Acta Phys. Hung. A / () –

HEAVY ION
PHYSICS

The interaction of ^{12}C and ^{16}O with medium-heavy nuclei

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Received 31 October 2005

Abstract. The results of a series of experiments on the interaction of ^{12}C and ^{16}O with medium and heavy nuclei (^{59}Co, ^{93}Nb, ^{103}Rh, ^{197}Au), in which the spectra of intermediate mass fragments and the excitation functions for production of a large number of evaporation residues have been measured up to 400 MeV incident energy, are reviewed. The scopes of these experiments were to get a comprehensive information on the reactions which may occur and to develop a model which might reproduce all the measured data within a unique global calculation. This was indeed found to be possible considering the complete fusion of the two interacting ions, the binary fragmentation of the projectile followed by the fusion of one of the fragments with the target nucleus, and the projectile inelastic scattering. The theoretical models which allow to reproduce the data, i.e., the fragmentation model and the Boltzmann Master Equation theory which describes nuclear thermalization are briefly summarized.

Keywords: ^{12}C, ^{16}O induced reactions, Nuclear fragmentation, Nucleon coalescence
PACS: 25.70.Gh; 25.70.Mn

1. Introduction

The program of this Symposium gives the proper weight to the applications of Nuclear Physics in interdisciplinary fields and for services useful to mankind. These are fields of growing importance, as shown by the Proceedings of the recent Santa Fe Conference on Nuclear Data for Science and Technology [1], which, however, are not separate from what we usually define basic research. One could say that in most cases they are just basic research with special emphasis to providing systematic,

1219-7580/04/ $ 20.00

accurate and comprehensive knowledge. Some of the most spectacular successes of Nuclear Physics came from studies of this kind (e.g., the study of slow neutron resonances) which in addition to significantly increasing our knowledge of the basic laws played a major role in many technological developments and applications.

In this paper we will review the results of a series of experiments which our research group did for acquiring information which could be useful for reaching a comprehensive knowledge of the interaction of light nuclei such as ^{12}C and ^{16}O with matter and understanding their basic reaction mechanisms with the aim of using this information in fields such as hadrotherapy and space radiation protection. In particular we will concentrate on the study of the interaction of such ions with heavier target nuclei up to incident energies of 35 MeV/n [2–8]. Another contribution to the Symposium deals with the interaction of two light nuclei [9].

2. Review of the experimental data and their theoretical analysis

In summarizing this work we will not enter into technical details which may be found elsewhere and will simply try to make clear our ideas and theoretical approaches.

Our first studies concerned the study of emitted particle spectra in complete fusion reactions and led us to recognize the enormous importance of describing the mechanism through which the initial energy distribution of the projectile and target nucleons within the composite nucleus, which the two nuclei form when they fuse, transforms into the thermal equilibrium distribution. We think that this mechanism (*nuclear thermalization*) consists of a cascade of nucleon-nucleon interactions which we describe by a set of coupled Boltzmann Master Equations (BMEs). Their solution gives the time evolution of the occupation probability of predefined bins of nucleon states as a result of nucleon interactions which redistribute the nucleons within different bins and emission of particles into the continuum. The set of BMEs considers the possibility of emission not only of single nucleons but also of clusters (light complex particles and intermediate mass fragments (IMFs)) which may be formed by coalescence of nucleons, and allows to predict their double differential spectra. Coupled with a Monte Carlo calculation it permits to evaluate the probability of particular sequences of events and thus of exclusive processes [10, 11]. Together with a statistical evaporation code describing the de-excitation of the equilibrated nuclei formed at the end of the thermalization, this theoretical simulation provides a comprehensive description of all possible reactions. These calculations allowed to reproduce accurately a large number of ejectile spectra given in literature.

On the other hand, with increasing interacting ion energy, complete fusion contributes increasingly less to the reaction cross section and one must consider the possibility of different mechanisms. We actually think that the most probable of these alternative mechanisms are, in the case of ^{12}C and ^{16}O, break-up-fusion reactions, i.e., binary fragmentation of the projectile followed by the fusion of one of the fragments with the target nucleus. We first thought that the spectra of the ejectiles produced in the fragmentation might be quite reasonably reproduced by the local plane wave approximation (LPWA) proposed in [12,13] as an improvement of the Serber's original theory [14]. However the analysis of a number of experiments suggested us that before fragmentation the projectile may suffer a quite considerable loss of energy. This conclusion was drawn by the analysis of the ^{8}Be^{gs} spectra measured in the interaction of ^{12}C with nuclei ranging from ^{59}Co to ^{187}Au which, at forward angles, were found to have an average energy smaller than that expected for elastic break-up and a considerably larger width around the maximum than that simply reflecting the internal motion of the fragments within the projectile [2,3]. The assumption that the observed fragment might suffer a final state interaction after being produced was considered less probable because it was thought that ^{8}Be^{gs} could not survive this interaction. The hypothesis of an initial state interaction

