Non-equilibrium Phase transitions in condensed matter physics

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Abstract

This paper gives a brief review of phase transition far from equilibrium, especially the universality classes of two main classes of non-equilibrium phase transitions. It also briefly point out the current conditions of the experimental study.

1. Introduction

This paper will give a brief review of the current progress of the study of non-equilibrium phase transitions. Non-equilibrium phenomena are such a broad subject that we can not include all the topics in this short review paper. So we will focus our attentions on the phase transitions far from thermal equilibrium in physical systems without covering biological systems and social events like traffic flows. Either we don't discuss the non-equilibrium quantum phase transitions and confine the paper to classical non-equilibrium phase transition.

In order to make a better connection between theoretical study and experimental study, we try to give some experimental results or phenomena for the theoretical models whenever it is possible.

A. Motivation

The study of non-equilibrium phase transitions is an intriguing field for both basic scientific interests and potential technical application. Although the features of equilibrium phenomena are relatively easier to be understood and have been extensively studied, besides biological systems, physical systems in Nature exist essentially at non-equilibrium state and "true" equilibrium phenomenon rather is an ideal concept. In contrast with phase transitions at thermal equilibrium which have been well studied to a large extent, especially under the frame of renormalization group methods, phase transitions out of equilibrium is far less understood, lacking a generalized theory. According to Schmittmann B, Zia RKP [1], we even can say, "to date, the theoretical development of nonequilibrium statistical mechanics is at a stage comparable to that of its equilibrium counterpart in the days before Maxwell and Boltzmann". Although some concepts in the modern theory of equilibrium phase transitions, like "universality", are so successful that we believe we can apply them to non-equilibrium phase transitions [2, 3], new physics could be expected to emerge. Yet it might also be possible that a general theory could not be found for non-equilibrium, like Goldenfeld and Kadanoff's opinion[4] "there no general laws for complexity…Maybe physics studies will become more like human experience".

Besides the scientific interests, on the other hand, the study of non-equilibrium phase transitions can inspire new methods in materials manufacturing and processing and other interesting methods in nano technology as it has done, like pattern formation [5], nonequilibrium structures of monomolecular organic films [6], beam-induced transformations and many others [7]. In fact, firstly, new steady states belonging to the system driven out of equilibrium can exhibits new intriguing or complex structures and hence may have new properties or better properties than those at equilibrium. While discovering new steady phases and structures of a system is exciting, theoretic understanding of phase transitions out of equilibrium can also help clarify the control parameters and the underlying mechanism and hence help to improve and develop new manufacturing methods. For example, self-assembly or self-organization is a hot topic for nanotechnology [8-12]. Here we need to point out that self-assembly and self-organization are often used as synonymous with each other in literature. To be more precise, however, according to John and Bar [13], self-organization is a phenomenon far away from thermal equilibrium while self-assembly occurs at equilibrium.

Moreover, the study of non-equilibrium phase transitions can even benefit the study of some social events, like traffic problems and population models [2].

B. At or near thermodynamic equilibrium

Phase transitions at equilibrium were initially described by thermodynamics and then were interpreted in statistical mechanics. And Landau used the concept of order parameter to construct the Landau free energy, which is essentially a mean field methods. Finally, the theoretical understanding of phase transitions at equilibrium is accomplished in the fame of renormalization group [14, 15].

Strictly speaking, dynamical systems are out of equilibrium if detailed balance is violated [16]. However, if the system is near or close to equilibrium, on certain scales the concepts of equilibrium physics can still work for then, one example of which is a steam engine[16]. These systems can be treated using the so called local equilibrium approximation [17]. One can use the mater equations and Langevin equations to study the dynamics near equilibrium. And a review about the fluctuation-dissipation theorem and dynamic critical phenomena was given by Hohenberg and Halperin [18].

