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Monte Carlo yields hadron masses

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positronium lives only about 1/8 of a nanosecond, one knows that the 1S–2S line recorded by the ionization signal represents the triplet-state transition $1^3S_1 \rightarrow 2^3S_1$. The two-photon transition frequency thus recorded turns out to be (41.4 ± 0.5) GHz below $\frac{3}{16} cR_\infty$, the first-order frequency of the positronium 1S–2S transition. (R_∞ is the ordinary Rydberg constant.) This result agrees within the experimental uncertainty (about one part in 10^6) with the second- and third-order QED corrections calculated by Thomas Fulton and Paul Martin (Johns Hopkins), and Richard Ferrell (Princeton). Fulton, who has recently updated[2] his earlier third-order calculation for comparison with this experiment, told us that such positronium predictions "make the Bethe–Salpeter formalism jump through hoops." Thus they should provide useful insights, he suggests, for analogous calculations of light-quark bound states in quantum chromodynamics, which also require the Bethe–Salpeter formalism.

"Nobody doubted that at this level of accuracy the result would agree with QED," Mills told us. "The number is interesting primarily because it points the way to ultrahigh-precision optical spectroscopy for positronium." The success of this rather eclectic experiment has already generated considerable enthusiasm among spectroscopists. The precision of the present result is limited basically by the linewidths of the calibrating H and D Balmer β absorption lines rather than by statistics. Thus, with better laser metrology and a continuous-wave dye laser, Chu and Mills, working with John Hall from the National Bureau of Standards, hope soon to measure the 1^3S_1–2^3S_1 transition to a part in 10^8.

Vernon Hughes (Yale), Hänsch and Richard Howell (Livermore) are planning to use a Livermore 100-MeV electron linac as a pulsed source of slow positrons for positronium spectroscopy. This should provide at least a thousandfold increase of positronium formation over the Bell Labs experiment, Hänsch told us. Chu and Mills are planning eventually to avail themselves of the beam dump from a free-electron laser being built at Bell Labs by Earl Shaw and Kumar Patel to achieve a ten-thousandfold increase in positronium intensity. —BMS

References

1. S. Chu, A. P. Mills Jr, Phys. Rev. Lett. 48, 1333 (1982).
2. T. Fulton, Johns Hopkins preprint JHU-HET 8206 (1982).

Monte Carlo yields hadron masses

The odds look increasingly favorable that Monte Carlo methods will pay off as a computational tool in the theory of quarks. Over a year ago, theorists began to gain insight into the nature of strong interactions by applying statistical methods to a formulation of quantum chromodynamics on a discrete space–time lattice, but their calculations involved only a pure gluon field and no quarks. The inclusion of fermions, and hence the calculation of physical observables, appeared to require formidable amounts of computer time. In the interim, several theorists have devised approximations and algorithms that allow them to estimate some hadron masses with fairly good agreement and with reasonably small errors. Reaction to this new work has ranged from careful scrutiny of the specific premises to great enthusiasm for the general promises of the technique.

The first estimates of hadronic masses were reported in several papers last winter. Herbert Hamber (Brookhaven) and Giorgio Parisi (National Institute of Nuclear Physics, Rome) based[1] their computations on the group SU(3) and found the masses of the rho meson, the proton and the delta resonance (among others) to be (800 ± 100) MeV, (950 ± 100) MeV and (1300 ± 100) MeV, respectively. (Compare these to experimental values of 765, 941 and 1236 MeV.) Enzo Marinari (G. Marconi Institute of Physics, Rome), Parisi and Claudio Rebbi (Brookhaven) performed[2] similar calculations using SU(2); although this group does not include the baryons it is similar to SU(3) and allows greater simplicity in calculations. They estimated the rho mass to be about (800 ± 80) MeV. At the same time Donald Weingarten (Indiana University) submitted[3] his results on the icosohedral subgroup $\bar{I}$ of SU(2). Weingarten cites a rho mass of (670 ± 100) MeV and argues that this value would not change if the calculation were performed on SU(3). Since then, Weingarten told us, he has repeated his computations for SU(3) and has obtained masses for the rho, proton and delta of 610 $(+100, -120)$, 1200 $(+380, -430)$ and 1490 $(+250, -310)$ MeV, respectively.

