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Exploring and Testing the Standard Model and Beyond

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The goal of this project was to extend and develop the predictions of the Standard Model of particle physics in several different directions. This includes various aspects of the strong nuclear interactions in quantum chromodynamics (QCD), electroweak interactions and the origin of baryon asymmetry in the universe, as well as gravitational physics.

Background and Research Objectives

One of the goals of this project was to understand how the quark model could be derived from quantum chromodynamics (QCD). We wanted to understand why this simple model works as well as it does. A hint of this arises from the success of perturbation theory and asymptotic freedom which works surprisingly well down to rather low momenta (as manifested, for example, in "precocious scaling" in structure functions). An explanation for this phenomenon follows from the observation that the perturbation series obtained by expanding QCD in the running coupling constant is an asymptotic one that allows it to be terminated after a finite number of terms. This number varies inversely with the size of the coupling, which increases logarithmically as the momentum decreases. Concomitantly, the error in making such a truncation increases with coupling. Taken to its infrared limit this suggests the possibility that only lowest order need be kept at very low momentum in order to get an acceptable approximation. So we pursued this idea to show how it could justify the quark model. In that case one could see how the model represents the leading order in a well-defined expansion related directly to QCD. We also explored how chiral perturbation theory can emerge dynamically from QCD (since this is related to the smallness of the pion mass and therefore the quark masses).

Two important tools in understanding low energy phenomenology are the Skyrme Model, which leads to an effective field theory for mesons and baryons (in which the nucleon appears as a soliton in the meson field), and "quantum hadrodynamics" (QHD) where the nucleon appears as an effective point-like Dirac field. Of particular importance,

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not only theoretically but also for purposes of extracting believable phenomenological predictions, was for us to prove the equivalence between both these approaches. The organizational principle behind this equivalence is the $1/N_c$ expansion where N_c is the number of colors in the underlying gauge theory. The key idea needed to prove this equivalence, order by order in $1/N_c$, was borrowed from the field of baryon number violation at high energies in electroweak theory—a surprising example of the interplay of fundamental concepts between different fields of theoretical particle physics. In a nutshell, it is the quantum interpretation of extended objects that satisfy the classical equations of motion of the field theory. In electroweak theory these configurations are the instantons, whereas in the strong interactions the most useful such objects turn out to be skyrmions, which are solitonic configurations in the pion condensate that can be used to model nucleons. Similar techniques of analytic continuation that are used to generate an effective Feynman diagram interpretation of the instanton in the former case can be extended to the skyrmion/nucleon in the latter case, providing the desired link to QHD.

Another major effort of this project was to understand the distribution functions of quarks and gluons inside a hadron since all the hadronic matter observed in the laboratory is made up of quarks and gluons. The precise number of quarks and gluons is not constrained in a relativistic field theory such as QCD—only the total color, spin, energy and momentum are conserved. Because the gluons are massless and the u and d quarks are very light, one can easily create pairs out of the vacuum. As a result the momentum (spatial) distribution of a particular flavor of quark depends on the momentum transferred to the probe. This unknown distribution, probed in deep-inelastic scattering, is characterized by structure functions and, due to the small mass of the quarks and gluons, contains both perturbative and nonperturbative pieces. Hadronic structure functions have played a central role in the development of our understanding of QCD.

A related problem is the question of form factors and the structure of the nucleon and the pion. The pion form factor has been measured by detecting exclusive electro-pion production and has recently received considerable attention. However, isolating the form factor from the data is not clean, since its contribution is not gauge invariant. We examined this in detail on the lattice since the old analysis was not based directly on QCD. This is an important object since the pion plays a special role in QCD, being the origin of chiral perturbation theory.

One new experimental development in QCD is the possibility of producing during a relativistic heavy ion collision a new state of matter described by QCD—namely the quark gluon plasma. In order to verify this, one has to understand the nonequilibrium dynamics of the quark-gluon plasma to find processes occurring during this phase that lead to

experimental signatures. Nonequilibrium phase transitions were shown to lead to some interesting signatures such as distorted particle spectra and dilepton spectra. Thus understanding of the nonequilibrium dynamics of the chiral phase transition and the deconfinement/confinement phase transition to the ordinary hadronic phase is crucial to the experimental program at RHIC and later the LHC.

These methods will also be useful in understanding the phase transitions that occur as the universe evolves. When we follow the time evolution of the universe from the big bang to the present time, the theory describing all the basic forces undergoes several phase transitions marking the lessening of symmetry and the divergence of the one into the many. Above several TeV one expects a unification of all the forces except gravity. Around 180 GeV the weak interaction scale manifests and the symmetry is reduced to $SU(3) \times SU(2) \times U(1)$. At around 200 MeV the quarks and gluons hadronize and one also has the breakdown of the chiral symmetry $SU(2) \times SU(2)$. In the time evolution of the early universe, as well as during the progression of a high energy collision, these phase transitions might occur in equilibrium or out of equilibrium. The out of equilibrium transitions will have either bubble growth (nucleation) or instability growth into coexisting phases (spinodal decomposition). The latter can lead to spectacular situations such as centauro events in cosmic rays.

