LOW ENERGY NUCLEUS–NUCLEUS REACTIONS: THE BME APPROACH AND ITS INTERFACE WITH FLUKA

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Abstract The interface to the FLUKA transport and interaction code of a module using the Boltzmann Master Equations to describe the nuclear thermalization of the non-equilibrated nucleus produced in the fusion of two ions, at any energy below 100 MeV/nucleon, is described.

1. Introduction

Many talks presented at this Conference have shown the enormous importance of nuclear physics data and concepts in fields ranging from astrophysics and space missions to archeology, from medicine to civil security, from energy production to material testing. All these applications require an accurate knowledge of basic quantities such as the double differential cross-sections of all particles emitted in a reaction initiated by a projectile with variable energy, the momentum distribution of the residual nuclei which may be produced, and their decay properties (including the subsequent $\gamma$ ray spectra). A great effort for measuring such data is made in case of nucleon induced reactions \cite{1, 2}. In the case of heavy ion reactions such information is still very scarce. In any case it is dubious that one could obtain a complete information for any possible combination of projectile and target which might reveal useful in the fields above mentioned and thus the need of computational codes which might provide reasonably accurate predictions of these observables is widely recognized. Many of such codes already exist or are in preparation in the case of nucleon induced reactions \cite{2}. In the case of heavy ion reactions we are still in a very early stage. To contribute to fill this gap in
present knowledge, since many years our research group started a series of experimental and theoretical investigations of the reactions induced by $^{12}$C and $^{16}$O on targets ranging from light to heavy nuclei. The results which are discussed in the next Section concern data measured at the iThemba Labs at incident energies up to about 35 MeV/nucleon for $^{12}$C and 25 MeV/nucleon for $^{16}$O and their subsequent interpretation with a model considering both projectile fragmentation in the Local Plane Wave Approximation (LPWA) and thermalization followed by evaporation of the excited composite nuclei created in break-up-fusion and complete fusion reactions calculated by a code based on the Boltzmann Master Equation (BME) theory \cite{3-12}. Reactions induced by different and higher energy projectiles which require different approaches have been also considered and are discussed in another contribution to this Conference \cite{13}.

For many applicative purposes one requires to know not only what happens in what we may call the primary interaction (PI) but also in the cascade of subsequent interactions which are induced by the PI products in a thick material such as a human body or a space ship. This is done with transport codes such as those described in other contributions to the Conference \cite{14, 15}. In the third section of the paper we will discuss how one of such transport code, FLUKA, may incorporate the BME approach. As we will see, in order to make feasible any calculation, the FLUKA-BME interface requires a rather complex and in the same time approximate procedure which will be briefly outlined.

2. **Systematic study of $^{12}$C and $^{16}$O induced reactions at energies of few tens of MeV/nucleon**

Most of the reactions which occur in a two ion interaction are the result of a series of complex processes such as a mean field interaction and the formation of an excited non-equilibrated nucleus (referred to as composite nucleus) which reaches a state of thermal equilibrium through a sequence of two-body interactions leading eventually to a compound nucleus the energy of which may be a small fraction of the energy of the composite nucleus formed in the fusion of the two ions. Along this paper this sequence of nucleon–nucleon elastic scatterings inside the composite nucleus will be called nuclear thermalization. The equilibrated nucleus may further evaporate particles and $\gamma$ rays thus leaving a residue which, if radioactive, generates beta and/or alpha particles and/or further $\gamma$ rays. For the purposes which we have briefly summarized in the Introduction, all this sequence of processes must be accurately simulated if
one aims to get information usable in interdisciplinary and applicative fields.

The measurement and the analysis of a large set of data including double differential spectra of light particles and intermediate mass fragments (IMFs) [3–10] and the excitation functions for production of a large number of residues [11, 12], shows a scenario the subsequent steps of which are: (a) an initial mean field interaction during which the projectile can lose a considerable fraction of its energy, (b) possibly its fragmentation in a large variety of modes, (c) the fusion of one or both fragments or of the non-fragmented projectile with the target nucleus, (d) the thermalization of the composite thus created, during which fast light particles and IMFs produced by nucleon coalescence may be emitted, (e) the final evaporation of particles by the equilibrated nuclei which are produced at the end of the thermalization process. The evidence for that is discussed in two recent papers by our group [11, 12]. All measured observables are quite reasonably reproduced by the calculations [3–12].

