Unification of Nature's Fundamental Forces

a continuing search

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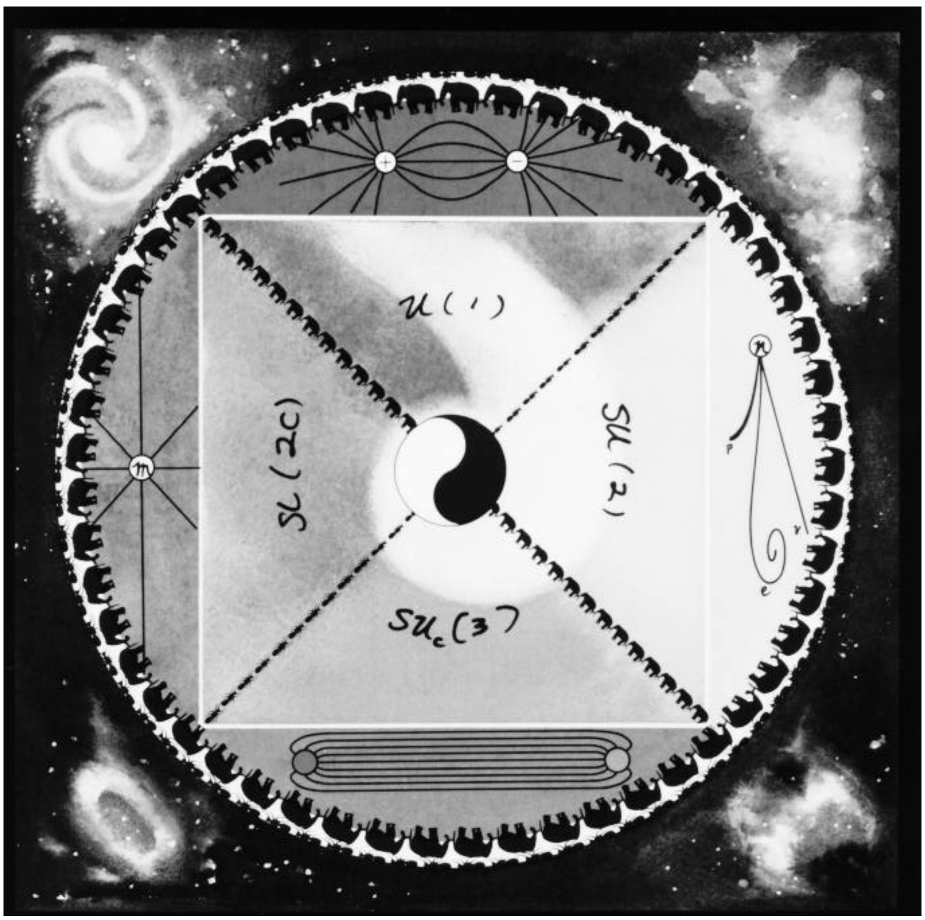


It is a well-known, and much-overworked, adage that the group of scientists brought to Los Alamos to work on the Manhattan Project constituted the greatest assemblage of scientific talent ever put together. Many of those scientists had made (or in some cases were destined to make) highly significant contributions to the development of our understanding of the basic laws of physics. They had grappled with deep questions concerning the consequences of quantum mechanics, the structure of the atom and its nucleus, and the development of quantum electrodynamics (QED, the relativistic quantum field theory describing the interaction of charged particles with radiation). Although those questions had to be put on the back burner for the duration of the project, the pot, so to speak, continued to simmer. Indeed, it was explicitly recognized at the time that basic research had an important and seminal role to play even in the highly programmatic environment of the Manhattan Project. Not surprisingly this mode of operation evolved into the remarkable and unique admixture of pure, applied, programmatic, and technological research that is the hallmark of the present Laboratory structure. Nowhere in the world today can one find under one roof such diversity of talent dealing with such a broad range of scientific and technological challenges—from questions concerning the evolution of the universe and the nature of elementary particles to the structure of new materials, the design and control of weapons, the mysteries of the gene, and the nature of AIDS!

Many of the original scientists would have, in today's parlance, identified themselves as nuclear or particle physicists. They explored the most basic laws of physics and continued the search for and understanding of the "fundamental building blocks of nature'' and the principles that govern their interactions. It is therefore fitting that this area of science has remained a highly visible and active component of the basic research activity at Los Alamos. Furthermore, in keeping with the historical development of the Laboratory, there continues to be a vigorous and productive interplay with other more applied and programmatic parts of the Laboratory (see "Testing the Standard Model of

Particle Interactions using State-of-the-Art Computers").

This article will give a brief overview of some of the exciting developments in this area of science that have taken place in recent years and in which scientists at Los Alamos have played significant roles.

From the end of the Manhattan Project until approximately 1970, the general taxonomy and phenomenology of the elementary particles was intensely studied. When the various mesons (such as the pions and the kaons) and baryons (such as the proton, neutron, §, ß, and •) were classified, it was discovered that there were four apparently quite distinct ways in which they interacted among themselves: (1) gravitationally, (2) electromagnetically, (3) weakly and (4) strongly. The first two interactions, or forces, are the most familiar since they are long-range and so manifest themselves macroscopically even over astronomical distances. The second two have very short ranges (less than 1 fermi, or 10^{-13} centimeter) and so are only important at the nuclear and subnuclear level. The weak interaction is the one responsible for beta decay (such as the decay of the neutron to a proton, an electron, and a neutrino), and the strong interaction is the one responsible for the binding of protons and neutrons to form the nuclei of atoms.

One of the great intellectual achievements of the twentieth century has been the realization that these four wildly different "fundamental'' forces may, in fact, be viewed as manifestations of a single unified force. Although this paradigm was originally the dream of Einstein, not until the 1970s was any serious progress made toward developing the theoretical framework for unification.

