Fragmentation of 200 and 244 MeV/u carbon beams

in thick tissue-like absorbers

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Abstract

Stacks consisting of thin CR-39 sheets sandwiched between thick Lucite and water absorbers were perpendicularly bombarded by ^{12}C ions at 200 and 244 MeV/u. Track radius distributions representing the charge composition of the fragmented beams were automatically measured by a particle track analysis system. After analysis of the nuclear charge distributions, the total charge removal cross sections and elemental production cross sections of fragments with atomic numbers from 5 to 3, were obtained down to the lower energies (~ 50 and 100

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MeV/u, respectively). It has been found that the measured total charge removal cross section agrees with theoretical predictions within ~ 10% and very well with previous experiments in corresponding energy regions. Two model calculations for production of B fragment are in good agreement with our measured data while a third model overestimates it by ~ 12%. Theoretical cross sections for Be and Li fragments differ strongly among the different models and from measured values.

1. Introduction

The interaction and transport of light energetic ions in tissue-like matter is of particular interest for therapeutic and diagnostic medicine [1,2]. Besides the evident medical advantages of light ions (i.e. a depth-dose distribution with controllable penetration depth, enhanced Relative Biological Effectiveness and minimal angular scattering in matter for a well defined edge) they exhibit the unfavourable effect of fragmentation. This diminishes the number of primary ions delivered to the volume under treatment or investigation, and produces a tail of damaging ionisation beyond the Bragg peak. Carbon ions play a special role in therapy. They produce the best physical dose distribution because of the decreased longitudinal and lateral scattering compared to protons and the relatively small fragmentation compared to heavier ions as neon. In addition, a small fragmentation rate into β^+-emitting carbon isotopes allows one to detect the

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stopping carbon beam inside the target via Positron Emission Tomography techniques.

Fragmentation reactions have been studied theoretically and experimentally for many years (see, for instance, a paper by Wilson et al. [3]). However there is still a paucity of experimental data, especially for light systems and for energy ranges below ~ 100 MeV/u, and their difference with theoretical models is sometimes quite large. In this work, which is a continuation of our previous studies [4], we have measured the total charge removal cross sections and elemental cross sections for production of fragments with atomic numbers from 5 to 3 in the interactions of an approximately two hundred MeV/u carbon beam with Lucite ($C_5H_8O_2$) and water. A comparison of our results is also made with those available from theoretical predictions [5-8] and other experiments [9].

2. Experimental

Three stacks, 4 x 4 cm^2 in area, consisting of thick absorbers (2.5, 2 and 1 cm thick Lucite slabs and 4 cm thick water column) interleaved with ~ 0.7 mm thick CR-39 ($C_{12}H_{18}O_7$) foils (Intercast, Italy) were perpendicularly irradiated with 200 and 244 MeV/u ^{12}C beams delivered by the Dubna synchrophasotron (JINR, Russia) and the Darmstadt heavy ion accelerator facility (GSI, Germany). Both absorber materials were selected as targets due to their similarity to human tissue and availability of experimental data for Lucite and water from previous experiments [9,11]. The fluences of the incoming particles were (0.9, 3.1 and 6.4) $\times 10^3$ cm^{-2}, depending on the stack. The best etching conditions for this type of CR-39 were found to be 7M NaOH at 80^0C for 17 hrs to achieve the best

charge resolution and to reveal the tracks of lower charge fragments such as Li. The whole area of each stack was covered by a broad ion beam. The area of about 14.4 cm^2 of each detector foil was automatically scanned at the J. Stefan Institute (Slovenia) with the TRACOS image analysis system (for details, see Refs. [10, 11]).

3. Results

In spite of the velocity spread of projectile-like fragments, the track etch method enabled us to measure charge peaks with a resolution σ_z of 0.09 to 0.5 elementary charge units, depending on the ion species and the location of a given detector foil in the stack. The fragments produced in a thick target have their energy loss spread resulting from the fact that the reaction can take place at any depth inside absorber. The thickness of absorbers used in this work corresponds to the plateau of the Bragg curve where the energy loss spread is still sufficiently small for good charge resolution. The higher the charge, and the further the location of the foil upstream from the Bragg peak of primary beam, the better is the resolution and vice versa. Figs. 1 and 2 show spectra of track radii (i.e. charges) after the 200 MeV/u ^{12}C beam penetrated a 2.5 cm and a 4.8 cm thick Lucite target respectively. Even in the case of the thicker target, the resolution is still enough to allow the charge peaks to be unambiguously resolved as seen in figure 2.

