

THE *Current*

September 30, 2025

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A rewarding dissertation on the strong nuclear force

Our account of the strong nuclear force is full of imaginative terms. Six flavors of quarks have color charges of red, green and blue, which dictate how they bind to form particles like protons and neutrons. Gluons mediate these interactions in a system called quantum chromodynamics, though its relation to color is in name only.

A postdoctoral scholar at UC Santa Barbara's Kavli Institute for Theoretical Physics (KITP), Bruno Scheiing-Hitschfeld, has received the American Physical Society's [award for dissertations in nuclear physics](#) for his theoretical work on this fundamental force done for his Ph.D. at MIT. The distinction "recognizes doctoral thesis research of outstanding quality and achievement in nuclear physics."

"I feel like there's this piece of work that I put together over five or so years that the physics community appreciates," said Scheiing-Hitschfeld.

"It's wonderful that Bruno has received this important recognition of his path-breaking work," said Lars Bildsten, director of KITP. "As a KITP postdoc, he's now actively exploring new scientific directions and taking full advantage of our institute's strength of being the place to forge new collaborations. He's off to an amazing start in just his first year."

Scheihing-Hitschfeld studies the fundamental particles found in the atomic nucleus, called quarks and gluons, and the strong nuclear force that binds them together. He's interested in how they behave under extreme conditions, like in particle accelerators or within the first millisecond after the Big Bang.

At these energies, protons and neutrons dissociate into a phase of matter called quark-gluon plasma. "In this state, the quarks and gluons are no longer confined inside nuclei, but rather they are released from their nuclear bindings," Scheihing-Hitschfeld explained. They're not exactly free — the strong nuclear force still affects them — but they're better thought of as interacting by themselves as opposed to within the protons and neutrons that they regularly form.

Experimentalists can recreate these conditions by smashing heavy ions, like atoms of gold, at relativistic speeds. The plasma forms and dissipates within ludicrously short timeframes: 10⁻²³ seconds, or a few dozen yoctoseconds. "It's essentially the time it takes for light to travel across these atomic nuclei," Scheihing-Hitschfeld said.

Fortunately, this is also just about the amount of time the plasma takes to settle to a fluid state that evolves according to the laws of hydrodynamics, expanding due to its own pressure. The first part of Scheihing-Hitschfeld's dissertation examines how this unfolds.

Scheihing-Hitschfeld developed a new approach to describe this process based on kinetic theory, a well studied framework often used to model gasses. Kinetic theories characterize the behavior of a fluid in terms of the motions and interactions between its constituent particles. This approximation provides a more familiar place from which to build a description of the plasma. "One of the things we do as theorists is to write equations that approximately describe what is going on, and then we start adding layers and layers of complexity to get a better and better description," he said.

Scheihing-Hitschfeld and his collaborators developed a framework to isolate the particular aspects of the system that govern how it evolves from initial conditions to a hydrodynamic plasma. They demonstrated how, as the unstable plasma transitions to a fluid, the number of variables you have to track in order to describe the system drops. In other words, most of the characteristics of the initial condition are lost once the transition is complete. This formalization provides insight into how the earliest

stages of the Big Bang unfolded, insights we can actually test in heavy-ion particle colliders.

The second part of his thesis investigates the behavior of composite particles that form in this plasma to learn more about the inner workings of the strong force.

Quarks come in six varieties, or flavors, of increasing weight: up, down, strange, charm, bottom and top. And each has its own antimatter counterpart. The charm, bottom and top quarks are each heavier than a proton or neutron, which consist of up and down quarks.

Despite the absurd energy density of a quark-gluon plasma, the strong nuclear force can often still bind these quarks together into composite particles. Scheihing-Hitschfeld is interested in quarkonium particles, which are made from one of the three varieties of heavy quarks (charm, bottom and top) bound to its own antimatter counterpart (charm antiquark, bottom antiquark and top antiquark). These pairs are inherently unstable, yet charm and bottom quarkonium particles can exist long enough to have meaningful interactions within the plasma.

As its name suggests, a pure quark-gluon plasma is a sea of dissociated quarks and gluons. But a typical heavy ion collision won't reach a high enough temperature to completely melt the quarkonium particles that may form. How long the quarkonium stays together depends on the energy of the plasma itself.

Scheihing-Hitschfeld and his coauthors formulated a way to calculate how quarkonium melts in the plasma, set in the framework of quantum field theory. The result accounts for the most relevant subtleties and adds some mathematical components that the authors noticed were missing in other descriptions of the system. Their framework provides a starting point for computational calculations to begin.

Now Scheihing-Hitschfeld plans to combine the tools he's developed with the tools he's learned to further explore complex quantum phenomena like quark-gluon plasma. While his own interests lie in understanding the strong force, his research also carries insights for strongly coupled quantum systems in other disciplines, such as condensed matter physics, materials science and quantum computation.

"One of the nice things about theoretical physics is that sometimes the conceptual framework to think about a problem is not specific to that problem," Scheihing-

Hitschfeld said. “You can apply it to many other physical scenarios that may actually come from an entirely different setup.”

Studying quantum chromodynamics provides a glimpse into some of the most fundamental aspects of our universe, however the field’s practical implications are sure to surprise us when they appear. “We never know when discoveries or new pieces of understanding will have unexpected consequences in the long distant future,” Scheihing-Hitschfeld said. “People didn't know how impactful the development of electrodynamics would be over a hundred years ago, and now it's all around us: our phones, cars, TVs, even artificial intelligence.”

Scheihing-Hitschfeld will receive the award in October 2025 at the APS Division of Nuclear Physics’ fall meeting, where he will give an invited talk on his research.

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