Eavesdropping on the particular chatter on the sub-atomic world

April 5 2017, by Kandice Carter

One supercomputer wouldn't do Jozef Dudek (left), staff scientist at Jefferson Lab and an assistant professor of physics at William & Mary, worked with JLab's Robert Edwards to run complex quantum chromodynamics calculations on several supercomputers. Credit: Jefferson Lab

Much like two friendly neighbors getting together to chat over a cup of coffee, the minuscule particles in our sub-atomic world also come together to engage in a kind of conversation. Now, nuclear scientists are developing tools to allow them to listen in on the particles' gab fests and learn more about how they stick together to build our visible universe.

Jozef Dudek is a staff scientist at the U.S. Department of Energy's (DOE) Jefferson Lab and an assistant professor of physics at William & Mary. He and his colleagues recently carried out the first complex calculations of a particle called the sigma. They published the result in *Physical Review Letters* in January.

"The sigma is often thought of as being part of the force that holds protons and neutrons together in the nucleus," Dudek explained. "You can think of there being a force between a proton and a neutron, which is due to the exchange of particles between them. One of the particles that a proton and a neutron may exchange is the sigma."

This exchange of sigma particles by protons and neutrons allows them to communicate through the strong force. The strong force is the force of nature that binds protons and neutrons into nuclei. In fact, the strong force is also responsible for the formation of protons and neutrons.

In decades of delving deep inside the heart of matter to uncover its building blocks, nuclear physicists so far have found that the smallest bits of matter are quarks. It takes three quarks to build a proton (and three to build a neutron). These quarks are bound together by the strong force, again through a conversation between quarks that manifests as the exchange of particles. In this case, the quarks swap strong-force 'glue'—particles called gluons.

So, if particles are able to converse via the exchange of strong force gluons directly, where does that leave the sigma? It turns out that if a proton and a neutron are really close together, they can hold their conversation with a simple swap of gluons. But in a spacious nucleus, it takes other particles, including the sigma, to converse efficiently.

"At larger distances, it makes sense to think about exchanging mesons between nucleons, where mesons are built out of quarks and gluons themselves, but sort of packaged up into confined packets," Dudek said .

These 'confined packets' may be the sigma, which is a meson built of quarks and gluons, or another meson called the pion, familiar to physicists as a particle that is often found hanging around the nucleus.

To put it all together, protons and neutrons may chat it up via the exchange of gluons at short distances, sigma mesons at medium distances and pions at larger distances.

Calculating the heart of matter

If this all sounds rather complicated, that's because it is. Dudek and his colleagues are the first to calculate the sigma particle directly from the theory that describes the strong force, the particles that interact through this force and the nature of those interactions. This theory is called quantum chromodynamics or simply QCD.

In fact, these calculations were so complicated, supercomputers were required to accomplish the feat.

According to Robert Edwards, a senior staff scientist in Jefferson Lab's Center for Theoretical and Computational Physics, the QCD calculations required the dedicated effort of several supercomputers.

The first part of the calculations were carried out on Titan, a supercomputer based at the Oak Ridge Leadership Computing Facility, a DOE Office of Science User Facility at DOE's Oak Ridge National Laboratory in Tennessee, and the Blue Waters supercomputer at the University of Illinois at Urbana-Champaign.

Edwards said these first calculations were used to develop snapshots of the environment of subatomic particles, or the "vacuum" of space described by QCD.

"The vacuum is not an empty place, it's seething with energy," Edwards explains. "And energy is manifested as electric and magnetic fluctuations, which can be thought of as the glue of the strong force. So, what QCD does is look at the strength of these fields at every point in space."

These snapshots of the fluctuating vacuum can be imagined as the surface of a pond being rained on, with the raindrops causing ripples on the pond. Each snapshot of the surface of the pond corresponds to a snapshot of the vacuum. He said 485 snapshots were generated by the Titan supercomputer.

Watching the scenarios play out

For the second part of the calculations, quarks were added to the snapshot. As quarks move through the vacuum, they respond to their environment. Their possible movements, called "propagators," were computed using the Titan and Blue Waters supercomputers. For each snapshot of the vacuum, 800,000 such propagators were computed.

With the propagators in place, several different scenarios were then posed for how specific quarks will interact with each other as they propagate through time. For each scenario, the supercomputer calculates the probability within the theory of QCD that the quarks are likely to interact that certain way.

"We have to evaluate a quantity called a correlation function. The correlation function says that you have some configuration of quarks, and you're watching the propagation as they go through time," Edwards explains. "This correlation function is effectively measuring the correlation, or its strength, between its initial configuration of quarks and its final configuration of quarks."

Continuing our analogy of the raindrops on the pond, now imagine that a rubber duck has been added to the pond. The correlation function calculations determine how likely it is that the rubber duck will float from one point to another on the pond.

Each of the 485 configurations were simulated many times to determine the probability of each scenario, yielding about 15 million results for comparison. The calculations were carried out on Jefferson Lab's LQCD cluster in the spring and summer of 2016.

Sigma comes to life

After all of the calculations were tallied, the researchers found that if the right quarks are present, the sigma can, indeed, be generated by the strong force.

After decades of catching brief glimpses of the sigma's fleeting existence from the experimental data showing its effects on other subatomic particles, Dudek and Edwards say that this calculation now gives scientists a new way to study this elusive particle.

"It's really a first step toward understanding what the sigma is. Does it really exist within the theory? Apparently, it does," Dudek explained.

The properties of the sigma in their calculations seem to match what scientists have come to expect of the real-world sigma's properties. What's more, now that these calculations have demonstrated that it's feasible to apply supercomputers to calculations of an elusive particle like the sigma, this may well open the door for calculations of other short-lived particles.

"We've demonstrated that we can show it exists within QCD. Now, the questions are: What is it? How is it formed? Why does this thing exist? Is there a way to understand it simply?" Dudek said. "Can we address those questions, now that we have a rigorous technique to study within QCD this object? And that's something for the future."

And studying the elusive sigma may allow researchers their first glimpse at this facet of the strong force that exists only deep inside the heart of matter. It may offer them a chance to eavesdrop, if you will, on the force as it goes about its business of building up our universe.

More information: Raul A. Briceño et al. IsoscalarScattering and theMeson Resonance from QCD, *Physical Review Letters* (2017). DOI: 10.1103/PhysRevLett.118.022002

Provided by The College of William & Mary