1. Nuclear (Strong) Force holds nucleons together - protons and neutrons.
   - Short range \( \sim 10^{-15} \) m
   - Electric force larger \( > 10^{-15} \) m "Coulomb Barrier"

   Isotope nomenclature \( ^{238}U \):
   - mass number = \# nucleons
   - atomic number = \# protons

   Alpha decay ex. \( ^{238}U \rightarrow ^{234}Th + ^{4}He + \text{energy} \)

   Beta decay ex. \( ^{14}C \rightarrow ^{14}N + e^- + \bar{\nu}_e + \text{energy} \)

   Gamma decay ex. \( ^{137}Cs \rightarrow ^{137}Ba^* + e^- + \bar{\nu}_e + \text{energy} \)
   \( ^{137}Ba + \gamma (0.662 \text{ MeV}) \)

2. Radioactive decay is random process due to probability nature of quantum wave mechanics.
   - Half-life \( T_{1/2} \) = length of time for 50\% probability of decay
   - \( T_{1/2} = \) length of time for 50\% to decay

   Shorter half life \( \rightarrow \) more "radioactive"
   - More mass \( \rightarrow \) more radio emission

   ex. \( ^{14}C \quad T_{1/2} = 5,730 \text{ y} \times 6,000 \text{ y} \) (\( \beta \))
   \( ^{3}H \quad T_{1/2} = 12 \text{ y} \) (\( \beta \))
   \( ^{226}Ra \quad T_{1/2} = 1600 \text{ y} \) (\( \alpha \))
Radiation unit: 1 Curie = 1 Ci = $3.7 \times 10^{10}$ decays/sec
(1 g of $^{226}$Ra, tribute to Curies)

Four natural decay series, e.g. $^{238}$U ("Radium") Series:

$^{238}$U $\rightarrow$ $^{234}$Th $\rightarrow$ $^{230}$Th $\rightarrow$ $^{226}$Rb $\rightarrow$ $^{208}$Pb stable

Carbon dating, medical labeling, tracing, etc.

Ionizing Radiation = $\alpha$, $\beta$, $\gamma$ tendency to ionize material

$\Rightarrow$ health risk
$\Rightarrow$ detectors e.g. cloud chamber

3. Weak Interaction

- fourth and final "force"
- very short range $\sim 10^{-18}$ m
- unified with EM in 1968: "electroweak"

(1) Beta decay $n \rightarrow p + e^- + \bar{\nu}_e$, etc.

(2) Solar fusion $p + p \rightarrow D + e^+ + \nu_e$

net: $6p + 2e^- \rightarrow ^4He + 2p + 26.7$ MeV

Slow process $\Rightarrow$ Sun lasts 10 billion years

Nuclear Binding Energy

- light nuclei fuse to release energy
- heavy nuclei fission to release energy
Fission: 
\[ {}^{238}U + n \rightarrow {}^{239}U \rightarrow {}^{92}Kr + 141 \text{I} + 3n \]

0.7% of natural uranium

\[ {}^{95}Sr + {}^{139}Xe + 2n \]

Can manufacture other fissionable isotope \( {}^{239}Pu \):
\[ {}^{238}U + n \rightarrow {}^{239}U \rightarrow {}^{239}N + e^- + \gamma \]
\[ {}^{239}Pu + e^- + \gamma \rightarrow {}^{239}Pu \]

Only two isotopes

Fission naturally!

(And only \( {}^{235}U \) occurs in nature)

Critical Mass = mass of sphere that experiences chain reaction from product neutrons producing more fission before escape

\( {}^{235}U \): 25 kg
\( {}^{239}Pu \): 8 kg

\[ \Rightarrow \text{Fission bomb: slam critical mass together first} \]

\[ \Rightarrow \text{Fusion bomb: slam D-T together, then fission} {}^{238}U \text{ with fast 14 MeV fusion neutrons} \]

WWII

"Little Boy" - \( {}^{235}U \), Hiroshima (untested "gun" style)

"The Gadget" - \( {}^{239}Pu \), Trinity test (implosion style)

"Fat Boy" - \( {}^{239}Pu \), Nagasaki (based on The Gadget)

"Manhattan Project" = US nuclear weapons program at Los Alamos during war

- continued to Cold War and nuclear escalation
4. QCD + Standard Model

Most "mass" is field energy

Natural matter is composed of u,d quarks and electrons:

\[ \text{U-quark: } u, c, t \]
\[ \text{D-quark: } d, s, b \]

"Generation I"  
\[ p = uud \text{ 928.7 MeV from field energy} \]
\[ n = udd \text{ 977.6 MeV} \]

Three forces (not gravity) mediated by "gauge bosons":

EM: $\gamma$, strong: $g$, weak: $Z^0, W^\pm$

5. Feynman Diagrams = powerful graphical tool to study particle interactions

\[ e^+ e^- \text{ scattering} \]
\[ e^+ e^- \text{ annihilation} \]
\[ e^+ e^- \text{ meson production} \]
\[ \pi^+ = u\bar{d} \]
\[ \pi^- = d\bar{u} \]
\[ \pi^0 = u\bar{u} \]

new particles like pions

6. Leptons

\[ e, \mu, \tau \]
\[ \nu_e, \nu_\mu, \nu_\tau \]

Standard Model

Particles + Fields

Higgs Boson = determines masses??

Need high energy = Large Hadron Collider at CERN