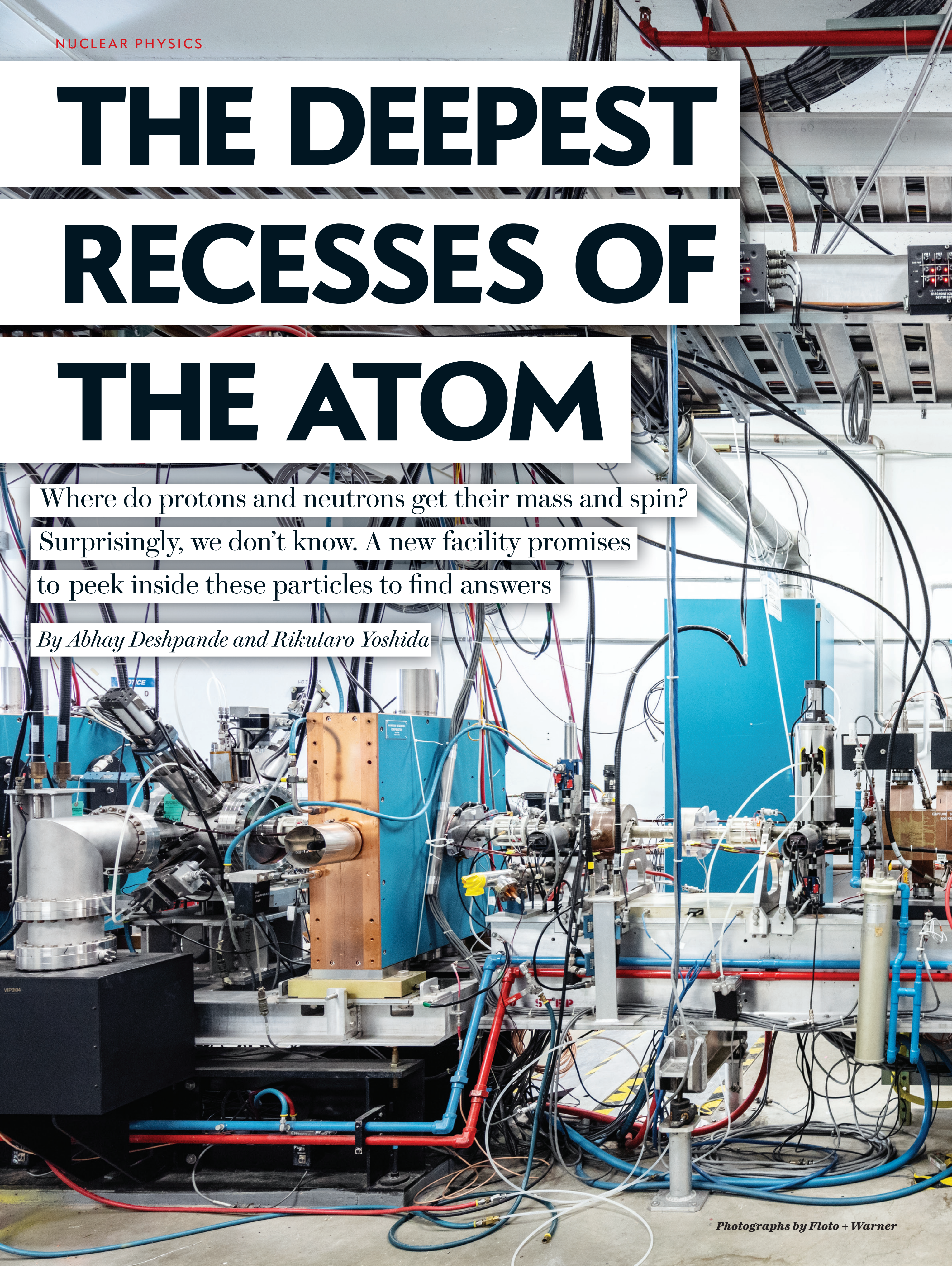