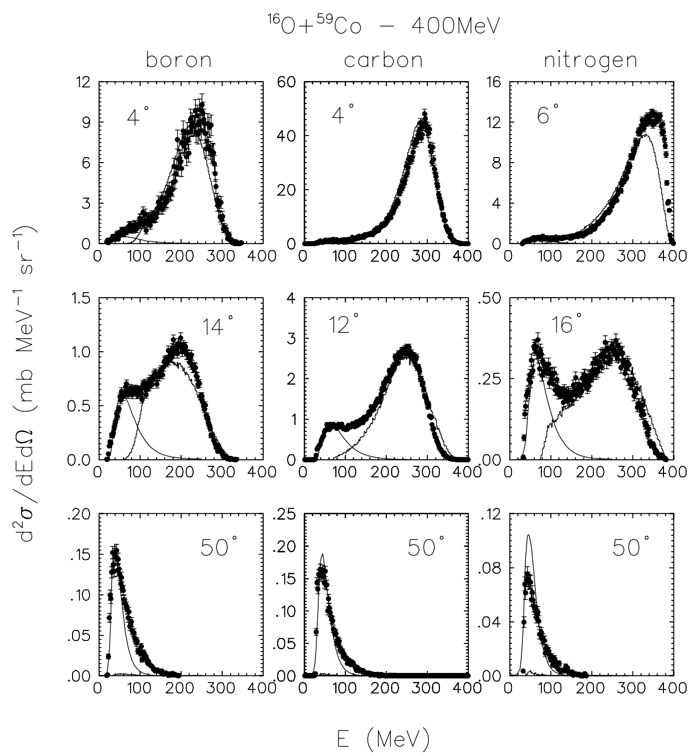

Fig. 1. Spectra of boron, carbon and nitrogen fragments produced in the interaction of ^{16}O with ^{59}Co at an incident energy of 400 MeV [4]. The experimental values are given by the solid dots. The theoretical prediction of the spectra of fragments produced by ^{16}O break-up is given by the solid line histograms extending up the highest emission energies. The expected contribution of fragments produced by nucleon coalescence is given by the solid lines peaking slightly above the emitted fragment's Coulomb barrier.

which might lead to a rather considerable loss of energy was not considered improbable because a quite substantial energy loss is also observed in the more peripheral inelastic scattering reaction. A formal description of this interaction was outside our scope and we adopted a much simpler phenomenological approach introducing the concept of the ***Projectile Survival Probability*** (PSP) to mass transfer and break-up

