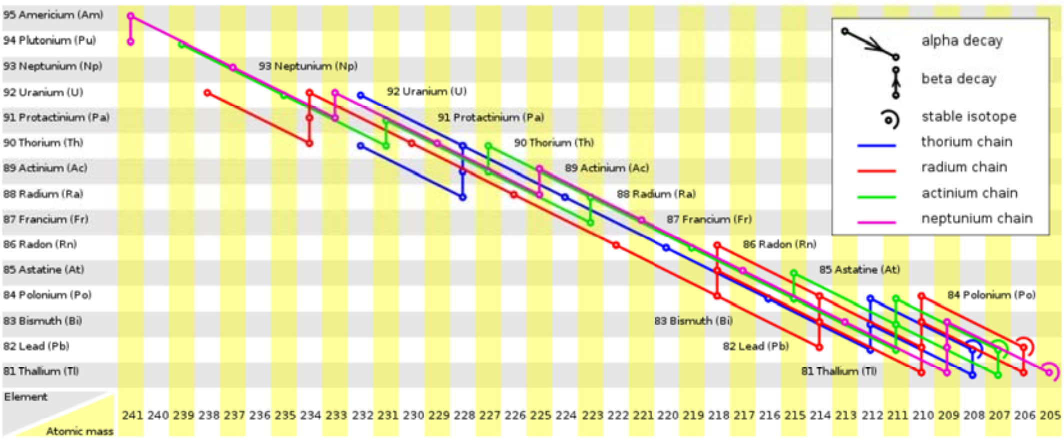
Nuclear dating

① Natural decay chains



a) Thorium series ($A = 4n$)

$^{232}Th \rightarrow \ldots (\alpha, \beta\text{-decays}) \ldots \rightarrow {}^{208}Pb$

(longest $^{232}Th \rightarrow {}^{228}Ra$, 14 bn years)

b) Neptunium series ($A = 4n+1$)

$^{237}Np \rightarrow \ldots \rightarrow {}^{209}Bi$ ($\rightarrow {}^{205}Tl$, 1.9×10^{19} yr)

now artificial

(longest $^{237}Np \rightarrow {}^{233}Pa$, 2.14 MM yr)

c) Uranium (or radium) series ($A = 4n+2$)

$^{238}U \rightarrow \ldots \rightarrow {}^{206}Pb$

(longest $^{238}U \rightarrow {}^{234}Th$, 4.5 bn yr)

d) Actinium series ($A = 4n+3$)

a.k.a. actinouranium $\rightarrow$ $^{235}U \rightarrow \ldots \rightarrow {}^{207}Pb$

(longest $^{235}U \rightarrow {}^{231}Th$, 0.7 bn yr)

② Radiometric dating

E.g. U/Pb, Sm/Nd, Rb/Sr, ...

Earth age $\rightarrow$ 4.5 bn yr old (universe ~ 14 bn yr old)

Early estimate:

Kelvin – the earth starts as molten rock,

Now temperature gradient 1°F every 50 ft down.

Assume surface $T_s \sim 0°C$, how long does it take to establish 1/50 °F/ft gradient?

Answer : 25 million years (< Kelvin's initial number)

Why? Radioactivity heats up the earth, roughly cancels the heat flow from the earth.

③ ^{14}C dating [human-history-relevant timescale]

* used for [once] living substances
* cosmic rays in upper atmosphere → n
  $^{14}N(n,p)^{14}C$, mostly in form of CO_2
* $^{14}C \rightarrow {}^{14}N + e^- + \bar{\nu}_e$, β-decay with 5370 yrs
* atmosphere : contains ~600 bn/mole of ^{14}C
* once dead, ^{14}C decays

  Shroud of Turin ~1300 A.D.
  Dead Sea scrolls ~ 0-200 A.D.

Nuclear energy

① Fission (^{235}U, ^{233}U, ^{239}Pu)

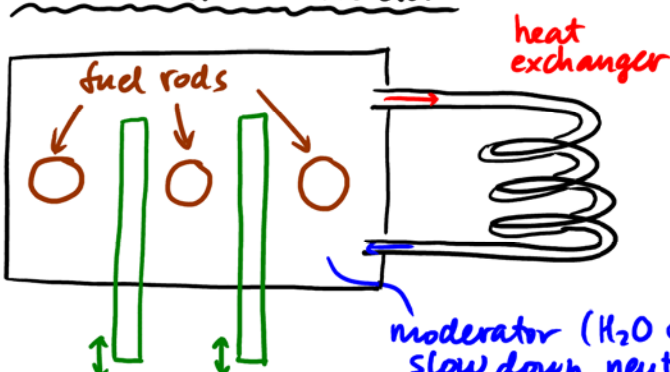
e.g. $n + {}^{235}U \rightarrow {}^{236}U^* \rightarrow \underbrace{{}^{141}Ba + {}^{92}Kr}_{A \sim 90-150} + 3n$

