PHYS 3446 – Lecture #20

Monday, Nov. 14, 2016

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- Elementary Particle Properties
  - Elementary particles
  - Quantum Numbers
  - Gell-Mann-Nishijima Relations
  - Production and Decay of Resonances
- Symmetries
  - Why do we care about the symmetry?
  - Symmetry in Lagrangian formalism
  - Symmetries in quantum mechanical system

Announcements

- Reading assignments: 10.3 and 10.4

Elementary Particles

- Before the quark concepts, all known elementary particles were grouped in four depending on the nature of their interactions

Particle	*Symbol*	*Range of Mass Values*
Photon	γ	$\lesssim 2 \times 10^{-16}$ eV$/c^2$
Leptons	$e^-, \mu^-, \tau^-, \nu_e, \nu_\mu, \nu_\tau$	$\lesssim 3$ eV$/c^2$ – 1.777 GeV$/c^2$
Mesons	$\pi^+, \pi^-, \pi^0, K^+, K^-, K^0,$ $\rho^+, \rho^-, \rho^0, \ldots$	135 MeV$/c^2$ – few GeV$/c^2$
Baryons	$p, n, \Lambda^0, \Sigma^+, \Sigma^-, \Sigma^0, \Delta^{++},$ $\Delta^0, N^{*0}, Y_1^{*+}, \Omega^-, \ldots$	938 MeV$/c^2$ – few GeV$/c^2$

Elementary Particles

- How do these particles interact??
  - All particles, including photons and neutrinos, participate in gravitational interactions
  - Photons can interact electromagnetically with any particles with electric charge
  - All charged leptons participate in both EM and weak interactions
  - Neutral leptons do not have EM couplings
  - All hadrons (Mesons and baryons) responds to the strong force and appears to participate in all the interactions

Elementary Particles: Bosons and Fermions

- All particles can be classified as bosons or fermions
  - Bosons follow Bose-Einstein statistics
    - Quantum mechanical wave function is symmetric under exchange of any pair of bosons

$$\Psi_B(x_1, x_2, x_3, \ldots x_i \ldots x_n) = \Psi_B(x_2, x_1, x_3, \ldots x_i \ldots x_n)$$

    - x_i: space-time coordinates and internal quantum numbers of particle i
  - Fermions obey Fermi-Dirac statistics
    - Quantum mechanical wave function is anti-symmetric under exchange of any pair of Fermions

$$\Psi_F(x_1, x_2, x_3, \ldots x_i \ldots x_n) = -\Psi_F(x_2, x_1, x_3, \ldots x_i \ldots x_n)$$

    - Pauli exclusion principle is built into the wave function
      - For $x_i = x_j$, $\Psi_F = -\Psi_F$

Bosons, Fermions, Particles and Antiparticles

- Bosons
  - All have integer spin angular momentum
  - All mesons are bosons
- Fermions
  - All have half integer spin angular momentum
  - All leptons and baryons are fermions
- All particles have anti-particles
  - What are anti-particles?
    - Particles that have the same masses as particles but with opposite charges and quantum numbers
  - What is the anti-particle of
    - A π^0? π^0
    - A neutron? $\bar{n}$
    - A K^0? $\bar{K}^0$
    - A Neutrinos? $\bar{\nu}$

Quantum Numbers

- When can an interaction occur?
  - If it is kinematically allowed
  - If it does not violate any recognized conservation laws
    - Eg. A reaction that violates charge conservation will not occur
  - In order to deduce conservation laws, a full theoretical understanding of forces are necessary
- Since we do not have a full theory for all the forces
  - Many of general conservation rules for particles are based on experimental observations
- One of the clearest conservation rule is the lepton number conservation
  - While photon and meson numbers are not conserved

Baryon Numbers

- Can the decay $p \rightarrow e^{+} + \pi^{0}$ occur?
  - Kinematically??
    - Yes, proton mass is a lot larger than the sum of the two final state masses
  - Electrical charge?
    - Yes, it is conserved
- But this decay does not occur ($<10^{-40}$/sec)
  - Why?
    - Must be a conservation law that prohibits this decay
  - What could it be?
    - An additive and conserved quantum number, the Baryon number (B)
    - All baryons (particles with 3 more quark compositions) have B=1
    - Anti-baryons? (B=-1)
    - Photons, leptons and mesons have B=0
- Since proton is the lightest baryon, it does not decay.