All these treatments adjust free parameters in the theory to fit the known pion mass and the slope of the Regge trajectory. (The Regge trajectory is the line in a plot of mass versus angular momentum along which lie all members of the same hadron family. In the quark theory, the slope of this line is equal to the "string tension," or long-distance potential between quark and antiquark.) The recent calculations also make the critical assumption that the mixing of a given state with extra quark pairs can be ignored. Equivalently, in the language of the parton model, they include only the "valence" quarks and ignore the effect of the quark–antiquark "sea." The gluon gauge field is treated exactly.

This approach has since proved fruitful for at least one other collaboration to explore[4] further aspects of quantum chromodynamics. The team consisted of John Kogut, Michael Stone and H. William Wyld (University of Illinois), Junko Shigemitsu (Brown University), Stephen H. Shenker (University of Chicago) and Donald K. Sinclair (Stanford). They have been investigating the range of forces responsible for the breaking of chiral symmetry—the symmetry dealing with the relative directions of velocity and spin—using a formulation of a theory involving a lattice of fermions that has no free parameters.

A European collaboration has taken an entirely different tack. Those involved are Anna Hasenfratz (Central Research Institute, Budapest) and Z. Kunzst (Eötvös University, Budapest) together with Peter Hasenfratz and Christian B. Lang (CERN). They treat all orders of quark interactions but use an expansion similar to a high-temperature expansion in statistical systems. The range of validity of their results is thus limited to lattice grid spacings greater than a certain length. They find the masses of some mesons and of the quarks, using the rho mass as one input.

Sidney Coleman (Harvard) is enthusiastic about the significance of this recent work for elementary-particle theory. He feels that, regardless of the validity of each particular step, the important contribution has been to show that quantum chromodynamics lies within the grasp of numerical computation. Coleman likens this period to the early days of quantum mechanics, when the crucial test of the new theory was not the exact derivation of the orbits in the hydrogen atom but rather the more complex numerical calculation of the ground state in the helium atom.

Details of the methods. The latest calculations build on the earlier progress in applying statistical methods to a lattice gauge theory of quantum chromodynamics (PHYSICS TODAY, October 1981, page 18). Kenneth Wilson (Cornell University) and Alexander Polyakov (Landau Institute in Moscow) first proposed a lattice gauge theory for particle physics. Formulating a gauge field on a discrete space–time lattice avoids the ultraviolet divergences because no wavelength can be shorter than twice the grid spacing. Associated with each pair of points on the lattice is the link variable, an element in a particular group representation. The amplitude for a particle to follow some path through the lattice in this theory is an integral of a product of these link variables along the particle's path. This integral over link variables is analogous to a sum in a statistical ensemble. Monte Carlo techniques can generate a random sequence of link variables and thus simulate the statistical ensemble.

The addition of fermions to this theory greatly complicates it. The path integral over quark degrees of freedom is not an integral in the usual sense because of their anticommutation relations. One way to circumvent the problem is to perform essentially a formal integral over the fermion degrees of freedom before applying the Monte Carlo technique. The remaining expression involves the determinant of the reciprocal quark propagator—still no cinch to evaluate with statistical means. The great simplification comes from approximating this determinant by the pure number 1. Both the Brookhaven–Rome collaborations and Weingarten give some arguments for the validity of this approximation. This step is essentially the neglect of the mixing with extra quark pairs.

The procedure for calculating the masses is to create a set of quarks and antiquarks with the quantum numbers of some hadron. The computer simulation propagates these quarks and then annihilates them at some time later. In the limit of large time, Hamber explained to us, the expectation value of the propagator goes as the exponent of the mass times the time. (In this limit the mass is that of the lightest hadron carrying those quantum numbers.)

The errors in these calculations are both statistical and systematic. The main source of the former is the inherently random nature of the Monte Carlo technique. One of the causes of the latter is the limitation to a finite size of lattice grid. Most of the lattices in this recent work have had space–time dimensions on the order of five by five by five by ten points. While these lattices are still substantial they are perhaps near the lower limit of lattice size that allows good statistics. Some critics worry that the grid spacing in all these treatments is too coarse relative to the size of the hadrons they are probing. The theorists try to answer this concern by checking whether certain parameters change in a predictable way as the grid size varies.

