Carbon induced reactions at low incident energies

F Cerutti[1,2], F Ballarini[3,4], G Battistoni[2], P Colleoni[1], A Ferrari[5], S V Förtsch[6], E Gadioli[1,2], M V Garzelli[1], A Mairani[3,4], A Ottolenghi[3,4], A Pepe[1], L S Pinsky[7], P R Sala[2], D Scannicchio[3,4] and G F Steyn[6]

[1] Department of Physics, University of Milan, Italy
[2] INFN, Section of Milan, Italy
[3] Department of Nuclear and Theoretical Physics, University of Pavia
[4] INFN, Section of Pavia, Italy
[5] CERN, Switzerland (on leave from INFN, Sezione di Milano)
[6] iThemba Lab. for Accelerator Based Sciences, South Africa
[7] Houston University, Texas, US

E-mail: `francesco.cerutti@mi.infn.it`

Abstract. Accurate knowledge of the reactions which occur when two heavy ions interact is of importance in many trans-disciplinary fields, particularly in cancer therapy and space radiation protection. In these cases one needs to know what happens in a natural process to which all possible reaction mechanisms contribute and thus a theoretical calculation, to be really usable, must indeed be able to reproduce large sets of data in wide energy and mass ranges.

We show here the results of an analysis of the spectra of intermediate mass fragments produced in the C+Al interaction at 13 MeV/n, both in direct and inverse kinematics, which supplies a very reasonable reproduction of a great number of data providing useful information on the leading reaction mechanisms.

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1. Introduction

The interaction between two heavy ions, involving two many body systems, produces a complex variety of processes. A theoretical calculation must provide a comprehensive description of them to be useful in application fields, such as hadrontherapy and space radiation protection. For this purpose Monte Carlo codes, such as FLUKA [1], simulating the propagation of radiation into any complex geometry material, represent a very helpful tool provided that they are supplied with reliable interaction models. One of these, used for describing the interaction of light nuclei with matter, is the Boltzmann Master Equation (BME) theory coupled with a binary fragmentation model [2–8]. Recently, we used this approach for the study of light systems, which are of particular interest for the mentioned fields of application. Some results concerning the C+Al system at 13 MeV/n, studied both in direct and inverse kinematics, are discussed in

Section 2. Section 3 is devoted to conclusions and a brief discussion on the perspectives of such calculations.

2. Low Energy Nucleus-Nucleus Reactions

At low incident energies (a few tens of MeV/n) the cascade of nucleon-nucleon interactions which develops when two ions overlap may be described by a set of BMEs the solution of which allows to estimate the variation with time of the nucleon state occupation probability and thus the evolution of an excited nucleus toward a state of statistical equilibrium and the emission of particles in the course of this thermalization process.

The BME theory as well as the theory which describes nuclear binary fragmentation (or break-up), which in the case of light ion interactions greatly contributes to the observed channels, is illustrated elsewhere [2–8]. Here we limit ourselves to discuss its use in the analysis of the reactions occurring in the interaction of two light ions which have attracted a wide interest due to their relevance in fields like hadrontherapy and radiation protection in space missions.

To illustrate the capabilities of our theoretical approach we show some results which have been obtained in the analysis of the spectra of fragments produced in the interaction of ^{12}C with ^{27}Al at 13 MeV/n [9] by generalizing the calculations which we have successfully made to describe the interaction of light projectiles with medium-heavy targets [2–8]. The model considers the possibility of both complete fusion of the two ions and incomplete fusion following the break-up. These mechanisms produce an excited system the de-excitation of which through a cascade of nucleon–nucleon interactions and particle emissions, which eventually lead to a thermally equilibrated nucleus which further decays by particle evaporation, is described by the BME theory [2, 3]. The light projectile break-up is described in the local plane wave approximation allowing however for an energy loss of the breaking-up nucleus before its fragmentation [4–8]. A significant fraction of the ejectiles produced in such interactions are intermediate mass fragments ($Z \geq 3$) which these studies have convincingly demonstrated to originate from two unrelated processes: the projectile's binary fragmentation and the coalescence of excited nucleons during the nuclear thermalization.

