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Why Hadron Physics?

1 The Birth of Hadron Physics

Much of the history of science has to do with understanding the very small. With increasing resolving power of microscopic probes, scientific investigation moves from the scale of the living cell down to the large organic molecules essential to life such as DNA, then to smaller molecules like the oxygen and nitrogen we breathe, and downward to the atoms and their central nuclei that comprise all ordinary matter. Inside those nuclei reside protons and neutrons. And inside them reside quarks. It is at this level that the field of hadron physics finds its home. Roughly stated, hadron physics is the study of the structure of objects directly built from quarks and their antiparticles.

In the 1950s and early 1060s the cyclotrons, synchrotrons, and linear accelerators built by particle physicists reached high enough energies (the GeV energy scale) to allow studies of the internal structure of the proton. And sophisticated experimental instrumentation, in particular large bubble chambers, allowed detailed study of the products of collisions with matter of the high energy particles produced by the accelerators. What was found was remarkable, unanticipated by the theorists of the day: a large number of new states of matter, then called "resonances" and now called hadrons. The catalogue of the new hadrons quickly grew into the hundreds.

And the challenge of classifying all these states was brilliantly fulfilled, especially through the work of theorist Murray Gell-Mann. He (and independently George Zweig) proposed that all these states could be built from hypothetical particles called quarks. In this picture, protons and neutrons, along with many closely related states called baryons, contain three and only three quarks, while another class of states called mesons contain one quark and one antiquark. Ordinary matter contains only two types ("flavors") of quark (up and down), while other forms of matter, identified in cosmic radiation in the 1950s and produced by the accelerators of the 1960s, require a third flavor of quark, dubbed "strange" by Gell-Mann.

This picture was revolutionary, as well as perplexing, because these hypothetical quarks possess only a fraction (1/3 or 2/3) of the electrical charge found on other fundamental particles such as protons and electrons, not to mention all of the newly discovered hadrons. Exquisitely sensitive searches for isolated particles with fractional charge turned up nothing, despite the fact that the behavior of the hadrons is that of an apparently loosely bound system of quarks and/or antiquarks.

The mystery only deepened when a landmark series of experiments in the late 1960s examined proton structure with very high energy beams of electrons, and found evidence for point-like constituents. Theorist Richard Feynman provided a simple, intuitive description. He visualized the process occurring in a reference frame different from the laboratory frame—one where electrons collide with energetic protons moving in the opposite direction at nearly the speed of light. In such a reference frame, the proton may be viewed as a beam of pointlike constituents, dubbed partons, with which the electron collides in a simple, easily interpretable way. The experiments not only provided evidence for such constituents, but that on average there were many of them, the number in particular being larger than three and increasing with energy. Most importantly, the charge of these constituents appeared to be fractional, just like quarks. After many series of measurements with electrons, as well as with similar ones performed with neutrinos, the interpretation of partons as quarks became decisive. But again careful analysis of the collision debris turned up no evidence for fractional charge, despite the violence of the initial electron-quark collision.

So as the field entered the early 1970s, it faced an unprecedented crisis. How was one to understand the successes of the quark picture of matter? In particular how could it be that quarks could not be knocked free, even in the most violent of collisions?

One theoretical response was that quarks were bound together by "elementary" strings, with a constant force independent of the length of the string. This idea was extensively developed, but did not succeed. It was later resurrected and applied, not to the theory of the force between quarks, but to a proposed synthesis of quantum mechanics with gravity and with all other forces known in nature. This program is under very active investigation to this day, with byproducts helpful to hadron physics. Meanwhile basic progress in finding the answer to the problem of the force between quarks came from a different direction.