The initial major breakthrough occurred around 1970 when a theory was proposed that unified the weak force with the electromagnetc force in a mathematically consistent fashion. This unification came almost a century after Maxwell had shown that electric and magnetic phenomena could themselves be unified in a single force carried by the electromagnetic field. In the modern language of QED, *all* electromagnetic phenomena can be understood in terms of a force-carrier that is exchanged between electrically charged particles such as electrons. This force-carrier, called the photon, is the quantum of the electromagnetic field and can be thought of as a massless elementary particle with no electric charge and spin angular momentum equal to one (in units of $\hbar$). The masslessness of the photon is a consequence of the so-called gauge (or phase) symmetry of the electromagnetic field and gives rise to the long-range nature of the electrostatic force between charged particles. Furthermore, it guarantees that electric charge is conserved. Technically, the gauge symmetry responsible for the masslessness of the photon is a reflection of the invariance of Maxwell's equations to arbitrary phase changes in the quantum fields associated with the electron and the photon. (Specifically, an arbitrary phase change of the electron field can be compensated for by a redefinition of the photon field, which leaves the form and structure of the equations of motion for electromagnetic interactions unchanged.) Because of its deep and seminal role, this local phase, or gauge, invariance of the electromagnetic fields is now viewed as a fundamental principle, or constraint, used to derive the form of the basic interactions among the quantum fields describing all elementary particles.

The unification of electromagnetism with the weak interactions was accomplished in the context of quantum field theory by extending the principle of gauge symmetry and the idea of a force-carrier to the case where the force-carrier can itself carry electric charge and therefore interact with itself. (In QED the photon is neutral and therefore cannot interact with itself.) A force-carrier of the weak interactions must have electric charge because some weak interactions cause the charge of a particle to change. For example, the neutron, which is neutral, decays through the weak interactions to a proton, which has one unit of positive charge. Further, the force-carrier of the weak interaction must be massive rather than massless because the range of the weak force is so short, less than 10^{-14} centimeter. (This follows from the original observation of Yukawa that the range of a force varies inversely with the mass of the force-carrier.)

The remarkable accomplishment of Glashow, Weinberg and Salam was to fashion a well-defined quantum field theory like QED for the weak interaction. It is based on an extended notion of gauge symmetry that Yang and Mills had invented earlier in an attempt to describe the strong interactions, but, in addition, is ideally suited for describing the charge-changing and charge-conserving interactions of the weak force. To obtain massive force-carriers, called the W^{+}, W^{-}, and Z^{0}, the gauge (or phase) symmetry of the quantum fields had to be dynamically broken in a rather subtle way analogous to the way the spontaneous symmetry breaking in a superconductor produces the Meissner effect. This dynamical symmetry breaking is referred to as the Higgs mechanism. It was designed to yield massive mediators of the weak force while preserving the masslessness of the photon. As mentioned above, the masslessness of the photon is the origin of both the long-range nature of the electrostatic force and the conservation of electric charge, so these properties of electromagnetism are sacrosanct and had to be maintained in any attempt at unifying electromagnetic and weak forces into a unified force law. These constraints turn out to be so tight that they lead to precise predictions for the masses of the W^+, W^-, and Z^0, which were brilliantly confirmed by experiment. The prediction and discovery of the mediators of the weak force can be likened in their profundity to the prediction and discovery of electromagnetic waves that followed from Maxwell’s formulation of electromagnetism.

The Higgs mechanism of dynamical symmetry breaking can be thought of as a spontaneous alignment of the vacuum (the state of lowest energy). The alignment is roughly analogous to the spontaneous magnetization encountered in ferromagnetic materials such as ordinary bar magnets. As particles such as the W^+, W^-, and Z^0 propagate through this aligned vacuum, they become massive as a result of their coherent interaction with the Higgs field (analogous to a magnetic field). It is believed at present that the dynamical interaction of particles with the vacuum is the origin of all the mass in the universe (including us!). The precise nature of the Higgs mechanism is not, however, well understood and remains the subject of intense study. In its simplest version small fluctuations of the Higgs alignment field manifest themselves as an elementary massive particle, dubbed the Higgs particle. The mass of the Higgs particle is not certainly known, but it must be less than approximately 1 TeV = 10^{12} eV.

The existence of the Higgs particle and the origin of electroweak symmetry breaking are therefore intimately related to the ancient and vexing question of the origin of mass itself. Indeed the hope of verifying this line of thinking has been one of the main justifications for constructing the $10 billion Superconducting Super Collider (SSC) just outside of Dallas. The SSC will collide two proton beams, each composed of protons accelerated to energies of 20 TeV. Compelling arguments suggest the collision energies are ample to either create and discover the elusive Higgs particle or, even if it doesn’t exist, to unravel the deep mystery as to the “origin of mass.”

Scientists at Los Alamos have been actively involved in several aspects of SSC physics. These have included theoretical studies concerning the nature and phenomenological implications of the Higgs mechanism as well as vigorous involvement in designing the huge (and very expensive) detectors needed to investigate these questions experimentally. Indeed the Los Alamos contribution to the SSC nicely exemplifies the breadth of the Laboratory’s unique and special characteristics: fundamental theoretical studies, detailed physics involvement with the design of the detectors, and superb engineering capability for its actual construction. This year over $7 million of SSC engineering funds will be spent at Los Alamos.

Baryon-Number Nonconservation and the Stability of Matter

One of the most intriguing possibilities for new physics at the SSC and an area in which Los Alamos has been heavily involved is the possibility of experimentally observing the violation of baryon-number (B) conservation. Baryon number appears to be an exactly conserved quantum number in nature. Its conservation, for example, prevents a proton (B = 1) from decaying into a state with B = 0 such as an electron and a pion or an electron and a photon, even though these decays are energetically very favorable. Indeed, it is the conservation of baryon number that keeps ordinary matter stable against radioactive decay (“diamonds are forever’’).

Notwithstanding a complete lack of experimental evidence for the violation of baryon-number conservation, the absolute validity of this law has always been viewed with some suspicion by theorists. Indeed, it has always appeared as a somewhat ad hoc phenomenological law with no fundamental basis for its understanding. There are two basic reasons for this skepticism. (1) Unlike the conservation of electric charge (which *is* believed to be exactly conserved) there is no known long-range force between baryons or local gauge symmetries associated with baryon number. Thus there is no fundamental reason for the exact conservation of baryon number; if exact, it would have to be viewed as an “accident’’ from our present viewpoint. (2) The second reason for skepticism is the well-known and remarkable fact that the universe appears to be overwhelmingly dominated by matter, which has positive baryon number, rather than antimatter, which has negative baryon number. This dominance is particularly hard to understand if baryon number is exactly conserved; in that case one would have to postulate that this gross asymmetry in the universe was put in “by hand’’ as an initial boundary condition at the moment of creation!

