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# THE PHYSICS OF HOT NUCLEI STUDIED WITH INDRA *

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Recent results obtained by the INDRA collaboration concerning the physics of hot nuclei produced in intermediate energy heavy-ion collisions are presented.

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## 1. Introduction

Hot nuclei are produced in dissipative nuclear reactions using either heavy ion projectiles at intermediate energies (say between 20 and 100 MeV/$u$) and in the relativistic energy regime or in multi-GeV hadron-nucleus interactions (see for instance [1]). The main motivations to study hot nuclei are manifold. The decay properties of such objects are by themselves an important piece of knowledge and are useful for a complete understanding of the production of neutrons and charged particles in spallation reactions which is nowadays a subject of current interest for the design of nuclear waste transmutation facilities [2].

However, the main interest lies in the link between the properties of hot nuclei and the fundamental characteristics of nuclear matter. The study of such characteristics over a wide range of temperature and density remains an important and unfinished challenge. Indeed, the properties of the equation of state (EoS) over a broad range of temperatures ($T$) and densities ($\rho$) are far from being elucidated. The nucleon-nucleon force exhibiting a short range repulsive part and a long range attractive part, the behaviour of nuclear matter should present some analogies with a Van der Waals macroscopic fluid. Thus, a liquid-gas transition is expected at a critical density around $\rho_0/3$ and $T \simeq 10 - 20$ MeV. On the other hand, hadrons are made up of quarks and gluons. A transition from hadronic matter to a quark-gluon plasma is thus predicted by QCD at $T_c$ around 150-160 MeV and/or $\rho_c \leq$ 5-10 $\rho_0$ [3]. There is also a strong interest in the study of medium effects related to chiral symmetry restoration at high matter density. This would result in changes in the masses of hadrons as well as their decay and scattering properties in the nuclear medium [4,5]. The properties of nuclear matter are however not only important for the understanding of the sub-atomic world but have also strong implications on the fate of astrophysical objects in the universe. The EoS is, for example, an essential ingredient in the description of the contraction of massive stars leading to supernovae explosion and neutron star formation [6].

From a more general point of view, hot nuclei constitute (with metallic clusters) rather unique systems in nature. They are perfect quantum objects and their fragmentation properties (see later) do truly correspond to their intrinsic structure and do not depend on specific defects. More, in hot nuclei, both a long range force (the coulomb force) and a short range force (the nuclear force) coexist. Last, as finite objects whose number of constituents and N/Z ratio can be controlled, they allow to study the behaviour of a finite mesoscopic system.

As already stated above, the only way to produce hot and dense matter in the laboratory is by means of dissipative nuclear collisions. The difficulty is then to extract the relevant observables from complex transient processes. Therefore, data of very good quality is a prerequisite to characterize quantitatively the system in terms of physical variables and reaction mechanisms. In this paper, we discuss experimental results obtained with a dedicated $4\pi$ detector, INDRA [7], used in a series of campaigns at the GANIL facility.

## 2. Reaction mechanisms in the Fermi energy range

The study of hot nuclei is intimately linked to the study of the collisions during which they are produced. Reaction mechanisms at "intermediate" beam energies are better understood when viewed with the help of concepts developed for energy regimes (high or low beam energies) in which reaction mechanisms are well known.

Reaction mechanisms in the coulomb barrier region and below 15 MeV/$u$ have been studied for a rather long time now [8]. Dissipative reactions, also called deep inelastic collisions (DIC) and possibly fusion, are observed for more central collisions. They are clear signatures of mean field effects leading to a collective behaviour of the involved nuclei. In the DIC case, projectile and target nuclei are strongly slowed down due to nuclear matter friction. For a short time they form a "quasi-molecular" state before reseparation. During this step, nuclei may exchange nucleons. Fusion corresponds to the most central collisions.

The dissipation process in relativistic heavy ion collisions (0.2–1 GeV/$u$ range) is dominated by hadronic cascades because the wavelength associated with nucleon-nucleon collisions is shorter than the nucleon size. The corresponding relative velocity between projectile and target nucleons is also much larger than the Fermi velocity. For these two reasons, collisions can be safely described by geometrical concepts leading to the so-called participant-spectator picture: nucleons which do not belong to the overlapping zone of the two incoming nuclei do not suffer hard nucleon-nucleon collisions and constitute the spectators while the other ones are the participants. Sizeable excitation energies can be deposited in the participant zone. Since these systems are produced in semi-peripheral collisions, one may expect that the corresponding nuclear matter is not compressed. Peripheral relativistic collisions thus appear as relevant tools to study hot but uncompressed nuclear matter (see [9]).

