Multifragmentation in central collisions at intermediate energies: a fast process?

A. Van Lauwe, D. Durand, G. Auger, N. Bellaize, B. Bouriquet, A.M. Buta, J.L. Charvet, A. Chbihi, J. Colin, D. Cussol, R. Dayras, A. Demeyer, J.D. Frankland, E. Galichet, D. Guinet, B. Guiot, S. HUDAN, G. Lanzalone, P. Lautesse, F. Lavaud, J.F. Lecolley, R. Legrain, N. Le Neindre, O. Lopez, L. Manduci, J. Marie, L. Nalpas, J. Normand, M. Pârlog, P. Pawłowski, E. Plagnol, M.F. Rivet, E. Rosato, R. Roy, J.C. Steckmeyer, G. Tăbăcaru, B. Tamain, E. Vient, M. Vigilante, C. Volant, J.P. Wieleczko

(INDRA collaboration)

a Laboratoire de Physique Corpusculaire de Caen, France
b Grand Accélérateur National d’Ions Lourds, Caen, France
c Institut de Physique Nucléaire, Orsay, France
d DAPNIA/SPhN, CEA/Saclay, France
e Dipartimento di Scienze Fisiche e Sezione INFN, Università di Napoli, Italy
f Institut de Physique Nucléaire, Lyon, France
g Conservatoire National des Arts et Métiers, Paris, France
h National Inst. for Physics and Nucl. Engineering, Bucharest, Romania
i Laboratoire de Physique Nuclaire, Université Laval, Québec, Canada.

November 6, 2018
Abstract

The kinematical characteristics of fragments and light particles observed in central highly fragmented nuclear collisions at intermediate energies are compared with the results of a model assuming that the initial momentum distribution of the nucleons inside the two partners of the reaction has no time to relax before the disassembly of the system. The rather good agreement between the results of the model and the experimental data suggests that multifragmentation is a fast process with a strong memory of the entrance channel.

1 Introduction

In central nuclear collisions at intermediate energies, multifragmentation, defined as the emission in a short time scale of several species of atomic number larger than two, is an important process as compared to other decay mechanisms such as the formation of heavy residues or fission (see for instance [1]). Such reactions are thus believed to be the ideal tool to study the transition from a liquid-like state (nuclei at normal density) towards a gas-like state associated with the vaporisation of the system [2]. In such a picture, nuclear multifragmentation is associated with the excursion of the excited system at low densities inside the coexistence region of the nuclear phase diagram [3]. There, a volume instability, the so-called spinodal decomposition, leads the system to fragmentation. Such a scenario is supported by microscopic transport calculations based on the nuclear Boltzmann equation and its stochastic extensions [4]. These models predict a compression-expansion phase driving the system at low density.

Recent experimental analyses based on nuclear calorimetry have claimed evidence for a liquid-gas phase transition through the study of various signals [5, 6, 9]. Some of these analyses make extensive use of the thermal multifragmentation statistical models [7, 8] to prove the existence of thermal equilibrium [6, 9]. In such a framework, charge distributions and fragment multiplicities are fitted with help of several parameters characterising the thermalised source. More involved studies are based on ‘back-tracing’ techniques and they allow to obtain not only the mean values but also the distributions of the parameters of the source [10]. It is worth noting that, in all cases, not all data are fitted. Indeed, it is very often assumed that a strong pre-equilibrium phase is present and this is why kinematical cuts are applied to the data before comparison with the predictions of the models. In such thermal models, the only source of fluctuations regarding the kinetic energy distributions of the emitted species is the thermal motion inside the thermalised source associated with a possible (usually assumed self-similar) collective motion [11]. Recently, deformation has been introduced to account for the observed anisotropies in the data [12].

Our aim in the present work is to explore the possibilities of a scenario in which the main hypothesis underlying the statistical models is abandoned. This means that we wish to compare the data (with as less kinematical cuts as possible) with a model taking
into account explicitly the entrance channel characteristics of the reaction as well as the initial correlations of the nucleons in momentum space. This is, of course, not the first attempt of this kind. For instance, molecular dynamics models have been used to understand fragmentation in such a scenario. Indeed, all molecular dynamics approaches, whether they are 'classical' or 'quantal', conclude that fragmentation is a fast process for which there is no time for the system to build compression or reach equilibrium. Here, we develop, in this spirit, a phenomenological and transparent approach allowing a detailed comparison with the data. Since the statistical models are able to correctly reproduce the 'static' properties of nuclear fragmentation, we focus our study on the 'kinematical' properties for both fragments and light particles obtained in central collisions in the Fermi energy range. The data used for the study have been collected by the INDRA collaboration near the GANIL facility. We consider central collisions for Xe+Sn at 32 and 50 MeV/u. This contribution is organised as follows: the model (hereafter called the ELIE event generator) is described in section 2 and a detailed comparison with experimental data is developed in section 3. Conclusions and perspectives are drawn at the end of the paper.