"Induced fission" :

cross-section for thermal n : ~500 barns

Q: How to thermalize n?
A: use elastic collision with same mass (H).
(e.g. parafin, water)

Nuclear fission reactor



moderator (H_2O or Na)
slow down neutrons

control rods (Cd)
capture neutrons : $n + {}^{113}Cd \to {}^{114}Cd + \gamma$
(stop reaction) $\sigma \sim 10^4$ barn for $KE_n < 1eV$

Fuel : typically enriched ^{235}U (from 0.7 to few %)
natural ^{238}U 99.3%

Ex. 1kg of enriched U $\sim 24 \times 10^9$ W-h
USA electric. consumption : $\sim 4 \times 10^{15}$ W-h / year
world $\sim 17 \times 10^{15}$ W-h / year
"economic" ^{235}U (\$60/lb), to last ~ 100 yr
with present consumption rate

② Fusion

* primary fusion reaction in the Sun:

$$\left.\begin{array}{l} p + p \to d + e^+ + \nu_e \\ p + d \to {}^3_2He + \gamma \\ p + {}^3_2He \to \alpha + e^+ + \nu_e \\ {}^3_2He + {}^3_2He \to \alpha + p + p \end{array}\right\} \quad 4p \to \alpha + 2e^+ + \underbrace{2\nu_e}_{\text{carries away 1\% of energy}} + 25\,MeV$$

* Controlled fission easy ; fusion not
Q: Why?
A: neutron → fission ; Coulomb repulsion (fusion)

* need $T \sim 10^7 - 10^8 K$, ⇒ plasma

dd fusion : $d + d \to {}^3_2He + n$, Q-val: 3.3 MeV
$d + d \to t + p$ escape from plasma 4 MeV

dt fusion : $d + t \to \alpha + n$ 17.6 MeV

Conditions for fusion

a) critical ignition temperature

power from fusion ≈ cooling

neutrons   x-rays

dd : 4×10^{8} K (35 keV)

dt : 4×10^{7} K (4 keV)

b) Lawson criterion

density

$n\tau > C$

cooling or confinement time

dd: $C = 10^{16} \frac{s}{cm^3}$, dt: $10^{14} \frac{s}{cm^3}$

Two approaches at the moment :

* tokamak (russian for toroidal chamber with magnetic coils)

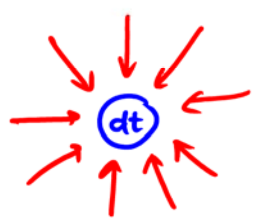
  contain plasma in magn. field,
  heat up by RF induction

  e.g. $\tau \sim 1s$, $\Rightarrow$ $n > 10^{14}\,cm^{-3}$ for dt fusion
  (5 orders of magn. less dense than gas at STP)

  ITER - international thermonuclear experimental reactor

* inertial confinement

  200 high power lasers
  (~500TW, ~2 MJ total)



compress few mg dt target
to $n \sim 10^{25}\,cm^{-3}$
(only $\tau \sim 10^{-11}s$ is needed)

NIF - national ignition facility
(Lawrence Livermore Nat'l Lab)

Elementary particles

Search for basic building blocks of matter

~100 chemical elements : periodic table explained by QM. All elements are made of 3 basic constituents : e^-, p, n

$\gtrsim$ 1960's : powerful accelerators
$e^- e^+$ colliders (lepton)
$p \bar{p}$ colliders (hadron)
} main HEP discovery tools

>400 particles discovered. Half-lives 10^{-6} to 10^{-23} s.
"particle zoo", no seeming order (cf. chemical elements before QM)

~1970 : quark. p, n are composite
QM of quarks → quantum chromodynamics

Standard Model : explains "zoo". Includes:
* strong force
* electroweak
* elementary particles : spin $\frac{1}{2}$ – quarks and leptons
  - strong
  - electroweak
  integer spin – "field" particles (gauge bosons)

