PHY 4154

Nuclear and Particle Physics

Sourabh Dube

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Particles

- Anything which can be treated as a single object in a dynamical framework; where shape of object can be roughly described by one parameter (eg. sphere).
  - Trajectory of ball using classical mechanics
  - α-particles in Rutherford's gold foil experiment
  - Formation of galaxies/stars in multi-body simulations
- Scale at which we probe; scale at which we desire answers; determines whether an object is a particle or not.
  - Stars in a galaxy simulation
  - Atoms in a Stern-Gerlach experiment

  can both be treated as particles.

Nuclear and Particle Physics

- Learn about particles at the scales not addressed in other courses ;)
- We will primarily study particle physics, and some nuclear physics.
- Of course, we will be studying within the context of fundamental particles and interactions.
- But what is fundamental is never known a priori.. this is why some historical development is needed.

Goals of Particle Physics

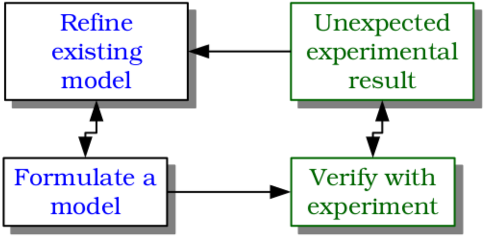
- What is the universe made of? What are the *fundamental* constituents of our universe?
- How do the fundamental constituents interact? (...with each other)

These aims are of course necessarily grand. It is not always obvious if a given problem is within the domain of particle physics or not —for example, dark matter.

The particle approach is complementary to the field approach (QFT), and is typically essential for experiments.

Studying Particle Physics

- Particles are usually studied from
  - Scattering events (eg. α particle experiment)
  - Decays (eg. β-decay)
  - Bound states ("spectroscopy")



Our aim is to have dynamics (force laws) which correctly describe (predict) the behaviour of particles.

Studying Particle Physics

Particles are small, and typically moving fast.
We need QM, and we need Relativity $\longrightarrow$ we need QFT.

Relativity allows tools to use conservation of energy, momentum; gives us presence of massless particles.

QM describes states ($|\psi\rangle$) and scattering/decay can be thought of as transitions from $|1\rangle \to |2\rangle$. QM also gives us ability to have probabilistic transitions.

Relativity$\bigotimes$QM gives us antiparticles, CPT theorem...

These are properties of the framework $\to$ not a particular model.

(See "Goals, models, frameworks and the scientific method", S. Mukhi, Current Science **109**, 05 (2015))

In the 60's and 70's, a collection of theories (merging QED and QCD) emerged, which we call the Standard Model (of particle physics).

History

- 1897: J. J. Thomson discovered electrons; cathode rays emitted by a filament are deflected by a magnetic field.

  [Problem: Griffiths 1.1 Charged particle traversing crossed E and B fields is undeflected].
- He got large e/m indicating small m (or large e).
- Plum pudding model for atoms.
- 1911: Rutherford's α particle scattering experiment. [Estimate energy]
- Positive charge concentrated in centre; He gave the name proton to the nucleus of the lightest atom (Hydrogen).
- 1914: Niels Bohr model for H-atom, calculated lines.
- 1932: Chadwick discovered neutron.
- Fundamental particles were protons, neutrons and electrons.

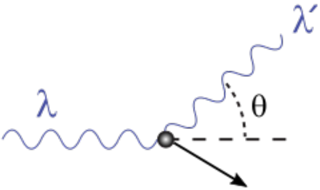
Properties

What are the properties of these particles? What defines them?

- Size? H-atom is about 10^{-10} m. Nucleus is about 10^{-15} m, or 1 Fermi. Roughly speaking. Electron size is even less well defined.
- Mass $m_e = 9.1 \times 10^{31}$ kg, $m_p \simeq 1836 m_e$.
- Charge $q_e = 1.6 \times 10^{-19}$ C, $q_p = -q_e$.
- Coupling strengths.
- Spin $= \frac{1}{2}\hbar$.
- Lifetime $\tau_e > 4.6 \times 10^{26}$ years, $\tau_p > 2 \times 10^{29}$ years, $\tau_{\rm neutron} \simeq 14.7$ minutes.
- Indistinguishability.