2 Quarks, Gluons, and Quantum Chromodynamics

In the 1970s the so-called standard model of elementary particles and forces emerged. Two new types, or "flavors" of quark (charm and bottom) were discovered, making the quark picture even more well-established. And one component of the standard model became the theory of the forces holding quarks together, called quantum chromodynamics (QCD). QCD was proposed in the early 1970s and, remarkably, by the end of the decade it was already quite well established. It is a theory which bears some similarity to the quantum field theory of electricity and magnetism, quantum electrodynamics (QED). To good approximation the QCD force between quarks at short distances is inverse square, just as the force between charged particles in QED. But in QED the effective charge of the sources gradually increase as the distance between the charges decreases, while in QCD the opposite occurs. This feature of small effective charges at short distances leads to a theory for which the effect of the forces on the quarks at short distances can be reliably calculated, just as in QED. In QED the effective charges at all distance scales relevant to experiment are small enough for reliable calculations to be performed; they are characterized by a famous pure number, 1/137, expressing this smallness. In QCD, at the shortest distance scales so far investigated, the analogous number is about ten times larger, but still small enough for reliable calculations. Consequently, for many purposes quarks at short distances can be considered as in free motion, temporarily unconfined. Reliable predictions for electron scattering from quarks in the proton in high energy, very short-distance collisions therefore can be made, given input data at low energies and distance scales of order the hadron size. Such predictions have been verified to great accuracy over a hundredfold range of energies and distance scales, and provide landmark evidence for the correctness of the basic force laws of QCD.

Another important feature of QCD is its prediction of another kind of pointlike constituent, the gluon. QED describes not only electric and magnetic forces, but also electromagnetic waves. The quantum theory exhibits this electromagnetic radiation not only as waves, but also as particles, the photons. Gluons are the QCD analogue of photons. They, like quarks, do not exist in isolation. But, as mentioned in the next section, there is convincing evidence for them in experiments done at very high energies. So the theory formulated and developed at short distance scales appears to be well-defined and well tested in its fundamental structure.

On the other hand, at large distances the inverse-square behavior of the force law breaks down. What is believed to replace it is a constant force, independent of quark separations. In this regime, calculations become difficult, and the theoretical arguments more uncertain. But the physical picture is close to the old string theory: the QCD analogue of QED electric flux emanating from the quarks is believed to be somehow compressed into a thin, stringlike "flux-tube" which connects the quarks together. An exotic analogue from condensed matter physics is often used to describe this: hypothetical magnetic monopoles embedded into a superconductor are analogous to quarks embedded in the "QCD vacuum". But it is only an analogue, and at present a fully reliable theoretical understanding does not exist. It remains a central goal of hadrons physics to provide such an understanding.

3 The Emergence of Hadron Physics

In the last two decades, particle physicists have built and exploited powerful new facilities which push the study of matter to increasingly short distance scales. The distance scales of primary interest are by now approaching the "TeV scale", one thousand times smaller than the "GeV scale" of the 1960s which revealed the inner details of proton structure. The strong-interaction arena of primary interest for particle physicists has become the short-distance world of "partonic" quarks and gluons. They are, remarkably, very directly seen in the debris of high energy processes as “jets”. A singular example is the decay of intermediate bosons Z^0, particles which are to the “weak” force as photons are to QED and gluons to QCD. Their mass is almost a hundred-fold larger than that of the proton, and they often disintegrate into a quark and antiquark, and occasionally an extra radiated gluon. While isolated quarks and antiquarks cannot and do not emerge, groups of hadrons (“jets”) do emerge in roughly the same directions as their partonic progenitors, carrying off the very large initial parton momentum. A space-time picture of *how* the quarks do not get out has in fact been put together rather well. It is understood where in space-time the extra quarks and antiquarks comprising the jets materialize in the process of jet formation. However, the fundamental issue of *why* the quarks and gluons themselves do not come out is finessed.

By now this short-distance world of quarks and gluons has come to dominate the study of QCD by elementary particle physicists as they move on to search for the Higgs boson and for phenomena which go beyond the standard model. But the difficult problems of hadron structure and quark confinement have not been completely ignored. Much progress has been made on many fronts. A very important one is the recognition that in QCD the “vacuum” state containing nothing at all—no quarks, no gluons, no hadrons—needs to be visualized as a medium with complex properties: “quantum ether”. These properties include the presence of a superfluid-like condensate (the “chiral condensate”) whose wave-like excitations are described by the lightest of all hadrons—the pi-mesons, weighing in at only one seventh of a proton mass. In the vacuum there are also complex configurations of gauge potentials, analogous to the electrostatic and magnetic potentials used in ordinary electromagnetic theory. Quantum fluctuations (described by objects called “instantons”) of these gauge potentials also organize the structure of this strange QCD-vacuum medium, including quite likely the chiral condensate. But neither of these vacuum structures seems to suffice in accounting for the phenomenon of confinement of quarks and gluons by flux-tubes or other means, and the search continues for other “condensates” or vacuum structures which fully account for the existence of the aforementioned string-like flux tubes and for the mystery of why quarks do not get out. This is the number one challenge to the field.