The intermediate energy range (discussed here) is typically a transition region in which both aspects of low and high energy reactions discussed above are present. The dominance of binary type collisions (as a reminiscence of low-energy like processes) has been observed in several heavy or medium-mass systems. However, the most spectacular signature of new reaction patterns at incident energies around the Fermi energy is certainly the formation of the so-called neck-like structures (see for instance [10]). From a theoretical point of view, strong deviations from a pure DIC scenario have been observed in the simulation of nuclear collisions at intermediate impact parameters in the framework of semi classical transport theories either BUU-like models [11] (as shown in figure 1) or based on molecular dynamics [12]. It is established that neck-emission is strongly connected with the projectile-target geometrical overlap during the collision [13, 14]. Thus, it can be tentatively interpreted as the first manifestation of the formation of a participant zone as observed at relativistic energies. However, it could also be due to deformation mechanisms involving longer time scales. Studies along this line are in progress [15].

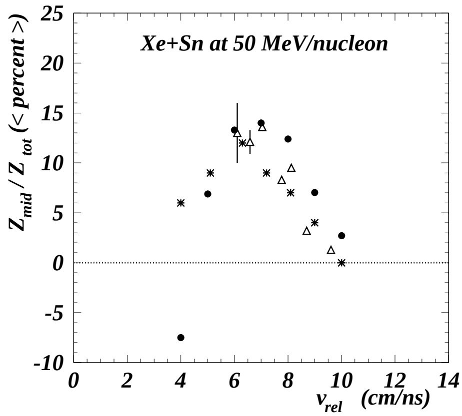


Fig. 1. Percentage of matter emitted at mid-rapidity as a function of the relative velocity $v_{\mathrm{rel}}$ between the two partners of a disipative binary collision (Xe+Sn at 50 MeV/$u$). This last quantity is a good measure of the impact parameter $b$ of the reaction: the larger $v_{\mathrm{rel}}$, the larger $b$. Data are solid circles, open triangles are the result of a semi-classical transport model (Landau–Vlasov in the present case). Stars are the predictions of stochastic mean field calculations (see the original paper for more details). From [13].

Central collisions are the key reactions to really probe matter in its extreme states since they correspond to the largest dissipated energies and presumably to the largest compression. But, for obvious geometrical reasons, the cross section corresponding to fused systems is quite small (a few tens of millibarns). This means that efficient selection methods have to be used. Lack of space does not allow us to discuss this subject in details. Let us mention that several methods have been developed recently by the INDRA collaboration making use of global variables [16], filtering techniques [17] and multi-dimensional analysis [18, 19]. Using such techniques, it is possible to isolate samples of events presenting a high degree of isotropy suggesting an almost complete loss of memory of the entrance channel [16, 20]. Such events are good candidates for the study of the decay modes of hot nuclei: they are discussed now.

## 3. Decay modes of hot nuclei

The key tools to study hot nuclei are based on the techniques of nuclear calorimetry and thermometry. These are very vast subjects which will not be discussed here (see for instance [10]). The decay modes of hot nuclei can roughly be decomposed into two regimes:

- The low energy decay modes associated with a moderate excitation energy $E^*$ (that is $E^*$ smaller than the binding energy): these are the evaporation of light particles accompanied by fission in the case of heavy or rapidly rotating nuclei.

- The high energy decay modes associated with $E^*$ of the order or larger than the binding energy: these are the fragmentation and the vaporization processes. A detailed analysis of nuclear fragmentation time scales reveals a gradual transition from a sequential process (as a reminiscent of fission) towards the emission of several fragments on a very short time scale (often denoted multifragmentation) [10]. Vaporization is defined as the process in which only light particles (up to $Z = 2$) are observed in the final state of the reaction. It corresponds to a complete disassembly of the system. Such events have been observed in Ar+Ni collisions [21].

We concentrate on nuclear fragmentation in the following. Data can be interpreted in the framework of nuclear thermodynamics. This is motivated by the predictions of those transport models [11] showing a rather fast thermalization of the system but we will see later on that other dynamical models (namely those based on molecular dynamics) suggest a different behaviour. In the context of a fast approach to equilibrium, a possible scenario for nuclear disassembly is the following:

- In the early instants of the collision, a compression phase is initiated during which a small part of the particles escapes the system: this is called pre-equilibrium emission. This latter can be evaluated by analysing kinetic energy and angular distributions. Such a component is presumably associated essentially with light particles.

