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# Challenges in nuclear dynamics and thermodynamics

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**Abstract.** The purpose and contents of this topical issue, *Dynamics and Thermodynamics with Nuclear Degrees of Freedom*, which grew out of a series of workshops in the years 2004 and 2005, are introduced. The central topics are the nuclear density functional, nuclear multi-fragmentation, and nuclear phase transitions.

**PACS.** 24.10.-i Nuclear reaction models and methods – 25.70.Pq Multifragment emission and correlations – 25.70.-z Low and intermediate energy heavy-ion reactions

## 1 Unveiling the nuclear density functional

Since the pioneering inclusive experiments of the Purdue group [1] and the first exclusive emulsion data [2] in the early eighties, it has been clear that the revolutionary discovery of Otto Hahn and Fritz Strassman in 1938 had been surpassed by new experimental evidence [3]. Not only is it possible to create smaller parts than the original nucleus by collisions of nuclear particles with atomic nuclei —what we know today as the phenomenon of nuclear fission— but also to break the nucleus into many different pieces. This intriguing phenomenon that we call nuclear multifragmentation has yet not reveiled all its secrets and continues to fascinate the nuclear-physics community. This fascination, and our wish to share it with a wider community, motivates this topical issue.

Since the very early days of heavy-ion experiments, it has been understood that collisions with heavy ions could create nuclear material with density and excitation energy radically different from that of the ordinary matter surrounding us. Such reactions would then be the only terrestrial window that could provide a transient glimpse of the hot nuclear matter that is so abundantly present in the universe, in the last evolution steps of all dying massive stars.

These collisions would therefore provide unique constraints to pin down the energy-density functional of nuclear matter in a large domain of energy, density, and isotopic composition, as well as the underlying effective interaction that binds atomic nuclei.

To get quantitative information on the nuclear density functional, the so-called nuclear equation of state, the different functionals produced by theory have to be implemented in transport equations that predict the dynamics of the collisions, and robust observables have to be constructed that are selectively sensitive to the different parts of the effective interaction. This requirement has boosted the development of quantum transport models, as well as of sophisticated large-coverage, high-resolution detectors, able to reconstruct the one-body global observables accessible to the theory. Such observables, probing different times and consequently different densities, are mainly collective flows, energetic particle production, and diluted matter emitted at mid-rapidity in peripheral collisions. The different aspects of this fascinating adventure, and our present understanding of the nuclear equation of state, are reviewed in the monographs by C. Fuchs and H.H. Wolter, A. Andronic *et al.*, A. Bonasera *et al.*, and M. Di Toro *et al.* The theoretical methods to address this problem, namely mean-field theory and its extensions, are not specific to nuclear physics. Rather, they are also applicable to the study of many different fermionic systems, as helium droplets and metal clusters. The common methods and challenges in the field of small fermionic systems are reviewed in the monograph by J. Navarro *et al.*

If our understanding of the basic features of the nuclear density functional has greatly improved with these studies, many questions have not been answered yet and new problems have arisen. The interplay in the reaction

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dynamics between the density functional and transport properties leads to huge error bars in the quantitative estimation of fundamental quantities like nuclear incompressibility. Better constraints can be achieved if different independent observables are examined comparatively.

In particular, the study of isoscalar collective modes, reviewed by S. Shlomo *et al.*, provides such complementary information, which in recent years has allowed us to estimate the nuclear incompressibility around saturation within a few tens of MeV.

Both the initial high-density state of the collision and the later low-density finite-temperature stage leading to the formation of many-body correlations, are, in principle, extremely interesting to probe. The problem is that both stages are transient in time, and only the final outcome of the collision can be measured. As a result, any information on the nuclear equation of state necessarily is obtained through the comparison with a nuclear model. At the moment our most sophisticated transport theories solve the time-dependent problem without off-shell effects, and include correlations beyond the mean field at the classical level if at all. Moreover, the different approximation schemes developed in the different codes do not produce entirely compatible results. Improvement in the predictive power of transport models is certainly one of the greatest theoretical challenges facing the field.

The irreducible time dependence of the reaction problem can be addressed not only through improved theoretical models predicting asymptotic observables, but also through more sophisticated analyses of data reconstructing the reaction information backward in time. In particular, correlation functions provide an extremely powerful technique to, at least partially, disentangle the space and time information from particle and fragment yields. This, in turn, leads to the challenge of developing new third-generation nuclear detectors with high granularity and high resolution. The numerous fascinating applications of correlation functions and imaging techniques are reviewed in the monograph by G. Verde *et al.*

The availability of radioactive ion beams from various facilities either already constructed or planned for the near future (RIKEN, SPIRALII, RIA, FAIR, EURISOL, MSU, TAMU) has given a strong boost to the field. Not only does the comparison of nuclear dynamics of similar systems with different isotopic content provide new selective observables to probe our nuclear models, but also the possibility emerges to probe quantitatively the dependence of the density functional on the relative neutron/proton content —the so-called symmetry energy— through heavy-ion collisions. This quantity is of fundamental importance in a number of astrophysical situations, such as supernovae explosion dynamics and neutron star structure. These new applications generate great enthusiasm in the community, and the field is rapidly evolving. Although definitive answers will only be obtained with the advent of exotic beams in the energy regime of some tens of MeV per nucleon, the information already collected with stable beams is reviewed in monographs by M. Di Toro *et al.* and by M. Colonna and M.B. Tsang.

