Multifragmentation and the liquid-gas phase transition: an experimental overview

W. Trautmann

aGesellschaft für Schwerionenforschung mbH, Planckstr. 1, D-64291 Darmstadt, Germany

Two roads are presently being followed in order to establish the existence of a liquid-gas phase transition in finite nuclear systems from nuclear reactions at high energy. The clean experiment of observing the thermodynamic properties of a finite number of nucleons in a container is presently only possible with the computer. Performed with advanced nuclear transport models, it has revealed the first-order character of the transition and allowed the extraction of the pertinent thermodynamic parameters. The validity of the applied theory is being confirmed by comparing its predictions for heavy-ion reactions with exclusive experiments.

The second approach is experimentally more direct. Signals of the transition are searched for by analysing reaction data within the framework of thermodynamics of small systems. A variety of potential signals has been investigated and found to be qualitatively consistent with the expectations for the phase transition. Many of them are well reproduced with percolation models which places the nuclear fragmentation into the more general context of partitioning phenomena in finite systems.

A wealth of new data on this subject has been obtained in recent experiments, some of them with a new generation of multi-detector devices aiming at higher resolutions, isotopic identification of the fragments, and the coincident detection of neutrons. Isotopic effects in multifragmentation were addressed quite intensively, with particular attention being given to their relation to the symmetry energy and its dependence on density.

1. INTRODUCTION

Multifragmentation reactions are often primarily seen and discussed in the context of the nuclear liquid-gas phase transition. Phase transitions in nuclear matter are indeed very special because they occur on temperature, pressure, and energy scales many orders of magnitude away from those familiar from ordinary matter. It is an interesting question in what form existing concepts for phase transitions can be applied to the phenomena governed by the strong force. The observation or proof of the existence of a phase transition has been an important objective of heavy-ion physics for quite some time.

There is little doubt that a liquid-gas phase transition should exist in extended nuclear matter [123]. It is also known that the corresponding conditions of density and temperature can be reached in reactions between finite nuclei. The problems encountered there, however, are not only related to the small size of the reaction system, i.e. to the severely
limited number of constituents, but also to possible dynamical effects which may hinder the homogeneous population of the phase space. A third difficulty arises from the limits in our control of the experiments. The identification of the complex reaction processes is incomplete, and even the detected fraction of a multi-particle event is only known with finite precision. To sort data according to impact parameter, excitation energy or temperature is limited in accuracy by statistical and systematic errors. To work with the best possible coverage and resolution is thus even more essential, which has motivated a continuing process of improving the experimental possibilities and devices.

More recently, a new direction for studying multifragmentation reactions has been derived from the importance of the symmetry term in the equation of state and of its density dependence for astrophysical applications. Supernova simulations or neutron star models require inputs for the nuclear equation of state at extreme values of density and asymmetry [4,5,6,7]. Isotopic effects in multifragmentation and other types of reactions have been shown to be sensitive to the symmetry energy coefficient, which may permit its study in the range of densities explored during the various stages of these collisions [8,9,10,11].

2. EXPERIMENTAL SITUATION

Data obtained with 4-π detection devices have been dominating the field for several years [12,13]. Besides solid-angle coverage, also the granularity and the dynamic range in particle type and energy are important parameters. A new standard for granularity has been set with the CHIMERA detector installed at the Laboratori Nazionali del Sud in Catania [14]. It comprises 1192 individual Si-CsI(Tl) telescopes which are arranged in a ring structure providing highest granularity at forward angles [15].

The obvious need for the coincident detection of neutrons is known since long ago. In heavy reaction systems, a major part of the released excitation energy resides in the neutron channels, and calorimetry without neutron detection has to rely on assumptions. For isotopic studies, the neutron-to-proton ratio is a primary observable. Measurements of neutron multiplicities and energy spectra in coincidence with 4-π charged-particle detection have been performed with the NIMROD detector installed at Texas A&M University at College Station [16]. The data sets collected for selected reactions have permitted a comprehensive comparison with transport models.