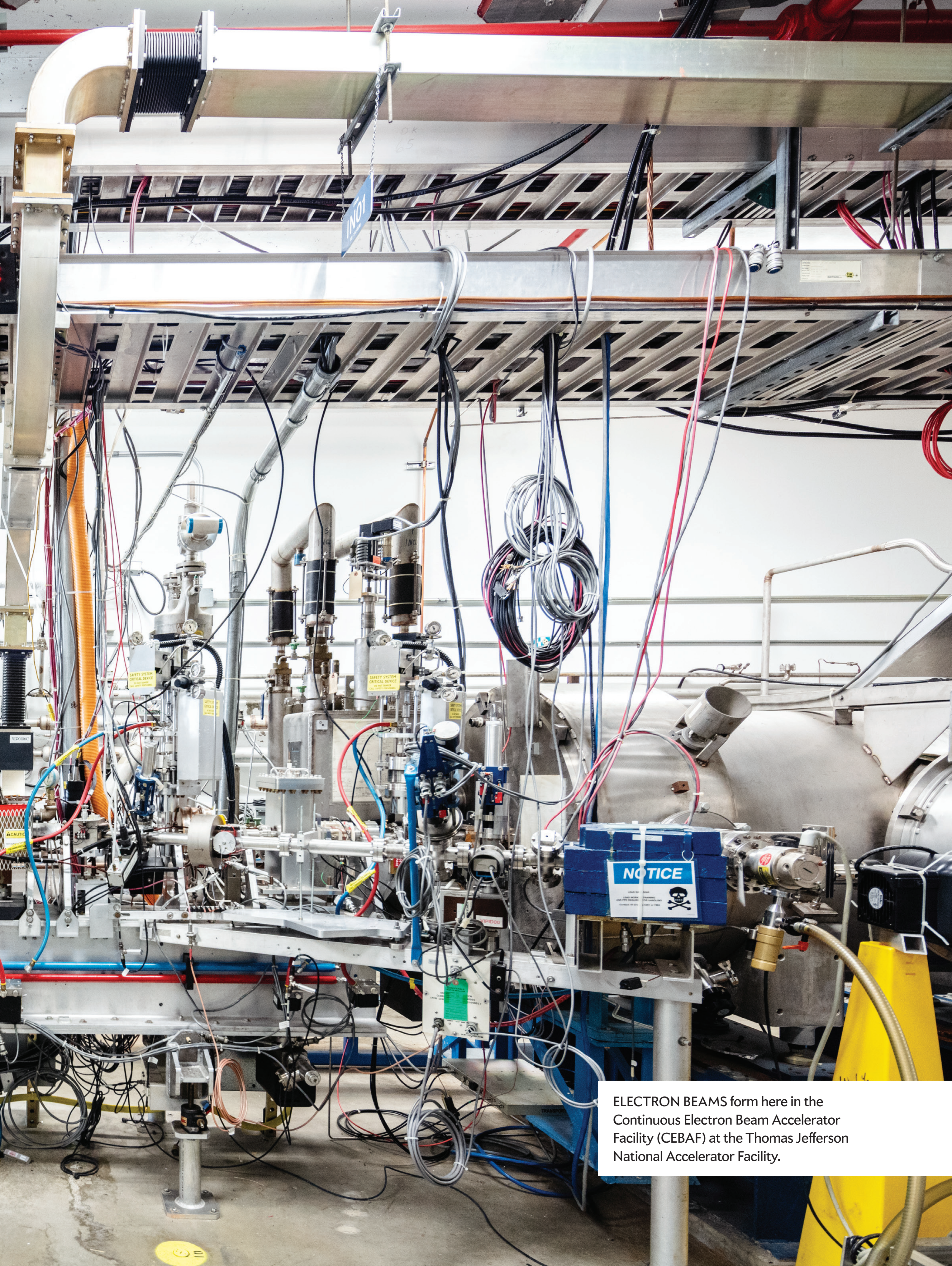
THE DEEPEST RECESSES OF THE ATOM

