FLUCTUATIONS AND TEMPORAL EVOLUTION IN HEAVY-ION COLLISIONS

Paolo Napolitani[1]
Institut de Physique Nucléaire d'Orsay (IPN), CNRS/IN2P3

Cédric Simenel[2]
CEA-Saclay , IRFU-SPhN

François Sebille [3]
Subatech, Nantes

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I. PROBLEMATICS

So far, one of the main concerns in low-energy nuclear dynamics and heavy-ion collisions evolved around the question: which is the phenomenology of a bundle of trajectories in the density-temperature space for a finite piece of nuclear matter? The dynamics resulting from the perturbations of a nuclear system gives access to three main features:

1. The density evolution of a nuclear system, like its compression and its expansion processes in nuclear collision, connected to the isoscalar properties of the nuclear interaction.
2. The thermal evolution of a nuclear system, which is ruled by the level densities.

1 napolita@ipno.in2p3.fr

2 cedric.simenel@cea.fr

3 sebille@subatech.in2p3.fr

3. These two subjects are unified in a third topic, which is the thermodynamics of a nuclear system and, in particular, its properties related by the equation of state and the nuclear liquid-gas phase-transition phenomenology.

Recent descriptions of nuclear dynamics aim at focusing more precisely onto the isospin degree of freedom. Its contribution to the energy functional is globally carried by the symmetry energy. Trajectories in a density-temperature-isospin space are described phenomenologically by current studies. When perturbations are injected in this space, density and isospin gradients appear, giving rise to transport phenomena like isospin migration and diffusion, reflected in neutron and proton currents among the nuclear medium. The study of these features is of fundamental interest for describing the form of the symmetry energy, the isovector properties of the nuclear interaction and the connection between finite nuclei, which can be probed experimentally, and dense matter, which can be mostly accessed through observational consequences. In a thermodynamical framework, when the isospin degree of freedom is accounted for in the phenomenology of phase transitions, new exotic processes like the isospin distillation appear in the region of liquid-gas phase coexistence. More precisely, the coexistence region contains a mechanically unstable region, named spinodal, which is expected to influence both the fragment formation in finite systems (nuclear collisions) and the developing of inhomogeneous phases in an astrophysical context.

The experimental approaches to investigate nuclear-dynamics observables have elaborated several techniques for measuring single-event correlations. However, they cannot access the equation-of-state properties, and a thorough and parallel development of nuclear theories is necessary. Very schematically, concerning nuclear collisions, the various developments which are still needed can be organised under two main issues: fluctuations in phase space and extension in time.

1. Fluctuations are to be addressed in the framework of stochastic dynamical models: fluctuations of correct amplitude should be introduced in the description of dynamical trajectories in order to achieve a more complete sampling of the density-temperature-isospin landscape. In semi-classical models several approaches were already explored in order to inject fluctuation seeds directly or as a projection on suitable dynamical coordinates, like the density space. The inclusion of the residual two-body interaction is however still to be studied in details when extensions of the TDHF theories are concerned. A more specific interest of a correct implementation of fluctuations is its relation to isovector fluctuations and the possible connection with spinodal decomposition and fragment formation in dissipative nuclear reactions.
2. The extension in time is a fundamental problematic for nuclear reaction modeling, especially connected to nuclear collisions at intermediate energies (Fermi regime). The initial time steps of dissipative nuclear collisions are efficiently described within dynamical transport models which follow the evolution of the one-body density coordinate in phase space. Usually, this dynamical description is supplement with statistical treatments to describe the secondary decay of the warm remnant: in this case, two descriptions apply to two stages of the reaction process, and their coupling imposes to deal with a complicated change of formalism. The techniques of connecting these two stages are a subject of intense discussion (formation and identification of hot fragments and assignment of specific thermodynamical and

nuclear characteristics). A possibility to study this problematics in details would require the extension of the first dynamical stage up to the first-chance emissions; such a long extension in time requires on the one hand to introduce quantum ingredients in the model and, at the same time, to reduce its numerical complexity.

To address both these goals, different models are developed, such as extensions of the Time-Dependent-Hartree-Fock mean-field theory, Quantum Molecular Dynamics, Boltzmann-Langevin Dynamics or recent developments of the nuclear statistical equilibrium. It is timely to compare these different approaches and define a program for further developments and refinements during the next years.

II. GOALS OF THE WORKSHOP

This workshop is intended to join a group of experts of dynamical modeling and experimental-data analysis, around the following topics:

1. Microscopic approaches, from nuclear structure to nuclear reactions.
2. Fluctuations in nuclear dynamics: the seeds of fragment formation.
3. Isospin transport: diffusion, migration, neck formation, equilibration.
4. Symmetry energy and spinodal decomposition.
5. Connection between theory and experimental observables for dissipative collisions.

