Partons: New Fundamental Particles in the Nucleons?

The search for the fundamental constituents of matter has led physicists to ever smaller sizes, higher energies, and seemingly more exotic particles. At issue currently is what the nucleons (protons and neutrons) are made of. Does the proton, for example, consist of some homogeneous substance or does it contain discrete and still more fundamental particles?

The latter picture has become increasingly popular with high energy physicists in the last 2 years as a result of experiments at the Stanford Linear Accelerator (SLAC). The evidence, although indirect, indicates that nucleons may have an inhomogeneous structure, with their charge concentrated into point-like constituents, called partons, rather than being evenly distributed. These unexpected findings have created a new wave of interest among high energy physicists, and theoreticians have put forward several explanations of the novel results and have speculated on how partons are related to earlier models of the nucleons.

There is still no conclusive evidence that partons exist; but, because of its simplicity, the parton concept, like the earlier quark model of the nucleons, has great appeal to physicists. The results of the Stanford experiments are consistent with a point-like substructure within the nucleons and hence provide support for, but not proof of, the parton concept. Preliminary results from the most recent analysis of the SLAC data, for example, indicate that neutrons differ from protons in ways that appear to disagree with predictions based on some parton models; other difficulties also exist with parton models, and it may turn out that the parton, like earlier theoretical concepts, must be abandoned. But further analysis of the SLAC data and related experiments on other accelerators will be required to settle the question.

The new clues about the structure of nucleons come from studying how energetic electrons are scattered from proton and neutron targets. Scattering experiments constitute one of the primary methods of exploring the properties of matter at sizes smaller than the atom; their use dates back to 1906, when Lord Rutherford established that the atom was neither a homogeneous particle nor the smallest unit of matter. The parallel between Rutherford's early experiments and the Stanford experiments is sufficiently strong, that, to some physicists, it seems as if history is repeating itself on a scale 100,000 times smaller. Both experiments depend on the electromagnetic force to scatter the charged particles impinging on the target; in both, scattering at large angles from the incident beam occurred far more frequently than had been expected—a result consistent with a target made up of point-like constituents.

Since the early part of this century, in fact, three different scales of matter have been identified. Atoms, with a radius of about 1 angstrom (10^{-8} centimeter), have been shown to consist of electrons surrounding a nucleus. The nucleus, with a radius of several fermis (10^{-13} cm) is composed of neutrons and protons. And these particles themselves behave, at least in the Stanford experiments, as if they were made of objects at least ten times smaller than the radius of the proton (0.7×10^{-13} cm).

The Stanford experiments were conducted by a team of physicists headed jointly by Richard E. Taylor of SLAC and by Henry Kendall and Jerome Friedman of the Massachusetts Institute of Technology (M.I.T.). In the experiments, electrons are raised to a maximum energy of 18 Gev as they pass down the 2-mile length of the accelerator. The electron beam is focused by a series of magnets and steered into a tank of liquid hydrogen, whose nuclei, consisting of a single proton, provide the target. In a variation of the experiment, liquid deuterium (heavy hydrogen, with both a proton and a neutron in the nucleus) is used to provide neutron targets as well. The electrons transfer some of their energy and momentum to the protons or neutrons with which they collide and are then deflected or scattered in ways that depend on the structure of the target particles. In inelastic scattering experiments, such as those done at SLAC, the target particle disintegrates or is raised to a higher energy state. The emerging electrons are analyzed with magnetic spectrometers to determine their energy and scattering angle, and the number of each type is determined with plastic counters that fluoresce when an electron hits them.

What the experimenters found was that the cross sections, or reaction probabilities, of the inelastic electron scattering did not decrease as much as expected when the momentum transfer between the electron beam and the proton target was increased. Theoretical predictions of the cross sections turned out to be as much as 40 times too low. Furthermore, the scattering pattern for the neutron differed substantially from that of the proton. But both the proton and the neutron scattering data exhibited a regularity known as "scaling," in which the results from a wide variety of experimental conditions could be represented by a relation involving the ratio of the square of the momentum transfer to the energy transfer. Such a relation also appears in formulas that describe the kinematics of scattering from point particles. The implication is that electrons in the Stanford experiments are scattered by the individual constituents, or partons, rather than by the nucleon as a whole. The scaling behavior, and the large cross sections that were observed, are the experimental basis for the idea that the nucleons are made of partons.

That scaling might occur had been suggested in 1969 by J. Bjorken of SLAC, prior to the Stanford experiments. At sufficiently high energy and momentum transfer, he conjectured, the mass of the particles involved in the scattering reaction could be neglected, compared to other variables, for theoretical calculations. As a result, the reaction process has no intrinsic dimensional scale, and the qualitative form of the cross section could then be derived by a kind of dimensional analysis. The Stanford data obeys a qualitative relation of the type predicted.