- The compression phase is followed by an expansion driving the system to low density. A clear (but not unambiguous (see later)) signature of such an expansion phase lies in the identification of a collective outwards motion of the matter. This motion has been quantified by comparing the mean centre-of-mass kinetic energy of the detected fragments with computer simulations in which a collective self-similar motion has been added to the thermal motion [20]. Such a flow has indeed been identified in nuclear collisions in the Fermi energy range. It corresponds to a couple of MeV/$u$ and is however always relatively small as compared to the dissipated energy and the binding energy of the system [10].

- The system reaches the so-called freeze-out stage and breaks into fragments whose excitation energies can be estimated with the help of light particle-fragment space-time correlations [22]. This is the time after which the chemical composition of the matter (this means the different populations of nuclear species) is kept fixed as well as its thermal properties. This assumes implicitely that no more matter or energy exchanges occur within the system. The species then propagate in the overall coulomb field.

Assuming equilibrium, the freeze-out stage can be described with different statistical approaches. Very commonly used models are the so-called multifragmentation models: namely the Copenhagen model (also called SMM [23]) and the Berlin model (MMMC [24]). A comparison of the INDRA data with the SMM model is shown in figure 2. A nice agreement is obtained between the model and the data once the input parameters of the model have been constrained by a multidimensional back-tracing technique ( [25]).

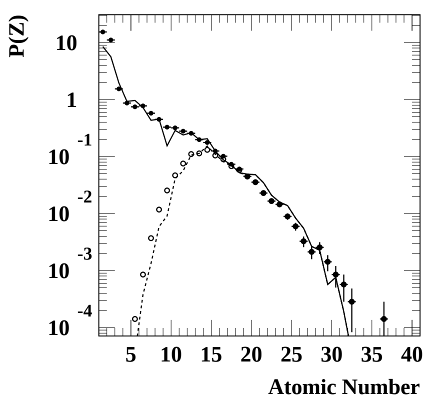


Fig. 2. Black points; atomic number distribution for central Xe+Sn collisions at 50 MeV/$u$. Open points: atomic number distribution of the largest fragment detected event by event. The solid (resp. dashed) line corresponds are the results of the SMM model for all (resp. the largest) fragment(s) of each detected partition. From [26].

The observation of a collective flow in the data suggests the key role that could be played by the dynamics in fragmentation phenomena. A detailed study of the liquid-gas phase coexistence region indeed reveals two distinct zones: one is associated with the metastability of the system while the other is the unstable region (also called spinodal region). There is a question to which extent the system really reaches the unstable region during its expansion phase as the consequence of the collective motion mentioned above. The INDRA data obtained in central Gd+U and Xe+Sn collisions have been sucessfully compared with the predictions of a microscopic model describing the dynamical path followed by the system. The model indeed predicts an excursion in the spinodal region. A signature of this process can be found in an analyses of the fragment charge distribution of the two systems. This is illustrated by the results displayed in figure 3. The scaling of the two charge distributions is clearly demonstrated as predicted by the transport model used for the analyses.

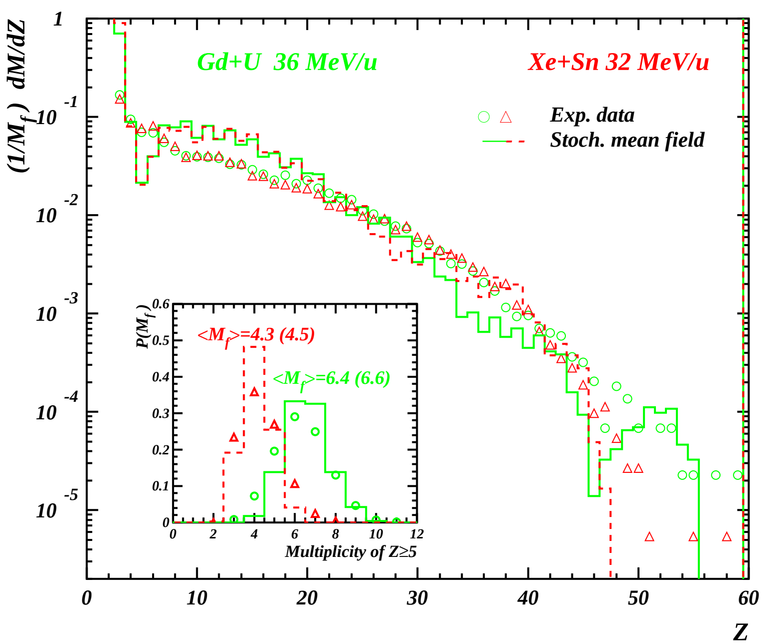


Fig. 3. Charge and multiplicity distributions in central 32 MeV/$u$ Xe+Sn (triangles) and 36 MeV/$u$ Gd+U (circles) collisions. Histograms (dashed: Xe+Sn, dotted: Gd+U) are the predictions of a dynamical simulation based on semi-classical transport theory with an additional stochastic term. The insert shows the corresponding fragment multiplicity $M_f$ with the same symbols as in the main figure. From [27].

