The Stuff of Protons

Gluing quarks to make protons, neutrons, and atomic nuclei

By IVARS PETERSON

At the frontiers of high-energy physics, electrons hurtle into protons, protons smash into antiprotons, and electrons collide with positrons.

Out of the showers and jets of exotic particles created in these high-speed crashes, physicists have fashioned what is now known as the standard model of particle physics: Matter consists of two kinds of fundamental particles, quarks and leptons, and four basic forces govern the attraction, repulsion, and transformations of these particles.

It's a remarkably tidy picture, but the rapid pace of this trek to the frontier has left in its wake a host of unsettled issues. Physicists are beginning to realize that they don't really understand the details of how protons and neutrons stick together to form atomic nuclei. It's not even clear how quarks combine to create a proton or neutron.

Unraveling these mysteries has proved no simple matter. Recent experimental results have revealed intriguing hints that a proton or neutron may not be perfectly round. Other data suggest that free protons and neutrons have characteristics that can change when the particles find themselves bound together inside a nucleus.

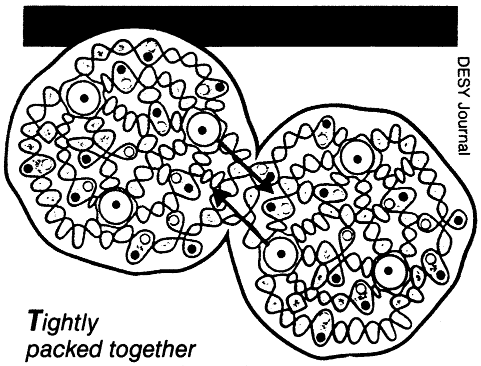
"The structure of the proton is a central problem in few-body physics," says Franz Gross of the College of William and Mary in Williamsburg, Va. Few-body physics concerns studies of entities — whether atomic nuclei or particles such as protons — made up of only a small number of constituents.

Researchers described progress in exploring this hazy borderland between nuclear and particle physics at an American Physical Society meeting held in April in Arlington, Va., and an international conference on few-body problems in physics that took place in May in Williamsburg, Va.

At the simplest possible 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. A neutron consists of one up quark and two down quarks. Quarks are held together by particles called gluons, which, in effect, shuttle between the quarks to keep them bound.

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

Ironically, QCD has been more thoroughly tested and is easier to use and understand at the high energies of particle collisions than at the much lower energies of nuclear physics and proton interactions. "This theory, which we know very well at high energies, is very difficult at low energies," says theorist Vicente Vento of the University of Valencia in Spain.



Tightly packed together inside an atomic nucleus, protons and neutrons can exchange quarks, antiquarks, and gluons. It's this "leakage" — a manifestation of the much stronger force between the quarks making up a proton or neutron — that corresponds to the nuclear force.

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Indeed, quark-gluon interactions are so complicated at the proton level that physicists have been forced to turn to the time-honored strategy of creating simple models that capture the essential features of the phenomena without carrying the unwieldy mathematical baggage of the full theory.

Consider an analogous situation in the realm of condensed-matter physics. In principle, it's possible to calculate what happens inside a material using quantum electrodynamics — the mathematical framework and theory for describing the behavior of electrons and other electrically charged particles. But for many purposes, researchers find such an approach far too unwieldy to account for observations and to make predictions.

For example, it's easier to talk about the coordinated behavior of pairs of electrons (known as Cooper pairs) than to calculate in detail the multifarious electrical and magnetic interactions among electrons and ions in a crystal. Such calculations would help to explain why some materials become superconductors at sufficiently low temperatures.

Similarly, physicists have created a number of simplified models — stand-ins for the full version of QCD — to describe and explain how quarks form into protons and neutrons and how protons and neutrons congregate to create atomic nuclei.

"These models are not directly gotten from QCD, but they may be inspired in some way by the theory," Vento says.

Two types of models representing two mathematical formulations have emerged. In one type, physicists assume that the necessary structures arise from simple arrangements of a few particles closely resembling quarks and that the leakage of gluons from these structures generates the force that at close range keeps protons — which would otherwise repel each other — from flying apart.

The other type of model eschews quarks entirely. Instead, it focuses on the behavior of protons surrounded by clouds of pions. Pions, consisting of pairs of quarks, play the same sort of simplifying role as Cooper pairs in superconductivity theory.

Conceptually, this means there's no such thing as a proton sitting all by itself. It's always accompanied by a swarm of pions, which are continually absorbed and emitted by the proton.

Though quite dissimilar, both models work reasonably well in predicting various characteristics of protons and neutrons, such as their masses and magnetism. Physicists can calculate quantities that generally match the values of parameters measured in a variety of experiments, and they can use the models to picture what may be going on inside a proton or nucleus.

But neither model works perfectly in all cases. So physicists would like to know which model may be more trustworthy when applied to new problems or in unfamiliar settings for which the experimental data are sparse or difficult to interpret.

To determine which model is better, physicists have looked for cases in which the constituent-quark and pion-cloud models give significantly different results. One such situation involves the possibility that the proton is slightly flattened — like a miniature, oblate Earth — instead of being perfectly round.

In other words, "the distribution of quarks inside [a proton] isn't, on the average, like a sphere," says Edward L. Tomusiak of the University of Saskatchewan in Regina. "It's not spherically symmetric."

The constituent-quark model predicts a smaller degree of flattening than the pion-cloud model. "If one gets a number for this deformation, one is signaling what kind of model of QCD at low energies works best," Vento says.

Nonetheless, "this is a small effect, and one wants to measure it carefully," Tomusiak adds.

To probe the structure of protons and neutrons, researchers rely on scattering experiments. They fire electrons or gamma rays at target nuclei, looking for changes in the energy and momentum of the deflected electrons, photons, and nuclei.

