Dynamical phase transitions in dissipative strongly-interacting atomic ensembles

Carlos Pérez-Espigares[1], Juan P. Garrahan[1], Igor Lesanovsky[1], and Ricardo Gutiérrez[1,2]
[1]School of Physics and Astronomy and Centre for the Mathematics and Theoretical Physics of Quantum Non-equilibrium Systems, University of Nottingham, Nottingham NG7 2RD, UK
[2]Complex Systems Group & GISC, Universidad Rey Juan Carlos, 28933 Móstoles, Madrid, Spain

The physics of highly-excited (Rydberg) atoms is governed by blockade interactions that hinder the excitation of atoms in the proximity of a previously excited one. In the limit of strong dephasing, the evolution is given by a classical master equation with configuration-dependent rates for transitions between the ground state and the excited state [1]. Those rates contain a single parameter R, which gives the length of the blockaded region around an excited atom [2]. From this blockade, which is reminiscent of the excluded volume effects of soft condensed matter, a space-time dynamic heterogeneity similar to what is observed in the dynamics of glass-forming systems arises.

We establish theoretically the existence of a glassy dynamical regime in a dissipative Rydberg gas, which originates from a phase coexistence at a first-order phase transition, see Fig. 1. In our analysis, we consider the activity per unit time $k = K/t$, where K counts the number of transitions in a trajectory of duration t, as the order parameter. The transition occurs between an active phase of low density in which dynamical processes take place on short timescales, and an inactive phase in which excited atoms are dense and the dynamics is highly arrested. The control parameter conjugate to k is the field s, which "tilts" the systems towards more (if $s < 0$) or less (if $s > 0$) active dynamics. The inactive space-time regions that appear as the transition is approached from the active side, are "bubbles of inactivity", corresponding to a manifestation in trajectories of fluctuations associated with the dynamical first-order transition (cf., e.g., vapor bubbles in a liquid near liquid-vapor coexistence). The natural dynamics ($s = 0$) lies precisely at the coexistence point between the two phases.

We probe the transition through the numerical diagonalization of the relevant dynamical generator for finite sizes. Furthermore, a mean-field approach gives us analytical insight into the transition, and allows us to explore the relevant phase diagram as function of the blockade length R, and also the decay rate κ of the excited state, which is a parameter of great experimental relevance. For small R, the transition is shown to end at a critical point beyond which a sharp crossover is observed, see Fig. 2. A sufficiently strong decay also smooths out the transition, the critical point corresponding to a value of κ that is experimentally accessible in modern cold atoms experiments.

Not only have we unveiled a dynamical phase transition from which a previously observed complex dynamics stems, but our results will also be useful in the development of protocols for engineering Rydberg interactions with the aim of attaining specific dynamical regimes.

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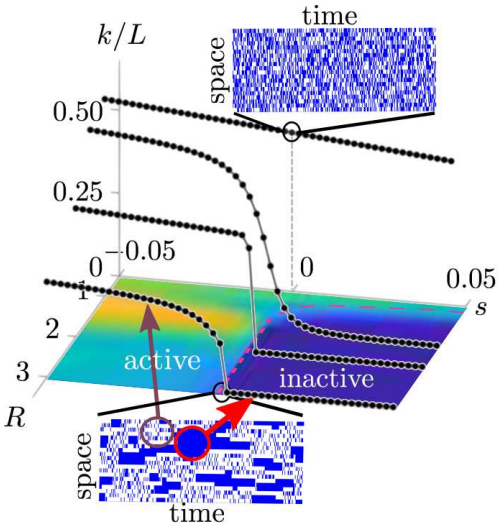

Fig. 1. Dynamical first-order phase transition underlying the dynamics of dissipative Rydberg gases. Activity $k(s)/L$ as a function of the tilting field s and the blockade length R. Representative trajectories for $R = 1$ (upper panel) and $R = 3$ (lower panel) are displayed. Blue and white indicate excited and ground state atoms, respectively.

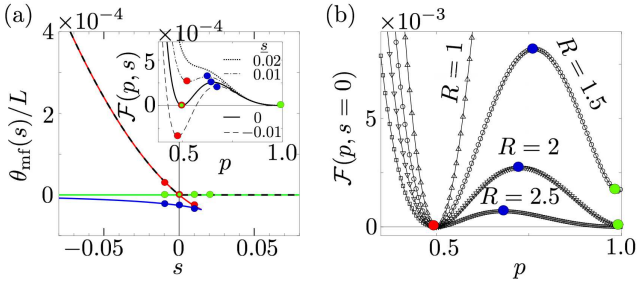

Fig. 2. Mean-field analysis of the dynamical phase transition. (a) Negative variational free energy $-\mathcal{F}(p, s)$ for $R = 3$ evaluated at the stationary points including two maxima (red and green lines) and one minimum (blue line), and normalized SCGF $\theta_{\rm mf}(s)/L$ (dashed black line). Inset: Variational free energy $\mathcal{F}(p, s)$ as a function of p in the neighborhood of $s = 0$. (b) Variational free energy $\mathcal{F}(p, s = 0)$ for values of R around the critical value for a transition at $s = 0$.