Final Exam: Thur. Dec. 21, 2:45-4:45 pm,
113 Psychology Building
Exam is cumulative, covering all material

Review Chap. 18: Particle Physics

- Particles and fields: a new picture
- Quarks and leptons
- The strong and weak interaction
- Unification and mass
- String theory

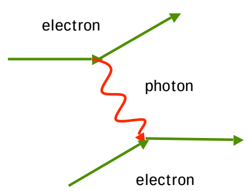
Particles as fields

- Electromagnetic field spread out over space.
  - Stronger near the the source of the electric/magnetic charge - weaker farther away.
- Electromagnetic radiation, the photon, is the quanta of the field.
- Describe electron particles as fields:
  - Makes sense - the electron was spread out around the hydrogen atom.
  - Wasn't in one place - had locations it was more or less probable to be. Stronger and weaker like the electromagnetic field.
- Electron is the quanta of the electron field.

Quantum Electrodynamics: QED

- Normal electromagnetic force comes about from exchange of photons.

Electromagnetic repulsion via emission of a photon



Energy uncertainty

- To make a very short pulse in time, need to combine a range of frequencies.
- Frequency related to quantum energy by $E=hf$.
- Heisenberg uncertainty relation can also be stated

(Energy uncertainty)x(time uncertainty) ~ (Planck's constant)

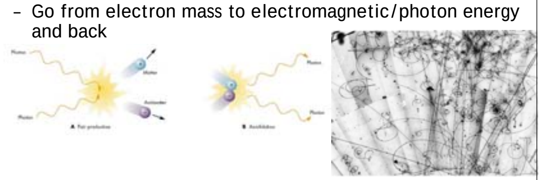
In other words, if a particle of energy E only exists for a time less than h/E,

it doesn't require **any** energy to create it!

These are the virtual particles that propagate fields

Pair production, annihilation

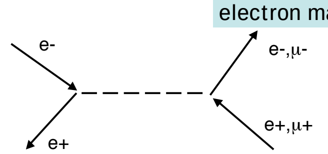
- Electron and positron can 'annihilate' to form two photons. An unexpected prediction!
- Photon can 'disappear' to form electron-positron pair.
- Relativity: Mass and energy are the same
  - Go from electron mass to electromagnetic/photon energy and back



Creating more particles

- All that is needed to create particles is energy.
- Energy can be provided by high-energy collision of particles. An example:
  - Electron and positron annihilate to form a photon.
  - This can then create particles with mc^2<photon energy.

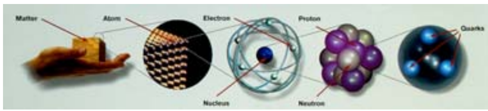
μ, Muon mass: 100MeV/c^2, electron mass 0.5 MeV/c^2



New particles found this way

What have we learned?

Matter is made of atoms

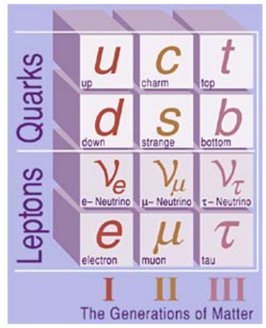


Atoms are made of leptons and quarks

Leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ Quarks $\begin{pmatrix} u \\ d \end{pmatrix}$

Interact via different forces carried by particles, photons…, simple except for the muon

Three 'generations' of particles



- Three generations differentiated primarily by mass (energy).
- First generation
  - One pair of leptons, one pair of quarks
- Leptons:
  - Electron, electron-neutrino.
- Quarks:
  - Up, down.
- All 3 generations seen

The 'generations'

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

	Leptons spin = 1/2			Quarks spin = 1/2		
	Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
Light	ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
	e electron	0.000511	−1	d down	0.006	−1/3
Heavier	ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
	μ muon	0.106	−1	s strange	0.1	−1/3
Heaviest	ν_τ tau neutrino	<0.02	0	t top	175	2/3
	τ tau	1.7771	−1	b bottom	4.3	−1/3

Charge

- These are the exchange bosons.
- What are they exchanged between?
- Or on what are the corresponding forces exerted?
- Example:
  - When a photon is exchanged between two particles, there is a electromagnetic or Coulomb force.
  - We know that only particles with electrical charge interact via the Coulomb force
  - Zero charge -> zero Coulomb interaction

Many Charges

- In this language, we say that the electrical charge is a 'source' of an EM field.
- A mass 'charge' is the source of a gravitational field
- A weak 'charge' (sometimes called 'flavor') is the source of a weak interaction field
- A strong 'charge' (sometimes called 'color') is the source of a strong interaction field

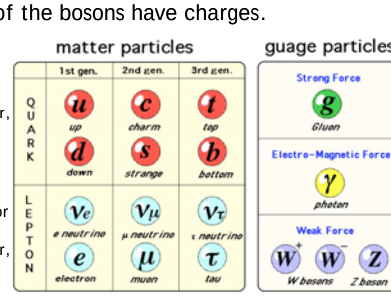
All those charges!

