"Lattice 88"

by Paul Mackenzie

The ability to understand the properties of the strongly interacting particles from first principles is a 40-year-old dream which is now approaching reality. Following the development of quantum chromodynamics (QCD) in the early 1970s, honest calculations of the masses and other properties of hadrons were made possible by Ken Wilson's inventions of lattice gauge theory and renormalization group methods. Lattice gauge theory became a major industry around 1980, when Monte Carlo methods were introduced, and the first prototype calculations of the hadron spectrum yielded qualitatively reasonable results. This past year has seen the most powerful attacks yet on the theory of the strong interactions and the richest variety of physics results.

(Fermilab photograph 88-961-9)

Peter Hasenfratz discusses the bounding of the mass of the Higgs.

(Fermilab photograph 88-962-22)

A. A. Migdal shown here "putting strings on the lattice."

From small workshops first held at CERN, lattice meetings have evolved into annual international conferences. For the last few years they have been alternating between Europe and the United States, and have been increasing in size every year. At the 1988 Symposium on Lattice Field Theory, "Lattice 88," which was held at Fermilab on September 22-25, 1988, over 200 physicists from around the world heard reviewers report major progress not only in attacking QCD, but in understanding all components of the Standard Model.

Peter Hasenfratz of Bern summarized recent lattice work on placing bounds on the mass of the Higgs particle in the Standard Model. It has been known for a long time that a sensible weak coupling theory of Higgs scalars does not exist

if the mass of the Higgs is greater than about 1 TeV. If the Higgs is very massive, however, its self-coupling is large, and until recently it has been an open question whether large Higgs self-coupling effects might affect this bound. A variety of recent nonperturbative lattice calculations have strengthened the bound and made it more precise: It has been impossible to obtain a sensible one-doublet elementary Higgs theory in which the Higgs weighs more around 600 - 700 GeV. According to these calculations, if a Higgs is not found with a mass less than around 700 GeV, it is a definite sign of physics beyond the Standard Model.

Julius Kuti of the University of California, San Diego, outlined further applications of lattice methods in the electroweak sector of the Standard Model, including bounds on the mass of the top quark and investigations of the viability of Abbott and Farhi's proposed strongly coupled Standard Model. Tantalizing indications of a new strongly coupled phase of quantum electrodynamics were discussed by John Kogut of the University of Illinois.

The calculation of the masses of hadrons is one of the most important and immediate goals of lattice gauge theory. At the present time, the inclusion of the effects of sea quarks is the most difficult part of the calculation. The quenched, or valence, approximation ignores these effects and is an important intermediate goal of the analysis. While it is not expected that this approximation will yield exactly the correct hadron spectrum, it is important to ascertain the precise degree of deviation from experiment while preparing to tackle the full calculation. Progress in this area was described by Enzo Marinari of the University of Rome. High-statistics calculations of a special purpose computer built by the APE collaboration, using improved calculational methods, have provided the clearest evidence yet that the proton/rho mass ratio in this approximation is between 1.4 and 1.5, as opposed to the physical answer of 1.22 which is expected in the full theory. While it is too early to be sure that this is the final prediction of the quenched approximation, it appears that we may be rapidly closing in on this result.

Massive improvement in the power of algorithms for producing sample QCD gauge field configurations was reviewed by Don Weingarten of IBM, Yorktown Heights, and Stephen Adler of the Institute for Advanced Study. Progress has been most spectacular in methods for including the effects of sea quarks. The hybrid Monte Carlo algorithms which are just beginning to be applied are around 10,000 times faster than the seven-year-old algorithms from which they descend.

A comparable improvement has been achieved in the hardware used for lattice calculations. The special purpose QCD machines now under construction at

various institutions around the world are roughly 10,000 times more powerful than the VAXes on which the original hadron spectrum calculations were done seven years ago. Norman Christ of Columbia University described machines now existing or under construction at Columbia, IBM, Rome, Fermilab, Caltech, and Tsukuba. He also described related commercial machines, some of which have begun to borrow ideas from the approach pioneered by the Columbia group and are now in universal use in machines constructed especially for lattice gauge theory: fast floating point chips on a massively parallel array of nodes.