C. Far from thermal equilibrium

The classification of systems far equilibrium is more subtle. According to Odor, nonequilibrium can be classified into two categories [2]: (1) "systems that have a Hermitian Hamiltonian and whose stationary states are given by the proper Gibbs-Boltzmann distribution"; (2) "systems without a Hermitian Hamiltonian defined by transition rates, which do not satisfy the detailed balance condition". And the second class has two subclasses. One has no equilibrium counterpart, hence being called "genuine nonequilibrium classes", while the other is refer to as "out-of-equilibrium classes". This sounds like a rather theoretical classification. In fact, Odor's classification is consistent with that given by Marro and Dicjman [19]. In their book, nonequilibrium problems can be group in three broad categories. The first category is the same as the first class of Odor's definition. The system is initially prepared far from the stationary state and then approaches equilibrium state. However sometimes it may not reach a true equilibrium [2]. Many systems, like phase ordering systems, glasses and spin glasses belong to this class. The second category which is driven far from equilibrium roughly corresponds to the "out-of-equilibrium class" defined by Odor. The difference is that systems belonging to "out-of-equilibrium class" may not have a steady state [2]. The rest non-equilibrium systems have no equilibrium analog and hence are termed as "genuine non-equilibrium systems" by Odor [2].

In this paper, we are interested in the phase transitions of the later two kinds of non-equilibrium systems and will not discuss the first class systems which are approaching the equilibrium. So, for simplicity, we will call the later two here as "out-of-equilibrium classes" and "genuine nonequilibrium classes".

Before we move on, it need to pointed out that the review papers of Odor [2], Hinrichsen[3, 16] and Lubeck [21] and the book of Marro and Dicjman [19] deal with phase transitions of "genuine non-equilibrium classes" or cover both topics while the reviews of Racz [17] and the book of Schmittmann and Zia [20] are more related with the so-called "out-of-equilibrium classes".

2. Theoretical studies

As we have mentioned, comparing with the theory of phase transition at thermal equilibrium, the theoretical understanding of non-equilibrium phase transition just begins. However, it is believe that the concepts like scaling and universality which are very successful for equilibrium model can be still apply to the study of non-equilibrium phase transition [2, 16, 21]. In the recent paper of Odor, a systematical review of most of the explored university classes for non-equilibrium lattice systems is provided [2]. This classification is useful because it's useful for experimentalists or researchers from other fields can "identify their models and find corresponding theories". The enhanced communications between different communities or between experimentalists and theorists can in turn benefit the advance of our theoretical understanding, especially for the current circumstance that few experiments have been done to test theory results [16].

A. Universality classes

The discussion in this part is mainly based on several recent review papers [2, 16, 21]. Firstly, the "out-of-equilibrium class" systems include four universality classes, namely, Ising classes, Potts classes, XY model classes and O(N) symmetric model classed. It is apparent that they have their equilibrium counterparts [2]. In fact, here we can obtain a non-equilibrium model, which has no Hermitian Hamiltonian and no equilibrium Gibbs state, by two ways [2]. One is combine different competing dynamics to the original model. For example we can add the system two reservoirs with different temperature. The other way is to create a current by apply external fields. The competing dynamics in general break the detailed balance. For the details one can refer to Odor's paper. Here we highlight one interesting model—the driven diffusive systems [1, 19, 20], which is an important example of non-equilibrium ordering. The prototype of a "driven diffusive system" is [1]: imaging "a two dimensional lattice on the surface f a cylinder and applying a linearly increasing magnetic field down the cylinder axis". Then one can get a current in the steady state if the particle is charged. As an example, Figure 1shows a phase diagrams of a driving diffusive model [1].

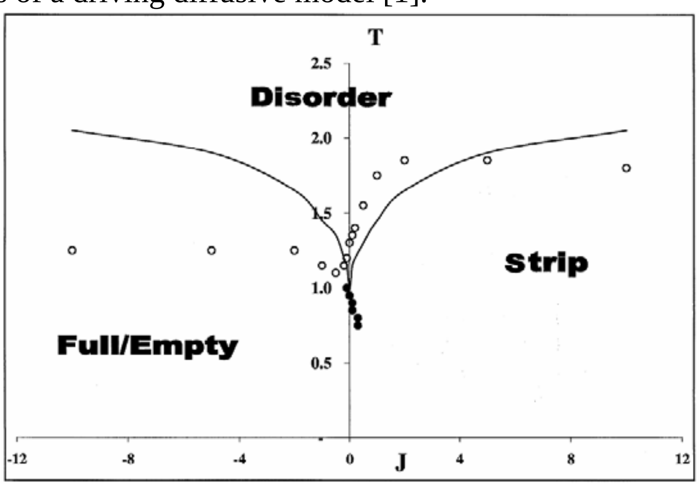

Fig.1 Phase diagrams for the bi-layer Ising lattice gas. Solid lines are second-order transitions in the equilibrium case. Open/solid circles are continuous/discontinuous transitions in the driven case.[1]

