Asymptotic Freedom

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(unfinished, unused)

Outline

- Paradoxes
  - Quarks' lack of radiation
  - Quantum field theory

Nucleus

- 1920's: Rutherford, Geiger, Marsden - protons
- 1932: Chadwick - neutrons
- 1960s: Gell-mann and Zweig - quarks

the Quark paradox

- no individual quarks observed (confinement), fractional charges (2/3 or 1/3 of e charge), do not follow quantum statistics (spin-1/2 quarks should have antisymmetric wavefunction, but baryons require symmetric wave functions)
- Friedman, Kendall, Taylor (SLAC) probed protons by photons - found that when the quarks are hit, they move like free particles. no strong radiation.

the paradox of SR and QM

- special relativity - fast
- quantum mechanics - small
- tension = treatment of space and time
  - 3 + 1 nobel prizes - common problem - ultraviolet divergences

Dirac (1933)

- uncertainties of position and velocity - faster than light - antiparticles

UV divergences

- special relativity deals with motion of particles moving at v ~ c
- SR introduces energy fluctuations over brief time intervals - generalizes ‘x-p complementarity’ in non-relativistic QM
- energy can be converted to virtual particles - “vacuum” is densely populated with virtual particles

UV divergences (continued)

- interaction between real and virtual particles change properties of the real particles - but the changes are divergent due to high-energy virtual particles
- this problem descends from Planck's "ultraviolet catastrophe" of black-body radiation (high energy modes of EM field occur as thermal fluctuations)

Energy Fluctuations

- in black body radiation: equilibrium at finite temperature requires infinite energy in the high energy modes
- problem: small fluctuations with rapid variations in space and time are possible
- discreteness in quantum theory eliminates such possibility since fluctuation size has a lower bound imposed
- large fluctuations = rare in thermal equilibrium and don't cause problems

Quantum fluctuations

- more efficient than thermal fluctuations at exciting the high-energy modes (virtual particles)
- divergence of energy of vacuum (zero-point energy)

Renormalization

- interaction with high-energy virtual particles cause divergent corrections - but the same divergences occur repeatedly in different physical processes (e.g., in QED, corrections in m and q of electron)
- apply a cut-off to exclude high-energy modes, then remove the cut-off at the end

Feynman, Schwinger, Tomonaga (1965)

- quantum electrodynamics
- found a way to write down corrections due to interactions with ‘internal loops’ in Feynman diagram

‘t Hooft and Veltman (1999)

- electroweak interaction
- shows that renormalization works with many more theories, e.g., Glashow, Salam, and Weignberg’s spontaneously broken gauge theories (later become electroweak theory)

Landau’s Problem

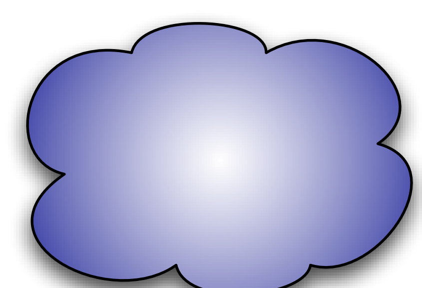
- if influence (e.g., electric charge) is non-zero, virtual particles accumulate around a real particle - this is called ‘screening’
- screening only terminates when the particle and its virtual cloud is of no interest to additional virtual particles - but in then there would be no interaction
- arbitrary number of virtual particles lead to nonsensical results

Screening

- in QED and electroweak - small finite number of virtual particles = calculations fit experiments very well
- however, we cannot expect that lots of strongly-interacting virtual particles won't come into play
- QM and SR seemed to lead to QFT, but QFT failed because of screening

Asymptotic Freedom (Antiscreening)

- antiscreening is the answer to the paradoxes
- screening: from a large charge at center, small observable influence far away
- antiscreening: a cloud of virtual particles enhanced the charge's power - the stronger influence the further away from the source ("thundercloud")



Source and Antisource

- confinement of quarks suggests that in Nature, there are sources (in this case, quarks) who cannot exist on their own
- we can avoid infinite growth of antiscreening thundercloud by putting an antiparticle nearby a source particle - when cloud of source overlaps anticloud of antisource, they cancel
- individual quarks and antiquarks would cause infinite disturbance, but together they can be accommodated with finite energy

Radiation explanation

- when Friedman, Kendall, and Taylor violently accelerated quarks - no radiation
- asymptotic freedom: charge of individual quark is small, but at large distance, growing cloud drives up its power - the source itself is loosely bound, because of its small charge - in small range and brief time, quark behaves like a free particle
- the virtual particles adjust to this change by rebuilding new cloud, but this process does not involve significant radiation of energy and momentum

- theories that display asymptotic freedom are called nonabelian gauge theories, or Yang-Mills theories
- several kinds of colors
- several color-carrying gluons (unlike photons)
- virtual gluons - antiscreening (absent in QED)

- strong interaction theory - must accommodate baryons (3q) and mesons (q qbar)
- color charges of 3q must cancel - SU(3) gauge group - 3 colors, 8 gluons

Paradigm of Quarks and Gluons

- e+ e- -> 2 jets, 3 jets, 4 jets

Quantum Chromodynamics

SU(3) Symmetry

Asymptotic Freedom

- a.k.a. antiscreening

Jets

Radiation

- hard - redirects flow of energy and momentum
- soft - produces new particles without changing the overall flow

Paradigm 3: Early U is simple

- before asymptotic freedom (1972): ultra high temperatures after Big Bang - lots of hadrons and antihadrons - extended strongly-interacting entities - overlapping mess - Universe seemed difficult to figure out
- asymptotic freedom: strong interaction is simple - quarks, antiquarks, gluons mostly free, with some rare hard interactions
- collision from STAR - little big bangs inside the lab

Paradigm 4: Symmetry

- unified field theories
- supersymmetry
- axions
- symmetry loss

Unification

- Standard Model: SU(3) x SU(2) x U(1)

Axions

- Peccei-Quinn symmetry explains absence of undesired interaction
- axions - very light, very weakly interacting

LHC

- to interpret LHC collisions, we have to understand how protons are assembled from quarks and gluons, and how quarks and gluons show up as jets