Suggestively, the unified electroweak theory has, as a dynamical consequence, the breakdown of baryon-number conservation. As with the Higgs mechanism and the generation of mass, so here, the origin of the violation has its roots in the terribly complicated vacuum structure of the theory. It turns out that the field configuration of the vacuum has a periodic structure in which the different minima are separated by a potential barrier whose height is $M_w/\alpha \approx 10$ TeV (where M_w is the mass of the $W^{+,-}$ and α is the strength of the electromagnetic interaction). Furthermore these different minima correspond to different values of baryon number. Normally, an isolated system (such as “the universe’’) sits at the bottom of a specific minimum with a given value of B. Now, B can change if either the system quantum mechanically tunnels through the barrier separating it from its neighboring vacuum (analogous to the way in which α particles tunnel through the nuclear potential barriers in the radioactive α decay of a nucleus), or the system has sufficient energy (nominally greater than about 10 TeV) to jump over the barrier (see Figure 1). It turns out that the probability for quantum-mechanical tunneling is ridiculously small, on the order of 10^{-170}. So even though baryon number can indeed change in the electroweak theory, the universe is still waiting for the first event of this kind to happen; diamonds are not going to spontaneously decay into radiation any time soon!

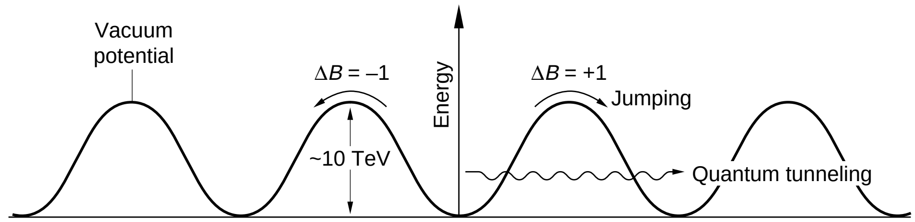


Figure 1. Structure of the Vacuum for the Electroweak Theory and the Possibility of Baryon-Number Nonconservation

This figure illustrates the periodic structure of the vacuum in the electroweak sector of the standard model. A system usually sits in the minimum of ar well of the vacuum potential where it is separated from adjacent minima by a very high energy barrier of about 10 TeV. Baryon number is conserved as long as the system remains in a single well of the potential. In principle, baryon-number conservation can be violated by two mechanisms: Either a system acquires enough energy, through heating or high-energy collisions, to jump over the barrier, or a system leaks through the barrier by quantum tunneling. A system will change its baryon number by one unit each time it jumps over or tunnels through the barrier. Collision energies at the SSC will be high enough to test the former mechanism of baryon-number violation.

However, the second possibility, namely jumping over the barrier, brings up two intriguing alternatives. One can, in principle, pump sufficient energy into a system either (1) by heating it up or (2) by performing some high-energy collision. In the former case one needs to heat the system to a temperature greater than roughly 10^{15} kelvins (100 million times hotter than the center of the sun!). Although this is clearly not feasible in the laboratory, the universe itself was at those extreme temperatures during its evolution following the big bang. The theory predicts that during that period baryon-number conservation was significantly violated by the system’s jumping over the 10-TeV potential barrier. It is therefore conceivable, though not yet proven, that the present overwhelming domination of matter over antimatter was generated at that time. As the universe cooled down (its present mean temperature is only 3 kelvins), this asymmetry of matter over antimatter was frozen in since tunneling through the potential barrier is so strongly suppressed. So, we are led to the satisfying possibility that the unified electroweak theory can potentially explain both the dominance of matter over anti-matter, which requires the violation of baryon-number conservation at an earlier epoch and, at the same time, explain the apparent exact conservation of baryon number today (and, consequently, the stability of matter).

The Elementary Particles and Field Theory Group at the Laboratory began to study the breakdown of baryon-number conservation in electroweak theory at high temperatures in 1987, and soon after, it was realized that the baryon-number-violating processes described above could be important in the evolution of the early universe. Los Alamos research played a major role in clarifying the mechanism of the process and convincing a skeptical scientific establishment of its importance. Today we are investigating the very exciting possibility that violations of baryon-number conservation could be directly observed in the very high-energy collisions at the SSC. This research is being carried out in collaboration with the Institute of Nuclear Research in Moscow. By combining Los Alamos computer resources and expertise with that of the Russians, we hope to make reliable predictions long before the SSC turns on in the next century.

The possibility of performing a controlled experiment at the SSC that would detect baryon-number violation experimentally is truly fantastic. Thus far, all experimental attempts to observe a violation of baryon-number conservation by detecting the decay of the proton have failed, implying that the proton lifetime must be greater than approximately 10^{32} years! (Recall that the age of the universe is only (sic!) on the order of 10^{10} years). Further, observing violation of baryon-number conservation in a proton-proton collision at energies below 10 TeV (in the center-of-mass system) is impossible because quantum tunneling through the 10-TeV barrier of the periodic vacuum is exponentially suppressed (just as the universe is suppressed from doing so at temperatures below 10 TeV).

Thus baryon number will always be exactly conserved in a high-energy proton-proton collision below 10 TeV. Recall, however, that the total center-of-mass energy available in a collision at the SSC will be 40 TeV, which is fortuitously in excess of the barrier height. A naive calculation indicates that at these energies the colliding protons could jump over the barrier and baryon-number conservation would be violated. In such a case a very dramatic effect would occur: the copious production of *W*’s and *Z*’s (and Higgs particles) (see Figure 2). Recall that ordinarily the probability of producing just one of these particles is, as with photons, at best on the order of the electromagnetic interaction strength, or less than 1 percent! Unfortunately many subtleties need to be carefully considered in these calculations, and it is not at all clear that this naive prediction will, in fact, be borne out. As stated above, this subject is under intense investigation at Los Alamos and elsewhere at the present time. If the predictions are true, the results would be quite spectacular.