Their aim is not so much to smash the target particles as to excite them. Hence, the energies involved – though still substantial – are considerably less than those required in modern particle physics.

For example, the search for the top quark at the Fermi National Accelerator Laboratory's Tevatron involved colliding beams of protons and antiprotons having a combined energy of 1,800 gigaelectronvolts (SN: 4/30/94, p.276). In contrast, proton studies require electron beams or gamma rays of only 1 to 6 GeV.

At these energies, electrons and gamma rays can tickle a proton into an excited state – called the delta resonance – without destroying the particle. Initially, two of the proton's quarks have spins pointing in the opposite direction of the remaining quark's spin. In the excited state, the spins of all three quarks point in the same direction.

At the Brookhaven National Laboratory in Upton, N.Y., researchers have been using the Laser Electron Gamma Source to study how protons deflect gamma rays and how this interaction also generates pions. By carefully sorting through the data generated in these scattering experiments, they hope to obtain an estimate of how much the proton is deformed.

But the analysis is tricky because various interactions produce very similar signals, obscuring the proton deformation effect. Experimenters must work with theorists to untangle the mess.

"The complication is that you have to go through your model very carefully and really check everything that it predicts to make sure that any agreement [between experiment and theory] you see isn't just an accident," says Brookhaven's Andrew M. Sandorfi.

"It's only very recently that we have finally gotten a rather complete set of data," he remarks. "And we've been able to adjust the parameters of one particular model to get what appears to be a consistent picture."

The results to date indicate that the proton is not spherically symmetric, Sandorfi says. "Our data appear consistent with the [pion-cloud] models," he notes.

Using a new electron accelerator known as ELSA, researchers at the University of Bonn in Germany have also obtained strong indications of proton deformation. However, they still require the help of theorists to interpret the results and determine the magnitude of this effect.

"You need the right model to extract the value [for the deformation] from the data," says Bonn's Berthold Schoch. "We're looking to the theorists for help."

To test their simplified theoretical models of proton structure, physicists can also study another type of proton deformation – the particle's polarizability. They look at how the distribution of electrical charge inside a proton shifts when the proton's constituents come under the influence of a strong electric field.

In the presence of an electric field, the positively and negatively charged quarks that make up a proton move in different directions to polarize the proton and change its overall shape. Such distortions should occur more readily if the pion-cloud model is a better description of proton structure than the constituent-quark model.

At the MAMI electron accelerator at the University of Mainz in Germany, researchers use electron beams of 855 megaelectronvolts to produce gamma rays for investigating proton polarization and related phenomena. The gamma rays serve as the polarizing electric fields.

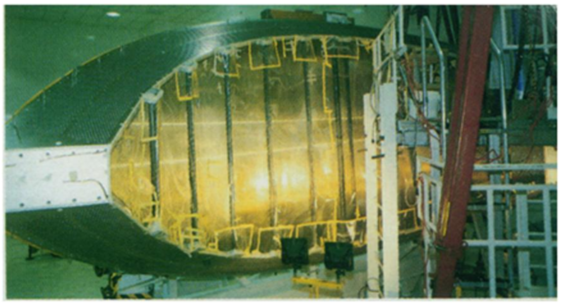
"We don't see the quarks, but we can measure global characteristics of nucleons [protons and neutrons]," says Thomas Walcher of Mainz. "By using models, we can extract some information about the structure of these particles."

Starting this fall, researchers will be able to obtain even more detailed information about proton and nuclear structure at the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, Va. This newly commissioned accelerator, specially designed for such studies, will provide continuous electron beams ranging in energy from 0.4 to 4.0 GeV.

"This accelerator will be the best machine in the world for this kind of work," William and Mary's Gross says.

One of the key questions that researchers at CEBAF will address lies at the ill-defined interface between particle and nuclear physics – how protons and neutrons, which are made up of quarks, combine to form a nucleus.

It's possible to explain much of the behavior of nuclei by assuming that pointlike protons and neutrons pack together to form a sequence of shells, or layers, inside a nucleus. In this picture, pions carry the force holding these particles together.


Chris Surber/CEBAF

Assembling a detector for CEBAF.

"Although everything is basically quarks, one can go a long way by describing the properties of nuclei in terms of just nucleons [protons and neutrons] and mesons [pions]," Tomusiak says.

But protons and neutrons have a finite size, and the nuclear binding force is really just a consequence of the more fundamental strong force carried by gluons. Somehow, gluons leak out of the individual particles to produce a wider effect.

Linking the two pictures – the quarks and gluons of QCD and the nucleons and pions of nuclear theory – has proved difficult.

It's not at all clear to what extent protons and neutrons retain their individual identities inside a nucleus. Several experiments have suggested that quarks may prefer to congregate in groups of six, perhaps flowing freely from one proton to another, inside a nucleus. Gluons themselves may jump from particle to particle.

"To what extent is the identity of anything changed? To what extent are nucleons still nucleons inside a nucleus?" Tomusiak asks. "These are the questions that everyone's trying to address experimentally in one way or another."

Such research efforts are leading to a convergence of nuclear and particle physics – toward explorations of the middle ground between viewing the nucleus as a bound state of protons and neutrons and viewing nucleons as assemblies of quarks and gluons.

"It's not like the forefront of particle physics, where you're looking for unknown phenomena," Gross says. "These phenomena have been observed already, and now we're trying to understand the details."

Nonetheless, both steps in gluing matter – quarks into nucleons and nucleons into nuclei – remain mysterious.

"All our experiments so far have really dealt with individual particles," says Brookhaven's Sandorfi. "It's taken years to get to the point where you see some light at the end of the tunnel for [understanding the structure of] the individual particle."

"Now you stick this particle in the nucleus," he says. "Wow, do you have complexity! We're a long way off from understanding that." □