The experimental results, in particular the indication of point-like constituents in the nucleon, also appear to agree in many respects with a new model of the nucleon which is being developed by Richard Feynman of the California Institute of Technology (Cal

Tech) and others. In its simplest form, the model pictures the nucleon as being made up of point-like entities, for which Feynman suggested the name partons. The partons share the momentum of the nucleon and can be considered to act independently in high energy collisions. Because there is a strong binding force within a nucleon, physicists believe that partons or any constituents of the nucleon must interact strongly with each other and cannot really act independently. What Feynman suggested, however, was that partons, when viewed from a rapidly moving reference frame (known in relativity theory as an infinite momentum frame), may be considered as instantaneously free, thereby allowing a simplified theoretical treatment. But the model does not specify how many partons may be expected, and some theorists think that the number may fluctuate in varying circumstances. The experimental data are also vague on this question—the Stanford experiments, although they agree qualitatively with the parton model, do not distinguish between three partons, for example, and a larger number.

The number of partons present in a nucleon is of interest because of attempts to relate partons to quarks, the hypothetical particles that form the basis of an earlier model of the nucleons. Quarks are particles with fractional electric charge; three quarks, in the model, combine to form a nucleon. The quark model deals primarily with the group structure of nucleons and mesons and is based on regularities observed in the families of short-lived particles created in high energy collisions. In contrast, the parton model is a dynamic model that suggests how the components of a nucleon might interact in a real experiment.

It is not yet clear how partons are related to quarks. Some theorists, including Victor Weisskopf of M.I.T., have suggested that partons and quarks may be the same particle or at least that partons may have quark-like attributes. One difficulty with the quark concept is that quarks, despite 7 years of intensive experimental efforts, have never been observed. It is known that quarks, if they exist, must be very massive (more than 5 or 6 proton masses), so that they would presumably be observed only at very high energies; an effect attributable to partons, on the other hand, is apparently detectable at the relatively low energies within the range of the SLAC machine.

A more detailed understanding of the Stanford scattering experiments may emerge from theoretical work now in progress. Some theorists are attempting to study how the parton model is related to quantum field theory. By making broad assumptions, Sidney Drell of SLAC and others have been able to derive the parton model and interpret the observed scaling behavior from field theory. Adherents of the parton concept have also proposed parton models for other types of reactions.

But the parton model is not the only theoretical framework in which the SLAC results can be interpreted. An alternate approach developed by other theoreticians in several countries is based on the properties of certain mathematical entities, known as current operators, in a specialized region of space-time known as the light cone. (The light cone is the boundary, in the four-dimensional geometry of relativity, of the region which can be influenced by events at a given point—it is the boundary between causal and noncausal processes.) This second type of analysis is characterized by more mathematical abstraction than is the intuitive approach of parton theory.

The debate about how quarks and partons are related illustrates one of the major difficulties that physicists face in studying the nucleon and the still poorly understood forces holding it together. Information about the intact nucleon, such as that obtained from scattering experiments, does not give the same picture as that obtained by analyzing the decay products and other debris which result from high energy particle collisions. This problem did not arise in Rutherford's experiments on the atom and in later experiments on the nucleus, in which all types of evidence gave similar pictures of the internal structure. With nucleons, however, and with other strongly interacting particles (which together make up the class of particles known as hadrons), the situation is more complicated because of the strong binding forces that are present.

These binding forces can significantly influence the apparent stability of a given particle. This influence can be seen even on a nuclear scale, where the forces are much weaker: A free neutron, for example, lives only about 20 minutes before decaying, but in a deuterium nucleus it appears as a stable particle. For the nucleus, the binding energy is less than 1 percent of the mass energy (the energy equivalent of the mass, M, given by $E = Mc^2$). For nucleons (and for other hadrons), the binding or excitation energy necessary to break up the particle is as great or greater than the mass energy of the particle. In reactions at high energies, pairs of particles (π-mesons and anti-π-mesons, for example) are created in undetermined numbers and appear in the reaction debris. The fragments resulting from the reaction cannot be clearly related to the structure of an intact particle, as they can for atoms and nuclei. Hence, with nucleons, the apparent structure as seen under the stabilizing influence of the binding forces—an instantaneous "snapshot" of which is provided by inelastic scattering experiments—can be very different from what emerges from a study of hadron-hadron collisions.

The complications that can arise in studying nucleon structure are also illustrated by the most recent analysis of the Stanford experimental results. The analysis, which is being conducted by a group headed by Kendall and Friedman, focuses on the differences between the proton and the neutron. Their preliminary and still controversial findings show that the neutron scatters the incident electrons much less than the proton under certain conditions, and that the ratio of cross sections (neutron to proton) decreases steadily as the scattering becomes less and less inelastic. An extrapolation of the data to the limit of elastic scattering would indicate that the ratio appears to vanish, in contrast to the prediction from both parton theories and light cone theories that the ratio should remain finite and greater than one half. These preliminary results are disturbing to theoreticians, and if confirmed, will apparently rule out quark-type parton models.

Whether partons are real particles, and how they are related to quarks and to the extensive experimental data already obtained about hadron particles, are still open questions. The intersecting storage rings recently completed at the European Organization for Nuclear Research in Geneva and the new 200-Gev proton accelerator near Batavia, Illinois, will enable experimenters to test quark and parton models at energies considerably higher than was previously possible. But it seems likely that the novel results of the Stanford experiments, coming after many years of fruitless attempts to find quarks, are a major step toward understanding the nucleons.—ALLAN L. HAMMOND