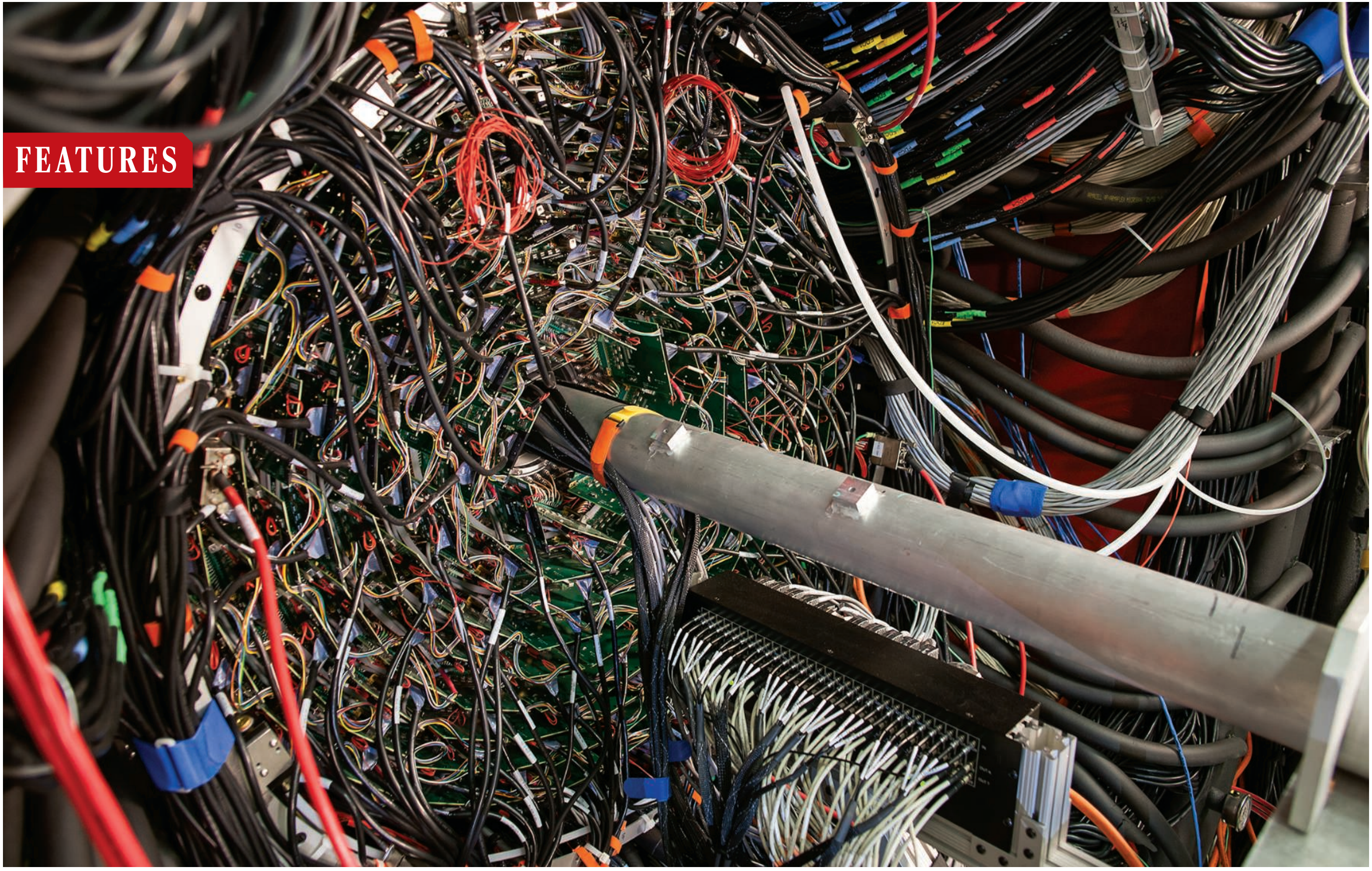


The GlueX detector will search for weird new particles predicted by the theory of the strong force.