Quantum Chromodynamics—The Theory of the Strong Interactions

Even as gauge symmetry was being recognized as essential to unification of the electromagnetic and weak forces, it was simultaneously playing a no less central role in understanding the strong force that binds protons and neutrons together in atomic nuclei. Our present understanding of the strong force is that it too arises from a force-carrier with spin angular momentum equal to one that is analogous to the photon of QED. The carrier of the strong force is called a “gluon.’’

The present theory of the strong interactions was developed during the 1970s and is based on the idea that all baryons and mesons are made of spin-1/2 particles called quarks that interact via the exchange of gluons. Quarks themselves were first postulated in the early 1960s independently by Murray Gell-Mann and George Zweig. They are indeed the “fundamental building blocks” and have the curious property of carrying an electric charge that comes in units of $e/3$, where e is the magnitude of the charge carried by electrons and protons; previously, e was thought to be the smallest unit of electric charge carried by any particle. Interestingly, Zweig is now a theoretical biophysicist at Los Alamos doing pioneering work on the physics of the ear and Gell-Mann is spending his sabbatical year at the Laboratory mostly involved in exploring new ideas concerning the concept of complexity.

At first the existence of these “quarks’’ was not taken very seriously, since no one had ever observed a free quark (or fractional charge) in a particle detector of any kind. However, the unmistakable presence of point scattering centers within protons discovered by the now famous deep-inelastic-scattering experiments at the Stanford Linear Accelerator Center (SLAC) in the early 1970s, as well as other indirect checks of the theory, finally led to the acceptance of quarks as the genuine building blocks of all the strongly interacting particles (known collectively as hadrons). Thus, in analogy with QED, quarks play the role of electrons and gluons that of photons. The analog to the electric charge—the “strong charge,’’ so to speak—was whimsically dubbed color, and so the theory of the strong interactions became known as quantum chromodynamics’ (QCD). A crucially new feature of QCD is that color comes in three varieties and that the gluon itself carries this color. In that respect the gluon resembles more the *W*s and *Z* of the weak interactions than the photon of QED in that it can now self-interact. On the other hand, the gauge symmetry of the vacuum of

QCD is *not* spontaneously broken, so the gluons, at least naively, remain massless like photons. The strength of the gluon self-interaction is, however, so large that it is believed to forbid color and, in particular, quarks from ever being liberated and observed directly in an experiment. Nevertheless, the theory dictates that at high energies quarks and gluons inside the proton should behave essentially as if they were free particles. In other words, in a high-energy collision between two protons, the quarks that make up the protons should briefly act as if they were not bound. The precise predictions of QCD were, in fact, brilliantly confirmed by the SLAC experiments for which the originators received the Nobel Prize. It should be recognized that truly free quarks and gluons have never been observed *directly* in *any* experiment. The situation recalls one encountered in an earlier period of the history of science. By the end of the last century, most working physicists and chemists tacitly assumed the existence of atoms in order to interpret a wide variety of experimental data. But not one of those scientists had ever seen a single atom, so that as late as 1916 no less a figure than Ernst Mach still doubted their existence.

The theoretical aspects of QCD have been studied most intensively in recent years by the technique of “lattice gauge theory” calculations, performed on state-of-the-art supercomputers. Rajan Gupta heads the Los Alamos effort in this area, which is recognized as one of the leading groups worldwide. In this decade the appearance of the Teraflop machine (capable of executing 1 *trillion* basic mathematical operations per second) is expected to make it possible for Gupta and his

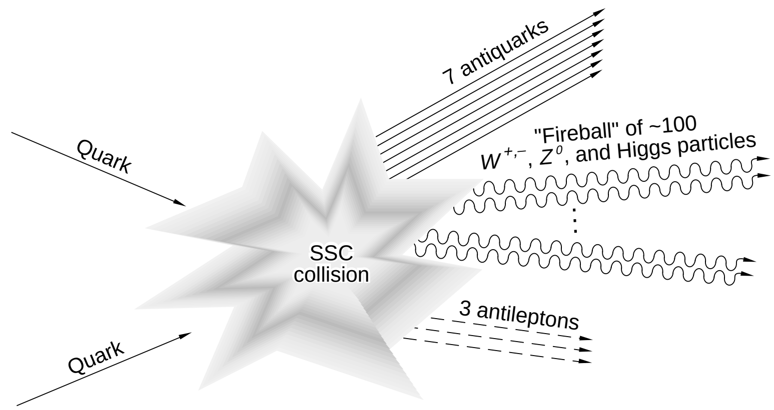


Figure 2. Baryon-Number Violation in a Collision at the SSC
The figure illustrates a collision at the SSC that violates baryon-number (B) conservation and lepton-number (L) conservation. (Muons, electrons, and neutrinos are leptons and have L = 1; their antiparticles have L = °1). In this collision B and L each change by three units. The prominent signature of such an event would be the production of an extraordinarily large number of *W*s, *Z*s, and Higgs particles. Currently theorists are sharply divided on whether B-violating events can occur at the SSC at an observable rate. Estimates of the rate published by prominent scientists differ by as much as a hundred orders of magnitude! For a review of the controversy see the article by Michael Mattis listed in Further Reading.

coworkers to obtain a “solution’’ to full QCD at an accuracy of about 10 to 20 percent (see “Testing the Standard Model Using State-of-the-Art Supercomputers). These calculations are based on Monte Carlo algorithms invented at Los Alamos forty years ago by Nick Metropolis and first used by Stanislaw Ulam and Enrico Fermi in now classic work.

Time-dependent Calculations of Heavy-Ion Collisions and the Quark-Gluon Plasma

Present lattice Monte Carlo simulations of QCD at finite temperature predict that although quarks and gluons can never get completely free of each other, when the temperature gets high enough (around 150 MeV, or more than 100,000 times hotter than the center of the sun), the behavior of matter changes and a phase transition takes place (like the transition from water to steam). In this new high-temperature phase quarks and gluons interact more weakly than they do in normal nuclear matter, somewhat like electrically charged particles in a plasma. For that reason this new phase of matter is called the quark-gluon-plasma phase.