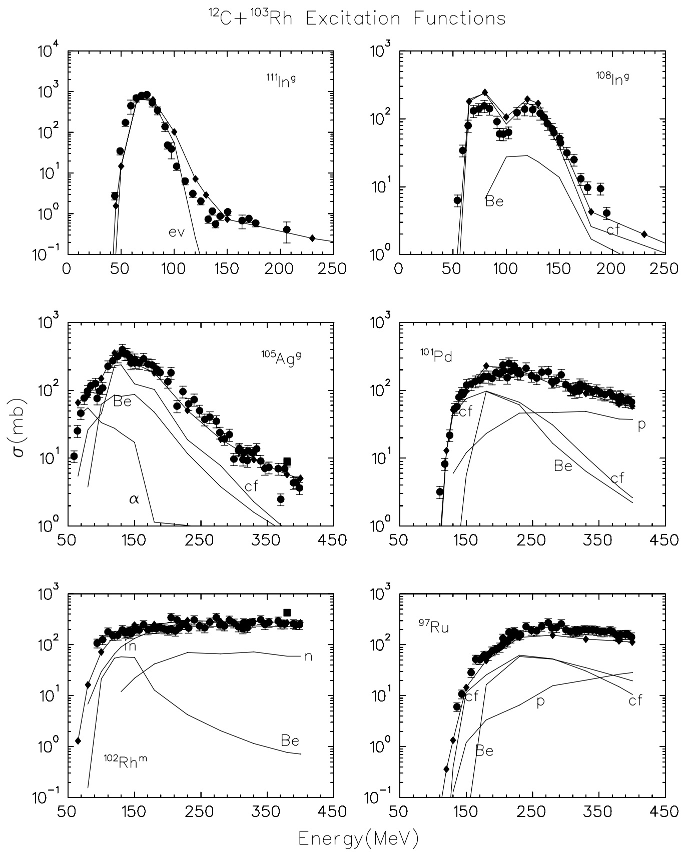

Fig. 2. The reaction mechanisms which are estimated to contribute mostly to the excitation functions for production of the indicated evaporation residues in the interaction of ^{12}C with ^{103}Rh are shown. ^{111}In$_g$ is produced only in the complete fusion. For this nucleus the excitation function (indicated as *ev*) which one would evaluate in absence of pre-equilibrium emissions during thermalization is shown. In the case of the other excitation functions, the meaning of the symbols associated with the shown contributions is: cf = complete fusion, in = inelastic scattering, Be = incomplete fusion of a berillium isotope, α = incomplete fusion of one α particle, p (n) = transfer of a proton (neutron) from the projectile to the target. The calculated total cross section is given by the line connecting the black rombuses, the experimental values are given by the black dots.

for which we assumed an exponential decrease with increasing the projectile energy loss as suggested by the energy averaged dependence of the inelastic scattering spectra as a function of the kinetic energy loss. The spectra of break-up fragments were then evaluated by folding the LPWA spectra with the PSP function [2–7].

In contrast with the quite extended information concerning nucleon and light particle spectra we could not find in literature sufficient data on IMFs in reactions induced by carbon and oxygen. So we made a series of experiments for measuring their spectra [4–7]. A few results are shown in Fig. 1 concerning B, C and N spectra for the system ^{16}O + ^{59}Co. In this figure one may see the two separate contributions due to fragmentation at high energy and nucleon coalescence at energies slightly above the Coulomb barrier. Both contributions display a forward peaked angular distribution, but that of the coalescence fragments decreases much more slowly with increasing emission angle, so, though it is quite small at the most forward angles, it becomes soon the dominant contribution.

Our systematic study of ^{12}C and ^{16}O reactions allowed us to estimate the parameters relevant for the theoretical calculations: the fragmentation cross sections, the average energy loss before fragmentation and so on [2–8]. These results indicate that the fragmentation process is considerably more complex than thought before, not only for the presence of the quite significant energy exchange before fragmentation, but also because ^{12}C and ^{16}O may fragmentate in many different ways and not exclusively into α-type fragments. As we mentioned before, our calculation simulates the processes which may occur in the two ion interaction and ends with the production of what is usually called an evaporation residue. Fig. 2 shows the experimental excitation functions for production of some of these residues in the interaction of ^{12}C with ^{103}Rh and their theoretical reproduction together with the estimated contributions of the most important reaction mechanisms [8].

3. Concluding remarks

The results which we have obtained for the different targets suggest that the scenario which we have delineated depends slightly and in a predictable way on the mass of the considered target nuclei and thus these calculations possess a considerable prediction ability comparable with that of the calculations made for nucleon induced reactions (see, for instance, many of the contributions to [1]). Obviously this is only the first step on the long way to get a comprehensive understanding of the reactions induced by heavy ions, even in the case of the ions which we have considered, since our results concern a quite restricted energy range.

Let us finally outline some of the ideas which we are taking into account for describing the interactions of heavier ions. A quite considerable number of papers originating by a seminal paper by Karol [15] (see [16] and references therein) show that the reaction cross sections of two heavy ions may be calculated over a very extended energy range as due to the nucleon-nucleon interactions in the overlap region of the two ions once they come into contact. At not too low incident energies it is conceivable that two slightly excited projectile- and target-like nuclei flying in almost opposite directions in the center of mass system and a highly excited middle source might be produced. This scenario reminds the well known multi-source mechanism invoked to describe the ejectile spectra in a great number of experiments. However a proper generalization of the concepts and computational techniques used in the calculations which we have here discussed might eliminate most of the unrealistic and naive hypotheses which are often adopted and provide also in this case a comprehensive description of the different reactions which may occur.

Acknowledgments

The series of experiments and theoretical calculations summarized in this paper are due to the joint effort of a large number of colleagues and students. We wish to thank in particular our colleagues E. Gadioli Erba, M. Cavinato and C. Birattari of the Milan University, S.H. Connell of the Witwatersand University, G.F. Steyn and S. Förtsch of the iThemba LABS, A.A. Cowley of the Stellenbosch University, and the late unforgettable colleagues E. Fabrici of the Milan University and J.P.F. Sellschop of the Witwatersand University.

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