PHOTO: BILL KELLEY III

Probing the proton

A newly upgraded accelerator explores the seething maelstrom at the heart of matter

By **Adrian Cho**, *in Newport News, Virginia*

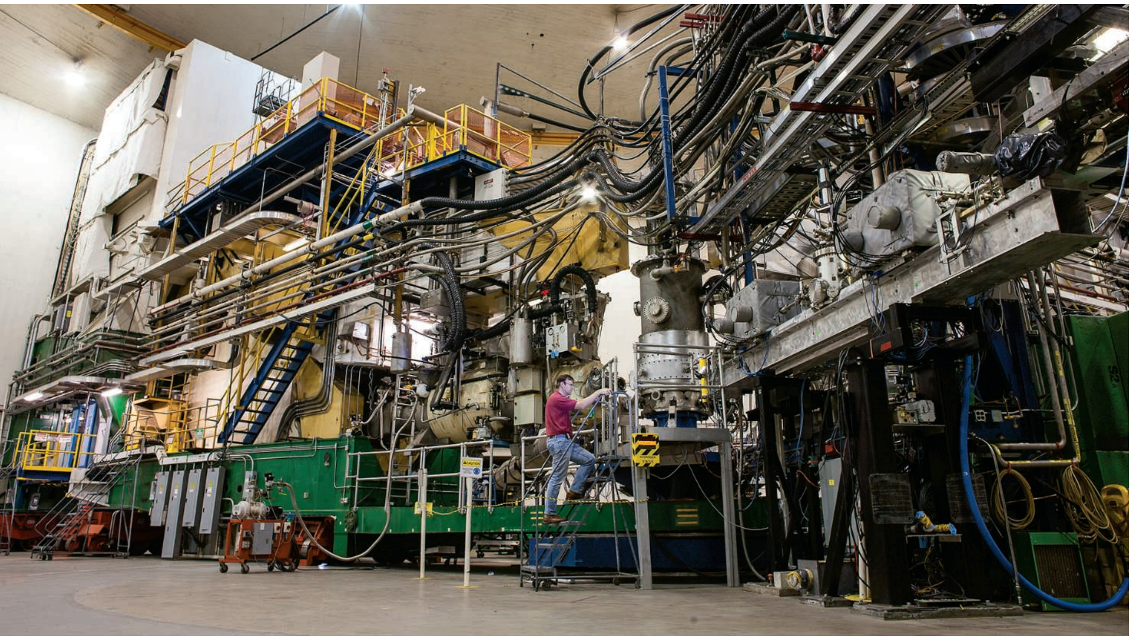
Hall A here at Thomas Jefferson National Accelerator Facility is everything a science fan could want from a physics lab. The cylindrical cavern, 24 meters from floor to dome and twice as wide, echoes like a cathedral. From high on the wall, a silvery pipe extends fingerlike to the center, from which fan out two vast machines, multitiered assemblages of steel, pipes, wires, and electronics that sweep up to the roof.

Think of it all as part of a giant electron microscope, designed to probe two of the most familiar yet mysterious constituents of the universe: the proton and the neutron. The pipe carries a beam of high-energy electrons from an accelerator, which smash into targets mounted at the room's center. The hall's two 1400-tonne spectrometers capture the subatomic particles blasted from the collisions, tracking their paths and energies. For 20 years, Jefferson Lab physicists have battered the nucleus without quite cracking its secrets. But starting this year, they will train a more powerful microscope on their quarry.

In the cartoon view, the positively charged proton and the uncharged neutron both consist of trios of particles called up quarks and down quarks. (Two ups and a down make a proton; two downs and an up make a neutron.) But earlier experiments have shown that those "valence" quarks are just a small part of the story. A nucleon—a proton or neutron—is really a pullulating mass of countless quarks, antiquarks, and gluons, particles that convey the strong nuclear force that holds quarks together. A proton or neutron is so messy that physicists can't say exactly how its most basic properties, such as its mass and spin, emerge from the tangle.