III. USEFUL REFERENCES

- *Reaction Dynamics with Exotic Nuclei*,
  V. Baran, M. Colonna, V. Greco and M. Di Toro. Physics Reports 410, 335 (2005).
- *Nuclear Spinodal Fragmentation*,
  Ph Chomaz, M Colonna and J Randrup. Physics Reports 389, 263 (2004).
- *Comparison of multifragmentation dynamical models*,
  J. Rizzo, M. Colonna and A. Ono. Physical Review C 76, 024611 (2007).
- *Fragmentation paths in dynamical models*,
  M. Colonna, A. Ono and J. Rizzo. Physical Review C 82, 054613 (2010).
- *Cluster formation in asymmetric nuclear matter: semi-classical and quantal approaches*,
  C. Ducoin, J. Margueron and Ph. Chomaz. Nucl. Phys. A809, 30 (2008).
- *Isospin fractionation: equilibrium versus spinodal decomposition*,
  C. Ducoin, Ph. Chomaz and F. Gulminelli. Nucl. Phys. A781,407 (2007) .
- *Wavelet representation of the nuclear dynamics*,
  B. Jouault, F. Sébille, and V. de la Mota, Nucl. Phys. A628, 119 (1998).

- *Dissipative and fluctuating effects in nuclear dynamics with a wavelet representation,* V. de la Mota and F. Sébille. The European Physical Journal A 12, 479 (2001).
- *Probing the nuclear matter isospin asymmetry by nucleon-induced reactions at Fermi energies,* F. Sébille, V. de la Mota, I.C. Sagrado Garcia, J.F. Lecolley, V. Blideanu. Phys. Rev. C 76, 024603 (2007).
- *Self-consistent dynamical mean-field investigation of exotic structures in isospin-asymmetric nuclear matter,* F. Sébille, S. Figerou and V. de la Mota, Nuclear Physics A 822, 51 (2009).
- *Towards a nonequilibrium Green's function description of nuclear reactions: one-dimensional mean-field dynamics,* A. Rios, B. Barker, M. Buchler, P. Danielewicz, Annals Phys.326, 1274 (2001).
- *Actinide collisions for QED and superheavy elements with the time-dependent Hartree-Fock theory and the Balian-Véneroni variational principle,* C. Simenel, C. Golabek and D.J. Kedziora. Proceeding of the FUSION11 conference, arXiv:1108.2448.
- *Particle number fluctuations and correlations in transfer reactions obtained using the Balian-Véneroni variational principle,* C. Simenel. Phys.Rev.Lett.106, 112502 (2011).
- *Constraining the density dependence of the symmetry energy with experimental results from heavy-ion collisions,* M.F. Rivet. Lecture at École Joliot-Curie (2009).
- *Nuclear multifragmentation and phase transition for hot nuclei,* B.Borderie and M.F. Rivet. Prog Part Nuc Phys 61, 551 (2008).
- *Study of Nuclear Stopping in Central Collisions at Intermediate Energies,* G. Lehaut et al. Phys. Rev. Lett. 104, 232701 (2010).

IV. PARTICIPANTS

- Z. Basrak, *Boskovic Institute, Croatia*
- E. Bonnet, *GANIL, France*
- B. Borderie, *IPN, Orsay, France*
- N. Chamel, *ULB Bruxelles*
- M. Colonna, *LNS, Catania, Italy*
- V. De la Mota, *Subatech, Nantes, France*
- C. Ducoin, *IPNL, Lyon, France*
- P. Eudes, *Subatech, Nantes, France*
- J. Frankland, *GANIL, France*
- F. Gulminelli, *LPC, Caen, France*

- M. Grasso, *IPN, Orsay, France*
- D. Gruyer, *GANIL, France*
- K. Hasnaoui, *Florida State University, US*
- E. Khan, *IPN, Orsay, France*
- O. Lopez, *LPC, Caen, France*
- J. Margueron, *IPN, Orsay, France*
- P. Napolitani, *IPN, Orsay, France*
- A. Rios Huguet, *University of Surrey, UK*
- M.F. Rivet, *IPN, Orsay, France*
- F. Sebille, *Subatech, Nantes, France*
- C. Simenel, *CEA, Saclay, France*
- M. Urban, *IPN, Orsay, France*
- N. Van Giai, *IPN, Orsay, France*

VI. PROGRAM AND LIST OF TALKS

Talks are up to 45 min long including questions, tutorials are up to 1h 30 min. long including discussions and questions. Sessions begin at **10h00** on Wednesday and at **9h30** on Thursday.

Wednesday 9 May 2012		
10h00	**Beginning**	
10h00	*Thermal pressure in heavy-ion collisions around Fermi energy*	**E. Bonnet**
10h45	*Transparency in heavy-ion collisions at Fermi energy, experimental probes*	**O. Lopez**
11h30	**Break**	
11h45	*The Balian-Véneroni variational principle to determine particle-number fluctuations and correlations*	**C. Simenel**
12h30	**Lunch**	
14h00	**Tutorial**: *Introduction to wavelet representations and their possible interest in Quantum Mechanics*	**F. Sebille**
	The Dywan model	**V. de la Mota**
16h15	**Break**	
16h30	*The determination of the nuclear incompressibility*	**E. Khan**

17h15	*Monopole oscillations in light nuclei with a molecular dynamics approach (FMD / AMD)*	**K. Hasnaoui**
18h00	**End**	