Photons

- As you may know, we have been back and forth about the particle nature of light.
- Planck in 1900 gave $E = h\nu$, quantized EM radiation; believed it a property of emission.
- Einstein in 1905 with PE effect; quantization is property of the EM field itself.
- 1923: Compton scattering



$$\lambda' = \lambda + \frac{h}{mc}(1 - \cos\theta)$$

This provided conclusive evidence of particle nature of light. (We shall see this problem).

Force carrier

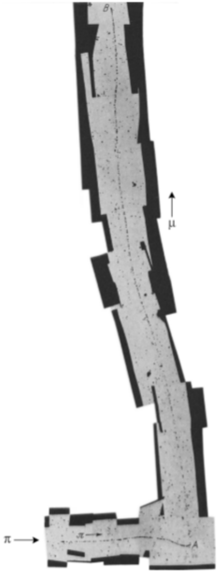
- Photon is carrier of electromagnetic force.
- Classical field $\rightarrow$ Quantized field.
- Exchange of information via force carriers... electromagnetic force mediated via photons.
- Exchange of information via force carriers... electromagnetic ~~force~~ interaction mediated via photons.
- Virtual vs Real.

Nucleus

- What holds a *nucleus* together?
- Evidently a *strong* force. Evidently also a short-range force.
- 1934: Yukawa proposed theory of strong force which keeps protons and neutrons together.
- Field mediated by a quantum.. with what properties?
- Boson. With larger mass than photon, about $300 m_e$.
- Meson (middle-weight). [Lepton (light-weight), Baryon (heavy-weight)].
- 1937: Andersen & Nedermeyer, Street & Stevenson, Oppenheimer $\rightarrow$ experiments on cosmic rays have middle-weight particles.
- No further updates till 1946. Why?

Mesons

- But the discovered particle interacted weakly with atomic nuclei. Its mass/lifetime measurements were inconsistent.
- Groups in Bristol/Rome showed there were two particles, π (pion) and μ (muon) c. 1947.
- The π decays to the μ.
  The π is the true Yukawa meson.



Anti-particles

- 1927: Dirac equation to describe free electrons with relativistic energy $E^2 - \mathbf{p}^2 c^2 = m^2 c^4$.
- This has two solutions $E = \pm\sqrt{\mathbf{p}^2 c^2 + m^2 c^4}$.
- Interpreted as "hole-in-the-sea". Wished it was proton, but p is too massive (x2000).

- Modern interpretation by Feynman/Stuckelberg for antiparticles.
- QFT says for every particle, there must exist antiparticle with same mass but opposite electromagnetic charge.
- Antiprotons, antineutrons discovered in 1955 (why 20 years?).
- Some quantum numbers also change sign (lepton-number, baryon-number).

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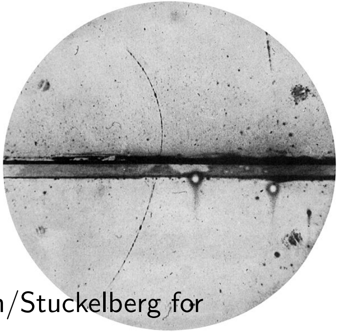

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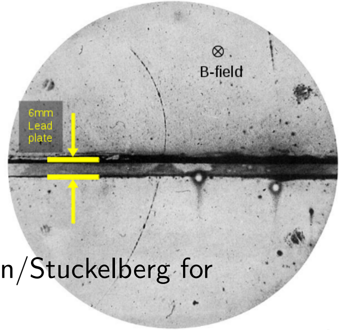
- 1931: Anderson's discovery of positron.



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Crossing symmetry

Denote antiparticles by overbar. So proton (p) and antiproton ($\bar{p}$). But also denote by charge, so μ^- is muon and μ^+ is antimuon.