2 The ELIE event generator

The main idea of the model is to consider the extreme hypothesis for which the initial momentum distribution of the nucleons has no time to relax before the fragmentation of the system and for which a (small) fraction of the nucleons suffers hard nucleon-nucleon collisions leading them to escape the system as free particles. For the (large) remaining part of the system, only a rearrangement of the nucleons in the final state inside the various emitted products is considered. As mentioned in the introduction, we are essentially interested in the kinematical properties
of multifragmentation. Therefore, the definition of the partition (that is the 'chemical' composition in terms of complex particles and fragments present in the final state of the reaction) is not determined from \textit{ab initio} calculations but we rather use the information given by the experimental data. In other words, the mean multiplicity of each species is put 'by hand'. However, since it is assumed that the fragments are excited, the total multiplicity of detected particles is the sum of two components. The first one is associated with the 'fast' production during the reaction time and the other corresponds to longer time scales and is associated with the evaporation of particles by the fragments. An iteration on the magnitude of these two components is performed until a reasonable agreement with the data is reached. As far as fragments are concerned, only the mean and the second moment of the multiplicity distribution are needed. Indeed, it appears that the charge distribution can be reproduced rather accurately by randomly choosing sequentially the size of the fragments (see Fig.5). Once the partition is fixed, the energetics of the process is considered. The energy balance writes:

\[ E_0 = E_{ko} + E_{pot} + Q + E_K + E^* \]  \hspace{1cm} (1) 

where \( E_0 \) is the available centre-of-mass energy, \( E_{ko} \) is the energy corresponding to the few knocked-out nucleons, \( Q \) is the mass energy balance between the entrance channel and the considered partition, \( E^* \) is the excitation in the fragments while \( E_K \) is the total kinetic energy carried away by the fragments and the light particles. Last, \( E_{pot} \) is the potential energy associated with the long range Coulomb force acting between the charged species of the partition. As far as light complex particles and fragments are considered, their composition is obtained by randomly choosing nucleons in the two initial Fermi momentum spheres separated by the relative momentum corresponding to the beam energy. The kinetic energy of each species is thus obtained by summing the momenta of all nucleons belonging to the considered complex product. The total kinetic energy obtained by this procedure is such that there is little chance to fulfill energy conservation. Thus, a Metropolis procedure is developed. An exchange of a nucleon (a Metropolis move) between two species chosen randomly is performed and the kinetic energies recalculated. The procedure is iterated until the value \( E_{K}^{(i)} \) at step \( i \) matches the value of \( E_K \) needed to fulfill Eq.1 with a given accuracy of typically less than a percent. Then, the partition is ready for propagation in order to 'burn' the excitation energy of the fragments and to transform the potential Coulomb energy into kinetic energy. The initial momenta are given by the procedure described above. The initial positions are obtained by randomly placing the species inside a volume sufficiently large so that nuclei and particles do not overlap: this gives the value of \( E_{pot} \). The volume in question is not a critical parameter since the key quantity to be compared with the data is not the separate values of \( E_{pot} \) and \( E_K \) but rather their sum (which is constrained by Eq.1) (see for instance [13] for a detailed discussion on this point). Then, the partition is
propagated in a similar way as in the SIMON event generator [17]. In particular, the decay in flight of excited species is considered in order to preserve space-time correlations. The generated event is then filtered through the INDRA software filter and stored for analysis. Apart from the fact that the partition is to a large extent put 'by hand', there remains essentially two parameters: The amount of fast knocked-out nucleons and the mean excitation energy in each fragment. These two parameters are chosen in order to get the best agreement with the experimental data (see next section). Let us discuss first the question of the excitation energy, $E^*$. Fig.1 shows the kinematical characteristics of the nucleons inside the fragments. The angular distributions are more and more forward-backward peaked as the beam energy increases meaning that the fragments in this approach are more and more deformed and thus more and more excited. Since, in the model, the short range interaction among the particles is only taken into account by means of the Q-values, nucleons do not interact individually and therefore the velocity distributions shown in Fig.1 are not physical. They however show little evolution and thus, it is expected that the excitation energy resulting from the deformation increases slowly with the beam energy. Anticipating the results of the next section, we have found a good agreement with the data for the following values of $E^*$: 3.5 and 5. MeV/u for resp. 32 and 50 MeV/u. These values are compatible with those found in [18]. The other parameters of the simulation, that is the amount of first chance knocked-out nucleons and the initial multiplicities of light particles and fragments are adjusted to reproduce simultaneously the observed multiplicities and the center-of-mass kinetic energy distribution of the proton as shown in Fig.2. The percentage of knocked-out nucleons increases with the beam energy as it should be since the phase space for in-medium nucleon-nucleon collisions opens gradually. In terms of the fraction of the total number of nucleons, one finds: 2. and 4. % for resp. 32 and 50 MeV/u. The mean and the width of the fragment multiplicity distribution are 6.5, 3 and 9, 3 resp. for 32 and 50 MeV/u.