Apart from 4-π devices, dedicated setups of high complexity have been developed for specific experiments. The measurement of neutron-neutron and proton-proton correlation functions has revealed isotopic effects in the space-time properties of the fragmenting source at breakup [17]. Fragment detection with mass identification is a prerequisite for studying isotopic effects in the fragment channels. For this purpose, new high-resolution arrays were constructed at Michigan State University [18] and Indiana University [19].

Possibilities for new experiments with existing detection systems have also been explored. By transporting the INDRA multi-detector [20] to GSI, a new range of energies and reactions has become accessible for high resolution studies with 4-π coverage. Proton-rich secondary beams have been employed in experiments with the ALADIN spectrometer at GSI for the study of isotopic effects in the fragmentation of relativistic projectiles. First, preliminary, results from this latter experiment are now becoming available [21], some of the results obtained in the former campaign will be discussed further below.
3. THEORETICAL EXPERIMENTS

The idea of studying the equilibrium dynamics of a finite number of nucleons in a container has first been realized by Schnack and Feldmeier several years ago [22]. The Fermionic Molecular Dynamics (FMD) model was used to propagate systems consisting of small numbers of nucleons over sufficiently long times, so as to allow them to establish equilibrium. With a weakly coupled thermometer, the temperature was measured as a function of the excitation energy of the system which was varied. A first-order transition from a Fermi liquid to a Fermi vapour within the confining oscillator potential is clearly observed. It appears as a natural consequence of the short-range repulsion and long-range attraction of the potential used for simulating the nuclear forces.

Theoretical experiments of this type, based on the Antisymmetrized Molecular Dynamics (AMD) model, were conducted by Sugawa and Horiuchi [23] and, very recently, by Furuta and Ono [24]. The outcome in these cases is very similar. The observed latent heat which is a function of the chosen volume or pressure indicates a first-order transition. The agreement reached by these studies for the location of the critical temperature near 12 MeV in medium-heavy systems is remarkable.

To validate these results, it is essential that the ability of the FMD and AMD models of realistically describing nuclear dynamics are thoroughly tested, and here considerable progress has been made. In particular, the AMD model is in the process of being intensively compared to reaction data, and very satisfactory agreement has been obtained [16,25]. Both, the AMD and the FMD, have also been developed into successful theories.
for ab-initio calculations of the structure of light nuclei [26,27]. The idea of deriving support for the nuclear liquid-gas phase transition from studies of cold nuclei seems rather intriguing.

4. THERMODYNAMICAL PARAMETERS

Temperature measurements are useful for localizing the breakup process in the nuclear phase diagram [28]. Here, a remarkable consistency has been reached recently. The systematics compiled by Natowitz et al. [29] of experiments selected according to standard criteria, but allowing for different methods, is shown in Fig. 1. The combined set of temperatures exhibit an apparent Fermi-gas-like rise at excitation energies up to 3-4 MeV per nucleon, a very slow rate of temperature increase at higher energies, and some indication of a further rise at the very high excitation energies above 9 MeV per nucleon. Temperatures of around 6 MeV prevail in the range of excitation energies 5 to 8 MeV per nucleon at which multifragmentation is the dominant reaction channel for heavy systems. On the scale provided by the Molecular Dynamics studies, they place multifragmentation well below the critical point and into the coexistence region where homogeneous systems cannot exist in equilibrium.

The apparent temperature spread (Fig. 1) disappears to some part if the measurements are sorted according to the mass of the studied systems [29]. The lower temperatures in the fragmentation domain (∼ 6 MeV) are associated with heavy systems of mass $A \approx 200$ while the higher temperatures (∼ 8 MeV) are observed for the light systems with $A < 100$. The steady rise of temperature with excitation energy for the very small systems may even indicate that here the breakup occurs close to the critical point [30]. This systematic dependence has been associated with the concept of the limiting temperature at which excited homogeneous systems become unbound [31]. According to these finite-temperature Hartree-Fock calculations, the limiting temperature should also strongly depend on the isotopic composition, a prediction to be tested experimentally.
The critical density of nuclear matter is approximately one third of the saturation density \[2\]. For the statistical models of multifragmentation, the assumption of similarly low densities has, very early on, been found essential for correctly reproducing the observed fragment multiplicities \[32,33,34\]. Many experiments have shown that the kinetic-energy spectra of emitted fragments are inconsistent with emission from a normal-density compound nucleus \[35,36,37,38\]. More direct information on source properties in coordinate space is accessible with the technique of interferometry. Here, the shape of the source, the extension of statistical descriptions to non-spherical sources \[39\], and possible connections to transparency and mutual stopping in the approach phase of the collision \[40\] have received particular attention recently.

