

Nuclear and subnuclear boiling

Frank Wilczek

Can nuclear material, compressed hard enough, turn into a still denser substance known as quark matter? According to Stephanov, Rajagopal and Shuryak of Stony Brook and MIT, we may be able to find out by doing experiments with existing particle accelerators¹. They apply the theory of phase changes to extend a bold analogy originally made by Niels Bohr.

Bohr's liquid-drop model of the nucleus is a crude but useful tool for understanding the masses and behaviour of heavy nuclei. The idea is that both liquids and atomic nuclei consist of closely but not rigidly packed hard constituents — molecules in one case, protons and neutrons in the other — so their equilibria and collective motions should follow similar patterns. For example, charged water drops are unstable to fission: they tend to break into smaller droplets. This was discussed theoretically by Lord Rayleigh in the nineteenth century and investigated experimentally by Bohr in his thesis. Many years later, when nuclear fission was discovered, Bohr quickly realized the analogy, and was able to carry over much of the old analysis². At the moment, a simple but startling question suggested by the liquid-drop analogy is receiving a lot of theoretical and experimental attention³. Does nuclear matter, like water, boil when heated?

On first hearing, it might seem that this question takes a model that was meant to be tongue-in-cheek far too literally. Upon reflection, however, one begins to realize its depth. For the logic of the liquid-drop analogy, rather than being strained, becomes more compelling when nuclei are heated. Indeed, a

great limitation of the liquid-drop picture is that for nuclei near their ground state, but not for ordinary liquids, quantum effects are important. Roughly speaking, the possible motions of the protons and neutrons are constrained, because they are allowed only certain discrete energies. There is no such constraint for ordinary liquids.

But the constraints introduced by quantum mechanics become less important — and the logic of the liquid-drop picture more convincing — when the nuclei are heated, so that there are many quanta of energy to share. Moreover, many important features of transitions are quite independent of the microscopic details, or 'universal'⁴. In particular, when the relevant control parameters, such as temperature and density, are close to those for which a continuous (second-order) transition takes place, fluctuations between the phases occur even over large distance scales. The nature of these fluctuations does not depend on the details of the underlying dynamics at short distances. It is the same, after renaming the variables, for wildly different systems.

Having convinced ourselves that the question is respectable, we can better appreciate the emerging answer. It is 'yes'. Nuclei do indeed have a sharp boiling phase transition⁵. The results of many measurements (Fig. 1) show how the temperature of nuclei rises as a function of the energy deposited. One sees that, as for water at the boiling point, there is a substantial range where the temperature changes very little in response to applied heat. This is the phenomenon of latent heat, the classic signal of a discontinu-

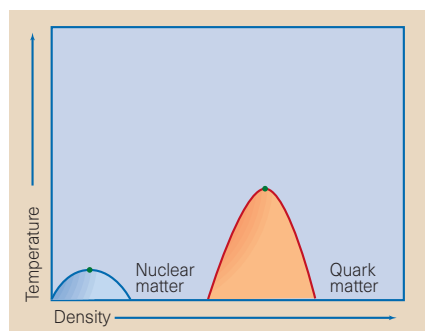


Figure 2 A conjectured phase diagram of extremely dense matter. In the blue region, free nucleons and nuclear matter can coexist in equilibrium, and as nuclear matter boils it passes from right to left through this region. Similarly, if quark matter can exist, there will be a region where nuclear matter and quark matter can coexist in equilibrium (red). The critical points (green) mark the limits of these phase transitions.

ous (first-order) transition, here occurring between the usual nuclear liquid phase and a gaseous phase of dissociated protons and neutrons.

More insight into the physics can be gained by nuclear collisions. Crucially, collisions can produce fireballs with different initial densities, as well as different temperatures. At high density, as we have seen, there is a first-order transition as the temperature is varied, with absorption of latent heat when one passes to the less ordered phase. As the density is lowered, the liquid state is more tenuous, and we would expect the quantity of latent heat to decrease. Then, at some critical density, the transition (as a function of temperature) will occur with zero latent heat — it will be a second-order transition. At still lower densities, the liquid and gaseous states will be continuous.

All this is familiar in the context of liquid-gas transitions, but what does it mean for nuclei? If the proposed phase diagram (Fig. 2) is correct, we should see large fluctuation phenomena in collisions where the nuclear fireball drops out of equilibrium at a temperature and density near the critical point. Specifically, one should see a power-law distribution in the size of fragments. According to universality, the slope in this distribution is precisely related to the distribution of domain sizes in an Ising-model magnet, or to the spectrum of critical opalescence at other liquid-gas transitions. Remarkably, there is some experimental evidence for such a distribution, and therefore for nuclear boiling⁶.

But Stephanov *et al.*¹ are concerned with the possibility of a second phase transition in the opposite direction, when nuclear matter is compressed. Some model calculations^{7,8} suggest that when one squeezes nuclear matter very hard, doing work of around 200–400 MeV per nucleon, there is a first-

