ^{28}Si (490 MeV/nucleon) and ^{40}Ar (550 MeV/nucleon). Fukumura et al. [12] made similar measurements with 290 and 400 MeV/nucleon ^{12}C and 400 MeV/nucleon ^{20}Ne on thick targets of water, CH_2, graphite, CaF, aluminum, copper and lead.

Also at HIMAC, Zeitlin et al. [13] have measured fragmentation of 230 MeV/nucleon ^{4}He, 290 MeV/nucleon ^{12}C, 400 MeV/nucleon ^{12}C, ^{14}N, ^{16}O, ^{28}Si, ^{20}Ne and ^{40}Ar and 600 MeV/nucleon ^{20}Ne and ^{28}Si in targets of C, CH_2, Al, Cu, Sn and Pb. The data are being analysed at present. A limited angular distribution (out to 10°) of fragments produced by 400 MeV/nucleon ^{12}C in a thick tissue equivalent target was taken, and shows that in excess of 99% of the absorbed dose is concentrated along the beam axis.

For the future, A. Moroni (INFN, Milan, Italy) and colleagues are preparing detector systems for measurements with carbon and oxygen beams at LNL, Legnaro, Italy (<15 MeV/nucleon) and LNS, Catania, Italy (30, 50 and 70 MeV/nucleon). They will measure production cross sections, energy spectra and angular distributions [14].

4. Neutrons

A recent workshop on neutron production [15] concluded that high energy secondary neutrons (> 10 MeV) will contribute up to 20% of the total dose equivalent to personnel on the International Space Station. These neutrons will be produced in roughly equal measure by cascades initiated by trapped protons and GCR heavy ions and by GCR projectile fragmentation. Until fairly recently there was a paucity of measurements of neutron production above beam energies on the order of tens of MeV, but that situation has been changing, with a number of recent measurements at beam energies above 100 MeV/nucleon. In particular Nakamura et al. [16, 17], Heilbronn et al. [18, 19] and Iwata et al. [20] have measured neutron angular distributions with a number of different projectile/target/energy combinations and thick targets. The cross section is forward peaked but with some neutron production at large angles and at energies well in excess of the beam energy, due to Fermi-boosting (Fig. 4). As is the case with charged particle production, none of the models of neutron production accurately reproduce the data in all cases [16-18].

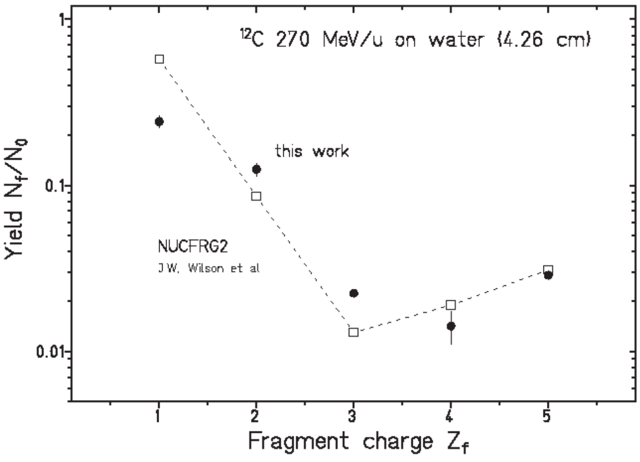

Fig. 3 – Measured yield of charged fragments produced by 270 MeV/nucleon ^{12}C ions in water compared to calculations with the NUCFRG2 model [6]. Data from Refs. [9, 10].

5. Target fragmentation

Target fragmentation is difficult to measure, due to the short range of the fragments. Malakhov et al. [21] have measured fragments produced by a 1044 MeV deuteron beam in a gold target at the Nuclotron (Dubna, Russia). Charged fragments up to nitrogen were detected. Typical energies were up to 20 MeV for protons, 10 MeV for α particles and 2-5 MeV for the heavier fragments. Although these measurements were with a heavy target, the number of light ions in the GCR and produced in secondary collisions makes them relevant, and argues for further measurements, perhaps with shielding and tissue equivalent targets.

