HIGH-ENERGY PHYSICS

HERA Physicists Finally Put Flesh on a Putative Particle

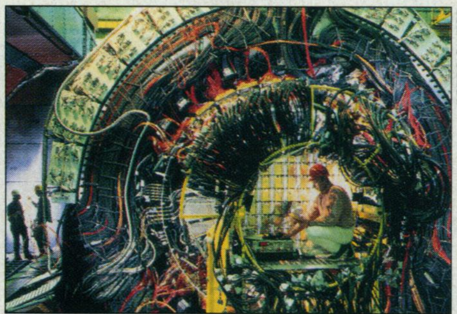
When particles crash against each other in the heart of the world's atom smashers, some bizarre events occur—and physicists have evoked some equally bizarre explanations for them. Take the case of so-called "soft collisions," in which two speeding particles such as protons strike each other with the merest glancing blow. Often one breaks up into a shower of particles while the other travels on virtually unscathed. It is intuitively easy to understand how particles are broken up in a head-on collision, but how does a glancing blow shatter the unfortunate loser in this exchange? In 1961, physicists offered a decidedly offbeat answer: The surviving particle emitted a force-carrying particle called a pomeron, which struck the other one and shattered it.

The idea was popular in the 1960s, but nobody could find any concrete evidence that pomerons really existed. And these putative particles were largely forgotten amid the excitement in the early 1970s surrounding quantum chromodynamics, or QCD, the now universally accepted theory of the strong nuclear force that is responsible for interactions between particles such as protons and which also binds together the constituents of the particles themselves. QCD has, over the past 20 years, been enormously successful at explaining the structure of subatomic particles and how they interact. Yet, for all its power, QCD hasn't been able to explain those mysterious soft collisions.

That failure, and the empirical success of pomerons, has been enough to keep the idea alive, and in experiments at some accelerator centers beginning in the mid-1980s, physicists even began to see hints that some such entity was indeed mediating soft collisions. Now, in results coming out of the HERA accelerator at Germany's DESY high-energy physics lab in Hamburg, researchers are finally getting some tantalizing hints about the character of the elusive beast: It is made up of pointlike particles whose distribution can be measured. These results have made the pomeron the talk of every particle physics conference in recent months. But even as physicists learn more, the debate surrounding the pomeron intensifies: Is it really a "particle," or simply an excited state of other particles in collision? And how does it fit in the framework of QCD? "[The HERA results] really set this field in motion in a way that hasn't happened before," says James Bjorken of the Stanford Linear Accelerator Center.

Soft collisions between protons in which one of the initial particles escapes unharmed are called diffractive scattering and make up about 15% of all collisions. Because this scattering involves strongly interacting particles, it must be controlled by the strong force. Theorists have, however, found themselves unable to use their cherished QCD to explain the outcome of diffractive scattering, because the collision is not violent enough. Nobody knows how to solve the equations of QCD exactly. Instead, theorists use an approximation technique, called perturbation theory, which only yields meaningful answers for so-called hard processes—those in which the quarks that make up protons, and the gluons that hold them together, themselves have high energies.

The first hint of a new understanding that has thrust pomerons back into the spotlight came in 1985. Physicists Peter Schlein of the University of California, Los Angeles, and Gunnar Ingelman of Uppsala University in Sweden reasoned that if the pomeron mediated a strong-force collision, it must itself contain gluons, the carriers of the strong force. If so, then those gluons could be revealed in the same way that gluons and quarks are seen inside protons: by studying the distribution of debris spewed out when a proton is hit. Their key idea was to look at particle collisions that probed deep enough inside the proton to reveal quarks and gluons but were really soft diffractive scattering and so involved the putative pomerons.



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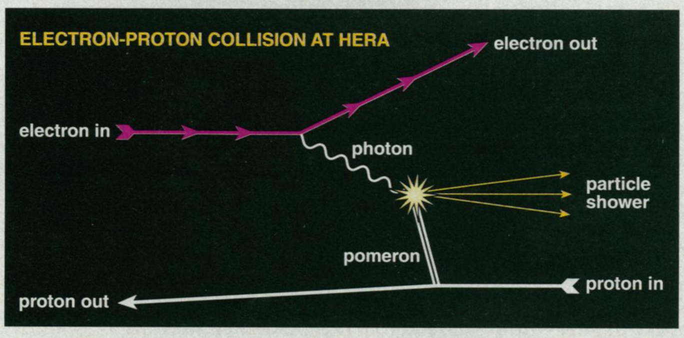


Hard glance. Results at HERA *(photo)* link protons emerging intact from electron-proton impacts to collisions between photons and pomerons.