The measured fluence of the carbon beam (initially at 244 MeV/u) after its penetration through different thicknesses of Lucite is shown in Fig. 3. The line in this Figure represents the best fit with a 3rd order polynomial function to the

experimental points (the zero order parameter was fixed to 1). Such a fit accounts for the change of slope in the normalised fluence curve which is expected above certain penetration distance (or, in the other words, related to the increase of cross section for the lower energies). Note that the number of carbon ions transmitted includes those with mass numbers lower than 12 since the track etch method is unable to distinguish the ions isotopically.

The Total Charge Removal Cross Section (TCRCS) was calculated from the fitted values of normalised fluence by the usual exponential absorption equation. The TCRCS values were obtained from a carbon beam energies from ~ 225 MeV/u down to ~ 50 MeV/u. Note that the energy losses and ranges were calculated by SRIM-97 code [12], the accuracy of which was found to be satisfactorily good, i.e. ~ 4%, in comparison with measured ranges in CR-39 [13, 14] . We assume that the calculations for Lucite and water are of similar accuracy. Fig. 4 presents our measured data for a Lucite absorber in comparison with values calculated by three models [5,6,8] and those of prior measurements [9]. Error bars in Fig. 4 are due to statistics and the standard deviation of the fit, while the lines (which are parallel to the X axis) indicate the energy of the beam in front of and behind the given amount of absorber. Note that the models from Refs. [5,6] present TCRCSs which were obtained by subtraction of cross sections for neutron removal reactions [5,8] from the total reaction cross sections for the corresponding energies of the carbon beam. For a 200 MeV/u carbon beam impinging on a 4 cm thick water absorber (outcoming energy 136 MeV/u) we obtained a value of TCRCS of (1303 ± 20) mb (the presented error is statistical only) which is very close to that measured earlier [9], i.e. (1264 ± 16) mb (incoming and outcoming energy values were 192 and 128 MeV/u, respectively).

Theoretical predictions [5 and 6] after subtraction of neutron removal reactions give TCRCS values of 1114 mb and 1277 mb, respectively.

In order to determine the elemental cross sections of carbon fragmentation leading to the production of lighter ions (with charges down to 3) the following expression [15] was used:

$$\sigma_f = \frac{(N_{F,x} - N_{F,0}) A_t}{N_{C,x} N_A \rho x},$$

where $N_{F,x}$ and $N_{F,0}$ are the numbers of fragments counted behind the target and in front of it, respectively, $N_{C,x}$ is the number of surviving carbon ions (i.e. counted behind the target), N_A is Avogadro's number, A_t, ρ and x are the molecular mass (atomic units), the density and the thickness of absorber, respectively. This formula is different from the usual e-function for production of fragments in a thin target and accounts for the loss of fragments within a thick target, assuming the TCRCSs for carbon ions and fragments are equal. Price et al. [15] estimate that even if they differed by as much as 50% this formula would be correct to within 10%.

The following three Tables present our measured elemental cross sections for reactions of carbon ions with Lucite and water in comparison with three models [5,7,8]. The values of energy given in the left hand column of Table 1 are averages of those in front of and at the back of the target, while the values in brackets are deviations from averages. The errors in brackets in the second column of each Table given for experimental σ_f are statistical only.

4. Conclusions

Our experimental TCRCS values agree well with those from the experiments of Schall et al. [9] and with model calculations after Sihver et al. [5] in the energy region from ~ 230 MeV/u to ~ 160 MeV/u for a carbon beam passing through Lucite. Theoretical predictions after Tripathi et al. [6] and Wilson et al. [8] overestimate them by ~ 11% in the corresponding energy range. A slightly stronger increase in TCRCS values was observed below ~ 140 MeV/u than is predicted by all these models. Our TCRCS value for ~ 168 MeV/u ^{12}C reactions with water is in a good agreement with the prior experiment [9] and the Tripathi et al. model [6] while the Sihver et al. model [5] underestimates it by ~ 15 %. In this case, the TCRCS values are dominated by the total reaction cross sections and the neutron removal is a small (but important) correction. The total reaction cross sections in this case are phenomenological fits to experimental data [6] and there is an uncertainty in the p + ^{12}C cross sections of about 20 percent on the range of 100 to 400 MeV and about 10 percent uncertainty for ^{12}C + ^{12}C on the equivalent energy range. There is little data on ^{12}C + ^{16}O in this energy region. The uncertainties in the neutron removal cross sections will little affect the uncertainty in the present estimates.

The models of Tsao et al. [7] and Wilson [8] better describe our measured data for production of boron fragments than that of Sihver et al. [5] (see Table 1). Both the Sihver et al. and the Wilson et al. models Refs. [5,8] overestimate the measured Be elemental cross section for 200 MeV/u C ions on Lucite by about 47%, while the cross section calculated according to Tsao et al. [7] is 37% lower.

