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September 1997

LPCC 97-15

Keynote Talk at the International Nucleus- Nucleus
Conference, Gattlinburg, USA, June 2-6, 1997

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Physics from Collisions below 200 MeV/u

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We discuss some aspects of nuclear collisions at incident energies below the pion threshold. The emphasis is put on the physics of hot nuclei with implications regarding the nuclear equation of state and the transport properties of nuclear matter. To this end, the production and decay of hot nuclear species are reviewed and nuclear disassembly is discussed in terms of bulk instabilities and phase transition in finite transient systems.

1. INTRODUCTION: WHY AND HOW?

The physics of nuclear collisions below pion threshold is rich of so many phenomena that it is impossible to cover the whole subject in a single paper. In view of the topics discussed in other talks at this Conference, we will concentrate on the physics of hot nuclei produced in very dissipative nuclear collisions in the Fermi energy range and in peripheral relativistic collisions.

The main motivations to study such collisions is two-fold:

- learn about the transport (i.e the propagation far from equilibrium of nucleons in nuclei) properties of nuclear matter in a region where resonances are marginally produced, i.e. in the pure nucleonic regime. In particular, there is an interest in understanding the modification of the nucleon-nucleon cross-section due to various medium effects (density effects, effective mass, quantum effects (Pauli blocking factors), three-body collisions,...)
- learn about the characteristics of the nuclear equation of state (EoS). Nuclear matter is the bridge between the nucleon-nucleon system and the nucleus N-body structure, the building of such a bridge remaining one of the fundamental goal of Nuclear Physics. The EoS is also an essential ingredient in the description of the contraction of massive stars leading to supernovae explosion and neutron stars formation.

These two fundamental aspects of nuclear reactions studies are 'probed' at different instants of a nuclear collision. This is suggested by the most achieved theoretical description of nuclear reactions in the Fermi energy range, namely the semi-classical transport models based on the Nuclear Boltzmann equation and its stochastic extensions [1].

Schematically, the transport properties (reflecting the properties of the collision term in the Boltzmann equation) play a role in the first instants of the reaction, where hard

Figure 1. Nuclear matter spinodal (dashed) and coexistence (solid) lines calculated with an effective Skyrme force in the temperature-reduced density plane.

nucleon-nucleon collisions are efficient to relax the internal degrees of freedom and lead the system to thermalization on time scales of the order of 50 fm/c. During this period, very high energy-cost or sub-threshold particles can be produced [2]: these are probes of the tails of the momentum distribution and their production rates are very sensitive to the features of nucleon-nucleon inelastic channels. Let us just mention for instance that kaons have been measured at the picobarn level at incident energies as low as 95 MeV/u [3]!

Sidewards flow measurements [5] are also crucial tests of the influence of medium effects by probing the elastic part of the nucleon-nucleon collisions.

As time goes on during the collision, if the interaction time is long enough for the system to reach equilibrium, it is justified to 'reduce' the description of the system in terms of thermodynamical variables allowing the study of the EoS. 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 real fluid as shown in fig.1.

Indeed, nuclear matter properties calculated with a Skyrme force [6] shows a critical temperature around 17 MeV and a critical density close to 1/3 of the normal density. Inside the mechanically unstable region, matter experiences a spinodal decomposition [7]. In between the spinodal line and the coexistence line, it is in a metastable state. One major difficulty is to project the concepts and results of infinite nuclear matter to transient and open systems such as excited nuclei produced in dissipative nuclear collisions. Surface, Coulomb and isospin effects play a major role in the stability of hot nuclei. For instance, mean field calculations predict the existence of a limiting temperature (for which finite

Figure 2. Galilei-invariant velocity distributions for $Z=2$ particles emitted in the reaction $\text{Xe}+\text{Sn}$ at 50 MeV/u. The centrality of the collision (from peripheral (a) to central (d)) is determined with the transverse energy distributions. From [4].

nuclei become unstable) substantially smaller than the critical temperature [9].

