Particle Physics

- JJ Thompson discovered electrons in 1897
- Rutherford discovered the atomic nucleus in 1911 and the proton in 1919 – (idea of gold foil expt)

  "*All science is either physics or stamp collecting*" – and this from a 1908 Nobel laureate in Chemistry

- In 1932 Chadwick discovered the neutron
- Also in 1932, the positron was discovered by Anderson, after being predicted by Paul Dirac in 1927 – (beta decay)

At this point many people thought we understood all

The Particle Zoo

- 1937 – muon (mistaken for the pion till 1946)
  - I.I. Rabi said of it: “Who ordered that?”
- 1947 – pion (predicted by Yukawa in 1934 as a spin 0 particle that is the intermediary particle of the strong nuclear force with a mass ~200 x electron’s mass) How?

  Yukawa said that the interactions between nucleons (protons/neutrons) were caused by “pions” such that

  $n \rightarrow p + \pi^-$ or $p \rightarrow n + \pi^+$; he could predict that pions came in 2 charges and had spin 0; since the time they took to travel across the nucleus at speed c was ~7 x 10^{-24} seconds, they had to have a mass given by

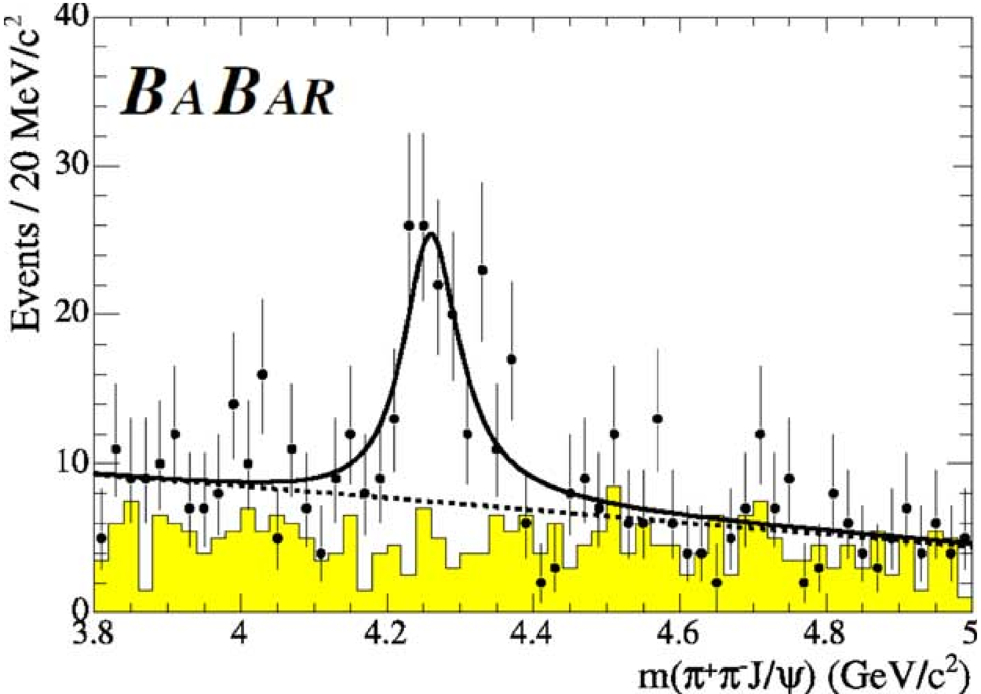
  $\Delta mc^2 \, \Delta t \geq \hbar$, which gives $m \sim 200 \times m_e$

More Particles

- 1947 – kaon (first of the “strange” particles)
- 1955 – antiproton
- 1956 – neutrino (proposed in 1931 by Fermi)
- 1960’s – 70’s – huge numbers of new particles
  - Pauli comments: "Had I foreseen this, I would have gone into botany"
  - By the late 1960’s over 100 particles were known

Particles = Resonances

- One common type of particle experiment is to do repeated collisions on a stationary target at increasing energy of the projectile and record the number of hits as a function of the projectile energy
- Plotting this as a “spectrum,” it is apparent when a new “particle is produced by the “resonance” peak – its position tells the particle energy while its width tells the lifetime since Δt ~ħ/ΔE



Forces in Nature (review)

- Remember that there are 4 fundamental forces in nature today:
  - Gravity – viewed classically as a long-range attractive force or relativistically as curvature in space-time
  - Electromagnetism – explained extremely well by QED and representing forces between electric charges
  - Two types of Nuclear forces: the Strong Force that holds the nucleus together and the Weak Force that is responsible for radioactivity

