Four fundamental forces of nature

- Focus on the strong force in this talk
Outline

- Brief historical survey of the strong interactions
  - atom $\rightarrow$ QCD (quarks and gluons)
- Overview of lattice QCD (enter the computer)
  - new branch of particle physics
  - current state of the art
- Quark confinement
- Constituent quark model
- Gluonic excitations
  - glueballs
  - hybrid mesons
- Future work
Age-old questions

- What is the world made of?
- What holds it together?

The thinker (1880)
by Auguste Rodin
The periodic table of the elements

- Dimitri Mendeleev’s periodic table of the elements 1869
  - great breakthrough towards answering these questions
  - pattern recognition → substructure
Rutherford’s scattering experiments

- experiments of Ernest Rutherford, Geiger, and Marsden (1909)
Large deflections

- expectation from Thomson’s “plum pudding” model of the atom

- found large deflections on rare occasions

- atoms must have small but massive cores
- birth of the nucleus! (1911)
Modern theory of the atom

- regularities in Mendeleev’s periodic table
- Rutherford’s $\alpha$–particle scattering experiments help fashion the modern theory of the atom

atom = massive nucleus (protons and neutrons) surrounded by cloud of light electrons
What holds the nucleus together?

- protons: positive electric charge
- neutrons: no charge
- like charges \textit{repel}
- what holds the nucleus together? \textRightarrow{} new force!

- new force must be \textit{strong} to overcome electrostatic repulsion, but short-ranged
Hideki Yukawa puts forward his theory of the nuclear force (1935)
- mediated by spinless exchange particle called the $\pi$ meson
- mass of $\pi$ meson about 250 times that of the electron

$\pi$ meson eventually discovered in 1947
(Lattes, Muirhead, Occhialini, Powell)
Particle zoo

- experiments reveal proton and neutron **not alone**
  - protons and neutrons lightest particles in a large spectrum of strongly-interacting fermions called *baryons*
  - pions lightest member of equally numerous sequence of strongly-interacting bosons called *mesons*

Particles discovered between 1898 and 1964

many more…
Eightfold way

- **pattern** recognition in the observed hadron spectrum 1961
  (reminiscent of Mendeleev’s periodic table)
  - Murray Gell-Mann → Buddhist eightfold path to enlightenment
  - Yuval Ne’eman
- conference at CERN in 1962
  - Gell-Mann, Ne’eman learn of discovery of two new baryons $\Xi^*, \Xi^{*0}$
  - recognize these nearly complete a group of ten related particles
  - G-M predicts new particle
  - $\Omega^-$ found BNL, CERN 1964
Two key papers on hadron symmetries

**DERIVATION OF STRONG INTERACTIONS FROM A GAUGE INVARIANCE**

Y. NE'ERMAN
Department of Physics, Imperial College, London
Received 15 February 1961

Abstract: A representation for the baryons and bosons is suggested, based on the Lie algebra of the 3-dimensional traceless matrices. This enables us to generate the strong interactions from a gauge invariance principle, involving 8 vector bosons. Some connections with the electromagnetic and weak interactions are further discussed.

**Symmetries of Baryons and Mesons**

MURRAY GELL-MANN
California Institute of Technology, Pasadena, California
(Received March 27, 1961; revised manuscript received September 20, 1961)

The system of strongly interacting particles is discussed, with electromagnetism, weak interactions, and gravitation considered. The electric current $j_e$, the weak current $j_w$, the gravitational tensor $\gamma_{\mu\nu}$, and all well-defined operators, with the matrix elements obeying dispersion relations. The extent of the dispersion relations for matrix elements of these operators in the vacuum and other states is highly convergent and saturated by contributions from intermediate one-pion states, with relations like the Goldberger-Treiman formula and unitarity principles like that of Sakurai according to which the $\rho$ is coupled approximately to the isotopic spin. Homogeneous dispersion relations, even without subtractions, do not fit to fix the scale of these matrix elements; in particular, for the mesons from the isospin $I=0$. The structure of the baryons and mesons is discussed with a view toward understanding the SU(3) symmetry of the strong interactions.