According to this reaction picture, in the interaction of two light nuclei both interacting partners may break-up and, except in the case of the lightest emitted particles, it is no longer possible to separate the ejectiles produced in the fast stage of the reaction from the evaporation residues, which in the interaction of a light projectile with a much heavier target nucleus have widely different masses. This represents a serious complication of the theoretical analysis.

In this preliminary study, to investigate if this model may describe successfully the interaction of two light ions it was important (i) to study the interaction of nuclei with somewhat different masses such as ^{12}C and ^{27}Al because the ejectiles produced by projectile and target fragmentation or originating from the coalescence of projectile and target nucleons in the composite system are more easily distinguished, and (ii) to study both the *direct* and the *inverse* reaction exchanging the roles of the projectile and the target.

In fact, for kinematical effects, in the laboratory system fragments originating from the projectile are mostly emitted at very forward angles with considerable energy, while those originating from the target are emitted at larger angles with greatly reduced

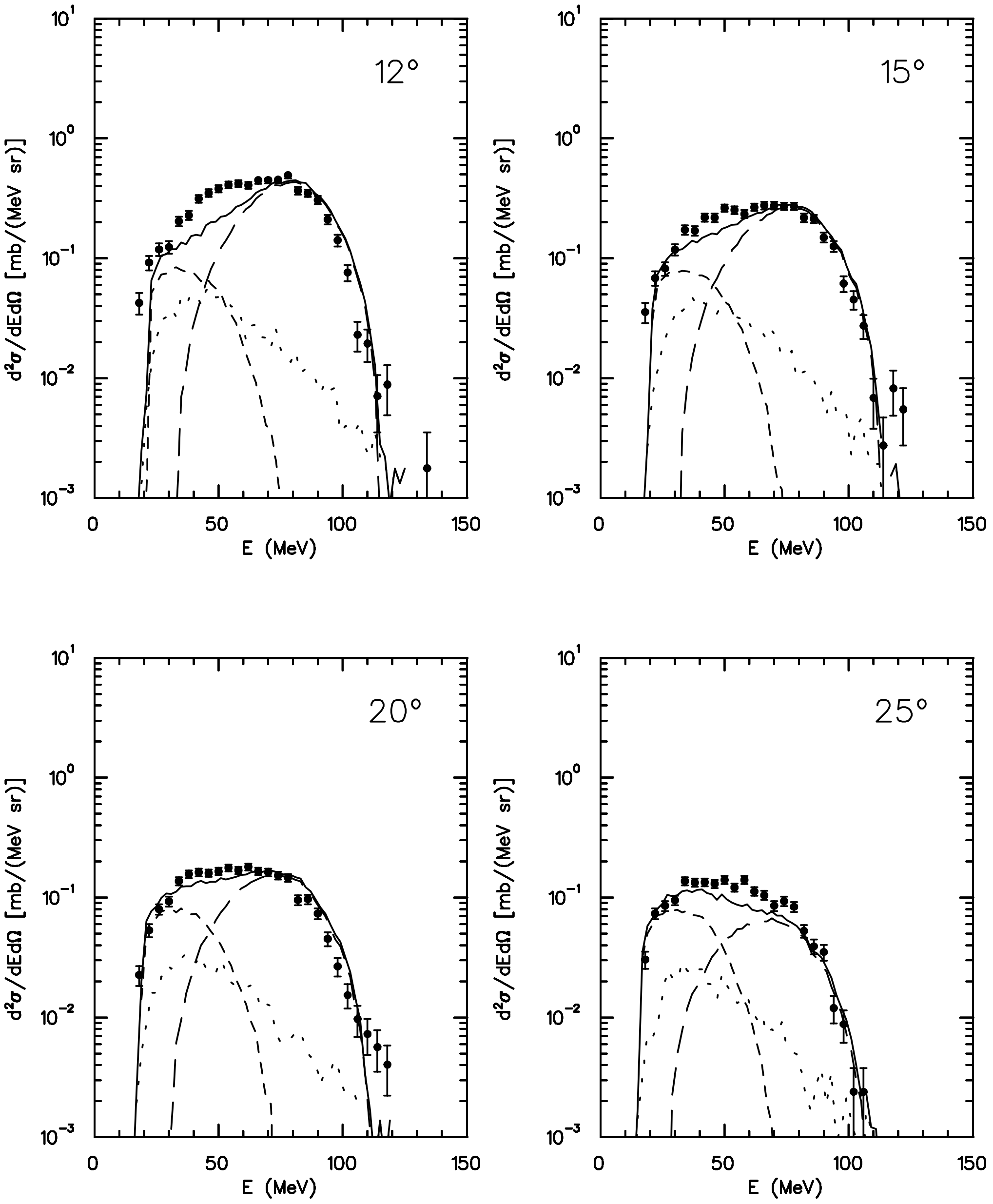

Figure 1. Double differential spectra of ^{7}Be in the ^{12}C+^{27}Al system at E_{Lab}=156 MeV. Experimental data (full circles with error bars) are compared with the theoretical prediction (solid line) given by the sum of three contributions: fragments from ^{12}C (long dashed line) and ^{27}Al (short dashed line) break-up, and nucleon coalescence in complete fusion reactions (dotted line).

energy. As a consequence, the spectra of the ejectiles produced in the *direct* and the *inverse* reaction may extend to considerably different energy ranges according to their origin and display quite different features as shown in the case of ^{7}Be and F fragments in Figures 1, 2, 3, and 4. The contemporary analysis of a large number of these spectra allows one to deduce realistic values of the computational parameters reducing the number of arbitrary assumptions.

In spite of the enormous variety of processes which might occur, most of the spectra are reproduced simply considering the complete fusion of the two ions as well as the break-up of one of the partners with the subsequent fusion of one of the two fragments

