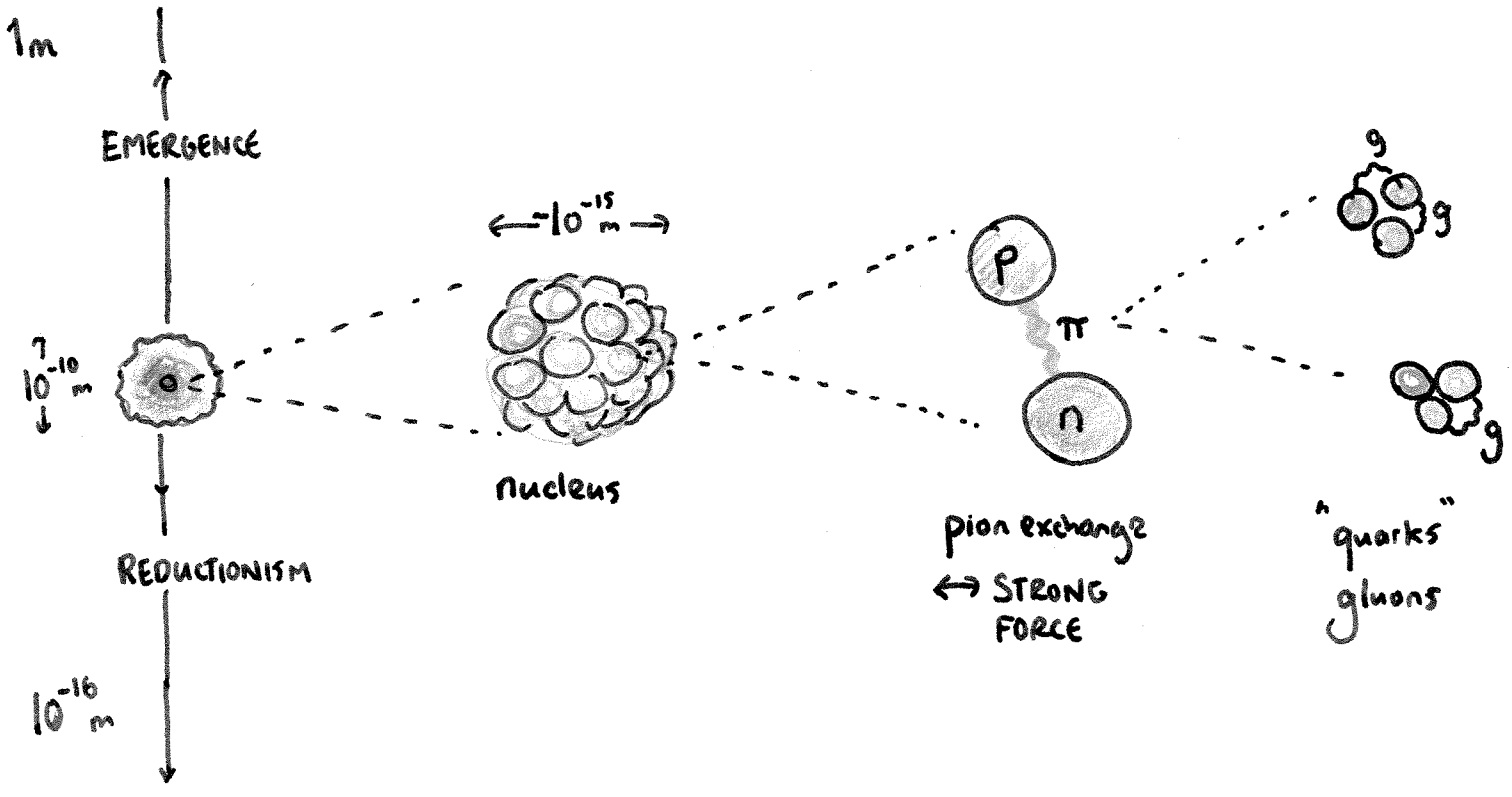
23 ELEMENTARY PARTICLE PHYSICS

There are two complimentary philosophies that underlie modern frontier science. The combination of quantum physics and electromagnetism is enough to "understand" all of chemistry & biology - however - as the great physicist Paul Dirac once said - the equations they give are much too complicated to solve! Understanding how the diversity of nature ~ from crystals, to superconductors & magnets - to biology & life itself - the understanding of <u>how</u> the microscopic laws give rise to all this richness, is the study of <u>emergence</u>. By contrast, if we seek to reduce the

universe to its most fundamental components, to its most fundamental forces – we are following a reductionist approach to science. Both approaches are needed if we are to understand the world we live in.

However, for the remaining four lectures, we will take a journey into the subatomic world – the world within the nucleus.