Where do protons and neutrons get their mass and spin? Surprisingly, we don't know. A new facility promises to peek inside these particles to find answers

By Abhay Deshpande and Rikutaro Yoshida



Photographs by Floto + Warner



ELECTRON BEAMS form here in the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility.

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THE OBSERVABLE UNIVERSE IS ESTIMATED TO CONTAIN ABOUT 10^{53} KILOGRAMS of ordinary matter, most of that in the form of some 10^{80} protons and neutrons, which, along with electrons, are the ingredients of atoms. But what gives protons and neutrons their mass?

IN BRIEF

Where do protons and neutrons get their mass and spin? Surprisingly, scientists do not really know.

Somehow the ingredients of these particles—quarks and gluons—combine in complex interactions that produce the properties of protons and neutrons.

To understand how, physicists want to build an Electron-Ion Collider that would smash protons and atomic nuclei with electrons to provide 3-D pictures of nuclei interiors.

The answer, it turns out, is not simple. Protons and neutrons are made up of particles called quarks and binding particles known as gluons. Gluons are massless, and the sum of the masses of the quarks inside protons and neutrons (collectively "nucleons") makes up roughly 2 percent of the nucleons' total mass. So where does the rest come from?

That is not the only mystery of these basic atomic pieces. Nucleons' spin is similarly inexplicable—the spin of the quarks inside them cannot account for it. Scientists now think that spin, mass and other nucleon properties result from the complex interactions of the quarks and gluons within. But precisely how this happens is unknown. Theory can tell scientists only so much because the interactions of quarks and gluons are ruled by a theory called quantum chromodynamics (QCD), which is devilishly difficult to compute.

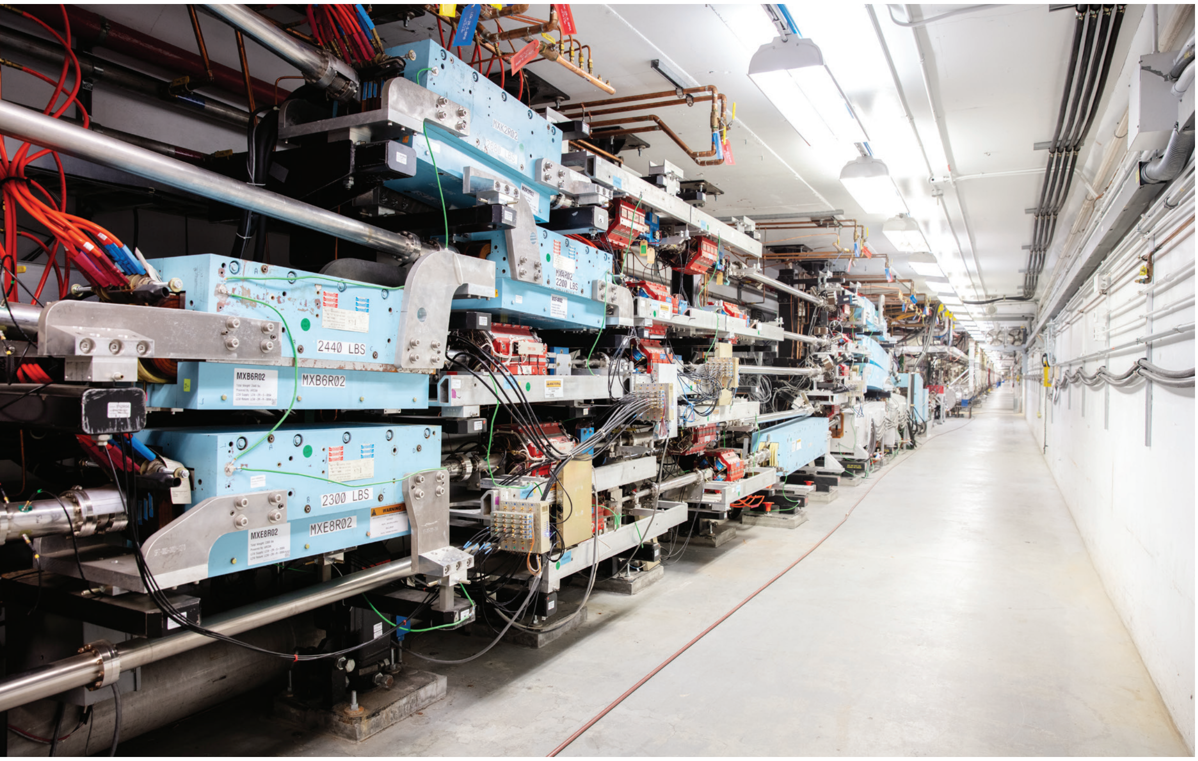
To move forward, we need new experimental data. That is where the Electron-Ion Collider (EIC) comes in. Unlike other atom smashers, such as CERN'S Large Hadron Collider near Geneva or the Relativistic Heavy Ion Collider (RHIC) in the U.S., which collide composite particles such as protons and ions, the EIC would collide protons and neutrons with electrons. The latter have no internal structure and become a kind of microscope to see inside the composite particles.

The EIC is one of the highest priorities of the U.S. nuclear science community and would most likely be built at one of two U.S. physics laboratories—Brookhaven National Laboratory on Long Island or the Thomas Jefferson National Accelerator Facility (Jefferson Lab) in Newport News, Va. If approved, the collider could begin collecting data around 2030. The machine will be able to see how the individual spin and mass of quarks and gluons, as well as the energy of their collective motion, combine to create the spin and mass of protons and neutrons. It should also answer other questions, such as whether quarks and gluons are clumped together or spread out inside nucleons, how fast they move and what role these interactions play in binding nucleons together in nuclei. The measurements at the EIC will deliver a trove of new information about how the basic constituents of matter interact with one another to form the visible universe. Fifty years after the discovery of the quark, we are finally at the threshold of unraveling its mysteries.

