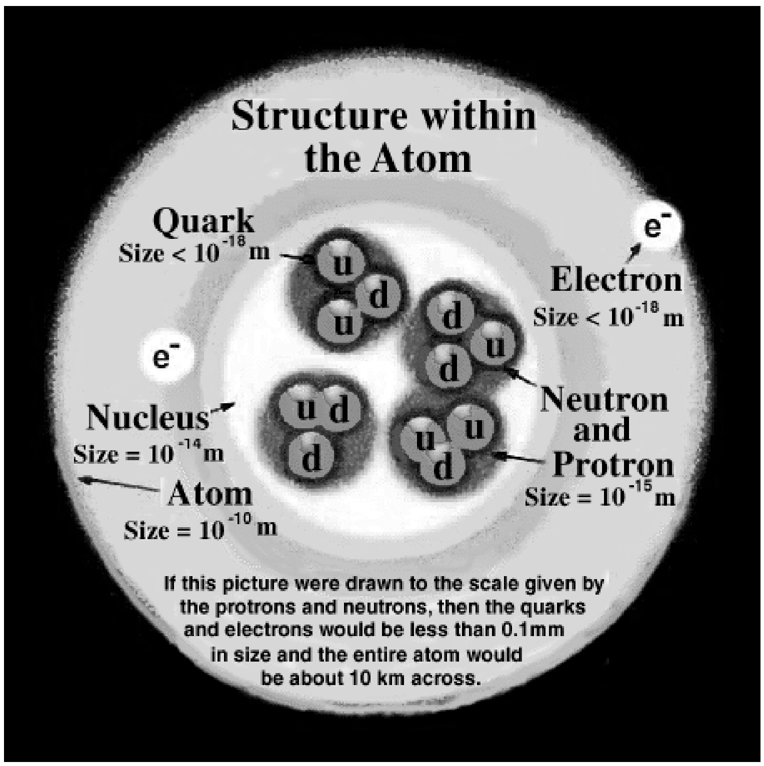
The Character of Particle Physics

Introduction

From the time humans began to ask questions about themselves and their world, they have wondered what the world is made of and how it behaves. Over and over, in different ages and with different methods, people have tried to answer the questions, "What is the smallest possible piece of matter? What are the fundamental forces of nature?" From the time of the Greeks, with their designation of the elements Earth, Air, Fire, and Water, this ongoing quest has yielded extraordinary advances in knowledge that make our universe more understandable. Today, the fundamental science of high-energy, or particle, physics continues to pursue answers to these most ancient, and most modern, of questions.

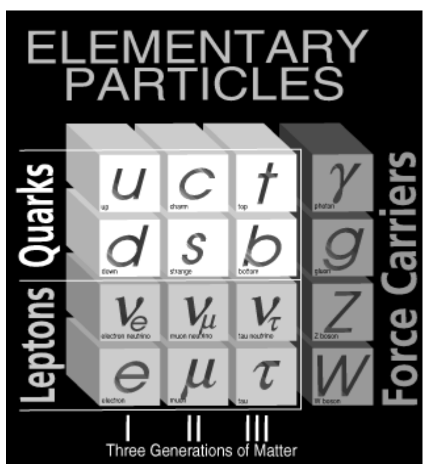


Building Blocks of Matter

Over the centuries of thought and experiment, there has gradually arisen a powerful belief in a simple framework underlying the seeming complexity of the universe. For example, in the 19th century, the periodic table of elements born of the Mendeleevian revolution gave simple family relationships to the welter of new elements that chemists had discovered, and led to the recognition that matter is made of atoms. In the early 20th century, further simplification came from the identification of the electron, proton and neutron as the constituent parts of atoms.

In the 1950's and 1960's, the discovery of hundreds of additional "fundamental" brothers and sisters of these three atomic constituents appeared to complicate these simple patterns. The query "Who needs so many building blocks?" led to a new level of understanding of the fundamental structure of matter. To explain the myriad particles, physicists conjectured even more elementary particles called quarks – the quarks that have now, in turn, been observed in experiments. Many studies world-wide have affirmed our current picture of the fundamental world of matter: all the particles of matter are composed of varying arrangements of six quarks (and their antimatter partners) and a corresponding set of six leptons, grouped into three pairings, called generations, with similar properties.