Experimentally, the exploration of the various regions of the EoS is made possible by producing hot and compressed pieces of nuclear matter in violent dissipative collisions. The major task of the experimentalists is then to properly characterize and to study all possible decay modes of such hot nuclei.

Nuclear collisions are complicated processes leading to the production of many different species with large mass and energy ranges. The major improvements of these last years have been the design and the building of sophisticated instruments allowing the recording of kinematically complete events. Most (if not all) of the results discussed in the following have been obtained by 4π collaborations. The amount of information gathered in such events is usually very large and techniques dedicated to the reduction of the information with the help of global variables and multi-dimensionnal analysis have been developed

Figure 3. Space time evolution of the matter as predicted by semi-classical transport models. The system is Ni+Zr ($b=b_{max}/2$) at 15, 40, 80 MeV/u from up to bottom. Time steps are 20 fm/c starting at 280, 120 and 80 from up to bottom. From [8].

(see e.g [12]).

2. REACTION MECHANISMS: PRODUCTION OF HOT NUCLEI

The Fermi energy range is a truly transition region. At lower incident energies (say less than 20 MeV/u) [13], the reaction mechanisms are essentially governed by the long range part of the nuclear force, hence by the mean field. The resulting phenomenology is fusion for the most central collisions and binary dissipative reactions for the more peripheral ones.

Fast processes associated with direct nucleon-nucleon collisions in the first steps of the reaction do not play a major role because such collisions are severely hindered by quantum effects. No compression effects are expected and moderate excitation energies are reached justifying the use of the compound nucleus theory.

In the relativistic energy range, the dynamics is dominated by hadronic cascades with a strong stopping power of the matter due to the opening of phase space and consequently the shortening of the mean free path. The reaction mechanisms is then governed by geometrical concepts leading to the so-called participant-spectator picture. The physics of the participants is discussed elsewhere in this conference [15]. The fate of the excited spectators produced in peripheral reactions shows similarities with the one of hot species formed in central collisions as shown in the next sections.

In the Fermi energy range, a general global trend is the dominance of the binary character of the collisions. This is true for light [16], medium [17,18] and heavy systems

Figure 4. Percentage of matter emitted in the mid-rapidity region for semi-central collisions. The solid line is associated with a value averaged over the fragment charge distribution. From [4,10,11].

Figure 5. Evolution of the competition between fission and 3-body decay as a function of the excitation energy. Data from [14].

[19,20] and is illustrated in fig.2. The two sources of emission associated with the two partners of the reaction present Coulomb rings for the emission of light charged particles. As the dissipation increases, the two sources become closer in momentum space and the mid-rapidity region is more and more populated showing very peculiar features.

Figure 6. Evolution of the reduced IMF multiplicity (see text) as a function of E^* . From [26,27].

Microscopic calculations suggest the formation of neck-like structures ending either as two extremely deformed partners (neck reabsorption for incident energies around 20 MeV/u interpreted as a natural continuation of the collision regime at lower energies) or to the formation of a third independent piece of very excited matter (as the onset of the participant-spectator picture described above) at higher incident energies (see fig.3).

A detailed analysis performed by different collaborations leads to the conclusion that the percentage of particles around the mid-rapidity region is indeed an important fraction of the emitted matter as shown in fig.4. In particular, fragment emission in this rapidity range is a dominant process in semi-central collisions. There, the interaction time is rather short so that the rupture of neck-like structures may be non-statistical [21]. Fast thinning and stretching of the matter could induce sheet instabilities [22]. There are some theoretical evidences for the production of neutron-rich matter [23] at mid-rapidity and some recent experimental results seem to confirm such a statement [24,25].

Although most of the collisions end up with rather elongated shapes associated with the binary character of the reaction, it is still possible to select the most compact configurations with help of global variable analysis [29–31]. For such collisions (the most central ones corresponding to a few tens of millibarns cross section), the shape of the events is nearly spherical, the interaction times are rather long (up to a few hundreds

of fm/c), matter is almost completely stopped leading to strong dissipation and thus to excitation energies close or even larger than the total binding energy of the system [31]. These are the collisions where a compression/expansion phase is possible and where bulk instabilities can take place on time scales compatible with thermalization [32]. The fate of hot nuclei produced in such collisions is now discussed.

