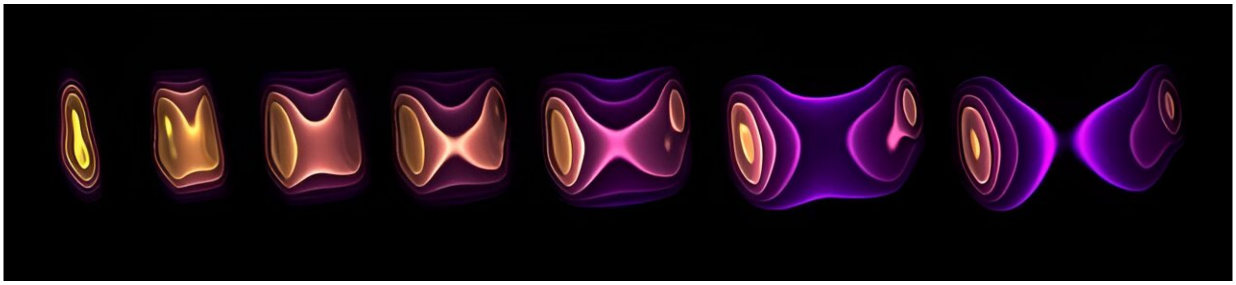
# How particles of light may be producing drops of the perfect liquid

August 22 2024, by Shannon Brescher Shea



A snapshot of a computer simulation showing how energy density changes over time in the collision of a lead ion with a photon emitted by another lead ion. Credit: Chun Shen, Wayne State University

The world's largest and most powerful particle accelerator may be producing the world's tiniest droplets of liquid, right under scientists' noses. Researchers are digging into this subatomic enigma.

Underground at the Switzerland-France border, the Large Hadron Collider (LHC) at CERN holds the record for the world's largest particle accelerator. Its ring alone is nearly 17 miles around. With this tool, scientists smash together subatomic particles to help them better understand the tiny building blocks of the universe. One area that scientists use the LHC to study is the quark-gluon plasma.

## The soup at the beginning of the universe

The quark-gluon plasma is an unimaginably hot, soupy liquid. It's so high-energy that the quarks and gluons that make up the visible matter are released from their usual confinement within the protons and neutrons in the nuclei. It actually flows so easily—much more easily than water—that scientists consider it a nearly "perfect" liquid.

Originally, the quark-gluon plasma existed at the very beginning of the universe, right after the Big Bang. A few fractions of a second later, the plasma cooled. As it did so, the quarks and gluons joined up to create the familiar protons and neutrons that make up the cores of atoms. In everyday life, quarks and gluons are always held together in protons and neutrons.

Currently, the quark-gluon plasma can only be created in two places on Earth—the LHC and the Relativistic Heavy Ion Collider (RHIC, a DOE Office of Science user facility) at the DOE's Brookhaven National Laboratory. Scientists study it to better understand both the origins of our universe and the particles that make it up.

To do so, scientists collide heavy ions. (Heavy ions are atoms of elements heavier than hydrogen with their electrons stripped off.) In particular, the LHC collides ions of lead, while RHIC collides ions of gold, among others. Some of the experiments also collide heavy ions with protons.

The collisions are so high-energy that the gluons no longer hold the quarks together. Both the quarks and gluons are released from their confinement in protons and neutrons. Just like at the beginning of the universe, the plasma cools quickly and reforms into new particles. By examining the number, types, and paths of the particles, scientists can work backward and obtain new details about the quark-gluon plasma.

## Identifying traces of the quark-gluon plasma

Because the quark-gluon plasma exists for such a short period of time, it can be difficult to tell when it has formed or not.

Back when scientists at RHIC started studying the quark-gluon plasma, they used physics theory to identify whether the plasma formed or not. They knew that the collisions would create many particles, but they did not know how strongly they would interact with each other. The experimental data showed that the science of fluid dynamics describes the quark-gluon plasma well.

When collisions between ions partly overlap, they create an uneven, oblong-shaped density distribution. The differences in pressure push particles from dense regions into regions with fewer particles. This forms an elliptical pattern of flowing particles.

As scientists further studied the quark-gluon plasma, they realized that this elliptical pattern is a key characteristic of it. That pattern is evidence that the quarks and gluons are interacting strongly, which they can only do in the quark-gluon plasma.