---

9/10/2001 CMU colloquium 13
Quark hypothesis

- pattern suggests substructure
- Murray Gell-Mann → quarks
  - James Joyce, *Finnegan’s Wake*
- George Zweig → aces
  - unpublished (CERN preprint)
- quarks:
  - fractional electric charge!
  - spin 1/2
  - come in flavors (up, down, strange)
    - three more flavors since found
- baryons = three quarks
- mesons = quark-antiquark pair

Gell-Mann

Zweig

9/10/2001  CMU colloquium
Mesons and baryons

Mesons
- pseudoscalars: $\pi^+ \pi^- \pi^0 K^+ K^- \eta \ldots$
- vectors: $\rho^+ \rho^- \rho^0 K^{*+} K^{*-}$ and more...

Baryons: $p \ n \ \Lambda \ \Sigma \ \Xi \ \Omega$ and more...

- proton ($p$)
- neutron ($n$)

Quark flavors:
- up
- down
- strange
Gell-Mann’s paper

- quark hypothesis brought order to the particle zoo
- fractional electric charge never observed
- Gell-Mann initially considered quarks as purely mathematical objects
- but on last page of paper:

“It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities...).”
AN SU$_3$ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig

CERN—Geneva

ABSTRACT

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into isospin doublet and singlet. Each ace carries baryon number $1/3$ and is fractionally charged. SU$_3$ (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. Quantitative speculations are presented concerning resonances that have not yet been definitively classified into representations of SU$_3$. A weak interaction theory based on right and left handed aces is used to predict rates for $|\Delta S| = 1$ baryon leptonic decays. An experimental search for the aces is suggested.

*) This work was supported by the U.S. Air Force Office of Scientific Research and the National Academy of Sciences—National Research Council.


The reaction of the theoretical physics community to the ace model was generally not benign. Getting the CERN report published in the form that I wanted was so difficult that I finally gave up trying.\textsuperscript{13,14} When the physics department of a leading university was considering an appointment for me, their senior theorist, one of the most respected spokesmen for all of theoretical physics, blocked the appointment at a faculty meeting by passionately arguing that the ace model was the work of a "charlatan." The idea that hadrons, citizens of a nuclear democracy, were made of elementary particles with fractional quantum numbers did seem a bit rich. This idea, however, is apparently correct.

☐ from talk at Baryons 1980 in Toronto

graduate student at CalTech

CERN preprint

9/10/2001

CMU colloquium
Discovery of the quark

- watershed experiments at Stanford Linear Accelerator Center (1968)
  - modern rendition of Rutherford scattering experiments
  - scattered electrons off protons
  - small-wavelength photons to resolve quarks inside the proton
- scattering consistent with quark hypothesis!
- further probing provides evidence that proton constituents have the expected fractional electric charges of quarks
- asymptotic freedom
  - interactions between quarks
    - weakens at very short distances
New quantum number

- nagging problem with quark hypothesis:
  - certain baryons seemed to violate the Pauli exclusion principle!
  - example: the $\Delta^{++} = uuu$ baryon with spin $J = \frac{3}{2}$
    - three identical fermion u quarks in symmetric state
      $\rightarrow$ forbidden by Fermi-Dirac statistics

- resolution by Greenberg 1964 (Han and Nambu 1965)
  - quarks must have a new quantum number

> SPIN AND UNITARY-SPIN INDEPENDENCE IN A PARAQUARK MODEL OF BARYONS AND MESONS

O. W. Greenberg
Institute for Advanced Study, Princeton, New Jersey (Received 27 October 1964)

Wigner's supermultiplet theory, transplanted independently by Gürsey, Pais, and Radicati, and by Sakita, from nuclear-structure physics to particle-structure physics, has aroused a good deal of interest recently. In the nuclear supermultiplet theory, the approximate independence of both spin and isospin of those forces relevant to the energies of certain low-lying bound states (nuclei) makes it useful to classify the states according to irreducible representations of SU(6). Three results associated with this SU(6) classification indicate its usefulness: (1) The best known baryons (in particular, the spin-$\frac{1}{2}$ baryon octet and the spin-$\frac{3}{2}$ baryon decuplet) are grouped into a supermultiplet containing 56 particles.

