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43. I thank F. Dieterlen, M. Rabinovitch, and J. Smith for their critical reading of the manuscript and A. Le Mouël, E. Bourson, B. Henri, and S. Tissot for the preparation of the typescript and illustrations. This work was supported by CNRS, INSERM, FRMF, and Ligue contre le Cancer and aided by Basic Research Grant 1-866 from the March of Dimes Birth Defect Foundation.

Elementary Particle Physics and the Superconducting Super Collider

CHRIS QUIGG AND ROY F. SCHWITTERS

The present status and future prospects of elementary particle physics are reviewed, and some of the scientific questions that motivate the construction of a major new accelerator complex in the United States are summarized.

ELEMENTARY PARTICLE PHYSICS, THE SCIENCE OF THE ULtimate constituents of matter and their interactions, has undergone a remarkable development during the past two decades. A host of experimental results made accessible by the present generation of particle accelerators and the accompanying rapid convergence of theoretical ideas have brought to the subject an unprecedented coherence. This clarity, however, brings into sharp focus fundamental limitations in the current picture that raise fresh possibilities and set new goals for advancing our understanding of nature. The progress in particle physics has been more dramatic and more thoroughgoing than could have been imagined only a dozen years ago. Many of the deep issues then current have been addressed, and many of the opportunities then foreseen have been realized. This progress and the profound questions emerging from it have brought particle physics to an intellectual turning point comparable to the synthesis of classical physics in the late nineteenth century that preceded the discovery of relativity and quantum mechanics.

Experimental pursuit of some of the fundamental questions in elementary particle physics requires energies higher than those provided by any accelerators now in operation or under construction anywhere in the world. For this reason, physicists in the United States are now preparing a proposal for a very high energy superconducting proton-proton collider, the Superconducting Super Collider (SSC) *(1)*. This major new accelerator complex would be based on the accelerator principles and technology that were developed in connection with the construction of the Fermilab Tevatron *(2)* and on extensive work on superconducting magnets in the United States over the past 20 years *(3)*. The proposed SSC would have an energy about 20 times that of the Tevatron collider recently tested at Fermilab. The high energy of SSC is needed to answer some of today's pressing questions in elementary particle physics. In addition, such a large increase in energy will open up new and uncharted territory. Historically, such openings lead to revolutionary advances for entire fields of science.

In this article, we summarize current understanding of the basic constituents and forces, which can be expressed entirely by what has come to be known as the "standard model" of particle physics. We describe recent progress, both theoretical and experimental, and we review the questions and problems raised by the standard model.

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We then briefly describe the SSC complex. In the main part of this article we examine some specific topics that will be studied with the SSC to illuminate current issues in particle physics and cosmology.

Historical Background

Forty years ago, ordinary matter was thought to consist of protons, neutrons, and electrons. Experiments probed the structure of these particles and explored the forces that bind them together into nuclei and atoms (*4, 5*). In the course of these experiments, over a period of 20 years, physicists discovered more than 100 new particles, called hadrons, that had many similarities to protons and neutrons. None of these particles seemed more elementary than any other, and by the mid-1960's there was little understanding of the mechanisms by which they interacted.

Since that time, a radically new and simple picture has emerged as a result of many crucial experimental discoveries and theoretical insights (*6*). It is now clear that the proton, neutron, and other hadrons are not elementary. Rather, they are composite systems made of more fundamental particles called quarks, much as an atom is a composite system made up of electrons and a nucleus. The existence of five kinds of quarks has been established, and initial experimental evidence for a sixth species has been reported.

Unlike the proton and neutron, the electron does appear to be an elementary constituent of matter, both structureless and indivisible. However, we now know that there are six kinds of electronlike particles called leptons. Both quarks and leptons appear to be grouped in three families of two members each. According to our present understanding, all matter is composed of quarks and leptons.

Nature derives enormous complexity of structure and dynamics from the six quarks and six leptons now thought to be the fundamental constituents of matter and from the forces that govern their interactions. All known natural processes may be understood as manifestations of a very small number of fundamental forces. For half a century, physicists have recognized four basic forces: (i) gravitation, (ii) electromagnetism, (iii) the weak interaction responsible for certain radioactive decays, and (iv) the strong force that binds atomic nuclei. An important difference between quarks and leptons is that one of these four interactions, the strong force that binds quarks together to form hadrons, does not affect leptons at all. Both quarks and leptons are acted on by the three other fundamental forces.

