Superradiant matter: A new paradigm to explore dynamic phase transitions

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If you put water in the freezer to make ice, you trigger a dynamic phase transition.

Physicists gave that fancy name to a process which takes a system across a phase transition in a realistic time, to distinguish it from the hypothetical process which goes across the transition infinitely slow. This latter, hypothetical case is discussed in any college textbook, while its dynamic, and therefore realistic, counterpart continues to pose fundamental questions. It matters how fast you 'quench' the system: If you cool water below its freezing point slowly, you'll get a big, pretty-looking ice crystal. If you flash freeze it, you'll get a poly-crystalline solid.

Furthermore, there are phenomena like supercooling, in which you cool the water below its freezing point, but the water remains liquid, if there are too few defects to seed crystallization. You therefore observe a delay until the water adjusts to the new, below-freezing temperature. These phenomena are not limited to the ice tray in your kitchen, but phase transitions are a key ingredient of our universe. In the life-sustaining water cycle of our earth the water undergoes several transitions alone, but beyond that the nucleogenesis and the condensation of the Higgs field following the Big Bang are dynamic phase transitions that made up the structure and the building blocks of matter itself.

In a new approach to understand dynamic phase transitions, now reported in the *Proceedings of the National Academy of Sciences* (*PNAS*), a joint experimental and theoretical effort was undertaken by a team of scientists lead by Andreas Hemmerich and Ludwig Mathey of the University Hamburg, using a novel type of quantum matter in a so-called superradiant state. 'We are used to atoms emitting light, and we are used to using light to manipulate atoms, but here we have created a self-organized, hybrid light-atom matter by putting ultracold atoms between two extremely high reflecting mirrors', explains lead author Jens Klinder. Photons scattered by the atoms, irradiated by laser beams, are absorbed and re-emitted by other atoms in the atomic cloud which forces the atoms to spontaneously order themselves as a crystal. It is this intriguing emergence of superradiant self-organization that the authors used to investigate the nature of dynamic phase transitions.

'We observe a delay of the onset of superradiance that is reminiscent of supercooling', explains Andreas Hemmerich. This delay seems to follow a universal hypothesis, that was first formulated by cosmologist Tom Kibble and later expanded to condensed matter systems by Wojciech Zurek. 'But the intriguing twist in this experiment is that a coupling to the environment is introduced in a very controlled way', says Ludwig Mathey. While the ideas of Kibble and Zurek have been studied in perfectly isolated systems before, here this artificial feature of the system has been removed. By taking the coupling to the environment into account, this work takes the ideas of Kibble and Zurek closer to the real world, and expands their scope. From understanding imperfect crystallization in a realistic system to understanding defects in the Higgs fields, this experiment and its theoretical understanding gives the first clue.

More information: Dynamical phase transition in the open Dicke model , Jens Klinder, Hans Keßler, Matthias Wolke, Ludwig Mathey, and Andreas Hemmerich *PNAS*.2015.112.(11).3290-3295 , www.pnas.org/content/112/11/3290

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