Elie:
an event generator for nuclear reactions

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Abstract
An event generator for the description of nuclear reactions in the
Fermi energy range is briefly introduced and first comparisons with
experimental data are shown.

1 Introduction
For several decades now, nuclear collisions in the Fermi energy range have
been used to explore the fundamental properties of nuclei under extreme con-
ditions of pressure, temperature and/or angular momenta [1]. From an ex-
perimental point of view, large detection facilities-the so-called 4\pi detectors-
have been developed to detect most of the emitted charged (sometimes also
neutral) particles [2]. Hence, complex events are recorded with high multi-
pticities. This leads to rather sophisticated analyses which may be affected
by kinematical cuts and/or by uncontrolled selection criteria. Thus, a safe
comparison between theory and experiment requires simulation tools based
on models as realistic as possible and based on assumptions that can be
safely tested. There are essentially two modes of description of the data.

- the microscopic transport models which in principle, should be the best
  solution. However, calculations are usually lengthy and the contact
  with experimental data may in some cases be difficult [2].
• the statistical models based on equilibrium hypotheses (such as SMM for instance) are widely used and have met some successes [3]. However, they rely on assumptions which may not be relevant in the context of nuclear reactions. More, their comparison with experimental data is performed only after severe (and maybe uncontrolled) event and particle selections.

Our aim in this work is to explore within a schematic model what happens when the hypothesis underlying the equilibrium statistical models are abandoned. In particular, we wish to take into account explicitly the entrance channel characteristics -the geometry- of the reaction as well as the initial correlations of the nucleons in momentum space, namely the internal Fermi motion.

2 Brief description of the model

The ELIE event generator [4] is based on a two-step scenario of the reaction:

• an entrance channel phase ending with the formation (for finite impact parameters) of a projectile-like fragment, a target-like fragment (both being moderately excited) and participants whose partition (Intermediate Mass Fragments (IMF) and light particles) is obtained by means of a random process (see later)

• a second phase considering secondary decay and propagation towards the detectors.

The geometry of the collision is borrowed from the high energy participant-spectator picture: the mass numbers of the projectile-like, target-like and participants are obtained by considering the geometrical overlap of the nuclei for each impact parameter. To build the kinematics of the projectile-like, the target-like and the partition of the participants, the following hypothesis are assumed:

1. the momentum distribution of the incoming nucleons inside the two partners is supposed to have no time to relax on a time scale comparable with the reaction time. This is a frozen approximation: only a few hard nucleon-nucleon collisions can occur and those latter are governed by a single parameter: the mean free path.

2. the partition of the participants is generated by a random process in momentum space. The mass number A of each species (including
A=1 free nucleons) is sequentially chosen at random by picking A nucleons from the nucleon momentum distribution. For IMF’s \((A \geq 4)\), the excitation energy, \(E^*\), is obtained by summing the center-of-mass kinetic energy of all nucleons belonging to the fragment. If \(E^*\) is larger than a maximum value associated with a maximum temperature \(T_{\text{max}}\), the fragment is rejected and a new try is made until all nucleons have been assigned. In the following, it turns out that a value of \(T_{\text{max}} = 5.5\) MeV allows to reproduce the experimental data (with a level density parameter equal to \(A/10\), \(E^* = 3\) MeV/u). This is in agreement with causality: the fragment lifetime should be at least comparable with the reaction time. In the Fermi energy range, this latter is of the order of a few tens of fm/c, thus leading to a maximum temperature around 5 MeV and to excitation energies close to 3-4 MeV/u.

3. the N/Z content of the projectile-like is taken equal to the N/Z of the projectile and the same rule is applied to the target-like and to the participants. For light particles \((Z \leq 2)\), all existing isotopes are randomly considered.

4. the projection of the partition in real space is accomplished by propagating the fragments (starting from the origin of space) according to their initial velocity assuming straight line trajectories until there are no more geometrical overlaps of particles.

In short, the model considers all possible random partitions compatible with geometry, conservation laws, a maximum internal temperature of about 5.5 MeV, a N/Z memory of the entrance channel and a nucleon momentum distribution close to the initial one.

In a second step, the partition is propagated in space-time and secondary decays are considered. This is done using the SIMON event generator \([5]\). Two major advantages of our approach are that it considers all impact parameters and, for each event, considers all nucleons. In particular, there is no distinction between equilibrium and pre-equilibrium particles. As such, there is no need for selection criteria and/or kinematical cuts and a full comparison with the experimental data is made possible.
3 Comparisons with experimental INDRA data

INDRA data [6] has been selected requiring that at least 80 % of the total charge and total linear momentum for charged particles emitted in the forward direction in the centre-of-mass be detected. A tensor based on the momenta of the fragments is built and its diagonalisation gives three eigen-values with which the so-called $\theta_{flow}$ angle is built. This is the angle between the main axis of the tensor and the beam axis. We consider only events with $\theta_{flow}$ larger than 25 degrees. In our model, this angular range corresponds to reduced impact parameter lower than .5 and centered around .3 (central collisions). The flow angle distribution as well as the isotropy ratio are correctly reproduced by the model (see Figure 1). This

![Figure 1: Comparison between INDRA data (black points) and ELIE data (histograms) for central Xe+Sn collisions at 25 (left), 32 (middle) and 50 MeV/u (right). From up to down: flow angle (in degrees) distribution, isotropy ratio, charge ($Z$) distribution, mean kinetic energy (in MeV) as a function of $Z$.](image-url)
latter requires a mean free path evolution from 30 fm at 25 MeV/u down to 10 fm at 50 MeV/u. The agreement for charge distributions and kinetic energies shows that a random process and an account of the nucleonic Fermi motion allow to reproduce experimental data without invoking a compression/expansion scenario as often assumed in multifragmentation statistical models. We show some results about light charged particles in Figure 2. We recall that most of them are produced by picking randomly nucleons from the initial two Fermi spheres. However, some of them are evaporated by the excited fragments on longer time scales. The mean number and kinetic energy as a function of the CM angle as predicted by ELIE are in correct agreement with INDRA data. We now consider a comparison of the model...
with minimum bias data for Ni+Ni reactions at 82 MeV/u (Figure 3) [7]. This corresponds to collisions for which only the completeness criterion for the forward-emitted particles has been considered. The optimum value for the mfp at such an energy is found close to 5 fm. Thus, the mfp evolves from 30 fm at 25 MeV/u down to 5 fm at 82 MeV/u. This decrease is interpreted as the opening of the phase space for in-medium nucleon-nucleon collisions due to a reduction of the Pauli blocking factor. An overall good agreement is obtained although the model overestimates the A=3 species. Notice that the rise and fall of the fragment multiplicity as a function of the total multiplicity is correctly reproduced. The kinematical observables (not shown here) are also in good agreement.
4 Summary

Simulated data produced by the ELIE event generator have been compared with INDRA data. The kinetic energy and angular distributions of both fragments and light charged particles are well reproduced. Most light particles as well as fragments are produced rapidly at nearly normal density by a random process. This latter is constrained by geometry, conservation laws and causality which is expressed by the fact that fragment lifetime should be longer than the reaction time. Thus, the projectile-like, the target-like and the fragments from the participant zone emerge from the reaction at a moderate excitation energy close to 3 MeV/u corresponding to a maximum temperature of about 5.5 MeV in agreement with internal temperature cluster measurements whatever the incident energy and the system considered. The strong memory of the entrance channel (transparency) as well as the internal motion of the nucleons inside the two partners of the reaction play a crucial role in our approach and are necessary to reproduce the experimental data. We thus believe that the present model is a valuable alternative to thermal statistical approaches based on equilibrium at low density.

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