Over the past two decades, great progress has been made in understanding the nature of the strong, weak, and electromagnetic forces. The description of weak and electromagnetic forces has been unified (*7*) by a theory whose predictions have been verified by many inventive experiments, culminating in the discovery (*8*) of the W and Z particles in 1983. These carriers of the weak force are analogs of the photon, the carrier of the electromagnetic interaction, whose existence was postulated early in this century and established experimentally by the 1920's. In addition, there is indirect but persuasive evidence for particles called gluons, the carriers of the strong force. The strong, weak, and electromagnetic interactions are all described by similar mathematical theories called gauge theories. At present, the role played by the gravitational force in elementary particle physics is unclear (*9*). The effect of gravity on the behavior of small numbers of elementary particles is so small that it usually can be ignored.

The experimental measurements and discoveries that shaped the revolution in particle physics were made possible by the harnessing of new accelerator and detector technologies, which permitted the exploration of new energy domains. Accelerator advances included the exploitation of the strong-focusing principle in synchrotrons; the creation of intense high-energy beams of neutrinos; the invention of colliding-beam accelerators (colliders) in which counterrotating beams of high-energy particles collide head on; the development of bright sources of nearly monoenergetic antiprotons (*10*); and the introduction of large-scale, energy-efficient, high-field superconducting accelerator magnets (*3*). Among the advances in observational techniques were the utilization of the bubble chamber for the observation of reaction products and the parallel development of a series of ever more capable electronic detectors; the mastery of fast digital electronics for data acquisition and processing; the evolution of methods for managing and analyzing vast quantities of data; and the construction of large, complex detector systems exploiting the capabilities of a variety of individual devices. Each sortie into a new energy regime, each improvement in our ability to search for rare processes, and each increase in sensitivity for their detection has led to new insights and, often, to the discovery of unexpected and revealing phenomena.

With the identification of quarks and leptons as elementary particles and the emergence of gauge theories as descriptions of the fundamental interactions, we possess today a coherent point of view and a single language appropriate for the description of all phenomena. This development has made particle physics a much more unified subject, and it has also helped us to perceive common interests and to make common cause with other specialties, notably astrophysics and cosmology, condensed matter physics, atomic physics, and intermediate-energy nuclear physics. Among many examples, one important by-product of recent developments in elementary particle physics has been a recognition of the close connection between this field and the study of the early evolution of the universe from its beginning in a tremendously energetic primordial explosion called the Big Bang (*11*). Particle physics provides important insights into the processes and conditions that prevailed in the early universe. Deductions from the current state of the universe can, in turn, give us information about particle processes at energies that are too high to be produced in the laboratory—energies that existed only in the first instants after the primordial explosion.

What We Want to Know

The quark model of hadrons and the gauge theories of the strong, weak, and electromagnetic interactions organize our present knowledge and provide a setting for going beyond what is now known. A useful analog can be made between our present-day understanding of elementary particle physics and the situation in the beta-decay studies in the 1930's.

Fermi's weak interaction theory was invented to explain the phenomena in the million-electron-volt (MeV) energy domain that characterizes the spontaneously occurring beta-decay processes (*12*). Its extrapolation to higher energies was remarkably fruitful, since it successively provided the appropriate framework to describe muon decay and muon capture, strange-particle decays, and, finally, neutrino interactions at energies of billions of electron volts (GeV). The precise agreement between theory and experiment was startling because it was apparent that the theory was only a low-energy approximation that broke down when taken to the domain of hundreds of billions of electron volts. Because of its successes, however, one could be confident that elements of the Fermi theory would eventually become part of a more complete description. This occurred when the unified electroweak theory was developed, and the Fermi theory emerged as its low-energy limit.

Particle physics may be in a similar situation today. Although the standard model provides a framework for describing elementary particles and their interactions, its success prompts us to seek a more comprehensive understanding. For example, we do not know what determines such basic properties of quarks and leptons as their masses. Nor do we understand fully the origin of the differences between the massless electromagnetic force carrier (the photon) and the massive carriers of the weak force (the W and Z particles). Existing methods for dealing with these questions involve the introduction of many unexplained numerical constants into the theory, a situation that many physicists find arbitrary and thus unsatisfying. Physicists are actively seeking more complete and fundamental answers to these questions.

