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CALCULATIONS OF DEPTH-DOSE DISTRIBUTIONS, CROSS SECTIONS AND MOMENTUM LOSS

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ABSTRACT

The ability to know with precision the depth-dose, dose average LET, fluence and energy distributions is of great importance in many research fields, including therapeutic and diagnostic medicine when using heavy ion beams, as well as in space research. We have therefore developed a model and a computer code for calculating these distributions when using high energy proton or heavy ion beams. In this model, we use semi-empirical total reaction and partial cross section formulas developed by us and a new prescription to take into account the energy and momentum loss of the secondary nuclei. In this paper, we will also present an empirical equation for the total inelastic ^{4}He-p cross section, as well as the partial cross sections for the production of ^{3}He, ^{3}H,^{2}H, p and n.

INTRODUCTION

When using heavy ion beams in therapeutic and diagnostic medicine, one needs to know the depth-dose, dose average LET, fluence and energy distributions. (One also needs to know the biological effects of the ion beams on tumors as well as on the healthy tissue, but this is beyond the scope of this paper.) We have therefore developed a model for calculating these distributions with accuracy. In this model we use our semi-empirical models for calculating all the cross sections, as well as our microscopic prescription to take into account the energy and momentum loss and spread of the secondary nuclei. To know these basic properties is also very important in many other research areas, including shielding against heavy ions originating from either space radiations or accelerators. The ability to calculate with precision the projectile fragmentation cross sections is also very important for cosmic ray propagation calculations, since cosmic ray nuclei are known to suffer high-energy nuclear collisions that alter (via fragmentation) the elemental and isotopic composition of the primary flux. All this information is also of importance for space missions, where human beings and the materials in the spacecraft are subject to a radiation environment of an intensity and composition available only by nuclear reactors or accelerators on earth. To determine the risk of deleterious effects of the space radiation to astronauts and the spacecrafts on long missions, one therefore needs a good knowledge of the radiation environment and the effects of shielding provided by the spacecraft and the bodies of the astronauts. In this paper, we will also present an empirical equation for the total inelastic ^{4}He-p cross section, as well as for the partial cross sections for the production of ^{3}He, ^{3}H,^{2}H, p and n.

DEPTH-DOSE AND FLUENCE DISTRIBUTIONS

The depth-dose distributions (Bragg curves) of heavy charged particles are characterized by a low dose plateau in the entrance channel and a sharp peak (Bragg peak) near the end of their ranges, which gives an excellent physical dose deposition. The biological effectiveness is also high in the Bragg peak region. Heavy ions are therefore expected to significantly improve the clinical results in tumor therapy, as compared to conventional radiation therapies using high energy photons or electrons. However, nuclear collisions along the beam path in the tissue cause an attenuation of the primary particle fluence and a build-up of both high and low-energy fragmentation products. These products come from the fragmentation of the projectile and the target, respectively. Light-ion beams such as ^{12}C or ^{16}O seem to offer the best compromise between the advantages of high-LET particles and the unwanted effects of nuclear fragmentation and the complications in the healthy tissue. In order to simulate the beam history in the tissue, we have developed a numerical method for calculating the depth-dose, fluence, dose average LET and energy distributions of protons and heavy ions in any media. This model will be published in detail elsewhere together with measured Bragg curves /1/. When calculating these distributions, the target material is first divided into many thin slabs. For every particle created in each step, the stopping power, path-length straggling and the attenuation of the primary beam is calculated for the whole range of the particle. The production of the projectile fragments and their momentum loss and spread, due to the fragmentation process, are also calculated /2/ in somewhat thicker steps along the beam path. The beam attenuation and the production of secondary and tertiary fragments are calculated with the semi-empirical formulas described below /3/. In Fig. 1, we show the measured fluence distributions /4,5/ for all fragments down to $Z=5$ (the fragments with $Z \leq 4$ could not be resolved in the measurements) from the reactions of 676 MeV/N ^{12}C, 674 MeV/N ^{14}N and 672 MeV/N ^{16}O in water, together with our calculated fluence distributions and those fitted to the data by using the method described in refs. /4,5/. As can be seen from this figure, our calculated fluence distributions are in very good agreement with the measured ones.