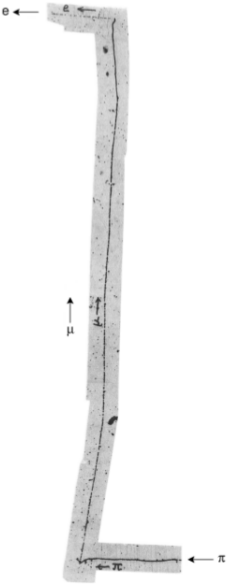
If $A + B \to C + D$ is allowed, then
$A \to \bar{B} + C + D$
$\bar{C} + \bar{D} \to \bar{A} + \bar{B}$ are allowed.

Compton scattering
$\gamma + e^- \to \gamma + e^-$ is same as
Pair annihilation
$e^- + e^+ \to \gamma + \gamma$.

Dynamically permissible is different from *Kinematically* permissible.

Onwards

Onwards



Onwards

Neutrinos

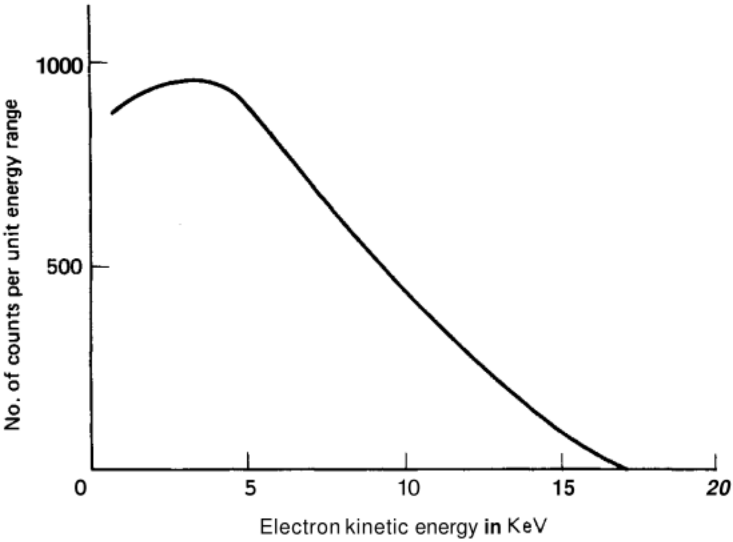
1930: Study of nuclear beta decay. $A \to B + e^-$
Apply conservation of charge to A, B. Thus we have
${}^{40}_{19}K \to {}^{40}_{20}Ca$ or ${}^{64}_{29}Cu \to {}^{64}_{30}Zn$.
Skipping ahead a bit, applying conservation of energy to A at rest, we get electron energy as

$$E = \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A} \right)$$

E is fixed once masses are fixed. Turns out, doing the experiment gives

$$E \leq \left(\frac{m_A^2 - m_B^2 + m_e^2}{2m_A} \right)$$

Pauli proposed a neutral particle (conserve charge, no track) and called it *neutron*.


1000
500
No. of counts per unit energy range
0
5
10
15
20
Electron kinetic energy in KeV

Neutrinos

- Of course, a different particle was called neutron.
- Fermi's theory of beta decay.
- Given that new particle must be very light, call it *neutrino*.
- Beta decay is understood as $n \to p^+ + e^- + \nu$
- Studying pion decay gives $\pi \to \mu + \nu$
- Studying muon decay gives $\mu \to e + \nu + \nu$ (why?)
- 1956: Cowan & Reines ; $\nu + p^+ \to n + e^+$.
- *anti*neutrinos?
- Compare $\nu + n \to p^+ + e^-$ and $\bar{\nu} + n \to p^+ + e^-$.
  Latter does not occur.

Conservation laws

- Theoretically suggest *lepton number*. Assign $L = +1$ to electron, muon, neutrino and $L = -1$ to positron, antimuon and antineutrino.(Others are $L = 0$.)
- Lepton number is conserved in all reactions.

Thus $\pi^- \to \mu^- + \bar{\nu}$
and $\pi^+ \to \mu^+ + \nu$.

And $\mu^\pm \to e^\pm + \nu + \bar{\nu}$.

Now consider $\mu^\pm \to e^\pm + \gamma$. This does not occur.

Law of conservation of μ-ness?