Jefferson Lab physicists are finishing a $338 million upgrade to their particle accelerator, the Continuous Electron Beam Accelerator Facility (CEBAF), to double its energy and probe the innards of protons and neutrons with unprecedented precision. Compared with meccas of particle physics such as CERN, Europe's particle physics lab near Geneva, Switzerland, Jefferson Lab is relatively obscure. But it will be the global focal point for this sort of nuclear physics. "It will be a very exciting program," says Fabienne Kunne, a physicist at the French Atomic Energy Commission in Saclay, who is not involved with the project. "It should make enormous progress."

Unlike particle physicists' quest for the famed Higgs boson, spotted in 2012 at CERN, Jefferson Lab's mission requires not one grand experiment but a mosaic of measurements. The diversity shows in the lab's four experimental halls: Two, including Hall A, feature spectrometers that can be reconfigured to study specific interactions, and two contain detectors designed to capture every interaction so that they can be sorted out later. "Jefferson Lab is a little bit more Wild West," says Cynthia Keppel, a physicist who oversees the two spectrometer halls. "You've got settlers coming in from all over with all manner of ideas."



The huge, reconfigurable spectrometers in Jefferson Lab's Hall A swivel around on massive steel wheels.

PHOTO: BILL KELLEY III

The mess inside a nucleon arises from the peculiar nature of the strong force. At first blush, that force works something like the electromagnetic force, which binds electrons to nuclei in atoms and produces light. Within an atom, the negatively charged electrons cling to the positively charged nucleus by exchanging massless quantum particles called photons. In the same way, the quarks within the nucleon cling to one another by exchanging massless particles called gluons, which carry the strong force.

But the strong force is far more complex than the electromagnetic force. Unlike the passive photons, gluons themselves exchange gluons—lots of them. Moreover, a nucleon's three valence quarks aren't the only ones inside it. Untold quark-antiquark pairs also flit into and out of existence. Those fleeting "sea" quarks need not be up and down quarks, but can be heavier strange and charm quarks, too. Thus, each valence quark is shrouded by a cloud of quarks and gluons in which "what you see depends on the scale at which you look," says Michael Pennington, chief theorist at Jefferson Lab.

That complexity makes calculating anything involving the strong force nearly impossible. For example, most of a nucleon's mass comes not from the valence quarks, but from the energy of the quark-gluon cloud (thanks to Einstein's equivalence of mass and energy). But only recently have theorists accounted for it in numerical simulations (*Science*, 19 December 2008, p. 1772). As for nucleons' spin, physicists once thought it came from the spins of the valence quarks. But since 1987, they have known that most of it must originate in some other way—either in the swirling motion of the quarks or in the gluons.

Unfortunately, physicists can't decipher nucleons by simply taking them apart. The strong force is so strong that they can't isolate a quark or a gluon the way they might pluck an electron from an atom. Strike a nucleon hard enough to smash it, and it will spew particles containing either three quarks or a quark-antiquark pair, forcing researchers to tease information from those composite particles instead.

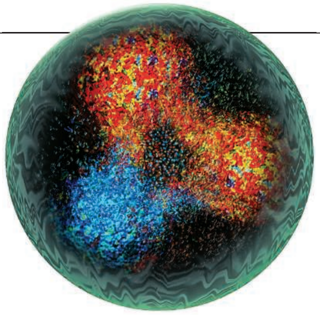
The "confinement" of quarks and gluons within other particles remains mysterious, says Colin Morningstar, a theorist at Carnegie Mellon University in Pittsburgh, Pennsylvania. Experiments and numerical simulations leave little doubt that it holds, but nobody has proved mathematically that it must or explained how the "field" of gluons arranges itself to make it happen. The Clay Mathematics Institute in Providence offers a $1 million prize for a proof. "I've demonstrated it numerically," Morningstar quips, "but they haven't sent me a check."

Jefferson Lab physicists are hardly the first to try to pierce the confusion. From 1967 until 1975, physicists at SLAC National Accelerator Laboratory in Menlo Park, California, used their linear accelerator to fire electrons into nucleons, discovering the quark in 1968. Since 1978, physicists at CERN have fired muons—heavier, unstable cousins of electrons—into nucleons, discovering the proton's "spin crisis." From 1992 to 2007, researchers at Germany's Electron Synchrotron lab in Hamburg collided beams of electrons and protons in their Hadron Electron Ring Accelerator.