PRL 13, 598
Origin of “color”

- Gell-Mann coins the term “color” for this new quantum number
- three different colors are needed: red, green, blue
- birth of quantum chromodynamics (QCD)
  - Fritzsch, Gell-Mann, Leutwyler 1973
  - based on an SU(3) local gauge symmetry (Yang-Mills)
  - quarks interact by the exchange of colored gluons
Quantum chromodynamics

- resemblance to quantum electrodynamics
  - quarks (3 colors) ↔ electrons
  - gluons (8 color varieties) ↔ photons (massless spin-1)
- major difference: gluon has color charge (photon neutral)

- seemingly simple difference
  - physical content of QCD completely unlike that of QED
- physical states (hadrons) colorless
  - color confinement
Charmonium

- discovery of $J/\Psi$ in November 1974 (BNL, SLAC)
- interpretation as bound state of new flavor of quark called *charm*

- charm quark rather heavy
  - nonrelativistic analysis
- Cornell potential
  - Coulomb + linear
    - short-range asymptotic freedom
    - long-range confinement
  - reproduces spectrum

---

Residual strong force

- true strong force = gluon exchange between quarks
- binding of protons + neutrons by pion exchange in nucleus
  - from feeble vestige of strong force (van der Waals-like)
Calculation problems

- calculational tools of QED (small coupling expansions)
  - work well for deep inelastic scattering in QCD
    - asymptotic freedom
  - *utterly fail* for hadron formation
    - bound state problem $\propto e^{-1/g^2}$

  - formulate QCD using a discrete space-time lattice
  - lattice acts as ultraviolet regulator
  - Wilson formulation preserves exact local gauge invariance

- advantage of this approach
  - facilitates computer simulations of quarks and gluons
  - theorists now free of the shackles of small-coupling expansions!
Confinement of quarks

Kenneth G. Wilson

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

(Arrived 12 June 1974)

A mechanism for total confinement of quarks, similar to that of Schwinger, is advanced which requires the existence of Abelian or non-Abelian gauge fields. It is shown how to quantize a gauge field theory on a discrete lattice in Euclidean space-time, preserving exact gauge invariance and tracing the gauge fields as angular variables (which makes a gauge-fixing term unnecessary). The lattice gauge theory has a computable strong-coupling limit; in this limit the binding mechanism applies and there are no free quarks. There is unfortunately no Lorentz (or Euclidean) invariance in the strong-coupling limit. The strong-coupling expansion involves sums over all quark paths and sums over all surfaces (on the lattice) yielding quark paths. This structure is reminiscent of relativistic strong models of hadrons.

I. INTRODUCTION

The success of the quark-parton picture both for resonances and for deep-inelastic electron and neutrino processes makes it difficult to believe quarks do not exist. The problem is that quarks have not been seen. This suggests that quarks, for some reason, cannot appear as separate particles in a final state. A number of speculations have been offered as to how this might happen.

Independently of the quark problem, Schwinger observed many years ago that the vector mesons of a gauge theory can have a nonzero mass if vacuum polarization totally screens the charges in a gauge theory. Schwinger illustrated this result with the exact solution of quantum electrodynamics in one space and one time dimension, where the photon acquires a mass \( m \) for any nonzero charge \( e \) [\( e \) has dimensions of mass \( \lambda \) in this theory]. Schwinger suggested that the same effect could occur in four dimensions for sufficiently large couplings.

Further study of the Schwinger model by Lowenstein and S威斯 and Casher, Kogut, and Kadanoff has shown that the asymptotic states of the model contain only massive photons, not electrons. Nevertheless, as Casher et al. have shown in detail, the electrons are present in deep-inelastic processes and behave like free pointlike particles over short times and short distances. The polarization effects which prevent the appearance of electrons in the final state take place on a longer time scale (longer than \( 1/m \), where \( m \) is the photon mass).