3. THE DECAY MODES OF HOT NUCLEI: FROM EVAPORATION TO VAPORIZATION

Hot nuclear species produced in central collisions described above can experience various decay modes according to their intrinsic excitation energy E^* , angular momentum, density, deformation....

Figure 7. Evolution of the various decay modes of Au nuclei as a function of the excitation per nucleon as predicted by a multifragmentation statistical model. From [28].

At moderate excitation energy, the dominant decay modes are evaporation leading to residues or fission accompanied by pre- and post- light particle emission. These two competing modes are discussed elsewhere in this conference [33].

When E^* is raised up to a significant fraction of the binding energy, Intermediate Mass Fragment (IMF's) emission takes place indicating the onset of nuclear fragmentation. The transition from fission to fragmentation has been studied for systems with mass around

200 units. In fig.5, the yield of three-body (fragmentation) vs two-body (fission) is shown as a function of E^* : a sharp increase is observed around 3 MeV/u. Fragmentation is then the dominant process (although evaporation and fission are still present). When E^* is close to the binding energies, there is a fall of IMF production as displayed in fig.6. The maximum IMF production is observed around 9 MeV/u and then drops down being progressively replaced by vaporization (i.e. the decay by particles with $Z=1$ and 2 only) as observed Ar+Ni collisions [34]. This is the ultimate decay mode in the nucleonic regime. Surprisingly, it was found possible to describe such a process with help of a statistical approach although the time scales are very short and the dissipated energies very large [35].

Figure 8. Evolution of the three fragment atomic numbers (shown as Dalitz plots) following the decay of excited nuclei with mass close to 200 units. From [14].

The successive transitions of the decay modes as a function of E^* are correctly predicted by multifragmentation statistical models [36,37] as shown for example in fig.7. Such calculations also point out the influence of the Coulomb long range force on the competition between the decay modes. The dominance of phase space as predicted by such calculations has been observed experimentally by analysing fragment multiplicities [39]. The highly debated conclusions [40–42] claim for 'reducibility' and 'thermal scaling' [39] in nuclear fragmentation raising questions about the instabilities responsible for nuclear disassembly as discussed now.

4. NUCLEAR FRAGMENTATION AND NUCLEAR INSTABILITIES

The onset of fragmentation has been observed for excitation energies around 3 MeV/u followed around 10 MeV/u by a fall coupled with the onset of nuclear vaporization. Fragmentation is therefore the transition regime from a liquid-like state to a gas-like state of hot nuclei. There is a question about the very nature of nuclear fragmentation: is it a

Figure 9. Systematic of the fragment emission times as a function of the excitation energy per nucleon. The arrows indicate the excitation energy associated with fusion when E^* was not measured. References can be found in [12].

natural continuation of fission or the signature for new physics? [22,43].

This issue is intimately related to the nature of the instabilities which can take place in nuclei. Fragmentation following deformation at normal density is a process similar to fission i.e dominated by Coulomb and surface instabilities while fragmentation occurring at low density is a process driven by a mechanical instability due to the entrance of the system in a region where density fluctuations are no more damped but exponentially amplified leading the system to the so-called spinodal decomposition.

The transition between these two regimes has been observed by following the evolution of the charge distribution of fragmented events as well as the evolution of the time scales for fragment emission.