A new result obtained with a promising method of interferometry is shown in Fig. 2. Two types of directional fragment-fragment correlation functions are used to determine the volume and the shape of the source at breakup following central collisions of \(^{129}\text{Xe} + \text{natSn}\) at 50 MeV per nucleon \[41\]. The \(\chi^2\) distributions given in the figure represent the quality of their fitting, under the assumption of negligible emission times, with results for model sources with different longitudinal and transverse extensions, \(R_z\) and \(R_{xy}\). Large radius parameters giving evidence for expansion are obtained with either technique. The correlation functions constructed from the projections of the relative velocities, in addition, indicate a longitudinally expanded shape with axis ratio \(\approx 1.7\).

![Figure 3. Mean thermal excitation energy (full circles) and collective flow energy (open circles) at freeze-out, extracted by means of the MMMC-NS model, as a function of the incident energy \(E_0/A\) for central collisions of \(^{129}\text{Xe} + \text{natSn}\) at 50 MeV per nucleon and \(^{197}\text{Au} + ^{197}\text{Au}\) at 60, 80 and 100 MeV per nucleon. The lines are linear fits to guide the eye (from Ref. \[43\]).](image)

A rapid expansion, following an initial buildup of pressure, will appear as a collective fragment motion. Collective radial flow refers to simultaneous transverse and longitudinal collective expansions which are observed in azimuthally inclusive experiments. Collective flow in central collisions of heavy systems is observed above a threshold energy of \(\approx 50\) MeV per nucleon \[34,42\] and starts to rise rapidly at higher energies. This range
of intermediate bombarding energies has been systematically covered in the set of experiments conducted with INDRA at GSI [43]. The statistical analysis of these data yields an equilibrated excitation energy $E^*$ of the fragmenting source which rises rather slowly over the energy range up to 100 MeV per nucleon, and a rapidly rising collective-flow energy $E_{\text{coll}}$. At 100 MeV per nucleon incident energy, both components have about the same magnitude (Fig. 3).

The successful description of these highly dynamical processes with statistical fragmentation models, including a decoupled flow [43], raises the question why the effects of the collective motion are not more clearly visible. Collective flow should affect the partitioning of the system and, in particular, the survival probability for heavier fragments [44,45,46,47,48,49]. The effect of the flow on the charge distributions, on the other hand, may be simulated by adapting the value of the thermalized energy in the model description [45,48]. It is, therefore, quite likely that the flow effect is implicitly included in the parameters of the statistical description. At moderate flow values, the changes are expected to be very small [47,48].

An alternative approach to the question of the coexistence of equilibrated partitions and collective motion has recently been presented by Campi et al. [50]. Using classical molecular dynamics calculations and specific clustering algorithms, these authors find fragments to be preformed at the beginning of the expansion stage when the temperature and density are still high. The fragment charge distributions, reflecting the equilibrium at this early stage when the flow is small, remain nearly unmodified down to the freeze-out density at which the flow has fully developed.
5. LARGEST FRAGMENT AS ORDER PARAMETER

In the search for an experimentally accessible order parameter of the phase transition, as observed in reactions, the largest fragment of the partition has appeared as a promising choice. It may be identified with the part of the system in the liquid phase, and it is correlated with the mean density which is the natural order parameter of a liquid-gas phase transition.

Statistical model calculations for nuclear multifragmentation show that the disappearance of the dominating fragment is associated with a maximum of the heat capacity which is the more strongly pronounced the larger the system [51]. The disappearance of the largest cluster, with the variation of a suitable control parameter, has been identified as a prominent signal also in fragmentations of other systems as, e.g., atomic hydrogen clusters [52], and the largest cluster is an order parameter in percolation theory [53]. In finite percolation lattices, the disappearance of a dominant largest cluster proceeds rather smoothly and with obvious similarity to the nuclear experiment (Figs. 4, 5).