An effective, albeit labor intensive method for measuring target fragments is with PNTD's. At the Loma Linda University Proton Treatment Center, Benton et al. [22] recently measured LET fluence spectra for 232 MeV proton beams at depth in a phantom at several sites inside U.S. and Russian extravehicular activity space suits. Preliminary data for the eye and brain have been analysed and analysis of the full data set is in progress. These data were taken as part of an extensive program of measurements by a LLU/NASA-JSC/USF/LBNL group, using both proton and electron beams and CR-39 PNTD's, TLD's, ionization chambers and silicon detectors.

6. Concluding remarks

Accelerator measurements are efficient for particle transport studies for space radiation research and charged particle radiotherapy. Ultimately, it is hoped that improved models of nuclear fragmentation and transport will greatly reduce the need for accelerator experiments. The increased activity in both experiment and theory in recent years argues for active cooperation among experimental groups and

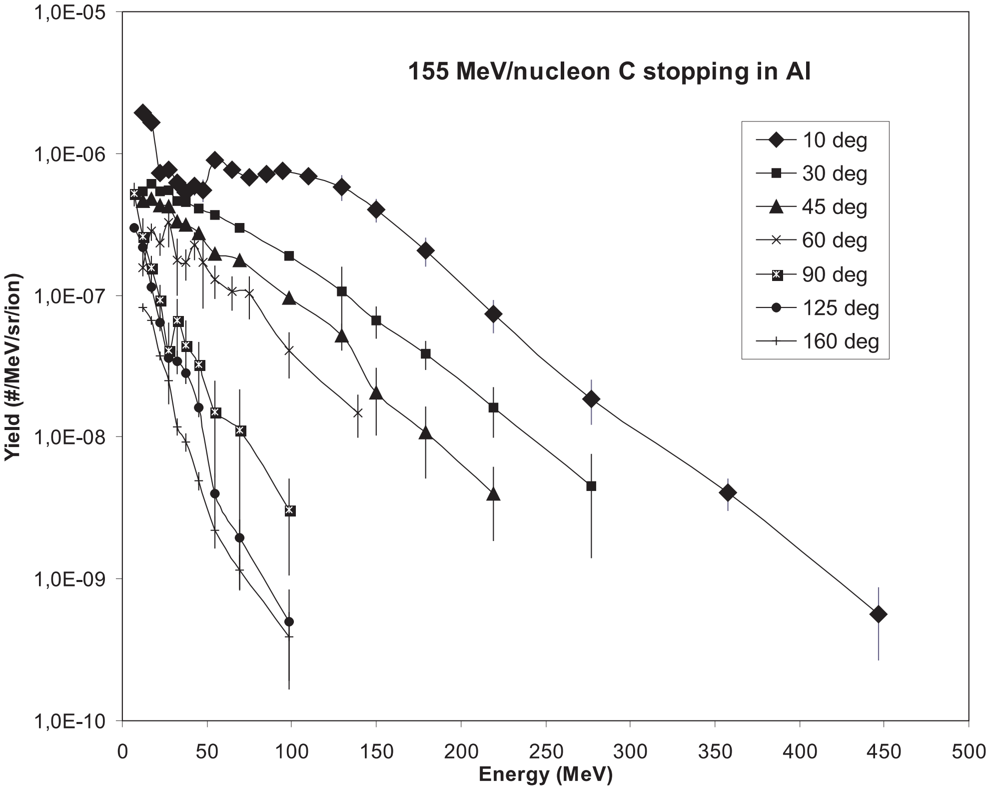

Fig. 4 – Neutron yield from 155 MeV/nucleon ^{12}C striking an aluminum target. Data from ref. [17].

theoreticians to ensure that scarce accelerator resources are used efficiently and that the observables and data points measured are those with the greatest leverage for solving problems in space radiation and charged particle radiotherapy.

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