Thursday 10 May 2012		
9h30	**Beginning**	
9h30	*Experimental exclusive observables: isospin-transport effects and kinematics of composite systems*	**M.F. Rivet**
10h15	*Order parameter distributions in nuclear multifragmentation*	**J. Frankland**
11h00	**Break**	
11h15	*Quantum transport in many-body systems: towards a Kadanoff-Baym approach for nuclear reactions*	**A. Rios Huguet**
12h00	*Nuclear stopping at intermediate energies - experiment versus simulation*	**Z. Basrak**
12h45	**Lunch**	
14h30	**Tutorial***: Stochastic transport theories as a tool to investigate nuclear dynamics*	**M. Colonna**
16h00	*Clustering in nuclear matter*	**C. Ducoin**
16h45	**Break**	
17h00	*Skyrme nuclear energy density functionals for atomic nuclei and neutron stars*	**N. Chamel**
17h45	**End**	

VII. FINANCES

For this workshop we planned to support the stay of 12 participants from outside of Île de France and abroad (breakfast, dinner plus hotel for a maximum of 100 Euros per day) and the stay of one participant (M. Colonna) for one full week (6 days). Six participants stayed two days in hotel as planned. One participant (O.Lopez) participated only one day and did not stay in the hotel. One participant (E.Bonnet) participated two days but did not stay in the hotel; he had however a dinner. Two participants stayed more than two days (M.Colonna and N.Chamel).In addition, lunch was supported for all participants. The total cost of the workshop was 2173€.

Last name	First name	University/Laboratory	Date of arrival and departure	Agreed support	Estimated overall support	Number of lunches at the cantine
Basrak	Zoran	Boskovic Institute, Croatia	8/05 – 10/05	200	200	2
Bonnet	Eric	GANIL, Caen	9/05 – 10/05	0	36	2
Borderie	Bernard	IPN, Orsay	9/05 – 10/05	0	0	2
Chamel	Nicolas	Institut d'Astronomie et d'Astrophysique, ULB, CP226, Boulevard du Triomphe, 1050 Bruxelles, Belgique	8/05 – 10/05	300	300	2
Colonna	Maria	INFN-LNS, via Santa Sofia 64, 95123 Catania	8/05 – 12/05	400	400	3
De la Mota	Virginia	Subatech, Nantes,	8/05 – 10/05	200	200	2
Ducoin	Camille	Université Lyon 1 / IPNL	9/05 – 11/05	200	200	2
Eudes	Philippe	Subatech, Nantes,	8/05 – 10/05	200	200	2
Frankland	John	GANIL, Caen	9/05 – 10/05	100	100	2
Grasso	Marcella	IPN, Orsay	8/05 – 10/05	0	0	0
Gruyer	Diego	UCBN/GANIL, Caen	9/05 – 10/05	100 (étudiant)	100	2
Hasnaoui	Karim	Florida State University	9/05 – 10/05	100	100	2
Khan	Elias	IPN, Orsay	9/05 – 10/05	0	0	2
Lopez	Olivier	LPC Caen, ENSICAEN-Université de Caen-CNRS/IN2P3	9/05 – 9/05	0	0	1
Margueron	Jérôme	IPN, Orsay	9/05 – 10/05	0	0	2
Napolitani	Paolo	IPN, Orsay	9/05 – 11/05	0	0	3
Rios Huguet	Arnau	University of Surrey	8/05 – 10/05	200	200	2
Rivet	Marie-France	IPN, Orsay	9/05 – 10/05	0	0	2
Sebille	François	Subatech, Nantes	8/05 – 10/05	200	200	2
Simenel	Cédric	CEA, Saclay	8/05 – 10/05	0	0	2
Urban	Michael	IPN Orsay	8/05 – 10/05	0	0	2
Van Giai	Nguyen	IPN, Orsay	9/05 – 10/05	0	0	2
				Total	**2236**	**39**
					Estimated workshop budget	**0**

VIII. COMMENTS

This workshop was dedicated to a very specific and technical topic, which is in general not represented exhaustively in large conferences.

In the past, the research on this field has been slowed down due to two reasons. 1) The absence of adequate numerical devices. 2) The absence of data which could be exploited only decades later in all their richness. The success of the workshop was the large participation of experts of nuclear-dynamics modeling and theories, and experimentalist who made available and explained in detail their most recent experimental results in the field. It came out from the workshop that a wide community exists, with the potential of inspiring future experimental projects in the framework of the future Frernch experimental developments.

All speakers had a large interval of time, which has always been fully filled by the discussions. Finally, the time resulted not to be sufficient and often the discussions had to be limited. Even more time should have been destined to the talks, the tutorials and the discussions. Three days instead of two would have been more appropriate.

We think that this atelier could be a good start for two kinds of future actions. 1) Trying to exploit the ESNT further for exploring other very specific topics in nuclear dynamics which touch the same community, and which may extend it through connections towards the nuclear structure and nuclear astrophysics communities. The subject of a future workshop should actually develop along this line. 2) On the basis of the participation to this workshop, we would like to encourage the proposal of an ANR project.

We thank sincerely the organization of the ESNT workshop for the excellent opportunity.