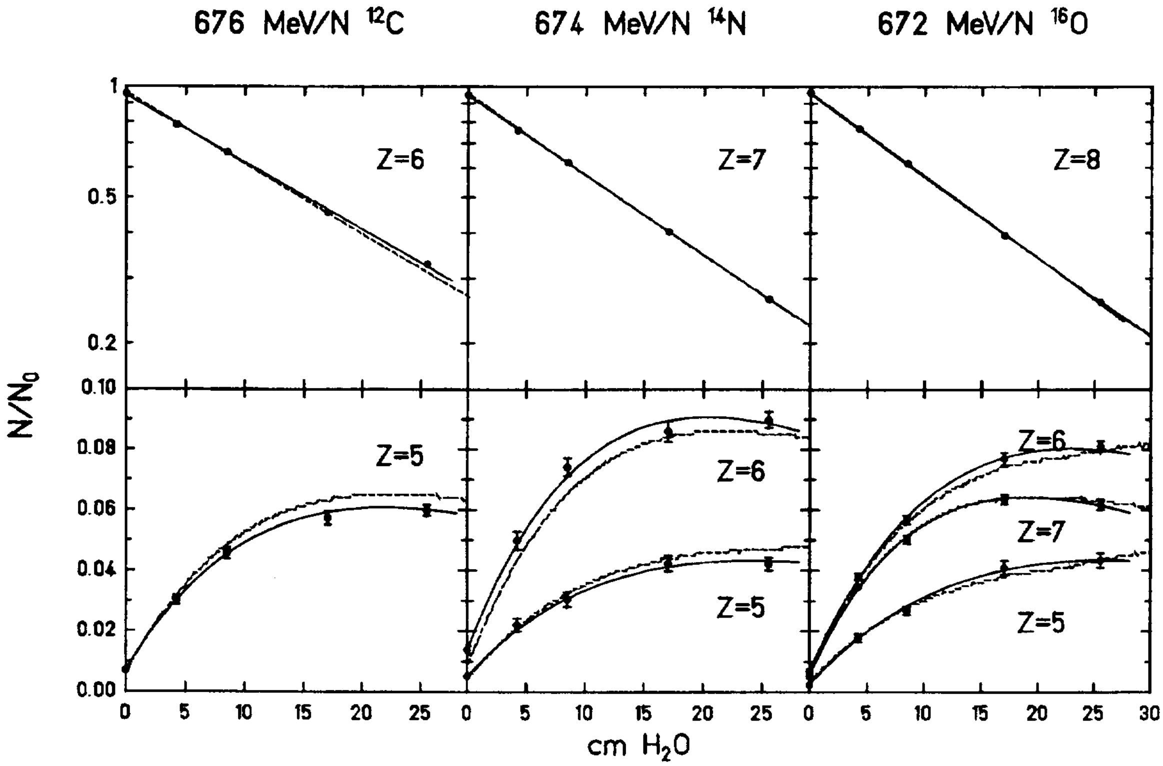

Fig. 1. Measured /5/ and calculated fluence distributions for 676 MeV/N ^{12}C, 674 MeV/N ^{14}N and 672 MeV/N ^{16}O in water. The experimental values are the open circles, the dashed and the solid lines are our calculated fluence distributions and those fitted to the data using the method described in refs. /4,5/, respectively.

In Fig. 2, we show the measured depth-dose distributions for 135, 270 and 330 MeV/N ^{12}C in water, together with the calculated total Bragg curves. The distribution for 135 MeV/N ^{12}C was measured at RIKEN (Japan) /6/ and the others at GSI (Germany) /7,8/. As can be seen from this figure, these calculated Bragg curves are also in very good agreement with the measured ones at all three energies. Even the dose enhancements behind the Bragg peaks, due to the fragmentation products, are very well reproduced.