At first, scientists assumed that only heavy ions colliding with each other could form the quark-gluon plasma. But as time went on, they examined new combinations. In collisions of ions with protons, they saw a very similar pattern.

Then scientists conducting research at CERN as part of the ATLAS Collaboration—some of them from DOE's Brookhaven National Laboratory—tried something even more radical. They examined what was happening in collisions between particles of light and ions in the LHC.

## Colliding particles of light

The LHC was already producing these collisions—the scientists just had to figure out how to study them.

When the LHC blasts lead ions at each other, these particles have a positive charge. As they move, they produce electromagnetic fields—very bright light. These fields produce particles of light called photons. As the lead ions move through the accelerator tube, they are each surrounded by a cloud of photons.

As big as they are for nuclei, lead ions are still very tiny in the grand scheme of things. Most of the time, the ions shot at each other don't collide. There are enough of them in the beam that do collide to collect data, but there are many near misses. Fortunately, the near misses are what the scientists on this experiment wanted to study.

When the near misses occur, one of the photons from the photon cloud surrounding one ion smashes into an ion going the opposite way. Think of avoiding running into someone on the sidewalk only to hit them with your backpack—the photon field here being the backpack. As there is an entire beam full of ions, these photon-ion collisions happen quite often.

## A pattern in the data

What the scientists at the LHC found surprised them. The way the particles flowed after the photon-ion collisions showed the distinctive elliptical pattern associated with the quark-gluon plasma. This was weird because photons simply shouldn't have enough energy to melt the protons and neutrons of the massive lead nuclei. It would be like throwing a match at an iceberg.

But quantum physics provided a potential explanation.

While antimatter sounds like a science fiction concept, it is definitely real. Antimatter particles are partners to matter particles. They're the same mass but have opposite charges. Almost 100 years ago, physicist Paul Dirac predicted antimatter. He also predicted that when a matter particle and an antimatter particle meet, they destroy each other and produce two photons. Later experiments showed his predictions were correct.

Here's the weird part—this process can also happen in reverse. Due to quantum fluctuations, two photons can also interact and create a quark and antiquark. Before the quark and antiquark destroy each other, they may form a very brief, intermediate particle. Particle physicists think that this intermediary particle may be the rho meson, a particle made of a quark and an antiquark held together by gluons. Unlike a single photon, a rho meson colliding with a lead ion could potentially have an impact.

But this was all experimental data. To ensure that experimental data fits into physics theory, scientists need to create calculations that accurately describe it.

## Crunching the numbers

Enter the theorists. Theoretical physicists at DOE's Brookhaven National Laboratory and Wayne State University supported by DOE's Office of Science dug into the data to make further sense of it.

Fortunately, they weren't starting from scratch. They already had the calculations that describe the collisions between lead ions and protons. These calculations are hydrodynamical calculations—they describe the movement of fluids.

Building off this framework, the scientists adapted these calculations so they could describe near-miss collisions as well. The first major change was to accommodate for the fact that a completely different type of particle was interacting with an ion. The other was to adjust for the fact that a rho meson (the intermediate particle) had much less energy than the protons that the accelerator typically collides with ions. As a result, the whole collision had less energy. That changed the particle flow.

With these adjustments, the theorists found that their calculations of the most obvious flow pattern matched up with the LHC experimental data.

They also drew similar conclusions to those of the scientists at the LHC—that there is a possibility that the photon-ion collisions are forming a "strongly interacting fluid." While this work doesn't prove it, these studies point to the possibility that these much smaller collisions may in fact be forming tiny droplets of quark-gluon plasma.

## Digging in deeper

These studies lay the foundation for research that can dig deeper into what exactly is happening. Future studies at the LHC and RHIC will help scientists sort out whether these collisions are forming the quark-gluon plasma or if there's an alternative explanation. The Electron-Ion Collider, a DOE Office of Science user facility that's under construction, should offer even more insights.

Once the quark-gluon plasma only existed at the very beginning of the universe. But now, we're finding that it may be showing up in our experiments in ways that we never would have expected. Sometimes, learning more about the very building blocks of our universe just requires a new perspective on the experiments we're already running.

Provided by US Department of Energy

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