Figure 2: Light charged particle and fragment multiplicities and center-of-mass kinetic energy distributions of protons emitted in central Xe+Sn collisions at 50 MeV/u (see section 3). Black points: experimental data. Filled histograms: results of the ELIE event generator. Data have been normalized to the number of events as explained in the text.
Figure 3: Up, left: experimental correlation between $\theta_{\text{flow}}$ and $E_{\text{trans}12}$ for Xe+Sn collisions at 50 MeV/u. Up, right: same but for the simulation. Down, left: distribution of $\theta_{\text{flow}}$. Black points are experimental data, the filled histogram is the result of the simulation normalised to the largest values of $\theta_{\text{flow}}$. The open points corresponds to the difference between the data and the calculation. Down, right: same but for $E_{\text{trans}12}$. Here, the normalisation used is the same as for $\theta_{\text{flow}}$.

Figure 4: 3-D plot (in log scale) of the parallel velocity vs charge of selected events for Xe+Sn at 50 MeV/u. Up, left: experimental data. Up, right: experimental data after 'subtraction' of the simulation (see text for explanation). Down, left: experimental data for central events as defined in the text (in this case, events with flow angles larger than 30 degrees). Down, right: same as down, left but for the simulation.

3 Comparison with the data

The selection of the data has been performed using first completeness criteria, requiring that at least 80% of the total charge and total linear momentum (for charged particles) be detected. This is a necessary condition to perform an event by event analysis. Then, for each event, a sorting is applied by means of two variables. First, a momentum tensor analysis is developed. The diagonalisation of the tensor gives three eigen-values with which several sorting variables may be defined. Here, we use the so-called $\theta_{\text{flow}}$ angle. This is the angle between the main axis
of the tensor and the beam axis. For more details, see [14]. Second, a variable using the characteristics of the light charged particles is built: This is called $E_{\text{trans}12}$ [19] defined as the sum of the transverse energies of all detected charged particles with charge lower or equal to 2. Fig. 3 shows the correlation between $\theta_{\text{flow}}$ and $E_{\text{trans}12}$ for an incident energy of 50 MeV/u. A comparison between the model and the experimental data shows that the model can reproduce the largest values of the $\theta_{\text{flow}}$ distribution while it misses the low energy part. This is tentatively interpreted by assuming that the low values of the flow angle distribution are associated with non-central collisions for which the binary character of the reaction remains until fragmentation. Indeed, in our model, this possibility is not taken into account due to the lack of geometry of the simulation. In other words, our model in its present shape is only able to treat reactions corresponding to a total overlap of the two partners and is thus unable to treat deep inelastic reactions. From now, we consider only events for which the $\theta_{\text{flow}}$ distributions of the model and the data coincide. This corresponds to flow angles larger than 30 degrees for 50 MeV/u and 60 degrees for 32 MeV/u. All forthcoming figures have been normalised to the total number of events fulfilling this condition. Fig. 4 shows the atomic number-parallel velocity plot for central Xe+Sn collisions at 50 MeV/u. The general trend of the experimental correlation is reproduced by the simulation as shown in the lower part of the figure. Fragments are essentially emitted at mid-rapidity. However, a closer look at the figures shows that the model underestimates the kinetic energy of the fragments around Z=20. This point will become clearer in the following. A tentative 'subtraction' procedure has been applied to the data and is displayed in the upper part of Fig. 4. It consists in subtracting from the experimental data the contribution predicted by the model and associated with central collisions with the normalisation discussed above. It reveals the presence of a rather 'pure' fast component.

