Titan Project explores the smallest building blocks of matter

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GlueX is an experiment located at the Jefferson Lab, whose purpose is to study nuclear confinement by mapping the spectrum of exotic mesons generated by the excitation of the gluonic field binding the quarks. Photo: Thomas Jefferson National Accelerator Facility

(Phys.org) —Our world is made up of particles so tiny they may actually be points in space. These are quarks, relative newcomers to the physics conversation that were not even postulated until the mid-1960s. Put them together and you get protons and neutrons. Put those together and you get the nuclei of atoms. Put those together and you get you and your universe.

A team from Thomas Jefferson National Accelerator Facility (JLab) in Virginia is working to deepen our understanding of quarks, enlisting the help of Oak Ridge National Laboratory's Titan supercomputer. An article in a recent issue of the journal *Physical Review D* discusses its work.

Quarks and their companion force carriers, known as gluons, are held together by the strong force, one of the universe's four fundamental forces—along with gravity, electromagnetism, and the weak force (responsible for nuclear decay).

The strong force is aptly named. When two quarks are pulled apart, the gluon field that holds them together gets stronger (unlike gravity, for instance, which weakens with distance). So much energy is required to break the bond, in fact, that the energy itself becomes a quark and an antiquark in accordance with the rules of Einstein's famous equation, $E=mc^2$, which governs the conversion between mass and energy.

In other words quarks are never found alone, even when they are pulled apart. Instead, they are always found in groups of two (called mesons) and three (called baryons). The rules that govern these groups, and the study of these rules, are known as quantum chromodynamics, or QCD.

The workings of QCD are analogous to the interplay of colors (hence the "chromo" in quantum chromodynamics). There are three color charges; you can think of them as the red, green, and blue of a television screen. There are also three "anticolors"; you can think of these as the cyan, magenta, and yellow of a color printer. To make things just a bit more complicated, quarks are either one color or one anticolor, while gluons are both one color and one anticolor.

According to QCD, quarks are always found in groupings that blend to make "white." Two-quark mesons do this by combining a color and an anticolor.

Part of the challenge for experimental scientists, then, is that they must glean what information they can about quarks and gluons by studying these composite particles. While they have made progress, there is much left to be learned. According to team member Jozef Dudek, we cannot claim to understand how the universe is put together until we understand this microscopic world much better.

"The Higgs boson was a huge story, and the claim is that this completes the standard model, that everything in the standard model is understood," he said. "Well, QCD is a component of the standard model, and we're telling you right here that we don't understand QCD."

The information we do have comes from smashing charged particles into protons and seeing what happens. Specifically, what can happen is that quarks within the particles absorb energy and become excited. This excitation is also known as a resonance.

"You can think of ringing a bell," said team member Robert Edwards. "We have a proton and thwack it. The proton rings. And these ring tones, which are actually the excited states of the collections of the quarks inside of them, give us information about the constituents inside the protons."

Part of the information lies in the energy needed to excite the particle.

"What you'll find is that with certain energies of the beam particles, nothing much happens," Edwards explained, "until you scan into a limited range of energy, where suddenly a very strong reaction happens. Then as you go to higher energies, nothing happens again."

He said the best everyday analogy might be the act of pushing a child on a swing. Push too fast or too slowly, and the swing goes nowhere in particular. Push at the right rate, however, and the swing will go as high as you care to send it.

In its recent Physics Review D article, the team explains how it was able, for the first time, to map out in detail the resonance—in this case the rho [r] resonance—created when two particles collide. The particles were pi mesons, which, like all mesons, contain a quark and an antiquark. The team uses a code known as CHROMA and a technique known as lattice QCD, or LQCD.

"It's a big deal that we could demonstrate the resonance with a lattice QCD calculation," Dudek noted, "because the way the calculation is performed, there were doubts that you could do this sort of thing at the level of detail we achieved."