The corresponding Li elemental cross sections calculated according to Wilson et al. [8] are in agreement with the experiments while the Tsao et al. model [7] is 36% lower and the Sihver et al. model [5] is 67% higher (see Table 2). The Sihver et al. model [5] agrees well with the elemental cross sections for production of B, Be and Li fragments measured in the reaction of a 200 MeV/u carbon beam with a 4 cm thick water absorber. In this case the Tsao et al. model [7] does well for B fragments but underestimates the cross sections for Be and Li by more than a factor of two. The Wilson et al. model [8] gives reasonable values for B and Be fragments but 100% underestimates the Li elemental cross section (see Table 3). In this case the model estimates of Tsao et al. [7] and Sihver et al. [5] are phenomenological fits (Rudstam formalism) and reanalysis with the present data set could improve their results. The Wilson et al. model [8] is a simplified nuclear reaction model with a phenomenological correction to the excitation spectrum and reanalysis with the present data would allow improved estimates of the excitation spectrum correction. In addition, media modification of the nucleon mean free paths are important in the 100 to 200 MeV/u region [16] and have not yet been incorporated into the Wilson et al. model.

The measured cross sections presented herein simulate a realistic picture of the phenomena of light ions passing through tissue. These results will help improve the existing database for medical applications in general and with respect to the production of Be and Li fragments in particular. The present method supplements the electronic detector experiments and provides an alternate method of improving for TCRCS measurements. In addition, these results will also give better estimates of light ion excitation spectrum of value to nuclear collision studies and model development.

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Figure captions

Fig. 1. Track radius spectrum behind a 2.5 cm thick Lucite absorber.

1 pixel = 0.89 μm

Fig. 2. Track radius spectrum behind a 4.8 cm thick Lucite absorber.

1 pixel = 0.89 μm

Fig. 3. Attenuation of 244 MeV/u carbon beams in Lucite. The errors are statistical. The line is the best fit with the 3rd order polynomial function to the experimental points.

Fig. 4. Total Charge Removal Cross Sections in reaction of carbon with Lucite vs beam energy. Error bars are due to statistics and the standard deviation of the fit (see Fig 3). Lines that cross the points indicate the energy of the beam in front of and behind a given absorber.

Table 1

Production of boron fragments in reactions of a carbon beam with Lucite

Energy (MeV/u)	σ_f, mb			
	Experiment	Theory [*]$\rightarrow$		
	This work	Tsao et al. [7]	Sihver et al. [5]	Wilson et al. [8]
225(15)	1037(88)	1246	1363	1285
216(25)	1159(74)	1245	1364	1283
201(9)	1277(248)	1247	1366	1282
191(19)	1295(151)	1248	1368	1281
182(9)	1183(322)	1251	1371	1281
175(25)	1155(65)	1255	1373	1281
172(19)	971(187)	1257	1375	1282
151(22)	1213(216)	1268	1391	1287
136(14)	948(242)	1278	1415	1296
109(14)	927(285)	1322	1508	1323
106(17)	1090(266)	1328	1522	1329
100(29)	1338(292)	1340	1559	1339

[*] These cross sections were calculated by summing the boron isotopes with mass numbers 11 and 10 only, since those for numbers of 12 and 8 are negligibly small and that for 9 can not be measured (the half life is too short).

Table 2

Production of Be and Li fragments in reaction of a 200 MeV/u carbon beam with a 2.5 cm thick Lucite absorber (outcoming energy 150 MeV/u)

| Fragment | σ_f, mb | | | |
| | Experiment | Theory [*] $\rightarrow$ | | |
	This work	Tsao et al. [7]	Sihver et al. [5]	Wilson et al. [8]
Be	462(41)	291	689	673
Li	602(51)	387	1005	553

[*] Model cross sections for Be and Li fragments were obtained by summing up values for mass numbers 10, 9, 7 and 9, 8, 7, 6, respectively.