A new mechanism which keeps quarks bound will be proposed in this paper. The mechanism applies to gauge theories only. The mechanism will be illustrated using the strong-coupling limit of a gauge theory in four-dimensional space-time. However, the model discussed here has a built-in ultraviolet cutoff, and in the strong-coupling limit all particle masses (including the gauge field masses) are much larger than the cutoff, in consequence the theory is far from covariant.

The confinement mechanism proposed here is soft (long-time scale). However, in the model discussed here the cutoff spoils the possibility of free pointlike behavior for the quarks.

The model discussed in this paper is a gauge theory set up on a four-dimensional Euclidean lattice. The inverse of the lattice spacing serves as an ultraviolet cutoff because of a Euclidean space (i.e., imaginary instead of real times) instead of a Lorentz space is not a serious restriction; the energy eigenstates (including scattering states) of the lattice theory can be determined from the "transfer-matrix" formalism as has been discussed by mir and reviewed by Wilson and Kogut. A brief discussion of the
Lattice regularization

- hypercubic space-time lattice
- **quarks** reside on sites, **gluons** reside on links between sites
- lattice excludes short wavelengths from theory (regulator)
- regulator removed using standard renormalization procedures (continuum limit)
- systematic errors
  - discretization
  - finite volume
Monte Carlo methods

- vacuum expectation value in terms of path integrals

\[ \langle \Phi(t)\Phi^*(0) \rangle = \frac{\int D\Phi \Phi(t)\Phi^*(0) e^{-S[\Phi]}}{\int D\Phi e^{-S[\Phi]}} \]

- S[\Phi] is the Euclidean space action, \( \Phi^*(t) \) creates state of interest
- evaluation of path integrals:
  - Markov-chain Monte Carlo methods
    - Metropolis
    - heatbath
    - overrelaxation
    - hybrid methods
  - no expansions in a small parameter
  - statistical errors
- first principles approach
New branch of particle physics

- Wilson’s paper marks beginning of new branch of particle physics
  - \textit{lattice QCD} or lattice gauge theory
- field has grown considerably during past 25 years
- large grand-challenge collaborations with dedicated supercomputer resources in several countries
  - USA, Japan, Germany, Italy, UK, Australia,…
- annual International Symposium on Lattice Field Theory
  - typically over 300 participants
- e-print archive at xxx.lanl.gov: hep-lat

- I am a member of the \textit{Lattice Hadron Physics collaboration}
  - focus on hadron physics relevant to experimental program at the \textit{Thomas Jefferson National Accelerator Facility} (Newport News)
  - acquiring large Pentium-based clusters at Jlab and MIT with funds obtained through DOE’s SciDAC Initiative
Role of lattice QCD

- useful for “brute force” calculations of strong interaction observables
  - spectra, decay constants $f_B$, structure functions
  - quantities needed to go beyond the standard model
- useful tool to help understand QCD
  - testing mechanisms of confinement
  - answering why the naïve quark model works as well as it does
  - do certain field configurations dominate path integral?
- develop better tools for nonperturbative aspects of gauge theories
  - repercussions beyond QCD
- lattice simulations have told us much about QCD
  - but still much more to learn!
Technology advancements

- significant advances in simulation techniques during 1990’s
  - improved actions (quantum corrections to couplings, tadpoles)
  - excited states using variational techniques with correlator matrices
  - anisotropic lattices
  - chiral fermions (domain wall, overlap)
- computers \(\rightarrow\) vastly improved performance, lower costs
- accurate calculations of many quantities for the first time
  - Yang-Mills glueball spectrum
  - quenched light hadron spectrum
  - quenched \(f_B\), etc.
- full incorporation of virtual quark-antiquark pairs still a problem
  - very active subject of research
### Current state of the art