That same year Schlein and a team of collaborators set out to test the idea in an experiment at CERN, the European particle physics center in Geneva. In this experiment, dubbed UA8, they looked for and found collisions of protons and antiprotons that gave jets of particles, but which also left either the proton or antiproton unscathed—the trademark of diffractive scattering. In these collisions, one or two jets of particles was emitted at large angles, signaling a hard collision between pointlike objects. Their data were consistent with collisions between a quark from the shattered proton or antiproton and pointlike objects within the pomeron that they deduced had been involved.

Although tantalizing, the UA8 results, published in 1992, gave few clues to the structure of the pomerons. According to the rules of QCD, the pomeron cannot be a lone quark or gluon, because removing one of these particles from the proton would leave it with an imbalance of charges, causing it to break up. A proton could, however, emit a pair of gluons, or even a more complex mix of quarks and gluons, and remain intact. With the incomplete UA8 data, physicists remained divided over what particles make up a pomeron and how pomerons are emitted from protons.

In the past few months, scientists working with the HERA accelerator have begun to shed some light on the internal structure of this ephemeral creature. Unlike UA8, HERA researchers collided electrons with protons; this has allowed them to see both how pomerons are emitted and how pointlike particles are distributed inside them. Their results have caused a stir in the particle physics community, because they can be so cleanly interpreted in terms of pomerons, and because the pomerons seen in their electron-proton collisions match so well the pomeron suggested by earlier proton-antiproton collisions.

In the HERA experiments, electrons and protons interact electromagnetically, because electrons do not feel the strong force. This interaction takes place when an electron emits a photon, which then strikes a charged component of the proton head-on—a type of hard collision known as deep inelastic scattering. The higher the energy of the collision, the shorter the wavelength of the photon, so the collision in effect probes the proton with a pulse of light that has a wavelength short enough to reveal the internal structure of the proton.

To study the pomeron, scientists using the two HERA detectors, H1 and Zeus, have looked at special cases of these deep inelastic events in which the proton emerges unscathed but with slightly reduced momentum. In other words, they have looked at events that appear to be diffractive but are nonetheless deep inelastic scattering.

The following picture emerged: As the proton and electron approached each other, the proton emitted a pomeron, which was then struck by a photon emitted by the electron. The proton was left unscathed, and the particles seen in the detectors came from the breakup of the pomeron when it was rammed by the photon. "The new results from H1 ... and then Zeus ... show that when the proton emerges from the violent electron-proton collision intact, the pomeron breaks up," says John Dainton, a member of the H1 collaboration.

And the pattern of particles detected provided some long-sought detail of the pomeron's internal structure. "[If we] assume that these diffractive processes are due to pomeron exchange, then the HERA results imply that the pomeron is made of point-like particles," says Günter Wolf, a physicist working on Zeus. Says Dainton: "We are able to see for the first time how the quarks and gluons, which describe the structure of the proton so well, rearrange themselves to make the pomeron, which is responsible for the majority of high-energy proton-proton interactions."

The hard-scattering aspect of the new HERA results has caused excitement among theorists, who now see opportunities to apply QCD and perturbation theory to the pomeron. The publication of HERA's results in the 6 April *Physics Letters B* and in DESY preprints (95–093 and 95–115) has been accompanied by a flurry of papers on "diffractive hard scattering" and pomeron models. But although the latest results from Zeus suggest a large gluon component in the pomeron, nobody is yet certain whether it is made up mostly of quarks or gluons. Although most physicists expect at least some gluons to be present, some argue that quarks should dominate.

The answer to this question could perhaps solve another particle physics conundrum at the same time. In theory, gluons can bind with one another to form so-called glueballs. Nobody has ever seen a glueball, although last year another experiment at CERN, dubbed WA91, detected a candidate glueball in proton-proton collisions. Could it be that pomerons are actually glueballs? If the answer is yes, this would be a huge simplification in particle physics.