The success of percolation models in describing the observed partitioning of nuclear systems [55,56,57] and the apparent critical behaviour [58] do not necessarily identify the transition as of second order but rather show that first- and second-order phenomena may be compatible in small systems [59]. Studies of the fluctuation properties of the largest fragment [60] or of the relative magnitude of the two or three largest fragments [61] are thus not sufficient to establish the first-order character of the observed transition. Alternative methods have been presented [62,63] which, however, require calorimetry on an event-by-event basis which cannot be performed without assumptions. Also methodological aspects are under debate [64,65]. Comparative studies of several of these signals are presently being performed by the INDRA collaboration [66,67].

6. NEW DIRECTIONS

The experimental study of particle and fragment production with isotopic resolution has led to the identification of isoscaling, a phenomenon shown to be common to many different types of heavy ion reactions [8,9,68,69]. It is observed by comparing product yields $Y_i$ from reactions which differ only in the isotopic composition of the projectiles or targets or both. Isoscaling refers to an exponential dependence of the measured yield ratios $R_{21}(N, Z)$ on the neutron number $N$ and proton number $Z$ of the detected products. The scaling expression

$$R_{21}(N, Z) = Y_2(N, Z)/Y_1(N, Z) = C \cdot \exp(\alpha N + \beta Z)$$

(1)

describes rather well the measured ratios over a wide range of complex particles and light fragments [70]. For illustration, the scaled isotopic ratios $S(N) = R_{21}(N, Z)/\exp(\beta Z)$ for the reactions $^{12}C + ^{112,124}Sn$ at 300 and 600 MeV per nucleon, studied with INDRA at GSI [71], are shown in Fig. 6. The slope parameter $\alpha$ is found to decrease with increasing centrality of the reaction.

Of particular interest is the connection of the isoscaling parameters with the symmetry-term $E_{sym} = \gamma(A - 2Z)^2/A$ in the nuclear equation of state which has been consistently established with several methods [9,10,70]. The coefficient $\gamma$ [72,73] is proportional to the isoscaling coefficient $\alpha$ according to $\alpha T \approx 4\gamma \cdot \left(Z_1^2/A_1^2 - Z_2^2/A_2^2\right)$ where $T$ is the
Figure 6. Scaled isotopic ratios $S(N)$ for $^{12}$C + $^{112,124}$Sn at $E/A =$ 300 MeV and 600 MeV for intervals of reduced impact parameter $b/b_{\text{max}}$, with ”central” indicating $b/b_{\text{max}} \leq 0.4$. The dashed lines are the results of exponential fits according to Eq. (1) (from Ref. [71]).

Figure 7. Isoscaling coefficient $\alpha$ (top), double-isotope temperatures $T_{\text{HeLi}}$ (middle) and resulting $\gamma_{\text{app}}$ (bottom) for the reactions $^{12}$C + $^{112,124}$Sn at $E/A =$ 300 MeV (full symbols) and 600 MeV (open symbols), as a function of the centrality parameter $1 - b/b_{\text{max}}$ (from [71]).

temperature and $Z_i$ and $A_i$ are the charges and mass numbers of the two systems at breakup. The results obtained for the $^{12}$C + $^{112,124}$Sn reactions are summarized in Fig. 7. Using the above equation and assuming that the isotopic compositions are practically equal to those of the original targets, an apparent symmetry-term coefficient $\gamma_{\text{app}}$ was determined, i.e. without sequential decay corrections for $\alpha$. The results are found to be close to the normal-density coefficient for peripheral collisions but drop to lower values at central impact parameters. If the corrections for sequential fragment decay after breakup are taken into account the resulting coefficient $\gamma$ for central collisions is even smaller [71].

This result as well as those obtained for other reactions [11,74] may be considered as first steps within a program of studying the symmetry term far from saturation density. In the future, such experiments may aim at profiting from the existence of new radioactive-beam facilities. Projectiles with large neutron excess seem to be best suited to study dynamical effects of the symmetry force, and central collisions at high incident energy will have to be chosen in order to reach the larger than normal densities at which the symmetry energy is least well known [75,76].

