Discovery of Quarks and Strong Interaction

A. Harindranath (SINP)

Plan

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- Classification of Particles
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Fundamental Forces of Nature

In the order of decreasing strength

- Strong

  Responsible for binding neutrons and protons in nuclei. short range

- Electromagnetic

  About 100 times weaker than strong force.

  long range

  Responsible for binding nuclei and electrons together in atoms.

- Weak

  About 1000,000 weaker than strong force.

  short range

  Responsible for radio active decay.

- Gravitational

  About 10^{38} times weaker than strong force.

  long range

  Responsible for macroscopic phenomena like coconut falling from tree, earth orbiting sun, ...

Fundamental Interactions of Particle Physics

Interaction	Range (fm)	Typical life time (sec)	Typical cross section (mb)	Typical coupling
Strong	1	10^{-23}	10	1
Electro-magnetic	∞	10^{-20} to 10^{-16}	10^{-3}	10^{-2}
Weak	10^{-3}	10^{-12}	10^{-11}	10^{-6}

$1 \text{ fm} = 10^{-13}\text{cm}$

$1 \text{ barn} = 10^{-24} \text{ cm}^2$

Classification of Particles

Particles with integral spin - bosons
Particles with half integral spin - fermions

Particles that experience strong force - hadrons

Hadrons further classified into
Baryons: proton, neutron, etc. (fermions)
and
Mesons: pion, omega, rho, etc. (bosons)

Particles that are immune to strong force - leptons (fermions)
electron, muon, tau, neutrino

Particles that mediate different forces (bosons):
gluon – strong force
photon – electromagnetic force
W, Z – weak force

Some Animals in the Particle Zoo

Electron - mass 0.5 MeV/c^2 (1897)

Proton – mass 938.27 MeV/c^2 (1913)

Mean life time $> 10^{31}$ years

Neutron – mass 939.57 MeV/c^2 (1932)

Mean life time 15 minutes

What holds the nuclei together?

Gravity too weak

Electromagnetism weak, infinite range, protons will repel

A strong, short range force is needed

Model after electromagnetism

Electromagnetic force due to exchange of photons

Massless photon exchange $\rightarrow$ infinite range

Massive particle exchange $\rightarrow$ finite range

Yukawa (1934) proposed a particle called meson

Lightest meson pion (mass 140 MeV/c^2 discovered in 1947.

Anti particles

1927 Dirac discovered his famous equation
Predicted anti particle for electron
A particle with the same mass but opposite electric charge as that of the electron
positron discovered in 1931.

Anti proton discovered in 1955.

Many other species of anti particles were discovered later, further enlarging the list of hadrons.

At present, electron-positron collider is at the forefront of High Energy Physics Research.

Quark Model

In the next few years number of hadrons proliferated!
In 1964 Gell-Mann and Zweig independently proposed Quark Model
The name Quark came from James Joyce's novel Finnegans Wake.

Basic Assumption: All hadrons are made up of elementary constituents called quarks.
Every baryon is composed of three quarks.
Every meson is composed of a quark and anti quark.
Baryons and mesons are no longer elementary, they are composite.

When proposed [1964], three quarks: up, down and strange
Three flavours.

Till now six flavours of quarks have been "discovered":
charm (1974), bottom (1977) and top (1994).

New Quantum Number colour

Evidence for colour:
Delta Baryon: spin $\frac{3}{2}$, charge +2
$\rightarrow u^{\uparrow}u^{\uparrow}u^{\uparrow}$

Wave function $\psi = \psi_{space} \times \psi_{spin} \times \psi_{flavour}$
Symmetric.

But we need ψ to be anti-symmetric.

Propose a new quantum number colour:
Each flavour of quark comes in three colours

$\psi = \psi_{space} \times \psi_{spin} \times \psi_{flavour} \times \psi_{colour}$
ψ anti symmetric since
ψ_{colour} anti symmetric.

Other evidences for colour:
Pion decay $\Pi^0 \rightarrow \gamma + \gamma)$
$e^+e^- \rightarrow hadrons$, ...

Quarks are fractionally charged.

up quark u $\frac{2}{3}$

down quark d $-\frac{1}{3}$

Proton uud $\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$

Neutron udd $\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$

Experimental searches for the existence of fractionally charged particles [started since the proposal of Gell-Mann] to date: Null Result!

Quarks are " purely mathematical entities"

"A search for stable quarks ... at the highest energy accelerators would help to reassure us of the nonexistence of real quarks".

M. Gell-Mann, Physics Letters, 8, 214 (1964).

"In view of the extremely crude manner in which we have approached the problem, the results we have obtained seem somewhat miraculous"

G. Zweig, CERN preprint 8182/TH401 (1964).

Elastic and Inelastic Scatterings

Consider a scattering process of a scatterer and a projectile.

