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Macroscopic/microscopic simulation of nuclear reactions at intermediate energies.

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Abstract

An event generator, HIPSE (Heavy-Ion Phase-Space Exploration), dedicated to the description of nuclear collisions in the intermediate energy range is presented. The model simulates events for reactions close to the fusion barrier (5-10 MeV/A) up to higher energy (100 MeV/A) and it gives access to the phase-space explored during the collision.

1. Introduction

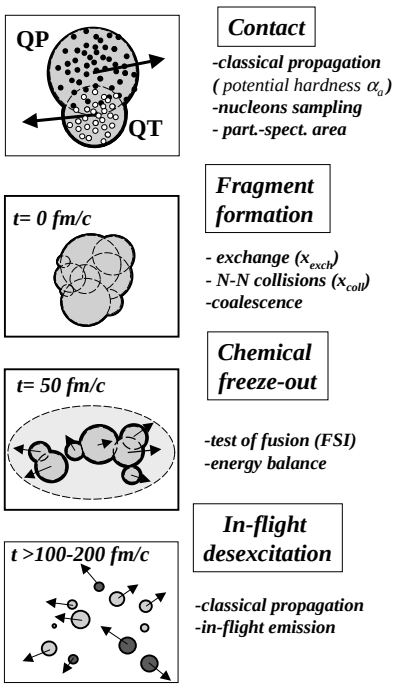

Figure 1: Illustration of the different steps used to build the event generator HIPSE. From top to bottom: the entrance channel phase, the step of early formation of fragments, the phase of chemical freeze-out taking into account final state interactions (after 50 fm/c) and the after-burner step (after a few hundred fm/c)

During the past thirty years, a large variety of microscopic models have been developped to understand nuclear reactions at intermediate energies. These models provide generally a rather good agreement with experimental observations[1]. The aim of the model described in this work is not to provide a further improvement of these models but instead to address, at the phenomenological level, specific open questions. In particular, we would like to discuss the issues concerning the time scale associated to the formation of fragments and the phase-space explored during the collision. This last point is of special importance in order to make the link between dynamical and statistical approaches.

2. A scenario for nuclear collisions

The development of the HIPSE event generator has been largely influenced by experimental observations. We have separated the reaction into four steps described in Fig.1. The general scenario is the following [2]:

2.1. *The phase of approach*

The approaching phase of the collision ending when the two partners of the reactions are at maximum overlap. This is considered by solving the classical equation of motion of the two partners in their mutual interaction potential. At that time, using the sudden approximation, the two interacting nuclei are described by a collection of nucleons whose momentum and spatial distributions correspond to the ground-state boosted by the relative momentum and distance associated with maximum overlap between the two incoming nuclei. Note that, at large relative distances (up to the fusion barrier), the potential between two nuclei is well known. In practice, we have used the proximity potential [3]. At smaller distances, it is expected that the potential depends on the

reorganisation of the internal degrees of freedom during the phase of approach and on the energy. We have thus introduced a free parameter (α_a) which defines the hardness of the potential. The value $\alpha_a = 1$ corresponds to no reorganisation of the internal degrees of freedom leading to a very hard potential while $\alpha_a < 0$ is expected when internal degrees of freedom reorganise instantaneously leading to the formation of a compound nucleus (see discussion in [2]).

2.2. *Early fragment formation: the relaxed participant-spectator hypothesis and the role of coalescence*

In the framework of the participant-spectator picture, the quasi-projectile (QP) and the quasi-target (QT) keep a strong memory of the entrance channel of the reaction. This scenario has been successfully applied at high energy. In order to define the QP and QT as well as the participant region, we have used the geometrical criteria illustrated in the second panel of Fig.1.

Nucleons of the participant region are those belonging to the intersection of the two spheres. This is called the overlap region in the following. Remaining nucleons originated from the target and projectile correspond respectively to nucleons of the QP and QT. The "pure" participant-spectator picture is however relaxed due to the exchange of particles between the target and the projectile. Such a process induces a reduction of the relative velocity between the two partners. In our model, this is introduced "by hand" by assuming that a fraction x_{tr} of the nucleons coming initially from the target (resp. projectile) and belonging to the overlap region are transferred to the projectile (resp. target). We do expect that the number of transferred nucleons decreases with the beam energy and thus x_{tr} should be energy dependent.