Stimulating discussions with my colleagues at the GSI and within the ALADIN and INDRA-ALADIN Collaborations are gratefully acknowledged. In addition, I would like to thank R.T. de Souza, H. Feldmeier, T. Furuta, J.B. Natowitz, H. Oeschler, and A. Pagano for providing me with graphics for the talk and for helpful comments.
REFERENCES

1. G. Sauer, H. Chandra, U. Mosel, Nucl. Phys. A 264 (1976) 221.
2. H. Jaqaman, A.Z. Mekjian, L. Zamick, Phys. Rev. C 27 (1983) 2782.
3. H. Müller and B.D. Serot, Phys. Rev. C 52 (1995) 2072.
4. J.M. Lattimer, C.J. Pethick, M. Prakash, P. Haensel, Phys. Rev. Lett. 66 (1991) 2701.
5. J.M. Lattimer and M. Prakash, Phys. Rep. 333 (2000) 121.
6. F.-K. Thielemann et al., Progr. Part. Nucl. Phys. 46 (2001) 5.
7. A.S. Botvina and I.N. Mishustin, Phys. Lett. B 584 (2004) 233.
8. M.B. Tsang et al., Phys. Rev. Lett. 86 (2001) 5023.
9. A.S. Botvina, O.V. Lozhkin, W. Trautmann, Phys. Rev. C 65 (2002) 044610.
10. A. Ono et al., Phys. Rev. C 68 (2003) 051601.
11. M.B. Tsang et al., Phys. Rev. Lett. 92 (2004) 062701.
12. for an overview see, e.g., W. Trautmann, Nucl. Phys. A 685 (2001) 233c.
13. for references see, e.g., Proceedings of the VIIIth International Conference on Nucleus-Nucleus Collisions, Moscow, Russia, 2003, Nucl. Phys. A 734 (2004).
14. M. Alderighi et al., Nucl. Instrum. Methods Phys. Res. A 489 (2002) 257.
15. E. Geraci et al., Nucl. Phys. A 732 (2004) 173.
16. R. Wada et al., Phys. Rev. C 69 (2004) 044610.
17. R. Ghetti et al., Phys. Rev. C 69 (2004) 031605.
18. A. Wagner et al., Nucl. Instrum. Methods Phys. Res. A 456 (2001) 290.
19. B. Davin et al., Nucl. Instrum. Methods Phys. Res. A 473 (2001) 302.
20. J. Pouthas et al., Nucl. Instrum. Methods Phys. Res. A 357 (1995) 418.
21. C. Sfienti et al., [nucl-ex/0410044], to be published in: Proceedings of the 18th Nuclear Physics Division Conference of the EPS (NPDC18) on Phase transitions in strongly interacting matter, Prague, Czech Republic, 2004, to appear in Nucl. Phys. A.
22. J. Schnack and H. Feldmeier, Phys. Lett. B 409 (1997) 6.
23. Y. Sugawa and H. Horiuchi, Phys. Rev. C 60 (1999) 064607.
24. T. Furuta and A. Ono, [nucl-th/0305050].
25. A. Ono, S. Hudan, A. Chbihi, J.D. Frankland, Phys. Rev. C 66 (2002) 014603.
26. Y. Kanada-En’yo, M. Kimura, H. Horiuchi, Nucl. Phys. A 738 (2004) 3.
27. T. Neff and H. Feldmeier, Nucl. Phys. A 738 (2004) 357.
28. J. Pochodzalla et al., Phys. Rev. Lett. 75 (1995) 1040.
29. J.B. Natowitz et al., Phys. Rev. C 65 (2002) 034618.
30. Y.G. Ma et al., Phys. Rev. C 69 (2004) 031604.
31. J. Besprovany and S. Levit, Phys. Lett. B 217 (1989) 1.
32. D.R. Bowman et al., Phys. Rev. Lett. 67 (1991) 1527.
33. J. Hubele et al., Phys. Rev. C 46 (1992) 1577.
34. P. Désesquelles et al., Nucl. Phys. A 633 (1998) 547.
35. U. Milka et al., Z. Phys. A 346 (1993) 227.
