Cosmology in the lab using laser-cooled ions

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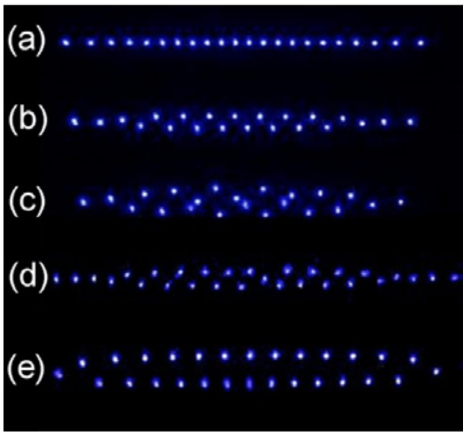
Application Note

An international team of scientists has probed the nature of the symmetry-breaking phase transitions that began the process of creating our universe – the Kibble-Zurek mechanism. Most cosmological scientists agree that within less than a billionth of a second of the Big Bang, the young universe had to 'decide' which new state to adopt and, everywhere that individual areas could not communicate their decisions to each other, topological defects occurred that led to the creation of the galaxies and solar systems we see today.

The Big Bang is not an experiment that can be repeated. However, the multinational team working with Dr. Tanja Mehlstäubler of the Physikalisch-Technische Bundesanstalt (PTB) in Germany has demonstrated atomic-scale topological defects under controlled laboratory conditions for the first time. They used laser-cooled ions in so-called "ion Coulomb crystals" to optically detect errors in the spatial structure caused by the breakdown of symmetry when the particles were unable to communicate with each other. Key to the detection system was the performance of an iXon 897 EMCCD camera from Andor.

Reporting their results in Nature Communications, the team from PTB, Los Alamos National Laboratory, the University of Ulm, and the Hebrew University of Jerusalem trapped Ytterbium ions in radio-frequency ion traps at ultra-high vacuum and laser-cooled them down to a few milli-Kelvin. The positively-charged ions repel each other inside the trap and, at such ultra-low temperatures, take on a crystalline structure – linear (a), two-dimensional zigzag (b) or three-dimensional helix (c). However, if the parameters of the trap enclosure are then varied faster than the speed of sound in the crystal, irregularities occur while the ions seek a new equilibrium (d and e).



Ytterbium ions in an ion Coulomb crystal as the ionized atoms fluoresce in the laser light. The distance between the ions is approx. 10 μm to 20 μm. In the upper rows, different symmetrical ion arrangements (phases) are encountered in the central area of the Coulomb crystal: (a) linear, like a string of pearls (symmetrical to the rotational axis); (b) two-dimensional in zigzag (Z2 symmetry), and (c) as a three-dimensional helix. If, however, a fast transition from one phase to another is induced, irregularities occur: (d) localized defect between two areas which are actually symmetrical, and (e) extended defect in which the ions slowly change from one zigzag orientation to its mirror symmetry.

The following movies present the phase transitions in Coulomb crystals: movie1.mp4, movie2.mp4, movie3.mp4.

The scientists from Germany, USA, and Israel have shown for the first time that the Kibble-Zurek mechanism can be demonstrated in a relatively simple optical experiment using laser-cooled ion Coulomb crystals. The resulting topological defects depend on the speed at which changes occur and the spontaneous re-orientation of the Coulomb crystal follows the same rules as those describing the early universe after the Big Bang. Capturing these topological defects in the laboratory opens up new investigational possibilities for quantum phase transitions and detailing the non-equilibrium dynamics of complex systems.

References
Pyka, K. et al. Topological defect formation and spontaneous symmetry breaking Nat. Commun. 4, 2291 (2013)
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