- Quarks and leptons have multiple charges.
- Some of the bosons have charges.

Electric, flavor, color, mass

Flavor

Electric, flavor, mass

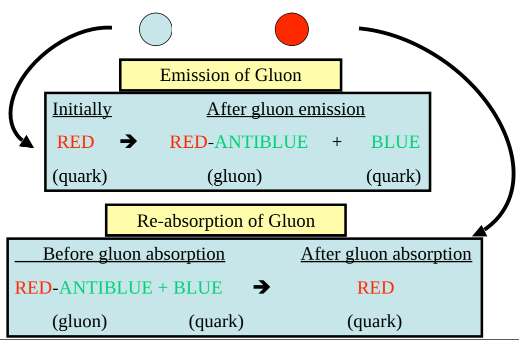


Color

None

Electric, mass

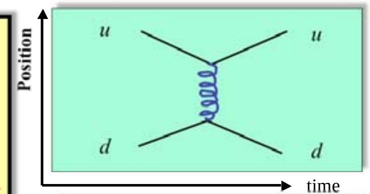
Interactions through Exchange of Color Charge



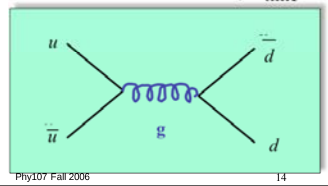
Feynman Diagrams (Quark Scattering)

Quark-quark **Scattering**

Could also be Quark-antiquark **Scattering** or Antiquark-antiquark Scattering



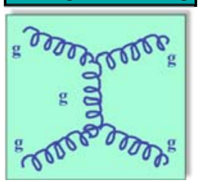
Quark-antiquark Annihilation



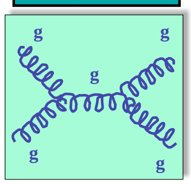
Gluon interactions

Since gluons carry "color charge", they can interact with each other !(Photons can't do that)
Very important, makes strong interaction stronger and leads to confinement

Gluon-gluon Scattering



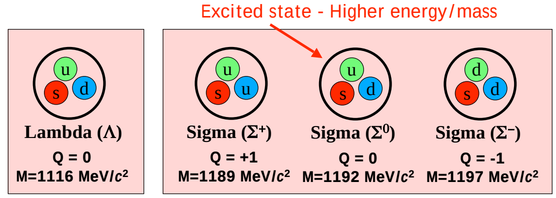
Gluon-gluon Fusion



More Baryons

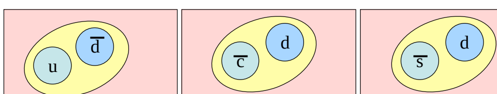
Quark	up	down	strange
Q	+2/3	-1/3	-1/3
Mass	~5 [MeV/c^2]	~10 [MeV/c^2]	~200 [MeV/c^2]
	u u u	d d d	s s s

Excited state - Higher energy/mass



Mesons

- They are formed when a **quark** and an **anti-quark** "bind" together.
- So far we've only seen 3 quark combinations. There are also 2 quark combinations.
- The hadrons: 2 quarks, meson and 3 quarks, baryon.



What's the charge of this particle?	**What's the charge of this particle?**	**What's the charge of this particle?**
Q=+1, and it's called a π^+	Q= -1, and this charm meson is called a D^-	Q= 0, this strange meson is called a K^0

Carriers of the weak force

- Like the Electromagnetic & Strong forces, the Weak force is also mediated by "force carriers".
- For the weak force, there are **three** force carriers:

W^+ W^- **Z^0**

These "weak force" carriers carry electric charge also !