The question naturally arises of how one could detect the presence of such a phase. The requisite high temperatures and densities occurred in the early universe, but it was soon discovered that even if this phase existed in the early universe, it would not have affected very much the standard nucleosynthesis processes that create helium from hydrogen because those processes mainly take place later in the evolution of the big bang. Thus, we would not be able to tell from looking at the relative abundances of hydrogen and helium in the present universe whether or not the quark-gluon plasma ever actually existed.

If the universe won't cooperate and provide us with a suitable laboratory for the quark-gluon plasma, then we have to build one ourselves. About ten years ago, it was realized that relativistic heavy-ion collisions—those in which each nucleon in the heavy-ion projectiles has an energy between 10 and 200 GeV (1 GeV = 10^9 eV)—could conceivably produce energy densities as high as 2–20 Gev/fermi^3 and temperatures on the order of a few Gev (or ten times larger than the quark-gluon-plasma phase-transition temperature). At CERN collisions of light-ion beams (typically consisting of carbon or sulphur nuclei) with other nuclei have produced conditions that approach these extreme temperatures and densities, but as yet they have not provided unmistakable evidence of a quark-gluon plasma. By 1996 the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will be smashing gold and even heavier nuclei together at even higher energies, well above those required to produce the new phase of quark-gluon plasma in the laboratory. Then the real problem will be to sift through the particle debris of such collisions and to recognize the "smoking gun" of the quark-gluon-plasma phase; that is, a signal that could be produced only by such a phase.

It will not be easy. One of the fundamental and most tantalizing problems in this field is, in fact, what constitutes a "smoking gun." Thus far no one has devised a clear unambiguous methodology for isolating the signal for the elusive quark-gluon plasma. Although lattice calculations predict the existence of the quark-gluon phase, those calculations predict only static equilibrium properties of the plasma. The situation in a high-energy heavy-ion collision is very far from equilibrium, at least initially, and the quark-gluon plasma is expected to persist for no more than 10^{-22} second before the nuclear fireball cools and begins to fragment into ordinary pions, protons, neutrons, and other hadrons. Hence any signal of the quark-gluon plasma could easily be masked by strong interactions taking place in the ordinary hadronic-matter phase. Thus it becomes imperative to understand in great detail the non-equilibrium processes taking place in the plasma.

In particular, we want to calculate the rate at which lepton particle-antiparticle pairs (such as muon-antimuon pairs) would be produced by electromagnetic interactions in the plasma. Leptons interact only through the electroweak interaction, and so, once produced, they would be unaffected by the strong forces and propagate straight through the plasma in the collision region to the particle detectors. In order to determine whether the rate and the energy spectrum of lepton-pair production in the quark-gluon-plasma phase would be different from those in ordinary matter, one needs to know the time evolution of the quark-gluon plasma. In particular, one needs to calculate the distribution of quarks and antiquarks as a function of time since quark-antiquark pairs would be the source of the lepton pairs. Although one can make estimates of these pair-production rates based on equilibrium QCD or perturbation theory, such estimates are neither reliable nor accurate enough to serve as a quantitative test of the presence of quark-gluon plasma.

This problem presents a new challenge for quantum field theorists. Previously theorists treated the interaction region of a collision as a "black box.'' They would calculate only the final state resulting from a collision based on the initial state preceding the collision. For example, they might predict how many particles of a certain type and with a certain amount of energy should reach a particular detector following a collision between two protons whose initial energies and momenta are known. This prediction does not require a calculation of the space-time evolution of the interacting particles: one doesn't have to solve the full time-dependent Schrödinger equation to answer questions about the asymptotic, or final, states of particles reaching the detectors. For the quark-gluon plasma, however, one needs to track the space-time evolution of the system *in detail* in order to make quantitative predictions that can be tested by experimenters. Remarkably, the need for a new formulation of quantum field theory had already arisen in connection with the time evolution of the early universe. In that case one needed to follow in detail the time evolution of quantum fields in a time-evolving gravitational field. The formulation required for that problem in early-universe cosmology turns out to be directly applicable to the time evolution of the quark-gluon plasma in a relativistic heavy-ion collision—a beautiful illustration of the underlying unity and interconnectedness of physics.

What then does a relativistic heavy-ion collision look like? The strong forces between hadrons in the colliding nuclei are mediated by the exchange of colored gluons. As a result of these exchanges, the initially colorless hadrons become charged with opposite colors and quickly separate since the hadrons are moving away from each other at velocities near the speed of light. As shown in Figure 3, this situation is analogous to two color-charged plates moving away from each other with a constant color electric field between them. When the energy density in the color field is large enough to produce quark-antiquark pairs, then the "vacuum'' between the hadrons becomes unstable and quark-antiquark pairs begin to pop out of the vacuum, just as electron-positron pairs can be created in a very strong electric field. These quarks then produce more color field that tends to reduce the original one. Thus the resulting quarks and gluons move through and interact with the original time-varying color electric field. The quarks in the quark-gluon plasma also emit pairs of leptons via electromagnetic processes. The lepton pairs leave the collision region and can be seen in standard particle detectors. As the system expands, the energy density decreases and the hadronic phase become energetically favorable so that the quark-gluon-plasma phase changes back into the ordinary hadronic phase.

Even five years ago, calculating the time evolution of this semi-classical model of heavy-ion collisions would not have been possible. Only now that supercomputers have be-

Figure 3. Creation of Quark-Gluon Plasma in Relativistic Heavy-Ion Collisions

(a) Electron-Positron Pair Production by an Electromagnetic Field

A battery maintains a high voltage difference between two parallel conducting plates. The electric field between the plates is sufficiently high that electron-positron (e^-e^+) pairs are created spontaneously from the vacuum.

