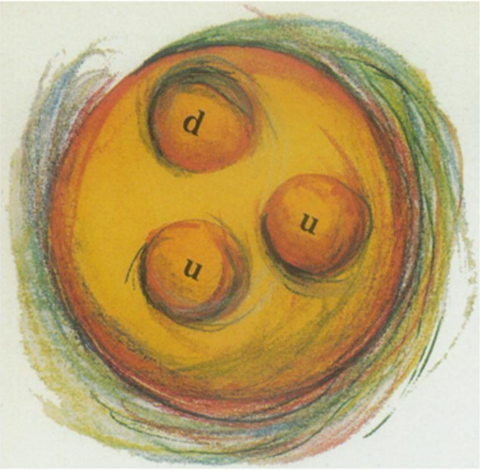

Proton-Go-Round

Whence does the proton get its spin?

By IVARS PETERSON

For generations, Rudyard Kipling's *Just So Stories* have entertained young and old with their fanciful accounts of such natural wonders as how the leopard got its spots and how the elephant got its trunk.

For the past decade, physicists have been trying to write their own, real-life tale of explanation. Their protagonist is the proton—the heart of the hydrogen atom and one of the main constituents of matter. Their long-standing pursuit is the origin of this particle's spin.

Standard reference books tell part of the story. The proton has a definite, measurable mass, electric charge, and spin, and its lifetime is at least as long as the universe is old. It is solid enough to be fired like a projectile in a particle accelerator.

On the other hand, the proton has a complicated internal structure. It's composed of different types of quarks held together by the so-called strong force, which is mediated by particles known as gluons.

The spin of any elementary particle is represented by a quantum number that must be some multiple of 1/2: 0, 1/2, -1/2, 1, -1, 3/2, -3/2, and so on. Because the proton has a well-defined spin of 1/2, the spins of the individual bits and pieces inside it should add up to exactly that value.

In 1988, however, physicists were shocked to find experimental evidence suggesting that very little—perhaps none—of the proton's spin comes from the spin of the quarks thought to make up the proton (SN: 4/8/89, p. 215). They called this apparent paradox the proton spin crisis.

Since then, researchers have refined their experimental results and their theoretical calculations. The scope of the problem is now understood and the apparent smallness of the quark contribution confirmed, but the origin of the proton's spin remains largely a mystery.

"It's been a remarkable few years from both the experimental and the theoretical side," says Timothy E. Chupp of the University of Michigan in Ann Arbor. Physicists are now preparing a new generation of experiments to probe the inner workings of the proton in even greater detail.

"We want to make sure that we have the correct picture or model of what is inside the proton and how it adds up to the numbers we know well," says Emlyn W. Hughes of the California Institute of Technology in Pasadena. "The proton is complicated, but it is a very, very important object in our lives. It is unsatisfying intellectually that we cannot understand how the inside of the proton behaves."

To understand how a proton works, physicists must try to relate its measured properties as a composite particle to its complex internal structure (SN: 8/27/94, p. 140).

At the simplest level, a proton consists of three quarks: two up quarks, each with an electric charge of +2/3, and a down quark, with an electric charge of -1/3. The quarks are held together by gluons, which, in effect, shuttle between the quarks to keep them bound.

The gluons embody the strong force, which binds the quarks in groups of three (as in protons and neutrons) or in quark-antiquark pairs (as in particles called mesons). The mathematical relationships of the theory known as quantum chromodynamics describe how quarks interact via gluons.

Each quark has a spin of 1/2, and each gluon a spin of 1. Initially, theorists made the naive assumption that two of a proton's quarks align like tops spinning in opposite directions, so their net spin is zero, while the third quark has an uncompensated spin of 1/2. This configuration leads to an overall spin of 1/2 for the proton, provided that the spins of the gluons somehow cancel out.

Theorists came to realize that such a model represents a gross oversimplification of the complex dynamics inside a proton, but they hoped it would suffice to account for important aspects of the proton's behavior. Indeed, quark-gluon interactions are so complicated that physicists have been forced to create simple models that capture the essential features of the phenomena, thus avoiding the unwieldy mathematical baggage of the full theory.