The greatly improved understanding of the glueball spectrum in SU(3) gauge theory without quarks was described by Andreas Kronfeld of Fermilab. Two years ago, confusion reigned in this area and there was no unanimity on even such an apparently simple question as whether the 0++ glueball state was heavier or lighter than the 2++. Improved methods of calculating glueball masses have helped to clarify the situation, producing a consensus, based on the work of several different groups, that the 2++ glueball is 1.5 ±.1 times as heavy as the 0++. Pierre van Baal of CERN summarized recent analytic work on the spectrum of the pure glue theory at small and intermediate volumes. In addition to being very beautiful, this work has been accurately verified by Monte Carlo methods, providing added confidence in the performance of the numerical methods.

The physics of QCD at high temperatures and densities has interesting applications in heavy-ion physics, astrophysics, and cosmology. A few years ago, this area of lattice theory produced the first apparently accurate, reliable result of Monte Carlo methods for nonabelian gauge theory: the temperature of the deconfining transition in pure gauge theory. Masataka Fukagita of Kyoto concluded that this calculation is still in good shape. The phase transition seems to be much weaker than originally thought, and an interesting controversy has developed between the Columbia group, who find a weak first order transition, and the APE collaboration whose data are consistent with a second-order phase transition. Of analogous calculations in full QCD, Fukugita echoed Marinari's summary of hadron massed in full QCD: *hic sunt leones* (here there be lions). Preliminary calculations of the deconfining phase transition in full QCD indicate that the transition temperature may be around 150 MeV. Frithjof Karsch of CERN examined the physics of the plasma phase of QCD and concluded that the simple picture of the hot QCD plasma as an ideal gas of quarks and gluons interacting perturbatively looks good so far, though much room remains for nonperturbative effects to be found.

Precision tests of the Standard Model, the determination of the Kobayasi-Maskawa angles, and the search for physics beyond the Standard Model all re-

quire a detailed understanding of hadronic weak matrix elements to exploit the large amount of data coming from increasingly sophisticated experiments. Lattice field theory methods are essential to the systematic analysis of the hadronic weak matrix elements. A great deal of important work has been done already in developing these difficult calculations, which was described by Claude Bernard of the Institute for Theoretical Physics in Santa Barbara, California. The prediction of the Q2 evolution of hadronic structure functions and form factors was one of the earliest successes of perturbative QCD, but prediction of the quantities themselves require lattice calculations. These were reviewed by Guido Martinelli of CERN. Chris Sachrajda of Southampton described the painstaking analytic work which has been done in setting up the operators of the Standard Model on the lattice.

The large-scale Monte Carlo simulation methods central to lattice gauge theory are being applied to other areas of physics as well, sometimes by people who also do lattice gauge theory. Jorge Hirsch of the University of California, San Diego, reviewed current theoretical ideas about high-temperature superconductivity. (Subtitle of Hirsch's talk: "What should a lattice gauge theorist be doing in his/her spare time?") Sasha Migdal of the Cybernetics Council in Moscow described recent progress in creating a lattice formulation of bosonic string theory. This work overlaps and extends analytic work on the subject based on Polyakov's conformal field theory approach. The fact that analytic and numerical calculations agree where both are supposed to be applicable is as important in this field as for QCD.

The last year has been the most active in the history of lattice gauge theory. The factor of 10^8 increase in combined algorithmic and hardware computing power which has been achieved over the last seven years will certainly be further increased by future developments. It now seems that calculations of hadron masses in the approximation of ignoring the effects of sea quarks are closing in on the reliability and accuracy already achieved for some simple calculations in pure gauge theory, and that calculation for full QCD, including the effects of the sea quarks, will not be too far behind. Then the exploration of the wide-open territory of all the nonperturbative aspects of the Standard Model and physics beyond the Standard Model will begin in earnest.