Classifying the Particle Zoo

- Early Scheme:
  - Photons: massless
  - Leptons: lightweights (electron, neutrino, muon)
  - Mesons: middleweights (pion, kaon)
  - Baryons: heavyweights (proton, neutron, lambda, sigma, xi)
- Leptons are fermions (with half-integral spin) and are fundamental particles (apparently point particles with no sub-structure). They do not experience the Strong Nuclear Force.
- Hadrons include the Mesons (which are Bosons with integral spin) and the Baryons (which are Fermions with half-integral spin) and are particles that are subject to the Strong Nuclear force.

Conserved Quantities

- We already know about some conserved quantities – the big 4 are electric charge C (in units of e), energy E, momentum p and angular momentum L (in units of ħ)
- In trying to make sense of all the new reactions and particles, a number of rules were discovered:
  - Any reaction with a photon in it must be electromagnetic
  - Any reaction with a neutrino in it must be weak (there are 3 types of neutrinos – one each associated with electrons, muons, or tau particles)

Two New Conserved Numbers

- **Lepton number L** is conserved – (remember leptons include 6 particles (electron ($L_{e-}=1$), muon ($L_{\mu-}=1$), tau ($L_{\tau-}=1$) + each of their associated neutrinos (ν_e ν_μ ν_τ) + 6 anti-particles with corresponding L values = -1)
  - Example reactions are $n \rightarrow p + e^- + \bar{\nu}_e$; $n + \nu_e \rightarrow p + e^-$
  - (Actually L may not be strictly conserved since $m_\nu \neq 0$)
- **Baryon number B** is conserved – all baryons are assigned B = 1, while all others (leptons and mesons) have B = 0
  - Examples: while $n \rightarrow \pi^+ + \pi^-$ satisfies charge conservation and could satisfy energy conservation, it does not satisfy baryon conservation and does not occur; $\pi^- + p \rightarrow K^+ + \Sigma^-$ does occur since charge, energy and B is conserved (p and Σ have B = 1)
  - (Some theories indicate B may not be strictly conserved – but then the proton should be unstable; current lower bound for the proton lifetime is 10^{25} years)

Another (conserved?) Number S

- Some reactions that satisfy all of the rules so far have never been observed – for example: $\pi^- + p \rightarrow \pi^- + \Sigma^+$
- New rule with a new number = Strangeness S
- Protons, neutrons and pions have $S = 0$, while all other hadrons have $S \neq 0$
- S is conserved in all reactions that involve the strong or electromagnetic interactions
- S is not conserved for the weak interactions

What’s fundamental?

- By the late 1950’s there had been an explosion in the numbers of “elementary” particles from the basic three (electron, proton, neutron)
- Several major questions:
  - Are they really fundamental, or composed of smaller more fundamental parts?
  - If there are smaller parts, what are they like and how many are there?
  - Where is the underlying simplicity expected in nature?

Quarks

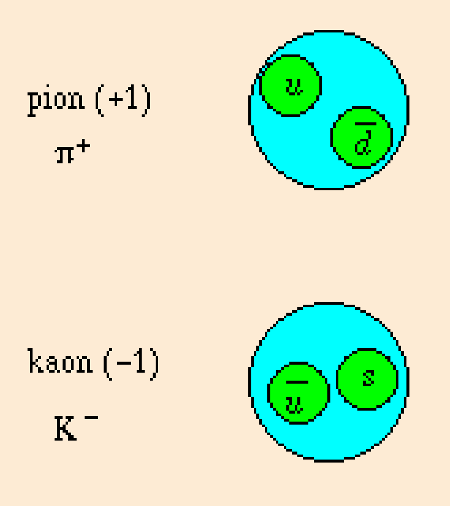

Fig. 6.35 Murray Gell-Mann (b.1929).