The first news that the simple quark spin model was inadequate came from the 1988 experiment at the European Laboratory for Particle Physics (CERN) in Geneva. Members of the European Muon Collaboration (EMC) fired a beam of high-energy muons (heavy analogs of the electron) into a frigid ammonia target. An ammonia molecule consists of one nitrogen atom and three hydrogen atoms. The protons of the ammonia's hydrogen atoms were all aligned, or polarized, so that their spins were either parallel or antiparallel to the direction of the muon beam. The researchers then recorded the directions in which the muons were deflected by the protons.

At high energies, the muons interact with individual quarks within the proton rather than with the proton as a whole. The pattern of muon scattering therefore carries information about the arrangement of the quarks. Armed with the EMC results, theorists were able to calculate the total spin content of the proton carried by the quarks. To everyone's amazement, they came up with an answer that was close to zero. In other words, the spins of all the quarks, when added together, cancel nearly completely.

Those startling results set off a flurry of theorizing. "Hundreds of theoretical papers were written," Hughes says. "The field exploded, and the famous 'proton spin crisis' was born."

Was there a problem with the theory, the experiment, or both?

One check on the experimental results was to perform a similar experiment using neutrons instead of protons. A neutron, which also has a spin of 1/2, consists of two down quarks and one up quark.

That experiment was done at the Stanford Linear Accelerator Center (SLAC). Researchers tracked electrons scattered by a target made up of helium-3 nuclei (each composed of two protons and a neutron). When the nuclei are polarized, the proton spins line up antiparallel to each other and cancel out. The results indicated that a neutron's quarks carry roughly 50 percent of its spin (SN: 9/18/93, p. 191).

Because the EMC and SLAC experiments were performed under quite different conditions, comparing the two sets of measurements directly proved difficult. A second round of experiments at SLAC and CERN was initiated to help resolve the discrepancy, even as theorists improved their methods of calculation.

At SLAC, researchers obtained high-precision results for the quark spin contribution in the proton and deuteron (composed of a proton and neutron), confirming that the constituent quarks of both the proton and the neutron carry only a fraction of the particle's overall spin. In 1995, the researchers more than doubled the energy of the electron beam to measure again the spin effects in helium-3 nuclei and in protons and deuterons.

Despite numerous technical difficulties, the SLAC team obtained enough high-quality data to pinpoint the quark contribution. "It is difficult to envision any future experiments outdoing the precision of these SLAC experiments in this energy range," Hughes comments.

At CERN, the Spin Muon Collaboration followed up the original EMC experiment, collecting data from firing muons at polarized protons until late last year. Both the SLAC and CERN data now essentially agree, indicating that only about 30 percent of the proton's and neutron's spin is found among the quarks.

The rest of the proton's spin must come from its gluons and the movements of gluons and quarks within the proton.

Complicating the picture, the number of quarks within the particle can actually fluctuate rapidly with the continuous creation and annihilation of quark-antiquark pairs. In other words, the three constituent quarks speed about within a foaming sea of virtual particles produced by short-lived quantum fluctuations, during which a gluon can momentarily split itself into a quark-antiquark pair.

It's also possible that not only up and down quarks but also the other varieties of quarks—strange, charm, bottom, and top (SN: 7/1/95, p. 10)—can take part in the fluctuations to create a mess of appearing and disappearing particles.

Recent experimental searches for evidence of strangeness in the proton imply that strange quarks carry an appreciable fraction of the particle's spin. On average, however, the spins of the strange quarks apparently point in the opposite direction to that of the proton itself.

That leaves a number of theoretical puzzles concerning the role played by strange quarks, says Robert L. Jaffe of the Massachusetts Institute of Technology.

At the moment, most physicists suspect that much of the proton's spin comes from its gluons. Somehow, these particles move or orient themselves in such a way that they produce a net spin.

In the Aug. 18 PHYSICAL REVIEW LETTERS, Ian Balitsky of Old Dominion University in Norfolk, Va., and Xiangdong Ji of the University of Maryland at College Park calculate that gluons contribute at least half of the proton spin. Hence, gluons are at least as important in determining proton spin as quarks, they argue.