Charge distributions of the three largest fragments detected per event are usually displayed with help of Dalitz plots. In such plots, the corners of the triangle are populated by events with one large remnant and two small fragments while the sides are associated with fission-like events (two large fragments and a small one) and the center with equal-mass fragments events. The evolution of such Dalitz plots as a function of the excitation

Figure 10. Comparisons of the measured charge distributions of fragmented events in central collisions with the predictions of a multifragmentation statistical model. Data (black points) have been compared with the results of the calculation (solid lines) with two sets of parameters: the freeze-out density indicated in each panel and $E^* = 6.0$ MeV/u in a) and $E^* = 4.8$ MeV/u in b). The dotted and dashed-dotted lines are calculations with 1 MeV/u variations in the excitation energies. From [44].

energy is displayed in fig.8 showing a clear evolution from a fission-like process towards more symmetric splittings as E^* increases from 3 to 5 MeV/u.

Is this evolution correlated with fragmentation time scales? To deal with this issue, fragment emission times have been estimated by analysing space-time correlations between fragments taking advantage of the 'proximity' effects induced by Coulomb interaction. The systematics is shown in fig.9 as a function of E^* . A strong decrease of the emission time with an increase of E^* is observed up to 5 MeV/u until a saturation is observed around 100 fm/c. This saturation is due to the sensitivity of the method: it is difficult to measure times shorter than the Coulomb repulsion time. For such short times, fragments are emitted almost 'simultaneously' so that fragment emissions cannot be treated independently. One should note that correlatively, sequential statistical models fail in reproducing the observed fragmentation characteristics in this energy range [45].

At high excitation energies, the nuclear phase space must be sampled with new hypothesis as compared to low energy prescriptions. Multifragmentation statistical models [36,37] assume a 'freeze-out' volume (about 3 to 5 times the volume of nuclei in their g.s.) in which nuclear partitions are generated according to their statistical weight namely their entropy. All particles and fragments are produced 'simultaneously' and they all 'freeze' at the same time. Such models have met a large success in their comparison with the data as shown for example in fig.10. It should however be noticed that input parameters

Figure 11. Systematics of the collective energy as a function of the excitation energy per nucleon. References can be found in [12].

must be provided in such calculations and there is thus room for the choice of both the 'freeze-out' density and the excitation energy. Nevertheless, these models can account for most of the characteristics of nuclear partitions assuming low density.

The transition from sequential to simultaneous fragmentation i.e from the decay at normal density to disassembly at low density is expected to be coupled with the onset of matter expansion. The more accurate experimental signature for radial collective motion is obtained by analysing the mean kinetic energy of the fragments and in particular the deviations from a pure Coulomb-like expansion. This is usually achieved by comparing data with the predictions of simulations assuming initial matter configurations such as the one obtained in statistical multifragmentation models and by adding a collective initial self-similar velocity field to simulate the expansion of the matter. This hypothesis corresponds to an isentropic expansion which is very nicely observed in microscopic transport model calculations [38].

A non-exhaustive compilation of the measured collective energy is shown in fig.11. There is a question whether E^* is the 'proper' variable to scale the collective energy. Another scaling as a function of the relative energy between the two incoming nuclei is also possible [38]. However, the results of fig.11 seem to indicate that the collective motion is controlled by the excitation energy (i.e. thermal energy + compression energy). Thus, it is difficult to isolate the effect due to the initial compression in the observed collective motion.

In the excitation energy region we are interested in, the collective motion remains moderate. Therefore, the variation of the nuclear volume on time scales associated with fragment formation is small (the system is almost stationary) and could explain the

success of statistical models to describe nuclear fragmentation.

5. NUCLEAR THERMODYNAMICS AND PHASE TRANSITION

In the last section, the experimental conditions associated with the transition from sequential fragment emission to multifragmentation have been established. There is evidence that above $E^* = 5$ MeV/u:

- the system is produced in collisions for which time scales are long enough for thermalization to occur and bulk instabilities to develop.
- the system is diluted to densities as low as one third of the normal density.
- the system has a moderate collective motion with respect to the total energy.

All these features are compatible with a spinodal decomposition. Such a process is associated with phase coexistence in dilute systems and therefore to the question of the thermodynamical features of small quantum systems.

Figure 12. Systematics of measured nuclear temperatures with the three methods described in the text as a function of E^* . References can be found in [12].