EMERGENT PHENOMENA

SCIENTISTS UNDERSTAND quite well how objects are made of atoms and how the characteristics of those objects arise from the characteristics of the atoms inside them. Indeed, much of our modern lives depends on our knowledge of atoms, electrons and electromagnetism—this knowledge is what makes our cars go and our smartphones work. So why is it that we do not understand how nucleons are made of quarks and gluons? First of all, nucleons are at least 10,000 times smaller than a proton, so there is no easy way to study them. Furthermore, the characteristics of the nucleons arise out of the collective behavior of quarks and gluons. They are, in fact, emergent phenomena, the outcome of many complex players whose interactions are too elaborate for us to fully understand at this point.

The theory that governs these interactions, quantum chromodynamics, was developed in the late 1960s and early 1970s. It is part of the overarching theory of parti-



BLUE DIPOLE MAGNETS help to steer electron beams as they accelerate around the CEBAF loop.

cle physics called the Standard Model, which describes the known forces of the universe (apart from gravity). Just as the electromagnetic force between electrically charged particles is carried by photons, or particles of light, QCD tells us that the strong force—the force holding nucleons together—is carried by gluons. The "charge" involved in the strong force is called "color" (hence "chromodynamics"). Quarks carry color charge and interact with one another by exchanging gluons. But unlike electromagnetism, where photons themselves have no electric charge, gluons carry color. Therefore, gluons interact with other gluons by exchanging more gluons. This wrinkle has profound implications. The feedback loop of interactions is why QCD is often too complicated to compute.

QCD also differs from more familiar theories because the strong force becomes weaker the closer together quarks get. (In electromagnetism, the opposite is true, and the force gets weaker as charged particles move farther apart.) At short enough distances within the nucleon, the quarks feel so little force they behave as if they are free. The discovery of this strange consequence of QCD won physicists David Gross, H. David Politzer and Frank Wilczek the 2004 Nobel Prize in Physics. When quarks move away from one another, the force between them grows rapidly and becomes so strong that quarks end up "confined" within the nucleon—that is why you will never find a quark or a gluon alone outside a proton or neutron. Scientists can calculate QCD interactions as long as the quarks are close together and interact weakly with one another; when they are farther apart, however—at distances close to the radius of the proton—the force becomes too strong, and the theory becomes too complex to be useful.

To understand the quantum realm of the strong force further, we need more information. Our mastery of the atomic realm, for example, did not come only from our understanding of atoms and their interactions—it came from our grasp of the emergent phenomena that arise on top of these fundamental building blocks. It was not possible to construct molecular biology from our knowledge of its foundations—atoms and electromagnetism. The eureka moment came when researchers discovered the double-helix structure of DNA. What we need to make progress in the quark-gluon world is to look inside the nucleus.

"SEEING" ATOMS

IN THE FIRST PART of the 20th century physicists discovered how to "see" atoms through a process called x-ray diffraction. By shining a beam of x-rays at a sample and studying the interference pattern that results when they pass through the material, scientists could see its atomic crystal structure. The reason this technology works is that the wavelength of an x-ray is similar to the size of an atom, giving us the ability to probe the atomic distance scale of nanometers (10^{-9} meter). In the same way, physicists first "saw" quarks 50 years ago in an experiment that collided electrons and protons in a process called deep inelastic scattering, or DIS.

In this method, an electron bounces off a proton (or neutron or nucleus) and exchanges a virtual photon with it. The virtual photon is not exactly real—it pops in and out of existence quickly as a consequence

Probing the Nucleus

Deep inelastic scattering (DIS) is a technique for studying atomic nuclei by hitting them with a beam of electrons at high speed. A new planned DIS facility called the Electron Ion Collider (EIC), proposed to be built at one of two U.S. laboratories (*right*), would provide 3-D pictures of the inside of protons, neutrons and atomic nuclei. With the EIC, scientists hope to solve the mystery of where protons and neutrons get their mass and spin—neither property can be accounted for by adding up the masses and spins of the quarks and gluons that make up these particles. Researchers also want to understand how the interactions between protons and neutrons arise from the quarks and gluons.