Another set of questions goes beyond the existing synthesis. For example, how many kinds of quarks and leptons are there? How are the quarks and leptons related, if they are related? How can the strong force be unified with the electromagnetic and weak forces?

Then there are questions related to our overview of elementary particle physics. Are the quarks and leptons really elementary? Are there still other types of forces and elementary particles? Can gravitation be treated quantum mechanically, as the other forces are, and can it be unified with them? More generally, will quantum mechanics continue to apply as we probe smaller and smaller distances? Do we understand the basic nature of space and time?

Given this list of questions, it is not surprising that there are many directions of theoretical speculation departing from the current paradigm. Many of these speculations imply important phenomena at energies that are beyond our present reach. Although theoretical speculation and synthesis are valuable and necessary, particle physics cannot advance without new observations. In the recent past, crucial observations have come from a variety of sources, including experiments at accelerators and nuclear reactors, nonaccelerator experiments (cosmic-ray studies and the search for proton decay), and deductions from astrophysical measurements. All our current ideas, embodied in the standard model, point to 1 TeV (10^{12} eV), an energy equivalent to approximately 1000 proton masses, as the mass scale on which new phenomena can be expected. But a diversity of experimental initiatives will have to be mounted in order to explore thoroughly the new regime of energy and distance (*13*). A detailed examination of a great variety of conjectured extensions of the standard model shows that the SSC, with the wealth of different measurements that its detectors would support, is the instrument of choice for exploring this new domain (*14*). At the same time, these extensions of the standard model set the parameters for the new accelerator.

Experiments under way and planned for accelerators now being built [such as the electron-positron colliders at the Stanford Linear Accelerator Center (SLAC) and the European Laboratory for Particle Physics (CERN), and the Tevatron proton-antiproton collider at Fermi National Accelerator Laboratory] will provide detailed quantitative tests of the standard model up to mass scales of order 0.2 to 0.3 TeV. These experiments will continue over several years. By the mid-1990's, the basic facilities at SLAC, CERN, and Fermilab will be 20 to 30 years old. New instruments will then be needed so that high-energy physics can proceed to the 1-TeV scale. The only accelerator technology (*15*) that will reach the 1-TeV mass scale by the mid-1990's is the superconducting hadron collider. The long interval (10 to 15 years) between conception and first exploitation of a large new accelerator dictates that we move forward now with the SSC.

In a more limited way, individual nonaccelerator experiments also may provide information about the 1-TeV scale. These might include, for example, more sensitive proton decay experiments, better neutrino mass measurements, improved searches for monopoles in cosmic rays, or more precise searches for forbidden decay processes. However, according to our present knowledge of elementary particle physics, our physical intuition, and our past experience, most clues and information will come from experiments at the highest energy accelerators.

Description of the SSC

The SSC will have two counterrotating beams of protons guided along circular orbits by superconducting magnets. Each beam will be accelerated to 20 TeV, and the two beams will be brought into collision at several (approximately six) different interaction regions around the circumference of the accelerator. Sophisticated detectors will be installed at the interaction regions or collision points. Many crucial experimental tests have already been framed, and preliminary designs of detectors have been carried out.

It is not the collisions of protons on protons as such that are of primary interest. Protons are composite systems formed of quarks and gluons, the latter providing the binding force that holds the proton together. The "hard" collisions of a constituent of one proton with a constituent of the other provide us with information about the fundamental interactions. Very roughly, each constituent carries on average about one-tenth of the proton's total energy, and thus colliding beams of 20-TeV protons were chosen for the SSC to produce numerous constituent-constituent collisions at a few trillion electron volts. The clarity with which the relatively rare hard scatterings of constituents have been observed in proton-antiproton collisions at the CERN collider (with a beam energy of about 0.3 TeV) gives us confidence that scientifically important results can be derived from the complex collisions that would occur in a super collider.

The proposed accelerator scheme makes use first of an injector system consisting of a linear accelerator followed by two circular accelerators. This system accelerates protons to about 1 TeV, at which point they are injected into the main ring for the final acceleration phase. The diameter of the main ring will be approximately 30 km, depending on details of the magnets used to guide the protons.