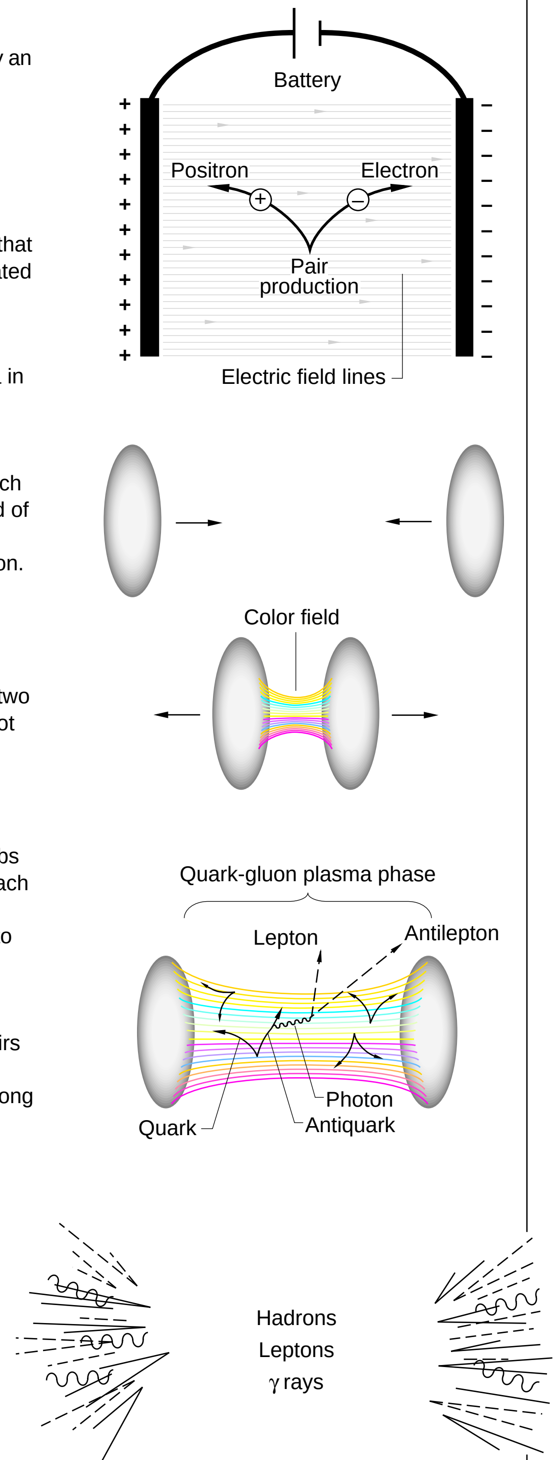
(b) Formation of Quark-Gluon Plasma in Relativistic Heavy-Ion Collision

Initial State: Two heavy nuclei approach each other at velocities near the speed of light. At these speeds they appear flattened because of Lorentz contraction.

Immediately Following Collision: The two nuclei have collided and produced a hot region between them.

Creation of Quark-Gluon Plasma: Blobs of nuclear material move away from each other. In the color field between them, pair-production processes analogous to those shown in (a) produce quark-antiquark pairs. The quarks and antiquarks can interact with the electroweak field to produce lepton pairs such as a muon-antimuon ($\mu^+\mu^-$) pair. The leptons are not affected by the strong force as they escape from the quark-gluon plasma.

Final State: Following the collision the quark-gluon-plasma phase has changed back to the hadronic phase and a large number of hadrons (baryons and mesons), leptons, and γ rays emerge from the collision.



come readily available, particularly at the Advanced Computing Laboratory at Los Alamos, is the problem beginning to become tractable numerically. Our calculations of this semi-classical model have already led to some interesting results. We have been able to check many assumptions of more phenomenological pictures of the time evolution of the quark-gluon plasma, such as the classical transport, or hydrodynamic, models. Such models typically do not start from the basic equations of QCD, but rather postulate some effective, essentially classical model. The importance of avoiding such ad hoc assumptions by calculating the evolution of the plasma directly from first principles of QCD (even in simplified approximations) cannot be overestimated. To our knowledge, no other group of researchers anywhere in the world has attempted to carry out this program. Yet, as we have already discussed, any hope of recognizing the quark-gluon-plasma phase in heavy-ion collisions at RHIC depends ultimately upon the detailed theoretical predictions of the signature of the plasma. These, in turn, can come only from such a first-principles QCD attack on the problem with the formidable computational resources available almost uniquely at Los Alamos. As in the SSC effort, our theoretical group is keeping in close contact with the experimenters in the Physics Division who are major participants in planning the search at RHIC for the quark-gluon plasma.

In conclusion, the long quest for a deep and unified understanding of the most basic laws of nature that govern fundamental processes has seen remarkable progress in the last twenty years. These basic laws fashion the incredible structure we see around us; they underlie not only the complex structures that constitute our macroscopic world but also the beginnings of the universe and the evolution of the heavens. From its earliest history Los Alamos has played its part in elucidating this structure. It continues to do so and in so doing provides a unique link between some of the most fundamental questions in science and their integration into a broader spectrum of problems facing society as we approach the twenty-first century. ■

Left to right: Rajan Gupta, Emil Mottola, Geoffrey West, Fred Cooper, and Michael Mattis

Further Reading

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Geoffrey B. West received his B.A. in natural sciences (physics) from the University of Cambridge in 1961 and his Ph.D. in Physics at Stanford University in 1966. He came to the Laboratory in 1974 as the first leader of what is now the Elementary Particles and Field Theory Group (T-8). In 1981 he was made a Laboratory Fellow and in 1988 resumed the leadership of T-8. His present interests revolve around the structure and consistency of quantum field theory and, in particular, its relevance to quantum chromodynamics and unified field theory.

Frederick M. Cooper received his Ph.D. from Harvard University in 1968 and came to the Laboratory seven years later. His research interests include hydrodynamical and transport-theory approaches to problems of multiparticle production, analytical methods for studying field theories and nonlinear dynamical systems, and understanding the masses of the heavy quarks. His long-standing interest in the time evolution of relativistic quantum systems led to the work presented here on the evolution of the quark-gluon plasma.

Emil Mottola received his undergraduate degree in astrophysics and, in 1979, his Ph.D. in physics, both from Columbia University. He joined the staff of the Elementary Particles and Field Theory Group at the Laboratory in 1986. His research focuses on quantum fields, quantum gravity, and the early universe and includes studies of baryon-number nonconservation and the evolution of the quark-gluon plasma.

Michael P. Mattis received his A.B. in physics from Harvard University in 1981 and his Ph.D. from Stanford University in 1986. After three years as Enrico Fermi Fellow at the University of Chicago, he came to the Laboratory first as a J. Robert Oppenheimer Fellow and then as a Staff Member. His recent work on baryon-number violation in electroweak theory has earned him a Superconducting Super Collider Fellowship.