HOW DEEP INELASTIC SCATTERING WORKS

In DIS, an electron exchanges a "virtual photon"—a semi-real particle that pops into and out of existence quickly—with the quarks inside a proton or neutron. By analyzing the energy and recoiling angle of the electron as it bounces off, scientists learn about the object it hit. The higher the energy of the collision, the smaller the wavelength of the virtual photon, effectively creating a smaller probe that can "see" tinier scales within the nucleus.

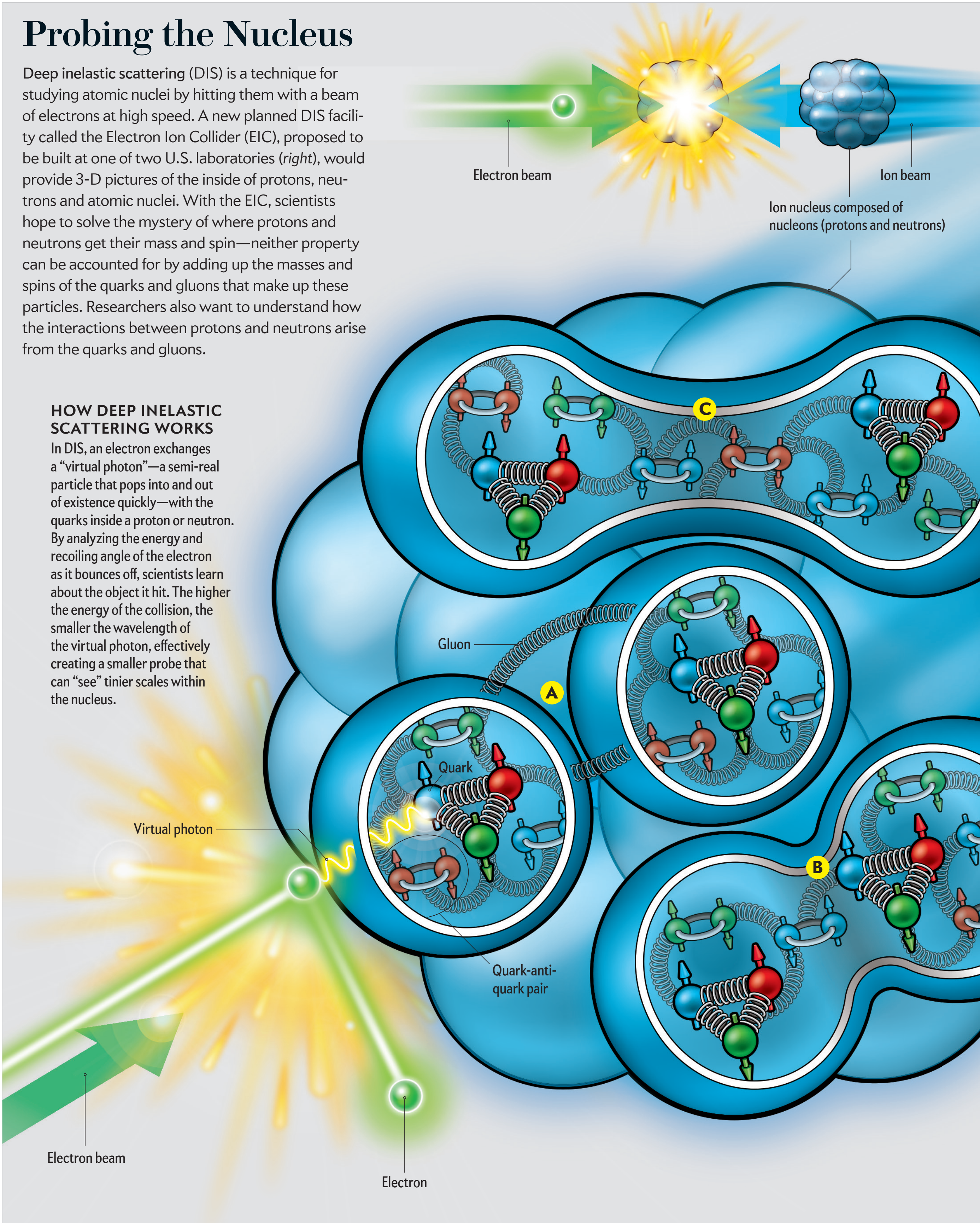
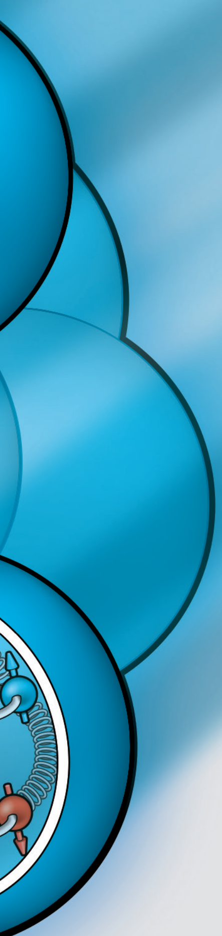
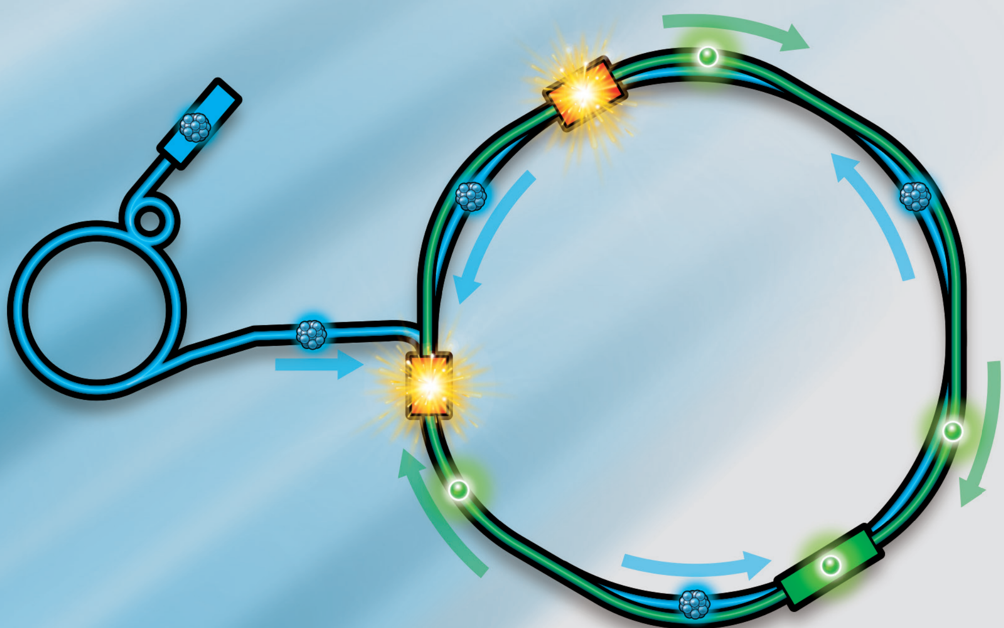