After this step, a number A_{over} of nucleons remains in the overlap region. When the beam energy increases, it is expected that more and more energy will be dissipated due to nucleon-nucleon collisions. Thus, we have assumed that the nucleons in the overlap encounter a percentage x_{coll} of nucleon-nucleon collisions. The number of collisions is thus: $N_{coll} = x_{coll} \times A_{over}$. After these steps, the nucleons act as a reservoir for a coalescence algorithm (described in detail in [2]) to produce complex light particles and fragments.

After the coalescence process, we end up with a set of fragments including the QP and the QT whose properties (mass, N/Z, position, momentum, spin ...) are calculated from the kinematical properties of the nucleons they are made of. At this point, a "clock" is started corresponding to $t = 0$ fm/c for the forthcoming dynamics.

2.3. *Chemical freeze-out and final state interactions*

The difficulty to produce partitions at high density lies in the need to treat as better as possible strong nuclear final state interactions (FSI's). Indeed, because fragments can overlap during times comparable to the reaction time (typically a few tens of fm/c), there is a need to propagate the partition before freeze-out is reached. This is first achieved during a time of $50fm/c$ according to the the classical evolution of the fragments in their two-by-two interacting potentials.

At that time, an important reorganisation both in spatial and momentum configuration may have occured. It leads generally to less compact configurations. It however may happen that two fragments cannot separate because their relative energy is lower than the fusion barrier. In this case, the two nuclei fuse and the properties of the fused system are calculated accordingly. After the test of all possible fusions of pairs of fragments, the configuration is frozen in that sense that a modification of the mass of the fragments is no more possible: this is the chemical freeze-out.

2.4. *The exit channel and the after-burner phase up to the detectors*

After the chemical freeze-out, the total energy balance in the center of mass frame reads:

$$E_0 = Q + E_K + E_{pot} + E^* + E_{rot} \qquad (1)$$

where E_K is the sum of the kinetic energies of the fragments, E_{rot} is the sum of the rotational energies and Q is the mass energy balance between the entrance channel and the considered partition. In our calculation, the rotational energy is estimated by assuming rigid spheres for the fragments. Finally, the quantity E^* corresponds to the total excitation energy. Note that if the quantity E^*

is negative, the partition is rejected since it then corresponds to unaccessible phase-space according to the initial available energy. The total excitation energy must be shared among fragments. This is achievd in the HIPSE model by assuming that the excitation energy is proportional to the internal kinetic energy of nucleons in each cluster (calculated at $t = 0$ fm/c).

At this stage, the partition is ready for the afterburner phase which consists in propagating the fragments in the overall coulombic field and in considering secondary decays. In numerical applications, the decay starts when the total potential energy is positive ($E_{pot} > 0$), generally after few hundred fm/c. The decay is achieved using the SIMON event generator [4]. In particular, the decay in flight of excited species is considered in order to preserve space-time correlations. In our approach, fragments and light particles are produced at all time scales from the very early instants of the collision (before 50 fm/c) up to several thousands fm/c's.

It is important to notice that the model presented above combines degrees of freedom associated to nucleons at the microscopic levels with those associated to nuclei at the macroscopic level. Indeed, in our model, "entities" considered can be either nucleons or nuclei. This is different from classical molecular dynamics where only nucleons are considered. In our case, although initial properties of nuclei are calculated from the partition of nucleons at the contact, once clusters are formed, they are treated in the macroscopic limit of the mean-field approximation (for instance by using proximity potential for nucleus-nucleus interaction or Wood-Saxon potential for nucleon-nucleus interaction). Note however, that in contrast to the mean-field approximation, nucleons are completely localised.

We believe that considering nucleons and nuclei at the same level is a key point of the present model. It is very helpfull to avoid ambiguity on fragment definition and to accelerate the calculation. Last, we have access to quantities associated to the phase-space before de-excitation like for instance excitation energies.

We now discuss the evolution of the free parameters of the model with the beam energy. In our approach, there are mainly three parameters: namely the percentage of nucleons transferred x_{tr} between the projectile and target, the parameter α_a which describes the hardness of the potential and the percentage of nucleon-nucleon collisions x_{coll}. These parameters have been adjusted for different reactions between nearly symetric systems. Data collected by the INDRA collaboration near the GANIL facility [5] (and references therein) for Xe+Sn collisions at 25 MeV/u and 50 MeV/u and Ni+Ni at 32, 52 and 82 MeV/u [6] have been used. We have also studied the reaction ^{48}Ca+^{40}Ca at lower beam energies. In this case, the parameters have been optimised to reproduce the experimentally measured fusion cross section. The evolution of the parameters as a function of beam energy is shown in Fig.2.

