Each time physicists probe the teeming interior of the proton, aswarm with short-lived particles, they seem to turn up more surprises

Exploring the Proton Sea

In the Dr. Seuss story "Horton Hears a Who!," Horton the elephant insists to his fellow animals, all deeply skeptical, that a speck of dust is teeming with life. With his sensitive ears, Horton can hear the chatter and buzz of its microscopic inhabitants—whole cities of them. Physicists studying the humble proton will understand his fascination. To most researchers, the proton is a workaday particle: the stuff that gives every atomic nucleus its positive charge, and the heart of the ubiquitous hydrogen atom. But recent studies probing deep into the proton are revealing a society as complex as the one on Horton's dust mote: a churning and bubbling sea of "virtual" particles that pop into existence for an instant, then disappear again, bathing more enduring components of the proton in a quantum flux.

The ephemeral nature of the sea's inhabitants, mass- and charge-carrying particles called quarks and force-carrying particles called gluons, belies their importance. "This virtual sea is responsible for many of the proton's properties, such as its mass, its structure, and its interaction with other particles and fields," says Michael Leitch of the Los Alamos National Laboratory in New Mexico. Charting the sea is also important for future experiments: The world's most powerful particle accelerator, the Large Hadron Collider now being built at the CERN particle physics lab near Geneva, will slam protons together at enormous energies. One aim is to create the Higgs boson, the particle thought to endow all others with mass, which has been on physicists' "most wanted" list for 3 decades. Knowing what is in the proton is essential for calculating what will come out of those collisions. "If new physics is to be discovered, we need to understand the predictions from the old physics with some precision," says Arie Bodek of the University of Rochester in New York.

Yet the normal theoretical apparatus used to describe the subatomic landscape can make few predictions at the energies found in the proton's interior. As a result, physicists found themselves in uncharted waters as they began exploring the interior of the proton by probing it with beams of other particles. Lately, a series of experiments at accelerators in Europe and the United States to measure the different types of quarks in the proton sea, compare the proportion of quarks to gluons, and identify differences in the quark sea of the proton and that of the proton's sister particle, the neutron, have delivered a string of surprises. As Anthony Thomas of the University of Adelaide in Australia puts it, "Every time we have tested a prejudice about the sea ... it has proven to be wrong."

When the proton was discovered by Ernest Rutherford in 1919, it was thought to be an indivisible basic building block of matter. But that fundamental status did not last long. Early proton-proton collision experiments in the 1930s revealed that the proton was more than an infinitesimally small "point-charge": It had a finite size and presumably some kind of structure. Further experiments revealed a bewildering array of particles related to the proton, whose properties fell into patterns that cried out for an explanation in terms of more fundamental building blocks. A breakthrough came in the 1960s, when theoreticians Murray Gell-Mann of the California Institute of Technology in Pasadena and his ex-student George Zweig at CERN proposed that fundamental particles called quarks make up protons, neutrons, and the short-lived particles called mesons. Protons and neutrons contain three quarks each, and mesons a quark and an antiquark. In 1969, electron-proton collisions at the Stanford Linear Accelerator Center confirmed the existence of pointlike nuggets inside the proton, which had to be quarks.

Flavor enhancers. Fermilab's NuTeV team found a shortage of strange quarks in the proton.

The new picture painted by Gell-Mann and Zweig was simple: The proton is made of two so-called "up" quarks and a single "down" quark—its "valence" quarks. Each quark has a fractional electric charge, and the combination in the proton adds up to provide its single positive charge. In the neutron the numbers of ups and downs are reversed, giving a one-up, two-down combination that makes the neutron electrically neutral. The theory later found to govern these quarks and their interactions was dubbed quantum chromodynamics (QCD), now part of the Standard Model by which physicists understand the subnuclear world. QCD predicts that quarks carry a "color charge," mimicking the familiar electrical charge, which is the source of the force binding them together and is carried by gluons, force particles analogous to the photons of electromagnetism.