Figure 5: Up, left: Angular center-of-mass distribution for all fragments emitted in central Xe+Sn collisions at 50 MeV/u. Up, right: same but for CM mean kinetic energy as a function of the emission angle. Down, left: same but for the charge distribution. Down, right: same but for the CM kinetic energy distribution.
associated with the remnants of a projectile-like and a target-like in mid-central collisions. However, for fragments with $Z$ lower than 10, a so-called neck emission corresponding to fragments located around mid-velocity is also evidenced. This mechanism has already been studied for the same system but for a different selection of the data [19, 20]. A detailed analysis of neck emission with such a technique is in progress. We now consider some properties of the fragments in Fig. 5 and 6. Due to problems with the software filter in the CM backward direction, we show only kinematical characteristics of particles emitted in the forward part of the angular range in the CM frame. The mean number and kinetic energy of the fragments as a function of the CM angle are rather well reproduced. The multiplicity is somehow overestimated. Here, we would like to point out that the comparison between the model and the experiment is made without kinematical cuts: In other words, the whole event is considered. This induces strong constraints on the model since any departure between the data and the model for some observables has strong feed-back effects on another set of observables. A general 'fitting' procedure such as a back-tracing analysis should be envisaged in this context. The kinetic energy distribution is nicely reproduced until large val-
ues showing the important role played by the internal motion of the nucleons inside the two partners of the reaction. Same conclusions can be drawn concerning the results at 32 MeV/u (Fig.6). However, here, a sizeable deviation in the angular distribution is observed at small angles indicating the presence of a contribution which is not accounted for in the model. We will come back to that point later. We now discuss the characteristics of light charged particles. 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. Both contributions lead to anisotropic angular distributions as shown in Fig.7. We stress here that even if the final angular distribution of the fragments may be isotropic (as is the case if one considers only events with $\theta_{flow}$ larger than 60 degrees), those particles which have been evaporated will show an anisotropic angular distribution. Although the proton distribution is underestimated at very forward angles, the general trend for other particles is well reproduced. A comparison of the mean kinetic energy as a function of the CM emission angle (Fig.8) exhibits a sizeable deviation, in particular for tritons and alphas, between the model and the data. This means that the model is far from perfect and some aspects of the emission process for light particles is missing in our formalism. It is however surprising that the general trends of the angular and kinetic energy distributions of light particles are rather correctly reproduced by the model using our crude ‘coalescence’ algorithm.

Let us conclude this brief comparison between ELIE and the experimental data by coming back to the kinematics of the fragments. In Fig.9 and 10, the mean and the width of the CM kinetic energy of the fragments as a function of their atomic number are displayed. At 50 MeV/u, the second moment is very correctly reproduced while the mean kinetic energy is underestimated as far as the charge exceeds values of 15-20. This could have been anticipated looking at the results of Fig.7. The memory of the entrance channel is stronger for the data than for the simulation. In other words, the model (by means of the Metropolis moves described

![Figure 8: Same as Fig.7 but for the mean kinetic energy as a function of the CM emission angle and for Xe+Sn at 32 MeV/u.](image-url)
above) allows too much mixing between the nucleons of the target and of the projectile as far as medium and large mass fragments are concerned. This means that an improvement of the model is needed to account for 'geometrical' effects. In its present version, our approach can only deal with those collisions for which an almost complete overlap of the projectile and the target is achieved. This corresponds to very small cross-sections and obviously does not cover the whole impact parameter range associated with multifragmentation. By considering only the transverse degrees of freedom (lower part of the figures), one gets rid more or less of such difficulties and the model then gives better results. An analysis (not shown here) of the data at larger impact parameters shows that the transverse energies of the clusters are almost independent of the centrality of the collision except for 'controllable' final state interaction. Our model should be able to reproduce such trends. Work on this point is in progress.

At 32 MeV/u, a large deviation between the data and the model is observed for the widths although a rather correct agreement is obtained for the mean values. We think the deviation is due to an additional mechanism in the data that is not considered in the model: This is the remaining binary character of the collision despite the already severe selection on the impact parameter. Deep inelastic collisions lead to a strong increase of the fluctuations in the kinetic energy distributions of the fragments, a fact that cannot be accounted for in the present version of our model. It is worth noting that no better agreement is achieved when comparing with transverse quantities. This suggests that the disagreement is not only due to geometrical effects but to collective effects such as, for instance, the influence of the mean field on the dynamics of the reaction.