This "weak force" carrier is electrically neutral

The "charge" of the weak interaction is called "weak charge"

Range of the interaction

- Electron doesn't have enough energy to create Z^o.
- Z^o only present due to uncertainty relation

(Energy uncertainty)x(Time uncertainty)~Planck cnst

It can only exist for a time determined by

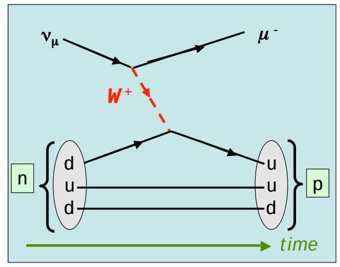
$$\text{Time uncertainty} \sim \frac{\text{Planck cnst}}{\text{Particle mass}}$$

Farthest it can travel in that time is

$$\text{Range} \sim (\text{Light Speed}) \times \frac{\text{Planck cnst}}{\text{Particle Mass}} \sim 10^{-18}\ \text{m}$$

Scattering from quarks in a nucleus

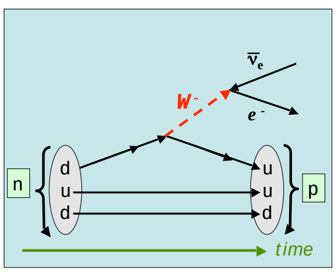
- What Ice Cube looks for is neutrinos emerging from collisions as muons.



- The neutrino interacts with quarks bound inside nucleons in the nucleus.
- Neutrino emits W^+, changing flavor into muon.
- Down quark bound in a neutron absorbs W^+, changing into a up quark.
- The nucleon then has two ups and one down quark, which is a proton.
- Always look to conserve charge in these interactions

Similar to nuclear beta decay

- Interaction via the W explains nuclear beta decay.



- d quark emits a W-, changing flavor into a u quark.
- W decays to an electron and anti-electron neutrino.
- The nucleon then has two ups and one down quark, which is a proton.
- Similar to the rotated Feynman diagram we studies with the electromagnetic force

Lepton decay

- Flavor change can occur spontaneously if the particle is heavy enough.

Generation I	Generation II	Generation III	Charge
e^-	μ^- ⇓	τ^- ⇓	-1 ⇓
ν_e	ν_μ	ν_τ	0
Electron is stable	Emit W^- 2×10^{-6} seconds	Emit W^- 3×10^{-13} seconds	

Quarks and the weak force

- Quarks have color charge, electric charge, and weak charge — other interactions swamp the weak interaction
- But similar to leptons, quarks can change their flavor (decay) via the weak force, by emitting a *W* particle.

Generation I	Generation II	Generation III	Charge
u	c ⇓	t ⇓	+2/3 ⇓
d	s	b	-1/3
	Emit W^+ 2×10^{-12} seconds	Emit W^+ 10^{-23} seconds	

Flavor change between generations

- But for quarks, not limited to within a generation!

Generation I	Generation II	Generation III	Charge
u ⇖	c ⇖	t	+2/3 ⇑
d	s	b	-1/3
	Emit W^- 10^{-12} seconds	Emit W^- 10^{-12} seconds	

Particles & their Interactions (Summary)

	quarks	Charged leptons (e,μ,τ)	Neutral leptons (ν)
Color Charge ?	Y	N	N
EM Charge ?	Y	Y	N
'Weak' Charge ?	Y	Y	Y

- ❑ Quarks can participate in Strong, EM & Weak Interactions.
- ❑ All quarks & all leptons carry weak charge.
- ❑ Neutrinos only carry weak charge.

Comparison of the Force Carriers

	EM	Strong	Weak	
Force Carrier	Photon (γ)	Gluon (g)	W^+, W^-	Z^0
Charge of force carrier	None	Color	Electric & Weak	None
Couples to:	Particles w/elect. charge	Particles w/color charge (Quarks,gluons)	Particles w/weak charge (Quarks, leptons) W,Z)	Particles w/weak charge (Quarks, leptons W,Z)
Range	Infinite ($1/d^2$)	$<10^{-14}$ m (inside hadrons)	$< 2x10^{-18}$ m	$< 2x10^{-18}$ m

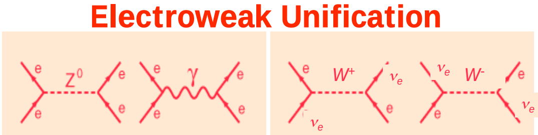
Key Points

- Differences between particles connected to how they interact, what charges they have.
- Quarks have all the charges.
  - Color charge: Quarks form composite states hadrons via the strong force.
  - Flavor charge: Heavy quarks decay to lighter quarks via the weak force.
- Leptons have no color change.
  - Don't form any composite states.
  - Neutrinos only interact via the weak force which means they rarely interact at all.

