Matter at extreme conditions of very high temperature and pressure turns out to be remarkably simple and universal

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Scientists at Queen Mary University of London have made two discoveries about the behavior of "supercritical matter"—matter at the critical point where the differences between liquids and gases seemingly disappear.

While the behavior of matter at reasonably low temperature and pressure was well understood, the picture of matter at high temperature and pressure was blurred. Above the critical point, differences between liquids and gases seemingly disappear, and the supercritical matter was thought to become hot, dense and homogeneous.

The researchers believed there was new physics yet to be uncovered about this matter at the supercritical state.

By applying two parameters—the heat capacity and the length over which waves can propagate in the system, they made two key discoveries. First, they found that there is a fixed inversion point between the two where matter changes its physical properties—from liquid-like to gas-like. They also found that this inversion point is remarkably close in all systems studied, telling us that the supercritical matter is intriguingly simple and amenable to new understanding.

As well as fundamental understanding of the states of matter and the phase transition diagram, understanding supercritical matter has many practical applications; hydrogen and helium are supercritical in gas giant planets such as Jupiter and Saturn, and therefore govern their physical properties. In green environmental applications, supercritical fluids have also proved to be very efficient at destroying hazardous wastes, but engineers increasingly want guidance from theory in order to improve efficiency of supercritical processes.

Kostya Trachenko, Professor of Physics at Queen Mary University of London, said, "The asserted universality of the supercritical matter opens a way to a new physically transparent picture of matter at extreme conditions. This is an exciting prospect from the point of view of fundamental physics as well as understanding and predicting supercritical properties in green environmental applications, astronomy and other areas.

"This journey is ongoing and is likely to see exciting developments in the future. For example, it invites the question of whether the fixed inversion point is related to conventional higher-order phase transitions? Can it be described by using the existing ideas involved in the phase transition theory, or is something new and quite different needed? As we push the boundaries of what is known, we can identify these new exciting questions and start looking for answers."

Methodology

The main problem with understanding supercritical matter was that theories of gases, liquids and solids were not applicable. It remained unclear what physical parameters would uncover the most salient properties of the supercritical state.

Armed with earlier understanding of liquids at lower temperature and pressure, researchers used two parameters to describe the supercritical matter.

1. The first parameter is the commonly used property: this is the heat capacity showing how efficiently the system absorbs heat and containing essential information about the system's degrees of freedom.

2. The second parameter is less common: this is the length over which waves can propagate in the system. This length governs the phase space available to phonons. When this length reaches its smallest value possible and becomes equal to the interatomic separation, something really interesting happens.

The scientists found that in terms of these two parameters, the matter at extreme conditions of high pressure and temperature becomes remarkably universal.

This universality is two-fold. First, the plot of heat capacity vs wave propagation length has a striking fixed inversion point that corresponds to the transition between two physically different supercritical states: liquid-like and gas-like states. On crossing this inversion point, the supercritical matter changes its key physical properties. The inversion point importantly serves as an unambiguous way to separate the two states—something that has occupied the minds of scientists for some time.

Second, the location of this inversion point is remarkably close in all types of systems studied. This second universality is notably different to all other transition points known. For example, two of these transition points—the triple point where all three states of matter (liquid, gas, solid) co-exist and the critical point where the gas-liquid boiling line ends—are different in different systems. On the other hand, the same inversion point in all systems at extreme supercritical conditions tells us that the supercritical matter is intriguingly simple.

Uncovering and proving this simplicity is the main result of the paper, "Double universality of the transition in the supercritical state," published in *Science Advances*.

More information: C. Cockrell et al, Double universality of the transition in the supercritical state, *Science Advances* (2022). DOI: 10.1126/sciadv.abq5183. www.science.org/doi/10.1126/sciadv.abq5183

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