Heavy-ion collisions: preliminary results of a new QMD model coupled with FLUKA

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Abstract. Quantum Molecular Dynamics (QMD) models are considered viable tools to simulate the initial hot stages of heavy-ion collisions and investigate the properties of the nuclear matter equation of state. A new QMD model has been developed by scratch by our group during the last few years and recently coupled to the FLUKA fission/Fermi break-up/evaporation module which describes the latest stage of the reactions, when slower processes leading nuclei to the equilibrium occur. Comparisons with experimental data collected both in symmetric and in asymmetric collisions are shown, covering a wide range of projectile and target masses. Reproduction of the experimental light particle ($Z < 3$) yields is one of the most difficult challenges to be met by QMD models, traditionally prone to underestimate α particle emission while dramatically overestimating proton and neutron emission. Our results seem to be quite satisfactory with respect to this issue, thanks to the form of the potential terms involved in the nucleon-nucleon interaction and to many refinements applied in the fragment definition scheme, based on the potential which each particle experiences because of its neighbors. Nucleon isospin is taken into account all over the simulation, as well as the experimental binding energy constraints on nuclear states. The introduction of further refinements to describe pre-equilibrium processes is under development.

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1. Introduction

In the last few years a microscopic model inspired to Quantum Molecular Dynamics theory has been developed by our group to describe the initial hot stage of heavy-ion collisions [1]. An interface to the FLUKA Monte Carlo tool [2] is under development and will allow to simulate the propagation and interaction of beams inside matter in complex geometries. The model is very general, and allows to describe collisions involving ions on a broad range of masses, despite the fact that only few parameters are introduced. At present, we are testing it in many reactions, symmetric and asymmetric, involving both light and heavy ions. The results of some of these tests are the subject of this paper.

2. Quantum Molecular Dynamics approach

According to this approach, each nucleus is described as a set of nucleons. These ones are not at rest, frozen into a static configuration, but move, thanks to their kinetic energy, in the potential well generated by an effective Hamiltonian, involving two-body and three-body interaction terms. Protons and neutrons are fully distinguished, both in their mass and in their isospin. In particular, a symmetry potential and the Coulomb term have been introduced in the Hamiltonian, so that n - n, n - p and p - p interactions have different strenght and behaviour. More detail about the Hamiltonian can be found in ref. [1, 3]. Furthermore, when two ions come close in collision, stochastic nucleon-nucleon collisions are introduced to simulate the hard scattering process. Their strenght has been deduced from the free p - n and p - p (n - n) experimental cross-sections [4]. The Pauli principle establishes which collisions may effectively take place, according to the final state phase-space availability.

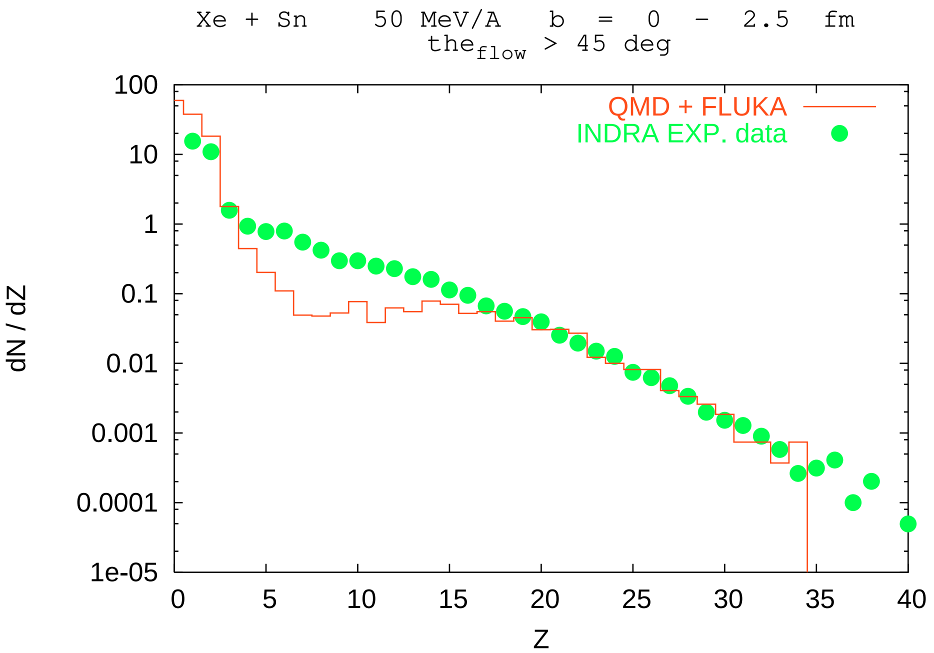

Figure 1. Fragment charge distribution from our theoretical simulation (solid histogram) compared to the experimental data [5] (filled circles) collected in central collisions by the INDRA detector at GANIL (filled circles) for Xe + Sn collisions at 50 MeV/A.

