Quark-gluon plasma reveals viscosity-free properties

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The early Universe was a strange place. The Universe was so dense and hot that atoms and nuclei could not form—they would be ripped apart by high-energy collisions. Even protons and neutrons could not survive. And that left us with quarks and gluons flying around to form something called a quark-gluon plasma.

We've observed these in the lab, but those findings are not without controversy—the quark-gluon plasma seemed to form under unexpected conditions. Now, it seems that science has done its job and done the experiments to confirm that, yes, those observations were almost certainly quark-gluon plasmas.

Quarks? Gluons? English or Klingon?

The Universe is divided into families of particles. On one side, we have the leptons: electrons and their overweight cousins, muons and tauons (and their invisible friends, a corresponding neutrino). Then there are the force carriers: photons, W and Z bosons, the Higgs, and gluons. On the other side we have a charming family of colorful quarks. All of these particles are a bit like Legos: put them together in various ways to create a Universe (the instruction book can be

a bit overwhelming though).

The quark family members are all charged, so they don't really like each other that much. Gluons play the role of grandkids. As long as there are gluons around, the quarks will turn up to family reunions and make nice with each other. In the early Universe, however, there was simply too much energy to hold a family gathering. Quarks and gluons were all jumbled up, but the gluons could not hold the quarks together.

Recreation of the early Universe in the form of quark-gluon plasmas was first reported in collisions of heavy atoms by teams at the Relativistic Heavy Ion Collider. But then the Large Hadron Collider came along and found that there might be signs of this material in collisions with light atoms. Following LHC observations, the folks at the Relativistic Heavy Ion Collider reexamined their data and found that they, too, seem to make a quark-gluon plasma without needing heavy atoms. As detectors were upgraded, new experiments revealed more and more details.

Interpreting this evidence requires a model, and the models for quark interactions are a bit insane in terms of difficulty, leaving things open to multiple explanations. Yes, some experiments were definitely quark-gluon plasmas, but some experiments were more ambiguous. Essentially, a quark-gluon plasma takes time to form, while the energy and size of collisions among small atoms didn't seem to allow time for the plasma to form.

A perfect fluid?

One property of a quark-gluon plasma is that it flows without viscosity—viscosity is the internal friction of a fluid that makes honey thick and slow-flowing, while water is fast and free-flowing. Fluids with no viscosity at all, like superfluids, have some really weird properties. So a common way to look for a quark-gluon plasma is to look for evidence

of flow without viscosity.

That evidence was found in the data. Unfortunately, theorists suggested that the same evidence might be obtained via the collisional process that creates the fluid in the first place. In this interpretation of the evidence, at the start of the collision, the quark-quark interactions set up a collective behavior. This collective behavior generates global properties in the later collision that *look* like a quark-gluon plasma but are not.

For the researchers to determine if they had the real McCoy, they had to vary the conditions under which they created the quark-gluon plasma. The experimental results could then be compared to extensive calculations using multiple models. This has now been done.

Behind door number two

The experiments, conducted at the Relativistic Heavy Ion Collider, fell into three categories: colliding protons with gold, colliding deuterons (a proton and a neutron) with gold, and colliding helium-3 nuclei (two protons and a neutron) with gold.

The difference in symmetry between the three experiments generates a different flow in the fluid. The very size of helium-3 is enough to ensure that the collective behavior generated by forces between quarks at the start of the collision cannot extend over the entire nuclei. Thus, the collective behavior required to generate an apparent frictionless flow is not as strong in the experiments with helium-3 compared to experiments with a single proton. If you still see that flow, then it’s strong evidence that this really is a quark-gluon plasma.

The researchers’ data supports the quark-gluon plasma model. The flow regime varies between the three experiments. They

also obtain relatively good agreement between their experimental results and two different models used to predict the fluid’s creation and behavior.

On the other hand, the comparison between experimental evidence and model predictions suggests that collective behaviors, generated from the collision’s initial conditions, do not imprint themselves on the end measurements.

Science works

This has been a long-running argument and really shows science at its best. Evidence is king, but evidence is meaningless without a theoretical framework. However, going from a theoretical framework to actual predictions is a process that is fraught; assumptions and approximations have to be made.

The decisions about what processes to include and how to include them make cut-and-dried cases very rare in modern science. Instead, the slow accumulation of evidence and the reevaluation of assumptions in response to new evidence gradually strengthen conclusions.

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