The magnets will use superconducting wire to carry the electric current that sets up the magnetic field and will require hundreds of miles of cryogenic plumbing (with several hundred thousand vacuum joints) to establish superconductivity. Such systems can confidently be planned for the SSC because they have been successfully used on a large scale at the Tevatron ring. Superconducting magnets make the SSC feasible by significantly reducing power consumption and making possible higher magnetic field strengths than are attainable with conventional room-temperature magnets.

The SSC will use mature technology that must be applied on an unprecedented scale. The linear dimensions of the SSC will be about 15 times those of the Tevatron and 4 times those of the electron-positron collider (LEP) (*16*) currently under construction by CERN. Although the Tevatron consists of about 1000 superconducting magnets, the SSC will contain approximately 8000. This very large scale presents extremely challenging problems in manufacturing techniques, quality control, reliability, civil engineering, instrumentation and controls, communications, and installation and repair logistics. The magnitude of these problems is new to accelerator science and technology but is manageable by an appropriate extension of present skills and experience. Creative solution of these problems calls for a new partnership between the basic research community and industry that is sure to bring additional advances in technology that can be applied elsewhere. Already, cooperative work to develop improved superconductor for the SSC has resulted in an increase in current densities from the 1800 A/mm^2 characteristic of

Tevatron wire to 2600 A/mm^2, with further increases of about 10 percent foreseen when industry begins large-scale mass production (*17*). The most obvious examples for the future include: (i) large-scale industrialization of superconducting wire fabrication and cryogenic refrigerator manufacture, making these technologies available to future power-distribution and transportation systems; (ii) improved tunneling techniques that may be applied to future public works and transportation projects; (iii) large-volume storage of helium, a potentially critical and nonrenewable resource; and (iv) computer control and mechanical alignment systems extending over very large areas.

Costs and engineering questions for the SSC were studied carefully by a group of approximately 150 physicists and engineers during the spring of 1984 in a Reference Design Study (*1*) sponsored by the Department of Energy. Three different styles of magnets were considered so that different budget scenarios could be examined. The total estimated cost of the accelerator itself, including contingencies, was consistent for the different approaches and ranged between $2.7 and $3 billion (1984 dollars). Since that study, a design group has continued to investigate technical and financial aspects of the SSC, and the budget figures have remained stable. A complete conceptual design based on a recently selected magnet style is due in the spring of 1986.

International participation in the construction and operation of the SSC would build upon the existing tradition of collaboration in high-energy physics and would be of great practical interest in view of the estimated costs. Exploitation of all high-energy accelerators in the Western world is governed by the scientific merit of experimental proposals, irrespective of the national origin or institutional affiliation of the proponents. It is hoped that the SSC will foster a new level of international collaboration. As the premier accelerator, it will surely attract many of the best particle physicists from all parts of the world. Early formation of international collaborations could allow significant foreign participation in the design and construction of the SSC and its detectors, not just in their utilization.

The detectors provide another great challenge to the physicists doing experiments with the SSC. The events resulting from collisions of interest will be complicated, with hundreds of particles flying out from the collision point. These must be tracked and measured to reconstruct the underlying physics responsible for the event. One particular challenge to SSC experimenters will be the high rate of collisions—about 100 million per second—out of which only a very tiny fraction will be of interest for a specific investigation. Developing the techniques necessary to identify and record these interesting events in a small fraction of a second will advance the frontiers of electronics and computer technology.

In planning detectors for the SSC, there are trade-offs to be considered between physics goals, the operating luminosity (rate of collisions) and energy of the SSC, and choices of detector technology. For example, for some physics processes, it may be possible to probe larger mass scales by increasing either the luminosity or the energy. Different detector strategies would have to be developed, depending on the path followed. Often, greater luminosity requires increasing the number of detector elements whereas higher energy may require higher performance from certain components. The cost of detectors depends critically on the total number of independent detecting elements and on the capabilities of the individual elements. In the case of the SSC, detector capabilities played an important part in the choice of maximum energy and luminosity. Because the outcome depends on the physics processes to be studied, there will probably be several complementary detectors installed in the SSC and they may operate simultaneously in different interaction regions at different luminosities, but at the same energy.