Lepton Numbers

- Quantum number of leptons
  - All leptons carry $\mathcal{L}$=1 (particles) or $\mathcal{L}$=-1 (antiparticles)
  - Photons or hadrons carry $\mathcal{L}$=0
- Lepton number is a conserved quantity
  - Total lepton number must be conserved
  - Lepton numbers by species must also be conserved
  - This is an empirical law necessitated by experimental observations (or lack thereof)
- Consider the decay $e^- + e^- \rightarrow \pi^- + \pi^-$
  - Does this decay process conserve energy and charge?
    - Yes
  - But it hasn't been observed, why?
    - Due to the lepton number conservation law

Lepton Number Assignments

Leptons (anti-leptons)	$\mathcal{L}_e$	$\mathcal{L}_\mu$	$\mathcal{L}_\tau$	$\mathcal{L}=\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_t$
e^- (e^+)	1 (-1)	0	0	1 (-1)
ν_e $(\bar{\nu}_e)$	1 (-1)	0	0	1 (-1)
μ^- (μ^+)	0	1 (-1)	0	1 (-1)
ν_μ $(\bar{\nu}_\mu)$	0	1 (-1)	0	1 (-1)
τ^- (τ^+)	0	0	1 (-1)	1 (-1)
ν_τ $(\bar{\nu}_\tau)$	0	0	1 (-1)	1 (-1)

Lepton Number Conservation

- Can the following decays occur?

Decays	$\mu^- \rightarrow e^- + \gamma$	$\mu^- \rightarrow e^- + e^+ + e^-$	$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
$\mathcal{L}_e$	$0 \rightarrow 1+0$	$0 \rightarrow 1-1+1$	$0 \rightarrow 1-1+0$
$\mathcal{L}_\mu$	$1 \rightarrow 0+0$	$1 \rightarrow 0+0+0$	$1 \rightarrow 0+0+1$
$\mathcal{L}_\tau$	$0 \rightarrow 0+0$	$0 \rightarrow 0+0+0$	$0 \rightarrow 0+0+0$
$\mathcal{L}=\mathcal{L}_e+\mathcal{L}_\mu+\mathcal{L}_\tau$	$1 \rightarrow 1+0$	$1 \rightarrow 1-1+1$	$1 \rightarrow 1-1+1$

  - Case 1: $\mathcal{L}$ is conserved but $\mathcal{L}_e$ and $\mathcal{L}_\mu$ not conserved
  - Case 2: $\mathcal{L}$ is conserved but $\mathcal{L}_e$ and $\mathcal{L}_\mu$ not conserved
  - Case 3: $\mathcal{L}$ is conserved, and $\mathcal{L}_e$ and $\mathcal{L}_\mu$ are also conserved

Quantum Numbers

- Baryon Number (B)
  - The additive and conserved quantum number assigned to baryons
  - All baryons have B=1
  - Anti-baryons have B= -1
  - Photons, leptons and mesons have B=0
- Lepton Number
  - The quantum number assigned to leptons
  - All leptons carry $\mathcal{L}$=1 (particles) or $\mathcal{L}$=-1 (antiparticles)
  - Photons or hadrons carry $\mathcal{L}$=0
  - Total lepton number must be conserved
  - Lepton numbers by species must be conserved

Strangeness

- From cosmic ray shower observations
  - K-mesons and Σ & Λ^0 baryons are produced strongly w/ large x-sec's
    - But their lifetimes are typical of weak interactions (~10^{-10} sec)
    - They are produced in pairs – a K with a Σ or a K with a Λ^0
  - Gave an indication of a new quantum number
- Consider the reaction $\pi^- + p \rightarrow K^0 + \Lambda^0$
  - K^0 and Λ^0 subsequently decay
  - $\Lambda^0 \rightarrow \pi^- + p$ and $K^0 \rightarrow \pi^+ + \pi^-$
- Observations on Λ^0
  - Always produced with a K^0 never with just a π^0
  - Produced with a K^+ but not with a K^-

$$\pi^- + p \rightarrow K^+ + \pi^- + \Lambda^0$$

$$\pi^- + p \not\rightarrow K^- + \pi^+ + \Lambda^0 \qquad \pi^- + p \not\rightarrow \pi^- + \pi^+ + \Lambda^0$$