The early history of QCD

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Quark Confinement and the Hadron Spectrum X

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universität wien

Contents

Why should one want to look back 50 years?

- particle physics looked very much different then:
  no sign of anything like today's Standard Model
- strong interactions ("nuclear force"):
  a hopeless case for quantum field theory
  (natural union of quantum theory and special relativity)
- within less than 15 years:
  quantum field theory arising like phoenix from the ashes
  common framework for electromagnetic, weak and strong interactions: Standard Model
- in moments of despair over lack of "New Physics":
  recall fascinating developments leading to Standard Model

Particle physics in the early sixties

already in those dark ages

4 fundamental forces in nature

gravitation	strong nuclear force
electromagnetism	weak nuclear force
long range	short range

Electromagnetism
Quantum Electrodynamics (QED)

- quantum corrections calculable
- precise predictions, but
- methodology (renormalization) not generally accepted

Dirac, Wigner, . . . : " . . . infinities are swept under the rug."

Feynman (1961):

"I do not subscribe to the philosophy of renormalization."

Weak interactions
$V - A$ 4-Fermi theory

- phenomenology of weak decays satisfactory, but
- quantum corrections not calculable (nonrenormalizability)

end of sixties, beginning of seventies:

renormalizable gauge field theory of electroweak interactions

Glashow, Salam, Weinberg (Nobel Prize 1979)

't Hooft, Veltman (Nobel Prize 1999)

Strong interactions ??

hopeless case for quantum field theory

- degrees of freedom: nucleons, pions, . . . (hadrons)?
- strength of interaction prohibits perturbative treatment

Landau : " It is well known that theoretical physics is at present almost helpless in dealing with the problem of strong interactions. We are driven to the conclusion that the Hamiltonian method for strong interactions is dead and must be buried, although of course with deserved honour."

Goldberger : “ My own feeling is that we have learned a great deal from field theory . . . that I am quite happy to discard it as an old, but rather friendly, mistress who I would be willing to recognize on the street if I should encounter her again.”

Alternative approaches

- Bootstrap (nuclear democracy) (Chew, . . .)

  politically correct, but not predictive
- Symmetries

  $SU(3)$ classification of hadrons (Gell-Mann, Ne’eman)

  fictitious constituents: quarks (Gell-Mann, Zweig)

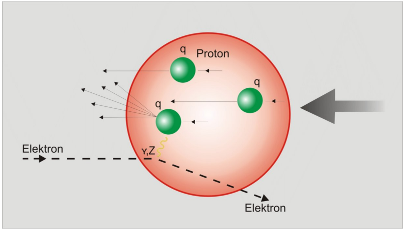
Symmetries explain classification of hadrons

but how does one calculate properties of hadrons?

French cuisine approach

Gell-Mann : We construct a mathematical theory of the strongly interacting particles, which may or may not have anything to do with reality, find suitable algebraic relations that hold in the model, postulate their validity, and then throw away the model. We may compare this process to a method sometimes employed in French cuisine: a piece of pheasant meat is cooked between two slices of veal, which are then discarded."

Scaling and asymptotic freedom



deep inelastic scattering

MIT-SLAC

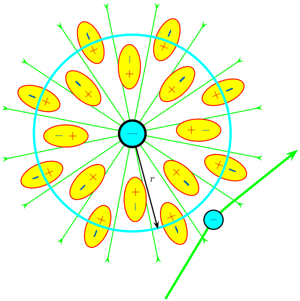
(late sixties)

surprising result (Friedman, Kendall, Taylor Nobel Prize 1990)

- at high energies (and large momentum transfer): scaling
  nucleons seem to consist of non-interacting part(on)s
- obvious candidates for partons (Feynman): quarks
- seeming paradox

  quarks quasi-free at high energies
  yet permanently bound in hadrons

Puzzle: strength of interaction energy dependent ?



electron-electron scattering

well-known effect in QED

charge screening

effective charge
decreases with distance
$\simeq$ increases with energy

QFT: β-function

$$\beta(q_{\rm eff}) \sim -r\frac{dq_{\rm eff}(r)}{dr} > 0$$

scaling requires negative β-function $\longrightarrow$

"anti-screening" $\Leftrightarrow$ asymptotic freedom

Asymptotic freedom in quantum field theories

majority view in early 1973 (Zee):

"...we conjecture that there are no asymptotically free quantum field theories in four dimensions."