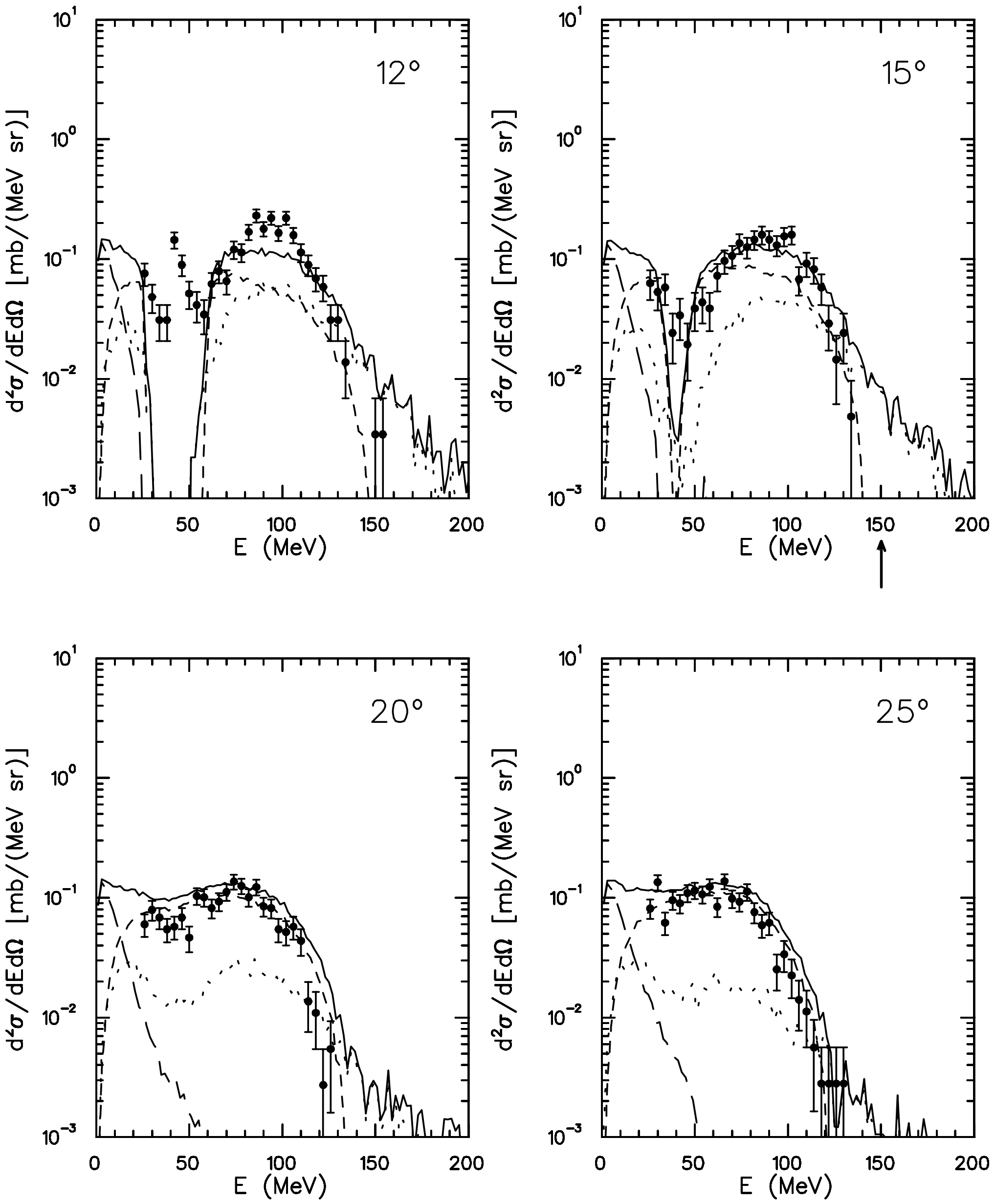

Figure 2. Double differential spectra of ^{7}Be in the ^{27}Al+^{12}C system at E_{Lab}=348 MeV. See Figure 1. The arrow indicates the high energy experimental threshold.

with the other ion. These processes lead to the production, with quite significant cross-sections, of a large number of ejectiles, ranging from fragments with mass smaller than the mass of the lighter interacting ion to residues with mass exceeding that of the heavier interacting ion.

Break-up fragments from both interacting ions and fragments produced by nucleon coalescence in complete fusion reactions contribute to the lightest ejectile spectra, as