FORCE	RANGE	STRENGTH	MEDIATING PARTICLE
gravity	∞ $\left(\frac{1}{r^2}\right)$	10^{-38}	Graviton $S=2$
electromagnetism	∞ $\left(\frac{1}{r^2}\right)$	$1/137$	Photon $S=1$
strong	10^{-15} m	1	Gluon $S=1$
weak	10^{-18} m	10^{-9}	Vector boson $W^{\pm}$ Z^0 $S=1$

FUNDAMENTAL PARTICLES

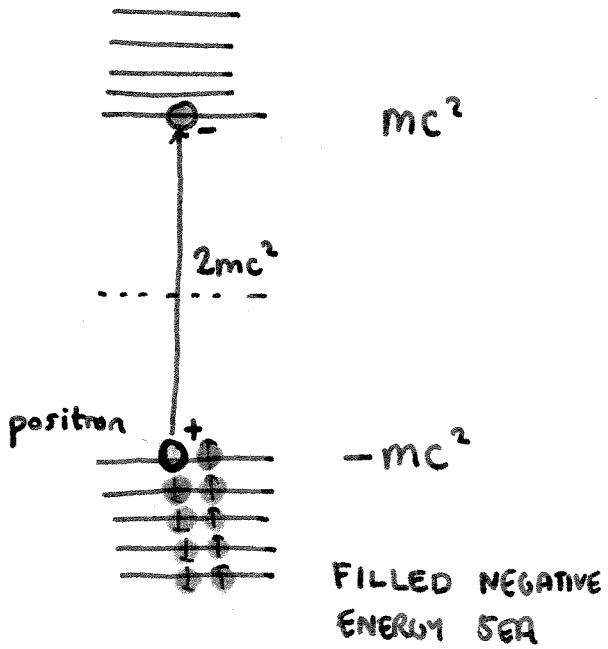
Electron / Positron: ANTIPARTICLE CONCEPT

Schrödinger – $E = p^2/2m + U(x)$

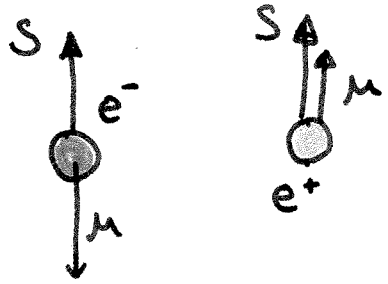
Dirac – RELATIVITY + QUANTUM 1928

$$\boxed{E^2 = p^2c^2 + m^2c^4}$$

$$E = \pm\sqrt{(mc^2)^2 + p^2c^2}$$



Positron = absence of negative energy electron



ANTI-: All conserved charges reversed

PARTICLE

	Q	B	L_e
e^+	+1	0	-1
e^-	-1	0	+1
p^+	+1	+1	0
$\bar{p}^-$	-1	-1	0
n	0	1	0
$\bar{n}$	0	-1	0

Dick Feynman:

positron = electron going backwards in time

Energy to pair-create = $E_{min} = 2m_e c^2$

$= 2 \times (9.109 \times 10^{-31})(2.998 \times 10^8)^2$

$\equiv 1.637 \times 10^{-13} J$

$\equiv 1.022$ MeV.

e.g Electron & positron both have kinetic energy $K = 2\,\text{MeV}$. Calculate energy & wavelength of photons produced when they annihilate each other

$$E = (K + m_e c^2) = 2 + 0.511 = \underline{2.511\,\text{MeV}}$$

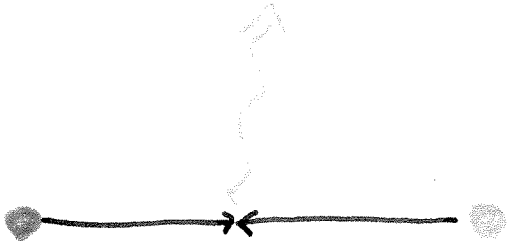
$$= 4.02 \times 10^{-13}\,\text{J}$$

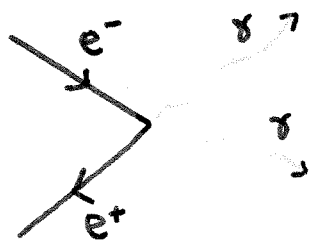
Total energy

$$2E = 2\frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E} = \frac{6.62\times10^{-34}\times3\times10^{8}}{4.02\times10^{-13}}$$

$$= \underline{5\times10^{-13}\,\text{m}}$$

$$E_{photon} = \underline{4.02\times10^{-13}\,\text{J}}$$

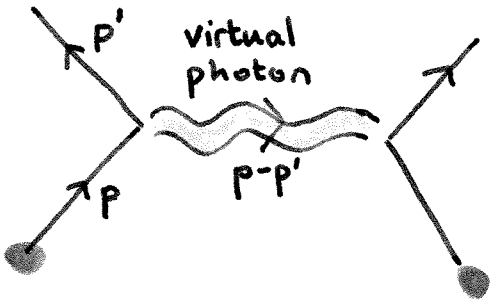




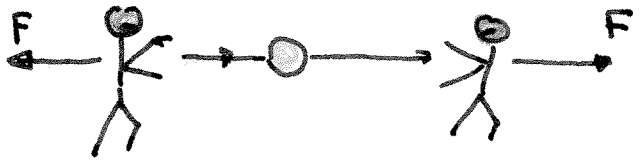
(Feynman)