Conservation laws

Suppose two kinds of neutrinos ν_e and ν_μ.
Assign *muon* and *electron* numbers as follows

$L_\mu = 1$ for μ^-, ν_μ
$L_\mu = -1$ for $\mu^+, \bar{\nu}_\mu$

$L_e = 1$ for e^-, ν_e
$L_e = -1$ for $e^+, \bar{\nu}_e$

Separate laws of conservation of electron-number and muon-number.

Thus the reactions are
$n \rightarrow p^+ + e^- + \bar{\nu}_e$
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

Muon decay is thus
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

1962: Two neutrinos verified at Brookhaven by Lederman et al by showing

$\bar{\nu}_\mu + p^+ \rightarrow \mu^+ + n$
happens

$\bar{\nu}_\mu + p^+ \rightarrow e^+ + n$
does not.

Strange particles

- 1947: Observe a neutral particle, decaying to two charged pions. Its mass is thus at least $2m_\pi$.
- K^0, neutral kaon. [$K^0 \to \pi^+ + \pi^-$]
- 1949: charged kaon, [$K^+ \to \pi^+ + \pi^+ + \pi^-$]
- Soon many other mesons discovered (η, ϕ, ω, ρ...)
- 1950: Neutral particle decaying to proton and pion, $\Lambda \to p^+ + \pi^-$. This is a baryon. [why?]

Conservation laws

We don't observe $p^+ \to e^+ + \gamma$ either.

There is a law of Conservation of Baryon number.

$n \to p^+ + e^- + \bar{\nu}_e$

Thus in $\Lambda \to p^+ + \pi^-$, Λ must be a baryon.

(There is no law of conservation of mesons.)

1952 Brookhaven Cosmotron operational. Now we can produce particles in lab (instead of cosmic rays).

New particles produced on timescale 10^{-23} s, but decay with timescale 10^{-10} s. Hence strange.

Produced via strong interaction, decay via weak interaction.

Strangeness

Introduce a new quantum number, strange-ness (like lepton-number, baryon-number).

Conserved in strong interactions, not conserved in weak interactions. Conserved when produced, not conserved when decay.

Particle	Strangeness
Kaons	$+1$
Σ's, Λ	-1
π, p, n	0

$$\begin{aligned}\pi^- + p^+ &\rightarrow K^+ + \Sigma^- \\ &\rightarrow K^0 + \Sigma^0 \\ &\rightarrow K^0 + \Lambda\end{aligned}$$

All conserve strangeness.

Strangeness

Particle	Strangeness
Kaons	$+1$
Σ's, Λ	-1
π, p, n	0

Thus we can't have

$$\pi^- + p^+ \to \pi^+ + \Sigma^-$$
$$\to K^0 + n$$

But in decays, we can have

$$\Lambda \to p^+ + \pi^-$$

$$\Sigma^+ \to p^+ + \pi^0$$
$$\to n + \pi^+$$

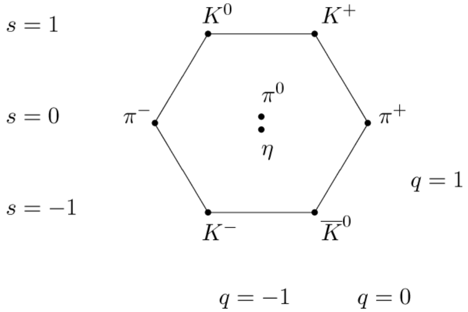
Organize

Lots of new particles, lots of new rules.

Needed order, like periodic table.

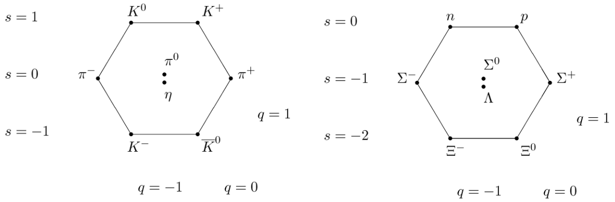
Eightfold Way

1961: Introduced by Murray Gell-Mann.