PhD from MIT at age 22

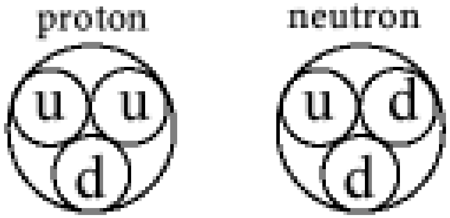
- In 1964 Murray Gell-Mann and George Zweig independently came up with a theory – dubbed the 8-fold way - that could explain the bulk of the experimental data
- It introduced the notion of quarks, coming in 3 types – called flavors – up, down and strange and their antiparticles.
- Quarks all have spin 1/2, B = 1/3, and differ in charge (u = +2/3, d = -1/3, s = -1/3; the anti-quarks having opposite signed charge) as well as in S (u = d = 0; s = -1; the antiparticles having opposite signed S)
- Gell-Mann's prediction of fractionally charged particles (quarks) was a leap – however he said: "If quarks are not found, remember I never said they would be; if they are found, remember I thought of them first."

Combining Quarks to make Hadrons

- Mesons are made from quark/antiquark combos in such a way that the electric charge comes out integral and the spin = 0 – so they are bosons

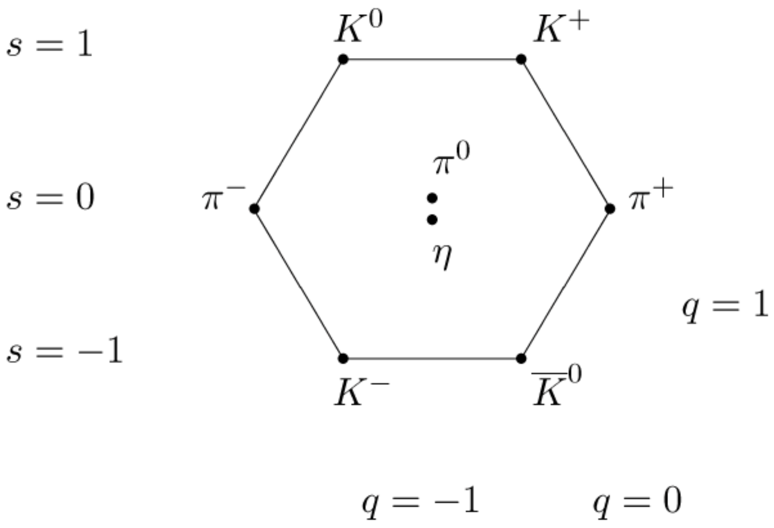


- Baryons are made from 3 quarks, again so that the charge comes out integral but the spin is half-integral so they are fermions

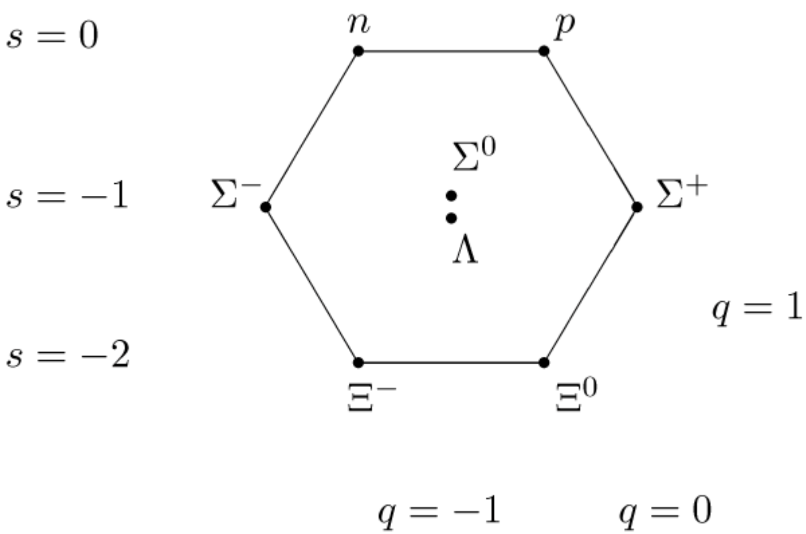


The 8-Fold Way; Families of Particles

- Gell-Mann was able to organize most of the known particles in families with differing quantum numbers – based on an area of math called “group theory” – Lie groups, in particular SU(3)



