The Discovery of Asymptotic Freedom

The 2004 Nobel Prize in Physics, awarded to David Gross, Frank Wilczek, and David Politzer, recognizes the key discovery that explained how quarks, the elementary constituents of the atomic nucleus, are bound together to form protons and neutrons. In 1973, Gross and Wilczek, working at Princeton, and Politzer, working independently at Harvard, showed that the attraction between quarks grows weaker as the quarks approach one another more closely, and correspondingly that the attraction grows stronger as the quarks are separated. This discovery, known as "asymptotic freedom," established *quantum chromodynamics* (QCD) as the correct theory of the strong nuclear force, one of the four fundamental forces in Nature.

At the time of the discovery, Wilczek was a 21-year-old graduate student working under Gross's supervision at Princeton, while Politzer was a 23-year-old graduate student at Harvard. Currently Gross is the Director of the Kavli Institute for Theoretical Physics at the University of California at Santa Barbara, and Wilczek is the Herman Feshbach Professor of Physics at MIT. Politzer is Professor of Theoretical Physics at Caltech; he joined the Caltech faculty in 1976.

Of the four fundamental forces --- the others besides the strong nuclear force are electromagnetism, the weak nuclear force (responsible for the decay of radioactive nuclei), and gravitation --- the strong force was by far the most poorly understood in the early 1970s. It had been suggested in 1964 by Caltech physicist Murray Gell-Mann that protons and neutrons contain more elementary objects, which he called quarks. Yet isolated quarks are never seen, indicating that the quarks are permanently bound together by powerful nuclear forces. Meanwhile, studies of high energy collisions between electrons and protons performed at the Stanford Linear Accelerator Center (SLAC) had probed the internal structure of the proton, and Caltech's Richard Feynman had suggested in 1969 that the results of these experiments could be explained if quarks inside a proton are nearly *free*, not subject to any force. Feynman's suggestion, together with the observation that quarks are unable to escape from nuclear particles, posed a deep puzzle: how could nuclear forces be both strong enough to account for the permanent confinement of quarks and weak enough to account for the SLAC experiments?

The discovery of asymptotic freedom provided a highly satisfying resolution of this puzzle. The calculations of Gross, Wilczek, and Politzer showed that in QCD quarks are held together strongly when separated by a distance comparable to the size of a proton, explaining quark confinement. Yet for the smaller separations explored in the high-energy SLAC experiments, the attraction is weaker, supporting Feynman's proposal.

Before this development, many physicists had anticipated that understanding the strong nuclear force would require revolutionary new concepts. But surprisingly, QCD has a remarkable mathematical similarity to quantum electrodynamics (QED), the theory that successfully explains electromagnetic phenomena. In QED the force between two electrically charged particles is mediated by the exchange of a photon (a particle of light) between the two particles; in QCD, the quarks carry a different kind of charge, called “color,” and the force between two colored particles is mediated by the exchange of a “gluon” between the particles. The crucial difference between the two theories is that while the photons of QED carry no charge of their own, the gluons of QCD are themselves colored particles. A quark is surrounded by a sea of “virtual” gluons that arise due to quantum fluctuations, and the color of the virtual gluons enhances the quarks own color. A probe coming closer and closer to the quark is influenced less and less by the virtual gluons, so that the effective color charge of the quark seems to weaken; this is asymptotic freedom.

Gross, Wilczek, and Politzer used pencil and paper to perform their breakthrough calculation. In 1973, the methods they needed were newly developed and fraught with subtleties. Today, the calculation is routinely assigned to physics graduate students as a homework exercise.

QCD predicts that the strength of the force between quarks changes with distance in a particular calculable way that has been well confirmed in experiments studying high energy collisions of elementary particles. The theory makes other detailed predictions, such as the masses of various strongly interacting nuclear particles, that can be extracted only through large-scale numerical computations performed using supercomputers; these too are in satisfying agreement with experiment.

Because QCD, the theory of the strong nuclear force, turned out to be so similar to QED and to the theory of the weak nuclear force, it became possible after the discovery of asymptotic freedom to conceive of unified theories that incorporate all three forces into a common framework. Such theories have been proposed, but still await experimental confirmation. A further challenge, being pursued by many physicists today, is to achieve an even broader unification that encompasses the gravitational force as well.

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