Physicists at HERA are now moving on to new experiments to find out more about the pomeron. They are studying the transition from head-on electron-proton collisions to glancing ones to see how the apparent nature of the pomeron changes. The relative contributions of quarks and gluons should become clearer, too.

In spite of the new flood of data, however, the theorists are still arguing over whether the pomeron is really a particle or not. "To me, the pomeron is a state, or set of states, in the proton—probably glueballs or resonant multigluon systems," says Schlein. Dainton is not so sure. "I would like to think that we will consign the word "pomeron" to a monument which for 30 years guided our understanding toward a full picture of the way strongly interacting particles interact at the highest energies in terms of their constituents, quarks and gluons," he says. "If you like, the pomeron will have been a wonderful laboratory in which theorists and experimentalists were able to develop their understanding of the interaction between protons in terms of their structure."

–Andrew Watson

Andrew Watson is a science writer in Norwich, U.K.

PHOTOVOLTAICS

Polymer Cells Achieve New Efficiency

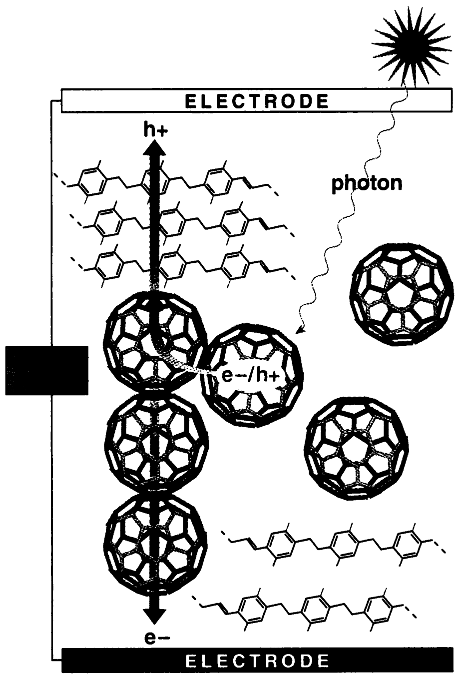
Ever since they were first developed in the 1950s to provide electrical power for spacecraft, solar cells have been touted as an energy source with a bright future. So far, however, they have been less than a shining success. Their high cost has limited their use in industrialized countries to niche applications, such as powering watches and calculators or providing electricity to homes beyond the reach of power lines. The problem is that the most reliable photovoltaic cells, which convert sunlight directly into electricity, are made from crystalline silicon in a costly, precision process akin to manufacturing computer chips. A possible solution might be to make them instead from cheap organic materials, such as polymers, but chemists have had trouble coming up with polymer-based cells capable of converting enough photons into electrical current. Now, however, there's a ray of hope that they may be on the right track.

Two groups of researchers, at the University of California, Santa Barbara (UCSB), and at Cambridge University in the United Kingdom, have recently reported using a similar new design to boost the efficiency of polymer-based solar cells by a factor of 100. Although that still makes them only about one tenth as efficient as commercial silicon solar cells, the progress is "very encouraging," says Zakya Kafafi, a chemist at the Naval Research Laboratory in Washington, D.C.

But these new devices aren't about to storm the market. One critical barrier: "These polymers are not stable when exposed to strong light," says Michael Grätzel, a solar cell researcher at the Swiss Federal Institute of Technology in Lausanne. That's a serious problem for a device that would sit in bright sunlight. For that reason, Richard Friend, who led the Cambridge team, says that, in the near term, these devices are more likely to succeed in less demanding applications, such as photodetectors, which detect photons for applications from medical imaging to astronomy. Detectors are typically exposed to much less light and therefore enjoy longer lifetimes.

To convert light to electricity, solar cells and photodetectors must accomplish two primary tasks. First, they must absorb photons, which knock an electron out of its position in the absorbing material, producing a positively charged void known as a "hole" that can move around freely. The displaced electron and the hole must then be separated and steered to separate electrodes. In a photodetector those charges are recorded, and in a solar cell they are stored in a battery.

Researchers have had a tough time coaxing organic materials to separate the charges.



In charge. Photons absorbed by C_{60} or MEH-PPV generate pairs of electrons (e–) and holes (h+), which separate at C_{60}-polymer junctions and migrate to opposite electrodes.

The electron-hole pairs tend to stick together, behaving as a composite particle known as an "exiton." These migrate in random directions, traveling approximately 10