Spin 0 Meson Octet



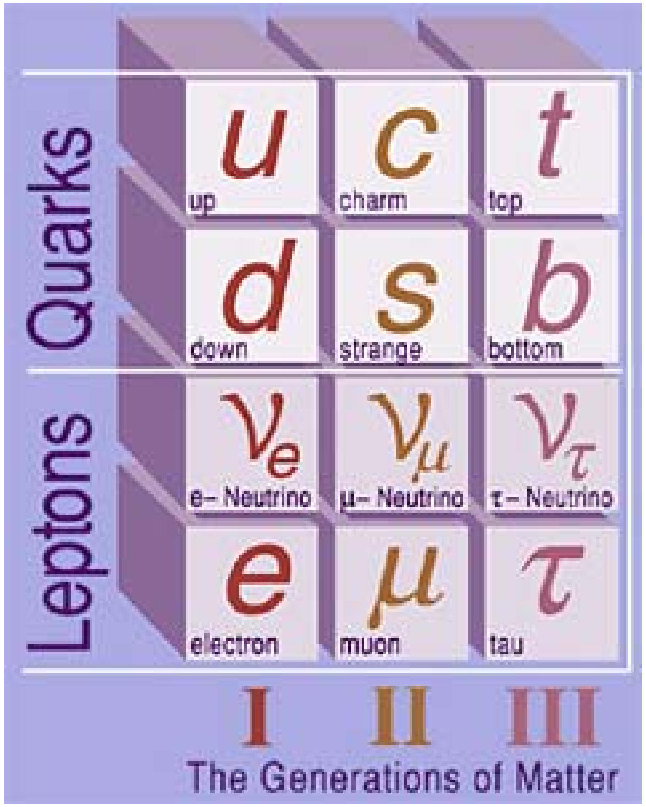
Baryon Octet

The Standard Model

Now for the complete picture as far as we know it

All particles are made from:

- Leptons – 6 spin ½ particles (and their anti-particles) –organized in 3 generations - do not feel strong force
  - Leptons come in 3 flavors (electron, muon, tau) + 3 neutrinos (1 type for each e, μ, τ)
- Quarks – 6 flavors, spin ½, in 3 generations, each with baryon number B = 1/3,Lepton number L = 0, and spin ½ - they make up the mesons and baryons, together called hadrons

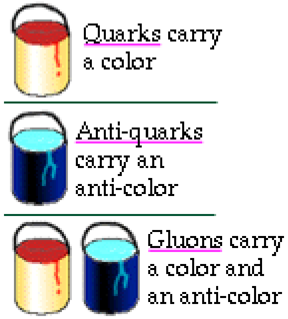


Total # = 24 so far
(with antiparticles)

The Top quark was discovered last in 1995, 20 years after its prediction

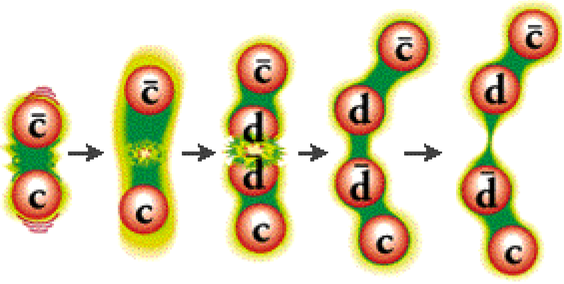
Particle Interactions – force carrying bosons

- We’ve studied that charged particles interact via the photon (massless spin 1particle = boson)
- Quarks interact electromagnetically (since they are charged), but also strongly via gluons – we say that quarks have color charge – or just color (nothing to do with a frequency/visible color) – and they come in 3 colors (RGB)
- All particles combine quarks in a way that makes them color neutral (white); So mesons, made of 2 quarks, must come in RR*, GG* or BB* varieties, where the * means the anti-color; And baryons must come with one each RGB, to add to white
- Gluons – they are also spin 1 bosons – each carry both a color and an anti-color; there turn out to be 8 (not 9) different types of gluons



More Strong Interactions (QCD)

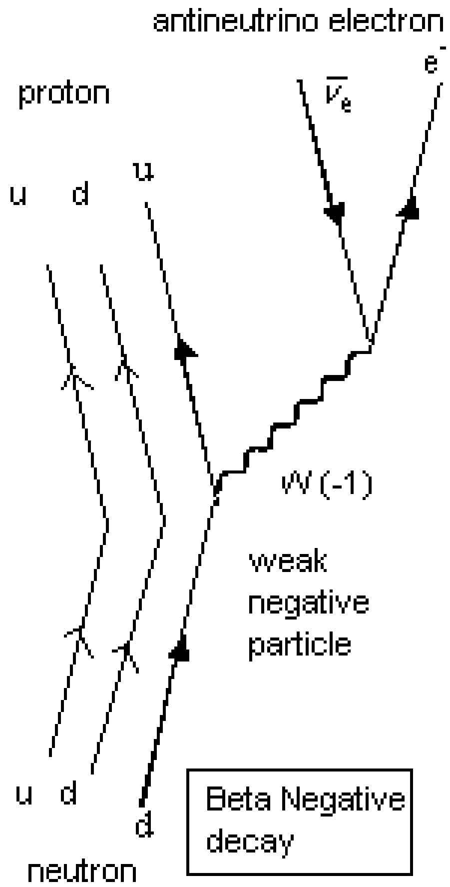
- Quark or Color Confinement – Color is invisible; quarks are "asymptotically free" inside the nucleons, but they are strongly "confined" by strong "spring-like" forces
- No colored quark combos are observed – all observed particles are color-neutral – Color is believed to be strictly conserved
- Exchange gluons create force field – they are responsible for the strong interactions that hold both the quarks together into nucleons and the nucleons together inside the nucleus
- Theory is called Quantum Chromodynamics or QCD