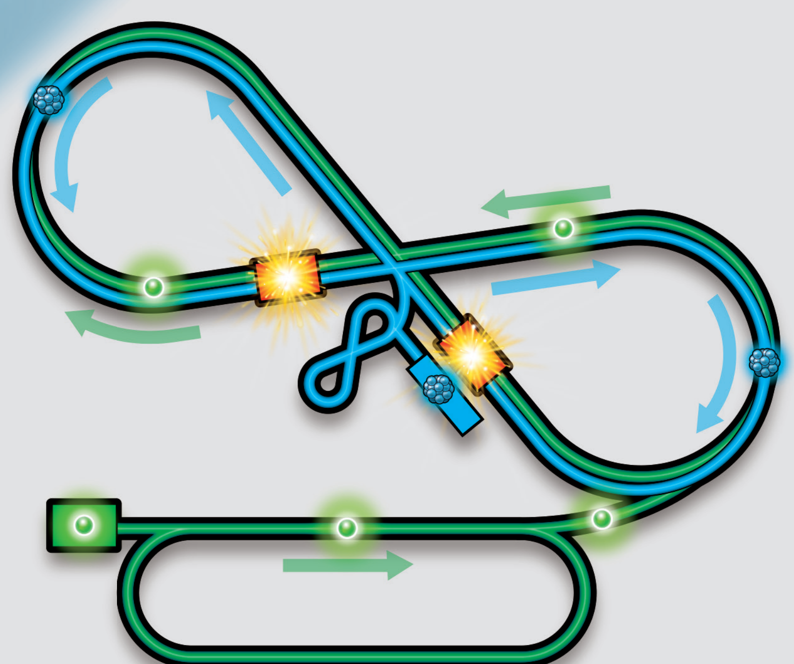
Illustration by Ben Gilliland



Scientists wonder if a proton and a neutron might sometimes share gluons between them A or prefer to pair up as in shape B or interact by exchanging quark-antiquark pairs C.



POSSIBLE SETUP AT BROOKHAVEN
One plan would build the EIC at Brookhaven Lab on Long Island, making use of the existing ring-shaped Relativistic Heavy Ion Collider (RHIC), which currently slams protons and heavier nuclei together. By adding a new electron accelerator inside the RHIC tunnel, researchers could collide electrons and ions at two points (*shown with flashes*) along the loop.