Eightfold Way: Meson and Baryon Octet

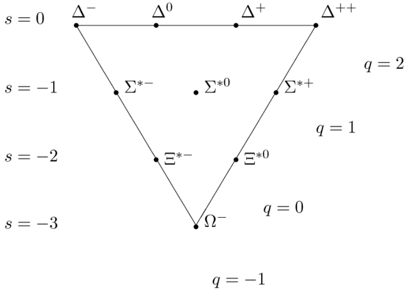
1961: Introduced by Murray Gell-Mann.



Eightfold Way: Baryon Decuplet

1961: Introduced by Murray Gell-Mann.

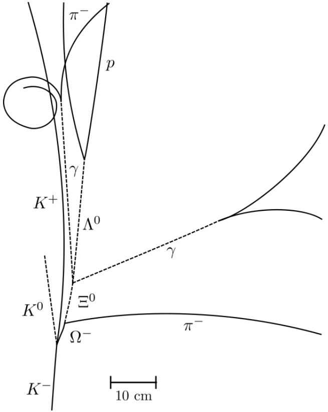
Particle	Mass $[\mathrm{GeV}/c^2]$
n	0.940
p	0.938
Σ^+	1.189
Δ	1.232
Σ^*	1.387
Ξ^{*-}	1.533
Ω^-	1.672



$$(m_\Delta - m_{\Sigma^*}) = (m_{\Sigma^*} - m_{\Xi^{*-}}) = (m_{\Xi^{*-}} - m_{\Omega^-})$$

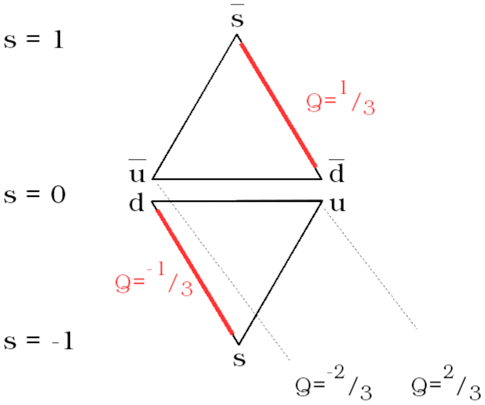
Omega Baryon

Discovery of the very first Ω^- at BNL in 1964. Adapted from original tracing. The tracks of neutral particles (dashed lines) are not visible in the bubble chamber. The collison of a K^- meson with a p creates an Ω^-, a K^0 and a K^+. The Ω^- decays into a π^- and a Ξ^0, which in turn decays into a Λ^0 and a π^0. The Λ^0 decays into a p and a π^-. The π^0, invisible due to its short lifetime, decays into two photons, which in turn each create an electron-positron pair.
https://en.wikipedia.org/wiki/Omega_baryon



Quarks

1964: Gell-Mann/Zweig predicted that all hadrons are made of *quarks*. Three types of quarks, *up*, *down* and *strange*.



Quarks

There are two composition rules:

1. Each baryon is composed of three quarks (antibaryon of three antiquarks)
2. Each meson is composed of a quark and antiquark

With this we can compose all of the previous baryons and mesons.

Thus a uuu combination $\rightarrow \Delta^{++}$, and $uus \rightarrow \Sigma^{*+}$

Note that $uud \rightarrow p^{+}$, and $uud \rightarrow \Delta^{+}$ as well.

H-atom, $\frac{\text{Difference in excited state}}{\text{Rest Energy}} \sim \frac{10 \text{ eV}}{1 \text{ GeV}} \sim 10^{-8}$

Here comparing mass(Δ^{+}) to mass$(p^{+}) \sim \frac{1232 \text{ GeV}/c^2}{938 \text{ GeV}/c^2} \sim 1.3$

Units

- Measure energy in eV. Energy acquired by electron when accelerated through 1 Volt.
  Thus $1\ \mathrm{eV} = 1.6 \times 10^{-19}$ Joules.
- We shall see energies in $\mathrm{keV}(10^3\ \mathrm{eV})$, $\mathrm{MeV}(10^6\ \mathrm{eV})$, $\mathrm{GeV}(10^9\ \mathrm{eV})$, $\mathrm{TeV}(10^{12}\ \mathrm{eV})$.
- Mass is measured in eV/c^2 or GeV/c^2 ($E = mc^2$)
- Momentum measured in eV/c, or MeV/c ($E = pc$)

The traditional SI units (Length L: meter, Mass M: kilogram, Time T: second) end up being inconvenient to describe quantities we want.