The lattice, or grid of points on which the quarks are represented mathematically, can be huge, with recent computations going as large as 16 million sites (40 sites in each of the three space dimensions and 256 sites in the time direction).

On the lattice, CHROMA first calculates gluon fields in about 1,000 possible configurations, running through a series of matrix equations (200 million by 200 million). It is this part of the process that requires Titan and its 18,688 NVIDIA GPUs.

"The first stage generates the snapshot of the gluon field in a vacuum," Dudek said, "and this is because the vacuum is actually quite a complicated affair. You'd think there's nothing here; it should be simple. But because of the quantum nature of QCD, there are gluon fields and quark fields bumping in and out of existence all over the place all the time."

As a result of these quantum fluctuations, the team needs to generate many such snapshots, typically aiming for about 1,000. Each snapshot is made from the previous one, attempting to capture a likely fluctuation of the fields at each step. To spread the work efficiently over Titan's GPUs, the project depends on Titan's Gemini interconnect to quickly share information.

The next phase of the project—swimming the quarks through the turbulent gluon vacuum—does not necessarily require a system of Titan's abilities, explained team member Balint Joo. In large measure this is because these later calculations can be tackled one snapshot at a time.

"Once we have the snapshots, we can work on more capacity-oriented systems," he said, "because we can treat the snapshots—or fluctuations of the gluon field—independently from each other for purposes of propagating the quarks through the gluon configurations. But that's something that we can't do when we're making them because we're making them in sequence."

The team was able to perform five runs at a time. In all it used 4,000 Titan nodes and reached 300 trillion calculations per second, or 300 teraflops. CHROMA is optimized for accelerators and relies heavily on Titan's GPUs, Joo said, adding that the team was working with GPUs before Titan came on the scene. Nevertheless, it was Titan that made this project possible.

"That kind of scale is not easy to find anywhere else. There's only one or two places in the world where you can find 4,000 GPUs in one place."

Much of the success of the LQCD team lies in the flexibility of its code. CHROMA contains a middle layer known as QDP++, with QDP standing for "QCD Data Parallel." Joo said the GPU version of this layer, known as QDP-JIT and developed by Frank Winter of JLab, uses a novel computational approach that not only allows the code to run on Titan, but should also serve as a basis for targeting future architectures.

"The innovation that allows the code to run on the GPUs is transferrable to other, future architectures," he noted. "So if another accelerated machine were to come along in the future, we'd still be able to retarget this middle layer to that new architecture efficiently, we believe."

With the confidence of having used LQCD to predict with unprecedented detail the rho meson resonance, the team has plenty of work ahead, replicating resonances that have been measured and predicting resonances that have not—at least not yet. One major goal of the LQCD team is to work hand in hand with JLab's Continuous Electron Beam Accelerator Facility to find new resonances. The facility is in the process of doubling the energy of its electron beam from 6 billion to 12 billion electron volts, or 12 GeV. The LQCD team hopes to help guide and explain new discoveries that will result from this upgrade.

"There are combinations of these quarks and gluons that should come from QCD—QCD says they're allowed—but they've never been determined experimentally," Edwards said. "And that's one of the big goals of the 12 GeV upgrade. There are exotic states of matter that could exist, but we don't know if these do exist experimentally."

The answers they get will help us better understand how we're put together. As Dudek noted, the recently confirmed Higgs boson, while necessary for explaining mass, is not enough.

"The amount of mass that the Higgs field gives to the up and down quarks that make up protons is only a few percent, with the rest coming from interactions between quarks and gluons. If you want to know where all the mass we've seen in the universe actually comes from, why we have mass, why planets and stars have mass, you'd better look to QCD."

More information: J. J. Dudek, R. G. Edwards, and C.E. Thomas, "Energy dependence of the ρ resonance in ππ elastic scattering from lattice QCD," *Physical Review D* 87 (2013): 034505.

Provided by Oak Ridge National Laboratory

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