Coleman and Gross work on a general proof ("Price of asymptotic freedom", July 1973)

Politzer and Wilczek, their graduate students, attempt to close a "loophole": β-function for nonabelian gauge theories (Yang-Mills theories) was still unknown (except to 't Hooft)

Earlier calculations of the β-function

Vanyashin, Terentyev (1965):

charge renormalization of charged vector bosons is negative
"absurd" result attributed to nonrenormalizability

Khriplovich (1969):

correct calculation of charge renormalization of Yang-Mills theories, no connection made with asymptotic freedom

't Hooft (1972):

complete calculation of β-function for Yang-Mills theories
Symanzik encourages publication (Veltman objects)
"I now regret not to have followed his sensible advice." (1998)

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April/May 1973 (Gross, Wilczek; Politzer Nobel Prize 2004)

Yang-Mills theories are asymptotically free !

reason photons are electrically neutral
gluons (quanta of strong interactions) carry "colour" charge

Asymptotic freedom and the QCD vacuum

Nielsen: analogy with electrodynamics of continuous media

vacuum of a relativistic QFT (Lorentz invariance) $\longrightarrow$

$$\varepsilon\mu = 1$$

QED: charge screening $\to$ dielectric constant $\varepsilon > 1$

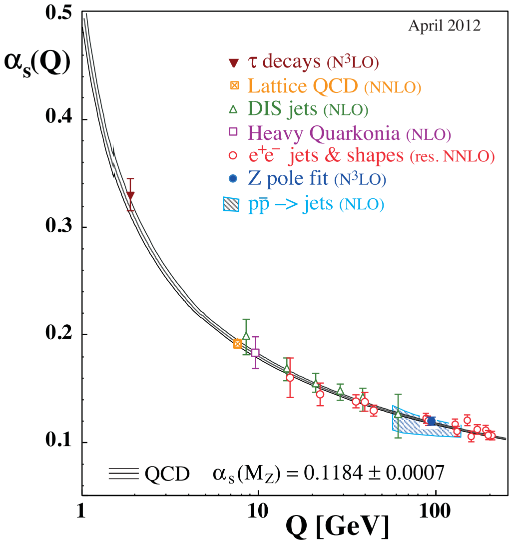
$\to$ QED vacuum is a diamagnet (permeability $\mu < 1$)

QCD: colour charge screening of quarks ($\varepsilon > 1$) is overcompensated by gluons (spin 1) acting as permanent colour dipoles ($\mu > 1$)

$\to$ QCD vacuum is a (colour) paramagnet for ($N_c = 3$)

N_F (number of quark types) $< 11\, N_c/2 < 17$ $\longrightarrow$

"anti-screening" ($\varepsilon < 1$) $\longrightarrow$ asymptotic freedom



energy dependence of strong force

Review of Particle Properties

compilation by Bethke

Quantum Chromodynamics (QCD)

Gross: "Like an atheist who has just received a message from a burning bush, I became an immediate true believer."

However: ingredients of QCD already "known" in 1972

- quarks come in 3 colours (. . . , Bardeen, Fritzsch, Gell-Mann)
- 8 gluons (??)

Fritzsch, Gell-Mann: toy model with coloured quarks and singlet gluon ($\rightarrow$ not asymptotically free)

Proc. ICHEP, Chicago 1972:
"Now the interesting question has been raised lately whether we should regard the gluons as well as the quarks as being non-singlets with respect to colour [5]."

Ref. [5]: J. Wess (private communication to B. Zumino)

SU(3) group theory

$$\overline{3} \times 3 = 1 \ + \ 8$$

$\longrightarrow$ gluons can only be

singlet or octet

definitely settled by Fritzsch, Gell-Mann, Leutwyler (Oct. 1973):
"Advantages of the colour octet gluon picture"

First (written) appearance of the name "QCD"?

Fritzsch, Gell-Mann, Minkowski (1975):
"A good name for this theory is quantum chromodynamics."

Quantum Electrodynamics (QED)

for simplicity: only electrons and photons

$$\mathcal{L}_{\rm QED} = \overline{\psi}\,(i\,\not{D} - m)\,\psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

Quantum Chromodynamics (QCD)

quarks (single flavour) and gluons

$$\mathcal{L}_{\rm QCD} = \sum_{i,j=1}^{3} \overline{q_i}\,(i\,\not{D} - m_q)_{ij}\,q_j - \frac{1}{4}\sum_{\alpha=1}^{8} G^{\alpha}_{\mu\nu} G^{\alpha,\mu\nu}$$

deceptively "simple", much richer than QED $\longrightarrow$

Thomas Mannel: The many facets of QCD