**Figure 9:** Up, left: Mean kinetic energy in the center-of-mass as a function of the atomic number $Z$ for fragments emitted in central Xe+Sn collisions at 50 MeV/u. Up, right: same but for the second moment of the kinetic energy distribution. Down, left: same as up, left but for the transverse energies. Down, right: same as up, right but for the transverse energies.
Figure 10: Same as Fig.9 but for 32 MeV/u.

4 Conclusions and perspectives

We have studied the kinematical characteristics of nuclear products emitted in central highly fragmented nuclear collisions at intermediate energies. Data have been compared with a phenomenological event generator, ELIE, in which it is assumed that the initial momentum distribution of the nucleons has no time to relax before the disassembly of the system. This distribution is thus used to sample the kinetic energies of the various species produced in the reaction under the constraint of conservation laws. It is worth noting that this technique is flexible enough to test rapidly other (possibly thermalised) momentum distributions when the system breaks. As far as partitions are concerned, they are produced 'by hand' except for the charge distributions which are reproduced by a combinatorial random algorithm, a puzzling result which remains to be understood. A rather good agreement with the data has been obtained. The kinetic energy and angular distributions of both fragments and light charged particles are well reproduced.

In particular, in our approach, both the collective energy and the deformation often claimed as being necessary to reproduce the data in the framework of thermal statistical models are 'naturally' obtained.

We thus believe that our model is a valuable alternative to thermal statistical approaches based on shape and/or momentum equilibration in the matter at low density. In our approach, most light particles as well as fragments are produced rapidly at nearly normal density. As such, they keep a strong memory of the entrance channel. In particular, fragments emerge from the reaction highly deformed. Then, they decay sequentially to reach their ground state by evaporation on longer time scales by a rearrangement and emission of nucleons and possibly other complex particles. The strong memory of the entrance channel and the importance of the internal motion of the nucleons inside the two partners of the reaction are such that, in our picture, the origin of kinetic energy fluctuations is to a large extent non-thermal. We would like to point out that this picture is very similar to the one proposed in [21].

Deviations between the model and the ex-
Experimental data are expected as far as the incident energy increases. Work along this line is in progress. Indeed, nuclear transparency is expected to decrease as the phase space for in-medium nucleon-nucleon collisions increases. Therefore, the two Fermi distributions should be progressively more and more relaxed on shorter and shorter time scales as the incident energy increases. In the near future, we also plan to extend the model to asymmetric systems and to non-central collisions.

References

[1] D. Durand, E. Suraud, B. Taman 'Nuclear Dynamics in the Nucleonic Regime', IOP Publishing, (2001)

[2] B. Borderie et al, Eur. Phys. J. A6 (1999) 197, M. F. Rivet et al, Phys. Lett. B430 (1998) 217

[3] Ph. Chomaz, Proceedings of INPC, Berkeley (2001), to be published

[4] M. Colonna et al, Nucl. Phys. A583 (1995) 525c

[5] B. Borderie et al, Phys. Rev. Lett. 86 (2001) 3252

[6] M. D’Agostino et al, Phys. Lett. B473 (2000) 219 and nucl-exp/0104024, (2001), in press

[7] J. P. Bondorf et al, Phys. Rep. 257 (1995) 133

[8] D. H. E. Gross, Rep. Prog. Phys. 53 (1990) 605

[9] R. Bougault et al, XXXVIII Bormio Meeting, Bormio (2000) and to be submitted

[10] N. Bellaize et al, XXXIX Bormio Meeting, Bormio (2001) and to be submitted, O. Lopez et al, These proceedings

[11] F. Lavaud et al, XXXIX Bormio Meeting, Bormio (2001)

[12] B. Bouriquet et al, XXXIX Bormio Meeting, Bormio (2001)

[13] R. Nebauer et al, Nucl. Phys. A650 (1999) 65

[14] J. Pouthas et al, Nucl. Inst. Meth. A357 (1995) 418

[15] N. Marie et al, Phys. Lett. B391 (1997) 15

[16] A.D. N’Guyen et al, XXXVI Bormio Meeting, Bormio (1998)

[17] D. Durand, Nucl. Phys. A451 (1992) 266

[18] N. Marie et al, Phys. Rev. C58 (1998) 256, S. Hudan et al, XXXIX Bormio Meeting (2001)

[19] J. Lukasyk et al, Phys. Rev. C55 (1997)1906

[20] F. Bocage et al, Nucl. Phys. A676 (2000) 391

[21] X. Campi et al, These Proceedings