The detectors will generally be big enterprises involving international collaborations among many different university and laboratory groups. Traditionally, these collaborations evolve from the common interests of experimental physicists to become scientific societies of students, postdoctoral researchers, and university professors supported by laboratory engineering and technical staffs. The data collected by the detector are available to the collaboration members who often work in very small groups according to their scientific interests. The challenges of building these detectors, the access to forefront experimental data, and the opportunity of working with top-ranking scientists will make the SSC one of the best training grounds for many of our brightest students, whose scientific leadership will play an important role in the future of our universities, high-technology industries, and government.

Scientific Questions for the SSC

A major accelerator facility is constructed not to carry out a single experiment or measurement but rather to make possible a great diversity of investigations over the accelerator's lifetime, which is measured in decades. The evolution of the experimental program is guided by results of early experiments, by improvements in detector and accelerator technology, and by hunches and theoretical insights. Because of this, we cannot describe in advance the full scope of the research program for a super collider. We indicate, however, some of the sorts of issues to be addressed in the first round of experiments. These are representative of the questions that form the basis for the scientific justification for constructing a super collider and of the opportunities that a super collider would present (*13*).

The origin of mass. Imagine a universe pervaded everywhere by a uniform magnetic field. In such a universe, the motion of charged particles would appear to be rather complicated, because the particles' motions would be influenced by the universal magnetic field as well as by specifically applied forces. Eventually, as physics developed, some genius would realize that a simple law of motion (namely Newton's) is really the basic one and that all the complicated spiralings observed in such a universe are caused by a pervasive background field.

The current standard model of the weak interactions suggests that a similar situation is realized in our universe. The field involved is not a magnetic field but rather what is called a Higgs field. The equations describing the weak interactions would take a simpler and more symmetrical form if there were no background Higgs field. One consequence is that weak interactions would obey a Coulomb force law and the masses of the W and Z bosons and of many other particles (including the electron) would vanish. This simplification evidently goes too far for the real world. The best we can do is to postulate that the basic model operates in a world pervaded by a background Higgs field that partially hides its full symmetry and simplicity. The standard model, built on this assumption, accurately describes a wide variety of observations—including the existence and mass of the W and Z bosons recently found at CERN—but requires the existence of one or more spinless particles associated with the background field.

Certainly one main area that we can hope to clarify with the SSC is the exact nature of the Higgs field and its interactions with other matter. Why is the SSC likely to be an appropriate tool? To see the answer, consider the reason that the Higgs field pervades our universe. It must be because the total energy density is minimized by its presence. To change the magnitude of the field significantly, or to make manifest one of its particles, one must supply enough energy density to overcome the natural tendency of the field to revert to its normal universal background value. The energies available at the SSC are sufficient to do so.

Present theoretical understanding of Higgs fields is primitive. There must be at least one such field, but there may well be many, each associated with its own particle. The SSC will open a window on this now dimly perceived sector of elementary particle theory and help us to understand the reason for the apparently disorderly pattern of elementary particle masses, caused, according to the present theory, by the interactions with the Higgs field or fields.

Families of particles. The recent discovery of members of a third family of quarks and leptons has sharpened the problem of understanding the replication of particles in families. Within a well-defined sense, the known families of elementary particles have identical strong, electromagnetic, and weak interactions but different masses. Why does nature repeat itself in this way? Are there still more families? Do Higgs particles come in families? Are there other particles that do not fit into the same repetitious pattern? There are many such questions, which will only be answered by experiments at energies higher than those we can now attain.

One theoretical approach to understanding families postulates new symmetries under which the different families are interchanged. Given such symmetries, the observation of one family implies the existence of others. A particularly appealing version of this idea involves combining the family symmetry and the gauge symmetries of the strong, weak, and electromagnetic interactions into one all-encompassing symmetry, hidden by the presence of suitable background Higgs fields. Implementing such symmetries could lead one to expect a new class of "family interactions" mediated by heavier analogs of the W and Z bosons that might be created at SSC energies.

