Electron scattering sheds light on the strong force

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Some 30 years after the quark layer of the cosmic onion was first revealed by scattering beams of high-energy electrons from protons, such experiments are still providing enigmatic results. For many years particle physicists have noticed a similarity between the data measured at extreme energies, where the electrons scatter from quarks in relative isolation, and those at lower energies, where the entire proton responds coherently. This has become known as "quark–hadron duality". (Hadrons are objects, like protons and neutrons, made of quarks and gluons, and they interact via the strong force.) It is generally agreed that this phenomenon tells us something about the way that the strong forces among these constituents actually form the hadrons, but precisely what this "something" is remains to be determined.

Now a team of particle physicists in the US has reported the most precise measurements of this duality yet and, for the first time, hints that it occurs for neutrons as well as protons (I Niculescu *et al.* 2000 *Phys. Rev. Lett.* **85** 1182, 1186). The quality of these data from the Jefferson Laboratory in Virginia promises to open a new area of activity in the coming years as the lab's accelerator moves to higher energies.

To set the scene, let's return to the 1960s. The scattering of electrons from proton targets had shown that as the momentum, q^2, that is transferred to the target grows, it becomes ever less likely that the proton recoils elastically. The interpretation was that the proton is an extended object and that the harder it is hit, the less likely it is to remain whole. The response of the proton as a function of q^2 to electromagnetic probes is summarized in its electric and magnetic form factors; these die away as the momentum transfer increases.

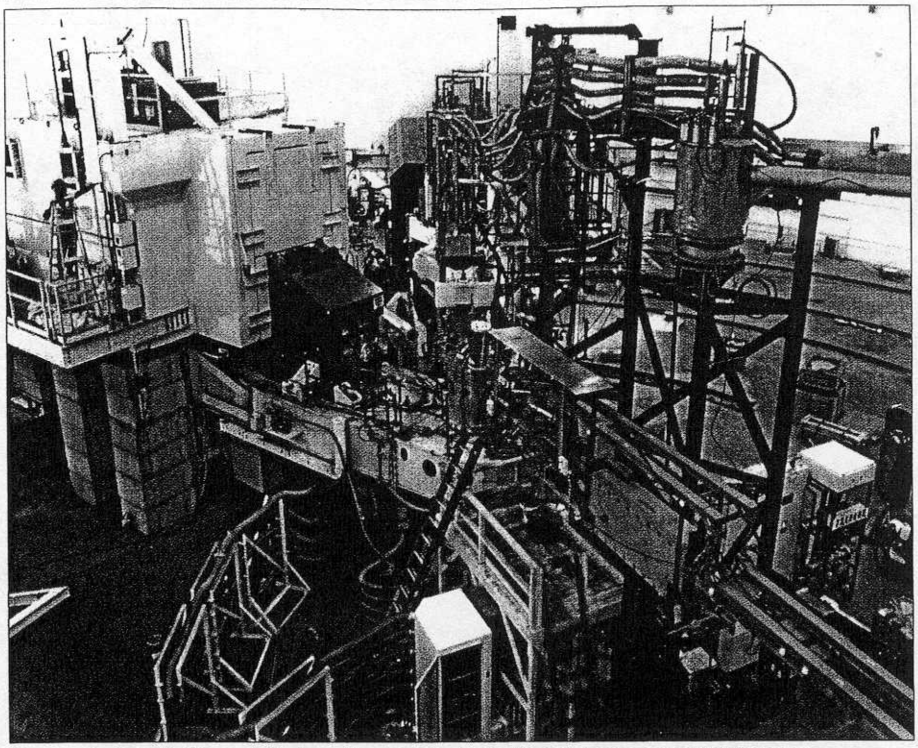
It was in such a climate that the Stanford Linear Accelerator Center (SLAC) in California was built. At 20 gigaelectronvolts (20×10^9 eV), the energy of the beams at the two mile long accelerator far exceeded anything ever available before. And the results around 1970 were even more dramatic. Although the elastic scattering and excitation of short-lived proton resonances died out as q^2 grew, the total response of the proton was independent of q^2. This so-called scaling behaviour would have been expected had the proton been a point-like particle, rather than an extended object in space. The reason was quickly understood: the proton – and indeed all hadrons – are made from point particles, the quarks. It was the scattering of electrons incoherently from the constituent quarks that gave rise to the q^2 independence.