One way of addressing the problem of vacuum structure is to imagine what happens if it is heated up. At low temperatures it is described by a gas of pi mesons, and at very high temperatures, appropriate to the early history of Big Bang cosmology, it has to be described by a dense gas of pointlike quarks, antiquarks, and gluons. Mapping out what happens in between, at the temperatures characterizing the transition between these two regimes, is a challenge for both theory and experiment. On the experimental side, high-energy collisions of heavy nuclei are expected to produce the necessary temperatures and environments where this transition occurs and can be studied. On the theoretical side, this is only one part of the study of "macroscopic hadron physics". Other parameters can be varied besides temperature, especially the density difference of quarks and antiquarks. A close connection is thereby made with nuclear physics and the study of macroscopic nuclear matter, such as found in neutron stars. Indeed nuclear matter must when highly compressed eventually make a transition to some form of quark matter, and this may be important for neutron-star physics. Important theoretical progress is at present being made, and this whole field, which spans nuclear physics, particle physics, and astrophysics, now enjoys great vitality.

The subfield of hadron spectroscopy, which gave birth to the quark idea, has also advanced. Analogous to atomic, molecular, and nuclear spectroscopy, this subfield is the study of how hadrons behave when set into, *e.g.*, rotational or vibrational states of motion, and in particular how they radiate the extra energy away. In addition to the discovery and classification of the properties of hadrons built from up, down, and strange quarks, study of the spectroscopic properties of hadrons built solely from the heavier charm and bottom quarks and antiquarks exhibit strong evidence for the correctness of the basic QCD force law: inverse-square at short distances and constant at large distances.

And the emergence of QCD has focused attention on possible new forms of hadrons comprised only of gluons ("glueballs"), or others whose structure or excitations manifestly depend upon the gluon degrees of freedom. For example, if strings connect quarks, they should vibrate, leading to distinct signatures in hadron spectra. The original, generic hadrons classified by Gell-Mann do not exhibit much of the gluonic side of QCD for reasons very poorly understood. But the capability of theory to understand and model hadron states has progressed to the point that properties of the "exotic", or "hybrid" hadrons, where gluon behavior does matter can be delineated well enough to provide guidance for experimental searches. Searches for glueballs, exotics, and hybrids have been performed, with occasional claims of sightings. But just as was the case for Gell-Mann's original classification schemes of the most commonplace hadrons, it is likely that a large database of candidate states must be built up before a decisive picture of these states will emerge. And it is fair to say that the concentrated effort which existed in the 1960s in providing the original databases which led to the idea of quarks has not existed in the last two decades.

A third major subfield of hadron physics is based on electron-scattering studies which generalize and extend those which led to the Feynman parton picture. With a large high-energy database, the details of the mixture of different quark flavors, momenta, and angular momenta which comprise the parton "beam" can be sorted out. It turns out that about half of the proton momentum is carried by gluons, and indirect methods allow much to be learned about the role of gluons. Also very important is the use of electron beams of moderate energy, at the interface between the low energies and relatively large distances where the Gell-Mann three-quark picture of the proton applies, and the high-energy, short-distance regime, where the large number of quark-partons of Feynman provides the best description of the proton structure.

Another subfield is the study of collisions of hadrons, with each other or with electrons at the highest possible energies. In this limit it turns out that a dominant feature is the disturbance of the QCD vacuum by the projectiles over large distance scales, directly proportional to the energy scales of the projectiles. These disturbances control the way the collisions evolve in space and time. In the Feynman parton picture for electron-proton collisions most of the many quarks and gluons assigned to the proton "beam" actually can be alternatively viewed as belonging to the QCD vacuum. Consequently there is a deep link between the study of collisions at extremely high energies and the nature of hadronic matter at the lowest energy scale. But, just as quark confinement remains a mystery, the nature of this link is also poorly understood. At a minimum, specialized experiments at the highest energies available will be needed in order to make real progress in this difficult field.