Chirality. There is a peculiar asymmetry in the weak interactions of the observed quarks and leptons. Simply put, the W bosons prefer to couple to these particles if they appear to be spinning clockwise, as viewed by an observer that they are approaching. We say that the weak interactions mediated by W bosons couple to left-handed quarks and leptons. Many people have speculated that this left-right asymmetry arises by a mechanism analogous to the one that causes the electromagnetic and weak interactions to appear different in the standard model. According to this view, there will be either W′ bosons that couple preferentially to right-handed quarks and leptons or new sets of quarks and leptons with right-handed couplings to the familiar W boson. In many models, the symmetry between left and right is broken by the same Higgs fields that conceal the fundamental electroweak symmetry. In such models, the masses of the new gauge bosons involved, or of the right-handed quarks and leptons, cannot be much larger than the known masses of the W and Z—which would make them observable at super collider energies. At the SSC, it will be possible to establish intermediate bosons up to at least 5000 GeV/c^2 (where c is the speed of light): 50 times the mass of the known W and Z.

Supersymmetry. Recently there have been many theoretical investigations of the physical consequences of a new kind of symmetry, called supersymmetry, that implies the existence of integral-spin partners of particles of half-integral spin and vice versa. If it is relevant to physics at all, supersymmetry must be hidden. For example, there is definitely no particle having the mass and charge of the spin-1/2 electron that has integral spin. Such a particle would have been observed long ago if it existed.

If supersymmetry plays a role in the mechanism for electroweak symmetry breaking, many supersymmetric partners of known particles could be produced at super collider energies. The advantages of such a scheme include resolution of the mathematical inconsistencies that arise in the calculation of many physical quantities, specifically the masses of the Higgs particles.

The conjectured supersymmetry would lead to a Higgs boson mass less than 1 TeV/c^2 and yield supersymmetric particles with masses also less than about 1 TeV/c^2. There is no conclusive experimental evidence for any superpartners, but there have been attempts to interpret some unusual events (with large amounts of energy radiated in an invisible form) observed at the CERN collider in terms of supersymmetric models.

Significant progress has been made recently in building unified field theories that include gravity. These ambitious theories, which incorporate supersymmetry in a fundamental way, involve objects called superstrings. They will be confirmed, significantly constrained, or ruled out by experiments that elucidate the possible role of supersymmetry at super collider energies.

Dynamical symmetry breaking. A second possible solution to the Higgs problem assumes that the Higgs boson does not correspond to an elementary field at all but is a composite object made of elementary constituents analogous to quarks and leptons. Although they would resemble the usual quarks and leptons, these new constituents would be subject to a new kind of strong interaction that would confine them in bound states within about 10^{-17} cm. Such new forces could yield new phenomena as rich and diverse as the conventional strong interactions, but on an energy scale a thousand times greater, around 1 TeV. The new phenomena would include a rich spectrum of new bound states akin to the spectrum of known hadrons. There is no evidence yet for these new particles.

Compositeness. The pioneering experiments at the CERN collider have recorded many events in which well-collimated sprays or jets of energetic particles are emitted at large angles to the axis of the colliding beams. These "hard scatters," so called because of their resemblance to billiard ball collisions, must result from the collision of an individual quark or gluon from a proton with an individual constituent of an antiproton. The CERN experiments have recorded collisions in which the total energy of the constituents is as high as 200 GeV. The SSC will make possible the detailed study of these elementary collisions among the fundamental particles for energies up to 10^4 GeV. These studies will stringently test the predictions of quantum chromodynamics, the theory of the strong force for the interactions among quarks and gluons, and will yield new insight into the way in which quarks and gluons materialize into the observed hadrons.

Violent collisions among quarks also provide a window on the possible internal structure of quarks. Some physicists feel that the known quarks and leptons are too numerous to be the ultimate elementary particles. If quarks are themselves composite, it should be possible to excite their internal structure in violent collisions. One sign of this kind of internal excitation would be spectacular multijet events quite unlike those anticipated in the standard model. The absence of such events and the agreement of the observed quark-quark scattering cross section with predictions of the standard model imply upper limits on the size of quarks. It will be possible with the SSC to look for quark substructure down to a distance of about 10^{-18} cm.

Cosmology and the SSC

Over the past few years, cosmology and particle physics have become increasingly interwoven. To understand what took place in the high-temperature, high-density early universe, one is forced to look at the physics of elementary particles. Similarly, the unified theories of elementary particle physics have striking consequences at extremely high temperatures and energies. The only "laboratory" available to check these extrapolations of unified theories is the first instants after the Big Bang, when extraordinarily high temperatures and densities were reached. The SSC will be operating at energies far beyond those previously achievable in a laboratory and will simulate the conditions that prevailed about 10^{-15} second after the primordial explosion when the temperature of the universe was about 10^{17} K.