Table 3

Production of B, Be and Li fragments in reaction of a 200 MeV/u carbon beam with a 4 cm thick water absorber (outcoming energy 136 MeV/u)

| Fragment | σ_f, mb | | | |
| | Experiment | Theory [*] $\rightarrow$ | | |
	This work	Tsao et al. [7]	Sihver et al. [5]	Wilson et al. [8]
B	232(21)	243	255	209
Be	115(18)	57	135	136
Li	182(19)	77	196	94

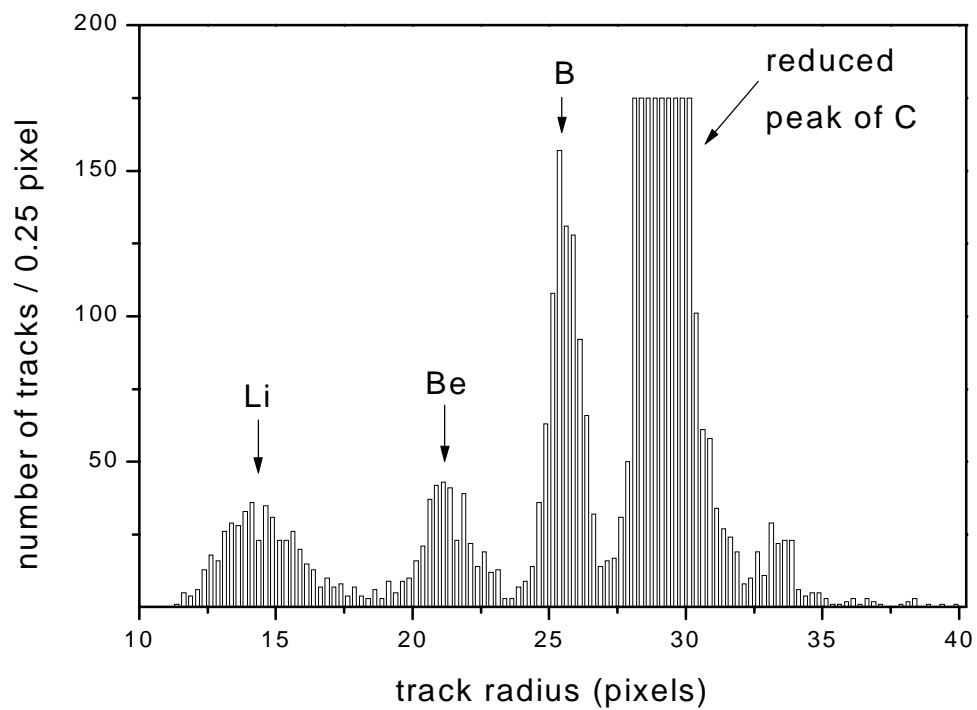[*] Model cross sections for B; Be and Li fragments were obtained by summing up values for mass numbers 11, 10, 8; 10, 9, 7 and 9, 8, 7, 6, respectively.
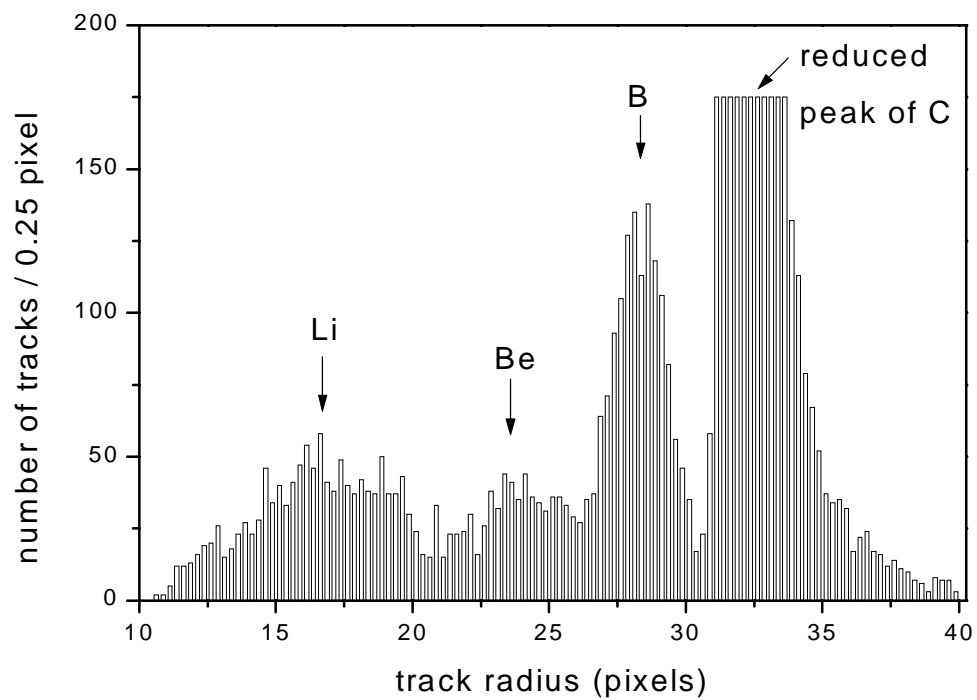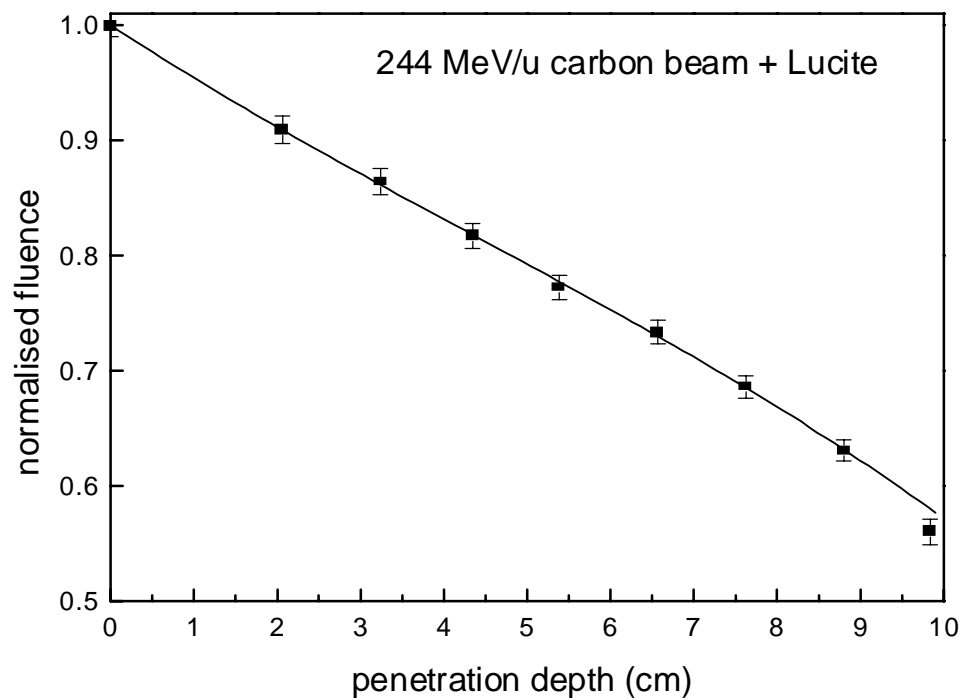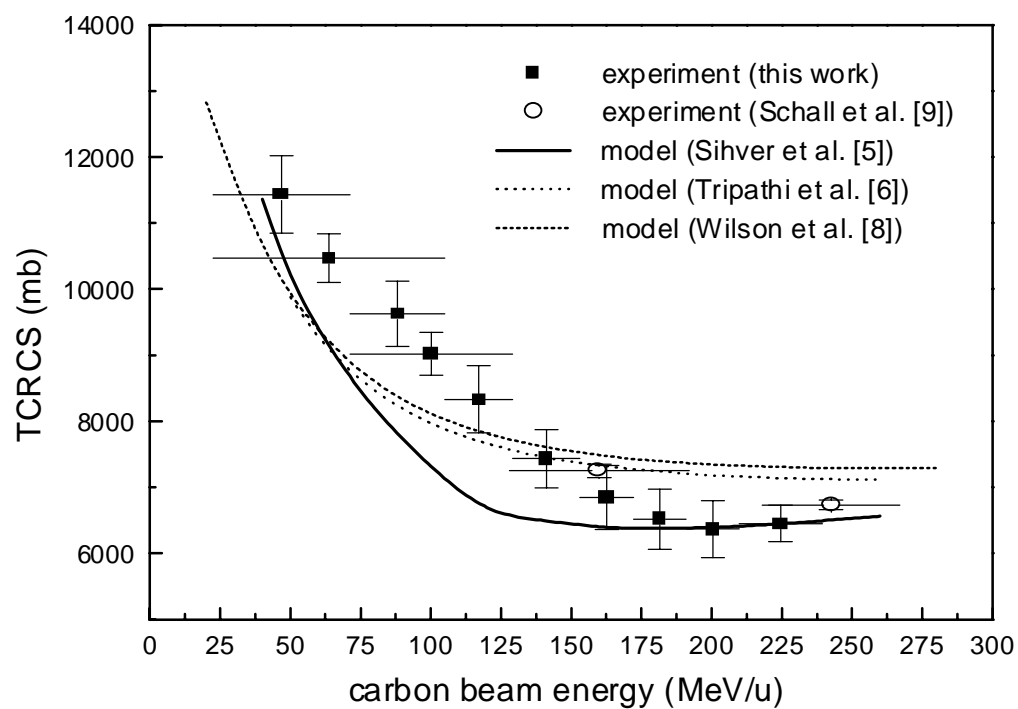
Figures

Fig.1

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