POSSIBLE SETUP AT JEFFERSON LAB
Another option would extend the recently upgraded electron accelerator called the Continuous Electron Beam Accelerator Facility (CEBAF, *bottom green loop*) at the Thomas Jefferson National Accelerator Facility in Newport News, Va. The electron beam would continue into a figure-eight-shaped "ring," and a new ion accelerator (*in blue*) running in the opposite direction would be added. Collisions between the two beams would occur at two points.

HEAVY IONS and polarized protons accelerate inside Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC).

of quantum mechanics, which governs particle interactions. By carefully measuring the energy and angle of the electron as it recoils, we gain information about what it hit.

The virtual photon's wavelength in DIS experiments is on the order of femtometers (10^{-15} meter)—the distance scale of the proton diameter. The higher the energy of the collision, the smaller the virtual photon's wavelength, and the smaller the wavelength, the more precise and localized the probe. If it is small enough, the electron in essence bounces off one of the quarks inside the proton (rather than the whole proton itself), providing a peek at the particle's inner structure.

The first DIS experiment was the SLAC-M.I.T. project at the facility then called the Stanford Linear Accelerator Center (SLAC). In 1968 it provided the first evidence of quarks—a discovery that won the experiment's leaders the 1990 Nobel Prize in Physics. Similar experiments discovered that quarks inside free protons and neutrons and those inside nuclei behave very differently. Furthermore, they found that proton and neutron spin does not come from the spins of the constituent quarks, as scientists had expected. This finding was first made in protons and initially called the "proton spin crisis." The first DIS collider, in which both electrons and protons were accelerated before crashing, was the Hadron-Electron Ring Accelerator (HERA) at the German Electron Synchrotron (DESY) research center in Hamburg, Germany, which ran from 1992 to 2007. The HERA experiments showed that what we thought was a simple configuration of three quarks inside each proton and neutron could in fact become a particle soup in which many quarks and gluons instantly appear and disappear. HERA significantly advanced our understanding of the structure of nucleons but could not address the Spin Crisis and lacked the beams of nuclei necessary to study quark and gluon behavior in the nuclei.

A major factor complicating all observations at this scale is the weirdness of quantum mechanics. These rules describe subatomic particles as hazes of probability: they do not exist in specific states at specific places and times. Instead we must think of quarks as existing in an infinite number of quantum configurations simultaneously. Furthermore, we must consider the quantum-mechanical phenomenon of entanglement, in which two particles can become connected so that their fates are intertwined even after they separate. Entanglement could pose a fundamental problem for observing at the nuclear scale because the quarks and gluons we would like to observe are at risk of becoming entangled with whatever probe we use to look at them—in the case of DIS, the virtual photon. It seems impossible to define what we mean by nucleon structure when what we find depends on how we probe it.

Luckily, by the 1970s QCD had advanced enough for scientists to figure out that the probe and the target in DIS experiments can be separated—a condition called factorization. At high-enough energies, scientists can essentially ignore the effects of quantum entanglement under certain circumstances—enough to describe the structure of the proton in one dimension. This meant that they could extract from DIS experiments a measurement of the probability that any given quark inside a proton is contributing a particular share of its forward momentum.

Recently theoretical advancements have enabled us to push further and describe the inner structure of nucleons in more than one dimension—not just how much quarks and gluons contribute to its forward momentum but how much they move side to side inside the nucleon as well.

But the real step forward will come with the EIC.

ELECTRON-ION COLLIDER

THE EIC WILL make a three-dimensional map of the interior of a nucleon. We expect the collider to deliver measurements of the positions and momenta of quarks and gluons and the amount each contributes to the nucleon's overall mass and spin.

The key advance of the EIC compared with previous DIS experiments is its brightness: it will produce between 100 and 1,000 more collisions per minute than HERA, for instance. In addition, the high energies of the colliding beams at the EIC will resolve distances of several hundredths the diameter of a proton, enabling us to investigate the regions where a large number of quarks and gluons each carry roughly 0.01 percent of the proton's forward momentum. The EIC will also let us control the alignment of the spin of the particles in its beams so that we can study how the spin of the proton arises from the QCD interactions of quarks and gluons. When incorporated into our modern theoretical framework, the EIC's measurements will allow us to create a truly 3-D image of the proton in terms of quarks and gluons.