Direct observations by optical telescopes are limited to events that occurred some 300,000 years after the Big Bang because the universe was opaque to photons at earlier times. To reconstruct what happened in the early universe, we must know the nature of basic interactions at high energies and the complete spectrum of elementary particles. In particular, the relics left over from those early times are of basic importance to cosmology. Any long-lived particle produced in the primordial explosion would survive and be an ingredient in the present-day universe.

One of the major issues in cosmology is to find the "dark matter" of the universe. Studies of the motion of stars within galaxies and of galaxies within clusters have established that these systems must contain a great deal of matter in addition to what is visible in the stars. This nonluminous matter may in fact account for the bulk of the mass in the universe. The properties that we impute to the dark matter depend on the character of the small density fluctuations in the early universe that grew into the galaxies and clusters observed today. According to current ideas about galaxy formation, the dark matter may be quite different from the ordinary matter of which we are made. Particle physics yields a mechanism for generating the primordial density fluctuations and provides candidates for the dark matter as well. Experimentation at the SSC will allow broad searches for new particles that may play the role of the dark matter.

In addition to the possibility of resolving the question of dark matter of the universe, the SSC will clarify the structure and symmetry of the fundamental interactions and allow us to extrapolate with greater confidence back to early times. One of the most interesting recent developments in cosmology has been the suggestion that the large-scale homogeneity and isotropy of the universe (*11*) were established during an early symmetry-breaking phase transition (*18*). According to these ideas, the universe began in a highly symmetric phase in which all the fundamental interactions were equivalent and evolved to the present phase in which different forces have different manifestations. The vacuum state of the universe is modified when the symmetry is broken. Below the transition temperature the vacuum is occupied by a Bose condensate of a type of Higgs particles, so that the vacuum energy of the universe changes during the transition. It is possible that during the transition the vacuum energy of the universe was large enough to cause the universe to expand exponentially. This exponential expansion, or inflation, is capable of explaining in a natural way a great deal about the present structure of the universe: homogeneity and isotropy in the large-scale distribution of galaxies, the great age of the universe, its spatial flatness, its large entropy, and possibly the existence of small primordial perturbations in the distribution of matter that eventually grew to become galaxies, stars, planets, and people.

We know that the exponential phase did not occur in the electroweak symmetry-breaking transition. However, if nature is more symmetric at high energies than at low energies, the electroweak transition is but the last in a series of similar transitions. Almost all proposals for inflation are associated with spontaneous symmetry breaking and have their own types of Higgs systems.

We are now faced with the prospect of the most revolutionary and exciting development in cosmology depending upon the least understood part of particle physics—the Higgs sector. Detailed exploration of the electroweak (1 TeV) scale at the SSC will give us a clearer picture of how the electroweak symmetry is hidden and will point the way to an understanding of the Higgs system of inflation.

Conclusion

The advances of the past decade have brought us tantalizingly close to a profound new understanding of the fundamental constituents of nature and their interactions. The standard model based on quarks and leptons organizes current knowledge and defines the horizon of particle physics at constituent energies of about 1 TeV and the horizon of cosmology at times of about 10^{-15} second. Important answers are to be found on the 1-TeV scale. There we await new discoveries about the unification of the forces of nature, the patterns of the fundamental constituents of matter, and the origin of the universe. The SSC is the instrument to lead this quest. The boldness of the project and the significance of the questions it will address give it the potential to be one of the great examples of the United States' commitment to excellence in science.

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19. This article is based on the Report of the Research Briefing Panel on Scientific Frontiers and the Superconducting Super Collider prepared under the aegis of the Committee on Science, Engineering, and Public Policy of the National Academies of Sciences and Engineering and the Institute of Medicine. Other members of the panel were S. Wojcicki (chairman), B. Barish, K. Fowler, B. H. Honig, A. K. Kerman, C. K. N. Patel, D. Schramm, S. B. Treiman, S. Weinberg, F. Wilczek, and H. Woolf. We are grateful to D. C. Shapero and R. L. Riemer for advice and assistance.