In his paper, Odor actually put emphasis on the discussion of the universality classes of the "genuine nonequilibrium classes" systems, which can not be obtained in dynamical generalizations of equilibrium systems [2]. We can describe these models using a master equation and the deduced stochastic action or Langevin equation. The best know examples are reaction-diffusion systems with order-disorder transitions, which can be encountered in the models of catalysis, enzyme biology, population and epidemics [2]. There are six universality classes listed, including directed-percolation classes, dynamical percolation classes, voter model classes and so on. However, there are some other nonequilibrium phase transitions in lattice gases with currents, in traffic models and some other model, the universality classed of which have no been studied [2]. Here for the "genuine nonequilibrium classes" systems, we want to highlight an important universality class of absorbing state transitions--the directed-percolation classes, which is important like the Ising model in equilibrium statistical physics [3, 16]. We can illustrate this type of phase transitions by considering a simple model for the spreading of an infectious disease where infected individuals may either recover by themselves or infect their nearest neighbours [3]. Varying the infection rate, one can find that in the limit of large system sizes the two regimes of survival and extinction of the spreading of disease are separated by a continuous phase transition [3]. The simple model is illustrated in Fig2a. And a phase diagram for directed percolation with immunization is shown in Fig2b.

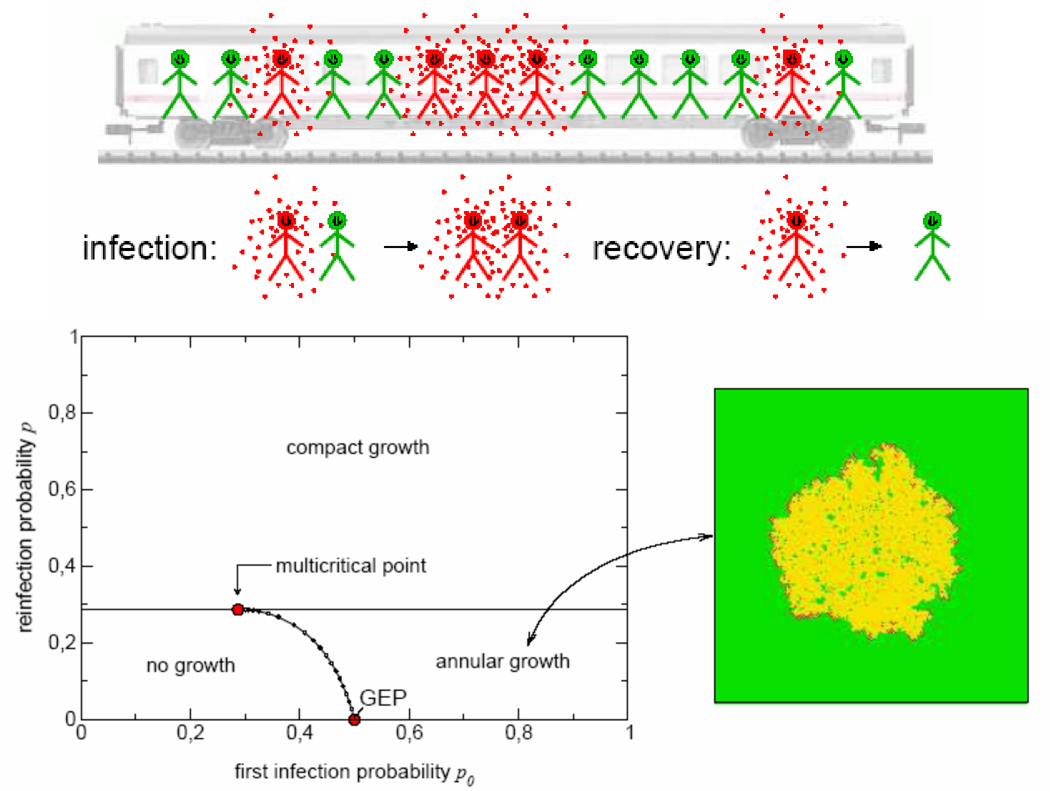

Fig.2. (a) Directed percolation as a caricature of an epidemic process; (b) Phase diagram for directed percolation with immunization (see text). The right panel shows spreading by annular growth with fresh (green), active (red), and immune (yellow) individuals.