The two preceding analyses implicitly assume a rapid equilibration of the system. Other analyses using the QMD (Quantum Molecular Dynamics) model support a different interpretation [12, 28]. In such models, no equilibration of the matter is achieved in the course of the reaction. Fragmentation is triggered by the initial correlations among the nucleons of the projectile and the target. The observed collective motion is the result of the Fermi motion of the nucleons and no sizeable compression is predicted by such models [28]. In [29], a systematic comparison with the data of the predictions of QMD has been performed. Figure 4 is an example of such a comparison for three different classes of events. A good agreement is achieved. It should however be noted that strong deviations between the model and the data are observed for very central collisions (those discussed in the two previous figures). Here, new analyses are necessary to disentangle between the various theoretical approaches proposed up to now.

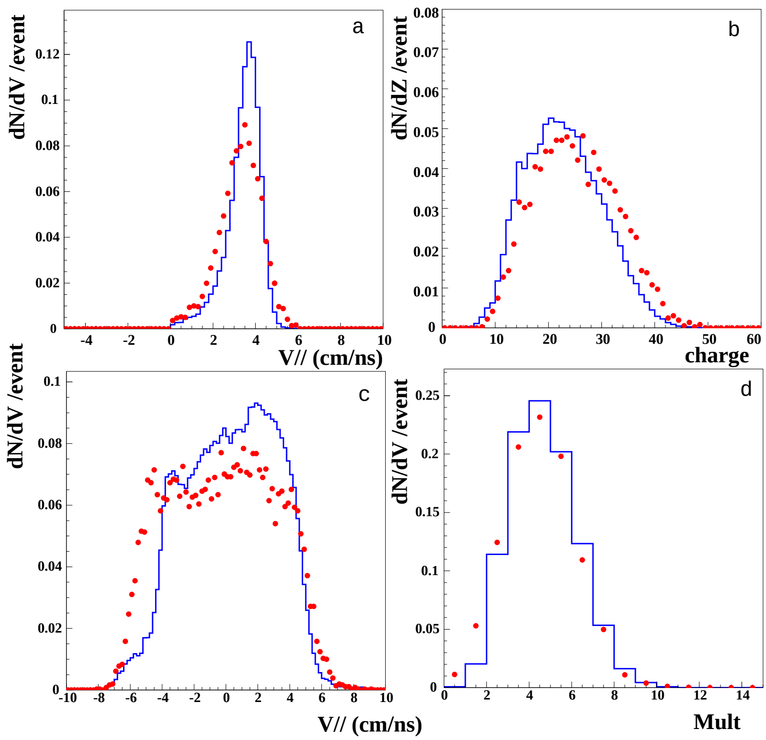


Fig. 4. Comparison of INDRA data (histogram) and QMD (dots) results for Xe+Sn reaction at $E_{lab} = 50\,\mathrm{MeV}/A$: a-center of mass longitudinal velocity of the heaviest fragment, b-charge distribution of the heaviest, c-center of mass longitudinal velocity of IMFs ($3 \leq Z \leq 20$), d-multiplicity distribution of fragments. From [29].

## 4. Summary and perspectives

The quality of the data obtained by the INDRA collaboration (and also by other collaborations) is an important step towards the understanding of the phenomena occurring in dissipative nuclear collisions in the Fermi energy range. New reaction mechanisms have been identified and carefully studied. In particular, the occurrence of mid-rapidity emission in semi-central collisions and the presence of a collective radial motion in central collisions are certainly interesting phenomena as far as the transport properties of nuclear matter are concerned.

Nuclear fragmentation data obtained in central collisions raises several fundamental questions concerning the behaviour of nuclear matter in extreme conditions. Results concerning the thermodynamical properties of hot fragmenting nuclei as well as the identification of the instability responsible for nuclear disassembly (namely the spinodal decomposition) are encouraging results. However, other interpretations involving more rapid processes have also been proposed. The situation is therefore contrasted and demands more involved theoretical analyses.

New data taken at the SIS facility are presently being analysed ( [30]). They will allow an excursion at incident energies up to 250 MeV/$u$ for heavy and medium mass symmetric systems. Useful comparisons with the results obtained by other collaborations (ALADIN, FOPI and EOS) will be possible. No doubt that such new data will help to clarify the points that have been briefly discussed in this paper.

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