But those efforts raised as many questions as they answered, Pennington says. "It's a little bit like the discovery of North America," he says. "These other experiments showed that there was something there, and we're going to map it out." Jefferson Lab physicists say the CEBAF accelerator is the ideal tool for the job.

Instead of a traditional circular accelerator or synchrotron, CEBAF consists of twin 235-meter linear accelerators, like the straights on a racetrack, connected by arcing beamlines. The electrons make five laps, passing through a different set of arcs each lap. The resulting beam has an extremely narrow range of energies, says Arne Freyberger, Jefferson Lab's director of accelerator operations. That narrow energy spread enables physicists to precisely measure the changes in a scattered electron's energy and momentum. And because the beam is continuous rather than pulsed like most accelerator beams, particle collisions don't bunch up in time, enabling researchers to use timing techniques to sift out rare decays.

Just to build CEBAF, which turned on in 1995 and cost $515 million, Jefferson Lab helped pioneer a whole new technology. Within an accelerator, charged particles gain energy by surfing radio waves sloshing in hollow "RF cavities" the size of a big salami. Until the 1990s, accelerators used copper cavities, but Jefferson Lab physicists opted for cavities of superconducting niobium. Although they must be cooled to near absolute zero with liquid helium, they consume just 5% as much power as copper cavities, says Robert Rimmer, an accelerator physicist at Jefferson Lab. "For a machine like CEBAF, you couldn't afford the power bill if you used copper cavities," he says. Superconducting cavities have become standard for accelerators.



The proton (artist's concept) is a bit like a troubled teenager: a mess inside and nearly incomprehensible.

In upgrading CEBAF, physicists doubled the accelerator's energy from 6 to 12 giga-electron volts simply by adding new cavities in empty space at the end of each linac. That extra energy will be a boon to the more than 70 experiments approved for the upgraded machine, most of which are devoted to fathoming the nucleon. In particular, the energy will literally add new dimensions to physicists' picture of nucleons.

For decades, physicists have made do with essentially one-dimensional views of nucleons. Ping electrons off a nucleon gently, and their deflections reveal the distribution of the quarks within—but only perpendicular to electrons' original path. Strike the nucleon hard enough to break it apart, and the electrons' deflections and energy losses will reveal the momenta of quarks and gluons within the nucleon—but only along the electrons' initial path.

In nuclear physics, higher energy means finer resolution. So the upgraded CEBAF will enable physicists to trace the distribution of the quarks' position and momentum in three dimensions. To do so, they must capture not only scattered electrons, but also other particles that shoot out of certain rare collisions. For example, Julie Roche of Ohio University, Athens, and colleagues will focus on a process in which an electron interacts with a quark by exchanging a photon that then rebounds out of the interaction. Working in the lab's Hall A, they aim to capture both the electron and the photon.

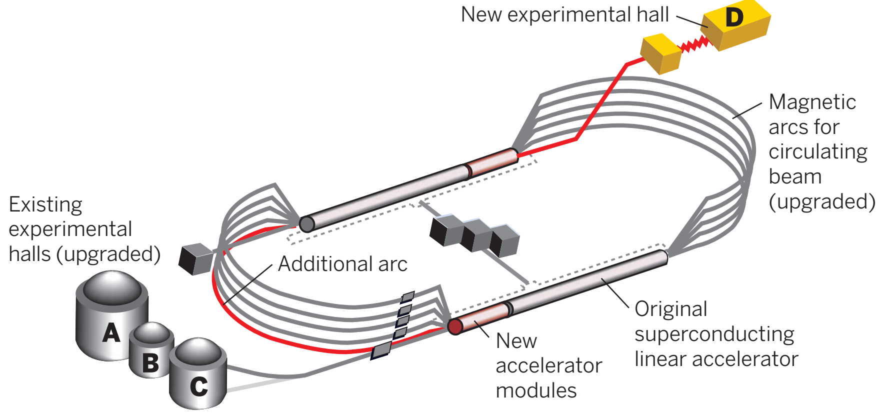
Tracking quarks in three dimensions would probe their swirling motion and could help explain the nucleon's spin. It would mark a "major advance" that could help unify physicists' understanding of the strong force, says Amanda Cooper-Sarkar, a physicist at the University of Oxford in the United Kingdom who does not work at Jefferson Lab.