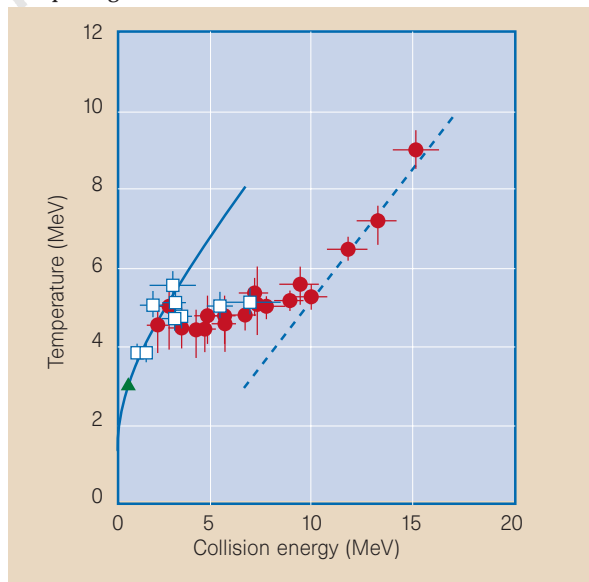


Figure 1 The change in temperature (measured through the kinetic energy of escaping particles) as a function of energy deposited in nuclear collisions. The plateau, where a higher energy input does not raise the temperature, is a sure sign of a discontinuous phase transition. This is nuclear boiling. (Adapted from ref. 5.)

order transition from nuclear matter to a new, sharply distinct phase that is several times as dense — quark matter. The cores of neutron stars may well consist of quark matter.

But this is controversial, and the physical characteristics of quark matter are mostly unknown. Quantum chromodynamics (QCD) is the theory that describes quark interactions, and its equations are very difficult to solve at high densities; even the numerical techniques that are wonderfully successful at low density fail miserably. So experimental information on this regime would be most welcome.

Unfortunately, to achieve sufficient compression to produce quark matter in the laboratory, one needs very energetic collisions — which will also deposit a lot of heat. That makes it very difficult to reach the putative transition at zero temperature. More generally, heat will be released as nuclear matter is compressed, warming the matter and making it expand, driving the material along the coexistence curve in the temperature/density plane towards the critical point.

For that reason, and others, the critical point appears to be a more hopeful experimental target. Stephanov *et al.* propose several ways to identify the subnuclear boiling critical point. Long-wavelength fluctuations should eventually materialize as low-momentum pions, which should be anomalously abundant (and exhibit anomalously

large event-by-event fluctuations in number) near the critical density and temperature. Also, because of the large specific heat near the critical point, collisions with a range of energies should be clustered around the critical temperature.

Finding the position of the critical point would shed light on aspects of QCD that are both fundamental and obscure. (Is quark matter truly a distinct phase? Does it boil into nuclear matter?) It would also be a truly remarkable example of the power of theoretical reasoning and the concept of universality in phase transitions. Hitherto, discussions of high-energy nuclear collisions have been dominated by the quest to create a quark-gluon plasma⁹. Now we see that there is another, equally worthy, goal: to smoke out the transition to quark matter. □

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Mutagenesis

Purposeful mutations

Myron F. Goodman

When DNA is passed from mother to daughter cells during replication, several mechanisms ensure that this occurs with a minimum of mutations. These include proofreading exonucleases and post-replication mismatch-repair enzymes¹. Nevertheless, “there’s many a slip ‘twixt the cup and the lip”², such as the spontaneous loss of DNA bases and DNA damage from external sources. Many cells contain systems to repair damaged DNA, but *Escherichia coli* also harbours proteins that do the opposite — they reduce replication fidelity. These proteins are induced in response to DNA damage as part of the so-called SOS response³, and reports by Bacher Reuven *et al.*⁴ in *Molecular Cell* and Tang *et al.*⁵ in *Proceedings of the National Academy of Sciences* detail the biochemical reconstitution of this system.

Given a choice between mutation and death, perhaps the SOS mutagenic response is a cell’s last ditch attempt to survive, when DNA damage outstrips its repair capacity. Two proteins, UmuD’ and UmuC, are induced in the SOS response to DNA damage by ultraviolet light and most chemical muta-

gens. A trimer of one UmuC and two UmuD’ molecules (UmuD’₂C) works with the replicative DNA polymerase III holoenzyme (pol III) and the RecA protein to form a

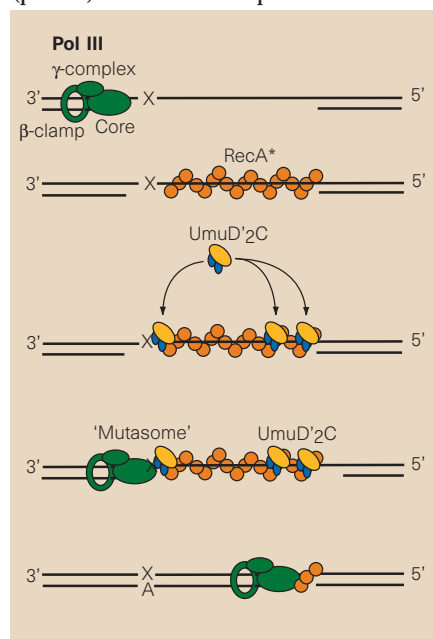


Figure 1 Possible mechanism of SOS-dependent translesion replication. The replicative DNA polymerase III holoenzyme (pol III), containing a catalytic core, β sliding clamp and γ -complex clamp loader, stalls when it encounters an abasic template lesion (X). RecA protein binds to the region of single-stranded DNA downstream from the lesion, forming an activated RecA* filament. The UmuD’₂C complex binds to various sites along the RecA* filament, but only those bound to the end of the filament are appropriately positioned to form a ‘mutasome’ consisting of UmuD’₂C, RecA*, pol III and, possibly, single-stranded DNA-binding protein (not shown). The nucleoprotein aggregate allows replication to proceed past the lesion, generating a base-substitution mutation, with preference for incorporating dAMP (A) opposite the abasic site. This process can now be dissected biochemically thanks to reconstituted *in vitro* systems developed by Bacher Reuven *et al.*⁴ and Tang *et al.*⁵. (Figure courtesy of R. Woodgate.)