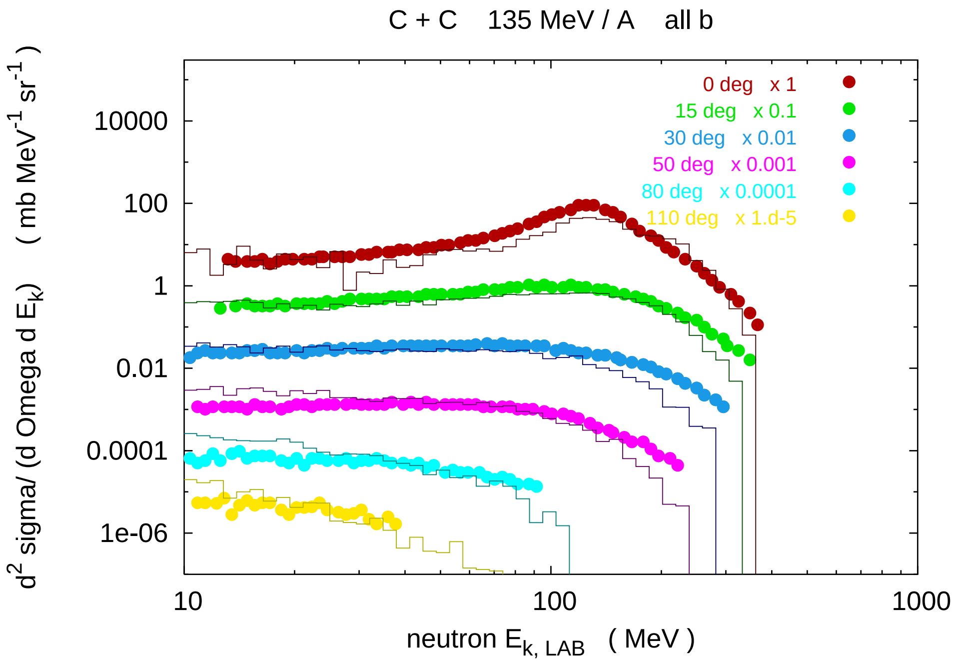

Figure 2. Double differential neutron production cross-section, for n energies > 10 MeV. The results of our QMD + FLUKA theoretical simulation, obtained at different angles (0, 15, 30, 50, 80, 110 deg) shown by solid histograms, are compared to the experimental data from ref. [8], shown by filled circles. The spectra at 15, 30, 50, 80, 110 degrees have been scaled by a factor 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}, respectively, to distinguish them on the same plot. No normalization factor has been introduced. The statistical uncertainty on the experimental data is in the (2 - 5) % range for E < 100 MeV and increases to about 30 % at the highest energies, while the total normalization uncertainty, due to many factors, is estimated within 17%. The largest irregularities in the theoretical distributions are mainly due to low statistics.

3. Charged particle distributions

Charged particle yields have been measured in many collision experiments and can be predicted by QMD tools, eventually coupled with models able to describe nuclear de-excitation. Here the results obtained by our theoretical simulation, concerning the Xe + Sn system at 50 MeV/A bombarding energy described in [5], are shown as an example of an heavy system (A_{tot} = 249). The agreement with the experimental data is satisfactory for heavy fragment yields (Z > 15), while for IMF ($4 \leq Z < 15$) the theoretical simulation underpredicts the experimental yields, as can be inferred from fig. 1. We are currently investigating if the origin of this discrepancy is due to more complication in describing asymmetric systems or is instead related to some uncertainty in the theoretical implementation of the experimental cuts. For lighter particles (p, n, d, t, α and Li isotopes), the agreement with the experimental data is better than obtained by other QMD tools [6], which dramatically overestimate single particle emission while underestimating α particle emission. Our results show this trend to a lesser extent. Even better results have been obtained for other reactions, which will be shown elsewhere.

4. Neutron production in light-ion reactions and hadrontherapy applications

A proper description of heavy-ion collisions at low energies is crucial for medical physics applications. At present, carbon ion beams are used for cancer therapy at GSI, Darmstadt, and at the National Institute of Radiological Sciences in Chiba, Japan, and are planned to be used at the CNAO facility under construction in Pavia, Italy [7]. Furthermore, the effectiveness of other light ion beams is under study. In order to optimize the treatment plans, a proper knowledge of the interactions taking place when the beams propagate inside the human tissues should then be achieved.

Neutron emission is crucial in radiotherapy with heavy ions. When two ions collide, neutron emission is always one of the most important contributions to the total yield since neutrons do not need to overcome any Coulomb barrier to leave the system. Furthermore, since they are not affected by electromagnetic interaction, they penetrate deep in matter. Double differential neutron production cross-sections for light ions in thin targets have been measured e.g. by [8]. Their experimental neutron distribution from C + C at 135 MeV/A, together with the results of our theoretical simulations, are shown in fig. 2. An overall good agreement appears, although at intermediate angles (30, 50 deg) the theoretical simulation slightly underpredicts the experimental high-energy tails, while at low n energies ($E_{\mathrm{k,LAB}} < 25$ MeV) it overpredicts the transverse neutron rates (50, 80, 110 deg).

The simulations of other systems (C + Al, C + Cu, Ne + Al, Ne + Cu), performed according to our model, lead to theoretical distributions showing a similar agreement with the experimental data and will be presented in a separate paper.

5. Conclusions

A QMD-like approach with many refinements and the relative code have been developed by scratch by our group and coupled with the FLUKA nuclear de-excitation routines. At present, the model is undergoing a rich program of validation tests. The results shown in this paper seem to be quite reasonable. We plan to add further refinements, like preequilibrium emission, to further improve the model.

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