Particle Physics

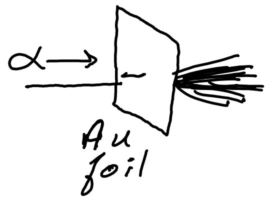
Atoms have substructure

- electrons in shells
- positively charged, massive nucleus

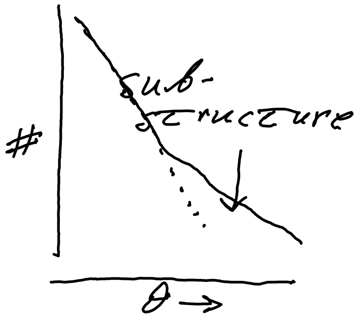
} Rutherford Experiment

Rutherford gold foil experiment *

- if charge evenly spread thru atom
  - no strong concentration of charge
  - slight deflections of α particles



- but saw some huge deflections
  - there must exist a strong repulsive force
  - cannot be due to e^-s : mass much too small
  - implies a nucleus
    - small, massive, positive charge
    - surrounded by electrons in "orbit"



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* Phil. Mag. xxi, 669 (1911).

The Nucleus:

Total charge
- integral # of charges with same magnitude as electron

→ opposite sign ⇒ **protons** } the Nucleus ("nucleons")

But additional mass observed ⇒ **neutrons**

How are like charges kept together in nucleus?

α particle (He nucleus)

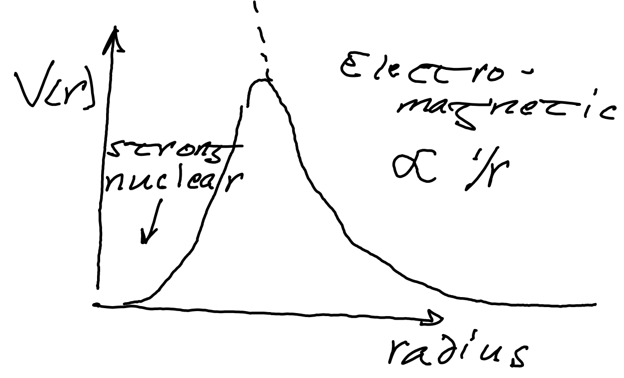
Mass?

Gravity 10^{-37} too weak

New force: "strong nuclear force"

→ affects protons + neutrons the same

→ limited range

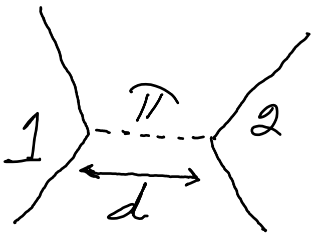


Weak nuclear force
- radioactive β decay

Ex. $\underline{\underline{n \to p e \bar{\nu}_e}}$

Yukawa Model

Particles interact via exchange of bosons
→ momentum transfer involved



Nuclear force has a range of ~2 fm

Suggests exchange of a massive "meson" (π)

Consider case where 1 is at rest
→ emission of a massive meson requires violation of energy conservation $\Rightarrow \Delta E \Delta t \approx \hbar/2$

→ assuming velocity of $\pi \sim c$
$\Delta t \sim d/c$

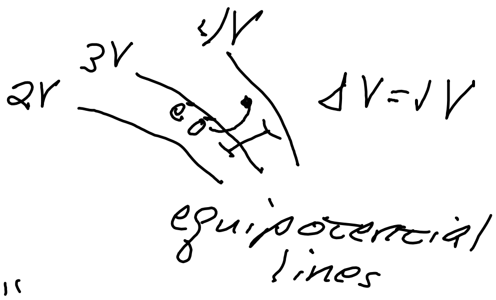
$\therefore \boxed{m_\pi = 130 \text{ MeV}}$ (1935)

→ first evidence of π in 1947!