<table>
<thead>
<tr>
<th>Category</th>
<th>Expression</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable single particle masses $N_f = 0$</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Stable single particle masses $N_f &gt; 0$</td>
<td>B-</td>
<td></td>
</tr>
<tr>
<td>Two particle energies</td>
<td>C-</td>
<td></td>
</tr>
<tr>
<td>EM Current matrix elements $N_f = 0$</td>
<td>A-</td>
<td></td>
</tr>
<tr>
<td>EM Current matrix elements $N_f &gt; 0$</td>
<td>C+</td>
<td></td>
</tr>
<tr>
<td>Unstable single particle masses</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Decay strengths, resonance widths</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>
Light hadron spectrum (quenched)

- CP-PACS collaboration (Japan)  Phys Rev Lett 84, 238 (2000)
Light hadron spectrum ($N_f=2$)

- CP-PACS collaboration  hep-lat/0010078
- Iwasaki gauge, SWTI fermion
- baryons $\rightarrow$ finite volume effects
- experimental values

![Graphs showing hadron mass spectrum vs. a (GeV$^{-1}$) for different values of $N_f$.]
**Key feature of QCD**

- fundamental degrees of freedom (quarks and gluons) cannot be observed in isolation
- attractive force between quark-antiquark is *constant* with separation
- suggests that gluon field forms a *string*-like object between quark-antiquark

---

Bali *et al.*
Static quark potential

- lattice simulations confirm linearly rising potential from gluon exchange

Bali et al.

$r_0 = 0.5$ fm
Quark confinement

- quarks can never be isolated
- linearly rising potential
  - separation of quark from antiquark takes an infinite amount of energy
  - gluon flux breaks, new quark-antiquark pair produced
Constituent quark model

- much of our understanding of hadron formation comes from the *constituent quark model*
  - motivated by QCD
  - valence quarks interacting via Coulomb + linear potential
  - gluons: source of the potential, dynamics ignored
- mesons: only certain \( J^{PC} \) allowed:
  - \( 0^{++}, 0^{-+}, 1^{--}, 2^{++}, 3^{--}, 4^{++}, ... \) forbidden
- *most* of observed low-lying hadron spectrum described reasonably well by quark model
  - agreement is amazing given the crudeness of the model
- experimental results now need input beyond the quark model
  - over-abundance of states
  - forbidden \( 1^{--} \) states

\[ P = (-1)^{L+1} \quad L = 0, 1, 2, ... \]
\[ C = (-1)^{L+S} \quad S = 0, 1 \]
Gluonic excitations

- QCD suggests existence of states in which *gluon* field is excited
  - glueballs (*excited glue*)
  - hybrid mesons (*q\bar{q} + excited glue*)
  - hybrid baryons (*qqq + excited glue*)
- such states not understood
  - quark model fails
  - perturbative methods fail
- lack of understanding makes identification difficult!
- clues to confinement
Experimental candidates

- scalar glueball: $f_0(1500)$ or $f_J(1710)$
  - mixing
- tensor glueball: $\xi(2230)$ or $f_2(1980)$
- $1^{++}$ hybrid mesons (E852 BNL 1997)
  - $1.4$ GeV (controversial)
  - $1.6$ GeV (lattice predicts $1.9$ GeV)
- higher $c\bar{c}$ and $b\bar{b}$ states
- hybrid baryon $P_{11}(1710)$
- others


Physicists Find Exotic New Particle

By MALCOLM W. BROWNE

Physicists working at Brookhaven National Laboratory on Long Island believe they have discovered a previously unknown particle, which they call an exotic meson.

The discovery of the new particle was reported yesterday in the journal Physical Review Letters by 31 scientists from Brookhaven, the University of Notre Dame, three other American institutions and two Russian research groups.

The particle, which was created by firing a beam of protons into a target of liquid hydrogen, has too short a life to be detected directly, but physicists deduced its existence from the pattern of subnuclei detected in the decay apparently created.

Ordinary matter consists of atoms whose nuclei are made of varying combinations of protons and neutrons, and each proton or neutron contains three quarks, with particles called gluons holding them together. Another type of particle, which survives briefly after creation in accelerators, laboratories, is the meson: a particle consisting just two quarks—a quark and an antiquark.