Key Points Cont.

- Properties of the force carriers determine the aspects of that force.
- Gluons and the strong force.
  - Gluon can interact with other gluons. Limits the range of that force and makes it stronger.
- W, Z and the weak force.
  - Force carriers are massive. Limits the range they can travel and makes the force weaker.
- Photon and the electromagnetic force.
  - Happy middle ground between strong and weak.

Electroweak Unification



Neutral weak	Electromagnetic	Pos. weak	Neg. weak
• Zero charge • Mass=91 GeV/c^2 • Range ~ 10^{-18} m	• Zero charge • Mass=0 GeV/c^2 • Range ~ inf.	• Pos. charge • Mass=80 GeV/c^2 • Range ~ 10^{-18} m	• Neg. charge • Mass=80 GeV/c^2 • Range ~ 10^{-18} m

These two both
exchange neutral bosons

Neither boson
changes the lepton flavor
(remains electron)

Have the same strength
at high energy!

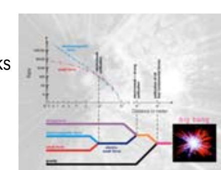
These two both
exchange charged bosons.

Both bosons
change the lepton flavor

From one source. Electroweak force. Need Higgs particle to give W, Z mass - and everything else.

Unification

- Details of weak interaction suggest
  - Diff. quarks are diff. 'orientations' of the same particle.
  - Diff. leptons are diff. 'orientations' of the same particle.
  - Weak and EM interactions are different parts of a single 'electroweak' force.
  - Electroweak interaction led to the introduction of the Higgs Boson
- Grand Unified Theories (GUTs)
  - Will 'combine' leptons and quarks
  - Unify strong and electroweak and gravitational interactions.



Checklist for a theory of everything

- Unify all the forces: strong force - gravity
- Quantize the forces - QFT very successful
- Unify the particles: quarks, leptons - 3 generations
- Explain all the different masses and strengths
- Explain dark matter
- Explain why universe is mostly matter
- Explain physics at very high energy - big bang

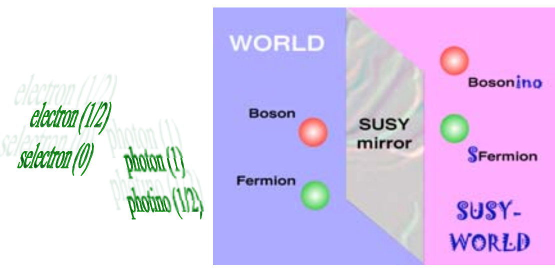
Kaluza-Klein: EM & gravity

- Connect electromagnetism and gravity in a classical relativistic theory.
- Kaluza and Klein found a theory in five dimensions (four space & one time) with one interaction (5-dimensional gravity).
- When one of the dimensions was 'compactified', two interactions resulted: gravity and electromagnetism.
- What appears to us as two distinct interactions originate from only one.

Kaluza & Klein, 1920

Only unifies gravity. Can't be quantized. Doesn't answer all the other questions!

Supersymmetry (SuSy)

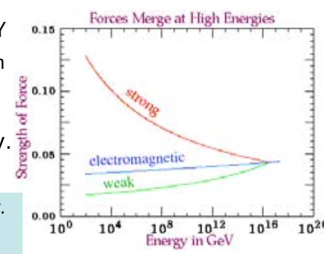


Superpartners (compare to anti-particles)
Every fermion has a boson partner and vice versa

Supersymmetry Successes

- Designed to explain behavior at very high energy
- Forces merge in SUSY
  - Same strength at high energy.
- Lightest SUSY particles don't decay.
- Dark Matter

Doesn't unifies gravity. Can't explain many of the other questions!



String theory

- A string is a fundamental quantum mechanical object that has a small but nonzero spatial extent.
- Just like a particle has a mass, a string has a 'tension' that characterizes its behavior.
- Quantum mechanical vibrations of the string correspond to the particles we observe
- Can include Kaluza Klein theory and Supersymmetry.

Checklist String Theory

- Unify all the forces: strong force - gravity
- Quantize the forces - QFT very successful
- Unify the particles: quarks lepton - 3 generations
- Explain all the different masses and strengths
- Explain dark matter
- Explain why universe is mostly matter
- Explain physics at very high energy - big bang
- Building experiments to explore all these theories including the Standard Model - Higgs not found yet!