Units

Energy

- amount of work to move e^- thru 1 Volt of potential



change in Kinetic Energy by electron

"1 electron volt"

$1\,eV = 1.6 \times 10^{-19}\,J$

Momentum: eV/c

Mass: eV/c^2

In particle physics, often take $c = \hbar = 1$

$\therefore$ mass, energy + momentum: eV

length + time: eV^{-1}

It's also useful to remember

$\hbar c = 0.2$ GeV fm ($fm = 10^{-15}\,m$) "fermi"

Cross section:

"1 barn" $= 10^{-28}\,m^2$

Energy Scales + Sizes:

atomic

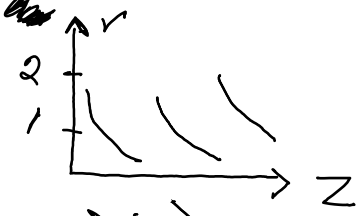
- set by electromagnetic interaction
- energy scales:

$$E_0 = -m_e c^2 \alpha^2/2 = -13.6\,\text{eV}$$

∴ in eV range

- size:

→ decreases as each shell fills (Z↑)



0.5–2 a_0 (Bohr radius)

∴ $O(10^{-10}\,\text{m}) \sim a_0$

- classical cross section

$$\sigma_{atom} \sim \pi a_0^2 \sim 3\times10^8 \text{ barns}$$

nuclear

- residual strong interaction
- energy scale:

$$\sim m_n c^2 \frac{\alpha_s^2}{2} \sim 100\,\text{MeV}$$ (many MeV)

- size:

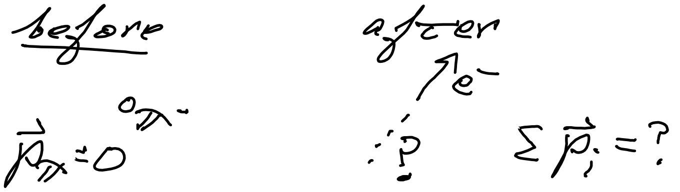
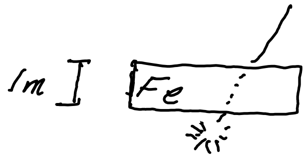
Compton wavelength of proton

$$ƛ_p = \hbar/m_p c \sim 0.2\,\text{fm}$$

Radius of close-packed array of nucleons: $a_N \sim ƛ_p A^{1/3}$ (fermi)

- classical cross section: $\sigma_N \sim \pi a_N^2 \sim 31\,\text{mb}$

Particle Milestones

	First indication
antiparticles: $e^+, \bar{p}$... every particle has one	Dirac Eq.
neutrino: (ν)  	*momentum conservation*
muon: (μ^-)  	*cosmic rays
pion (pi meson): $(\pi^\pm, \pi^0)$	strong nuclear mediator
higher mass hadrons - mesons: $(K, \rho, \eta ...)$ - baryons: $(\Lambda, \Sigma, \Xi, ...)$	*cosmic rays & accelerators
quarks: (up, down, strange, ~~bottom~~)	*patterns in observed hadrons
gluons/jets:	QCD model
W + Z bosons:	electroweak model
charm, top quarks, ν_τ	" "

Hadrons, QCD and Jets

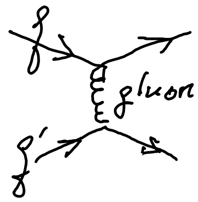
→ quarks are fundamental particles bound inside hadrons by strong interaction

mesons: $q\bar{q}'$ pairs (bosons / integer spin)

baryons: $qq'q''$ triplets: (fermions / half-integer spin)

Strong Interactions

- increasing strength with distance (compare to E+M $V(r) \propto 1/r$)



"asymptotic freedom":

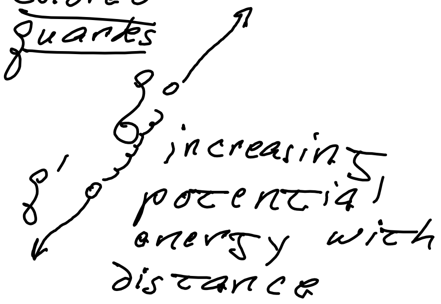
@ small distance (large energy), strength is small:

"confinement":

coupling strength large $\boxed{(\alpha_s \sim 1)}$

∴ quarks remain in hadrons

Colored quarks



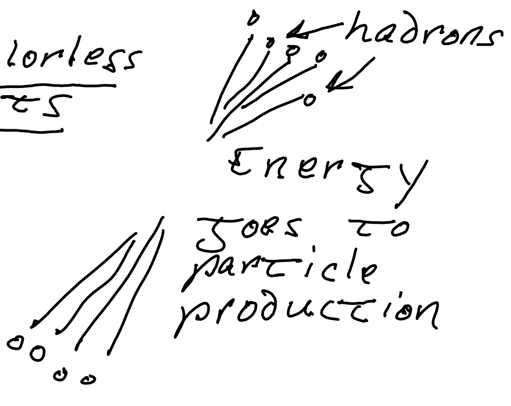
Difficulty in calculating "soft" (low energy) strong processes:

→ nuclear reactions

→ inelastic hadron processes

→ jet production

Colorless Jets



Each will come up in portions of this course.

Fundamental Interactions + Particles

Four "interactions" (forces renamed)

	Distance	Strength	Mediators
strong	10^{-14} m	~1	8 gluons
electro-magnetic	∞	10^{-2}	1 photon
weak	10^{-18} m	10^{-5}	3 bosons ($W^{\pm}$, Z^0)
gravity	∞	10^{-38}	(graviton?)

Three Generations of Particles (Fermions)
(mass in MeV)

	1st	2nd	3rd	Q	L	B
charged leptons	e^- (0.5)	μ^- (105)	τ^- (1700)	-1	$+1$	0
neutrinos	ν_e (~0)	ν_μ (~0)	ν_τ (~0)	0	$+1$	0
up-type quarks	u (~100)	c (1400)	t (173k)	$+2/3$	0	$+1/3$
down-type quarks	d (~100)	s (~350)	b (4500)	$-1/3$	0	$+1/3$

Relativistic Kinematics

Consider a relativistic particle

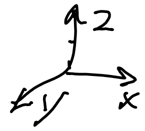
$$\xrightarrow{\vec{v},\ \vec{\beta} = \vec{v}/c}$$

momentum: $\vec{p} = mc\gamma\vec{\beta}$

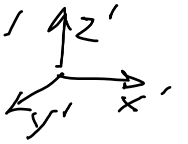
energy: $E = mc^2\gamma$ $\quad (\gamma = 1/\sqrt{1-\beta^2})$

Lorentz Transformation

frames: S



and S'



S has velocity $\vec{\beta}_0$ compared to S' frame ($-\vec{\beta}_0$ in $-z$ direction)

$p_x = p_x'$; $p_y = p_y'$

$$p_z = \gamma\left(p_z' + \beta_0 \frac{E'}{c}\right)$$

$$\frac{E}{c} = \gamma\left(\frac{E'}{c} + \beta_0 p_z'\right)$$

↳ interpret as "four-momentum"

$$\tilde{p} = (E/c, \vec{p})$$

Time Dilation

→ for particle with finite lifetime τ in rest frame $\underline{\tau_{LAB} = \gamma\tau}$

Particle Decay:

Only a few particles appear to have infinite, or nearly infinite, lifetimes:

$e^{\pm}, \nu_e, p, \gamma$

For particles with finite lifetime

Distance traveled in Lab

$$\lambda_D = c\tau = \gamma c\tau = \left(\frac{p}{mc}\right) c\tau$$

$$\propto p$$

If N_0 unstable particles at $x = \tau = 0$,

$N(x)$ = number particles at position x

$dN(x)$ = number in interval dx around x

$$dN(x) = -N(x)\,\frac{dx}{\lambda_D}$$

Integrating: $\underline{N(x) = N_0\, e^{-x/\lambda_D}}$

Some Important Decaying Particles

Long-lived particles: travel meters or more in typical lab frame

μ, $\pi^\pm$, n, K_L^0, $K^\pm$

these particles may strike a detector near where they're produced

Short-lived particles:

→ some live long enough that their distance traveled in the lab frame is detectable

K_S^0, Λ: several cm in rest frame

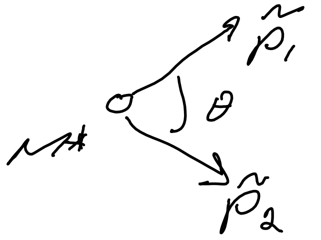
τ lepton, c, b quarks: up to several 100 μm in LAB frame

Some important decays:

	Branching Fraction
$\pi^0 \to \gamma\gamma$	98.8%
$\mu \to e\bar{\nu}_e\nu_\mu$	100%
$\pi^+ \to \mu^+\nu_\mu$	100%
$\tau \to \pi^+\pi^-\pi^+\nu_\tau$	9%
$b \to c\mu\nu_\mu$, $ce\nu_e$	17% each

Lorentz Invariant Quantities

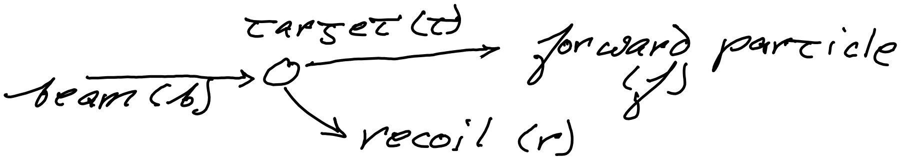
"Invariant mass" of two decay particles

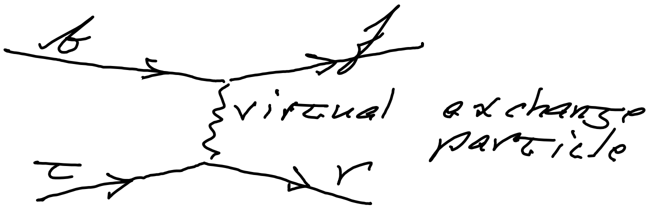


$$M = (\tilde{p}_1 + \tilde{p}_2)^2$$
$$= (\tilde{p}_1^2 + \tilde{p}_2^2 + 2\tilde{p}_1 \cdot \tilde{p}_2$$
$$= m_1^2 + m_2^2 + 2(E_1 E_2 - p_1 p_2 \cos\theta)$$

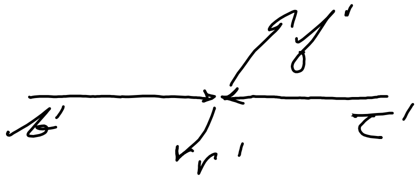
Total center-of-momentum (CM) frame energy;

In LAB:





In CM frame:



In either case (primed or unprimed), total energy involved in interaction:

$$\boxed{s = (\tilde{p}_b + \tilde{p}_t)^2 = m_b^2 + m_t^2 + 2(E_b E_t - \vec{p}_b \cdot \vec{p}_t)}$$
$$= W^2 \text{ (total energy)}$$

In symmetric collider

$$s = (\tilde{p}_b + \tilde{p}_t)^2 = (E_b + \vec{p}_b + E_t + \vec{p}_t)$$

$$= (E_b' + E_t')^2 = W^2$$

$$W = \sqrt{2}\, E_b \propto \underline{\underline{E_b}}$$

In fixed target ($\vec{p}_t = 0$)

$$s = m_b^2 + m_t^2 + 2 m_t E_b$$

At high energy ($E_b \gg m_b$ or m_t)

$$W^2 \propto E_b$$

$$W \propto \sqrt{E_b}$$

∴ colliders more efficient to turn beam energy into collision energy

→ and possibly mass, for heavy particles