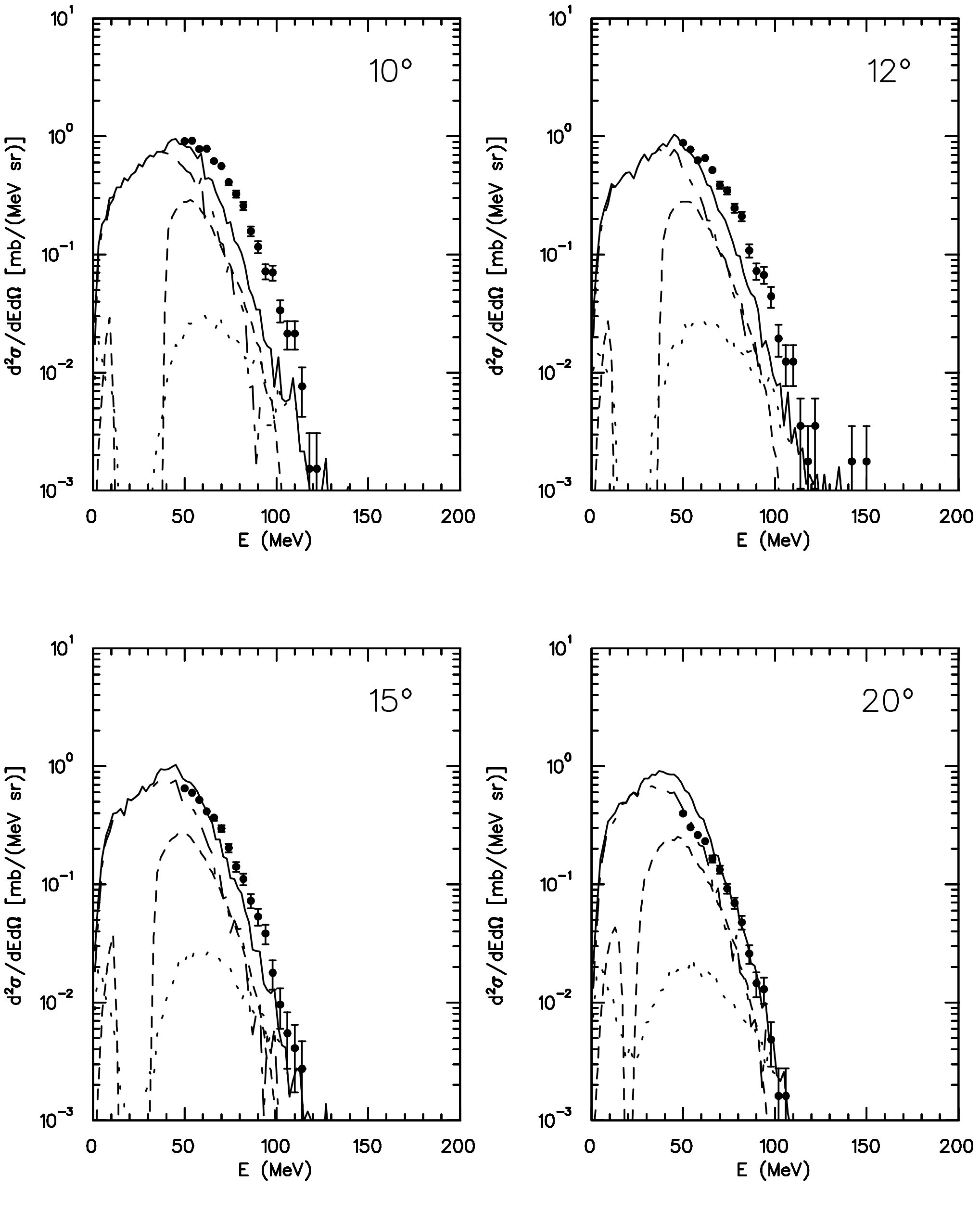

Figure 3. Double differential spectra of F in the ^{12}C+^{27}Al system at E_{Lab}=156 MeV. Experimental data (full circles with error bars) are compared with the theoretical prediction (solid line) given by the sum of three contributions: fragments from ^{27}Al (short dashed line) break-up, from nucleon coalescence in complete fusion reactions (dotted line), and produced as evaporation residues in complete fusion and break-up-fusion reactions (dashed dotted line).

shown for ^{7}Be in Figures 1 and 2. At low incident energy we expect the contribution of nucleon coalescence in incomplete fusion reactions to be small. These light fragments do not seem to be produced in substantial amounts as evaporation residues neither in complete fusion nor break-up-fusion reactions.

Nuclei with mass intermediate between those of the interacting ions may be produced by the heavier ion fragmentation, by nucleon coalescence in complete fusion reactions, and at the end of the full de-excitation chain as evaporation residues. The importance of the last contribution increases with increasing the residue's mass. As an example for this kind of fragments, spectra of F are shown in Figures 3 and 4.