Beyond the above classification of the universality classes, Lubeck [21] addresses the importance of another important concept-- scaling function. He proposed that besides the values of the critical exponents, universal scaling functions are a very sensitive and accurate tool to identify different universality classes [21].

B. Other theoretical studies

Besides the above study, other methods have also been exploited. In this section, we will briefly point out a few other methods.
The concept of Yang-Lee Zeros is applied to the study of non-equilibrium phase transitions, including driven diffusive systems and reaction-diffusion systems [16, 22].
Stinchcombe in his review of the theory of non-equilibrium systems mention the method that tries to map the stochastic non-equlibrium to quantum many-body systems, which might allow the use of some standard techniques in quantum mechanics[23].
Aranson and Kramer recently give a comprehensive review of various dynamic phenomena described by the complex Ginzburg-Landau equation [24]. And it is expected to gain some insight from the complex Ginzburg-Landau equation for the study of non-equilibrium phenomena [24].
In the viewpoint of synergetic, Olemskoi and Klepikov [25] describe the spatiotemporal pattern in non-equilibrium systems in a unified way using the concept of order parameter, conjugate field and control parameter.
Casas-Vazquez and Jou[26] recently give a comprehensive review about the study of the concept of temperature in non-equilibrium states. To meet the need of computer simulation, new experiments, and study of nanoscale systems, new concepts of temperature in non-equilibrium conditions have been proposed from both macroscopic and microscopic basis [26].

3. Experimental studies

Although there is a large variety of phenomenological non-equilibrium phase transitions in nature, there is few experiments have been conducted to test the universality classes given by theory studies. For example, till now no experiments produced the exponents of the important directed-percolation classes in a reliable way [16]. However, Hinrichsen has proposed some possible experimental realizations [27].

On the one hand, there are many recent developments in the study of non-equilibrium phase transitions in the lattice models and need the experimental confirmation. On the other hand, the experiments have not been conducted for test the theories although there are intense experiment activities conducted in different fields.

For example, pattern formation out of thermal equilibrium attracted a lot of attention of experiments. A comprehensive review can be seen in Cross and Hohenberg's paper[5]. And there are a lot of groups studying self-assembly and self-organization at or far from equilibrium [28, 29]. Here we just mentions a few examples and do not discuss them in detailed since there is still a lack of direct connection between the experiments and theory studies.

4. Conclusion

In conclusion, in this paper we briefly review the current developments of non-equilibrium phase transitions, especially the theoretical studies. We also point out the current conditions of the experimental study.