But even this tidy model of three valence quarks and a buzz of gluons holding them together proved to be far from the whole story. Experiments at CERN in the early 1970s probing protons with ghostly particles called neutrinos revealed the presence of antiquarks along with the three valence quarks, and soon researchers' image of the proton began to change. A proton "is not a rigid thing with three balls in it all hooked up with

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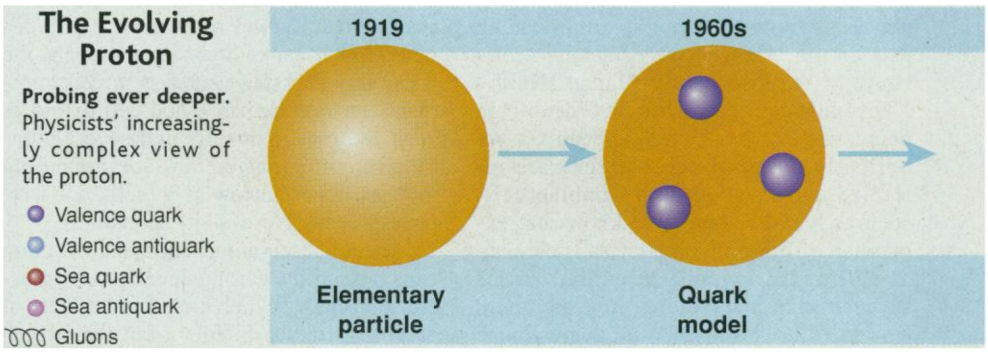
The Evolving Proton

Probing ever deeper. Physicists' increasingly complex view of the proton.



springs or something," says James Stirling of Britain's University of Durham. Instead, the gluons exchanged by the valence quarks have a tendency to split spontaneously into more gluons or quark-antiquark pairs, creating a lively "soup" made up of a seemingly infinite number of particles. "The valence quarks excite from the neighboring vacuum a dynamic 'sea' of short-lived gluons and quark-antiquark pairs," says Leitch.

Physicists soon realized that to understand the proton they would have to understand the quark sea. "Past experiments have shown that a major part of the proton's momentum is carried by sea quarks and gluons," says Dietrich Harrach of CERN. "[The sea] is going to tell us a lot of interesting detail about how QCD works on the scale of proton," says Stirling. "We can't claim to understand QCD without understanding this."

Getting an inside look

A window on the interior of the proton opened in 1992 with the inauguration of HERA, an electron-proton collider at Germany's DESY accelerator center that was especially designed to probe the proton's structure. Whereas earlier experiments explored the proton by firing electrons at a fixed proton target and examining the debris, HERA can accelerate both a beam of protons and a beam of electrons (or electrons' antimatter counterparts, positrons) and smash them together head-on. In such a collision, the probe electrons throw out photons that scatter off proton constituents, creating a freeze-frame image of the seething mass of quarks, antiquarks, and gluons in the proton.

Over the past 7 years, researchers have used HERA to take a census of the sea's inhabitants. One way to classify them is by the fraction of the whole proton's momentum they carry, revealed through the scattering angles and energies of the probe particles leaving the collision. Many measurements have confirmed that valence quarks carry a lot of momentum, while the number of virtual quarks and gluons mushrooms at smaller momentum fractions. That has come as no surprise. "The pileup of the gluons and … sea quarks at small momentum fractions is expected," says Stirling. QCD predicts such a distribution because valence quarks naturally throw off gluons having a smaller momentum than themselves, and these gluons in turn spark quark-antiquark pairs having still smaller momenta, and so on down the line, explains John Dainton, a member of the team operating HERA's H1 detector.

Ongoing measurements at H1 and its sister detector ZEUS are also confirming another prediction of QCD: that at the smallest momentum fractions, virtual gluons greatly outnumber virtual quarks and antiquarks. "[Gluons] just prefer to split into each other," says Stirling. With each split sharing the parent's momentum between the daughters, the result, according to QCD, is a burgeoning population of low-momentum gluons.

Severing symmetry. DESY's Hermes team found an imbalance of up and down antiquarks.

So far so good. But researchers got a surprise when they began to look at the types, or flavors, of quarks that inhabit the sea. "The obvious first guess would be that there is no flavor structure of the sea, it's just democratic," says Stirling. The complication is that the different quarks have different masses, and heavier quarks will have a harder time popping into existence. This should mean that the three heaviest of the six quark flavors—charm, bottom, and top—should be rare within the proton. The lightest, up and down, should be present in equal amounts, and strange quarks, with a slightly higher mass, should be a bit less numerous.

HERA's electron beam has trouble mapping out these flavor distributions, however, because electrons are "flavor blind." Hence a team at the Fermi National Accelerator Laboratory in Illinois is probing the nucleus using neutrinos, in an experiment called NuTeV. These wispy particles interact with quarks via a particle called the W boson, rather than a photon, in such a way that the debris of the collision reveals what kind of quark was involved. "What we have found," says Michael Shaevitz of Columbia University in New York City, a member of the NuTeV team, "is that [the strange content] is much smaller than expected, about one-half the amount of the up or down quark sea." He expects the result to be confirmed by further NuTeV measurements later this year.