As expected, α_a and x_{coll} increase with E_B while the number of transfered nucleons decreases. It is worth noting that parameters scales almost perfectly with the size of the system underlying the importance of the geometrical aspects included in our model. While it is more difficult to trace-back the exact physical origin of the evolution of α_a, the two other parameters can be easily interpreted. For instance, the exchange of particle is inversely proportional to $\sqrt{E_B}$ indicating that the dominant effect in the exchange process is the reaction time. Concerning the percentage of collisions, we do expect that x_{coll} is proportional to the in-medium cross section $\sigma_{in}(E_B)$. Indeed, the evolution of x_{coll} is compatible with the beam energy dependence of the in-medium cross section given for instance in [7]

3. From the compound nucleus formation to the participant-spectator reactions

In order to illustrate the different mechanisms accounted for by the event generator HIPSE, the fragment mass distributions after the FSI stage as a function of the impact parameter in the reaction ^{48}Ca+^{40}Ca for beam energy $E_B = 10$, 25, 50, and 80 MeV/A are displayed in Fig.3. At low energy, the dominant mechanism is the formation of a compound nucleus. When the energy increases, this mechanism is reduced and a transition towards a participant-spectator picture is observed. Note that, from this calculation, it is possible to estimate fusion cross sections which are compatible with the systematic presented in [1]. It is important to notice the essential role of

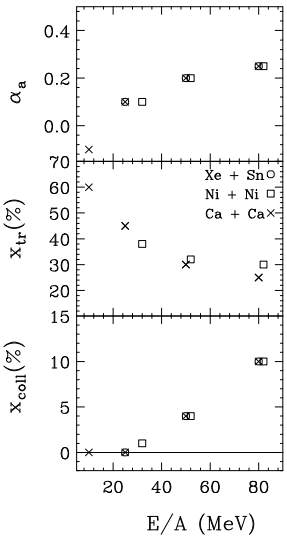

Figure 2: Values of the different parameters of the model as a function of the beam energy for the reaction ^{48}Ca+^{40}Ca (triangles), ^{129}Xe+^{120}Sn (circles) and ^{58}Ni+^{58}Ni (squares). From top to bottom, the evolution of the parameter associated to the potential hardness α_a, the rate of exchange of particles between the target and projectile x_{tr} (in percent) and the percentage of nucleon-nucleon collisions in the overlap region x_{coll}(in percent) are respectively presented.

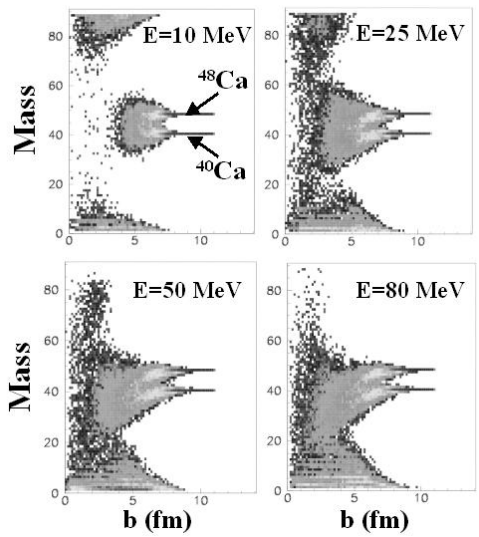

Figure 3: Evolution of the reaction mechanism with the beam energy as predicted by HIPSE. At each beam energy (10 MeV, 25 MeV, 50 MeV and 80 MeV), the fragment mass distribution (before the after burned phase) is presented as a function of the impact parameter. At low energy and small impact parameter, a single compound nucleus is formed while at higher energy, the system is largely fragmented even before the de-excitation.

FSI's. Indeed, without the possible strong chemical reorganisation during the first instants of the reaction, it is not possible to properly describe the fusion-evaporation process.

4. Conclusions

In this paper, we have presented an event generator to describe nuclear collisions in the intermediate energy regime at all impact parameters. It is based on a few well-defined hypotheses that can be conveniently and easily tested by a direct comparison with experimental data. It thus can be useful for a study of various mechanisms such as neck fragmentation or multifragmentation.

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