Elastic scattering is the one which changes only the share of their energy and momentum.

Fully characterized by one independent quantity, say, momentum transfer.

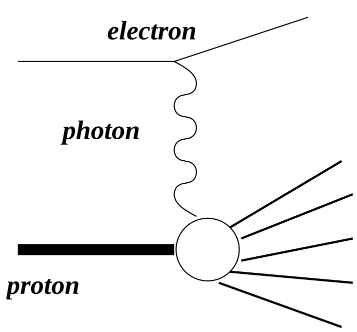
Example: electron + proton → electron + proton

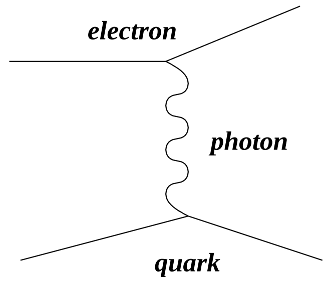
Inelastic scattering is the one in which part of the energy transfer is lost inside the scatterer and gives rise to some internal process.

Momentum transfer and energy transfer completely independent.

Example: electron + proton → electron + anything

Deep Inelastic Scattering





Tool: Deep Inelastic Lepton-Hadron Scattering (DIS):

P Target four momentum

q Virtual photon four momentum

$q = (q^0, \mathbf{q}), \quad q^2 < 0.$

Deep Inelastic:

$-q^2 >> m^2_{proton}, \quad (P+q)^2 >> m^2_{proton}$

Let $Q^2 = -q^2$, $\nu = P.q$

Define $x = \frac{Q^2}{2\nu}$, Bjorken scaling variable.

Differential cross section $\propto W(Q^2, \nu)$, hadron structure function.

Extracted from experimental data.

Tells us about the structure of hadron in detail knowing the nature of interaction responsible for scattering.

Constituent Picture of Matter

Consider a nuclear target.

At very low resolution,

$\frac{1}{\sqrt{Q^2}} \gg Radius_{Nucleus}$

$q^0 \approx Nuclear\, energy\, level\, spacing$

Data shows elastic scattering from nucleus, excitation of nuclear energy levels

But as $\frac{1}{\sqrt{Q^2}} \ll Radius_{Nucleus}$

$q^0 \gg nuclear\, level\, spacing$

yet $\frac{1}{\sqrt{Q^2}} \gg Radius_{Nucleon}$

Data shows a quasi-elastic peak which corresponds to elastic scattering from nucleons, point-like constituents of the nucleus.

For point-like nucleons, only elastic scattering can occur.

In the impulse approximation, we expect the structure function to scale.

Scaling function tells us about the momentum distribution of nucleons in the nucleus.

As $q^0 \approx Nucleon\,energy\,level\,spacing$

data shows excitation of nucleon resonances

But as $\frac{1}{\sqrt{Q^2}} \ll Radius_{Nulceon}$

$q^0 \gg Nucleon\,energy\,level\,spacing$

constituents of the nucleon are revealed.

For point-like constituents, only elastic scattering can occur.

In the impulse approximation, we expect the data to scale.

Existence of scaling $\rightarrow$ point-like constituents inside the nucleon - partons (Feynman)

$W(Q^2, \nu) \rightarrow F(\frac{Q^2}{2\nu}) = F(x)$

Scaling function tells us about the electric charges, spins, and momentum fraction distribution of the constituents of the nucleon.

Partons are fractionally charged! (quarks)

From structure function studies, quarks carry only half the momentum of the nucleon. Rest carried by gluons (stuff that bind quarks).

Operational Meaning of

Constituent Picture

Distribution of constituents present at any instant in the system (wave function)

Requires probing the system over a time duration small on the scale of internal motion of constituents

Natural for nonrelativistic systems   But nucleon is a relativistic system

It seems that only a fuzzy picture of the instantaneous state of the nucleon could be obtained. Feynman to the rescue!

Wave function of a relativistic system has non-trivial frame dependence

Normally thought of as bad news But turn it into good news

Therefore, one may hope that certain properties of the system are more easily seen from the wave function in one frame of reference than in another.

FEYNMAN: Study hadron in a frame of reference in which it moves with nearly the speed of light

Due to time dilation, internal motion of the constituents slow down!

$P \to \infty$ [Infinite momentum frame]

Note only does the internal motion of the constituents slow down, transverse dynamics looks non-relativistic!

Consider energy momentum relation for a free relativistic particle:

$E = \sqrt{k^2 + m^2}$. $k^2 = k_L^2 + k_T^2$, $k_T^2 = k_x^2 + k_y^2$.