## 2 Experimental and theoretical challenges of nuclear multi-fragmentation

The field of multi-fragmentation deals first and foremost with the phenomenon of multiple fragment production. Such a phenomenon shows a clear character of universality: it has been observed with heavy-ion collisions using beams of a few tens of MeV per nucleon and in the relativistic target or projectile fragmentation regime as well as with light-particle, pion- or antiproton-induced reactions. The global characteristics of fragment production as revealed by the different experiments are reviewed in the contribution by B. Tamain.

Understanding the multi-fragmentation phenomenon raises the theoretical challenge of modeling the development of instabilities and correlations in finite quantum many-body systems. This interdisciplinary problem calls for important future developments that also will have implications to nuclear structure close to the driplines and to cluster physics. A partial review of this vast subject is presented in the monographs by V. Baran *et al.* and by A. Ono and J. Randrup.

The complexity of nuclear systems and the apparent universality of fragment observables encourages statistical treatments: together with the progress in transport theories, heavy-ion experiments have triggered an enormous theoretical effort in the development of sophisticated statistical descriptions of fragment production, reviewed in the article by A.S. Botvina and I.N. Mishustin. The predictive power of such models is tested through a detailed comparison of different codes associated with the models compiled by M.B. Tsang *et al.*

The construction of complex collective observables, as well as the exclusive analysis of isotopically resolved fragment yields, requires very sophisticated apparatuses capable of detecting all nuclear systems in the mass table from neutrons to uranium isotopes, and combining high granularity, geometrical coverage, and detection efficiency, with low thresholds for detection and identification. The present state of the art of nuclear detection and the challenges for third-generation detection systems are presented in the monograph by R.T. de Souza *et al.*

## 3 Phase transitions in finite, transient, non-extensive systems

Since the early days of multi-fragmentation, the breaking of a nucleus into many pieces has been tentatively associated with a phase transition. The intuitive association of fragmentation with a disordered phase is supported by different arguments. On the theoretical side, realistic mean-field calculations of the nuclear phase diagram consistently predict that nuclear matter should present a liquid-gas phase transition at sub-saturation densities and temperatures below 10–15 MeV. On the experimental side, evidence has been accumulated for fragment formation actually occurring under similar conditions of density and temperature. The rapid opening of the multi-fragmentation channel around a specific energy recalls the onset of a phase transition, and the observed scaling properties of fragment abundancies suggest a critical phenomenon.

The experimental measurement of the fragmentation phase transition would offer a unique possibility for settling the whole finite temperature phase diagram of nuclear matter. The extraordinary importance and ambition of this program can be appreciated if we consider that in the last 50 years of nuclear physics, only the saturation point of the nuclear matter phase diagram has been measured with good precision. The phase structure of exotic nuclear matter is also of particular interest for the static and transport properties of a number of compact objects in the universe, such as neutron star crusts and supernovae cores, as reviewed in the contribution by C. Horowitz.

To achieve this goal, sophisticated tools have been developed to measure the excitation energy and temperature of the transient multi-fragmenting stage of the collision. These tools are presented and discussed in the reviews by V.E. Viola *et al.* and by A. Kelić *et al.* A number of indications of such a phase transition have been accumulated, and are critically analyzed in the monographs by D. Santonocito and Y. Blumenfeld, by Y.G. Ma, by B. Borderie and P. Désesquelles, by F. Gulminelli and M. D'Agostino, and by O. Lopez and M.F. Rivet. Even if a global coherence of the different signals has been attained, and some quantitative estimates of the transition region start to be available, the order and the nature of the phase transition are still subject to uncertainties and debate.

The understanding of the phase transition is a particularly challenging problem since it is predicted theoretically that such a transition should be accompanied by numerous scalings and hyper-scalings as well as by thermodynamic anomalies like negative specific heat and bimodalities. Such anomalies are generic features of first-order phase transitions in non-extensive systems, and as such have been reported in other fields, such as cluster physics and self-gravitating systems. These interdisciplinary connections, which make heavy-ion thermodynamics a unique laboratory of statistical mechanics of finite systems, are explored in the monographs by D.H.E. Gross and by Ph. Chomaz and F. Gulminelli. Fragmentation is not the only phase transition expected in nuclear matter: at much higher energy density a transition towards a quark-gluon plasma has been predicted and is presently being explored at the high-energy heavy-ion facilities at CERN and Brookhaven National Laboratory. Some of the possible connections between the two phase transitions are addressed in the article by I.N. Mishustin.

## 4 Final remarks

Before concluding this introduction, a few remarks are necessary. The present topical issue gives a report of the momentary status of the field of dynamics and thermodynamics with nuclear degrees of freedom, as seen by the collection of authors. But it is not meant as a definitive and unique description of all of the relevant physics issues. The different articles are also different in character, reflecting both the preferences of the authors and the uneven state of the development of the various topics. In particular, the articles appearing in the last chapter making connections to neighboring fields have to be taken with a caveat. The authors have tried to make them as objective as possible in a developing field subject to discussions and controversies.

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