論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Nonequilibrium phase transitions in driven vortex matter: the reversible-irreversible transition, dynamical ordering, and Kibble-Zurek mechanism
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出典(和文)	学位:博士(理学), 学位授与機関:東京工業大学, 報告番号:甲第12314号, 授与年月日:2023年3月26日, 学位の種別:課程博士, 審査員:大熊 哲,藤澤 利正,平原 徹,賀川 史敬,村上 修一
Citation(English)	Degree:Doctor (Science), Conferring organization: Tokyo Institute of Technology, Report number:甲第12314号, Conferred date:2023/3/26, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	論文要旨
Type(English)	Summary

（博士課程）
Doctoral Program

論 文 要 旨

THESIS SUMMARY

系・コース： Department of, Graduate major in	物理学 系 / 物理学 コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of （ 理学 ）
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		指導教員（副）： Academic Supervisor(sub)	

要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

In recent years, there has been a growing interest in nonequilibrium phase transitions that are outside the framework of conventional equilibrium physics. Compared to equilibrium phase transitions, the study on the nonequilibrium phase transitions is still in its infancy and more exploration is needed. To progress our understanding, in this thesis, we experimentally investigate two kinds of nonequilibrium phase transitions in externally driven many-particle systems by ac and dc forces. As a well-controlled many-particle system, we use a superconducting vortex system of amorphous Mo_xGe_{1-x} films. The amorphous Mo_xGe_{1-x} film is a conventional superconductor with random point pinning, thus free from complicated effects that might affect transport properties and vortex dynamics, such as special band structures, specific crystal symmetry, and edge contamination effects. Therefore, our findings are of fundamental and general importance, and universal.

First, we study a reversible-irreversible transition (RIT) induced by ac drive. It is known that with an increase in shear amplitude d, a periodically sheared particle (vortex) system undergoes the transition from a time-periodic reversible phase to a diffusive irreversible phase accompanied by a diverging relaxation time $\tau(d)$. In this work, we study RIT driven by particle (vortex) density as well as shear amplitude. We perform shearing experiments by changing the magnetic field (vortex density) B under the fixed d and again observe the power-law divergence of $\tau(B)$ at RIT. We obtain two critical exponents and find that the critical behavior of RIT is identical irrespective of the control parameters, B and d. Both types of RIT belong to the same universality class as two-dimensional directed percolation (DP). We also find two distinct flow regimes in the reversible phase, corresponding to a collisionless point-reversible state and a loop-reversible state with vortex-vortex collisions for the first time. Surprisingly, the same critical behavior of RIT is observed at the same critical point in either reversible regime. We also conduct shearing experiments over broad velocity regions and find that the dynamics of RIT is described in terms of the potential-energy landscape perspective, which has been previously used solely in equilibrium systems.

Next, we investigate a dynamical ordering transition induced by dc drive for a many-particle system driven over a disordered substrate. It has been shown theoretically that with an increase in the dc drive, the system changes from a disordered plastic flow to an anisotropic smectic flow with transverse periodicity, and from the smectic flow to an isotropic moving Bragg glass. Despite many theoretical studies, the dynamical ordering from the plastic flow to the smectic flow has not been verified by any experiment because of lack of suitable experimental methods. To acquire the information on the transverse configuration of the vortex flow, we prepare a cross-shaped sample in which mutually perpendicular driving forces can be applied to the vortex system. Three experimental methods are developed: two-step measurements of transient voltage, transverse mode locking (ML) resonance, and transverse current-voltage (force-velocity) measurements. In the two-step measurement, the vortices were first driven in one (longitudinal) direction by dc current and frozen in the steady state. Then, we examine the transverse response of the frozen vortices. As a result, we observe the dynamical ordering from the plastic flow to the anisotropic smectic flow with an increase in the driving current. In the ML experiments, we observe larger signals of transverse ML than those of longitudinal ML, which provides convincing evidence of the moving smectic phase with higher transverse order than the longitudinal one. From the transverse current-voltage measurements, we examine the transverse response of longitudinally flowing vortices. We find a continuous change of the transverse response from glasslike to liquidlike behaviors at a well-defined longitudinal current, which corresponds to the dynamical ordering current from the plastic flow to smectic flow. We also find the scaling collapse of the transverse current-voltage curves to a universal scaling function, providing direct evidence of the second-order dynamical ordering transition.

Finally, we test the applicability of the Kibble-Zurek (KZ) mechanism to the nonequilibrium phase transition, using the dynamical ordering transition from the plastic flow to smectic flow. We examine the configurational order of vortices in the course of dynamical ordering with various quench rates (sweep rates of the driving current) and find a power-law scaling of defect density with the quench rate, consistent with the KZ prediction. We also find in the ordered phase the crossover from the impulse regime around the critical point where critical slowing down occurs to the adiabatic regime where the time evolution of the system resumes, which is also the key prediction by the KZ mechanism. The scaling exponents obtained in this work are, within errors, consistent with those reported in the recent simulation and theoretical values for the one-dimensional DP universality class. While the KZ mechanism has been extensively studied for equilibrium phase transitions since 1970's, our results provide first experimental evidence for the applicability of the KZ mechanism to the nonequilibrium phase transition.

Our results indicate that both RIT and the dynamical ordering transition belong to the DP universality class that is the fundamental class of nonequilibrium phase transitions, and hence our findings will be generalized to other nonequilibrium systems and stimulate research in them.