The origin of the mass of the Higgs and the mass of the top quark is one of the central problems of the standard model. One of the reasons for the lack of clarity concerning the origin of mass presently is that the Higgs sector of the standard model is at best an effective field theory since the interactions become trivial as one removes the cutoff from the theory. Instead of taking this as a defect, one can exploit the cutoff dependence of the theory to relate the masses of the particle to a reasonable cutoff scale where we expect new physics to occur. The constraints on such a scenario can help determine the dynamics that yield the mass of the top quark and give a prediction for the Higgs mass. We studied this problem using large N expansions, strong coupling expansions as well as lattice simulations. It has long been known that baryon and lepton number (B and L) are not exactly conserved in the Standard Model, but are broken nonperturbatively by chiral anomalies. An important consequence of this fact is that at sufficiently high temperatures, $T > 10$ TeV, B and L violating processes are unsuppressed. Such processes may be observable at LHC energies. To determine whether the effects are large enough to be measurable requires a detailed understanding of multi-instanton and periodic instanton contributions to anomalous scattering.

Topics beyond the standard model include supersymmetry and superstring theory, which incorporates quantum gravity and supergravity. We studied various aspects of this

important venture. We developed a method to study the quantum effects of gravity at very large distance scales. Contrary to what is commonly believed, the quantum effects of massless particles can modify the Einstein theory in the far infrared, and give a resolution of why the zero point energy of quantum fluctuations does not curve space-time (the cosmological constant problem). The effective theory of the conformal part of gravity has been obtained in four dimensions by consideration of the general form of the trace anomaly of massless matter fields in curved space-time. This theory is expected to give the correct behavior of the conformal part of gravity in the infrared. The issue of unitarity in this new theory, as well as applications to cosmology and large scale structure of the universe, have been investigated. We investigated this new theoretical framework for gravity by both analytic and numerical methods in order to confront the theory with the data on large scale structure of the universe and the cosmic microwave background anisotropy observed with the COBE spacecraft. This approach has the potential of completely changing our understanding of the large scale structure and evolution of the universe.

Importance to LANL's Science and Technology Base and National R&D Needs

This LDRD project is one of basic research in elementary particle physics and quantum field theory. Although motivated by purely basic research objectives, nevertheless methods developed (for example in the context of nonequilibrium phase transitions in heavy-ion collisions) have already turned out to be applicable in other situations of direct interest to Laboratory programs with spin-offs to the science and technology base, such as nonequilibrium phase transitions in high-temperature superconductors and shock induced phase transitions in metals. The numerical algorithms developed in lattice QCD are of the same general kind that find application in many other applied fields. By stretching supercomputer facilities these simulations also provide a testbed for computational methods at Los Alamos.

Scientific Approach and Accomplishments

Lattice QCD provides us with the possibility of computing the quark structure functions themselves directly from the QCD Lagrangian. With presently available computers we can calculate only the moments of these structure functions. However, by comparing these with perturbative results, one gains information on the role of soft gluons because lattice techniques sum up these contributions nonperturbatively. We developed the computer codes necessary to analyze the structure functions for pions and nucleons on an ensemble of a hundred $32^3 \times 64$ lattices generated on the CM-5. We used the light quark

propagators, generated for an earlier study of spectrum and weak matrix elements, for these calculations. This study on a large lattice provided results that were then compared with phenomenology.

In the time period of this LDRD effort, the formalism for attacking the nonequilibrium evolution of the quark-gluon plasma in an ultrarelativistic heavy-ion collision was developed in a series of papers. We showed that as the plasma goes through a nonequilibrium phase transition, large numbers of low momentum pions are produced that distort the final spectrum of secondaries away from an equilibrium distribution and that this also effects the dilepton spectra. We studied one aspect of this nonequilibrium phase transition in a large flavor $1/N$ expansion.

Numerical simulations of the $O(3)$ nonlinear sigma model were performed by means of a real time Langevin method using the CM-5. The data collected are the most accurate to date on finite-temperature anomalous transitions. We determined the transition rate relevant for generating the baryon number of the universe at the electroweak phase transition in the hot, dense early universe. In addition, we have (with Peter Tinyakov of the Institute for Nuclear Research in Moscow) found new periodic instanton solutions in the $O(3)$ nonlinear sigma model numerically, and are extending the method to include complex classical solutions, which have a bearing on the rate of fermion-violating processes in high energy collisions. The analytic and numerical work on the $O(3)$ model has paved the way for the detailed study of the corresponding solutions in the $SU(2) \times U(1)$ theory of the electroweak interactions, and code is now being developed for that study.

The anomalous scaling of the gravitational field under global conformal transformations has been obtained for the first time in four dimensions, and predictions of criticality and scaling relations in 4-D Monte Carlo simplicial simulations have been made. In the summer of 1997 we ran a two week workshop "New Directions in Simplicial Quantum Gravity" in Santa Fe, NM, which brought together the leading researchers in this field. These novel ideas have been applied to the spectrum and statistics of the cosmic microwave background radiation (CMBR). Genuinely testable predictions of deviations from Harrison-Zel'dovich scale invariance and non-gaussian statistics of the CMBR have been made. If verified in the next generation of CMBR observations they could lead to a dramatic reappraisal of current models of the origin of primordial density fluctuations and the formation of structure in the universe.

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