PARTICLES AS FORCE MEDIATORS

QUANTUM ELECTRO DYNAMICS



NOT INSTANTANEOUS (relativity)



(Feynman, Schwinger, Tomonaga, 1948)

$$V_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}$$

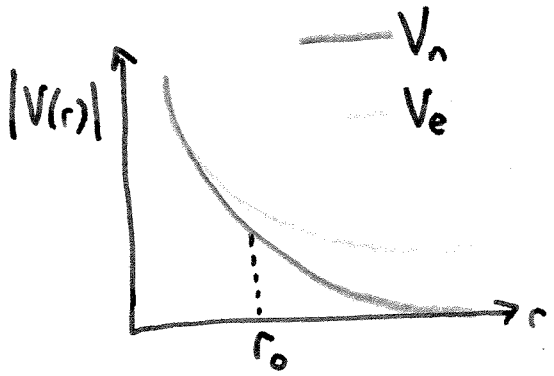
$$\Delta E \Delta t \gtrsim \hbar$$

"THE MORE YOU BORROW THE SOONER YOU HAVE TO PAY IT BACK"

The nuclear force is short-ranged, given by

$$V_n(r) = -f^2 \frac{e^{-r/r_0}}{r}$$

YUKAWA



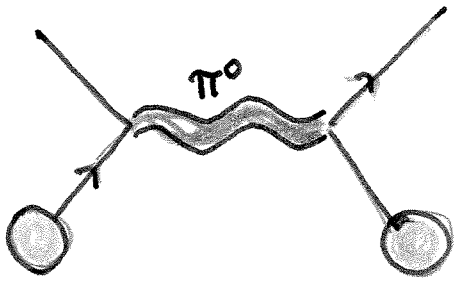
$$\Delta t = \frac{r_0}{c} = \frac{1.5\times10^{-15}\,m}{3\times10^{8}} = 5\times10^{-24}\,s$$

$$\Delta E = \frac{\hbar}{\Delta t} = \frac{1.1\times10^{-34}\,Js}{5\times10^{-24}} = 21\times10^{-11}\,J \equiv 130\,MeV \sim mc^2$$

$$m \sim 130\,MeV/c^2$$

Historically misidentified as the muon (μ^-, $m_\mu = 207\, m_e$).

1947 — pions or pi-meson. π^+, π^0, π^-



Exchange of massive pion
$\Rightarrow$ SHORT RANGE FORCE

$m_\pi \approx 270\, m_e$

$$\Delta t \sim \frac{r_0}{c}$$

$$\Delta E \sim \frac{\hbar c}{r_0} \sim mc^2$$

$$m \sim \frac{\hbar}{c r_0}$$

$$\begin{cases} r_0 = \infty & m \sim 0 & \text{(photons, gravitons)} \\ r_0 \sim 1\,\text{fm} & m \sim 100\,\text{MeV} & \text{(pions)} \\ r_0 \sim 10^{-3}\,\text{fm} & m \sim 100\,\text{GeV} & \text{(vector bosons)} \end{cases}$$

$$\left.\begin{aligned} [f^2] &= \text{J m} \\ [\hbar c] &= \text{J m} \end{aligned}\right\} \quad \frac{f^2}{\hbar c} = \text{DIMENSIONLESS COUPLING CONSTANT}$$

$\frac{f^2}{\hbar c} \sim 1$ STRONG FORCE $\qquad \frac{e^2}{4\pi\varepsilon_0 \hbar c} \approx \frac{1}{137}$ E.M.

44.3 FAMILIES OF PARTICLES

Two major subdivisions

- **Fermions** — half integer spin $\frac{1}{2}, \frac{3}{2} \ldots$ ($e^-, p, \nu_e \ldots$)
- **Bosons** — integer spin $0, 1, 2$ ($\pi, Z, W^\pm$, graviton)

- **Leptons**

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

$L_e = 1 \qquad L_\mu = 1 \qquad L_\tau = 1$

- **Baryons**
- **Mesons**

"HADRONS"

BARYONS $S = 1/2, 3/2$.

p, n	$B = 1$
$\bar{p}, \bar{n}$	$B = -1$

MESONS

π^{+-0} k^{+-0} η	$S=0$
ρ^{+-0}	$S=1$

In all interactions, Lepton numbers & Boyon number are conserved.

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$L_\mu = 1 \qquad L_e = 1 \qquad L_e = -1 \qquad L_\mu = +1$