BROOKHAVEN NATIONAL LABORATORY

We have many questions we hope to explore: For instance, are the constituents of the proton equally spread out within it, or do they clump together? Do some contribute more toward the particle's mass and spin than others? And what role do quarks and gluons play in binding together protons and neutrons to form nuclei? These quandaries are only beginning to be explored at existing facilities on the femtoscopic level. The EIC is the first machine that will lead us to complete answers.

One of the biggest unknowns in our conception of nucleon structure is what happens when we look at these particles with an extremely fine probe at very small scales. Here strange things start to happen. QCD predicts that as you probe at higher and higher energies, you will find more and more gluons. Quarks can radiate gluons, and those gluons in turn radiate more gluons, creating a chain reaction. Strangely, it is not the action of measurement that causes this gluon radiation but the weirdness of quantum mechanics that tells us the inside of the proton is different—there are simply more gluons—the closer you look.

Yet we know this cannot be the entire solution, because that would mean matter is growing with no limit—in other words, atoms would have an infinite number of gluons the closer you looked at them. Previous colliders, including HERA, have seen hints of a state of "saturation," in which the proton simply cannot fit any more gluons and some start to recombine, canceling out the growth. Physicists have never detected saturation unambiguously, and we do not know the threshold at which it occurs. Some calculations suggest that gluon saturation forms a novel state of matter: a "color glass condensate" with extraordinary properties. For instance, the energy density of gluons may reach an unprecedented 50 to 100 times the energy density inside neutron stars. To reach regions of the highest possible gluon density, the EIC will use heavy nuclei instead of protons to detect this fascinating phenomenon and study it in detail.

BUILDING THE EIC

PLANS FOR THE NEW COLLIDER have strong endorsements from the most recent (2015) long-range planning meeting of the U.S. nuclear science community as well as the U.S. Department of Energy, which in 2017 requested an independent evaluation of the EIC from the U.S. National Academies of Sciences, Engineering, and Medicine (NAS). In July 2018 the NAS committee found the scientific case for the EIC to be fundamental, compelling and timely.

There are two possible paths for building this machine. One would upgrade the RHIC at Brookhaven. This plan, dubbed the eRHIC, would add an electron beam inside the existing RHIC accelerator tunnel and have it collide at two different points with one of the RHIC's ion beams.

Another possibility is to use the electron beam at the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab. Under a design called the Jefferson Lab EIC (JLEIC), the CEBAF beam would be routed into a new collider tunnel to be built next door.

Either of these facilities would provide a huge leap in our understanding of QCD and, at last, a visualization of the interior of nucleons and nuclei. Either should allow us to tackle the questions of spin, mass and other characteristics of nucleons that have perplexed us so far. And either would have the capability to collide many species of nuclei, including heavy gold, lead and uranium, which would enable us to study how the spread of quarks and gluons changes when their nucleons are part of larger nuclei. We would like to know, for instance, whether some gluons begin to overlap and become "shared" by two different protons.

FEMTOTECHNOLOGY?

IN THE 21ST CENTURY the very size of the atom is the limiting factor in our technologies. In the absence of a major breakthrough, the length of 10 nanometers (about 100 atoms wide) is probably as small as electronic parts will get, suggesting that conventional computing power is unlikely to advance in the future at the rate it has for more than 50 years.

Yet nucleons and their internal structure exist at a scale a million times smaller. The strong force that governs this realm is roughly 100 times stronger than the electromagnetic force that powers current electronics—in fact, it is the strongest force in the universe. Might it be possible to create "femtotechnology" that works by manipulating quarks and gluons? By some measure, this kind of technology would be a million times more powerful than current nanotechnology. Of course, this dream is a speculation for the far-off future. But to get there, we first have to gain a deep understanding of the quantum world of quarks and gluons.

The EIC is the only experimental facility being considered in the world that could provide the data needed to understand QCD to the fullest extent. Building the EIC, however, will not be without its challenges. The project must deliver very bright and highly focused beams of electrons, protons and other atomic nuclei over a wide range in energies to create 100 to 1,000 times more events per minute than the HERA collider. The spin studies demand that the machine provide beams of particles whose spins are maximally aligned and can be controlled and manipulated. These challenges will require innovations that promise to transform accelerator science, not only for the benefit of nuclear physics but also for future accelerators studying medicine, materials science and elementary particle physics. SA

MORE TO EXPLORE

An Assessment of U.S.-Based Electron-Ion Collider Science. National Academies of Sciences, Engineering, and Medicine. National Academies Press, 2018. **https://doi.org/10.17226/25171**

FROM OUR ARCHIVES

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