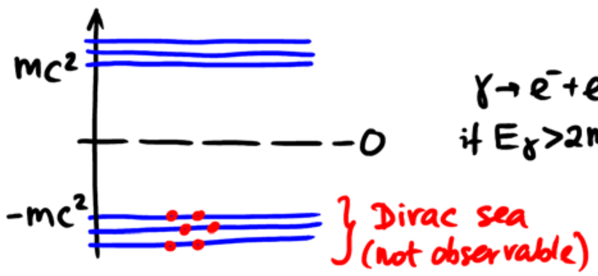
Issues with SM:
* gravity not included
* needs 25 numerical const (masses of particles, coupling const)
* astrophysics (last 3 decades):
  baryonic matter ~5%
  (non EM inter.) dark matter ~23%
  (neg. pressure) dark energy ~72%

① Antiparticles

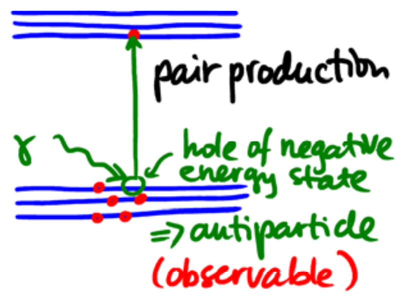
consequence of relativistic QM (Dirac eqn. for fermions)

$$E^2 = (pc)^2 + (mc^2)^2, \text{ or } E = \pm\sqrt{p^2c^2 + m^2c^4}$$

Dirac : the negative energy states completely filled in vacuum



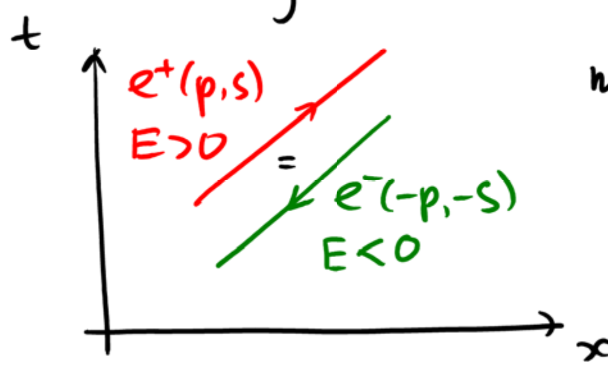
$\gamma \to e^- + e^+$
if $E_\gamma > 2mc^2$



Every fund. fermion : has an antiparticle
all intrinsic quant. numbers
are opposite
(absence of a particle
with negative energy)

Problem with Dirac sea : infinite (negative) energy of vacuum ; e^+/e^- are not treated symmetrically (holes)

A better picture: $E<0$ solns of a particle are
Stueckelberg-Feynman $E>0$ solns of its antiparticle moving backwards in time



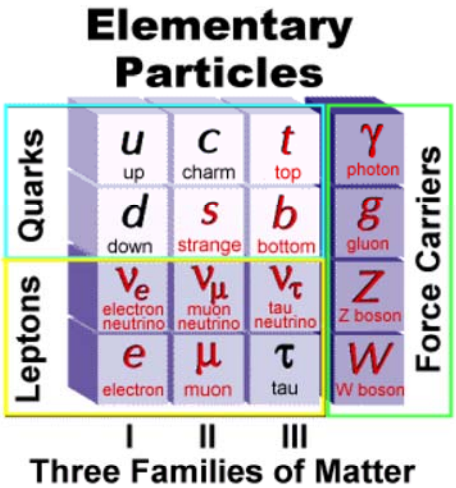
no more holes

② Crossing symmetry

if $A+B \to C+D$ reaction possible :
cross any particle and change to antiparticle

$\left.\begin{array}{l} A \to \overline{B} + C + D \\ \overline{C} + \overline{D} \to \overline{A} + \overline{B} \end{array}\right\}$ also possible

Ex. $n \to p + e^- + \overline{\nu}_e$ neutron β-decay
$n + \nu_e \to p + e^-$ inverse β-decay ($p + \overline{\nu}_e \to n + e^+$) used to detect neutrinos
$n + \overline{p} \to e^- + \overline{\nu}_e$ neutron/antiproton annihilation



③ Leptons (elementary)
spin ½ ; 6 types
3 families (generations) : electron, muon, tau

generation		mass (MeV/c^2)	charge (e)	flavor e	flavor μ	flavor τ
1	e^-	0.511	−1	1	0	0
	ν_e	$< 2\times10^{-6}$	0	1	0	0
2	μ^-	105.7	−1	0	1	0
	ν_μ	< 0.17	0	0	1	0
3	τ^-	1777	−1	0	0	1
	ν_τ	< 15.5	0	0	0	1