Theorists have trouble explaining this because their trick for deriving predictions from QCD, called perturbation theory, cannot handle particles with a mass as small as the strange quark's. The more massive charm quark does, however, fall within the scope of perturbation theory, and estimates of the charm quark population inside protons compare favorably with recent measurements made by H1 and ZEUS at HERA, which have looked for charm quark–containing particles dislodged from the proton by collisions.

More depth to the sea

Leitch and his colleagues on another Fermilab experiment, nicknamed NuSea, last year uncovered an even more startling inconsistency: The number of antiup quarks in the proton sea is not the same as the number of antidowns. Physicists had always assumed that up and down quarks—and their antimatter partners—populate the sea equally. The NuSea team compared populations of these two antiquarks by firing a proton beam at two targets: a flask of hydrogen, which essentially contains nothing but protons, and a flask of deuterium, an isotope of hydrogen that contains equal numbers of neutrons and protons. Collisions between quarks in the proton beam and antiquarks in the target nuclei yield muons—heavy cousins of the electron—paired with antimuons, which a detector picks up. The ratio of the yields from the two different targets translates into the ratio of antidown to antiup quarks in the proton sea. The result, reported last year in the 27 April issue of *Physical Review Letters*, "establishes totally unambiguously that there are more antidown than antiup quarks in the proton," says Thomas.

The case strengthened recently when ex-

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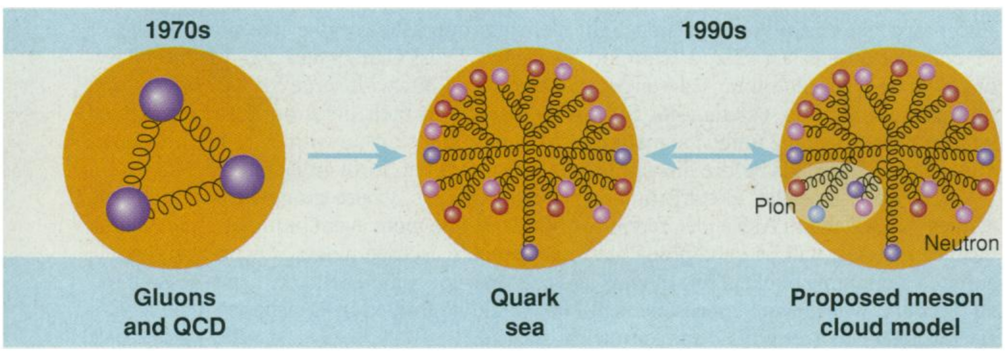

perimenters at Hermes, HERA's third detector, collided positrons with both protons and deuterium and compared the numbers of positively and negatively charged pions that emerged. The experiment "is based on the fact that scattering [a positron] on an up antiquark most likely results in a negative pion, while hitting a down antiquark would lead to a positive pion," says Antje Brüll of the Hermes team. The pion counts revealed an excess of down antiquarks.

The agreement between the Hermes results, reported in the 21 December 1998 *Physical Review Letters*, and the results from NuSea is "good," says Brüll. The two experiments found that down antiquarks outnumber up antiquarks by as much as three to two, implying that the up and down quark populations of the sea are similarly unbalanced. This "relatively huge" difference is not really understood, says Stirling. "It is a fundamental property of perturbative QCD that the sea would have to be 'flavor symmetric,' " says Thomas. The antidown-antiup imbalance "is telling us something vitally important about the … structure of the [proton]" beyond the range of perturbation theory, he says.

Thomas has proposed an explanation for this imbalance, called the meson cloud model, in which the proton fluctuates between being a pure proton and a mixture of a neutron plus a positively charged pi meson, and several other overlapping particle combinations allowed by quantum theory. Because a positive pi meson consists of an up quark and down antiquark, an experiment that "sees" the proton as a neutron plus a pion will record more down antiquarks than up antiquarks, according to Brüll. Both Hermes and the NuSea data "clearly favor the so-called meson cloud models," she thinks.

Not everyone is so enthusiastic, however. "There are many high-energy people who refuse even to imagine that pions could contribute" within a proton or in such a simplistic way, says Thomas. Stirling feels that, because physicists cannot count quarks directly but must rely on the debris of collisions, there may be some bias in the way debris from certain collisions rearranges into observable particles.