These calculations also allowed one to reproduce more exclusive processes such as the double differential spectra of light particles observed in central collisions in coincidence with a heavy fragment emitted in a narrow angular and velocity range [3, 4], thus suggesting that this theoretical approach might quite accurately predict still unmeasured observables.

3. The BME-FLUKA interface for nucleus–nucleus interactions below 100 MeV/nucleon

The processes which may occur during the thermalization of a composite nucleus created in the complete or incomplete fusion of two ions are simulated by means of a Monte Carlo event generator able to incorporate as input the results of the numerical integration of the BMEs [4]. These equations describe the time evolution of the momentum distributions of the nucleons of the composite nucleus via two body elastic scatterings and particle emissions into the continuum (both single nucleons and clusters such as a light particle or an IMF) [3].

If one aims to simulate the interaction of an ion beam with the biological tissue in hadrontherapy or to perform accurate dose calculations for cosmic radiation protection purposes in deep space, the nuclear interaction of many projectile-target pairs of varying energy has to be described into a radiation transport context. In fact, in this case the Monte Carlo code should need as input the evaluated angle-energy multiplicity spec-
tra (as a function of time) of all pre-equilibrium particles emitted both in the primary and the secondary interactions along the nuclear reaction chain. Their run-time calculation would be too time-consuming for allowing in practice the simulation of the reactions induced by energetic ions in thick materials of complex geometry. Even the run-time access to pre-computed spectra becomes impossible if we have to consider every possible projectile-target-energy combination.

Thus, in order to provide the FLUKA code with a more realistic treatment of nucleus–nucleus interactions below 100 MeV/nucleon, the BME theory has been used for evaluating pre-equilibrium emissions for a representative set of ion pairs at different energies, carrying out a proper parametrization of the calculated ejectile multiplicities and double differential spectra and creating a database of the obtained parameters. A few examples of such procedure are shown in Figs. 1-3. By a proper interpolation of these parameters the pre-equilibrium emissions in complete fusion events - whose probability of occurrence is evaluated as a function of the incident energy and the mass and atomic numbers of the interacting nuclei - can be simulated along the reaction chain for any pair of interacting ions while the final de-excitation of the remaining equilibrated nuclei is handled by the FLUKA evaporation/fission/fragmentation module.

For more peripheral collisions, the impact parameter $b$ is chosen according to the differential expression of the reaction cross-section $d\sigma_R/db$, 

![Figure 1. Theoretical prediction of the average total multiplicity of pre-equilibrium particles emitted in complete fusion events for the indicated nucleus pairs, as a function of incident energy. The symbols give the BME results, the lines represent the adopted parabolic fit.](image)
evaluated by improving a model proposed long ago by P.J. Karol [19]. Within this model [20], a three body picture of the reaction quite naturally follows, envisaging the production of rather cold projectile-like and target-like nuclei, and a middle source preferentially excited, the mass number of which is obtained by integrating the projectile’s and target’s Fermi densities over their overlapping region. At still higher impact
Figure 3. Theoretical prediction of double differential spectra (in the center of mass frame) of protons emitted during the thermalization of the non-equilibrated system formed by the $^{16}$O+$^{12}$C complete fusion at 50 MeV/n. The points with the error bars give the BME results, the lines represent the adopted fit $(d^2M/(dE d\Omega)) = \frac{E^2}{2\pi}\exp(-P_2(\theta) - P_1(\theta)E))$.

parameters, this reaction mechanism smoothly develops into a sort of inelastic scattering.
This implementation is still in a preliminary stage, since other systems have to be investigated in order to enrich the complete fusion database, and an extensive cross-checking of the theoretical predictions against thin target experimental data is needed. However, its use for the calculation of dose and activity profiles of therapeutic heavy ion beams already provided encouraging results (see Fig. 4).

References


[13] M. V. Garzelli et al., Contribution to this Conference

[14] A. Ferrari et al., Contribution to this Conference