At the time the quarks and leptons were proposed, it was by no means understood that they came in three generations. In the original conjecture, three quark types – named 'up', 'down', and 'strange' (u, d, and s in the figure below) – sufficed to explain the observations. Four leptons – the charged electron (e) and muon (μ) and their companion electrically neutral neutrinos (ν_e and ν_μ) – were also known. In 1974, experiments at Stanford Linear Accelerator Center (SLAC) and at Brookhaven National Laboratory identified a fourth 'charm' (c) quark. The mass of the charm quark was noteworthy – five times that of its strange partner in the second generation. For the moment, the symmetry of two generations of quarks and leptons seemed to signal the end of the road of particle discovery. Then, in 1976, an additional pair of leptons, the tau (τ) and its neutrino (ν_τ) was found at SLAC. The following year, experiments at Fermi National Accelerator Laboratory (FNAL) found one more quark, the 'bottom' (b), with a mass about three times that of the charm quark.



From theory we expect that the number of quarks and leptons should be equal, and several experiments implied that there are but six leptons. This symmetry thus strongly suggested that a final quark should exist – the 'top' (t) quark, the partner to the bottom. The hunt for the top quark began in a series of ever more sensitive experiments at laboratories around the world. In early 1995, dramatic confirmation of this picture was made with the discovery at FNAL that the top quark does indeed exist.

But the completion of the "periodic table" of matter comes with a twist: the top quark finally weighs in with a mass of about 35 times that of the bottom quark! And so, along with the satisfaction of completing the search for the elementary bits that everything is made of, come intriguing new questions. Is there a deep reason for the extraordinary massiveness of the top? Does it hold some clue to the underlying reason for nature's provision of mass to matter's building blocks? Why are there three full generations of quarks and leptons, and not one, two or more? The world we actually see and touch is in fact made of quarks and leptons of only the first generation. Why are there more?

Forces of Nature

Our understanding of the fundamental forces has evolved along with our growing knowledge of the particles of matter. Early observations identified the gravitational, electric, and magnetic forces as distinct, but the multitude of everyday phenomena seemed to be governed by a long list of idiosyncratic forces, each operating in special circumstances. A large step toward simplification came in the mid-19th century with Maxwell's unification of the electric and magnetic forces into a single electromagnetic entity. Fifty years later came the recognition that the newly discovered atoms are also governed by the same force. By the late 1800's, all commonly observed phenomena could be understood with only the electromagnetic and gravitational forces.

At the turn of the century, new experiments began to explore the subatomic world. They revealed the necessity for a very short-range 'strong' force to bind together the elements of the nucleus, and a similarly short-range 'weak' force to account for radioactive decays. All four forces – electromagnetic, gravitational, strong, and weak – became more understandable when the development of quantum mechanics and the quantum theory of fields allowed physicists to postulate the existence of the force-carrying particles called bosons. In our current understanding, the electromagnetic and weak forces are further unified as the electroweak force, carried by combinations of the ordinary photon of light (γ) and very heavy bosons called W and Z. The W and Z bosons were discovered in 1983 at European Center for Nuclear Research (CERN), and demonstrated that at very large energies, the weak and electromagnetic forces merge into a single entity.

The understanding of the strong force that binds the nucleus has also undergone stages of simplification over the past 30 years. Early descriptions focused on dozens of force-carrying particles and a tangle of difficult-to-determine parameters. Again a single force-carrier operating at the level of quarks was postulated. This theory, called quantum chromodynamics or QCD was based on the properties of electromagnetic theory (QED). QCD postulates the existence of massless gluons (g), bosons which mediate the strong force; these were discovered at experiments at the Deutsches Elektronen-Synchroton in Germany in the 1970's.

Of all the forces, gravity remains the odd man out. We expect there to be a force-carrying graviton, but gravity is such a weak force that its observation has thus far eluded experiment.

However the satisfying simplicity and harmony of the picture of the forces again evokes questions. Having gone from many forces to just three, we ask whether further unification cannot be made. It seems plausible to join the electroweak and QCD forces. This would satisfy our intuitive guess that nature is at root simple and elegant. In our dreams, we envision still further unification incorporating quantum gravity as well. We even know roughly at which energy the various forces should reach equal strength and thus exhibit their underlying unity. But present experiments have also shown us that with only the three generations of quarks and leptons now known, it would seem unlikely that the forces we observe in our labs today could evolve to the unification scale. The price to be paid for tidiness and the dream of further unification of forces may be a further revolution in our picture of the fundamental constituents!