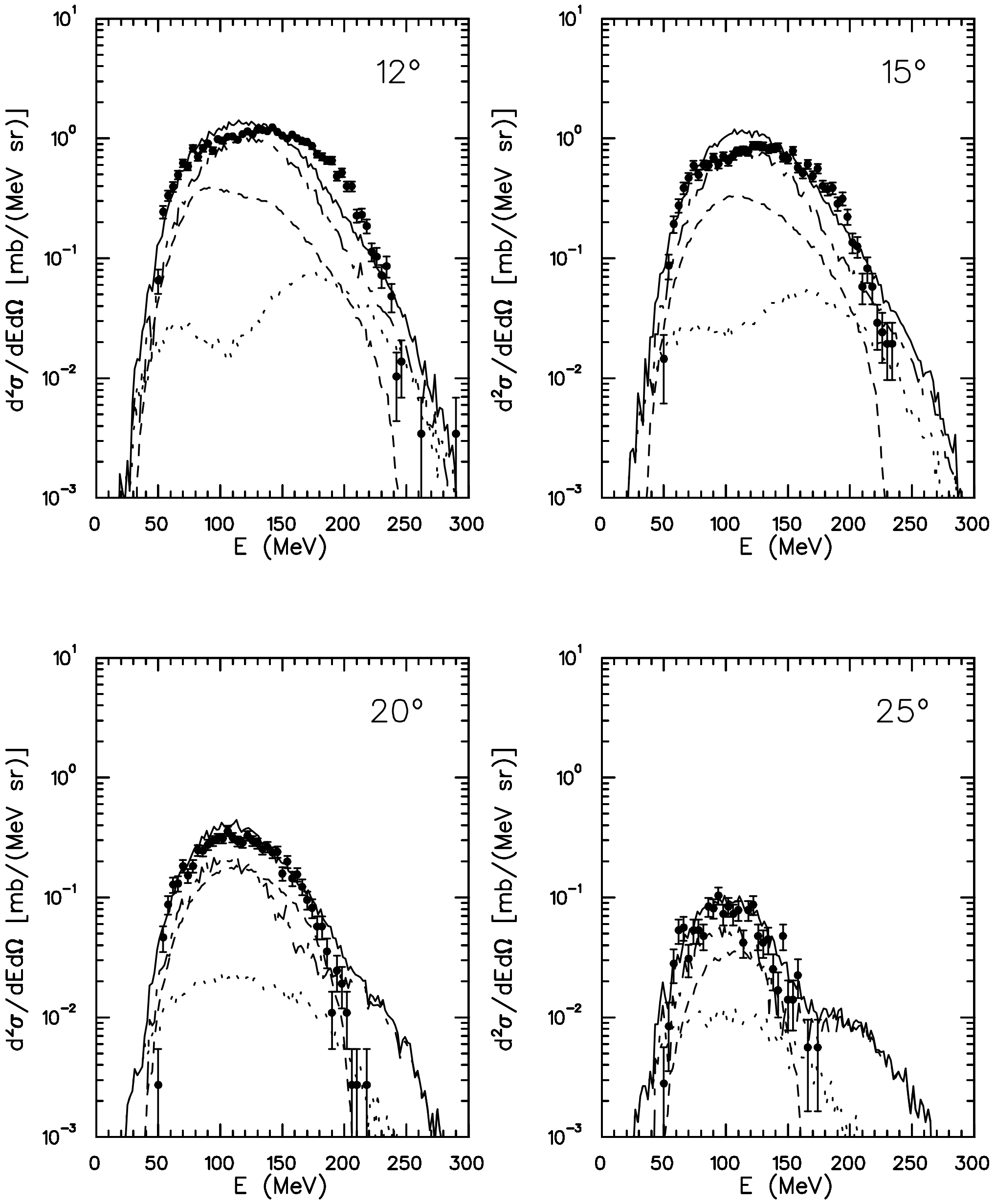

Figure 4. Double differential spectra of F in the ^{27}Al+^{12}C system at E_{Lab}=348 MeV. See Figure 3.