For large k_L, $E \simeq k_L + \frac{1}{2}\frac{k_T^2 + m^2}{k_L}$.

Wave function in terms of longitudinal momenta k_L, transverse momenta k_T of the constituents.

$k_L = \eta P$, k_T small

Simple kinematical considerations $\Longrightarrow$

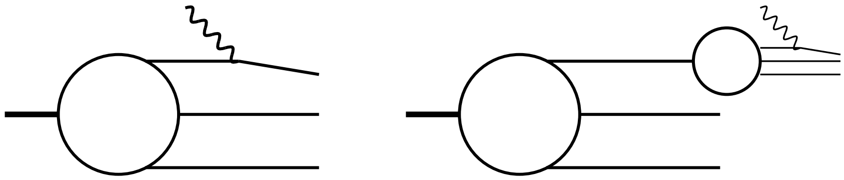
longitudinal momentum fraction

$\eta = x$, Bjorken scaling variable.

Constituents of the hadron = partons

Scaling function $F(x) = xq(x)$

$q(x)$ Number density of partons with longitudinal momentum fraction between x and $x + dx$



Q_0^2 Q_1^2

$Q_1^2 >> Q_0^2$

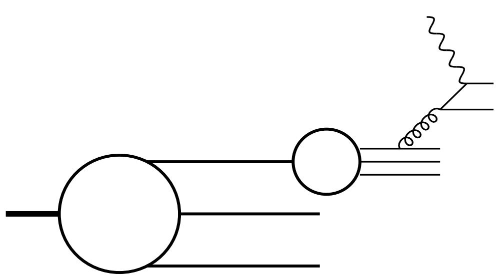
Quasi Elastic Scattering:

Data implies finite number of constituents in the nucleus $\Longrightarrow$ One can ignore the dynamical aspects of the *stuff* responsible for nuclear binding $\Longrightarrow$ Non-relativistic character of the system

Deep Inelastic Scattering:

Data implies infinite number of constituents in the nucleon

Scaling is not perfect, $F(x, Q^2)$ (logarithmic Q^2 dependence) $\Longrightarrow$ Dynamical aspects of the *stuff* responsible for nucleon binding cannot be ignored $\Longrightarrow$ Relativistic character of the system.



Quantum Chromo Dynamics

Problems! Problems!

Problem 1: In the parton picture of DIS, at very high energy, nucleon behaves as a collection of almost free constituents. (Scaling violations very weak)

Can one justify parton picture in Quantum Field Theory?

In Quantum Electro Dynamics, Coulomb potential between two electrons $\sim \frac{\alpha}{r}$.

In momentum space $\sim \frac{\alpha}{q^2}$.

Quantum corrections $\sim \frac{\alpha(q^2)}{q^2}$.

$\alpha(q^2)$ increases with increasing q^2. $\alpha(r)$ grows with decreasing r.

For parton picture to emerge, we need the opposite behaviour: coupling $\alpha_s(q^2) \to 0$ as $q^2 \to \infty$.

Theory of strong interactions should possess Asymptotic Freedom.

In 1973 it was discovered that Quantum Chromo Dynamics (QCD) has asymptotic freedom.

Problem 2: Free quarks and gluons have never been observed in nature. To explain this absence QCD should have the property of confinement. Quarks and gluons are permanently confined inside hadrons.

What happens when we try to take the quarks apart?

Consider the simplest system: a meson containing a quark and an anti quark.

Just as when we try to separate the north pole and south pole of a bar magnet, result is two bar magnets each with its own north and south pole, trying to separate the quark and anti quark in a meson, results in two mesons!

Does QCD have confinement?

Evidence for confinement comes from putting the theory on a space-time lattice and performing numerical calculations on supercomputers!!

Solving QCD: Still an ongoing research

Summary

After a brief introduction to fundamental interactions in particle physics and particles (elementary and composite) we took an elementary overview of quark model and color quantum number.

After looking at elastic and inelastic scatterings we discussed the main tool for revealing fundamental constituents of matter, namely, Deep Inelastic Scattering.

To gain an operational meaning of constituent picture we looked at the concept of infinite momentum frame and Feynman's partons.

Finally, we discussed some features of the theory underlying strong interaction, namely, Quantum Chromo Dynamics.

This talk is based on the following:

Books:

- Introduction to Elementary Particles D. Griffiths John Wiley & Sons, Inc., (1987).
- An Introduction to Quarks and Partons F. E. Close Academic Press (1979).
- Constructing Quarks: A Sociological History of Particle Physics A. Pickering University of Chicago Press; Reprint edition (December 1999)

Particle Data Group (PDG):

http://pdg.lbl.gov

Also see

Second Creation R.P. Crease and C.C. Mann Rutgers University Press; Reprint edition (February 1996)