Nonthermal control of excited quantum materials following an interaction quench

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Quantum material systems upon applying ultrashort laser pulses provide a rich platform to access excited material phases and their transformations that are not entirely like their equilibrium counterparts. The addressability and potential controls of metastable or long-trapped out-of-equilibrium phases have motivated interests both for the purposes of understanding the nonequilibrium physics and advancing the quantum technologies. Thus far, the dynamical spectroscopic probes eminently focus on microscopic electronic and phonon responses. For characterizing the long-range dynamics, such as order parameter fields and fluctuation effects, the ultrafast scattering probes offer direct sensitivity. Bridging the connections between the microscopic dynamics and macroscopic responses is central toward establishing the nonequilibrium physics behind the light-induced phases. Here, we present a path toward such understanding by cross-examining the structure factors associated with different dynamical states obtained from ultrafast electrons scattering, imaging, and modeling[1]. We give the basic theoretical framework on describing the non-equilibrium scattering problems and briefly describe how such framework relates to the out-of-equilibrium phenomena. We give effective models outlining the emergences of nonthermal critical points, hidden phases, and non-equilibrium relaxational responses from vacuum-suspended rare-earth tritellurides[2], tantalum disulfides[3] thin films, and vanadium dioxide nanocrystalline materials[4] upon light excitations. Rich scenarios as those involve competitive broken-symmetry orders, vestigial orders, and the intertwined ground states could be identified, leading to intriguing nonequilibrium states and hidden phases. Facing the challenging issues with the multiscale dynamics, the technological aspects of the multi-messenger approaches based on a unified framework of ultrafast electron microscopy system will also be discussed. Our goals here are twofold. One is to understand the still mysterious hidden phase phenomena in nonequilibrium quantum materials[5]. The second is to explore the ideas of using the light-excited quantum material as a platform to study the nonequilibrium physics.

References:

[1] X. Sun, S. Sun, C.-Y. Ruan, Toward nonthermal control of excited quantum materials: framework and investigations by ultrafast electron scattering and imaging, Comptes Rendus. Physique, Online first (2021), pp. 1-59 (2021).
[2] F. Zhou, J. Williams, S. Sun, C.D. Malliakas, M.G. Kanatzidis, A.F. Kemper, C.-Y. Ruan, Nonequilibrium dynamics of spontaneous symmetry breaking into a hidden state of charge-density wave, Nature Communications, 12 (2021) 566.
[3] T.-R.T. Han, F. Zhou, C.D. Malliakas, P.M. Duxbury, S.D. Mahanti, M.G. Kanatzidis, C.-Y. Ruan, Exploration of meta-stability and hidden phases in correlated electron crystals visualized by femtosecond optical doping and electron crystallography, Science Advances, 1 (2015) e1400173.
[4] Z. Tao, F. Zhou, T.-R.T. Han, D. Torres, T. Wang, N. Sepulveda, K. Chang, M. Young, R.R. Lunt, C.-Y. Ruan, The nature of photoinduced phase transition and metastable states in vanadium dioxide, Scientific Reports, 6 (2016) 38514.
[5] C.-Y. Ruan, Hidden in plain light, Nature Physics, (2021).