Evaporation residues heavier than ^{27}Al are also observed with sizeable cross-sections and their spectra are reasonably reproduced by our calculations.

Generally the experiment did not allow one to discriminate between isotopes contributing to the same elemental spectrum. While many different isotopes may be produced by coalescence or as evaporation residues, for sake of simplicity we considered only the break-up modes having the lowest fragmentation energies, and the spectator fragments are assumed to be in their ground state or have at most a small excitation energy. The evaluation of the evaporation residue spectra includes the contribution of complete fusion and many incomplete fusion reactions. The fusion of the participant fragment with the partner ion produces an excited intermediate nucleus which, at such low incident energy, may just evaporate light particles. Table 1 lists, as an example, the break-up-fusion reactions which together with complete fusion are expected to contribute to the formation of oxygen isotopes as evaporation residues. The cross-section of each of these reaction mechanisms is assumed to be equal to the cross-section for production of the complementary spectator fragment as deduced from the analysis of the measured spectra.

Table 1. Reaction mechanisms, with their assumed cross-section, creating excited nuclei (asterisk) which may produce oxygen isotopes as evaporation residues.

reaction mechanism					σ [mb]
^{27}Al + ^{12}C	$\rightarrow$	^{23}Na + ^{4}He + ^{12}C	$\rightarrow$	^{23}Na + ^{16}O*	35
^{27}Al + ^{12}C	$\rightarrow$	^{22}Ne + ^{5}Li + ^{12}C	$\rightarrow$	^{22}Ne + ^{17}F*	40
^{27}Al + ^{12}C	$\rightarrow$	^{19}F + ^{8}Be + ^{12}C	$\rightarrow$	^{19}F + ^{20}Ne*	12
^{27}Al + ^{12}C	$\rightarrow$	^{16}O + ^{11}B + ^{12}C	$\rightarrow$	^{16}O + ^{23}Na*	30
^{27}Al + ^{12}C	$\rightarrow$	^{14}N + ^{13}C + ^{12}C	$\rightarrow$	^{14}N + ^{25}Mg*	30
^{27}Al + ^{12}C		$\rightarrow$		^{39}K*	225

The total cross-section obtained by adding up the contributions of all the considered mechanisms and the cross-section for inelastic scattering, pick-up as well as stripping reactions, estimated from the measured spectra, amounts to about 80% of the reaction cross-section of 1700 mb [10].

The results of this analysis are encouraging because the qualitative features of all observed spectra are very satisfactorily reproduced and the theory seems to be able to provide also a very reasonable quantitative account of them in spite of the simplifying assumptions which are made. Some results were rather unexpected such as the sizeable production of evaporation residues with mass exceeding the interacting ion masses, as a consequence of the leading role of complete and incomplete fusion reactions.

3. Conclusions

In order to increase the prediction ability of Monte Carlo transport and interaction codes, a reliable description of nucleus–nucleus interactions has to be assured. To this aim the development of comprehensive models, considering the leading reaction mechanisms in the different energy ranges, is crucial.

In this paper we have shown how the BME theory and a binary fragmentation model may successfully describe the interaction between light ions. The obtained results encourage us to extend the calculations to even lighter systems, such as ^{12}C+^{12}C and ^{12}C+^{16}O. This investigation is particularly significant because these reactions occur in the interaction of therapeutic hadron beams with the biological tissue. In this context it is of primary importance to provide a realistic estimate of the rate of production and the energy and angular dependence of positron emitters which may be used for visualizing the beam and maximizing its effectiveness in cancer treatment reducing the damage to the healthy tissue. Another important issue is the realistic estimate of the production rate of evaporation residues with mass exceeding those of the interacting ions and relatively small kinetic energy which might increase the beam biological effectiveness in the Bragg peak region.

Acknowledgments

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