Natural Units

- We have $\hbar = \frac{h}{2\pi} = 1.055 \times 10^{-34}$ J sec
- and $c = 2.998 \times 10^{8}$ m sec^{-1}
- In natural units we have one unit of action be $\hbar$, and one unit of velocity be c. Thus we set $\hbar = 1$ and $c = 1$.
- Note that thus L and T have same dimensions, and M and L have opposite dimensions.
- Now energy, mass, and momentum are all measured in eV, MeV, GeV etc.
- Charge is measured in units of e, and thus electron has charge of -1, proton has charge $+1$.

Natural Units

Remember $\hbar c = 197.3 \text{ MeV fm} = 1$
$2.998 \times 10^8 \text{ m/s} = 1$

I will usually try to keep $\hbar, c$, but years of habit is hard to overturn. I might slip, so please correct me or ask me to clarify. Sometimes its easier that way.
Unless I explicitly ask you; you are also allowed to $\hbar = c = 1$; unless the problem at hand disallows it.

To get a feel, H-atom ionizes at 13.6 eV,
nuclear fission needs neutrons with energy $\sim$ MeV, and release a few hundred MeV,
$m_p = 938 \text{ MeV}/c^2 \sim 1 \text{ GeV}/c^2$,
mass(Higgs)$= 125 \text{ GeV}/c^2$
and LHC collides protons at 13.6 TeV.

Quarks

No one has observed an individual quark.

Experimental evidence a la 'gold-foil' shows three lumps inside a proton. But can't knock a quark out.

For some reason quarks are confined inside baryons or mesons.

Consider *uuu* combination; the Δ^{++} particle with mass$= 1.2\ \mathrm{GeV}/c^2$. Doesn't this violate Pauli's exclusion principle?

Color hypothesis: quarks come in *red, green, blue* 'colors'. Color is just another quantum number.

All naturally ocurring particles are colorless.

November Revolution

For significant time, no one believed in quarks. 1974: Dicovery of ψ meson (C. C. Ting) [also called J by Burton Richter]. Remarkable for its unusually long lifetime ($\times 1000$ typical lifetimes).

Quark model explained it by existence of a fourth quark, the *charm* quark.

Now we have u, d, s, c quarks, and many additional mesons/baryons were predicted. 1975: charmed baryons $\Lambda_c^+ = udc$, $\Sigma_c^{++} = uuc$ nailed it.

Rest of the fermions

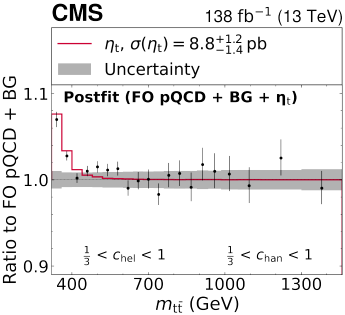
1975: new lepton, τ discovered (its own neutrino discovered in 2000).

1977: Discovery of $\Upsilon = b\bar{b}$ meson.

1995: Discovery of top quark.

~~Note: there are no *top* hadrons. Its lifetime is too short.~~

Turns out this may not be true...
April 2025
https://cerncourier.com/a/cms-observes-top-antitop-excess-2/



Vector Bosons

Rewinding a bit, consider the decay $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$,
or beta decay $n \to p^+ + e^- + \bar{\nu}_e$

Fermi modeled these as a contact interaction, at a single point.

This approach does not work at high energies. We need the 'messenger' particles.

Electroweak theory of Glashow, Weinberg, and Salam predicted three intermediate vector bosons, which were massive.

1983: Discovery of W, Z bosons at SPS at CERN.

Discovery of gluons completes the story.
Of course discovered in 1979 (before W, Z) at PETRA collider at DESY.

Standard Model