Hamber and Parisi not only estimated masses and decay constants for some mesons but also investigated the property of chiral symmetry. They discovered that this symmetry is spontaneously broken. Kogut and his collaborators pursued that result in detail and found that chiral symmetry becomes broken at a length scale shorter than that of confinement. They conclude that the symmetry breaking is independent of the forces of confinement but depends strongly on the color representation of the quarks. This result may be significant in understanding the dynamic symmetry breaking necessary to make realistic models of weak interactions.

David Politzer (Caltech) is particularly excited about these latter results, for to him they give a rationale for the neglect of the internal quark loops: They suggest that the quarks may have a "soft" mass large enough to render them nonrelativistic in bound states. Thus, at least for some masses, no extra quark loops could contribute without altering the hadron mass. More generally, we asked Politzer what items were on his wish list for tests of quantum chromodynamics that might now be feasible. His list includes: some static properties of hadrons, the masses of the glueballs and their mixing with quark–anti-quark states and the cross section for lepton–hadron inelastic scattering.

Buoyed by success, Parisi and his collaborators and Weingarten are currently attempting to estimate the hadron masses with the inclusion of the quark loops. Weingarten is extending his work to SU(3). Kogut and his colleagues are hoping to calculate masses at some higher energy scales. And many others are continuing to contribute their energy and insights in this promising direction. —BGL

References

1. H. Hamber, G. Parisi, Phys. Rev. Lett. **47**, 1792 (1981).
2. E. Marinari, G. Parisi, C. Rebbi, Phys. Rev. Lett. **47**, 1795 (1981).
3. D. Weingarten, Phys. Lett. **109B**, 57 (1982).
4. J. Kogut, M. Stone, H. W. Wyld, J. Shigemitsu, S. H. Shenker, D. K. Sinclair, Phys. Rev. Lett. **48**, 1140 (1982).

High-resolution scanning ion microscopy

Scanning electron microscopes operating in the reflecting mode can resolve surface detail at the level of a few tens of angstroms. A University of Chicago–Hughes Research Laboratories collaboration expects to do about as well with ions by the end of the year. A pair of scanning ion microscopes being built at Hughes (Malibu, California) is designed to achieve a resolving power as fine as 20 Å.

The design of these high-resolution microscopes embodies the experience gained in the past few years by Riccardo Levi Setti at Chicago and Robert Seliger at Hughes with scanning ion microscopes capable of 1000-Å resolution. Although conventional (nonscanning) ion microscopes of comparable resolution had been built in France and Germany in the 1950s, the further development of high-resolution microscopy had largely been deferred in subsequent decades by the spectacular successes of the scanning electron microscope. Japan Electro-Optical Laboratories (Tokyo) expects to market the world's first commercial scanning ion microscope—a 1000-Å device—at the end of this year.

Because the interactions of ions and electrons with target materials are quite different, ion microscopy is potentially capable of complementing electron microscopes with important subsurface information not readily accessible to the latter. The secondary electrons that provide the primary imaging signal in a scanning electron microscope are for the most part sensitive only to surface topography; deeper information is provided only by energetic backscattered electrons, which are much less copiously produced than are the secondary electrons.

The secondary electrons generated by ion beams, on the other hand, come mainly from hard Rutherford scattering off (shielded) nuclei. Therefore, Levi Setti told us, they can serve as a more sensitive probe of the underlying atomic structure of the target. Cascades of such hard-core collisions transport bulk information out to the surface. The Chicago group has found that the direction-sensitive deep channeling of incident ions between crystal planes produces secondary-electron pictures with "astonishing" crystallographic contrast. Levi Setti believes that this channeling-induced contrast will prove to be important for microscopic analysis in metallurgy, microelectronic fabrication and mineralogy.

Ion beams also sputter ions off the surface under examinations. These secondary ions also exhibit channeling contrast, and they can be passed through a mass spectrometer to provide elemental analysis of the sample.

The incident ions also serve to clean contamination layers off the surface under scrutiny, Levi Setti told us. His Chicago group finds that micrographs of metallic surfaces became progressively brighter during the first few minutes of examination under the scanning ion microscope, as the bombarding heavy ions (60-keV gallium) clean off the contaminating oxide layer. This "milling effect" could be exploited, he suggests, to study bulk samples layer