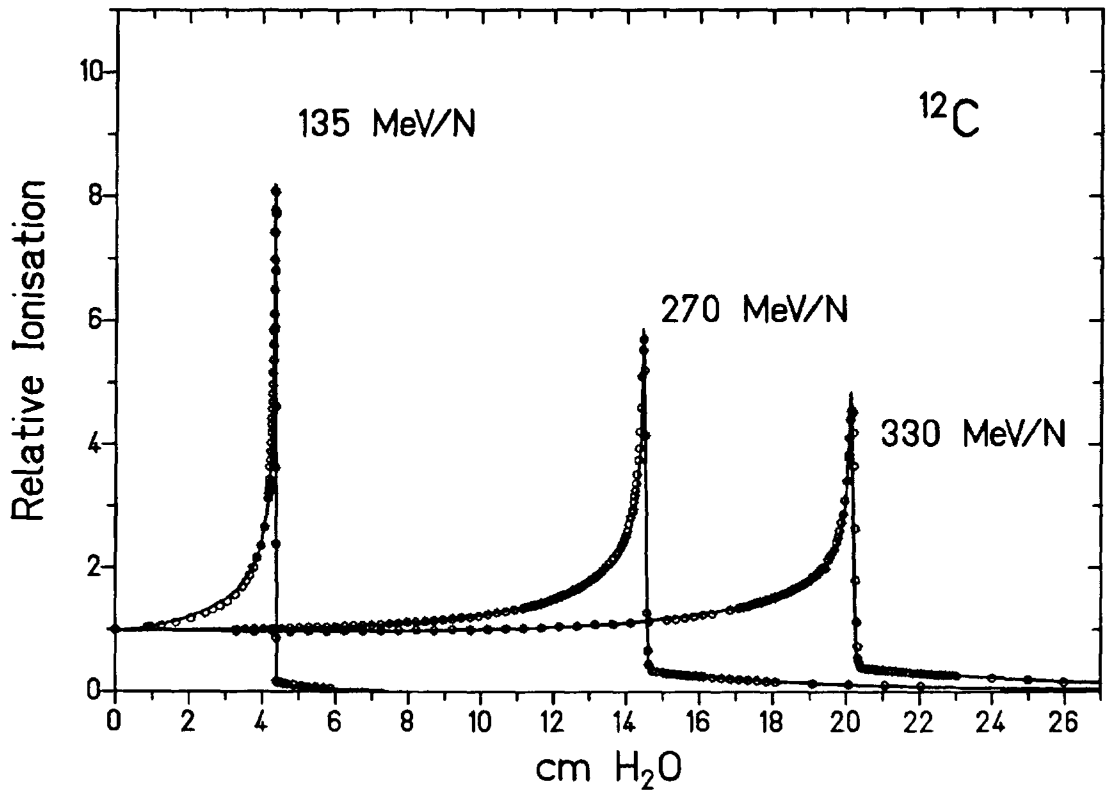

Fig. 2. Measured Bragg curves for 135, 270 and 330 MeV/N ^{12}C in water /6,7,8/ (open circles), together with the calculated total Bragg curves (solid lines).

CROSS SECTIONS, ENERGY AND MOMENTUM LOSS

We have earlier developed semiempirical equations for calculating the total reaction cross sections for proton-nucleus and nucleus-nucleus reactions /9/. These formulas are of Bradt-Peters-type and assumed energy independence for energies above 200 MeV and 100 MeV/N, respectively. We have now improved these formulas by adding energy dependence terms valid for all energies between 20 MeV/N and 1000 MeV/N for both proton-nucleus and nucleus-nucleus reactions /3/. We have also constructed two algorithms for calculating the projectile-fragment cross sections in nucleus-nucleus collisions from the corresponding proton-nucleus ones. Both algorithms take advantage of the weak factorization property of the projectile fragments. The first algorithm /9/ uses a scaling parameter, which is based on a Bradt-Peters-type law, the second algorithm /10/ also includes the participant-spectator picture, Glauber scattering theory and approximates the collisions's sum rule. The first algorithm gives better agreement with the measured total ΔZ cross sections from the interactions of light projectiles with water in the energy region 300-700 MeV/N /4,5/. To further improve this algorithm, we have now modified it by adding energy dependence terms in this energy region and introduced some additional correction factors /3/. For calculating the breakup and stripping of helium in cosmic rays, we have also developed an empirical equation for the total inelastic ^{4}He-p cross section, as well as for the partial cross section for the production of ^{3}He, ^{3}H,^{2}H, p and n

