Particles

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PHYS6260: Experimental Methods is HEP
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August 23, 2017
Particles

- High Energy Physics = Particle Physics
- HEP addresses fundamental questions, just to name a few:
  - what is the origin of mass?
  - what is dark matter and dark energy?
  - why there is an imbalance of matter and antimatter in the Universe?
  - hierarchy problem (why gravity is so weak)?
  - where are magnetic monopoles?
  - is the proton stable?
- The way it tries to solve these problems is by looking at fundamental particles and their interactions
  - “fundamental” = can’t be made by a combination of other particles
Particles and fields

- We can’t look at particles directly – they are “too small”
  - we study properties of particles through their interactions which are carried out by fields

- There is no real boundary between particles and fields:
  - particles are localized in space and fields exist everywhere – but this distinction is moot because of uncertainty principle
  - particles exhibit wave properties, and fields are quantized

- Most of the particles we are interested in are extremely short-lived and quickly convert to other particles
  - these conversions are also carried out by interactions
Standard Model

- A little “periodic table” that includes all known fundamental particles and carriers of all fundamental interactions
  - gravity is not included (and we have no clue about it)

- $e, \mu, \tau, \nu$ are leptons, $u, d, c, s, b, t$ are quarks
- leptons and quarks are fermions, field carriers are bosons
- $\nu, Z, \gamma$ do not have a charge, $e, \mu, \tau$ have “integer” charge, and quarks have “fractional” charge
- $\gamma, g$, and $\nu$ (in SM!) don’t have a mass
Baryons and mesons

- In addition to fundamental particles, there are many composite particles
  - “If I could remember the names of all these particles, I’d be a botanist” (E. Fermi)
- Baryons: made of three quarks

- Proton
- Δ++
- Λ
- Neutron
- Σ+
- Ξ
Baryons and mesons

- In addition to fundamental particles, there are many composite particles
  - “If I could remember the names of all these particles, I’d be a botanist” (E. Fermi)
- Mesons: made of a quark and an antiquark
  - pion
  - D-meson
  - J/ψ
  - kaon
  - B-meson
  - Υ

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Most common particles

- To explain most of matter around us, we just need electrons, protons, and neutrons.
Stable and unstable particles

- There are very few particles which have infinite (or at least very large) lifetime
  - photon – the one we can detect by naked eye
  - protons and electrons (is the proton really stable?)
  - neutrinos (but they oscillate)
  - gluons / light quarks – but they can’t be observed directly
- neutron is not stable but its time is macroscopic (15 minutes)
  - it’s for a “free” neutron, those inside the nucleus keep turning into protons and vice versa
- muons: 2.2 $\mu$s, charged pions: 26 ns ($\pi^0$ is only $8.4 \times 10^{-17}$ s)
  - doesn’t look much but think of the path it may travel:
    $c = 3 \times 10^8$ m/s, 1 ns means 30 cm
- most particles (including $W/Z$ and Higgs) decay so fast there is no way to “catch” them
How unstable is unstable?

- To address this question, need to compare particle’s lifetime to its mass
  - mass is energy: \( E = mc^2 \)
  - energy is time: \( \Delta E \Delta t \geq \hbar/2 \)
  - 1 GeV corresponds to \( 3 \times 10^{-25} \) s

- measurement of lifetime is intrinsically uncertain
  - having done it many times, we will get a bell-shaped distribution (strictly speaking, a Breit-Wigner one: \( \sim \Gamma/((E - E_0)^2 + (\Gamma/2)^2) \))

- At some point, the “particle” is no longer a particle!
Other particles

- So far we are not aware of any other particles which might be there.
- But there are many reasons to believe that more particles exist:
  - Composite particles which are not baryons/mesons (e.g. glueballs)
  - Supersymmetric particles
  - More SM generations
  - More Higgs particles
  - Monopoles, gravitons, axions, KK excitations
  - ?