Testing the Standard Model of Particle Interactions Using State-of-the-Art Supercomputers

Rajan Gupta

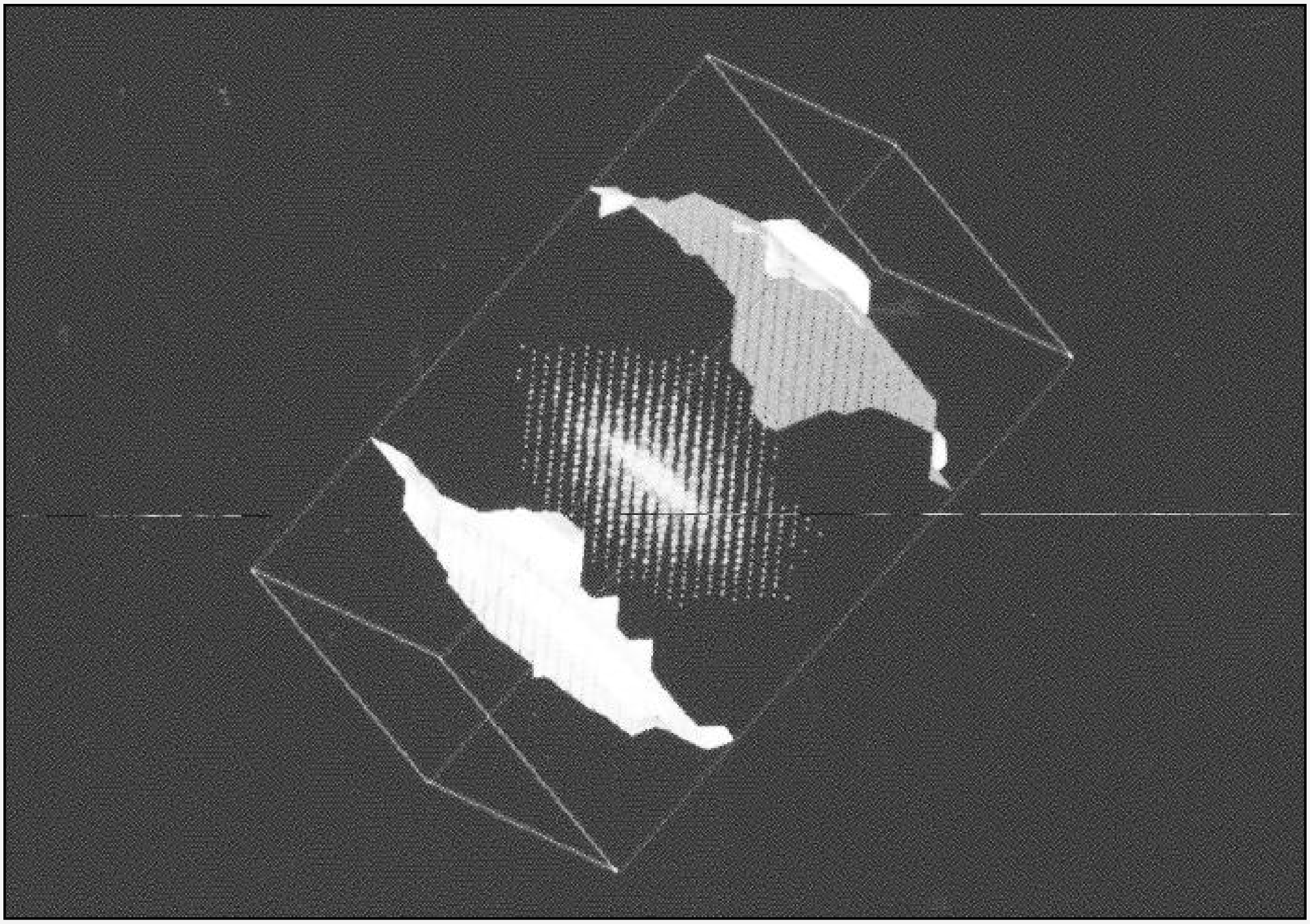
The successes of the standard model of electromagnetic, weak, and strong interactions have been remarkable. Nevertheless, this model contains many assumptions and undetermined parameters that are displeasing aesthetically. Also, the model has not yet produced a satisfying route to unifying gravity with the other three fundamental forces.

The goal of particle physicists now is to discover where the standard model fails and so to find clues to a better theory, perhaps ultimately achieving Einstein's dream of unifying all forces including gravity. It is hoped that the clues will emerge from highly sophisticated experiments in which particles are accelerated and smashed together at very high energies. To date, however, no deviations from the standard model have been found, and so the search for new clues must be performed at even higher energies—such as those that will be achieved at the Superconducting Super Collider (SSC) now under construction in Texas.

Much theoretical analysis is still needed to interpret the results of these extraordinary and expensive experiments. The strong-interaction part of the standard model—quantum chromodynamics, or QCD—presents the major computational stumbling block. Qualitatively, QCD has all the right properties, but so far theoretical physicists have not been able to extract accurate predictions from this precise mathematical model with the traditional tools of the theoretical physicist—pencil and paper. To obtain reliable self-consistent results when dealing with the strong force between, say, two protons requires calculating many subprocesses involving quarks and gluons. In fact, the number of subprocesses is so large that the calculation far exceeds the scope of analytical techniques.

The solution is to turn to a new tool: the supercomputer. Large-scale numerical simulations of QCD are the most promising technique for analyzing the strong interactions. In order to solve QCD on a computer one has to approximate space and time by a four-dimensional grid, or lattice, of points. The discretized version of the theory is called lattice QCD. Experimentally measurable quantities (such as the particle masses and the probabilities of specific transitions) are determined from a statistical average over quantum fluctuations in the quark and gluon fields. The fluctuations at each position in the lattice are simulated by a Monte Carlo procedure, so each Monte Carlo calculation determines one state in a statistical sample of possible states of a system. Monte Carlo methods are an efficient way of sampling the important states, that is, states that give the dominant contributions to the process. The best Monte Carlo calculations to date have used lattices of size up to $32^3 \times 48$ and generated only a small statistical sample (twenty to fifty of the possible states). The three sources of errors in such simulations are the lattice size, the lattice spacing, and the limited statistical sample. These errors can be systematically reduced by making the lattice size larger, the statistical sample larger, and the lattice spacing smaller.