Particles and the Universe

Particle physics has brought answers to many questions that once seemed all but unanswerable. Through the study of particles and forces, we have found crucial keys to the way the universe itself developed in the first moments following the Big Bang burst of energy. We see that the pattern of particles uncovered in our present-day laboratories influenced the initial conditions of the universe so as to produce the particular world that we experience today. Among the most mysterious links between cosmology and particle physics are two seemingly disparate observations. First, by observing the heavens, we see that the universe contains a preponderance of matter over antimatter. We thus conclude that the laws of nature must somehow discriminate between these opposite forms. Second, our seemingly unrelated study of particles tells us that the simplest pattern of quarks allowing such matter-antimatter distinction requires at least three generations of quarks. In the past two years, striking new progress in understanding the distinction between matter and antimatter has come from experiments at the Cornell Electron Storage Ring.

Thus, in a broad and perhaps unsatisfying anthropomorphic manner, we can suggest that in order for matter – that which now forms stars, people and proteins – to exist without having been annihilated in the very early universe, we need the three pairs of quarks and leptons that had on first sight seemed redundant. In this surprising view, our own existence seems to depend upon the existence of the newly discovered top quark, whose life lasts but a trillionth of a trillionth of a second and whose earthly utility is hard to imagine!

We recognize that our present understanding of the constituents of matter and fundamental forces, though conceptually pleasing and consistent with all observations so far, is likely to be only a stage on the way to deeper appreciation of the structure of our world. We know the taxonomy of particle and forces, but we know little as yet of what underlies our classification system. Nevertheless, the questions we can now think to ask were unthinkable a few years ago. “What is the origin of the mysterious attribute of matter called mass?" "What causes the peculiar pattern of quarks and leptons with their strong family relationships but differing individual characteristics?" "How did the particles we see in the laboratory influence the character of the universe at large?" "Can we find connections between such seemingly disparate phenomena as black holes and fundamental particles, as twists in space-time?" A next stage of accelerators and experiments is needed to point the way.

Conclusion

This overview has focused on the evolution of particle physics to the present level of understanding, and on the nature of the questions that we are poised to explore. It is indeed true that the basic urge to pursue such studies originates in our innate desire to understand the character of our world. Analogies are often made with our urge to create and enjoy music, art or literature, as a fundamental aspect of our humanity.

However, this is not to gainsay the pragmatic benefits of scientific research. Every basic scientific field of study has enriched society by the new understanding gained. The ability to produce the materials to clothe, feed and serve us results from the understanding of atoms, molecules and the chemical bond. The understanding of the enormously complex couplings of organic macromolecules has led to tremendous improvements in our ability to heal and prolong life. Our electric power and transportation industries are dependent on esoteric studies of electric, magnetic, and thermal phenomena of a century ago. Our computer-based information age rests upon the intellectual foundation of the quantum revolution early in this century. All scientists are proud that our studies can simultaneously serve to illuminate the fundamental character of the world that we inhabit and contain a spark which, somewhere down the road, enriches our individual and collective lives.

From the present vantage point, we can appreciate both the panorama of past achievements and the next range of peaks to climb. In the last few years alone, new discoveries have opened new vistas. This glimpse into the regularities and order inherent in the physical world represents an achievement of impressive proportions. The questions about the structure of matter, and the forces through which they interact, are now clearly posed and cry out for answers. The program now proposed has the bright opportunity to profide these answers and lead to new understanding which enriches our culture and benefits our society.

This brochure is adapted from the introduction to *Particle Physics – Perspectives and Opportunities*, published by World Scientific Press. This book is an overview of the field written by many active physicists of the Division of Particles and Fields (DPF) of the American Physical Society. For information on obtaining a complete volume of this report, please contact the DPF Secretary, Jonathan Bagger (bagger@jhu.edu) or the DPF chair, Paul Grannis (pgrannis@sunysb.edu). Interactive tours of particle physics ideas can be found in *The Particle Adventure* at `http://pdg.lbl.gov/cpep/adventure_home.html`.