However, there is scant experimental evidence concerning the gluon's effect on the proton's spin. So the gluon hunt is on.

At the Deutsches Elektronen-Synchrotron (DESY) facility in Hamburg, Germany, physicists participating in the HERMES experiment are now studying collisions between high-energy, spin-polarized positrons (the antimatter counterpart of electrons) and a gas of spin-polarized helium-3 nuclei. As reported earlier this year, preliminary data from HERMES confirmed the results of the SLAC neutron experiments, which were done with a solid target. By upgrading the instrumentation to detect particles dislodged from the gas, the researchers hope to obtain evidence of the presence of strange quarks.

At CERN, physicists are looking forward to a new experiment called COMPASS, which stands for Common Muon and Proton Apparatus for Structure and Spectroscopy. They expect to probe the gluon content of the proton by firing high-energy muons at polarized targets and looking for ejected mesons containing the charm quark.

Perhaps the most promising effort is slated to start in 1999 at the new Relativistic Heavy Ion Collider at the Brookhaven National Laboratory in Upton, N.Y. (SN: 9/21/96, p. 190). High-energy collisions between polarized protons should make it possible to detect clear evidence of gluon spin.

When these and several related experiments are completed, physicists should have the data they need to tell their story of how the proton's constituents give it its spin.

Studies of the proton furnish insights into the strong force, which governs how quarks bind together and how protons and neutrons form atomic nuclei, Hughes says. Moreover, to understand what happens when one proton collides with another in the sorts of cataclysmic crashes that create the top quark and other particles, it helps to know as much as possible about the proton itself.

There's also a deeper question that underlies investigations of proton spin. In general, why do quantum particles exhibit the quality of spin at all?

"Spin is a quantum number and a property of matter," Hughes notes. Yet in a fundamental sense, "we do not understand where it comes from or why it is there." ☐

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all the current service providers to agree on a new—and marketable—scheme that does not violate restraint-of-trade laws. What will be done about overseas providers?

Any change in pricing will most likely evolve as a result of environmental pressures, not as a result of anyone's concept of what would be nice.

John Hannah
Silver Spring, Md.

The issues involved in flat-rate pricing are certainly not new (consider buffet lunches, unmetered phone calls, freeway use), and the occurrence of congestion should surprise no one.

The future of routing is probably a pay-for-priority scheme. Though billing per byte sounds satisfyingly simple, the nature of the World Wide Web in particular makes this problematic. It is easy to estimate costs for sending *N* bytes of E-mail, but the cost of connecting to many of today's graphics-heavy sites is impossible for the end user to estimate.

While there may eventually need to be a surcharge for multimedia transfers, a show of restraint on the part of Web designers should reduce much of the day-to-day congestion. Perhaps a picture is worth only 10 words on the Internet.

John M. Vinopal
Berkeley, Calif.

It's easy for the researchers to suggest that users are to blame for Internet congestion and should be charged according to the data they use. The researchers' own usage is paid for by the grants given them by Xerox and the University of Michigan.

I can understand Xerox's interest in the study. As for public university studies which suggest the public should pay more and more fees for using a public resource, maybe taxpaying users should conduct a study that investigates such research studies.

Maybe a scalable grant scheme is in order. I think a wise and sound approach would be to measure those studies that suggest "improvements" which increase (worsen) users' quality of life while saving (costing) money and then grant the studies more or less research money accordingly.

As it stands now, because researchers do not personally pay costs linked to their performance, they seem unable or unwilling to differentiate between activities that may require users to spend more money and irresponsibly thinking that their actions have little effect on the users.

Nancy Jane Mathews
Davis, Calif.

I have had many years' experience managing large segments of the Internet. I agree that the short-lived storms observed are normal, but I take issue with the conclusion that somehow charging for access (or altering the current charging scheme in some undefined way) will make the storms go away. The article presents no evidence linking the conclusions to the data.

Craig A. Finseth
Saint Paul, Minn.