+ corresponding antiparticles

* leptons interact via electroweak interaction ; no color (= no strong interaction)
* lepton number conservation in all reactions (antilepton counts as −1)
* lepton flavor conservation : almost always
  explains why $e^- + \bar{\nu}_e$ in β-decay (electron flavor is 0)
  But "neutrino oscillations": only ⅓ to ½ of ν_e flux from the Sun is observed. ν_e oscillates into ν_μ and ν_τ.
* leptons decay into lighter ones :

$\tau^- \to e^- + \nu_\tau + \bar{\nu}_e$
$\tau^- \to \mu^- + \nu_\tau + \bar{\nu}_\mu$ } τ^- half-life 3.3×10^{-13} s

$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$ 2×10^{-6} s half-life

e^- is the lightest of leptons => stable

* 4th generation?? at least 100.8 GeV/c^2 (lepton) and 45 GeV/c^2 (neutrino)
Not observed (yet).

④ Quarks (elementary)

spin 1/2 ; 6 flavors ; 3 families

* quarks interact via strong and electroweak forces
* quark confinement: not found free in nature, only bound as hadrons
* fractional charge

	mass (MeV/c^2) bare	bound	charge (e)	Isospin	S	C	B	T
up (u)	1-5	310	2/3	1/2				
down (d)	3-9	310	-1/3	-1/2				
strange (s)	75-170	483	-1/3		-1			
charm (c)	1150-1350	1500	2/3			1		
bottom (b)	4000-4400	4700	-1/3				-1	
top (t)	174.3×10^3	175×10^3	2/3					1

(flavor: Isospin, S, C, B, T)

* quark number conservation in all reactions
* quark flavor conservation in strong and electromagn. but not in weak

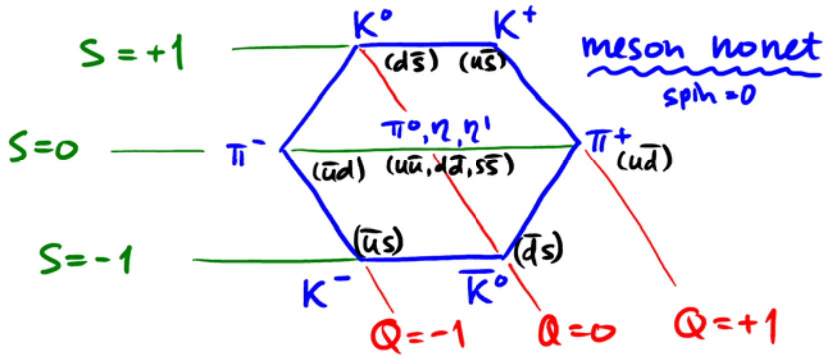
⑤ Hadrons - composite systems of quarks

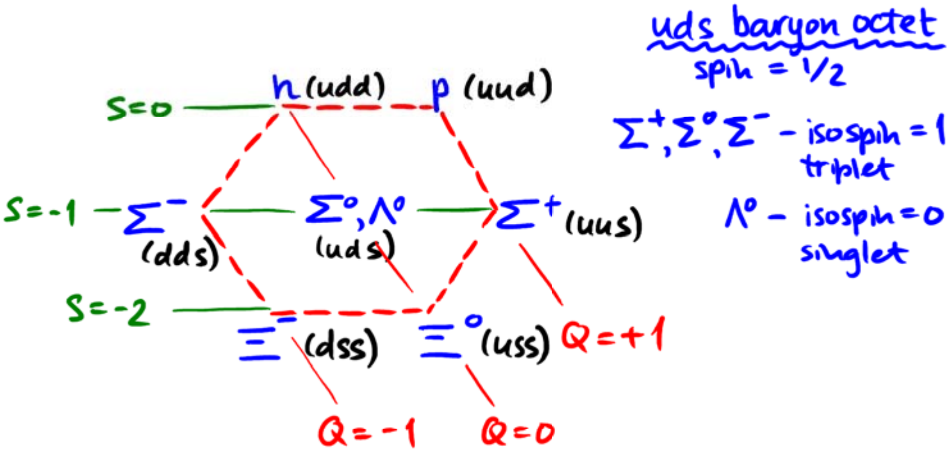
mesons - quark and antiquark, integer spin
baryon - 3 quarks, half-integer spin

measured first, before discovery of quarks (remember: quark confinement)

tetraquark - made of 4 quarks (possibly seen in Fermilab)
pentaquark — " — 5 — " — (— " — JLAB)

Ex.





Color

* Additional quant. number required to make wavefcn antisymmetric for baryon decuplet (spin = 3/2). red, green, blue
* like electric charge for strong force
* each quark must come in 3 colors
* naturally occurring baryons are colorless (RGB)
  mesons —— " —— (color-anticolor)
* leptons have no color