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Title: The critical endpoint in QCD thermodynamics with heavy quarks

Abstract:

The strongly interacting quark gluon plasma can show similar critical behaviour to heated ferromagnets. This criticality was studied by Wuppertal scientists with a short-cut in theory space where numerical simulations are feasible.

When physics students learn about melting, freezing, evaporation, or, in short, phase transitions, there is a very popular model that all learn. Imagine a mesh of small compasses all aligned either parallel or anti-parallel to a magnetic field that we provide from the outside. This is the Ising model, named after the german physicist Ernst Ising, but originating from his supervisor Wilhelm Lenz. Originally, it was taught to explain ferromagnetism and its loss at high temperature.

However, the same model was found to describe many other, seemingly unrelated physical situations. One example for a surprising appearance of the Ising model is the theory of strong interactions, that could at certain temperatures and densities behave similarly as a ferromagnet close to its critical point. Near the critical point distant parts of the system engage in correlated behaviour and the thermodynamic functions that describe its energy, entropy, heat capacity show singular behaviour if we study these as a function of volume or temperature.

Critical behaviour in the strong interactions is expected to emerge in experimentally accessible situations. These have in common, that one assumes unlikely temperatures, 100000 times those we find in the core of the sun. Nowadays, however, such hot matter, is routinely produced in collider experiments. The hot matter can be critical if temperature and density both match a specific, alas, so far unknown, value.

Current experiments, especially the STAR at the Relativistic Heavy Ion Collider at Brookhaven, USA are actively searching the location of this point, by studying the proton statistics of the collision outcome.

At the same time the theoretical physics community is challenged to make a prediction of this point, the critical endpoint, where the theory of strong interaction, Quantum Chromodynamics (QCD), behaves like the ferromagnet in the Ising model. While this model predicts in what way the critical end point is singular, it tells no information on its location on the phase diagram. While the theoretical apparatus can solve many simplified models, it has always been immensely difficult to make predictions on real-life systems: the complicated phase structure of water, for example, comes from experimental investigations, not from theory.

Scientists at the University of Wuppertals started new initiatives to change this situation. They follow up on the fact that the location of the critical end point depends on Nature’s parameters, like the masses of the quarks that the strong force connects. Simulations at finite density are, in general, very difficult in computer simulations, but in one possible scenario, the critical end-point can be shifted out to zero density by making the quarks heavier than natural.

In this project the PI and his group calculated how high the quark mass needs to be in order the critical end-point is shifted to zero density, which is then much easier to study than with Nature’s original parameters. In earlier projects the universality class was studied by the theory group at the University of Pisa, and in a different setup in Frankfurt.

The critical quark mass that arose from the simulations on the JUWELS/Booster system is expressed through the meson mass to temperature ratio,19.1(1).

The novelty in the Wuppertal researcher’s approach was the use of the parallel tempering algorithm that accelerates the progress of numerical simulations. With this algorithmic improvement several replicas are simulated, each with a different temperature. The replicas can occasionally swap temperatures, thereby getting sometimes above, sometimes below the critical temperature, thus, better exploring the space of relevant configurations.

The use of this algorithm allowed the Wuppertal group to ask further questions on the vacuum structure and its relation to the high temperature phase. Like in ordinary matter, defects can also be found in the strong interacting plasma, however, their density is different in the high and low temperature phases. This difference has been quantified now and explained by the well-known Clausius Clapeyron equation.