On the theoretical side, a major advance in the last two decades has been in numerical methods using very large-scale computations. Many of the basic parameters of the low-energy spectroscopic world, including hadron masses, can be computed this way, although the limitations of accuracy most often depend upon available computing power. In addition, these methods are in principle well-suited to the number one problem of QCD vacuum structure and quark confinement. In particular the computer experiments provide evidence for the constant force between quarks at large distances, and the beginnings of evidence for the existence and properties of the flux tubes connecting them.

4 The Future of Hadron Physics

Hadron physics is a young, interdisciplinary field. The basic questions it seeks to answer are the very difficult ones outlined in the previous subsections:

1. Why are quarks and gluons confined, unable to exist in isolation?

2. What is the structure of the strange medium called the "QCD vacuum", and of other "macroscopic QCD" states, such as the quark matter which exists in neutron stars and supernovae?

3. What is the role of gluon degrees of freedom in hadron structure, especially with respect to the spectroscopy of hadrons?

4. How are the three "spectroscopic" quarks of the Gell-Mann proton connected to the large number of "partonic" quarks of Feynman's proton?

5. More generally, how are the many disparate methods of describing hadrons which are now in use related to each other and to first principles of QCD??

At present there are opportunities for making great progress. High energy collisions of heavy nuclei are being observed and under construction is a facility for greatly extending the energy scale. The experimenters will attempt to find evidence for dense, hadronic, subnuclear matter: the quark-gluon plasma. Electron-proton collisions are produced at several laboratories, with experimental programs of very high quality. While experimental work in spectroscopy has languished somewhat, the opportunity exists for increasing by at least a thousandfold the quality of the database, much of which dates back to the bubble chamber days, by utilizing the modern detector techniques commonplace in the larger-scale elementary particle-physics world. And high energy collisions of hadrons with each other, especially at extremely high energies, will provide insight not only into the structure of the hadrons themselves, but also into the structure of the QCD vacuum surrounding those hadrons.

On the theoretical side, increasing the power of computer simulations ten to hundredfold is anticipated to be sufficient to greatly extend the range and reliability of the computations, and to help greatly in attacking the fundamental questions of hadron physics enumerated above.

Answering those questions is made more difficult by the fact that at present the field is so interdisciplinary. Much of the heritage of hadron physics is in elementary particle physics. As we already mentioned, most—although not all—elementary particle physicists have moved on to study nature at much shorter distance scales. To considerable extent, nuclear physicists have replaced them. In their quest to understand the basics of the force between protons and neutrons, they have been led to consider them at the level of the quark constituents. At present, more than half of the nuclear-physics community is in fact doing hadron physics. But hadron physics is not nuclear physics either. It is a field of its own, emergent from elementary particle physics, just as chemistry, atomic physics, and nuclear physics in turn emerged from the particle-physics of previous eras. Hadron physics does not yet possess as distinct an identity as its predecessors. However, it is needed.

The support of hadron physics at all levels suffers when the basic identity and goals of the field are not clearly recognized. At the level of government funding of the field, this is evident, given that no clear administrative structure or peer review system dedicated to hadron physics is in place. The experimental program of hadron physics is not limited to laboratories dedicated thereto. Important opportunities exist in high-energy physics laboratories as well. But hadron-physics initiatives at such laboratories are at great disadvantage when they compete directly with the initiatives of primary interest to particle physicists. Independent funding and peer review by hadron physicists is necessary if hadron physics is to thrive at such laboratories.

In the universities at administrative levels both above and within physics departments, the maintaining and creation of professorships in hadrons physics suffers if the academic community does not see hadron physics as a discipline just as distinct as nuclear or particle physics, with clear, challenging goals of fundamental scientific importance. And, perhaps most important of all, the lack of a clear identity and scientific agenda for hadron physics may impede those students who should be the basis for the future of hadron physics from entering the field.

A natural starting point for improving this situation is within the professional societies. At present there is the beginning of an initiative to create a Topical Group in Hadron Physics in the American Physical Society, with the possibility of this group to grow into a division in the longer run. This would seem to be an appropriate venue for airing the problems and creating progress, especially with respect to serving the interests of the younger generation.

The future of hadron physics should be a bright one. Important science is there, waiting to be done. Hard work, both scientific and political, will be necessary for it to be properly served.