36. S.P. Avdeyev et al., Eur. Phys. J. A 3 (1998) 75.
37. J. Cibor et al., Phys. Lett. B 473 (2000) 29.
38. D.S. Bracken et al., Phys. Rev. C 69 (2004) 034612.
39. A. Le Fèvre, M. Plozaiczak, V.D. Toneev, Phys. Rev. C 60 (1999) 051602.
40. W. Reisdorf et al., Phys. Rev. Lett. 92 (2004) 232301.
41. A. Le Fèvre et al., in: I. Iori, A. Moroni (Eds.), Proceedings of the XL1st International Winter Meeting on Nuclear Physics, Bormio, Italy, 2003, Ricerca Scientifica ed Educazione Permanente Suppl., vol. 120, Milano, 2003, p. 178.
42. N. Marie et al., Phys. Lett. B 391 (1997) 15.
43. A. Le Fèvre et al., Nucl. Phys. A 735 (2004) 219.
44. G.J. Kunde et al., Phys. Rev. Lett. 74 (1995) 38.
45. S. Pal, S.K. Samaddar, J.N. De, Nucl. Phys. A 608 (1996) 49.
46. S. Chikazumi, T. Maruyama, K. Niita, A. Iwamoto, Phys. Lett. B 476 (2000) 273.
47. C.B. Das, S. Das Gupta, Phys. Rev. C 64 (2001) 041601.
48. F. Gulminelli, Ph. Chomaz, Nucl. Phys. A 734 (2004) 581.
49. W. Reisdorf et al., Phys. Lett. B 595 (2004) 118.
50. X. Campi, H. Krivine, E. Plagnol, N. Sator, Phys. Rev. C 67 (2003) 044610.
51. S. Das Gupta and A.Z. Mekjian, Phys. Rev. C 57 (1998) 1361.
52. F. Gobet et al., Phys. Rev. Lett. 87 (2001) 203401.
53. D. Stauffer and A. Aharony, Introduction to percolation theory, Taylor and Francis, London, 1992.
54. A. Schütttauf et al., Nucl. Phys. A 607 (1996) 457.
55. P. Kreutz et al., Nucl. Phys. A 556 (1993) 672.
56. W. Bauer and A.S. Botvina, Phys. Rev. C 52 (1995) 1760.
57. M. Kleine Berkenbusch et al., Phys. Rev. Lett. 88 (2002) 022701.
58. X. Campi, Phys. Lett. B 208 (1988) 351.
59. F. Gulminelli and Ph. Chomaz, Phys. Rev. Lett. 82 (1999) 1402.
60. J.D. Frankland et al., nucl-ex/0404024.
61. M. Pichon et al., in: I. Iori, A. Moroni (Eds.), Proceedings of the XL1st International Winter Meeting on Nuclear Physics, Bormio, Italy, 2003, Ricerca Scientifica ed Educazione Permanente Suppl., vol. 120, Milano, 2003, p. 149.
62. M. D’Agostino et al., Phys. Lett. B 473 (2000) 219.
63. J.B. Elliott et al., Phys. Rev. Lett. 88 (2002) 042701.
64. X. Campi, H. Krivine, E. Plagnol, N. Sator, nucl-th/0406056.
65. M. D’Agostino et al., Nucl. Phys. A 734 (2004) 512.
66. O. Lopez, Nucl. Phys. A 685 (2001) 246c.
67. B. Borderie et al., Nucl. Phys. A734 (2004) 495.
68. W. A. Friedman, Phys. Rev. C 69 (2004) 031601.
69. G. A. Soulhotis et al., Phys. Rev. C 68 (2003) 024605.
70. M.B. Tsang et al., Phys. Rev. C 64 (2001) 054615.
71. A. Le Fèvre et al., nucl-ex/0409026.
72. the notation follows that originally chosen in Ref. [73]; alternatively $C_{\text{sym}}$ is frequently used for the same quantity.
73. J.P. Bondorf et al., Phys. Rep. 257 (1995) 133.
74. T.X. Liu et al., Phys. Rev. C 69 (2004) 014603.
75. Bao-An Li, Phys. Rev. Lett. 88 (2002) 192701.
76. V. Greco et al, Phys. Lett. B 562 (2003) 215.