The suspected new meson is definitely one of the well-known quark-antiquark kinds, the group reported. Among the possibilities the collaboration intends to investigate is a tetraquark particle, which contains four quarks.
Future experiments

- experimental focus on such states intensifying

**glueballs**

**hybrid mesons**

CLEO-c and CESR-c: A New Frontier of Weak and Strong Interactions

9/10/2001 CMU colloquium 40
### Lattice takes aim

<table>
<thead>
<tr>
<th>Category</th>
<th>$N_f = 0$</th>
<th>$N_f &gt; 0$</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>glueball masses</td>
<td>C.M., Peardon</td>
<td>SESAM</td>
<td>99</td>
</tr>
<tr>
<td>glueball decays</td>
<td>IBM (GF11)</td>
<td>IBM (GF11)</td>
<td>99</td>
</tr>
<tr>
<td>glueball-$q\bar{q}$ mixing</td>
<td>Juge, Kuti, C.M.</td>
<td>IBM (GF11)</td>
<td>99</td>
</tr>
<tr>
<td>excitations of $QQ$ potential</td>
<td>Juge, Kuti, C.M.</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>light $1^{++}$ meson mass</td>
<td>UKQCD</td>
<td>MILC</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0(2) GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MILC</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.1(1) GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lacock, Schilling</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.9(2) GeV</td>
</tr>
<tr>
<td>$c\bar{c}$ $1^{++}$ meson mass</td>
<td>MILC</td>
<td>CP-PACS</td>
<td>98</td>
</tr>
<tr>
<td>(above $1S$)</td>
<td></td>
<td></td>
<td>1.22(15) GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP-PACS</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.32(2) GeV</td>
</tr>
<tr>
<td>$b\bar{b}$ $1^{++}$ meson mass</td>
<td>UKQCD</td>
<td>CP-PACS</td>
<td>98</td>
</tr>
<tr>
<td>(above $1S$)</td>
<td></td>
<td></td>
<td>1.68(10) GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CP-PACS</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.542(8) GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Juge, Kuti, C.M.</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.49(2)(5) GeV</td>
</tr>
</tbody>
</table>

9/10/2001  CMU colloquium  41
Yang-Mills SU(3) Glueball Spectrum

- gluons can bind to form glueballs
  - e.m. analogue: massive globules of pure light!
- technology advancements permit first glimpse of glueball spectrum
- states labeled by $J^{PC}$ and scale set using $r_0^{-1} = 410(20)$ MeV
- probe of confinement
- “experimental” results in simpler world (no quarks) to help build phenomenological models
- first step towards realistic glueball study

Clay Millenium Prize

- understanding this glueball spectrum worth $1 million
- www.claymath.org

To celebrate mathematics in the new millennium, The Clay Mathematics Institute (CMI) identified seven old and important mathematics questions that resisted all past attempts to solve them. The CMI designated the $7 million prize fund for their solution, with $1 million allocated to each Millennium Prize Problem.

Millennium Prize Problems

- P versus NP
- The Hodge Conjecture
- The Poincaré Conjecture
- The Riemann Hypothesis
- Yang–Mills Existence and Mass Gap
- Navier–Stokes Existence and Smoothness
- The Birch and Swinnerton–Dyer Conjecture
Excitations of static quark potential

- gluon field in presence of static quark-antiquark pair can be *excited*
- classification of states: (notation from molecular physics)
  - magnitude of glue spin
    - projected onto molecular axis
      \[ \Lambda = 0, 1, 2, \ldots \]
      \[ = \Sigma, \Pi, \Delta, \ldots \]
  - charge conjugation + parity about midpoint
    \[ \eta = g \text{ (even)} \]
    \[ = u \text{ (odd)} \]
  - chirality (reflections in plane containing axis)
    \[ \Sigma^+, \Sigma^- \]
    \[ \Pi, \Delta, \ldots \text{doubly degenerate} \]
    \[ (\Lambda \text{ doubling}) \]