And the proton keeps turning up new surprises. Two months ago, Thomas published a new analysis of Fermilab neutrino-nuclei data and a CERN experiment that scattered muons from protons and found what might be another anomaly of the quark sea. In the 9 November 1998 issue of *Physical Review Letters*, Thomas and his collaborators, Csaba Boros, also in Adelaide, and Tim Londergan at Indiana University, Bloomington, claim that for momentum fractions of less than about 10%, the number of up antiquarks in the proton does not equal the number of down antiquarks in the neutron.

If true, this would send shock waves through the particle physics community, as researchers have always assumed that protons and neutrons are related by a simple interchange of up and down quarks and antiquarks. "The effect, if it holds up experimentally, is huge," says Thomas. "We know of no theoretical mechanism which could explain these data." According to Shaevitz, however, forthcoming data from two Fermilab experiments may contest Thomas's ideas.

The challenge ahead will be to fit this swath of unexpected results into the framework of QCD. "While QCD is an amazingly beautiful theory, most of its consequences remain inaccessible to [theorists]," says Sarada Rajeev of the University of Rochester. But the clues that experimenters have been able to tease out of the proton have put some of the answers within reach. Forthcoming experiments may serve up more clues, and perhaps more surprises. Dr. Seuss's Horton finally gets the dust speck's inhabitants to shout loudly enough to be heard, convincing all the doubters. Perhaps diviners of the proton's sea could use some similar inside help. **–ANDREW WATSON**

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NUCLEAR PHYSICS

Element 114 Lumbers Into View

The race to capture one of the biggest prizes in nuclear physics—an exceptionally long-lived superheavy element—appears to be over. In a cautiously worded e-mail to a close-knit group vying for the trophy, scientists at the Joint Institute for Nuclear Research in Dubna, near Moscow, this month unveiled evidence for the creation of a nucleus with 114 protons—the heaviest element yet forged.

If confirmed, the sighting would mean far more than just another entry in the periodic table. Element 114 appears to last for 30 seconds before decaying, a longevity that would verify predictions of an "island of stability" beyond the lighter, less stable nuclei glimpsed earlier. "This is the most exciting event in our lives," says Albert Ghiorso of Lawrence Berkeley National Laboratory (LBNL) in California, who has spent 35 years hoping his group would plant the flag on the fabled terrain. The finding, adds Sigurd Hofmann of the Institute for Heavy Ion Research (GSI) in Darmstadt, Germany, whose team many observers expected to get there first, "opens up a window to a quite new field of research."

"This is the most exciting event in our lives."

—Albert Ghiorso

For a half-century physicists have used nuclear reactors and particle accelerators to forge new elements, beyond the 94 known to exist in nature. Like climbing taller and taller peaks, each successive effort has required vastly more energy and greater technological legerdemain. And for ever-more fleeting results: Although some transuranic isotopes last for years, an isotope of the last element created—number 112—is so unstable it sticks around a mere 280 microseconds. Theorists have predicted, however, that this trend toward instability would be reversed as additional protons and neutrons filled out nuclear shells. With a full shell of protons, element 114 should lie well within the stable island.

To make the element, the main contenders—GSI, LBNL, and Dubna in collaboration with Lawrence Livermore National Laboratory (LLNL) in California—plotted varying strategies (*Science*, 24 October 1997, p. 571). GSI went with cold fusion, a technique in which two medium-sized isotopes are fused in an accelerator—an approach that already secured their claim to bohrium (element 107), hassium (108), meitnerium (109), and the unnamed elements 111 and 112. Last spring Hofmann's GSI team tried to create element 113 but failed.

The Dubna-LLNL group took a different tack, heading straight for 114. Their hot-fusion approach involves smashing light elements into a heavy one like plutonium. For several weeks late last year, a team led by Dubna's Yuri Oganessian and Vladimir Utyonkov pounded a plutonium-244 target provided by LLNL with some 5×10^{18} atoms of a rare calcium isotope, calcium-48. Sifting the data from their detector, the team spotted what appears to be the unique signature of a decay chain starting with $^{289}114$, which hung around for 30 seconds before hiccuping an alpha particle to form an isotope of 112.

More work is needed to confirm the find, says Ghiorso, whose group will do follow-up studies. Says Dubna's Alexander Yeremin: "If at least one more event [is] found with similar characteristics, it will be good proof." In a sad footnote, isotope pioneer Glenn Seaborg, 86, suffered a crippling stroke a few months ago and may not comprehend the news, says Ghiorso. Seaborg, whose name graces element 106, would be thrilled by a discovery that, if verified, would open a terra incognita for nuclear science. **–RICHARD STONE**