To reduce statistical and systematic errors to the level of a few percent requires a computer with a very large memory and a very high operating speed, over 1000 billions of arithmetic operations per second. For comparison, a typical state-of-the-art home computer has a few million bytes of memory and runs at a few million operations per second. The required technology is just beginning to appear in the form of the parallel supercomputer. In fact, scientists interested in solving the riddle of QCD have played a significant role in the development of parallel supercomputers. The basic principle of these new machines is simple—thousands of



The Pion Propagator

The event depicted here was generated using Monte Carlo simulations of lattice QCD and shows the creation of a pion near the center of the box and its propagation through space both forward and backward in time. The pion propagator, which describes this event, is the correlation function defining the probability amplitude for finding a pion at **x** at time *t* given that it started at the origin at time *t*=0. The propagator is a function of the three spatial coordinates and the time coordinate, but for the purposes of visualization, the data have been averaged over the *z* coordinate and displayed as a function of x and y (the short axes of the box) and time (the long axis). The size of the green "bubbles" at each point represents the magnitude of the propagator at that point in space-time. Note that the "bubbles" decrease in size with distance from the origin, indicating that the magnitude of the propagator decreases. The white surfaces at the ends of the box represent surfaces on which the probability amplitude of the propagator is a constant. The mass of the pion can be calculated from the rate at which the propagator dies out as a function of time. Since the mass of the pion is known from experiment, such calculations of the pion mass can be used to calibrate Monte Carlo simulations of more complicated processes. The data for this Monte Carlo lattice-QCD event were generated on the CM-200, a Connection Machine with 16,000 processors. Many such Monte Carlo events must be calculated to generate a statistically reliable sample for estimating the pion mass. This numerical calculation of the pion propagator exemplifies the first-principles approach to solving strong interactions using lattice QCD.

small but powerful computers work simultaneously to solve one big problem.

The first large-scale simulations of lattice QCD were performed around 1980. Because in those days the fastest computer generally available had the same power as today's desktop workstation, the simulations involved so many approximations that the results were not realistic. To overcome this limitation, physicists turned to parallel computers, often building them themselves. Though the capabilities of the earlier versions of such computers were quite limited, a start had been made, and scientists in other fields became excited by the potential of parallel computation.

A watershed for parallel computing came in 1988. In that year Thinking Machines Corporation introduced the first commercial parallel supercomputer, the Connection Machine 2 (CM-2), and DOE announced its first "Grand Challenges" program, which allocated large grants of supercomputer time to scientists working on key computationally intensive problems. The Los Alamos QCD collaboration was one such recipient. Building on the cruder calculations of 1980–88, we demonstrated, using the most powerful Crays and the CM-2, the viability of numerical methods for QCD. We obtained many new results with an accuracy comparing favorably with the best analytical estimates, though the computational power was still too limited to make definitive predictions. The Los Alamos QCD collaboration also played a key role in technology transfer by pioneering the use of the CM-2 and showing other scientists at the Laboratory and around the world how to use this machine as a production supercomputer.

The revolutionary nature of parallel computing poses new challenges beyond the design of faster hardware: We also need to develop software paradigms for parallel supercomputers that simplify their use for a wider variety of problems and fully exploit the advantages of parallelism. Progress requires close collaboration between scientists, computer engineers, and applied mathematicians. A successful collaboration of this type has begun between our Los Alamos QCD group, the Advanced Computing Laboratory (a DOE High Performance Computing and Research Center at Los Alamos), and Thinking Machines Corporation. This collaboration has received a Grand Challenge grant from the DOE to perform the next generation of QCD calculations on the 1024-node CM-5 located at Los Alamos National Laboratory.

Compared with the computing power of the Cray computers and the CM-2 used in our previous Grand Challenge calculation, the available memory in the CM-5 will be more than an order of magnitude greater, and the available computer speed will be at least two orders of magnitude greater. We plan to use these improvements in computer hardware in three ways. First, we will exploit the increased speed to generate much larger statistical samples for the processes we have already calculated. These simulations will be done on lattices of the size we used previously, $32^3 \times 64$. Second, once the new computers become stable and the proposed hardware upgrades are in place, we will begin simulations on much larger lattices of size $64^3 \times 128$. Finally, we will exploit the larger memory to undertake more complex calculations than have been feasible so far.

Our calculations will yield predictions for a large number of observables affected by strong interactions. The theoretical uncertainties in these quantities will be as low as a few percent. An illustrative and important example concerns the violation of "CP" symmetry. All interactions except the weak are unaffected if one simultaneously interchanges particles and antiparticles (charge conjugation, or C) and takes the mirror image of space (parity transformation, or P). The only experimentally established violation of CP symmetry occurs in the transmutation of a neutral strange meson (K^0) into its antiparticle ($\bar{K}^0$). This discovery was made more than twenty-five years ago and was rewarded with the 1980 Nobel Prize. To test the standard model against this long-standing experimental result requires calculating a parameter called B_K. The more accurately we can determine this quantity, the more precisely we can probe the validity of the standard model. Prior to numerical calculations, the uncertainty in B_K was at least 50 percent. Our present Grand Challenge calculation has reduced this error to about 15 percent. We expect that the planned calculation will further reduce the level of uncertainty to a few percent.

To search for physics beyond or in contradiction to the standard model, one must combine experimental and theoretical knowledge of many quantities. Our calculations will provide theoretical results for a number of the standard-model observables with an accuracy of 10 to 25 percent, small enough to put meaningful constraints on the unknown parameters of the model. Thus, over the next few years, theoretical predictions combined with new experimental results will provide stringent tests of the standard model. □

Further Reading

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Rajan Gupta was awarded an M.S. by the University of Delhi, India, and a Ph.D. by the California Institute of Technology in 1982. In 1985 he became an Oppenheimer Fellow at the Laboratory and three years later joined the staff of the Elementary Particles and Field Theory Group. Among his scientific interests are the development of non-perturbative methods to solve QCD, using lattice QCD to constrain the standard model, and studying the critical behavior of statistical-mechanics models by means of Monte Carlo renormalization-group methods.