For other clues to the strong force, Jefferson Lab researchers will look for new, exotic particles made of quarks and gluons. Physicists know of only two general kinds of particles cemented by the strong force: baryons, which contain three quarks or three antiquarks, and mesons, made of a quark-antiquark pair. But simulations suggest other combinations are possible. Particles called glueballs would consist entirely of gluons, and "hybrid" mesons and baryons would contain an extra "valence" gluon. They would have distinctive combinations of mass, spin, and symmetry properties that would show through in their decays.

A dedicated detector called GlueX housed in the new Hall D will search for those odd particles. GlueX researchers will first fire the CEBAF electron beam into a diamond crystal to produce polarized high-energy photons. These will then crash into a liquid hydrogen target to produce particles familiar and novel. If newcomers appear, the GlueX team aims to study the pattern of their properties, says Eugene Chudakov, a physicist at Jefferson Lab who oversees Hall D. "You cannot say anything [about the theory] if you see only one," he says. "You really need to be able to see several."

Electron racetrack

The CEBAF accelerator comprises two linear accelerators connected by arcing beam pipes. Electrons take up to five laps of the track. Thanks to a last-minute design change to the original accelerator, physicists had room to double CEBAF's energy just by extending each accelerator.



IMAGES: COURTESY OF JEFFERSON LAB (2)

Jefferson Lab physicists will also explore a long-standing mystery: why an isolated proton or neutron behaves differently from one in a nucleus. In 1983, researchers with the European Muon Collaboration (EMC) at CERN fired muons both into deuterium nuclei, which contain one proton and one neutron, and into iron nuclei, which contain 26 protons and typically 30 neutrons. In theory, the momentum distribution of the quarks should be the same in the nucleons in each nucleus. Instead, researchers found a deficit of higher momentum quarks in the larger one. That "EMC effect" is unexplained.

Or Hen of Tel Aviv University in Israel and Douglas Higinbotham of Jefferson Lab have an idea of how it comes about. In 2008, researchers working in Hall A found that in the nucleus of carbon-12, the six protons and six neutrons tend to form fleeting proton-neutron pairs. Last October, they spotted similar pairs in heavier nuclei, too. The paired particles overlap spatially, and the commingling of their quark-gluon clouds could cause the EMC effect.

To test that idea, the physicists will fire electrons from CEBAF into deuterium nuclei to probe the quarks inside the neutron. The electrons will also break up the nuclei. In each event, measuring the momentum of the recoiling proton should tell physicists how much the proton and neutron in the nucleus overlapped when the electron struck. If the number of high-momentum quarks in the neutron decreases when the neutron and proton overlap more, then such pairing could explain the EMC effect, Hen says.

Will the upgraded CEBAF completely decipher the proton and the neutron? Not quite. The machine should be adept at mapping the quarks. But to fully probe the gluons will require higher energy collisions than CEBAF can muster. Jefferson Lab researchers now hope to build a second accelerator that would fire protons or nuclei into their electron beam, boosting the collision energies. But they have competition: Physicists at Brookhaven National Laboratory in Upton, New York, want to build an electron-ion collider by adding an electron accelerator to their $1.1 billion 4-kilometer-long atom smasher, the Relativistic Heavy Ion Collider (*Science*, 19 October 2012, p. 324).

Wherever it winds up, such a machine is at least a decade away. For now, the Department of Energy has asked both labs to work together on developing the science case for building one, says Jefferson Lab Director Hugh Montgomery: "Unless we can convince people that it's worth doing this, there's no point in discussing where it could be built." Meanwhile, Jefferson Lab physicists are ready to ramp up their new experiments. For the proton, clarity may be coming. ■