References

[1] Schmittmann B, Zia RKP, "Driven diffusive systems. An introduction and recent developments", PHYSICS REPORTS-REVIEW SECTION OF PHYSICS LETTERS 301 (1-3): 45-64 JUL 1998
[2] Odor G, "Universality classes in nonequilibrium lattice systems", REVIEWS OF MODERN PHYSICS 76 (3): 663-724 Part 1 JUL 2004
[3] Hinrichsen H, "Non-equilibrium critical phenomena and phase transitions into absorbing", ADVANCES IN PHYSICS 49 (7): 815-958 NOV 2000
[4] Goldenfeld N and Kadanoff LP, "Simple lessons from complexity", SCIENCE, 284, 87-89, APR 1999
[5] Cross MC and Hohenberg PC, "Pattern Formation outside of Equilibrium", REVIEWS OF MODERN PHYSICS 65, 851, 1993
[6] Mikhailov AS and Ertl G, "Nonequilibrium structures in condensed systems", SCIENCE, 272, 1596, 1996
[7] Ma E, Atzmon M, et al., eds., *Phase Transformations and systems driven far from equilibrium*, Materials Research Society Symposium Proceedings, vol 481, 1998
[8] Whitesides GM and Grzybowski B, "Self-assembly at all scales", SCIENCE, 295, 2418, 2002
[9] GHONIEM NM, et al., "Theory and experiment of nanostructure self-organization in irradiated materials", Journal of Computer-Aided Materials Design, 8, 1, 2002.
[10] Teichert C, "Self-organization of nanostructures in semiconductor heteroepitaxy", Physics Reports 365, 335, 2002
[11] Stangl J, et al.,"Structural properties of self-organized semiconductor nanostructure", Reviews of modern physics, 76, 725, 2004
[12] Misteli T, "The concept of self-organization in cellular architecture", Journal of Cell Biology 155, 181, 2001
[13] John K and Bar M, "Alternative mechanisms of structuring biomembranes: Self-assembly versus self-organization", PHYSICAL REVIEW LETTERS, 95, 198101, 2005
[14] Goldenfeld N, *Lectures on Phase Transitions and the Renormalization Group*, Frontiers in Physics, vol 85, Perseus Publishing, 1992
[15] Pelissetto A, Vicari E, "Critical phenomena and renormalization-group theory", PHYSICS REPORTS-REVIEW SECTION OF PHYSICS LETTERS 368 (6): 549-727 OCT 2002
[16] Hinrichsen H, "Non-equilibrium Phase transitions", Lecture notes for the international summer school on problems in statistical physics XI, Leuven, Belgium, September 2005, the web link: http://fys.kuleuven.be/vsm/FPSPXI/notes/Hinrichsen.pdf
[17] Racz Z, "Nonequilibrium Phase transitions", Lecture notes for Troisieme Cycle Lectures, Jan 2004, Lausanne; the web links: http://cgl.elte.hu/~racz/noneq-lect.html

[18] Hohenberg PC and Halperin BI, "Theory of dynamic critical phenomena", REVIEWS OF MODERN PHYSICS, 49, 435, 1977

[19] Marro J and Dicjman R, *Nonequilibrium Phase Transitions in Lattice Models* (Cambridge University Press, Cambridge, 1999)

[20] Schmittmann B, Zia RKP, 1995, "Statstical Mechanics of Driven Diffusive Systems", *Phase Transitions and Critical Phenomena*, Vol. 17, edited by C. Domb and J.L. Lebowitz (Academic Press, U.K., 1995)

[21] Lubeck S, "Universal scaling behavior of non-equilibrium phase transitions", INTERNATIONAL JOURNAL OF MODERN PHYSICS B 18 (31-32): 3977-4118 DEC 30 2004

[22] Blythe RA, Evans MR, "The Lee-Yang theory of equilibrium and nonequilibrium phase transitions", BRAZILIAN JOURNAL OF PHYSICS 33 (3): 464-475 SEP 2003

[23] Stinchcombe R, "Stochastic non-equilibrium systems", ADVANCES IN PHYSICS 50 (5): 431-496 JUL 2001

[24] Aranson IS, Kramer L, "The world of the complex Ginzburg-Landau equation", REVIEWS OF MODERN PHYSICS 74 (1): 99-143 JAN 2002

[25] Olemskoi AI, Klepikov VF, "The theory of spatiotemporal pattern in nonequilibrium systems", PHYSICS REPORTS-REVIEW SECTION OF PHYSICS LETTERS 338 (6): 571-677 NOV 2000

[26] Casas-Vazquez J, Jou D, "Temperature in non-equilibrium states: a review of open problems and current proposals", REPORTS ON PROGRESS IN PHYSICS 66 (11): 1937-2023 NOV 2003

[27] H. Hinrichsen, On possible experimental realizations of directed percolation, Braz. J. Phys. 30, 69-82, 2000

[28] 2. Whitesides GM and Grzybowski B, "Self-assembly at all scales", Science, 295, 2418, 2002

[29] Schreiber F, "Structure and growth of self-assembling monolayers", PROGRESS IN SURFACE SCIENCE 65 (5-8): 151-256 NOV-DEC 2000