Nuclear thermodynamics is based on nuclear calorimetry (measurement of the excitation energy E^*) and nuclear thermometry (measurement of nuclear temperature T). The estimation of E^* is based on different methods [12] (neutron multiplicity measurements, total kinetic energy loss evaluation, reconstruction and energy balance of well-identified sources) which will not be discussed here.

Nuclear temperatures can be measured with the three following techniques:

- estimation of the slopes of the kinetic energy distributions of evaporated light particles ('kinetic' temperatures)
- ratio of population of discrete state for selected clusters ('excited states' temperature) [46]
- double-ratio of population of isotopic yields ('double-ratio' temperature) [47]

The three methods have been widely used for a variety of systems in different collision regimes. Some recent results have been compiled in fig.12. Within a given method, data from different collaborations do agree while the three methods do not give the same values meaning that only apparent temperatures are measured. The 'kinetic' temperatures follow approximatively a Fermi gas law while the 'excited state' temperatures seem to saturate (see also [48]) and the 'double ratio's to slowly increase. This apparent contradiction can be resolved in the frame of the Quantum Statistical Model [49] by including excluded volume effects [51] but other explanations are possible.

In particular, cooling [50] may be an important effect: nuclear species would be produced at different steps of the disassembly process, thus light particles could be emitted first (even at the pre-equilibrium stage) while fragments would be emitted later at lower temperatures implying a hierarchy in the different temperatures as observed experimentally.

Assuming the 'double ratio' temperature to be the correct one, it has been claimed that the E^*-T correlation (the so-called 'caloric curve') was the signal for a first order liquid-gas phase transition [52]. This statement is highly debated. There is a question about the physical conditions of the system: is it at constant pressure or constant volume? These two situations lead to different E^*-T plots [39].

Another issue is related to the nature of the phase transition in nuclear systems. As pointed out in [39], evaporation is the liquid-gas phase transition and thus is present as soon as the system is excited. The main issue is whether the system presents coexistence phase. The experimental signatures for such a feature may be deduced from a comparison of the models with the experimental caloric curves but also from a detailed study of nuclear partitions [53]. Last, second order phase transition can be studied in searching for critical exponents (see e.g [54]).

6. SUMMARY AND PERSPECTIVES

Our understanding of nuclear processes in the Fermi energy range has improved a lot during last years. From an experimental point of view, the use of efficient large detection arrays and the development of the associated analysis tools have made possible estimations of several fundamental quantities such as excitation energies, time scales, temperatures, radial collective flows,...

From a theoretical point of view, the improvements of the models based on microscopic transport theories have allowed accurate quantitative comparisons with the data. The study of reaction mechanisms in the Fermi energy range has revealed new characteristics. In mid-central collisions, the occurrence of space-time configurations corresponding to neck-like structures have been observed. The study of the decay of such structures opens

the possibility to investigate neutron-rich matter at low density in dynamical situations. Although the overall trend of the collision corresponds to binary reactions, fusion or quasi-fusion associated with very compact nuclear shapes have been recognized in very central reactions.

In such collisions, all possible decay modes of excited matter have now been observed from evaporation to vaporization via fission, sequential fragmentation and multifragmentation. The transition from one mode to another one have been clearly marked and they agree with statistical models claiming for a strong phase space dominance.

However, the physical conditions for the disassembly of pieces of hot and dilute matter have been identified suggesting a spinodal decomposition as predicted by semi-classical transport theories. Concerning nuclear thermodynamics, there remains questions about the interpretation of the E^*-T correlations (caloric curves). Ambiguities in nuclear thermometry must be resolved and the concepts of phase transitions in hot nuclei clarified.

Then, it will be time to explore a new 'chemical' instability (see for instance [55]) induced by extreme values of the isospin degree of freedom by studying nuclear collisions with exotic beams.

Acknowledgments

The author would like to thank warmly his friends from the Nautilus and Indra collaborations and F. Gulminelli, Ph. Chomaz, B. Lynch, J. Natowitz, R. Siemssen and W. Trautmann for fruitful discussions.

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