Juge, Kuti, Morningstar

9/10/2001 CMU colloquium
Heavy-quark hybrid mesons

- more amenable to theoretical treatment than light-quark hybrids
- possible treatment like diatomic molecule (Born-Oppenheimer)
  - slow heavy quarks $\leftrightarrow$ nuclei
  - fast gluon field $\leftrightarrow$ electrons (and light quarks)
- gluons provide adiabatic potentials $V_{Q\bar{Q}}(r)$
  - gluons fully relativistic, interacting
  - potentials computing in lattice simulations
- nonrelativistic quark motion described in leading order by solving Schrödinger equation for each $V_{Q\bar{Q}}(r)$

$$\left\{ \frac{p^2}{2\mu} + V_{Q\bar{Q}}(r) \right\} \psi_{Q\bar{Q}}(r) = E \psi_{Q\bar{Q}}(r)$$

- conventional mesons from $\Sigma^+_g$; hybrids from $\Pi_u, \Sigma^-_u, \ldots$
Leading Born-Oppenheimer

- results obtained (in absence of light quark loops)
- good agreement with experiment below BB threshold
- plethora of hybrid states predicted (caution! quark loops)
- but is a Born-Oppenheimer treatment valid?

Testing LBO

- test LBO by comparison of spectrum with NRQCD simulations
  - include retardation effects, but no quark spin, no light quarks
  - allow possible mixings between adiabatic potentials
- dramatic evidence of validity of LBO
  - level splittings agree to 10% for 2 conventional mesons, 4 hybrids

\[
\begin{align*}
H_1, H_1' &= 1^{--}, 0^{--}, 1^{--}, 2^{--} \\
H_2 &= 1^{++}, 0^{--}, 1^{--}, 2^{--} \\
H_3 &= 0^{++}, 1^{--}
\end{align*}
\]
Compelling physical picture

- Born-Oppenheimer provides simple physical picture for heavy-quark conventional and hybrid meson states
  - partial explanation of quark model success (light quarks?)
  - allows incorporation of gluon dynamics (beyond quark model)
- does this BO picture survive inclusion of
  - quark spin?
  - light-quark effects?
- quark spin: two recent studies suggest BO picture survives
    - looked at 4 hybrids degenerate in LBO
    - found significant shifts from $\sigma \cdot B / M$ but used bag model to interpret results as not arising from surface mixing effects
    - found very small probability admixture of hybrid in $\Upsilon$ from $\sigma \cdot B / M$
- more conclusive tests needed
Light quark spoiler?

- spoil B.O.? → unknown
- light quarks change $V_{qar{q}}(r)$
  - small corrections at small $r$
    - fixes low-lying spectrum
  - large changes for $r > 1$ fm
    → fission into $(Qar{q})(ar{Q}q)$
- states with diameters over 1 fm
  - most likely cannot exist as observable resonances
- dense spectrum of states from pure glue potentials will not be realized
  - survival of a few states conceivable given results from Bali et al.
- discrepancy with experiment above $B\bar{B}$
  - most likely due to light quark effects

9/10/2001  
CMU colloquium
Future work

- heavy-quark hybrid mesons
  - revisit quark spin effects
  - $V_{qar{q}}(r)$ in presence of virtual light quarks (string breaking)
- light quark hybrid mass calculations
- glueball mixing with scalar quarkonium
- tests of confinements scenarios with glueball spectrum
- “baryon” potentials (gluons in presence of static $qqq$)
- $N^*$ spectrum
- $qqqq$ states (study of the $a_0(980)$, the light $1^{-+}$ exotic)
- flux tube profiles (energy, angular momentum)
- strings in other representations (adjoint, …)
- torelon spectrum
- much, much more….
Conclusion

- quest to understand the strong force is a classic story

- great conceptual leaps
- great experiments
- heroes
- the horribly wronged
- incredible violence

- confinement
- freedom (asymptotic)
- amazing technology
- large sums of money
- comic relief

- lattice simulations of quarks and gluons will continue to play an important role in this quest