$$\sigma=(1-E_0/E)\,(a[1-b\ \exp(-E/E_1)]+c\ \exp[-(E/E_2)^d]) \tag{1}$$

where the parameters E_1, a and d are specified for the products ^3He, ^3H, ^2H, p and n. This equation has been fitted to experimental data from 25 to 2,000 MeV/N. Beyond 2,000 MeV/N the cross sections should reach nearly asymptotic values, in agreement with the concept of limiting fragmentation, thus the equation is also applicable at energies greater than 2 GeV/N. The equation is based on experimental data from J.P. Meyer /11/ and Monte Carlo results compiled by F.A. Cucinotta /12/, who has also developed parameterizations for the above cross sections. The knowledge of energy and momentum loss of the secondary nuclei is of great importance both for calculating the energy deposition in biological and non-biological systems, as well as in cosmic ray data analysis. We have therefore also developed a simple microscopic model in which energy and momentum degradation of secondaries produced in proton and heavy-ion induced spallation reactions can be estimated /2/. This model is based on the participant-spectator picture of high-energy nuclear collisions using three empirically determined microscopic non-adjustable nuclear-transport parameters, which allows us to estimate the average energy loss $<dKE>$ of a given fragment A_f from a given collision $A_p + A_T \rightarrow A_f + X$. The fragment can be either a projectile or a target fragment. The standard deviation σ_{dKE} can also be estimated using an effective reaction temperature and assuming a Gaussian-like distribution for the momentum transfer.

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REFERENCES

1. L. Sihver, D. Schardt and T. Kanai (to be published).

2. C.H. Tsao, R. Silberberg, A.F. Barghouty, and L. Sihver *ApJ* (submitted).

3. L. Sihver (to be published).

4. I. Schall, Ph.D. Thesis, Technische Hochschule Darmstadt, April 1994; I. Schall, D. Schardt, H. Gazelle, G. Kraft, A. Mogul, M.F. Mohar, G. Münzenberg, F. Nickel, C. Scheidenberger, W. Schwab, E. Kankeleit, and A. Fukumura, *Radiation Effects and Defects in Solids* 126, 385 (1993).

5. D. Schardt, I. Schall, H. Irnich, G. Kraft, A. Magel, M.F. Mohar, G. Münzenberg, F. Nickel, C. Scheidenberger, W. Schwab, and L. Sihver, this issue.

6. T. Kanai, S. Minohara, T. Kohno, M. Sudou, E. Takada, F. Soga, K. Kawachi, A. Fukumura and F. Yatagai, NIRS-M-92, HIMAC-004, NIRS, Japan (1993).

7. D. Schardt, H. Stelzer, H. Junk, G. Lenz, and U. Arndt GSI Scientific Report 1992, 336 (1993).

8. L. Sihver, D. Schardt, and T. Kanai, GSI Scientific Report 1993, 233 (1994).

9. L. Sihver and T. Kanai, NIRS-M-87, HIMAC-002, NIRS, Japan (1992); L. Sihver, C.H. Tsao, R. Silberberg, T. Kanai, and A.F. Barghouty, *Phys. Rev.* C47, 1225 (1993).

10. C.H. Tsao, R. Silberberg, A.F. Barghouty, L. Sihver, and T. Kanai, *Phys. Rev.* C47, 1257 (1993).

11. J.P. Meyer, *Astr. & Ap. Suppl.* 7, 417 (1972).

12. F.A. Cucinotta, NASA Technical Paper 3354, (1993).