In the subsequent 30 years, these experiments have been extended to higher energies, most recently at the DESY laboratory in Hamburg, Germany. Higher-resolution images of the proton have been obtained and the fundamental theory of quarks and gluons, quantum chromodynamics (QCD), has been tested evermore rigorously. Its ability to describe the interactions of quarks and gluons at distance scales below 10^{-16} m (or at correspondingly large q^2) is not as well developed as its cousin quantum electrodynamics, but it is heading that way.

The enigmas arise when one probes hadrons at lower energies such that the resolution scale is around 10^{-15} m, similar to the size of a proton or neutron. Under such conditions the quarks and gluons coalesce strongly and the QCD theory becomes much harder to solve. Phenomenologists look for regularities in the data in the hope of building models, ideally containing essential features of QCD, from which a more profound understanding may follow.

Two physicists at SLAC, Elliot Bloom and Fred Gilman, noticed nearly 30 years ago that when resonances of the proton were excited in low-energy experiments, the average behaviour of these coherent excitations resembled the scaling behaviour of the high-energy data. It was suggested that this relationship between the resonance excitation and the highly inelastic data hinted at some underlying "duality" between the strong interaction region of QCD and the short-distance dynamics. An analysis of the phenomenon in QCD theory was made by Alvaro De Rujula, Howard Georgi and David Politzer soon afterwards. But in the absence of more precise data, progress in this area has not advanced significantly in the last 20 years. It is here that the Jefferson Lab data are intriguing.

The precursor for these data goes back to Daresbury Laboratory in the UK. In the 1970s its 4 GeV electron accelerator produced what, until recently, have been the clearest data on the excitation of proton resonances by electron beams. These results complemented the higher-energy SLAC data and produced early detailed information on how the quarks combined coherently to make the proton and the resonances. With the modern theory of QCD underpinning hadron dynamics, and advances in technology, the Continuous Electron Beam Accelerator Facility (CEBAF) at the Jefferson Lab was built.



The experiment at Jefferson Lab where the precision tests of quark–hadron duality were made.

During the last couple of years, the accelerator has begun to produce data of unheralded quality. The reported data were taken at energies up to 4 GeV, and plans are already in hand to extend these measurements to 6 GeV. The results confirm the duality for proton targets more precisely than ever before. There are also the first hints that quark–hadron duality occurs for neutrons as well. I am on the scientific advisory committee at Jefferson Lab, and these data were a source of great interest at our meeting last month.

Some preliminary investigations of these phenomena are being made where both the electron and target are "spin polarized". This means that the intrinsic angular momentum or "spin" of the particles is made to point in the same, or in opposite, directions. In the 1980s spin-polarization measurements made at high energies by the European Muon Collaboration (EMC) at CERN gave rise to the so-called "spin crisis". The EMC team discovered that the scattering, which should have been proportional to the incoherent sum of the individual quark spins, did not seem to add up to the spin of the proton. The new round of experiments at CEBAF will show how spin-polarized scattering behaves at lower energies and whether duality holds there too. Whatever the results, they promise to give important complementary information on this enigma.

To get the full import from these data will require a more profound understanding of what this duality is, and whether it is specific to protons or applies more generally. Is duality a curiosity or is it fundamental? If it is fundamental, then there is one enigma that will certainly need to be addressed. The highly inelastic data, as analysed in QCD, involve the incoherent scattering from the quarks. In this case, the scattering probability is proportional to $\sum e_q^2$, the sum of the squares of the electric charges on the quarks, e_q. However, the excitation of resonances is coherent. As such, the scattering probability is proportional to $(\sum e_q)^2$, the square of the sum over the quark charges. By chance these values are the same for the proton, which contains two "up" quarks, each with a charge of $2/3e$, where $-e$ is the charge of the electron, and a down quark with a charge of $-1/3e$.

However, this feature is not sufficient to explain quark–hadron duality. The Jefferson Lab data show that the duality also appears to hold for the neutron, where this situation does not occur, and for magnetic multipoles where there are non-trivial correlations among the quark charges and spin orientations controlled by the Pauli exclusion principle. How the "square of the sum balances the sum of the squares" in the proton is one part of an enigma that we shall surely hear more about in the next year.