Two new quarks form and bind to the old quarks to make two new mesons. Thus, none of the quarks were at anytime in isolation. Quarks always travel in pairs or triplets.

Electroweak Theory – Last Piece of Standard Model

- Force carrier of the weak interactions are the W^+, W^- and Z^o – these are massive particles (~90 GeV, unlike the photon
- The weak interaction changes flavors of quarks in interactions



- Electroweak theory basically says that in the early universe, when the mean thermal energy was very high (in excess of 100 GeV), the weak and electromagnetic forces were the same

- As the universe cooled, "spontaneous symmetry breaking" led to the different masses of force carriers

- This also predicts another particle, the Higgs particle, not yet detected – the only particle in the Standard Model not yet seen

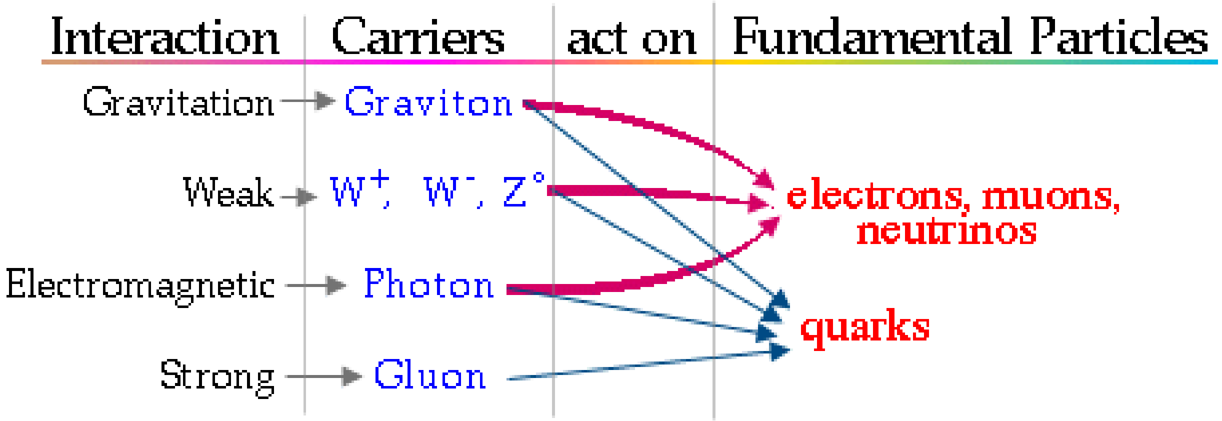
Examples of Successes of Standard Model

- **The Standard Model predicted the existence of W and Z bosons, the gluon, the top quark and the charm quark before these particles had been observed. Their predicted properties were experimentally confirmed with good precision.**

To get an idea on the precision of theory:

Quality	**Measured (GeV)**	**SM prediction (GeV)**
Mass of W boson	80.4120±0.0420	80.3900±0.0180
Mass of Z boson	91.1876±0.0021	91.1874±0.0021

Totals: 12 quark-antiquarks; 8 gluons; 12 lepton-antileptons; 1 photon; + intermediate vector bosons (3) for weak force + 1 Higgs = 37 particles (without colors)



Interaction | Carriers | act on | Fundamental Particles

Gravitation → Graviton

Weak → W^+, W^-, Z°

Electromagnetic → Photon

Strong → Gluon

electrons, muons, neutrinos

quarks

table 29-1 The Four Forces

Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	1⁄137	photons	charged particles	infinite	holding atoms together
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

Four basic forces—gravity, electromagnetism, the strong force, and the weak force—explain all the interactions observed in the universe

NOVA – Standard Model Video