PHY492: Nuclear & Particle Physics

Lecture 12

Elementary Particle Physics

Reference for elementary particle physics

http://pdg.lbl.gov

Particle Data Group

Lawrence Berkeley Laboratory

Hadron masses and binding energy

- ^{3}He Nucleus (ppn)
  - proton, mass = 938.27 MeV/c^2
  - neutron mass = 939.57 MeV/c^2

$$(2m_p + m_n)c^2 = 2816.11 \text{ MeV}$$
$$(m_{^3\text{He}})c^2 = 2808.39 \text{ MeV}$$
$$BE = (m_{^3\text{He}} - 2m_p - m_n)c^2 = -7.72 \text{ MeV}$$

BE is negative. Energy is radiated to form the nucleus. i.e., energy is needed to break it up

- Proton (uud)
  - *u*, up, mass ~ 3 MeV/c^2
  - *d*, down, mass ~ 7 MeV/c^2

$$(2m_u + m_d)c^2 \approx 13 \text{ MeV}$$
$$m_p c^2 = 938.27 \text{ MeV}$$
$$BE = (m_p - 2m_u - m_d)c^2 = +\ 925 \text{ MeV}$$

BE is POSITIVE ? Is this "binding"? Proton should blow apart!

Quantum Chromo-Dynamics (QCD) resolves the paradox

QCD allows quarks to remain low mass (asymptotic freedom) when inside a hadron. However, the color force increases the quark mass greatly ($m_{quark} >> m_{hadron}$) if separated >1 fm from others. Quarks are confined within hadrons, there are NO free quarks.

Baryon quantum number

- Baryon number (**B**)

  $\mathrm{B} = +1$ for three quarks (qqq) in a color singlet (r, g, b)

  $\mathrm{B} = -1$ for three anti-quarks $(\bar{q}\,\bar{q}\,\bar{q})$ in a color singlet $(\bar{r}, \bar{g}, \bar{b})$

  $\mathrm{B} = 0$ for meson $(q, \bar{q})$ color singlet states

  Note: five quark $(qqqq\bar{q})$ baryon states not (yet) excluded .

- Baryon number conservation
  - Experiment finds *B* conserved in all interactions
  - Baryon number violation required to generate matter asymmetry
  - Unseen transformation lepton <--> quark violates *B* conservation
  - Proton decay violates *B* but may conserve *B* - *L* (e.g., $p \to e^+ \pi^0$)

Examples

Decay:	$p \not\to \pi^+\pi^0$	$\mathrm{B} = +1 \not\to$	$\mathrm{B} = 0$
Collision:	$pp \to ppp\bar{p}$	$\mathrm{B} = +2 \to$	$\mathrm{B} = +3 - 1 = +2$

Lepton quantum number

- Lepton number (L_x, x = e, μ, τ and $L = L_e + L_\mu + L_\tau$)

	Lepton quantum numbers		
Leptons	L_e	L_μ	L_τ
(e^-, e^+)	(+1, -1)	0	0
$(\nu_e, \bar{\nu}_e)$	(+1, -1)	0	0
(μ^-, μ^+)	0	(+1, -1)	0
$(\nu_\mu, \bar{\nu}_\mu)$	0	(+1, -1)	0
(τ^-, τ^+)	0	0	(+1, -1)
$(\nu_\tau, \bar{\nu}_\tau)$	0	0	(+1, -1)

- All experimental evidence points to lepton number conservation

Examples

Decay: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \quad (L_\mu = -1, L_e = 0) \rightarrow (L_\mu = -1, L_e = -1 + 1 = 0)$

Collision: $\bar{\nu}_\tau p \rightarrow \tau^+ n \quad (L_\tau = -1) \rightarrow (L_\tau = -1)$

Quark flavor quantum numbers

- Quark flavor quantum number (+1 or –1 for each quark)
  Sign is the same as the quark electric charge

	Quark flavor operators			
Quarks	Strange (S)	Charm (C)	Bottom (B_q)	Top (T)
$(u, \bar{u})$	0	0	0	0
$(d, \bar{d})$	0	0	0	0
$(s, \bar{s})$	(–1, +1)	0	0	0
$(c, \bar{c})$	0	(+1, –1)	0	0
$(b, \bar{b})$	0	0	(–1, +1)	0
$(t, \bar{t})$	0	0	0	(+1, –1)

Examples:

particle	flavor quantum numbers
$\Omega^-(sss)$	$S\left\|\Omega^-\right\rangle = -3; \quad C, B_q, T = 0$
$K^+(\bar{s}u)$	$S\left\|K^+\right\rangle = +1; \quad C, B_q, T = 0$
$\Xi_b^-(sdb)$	$S\left\|\Xi_b^-\right\rangle = -1; \quad B_q\left\|\Xi_b^-\right\rangle = -1; \quad C, T = 0$

Strong interactions (i.e., color interactions) conserve quark flavor

Isotopic spin (Isospin)

Charge states for each hadron: Isospin = I, 2I+1 states of I_z (I_3)

- Baryons (3 quarks, color singlet)
  - Nucleons; spin J = 1/2
    Isospin I= 1/2

    $$\mathrm{p}\ (\mathrm{uud}) \quad I_3 = +\tfrac{1}{2}$$
    $$\mathrm{n}\ (\mathrm{udd}) \quad I_3 = -\tfrac{1}{2}$$

  - Delta resonance:spin J = 3/2 (3 spins up)
    Isospin I= 3/2 (4 states)

    $$\Delta^{++}(\mathrm{uuu}) \quad I_3 = +\tfrac{3}{2}; \quad \Delta^{+}\ (\mathrm{uud}) \quad I_3 = +\tfrac{1}{2}$$
    $$\Delta^{0}\ (\mathrm{udd}) \quad I_3 = -\tfrac{1}{2}; \quad \Delta^{-}\ (\mathrm{ddd}) \quad I_3 = -\tfrac{3}{2}$$

- Mesons (quark/anti-quark pair, color singlet)

Pi meson, J = 0
Isospin I = 1

$$\pi^{+}\ (\mathrm{u\bar{d}}) \quad I_3 = +1$$
$$\pi^{0}\ \left(\tfrac{\mathrm{u\bar{u}-d\bar{d}}}{\sqrt{2}}\right) \quad I_3 = 0$$
$$\pi^{-}\ (\mathrm{\bar{u}d}) \quad I_3 = -1$$

K meson, J = 0
Isospin I = 1/2

$$K^{+}\ (\mathrm{\bar{s}u}) \quad I_3 = +\tfrac{1}{2}$$
$$K^{0}\ (\mathrm{\bar{s}d}) \quad I_3 = -\tfrac{1}{2}$$

Rho meson, J = 1
Isospin I = 1

$$\rho^{+}\ (\mathrm{u\bar{d}}) \quad I_3 = +1$$
$$\rho^{0}\ \left(\tfrac{\mathrm{u\bar{u}-d\bar{d}}}{\sqrt{2}}\right) \quad I_3 = 0$$
$$\rho^{-}\ (\mathrm{\bar{u}d}) \quad I_3 = -1$$

K* meson, J = 0
Isospin I = 1/2

$$K^{*-}\ (\mathrm{s\bar{u}}) \quad I_3 = +\tfrac{1}{2}$$
$$K^{*0}\ (\mathrm{s\bar{d}}) \quad I_3 = -\tfrac{1}{2}$$

- Isospin relates charge Q and hypercharge $Y{=}B{+}S{+}C{+}B_q$: $\boxed{Q = I_3 + Y/2}$
- Isospin conserved in strong interactions/decays

Producing the first hadronic "Resonance"

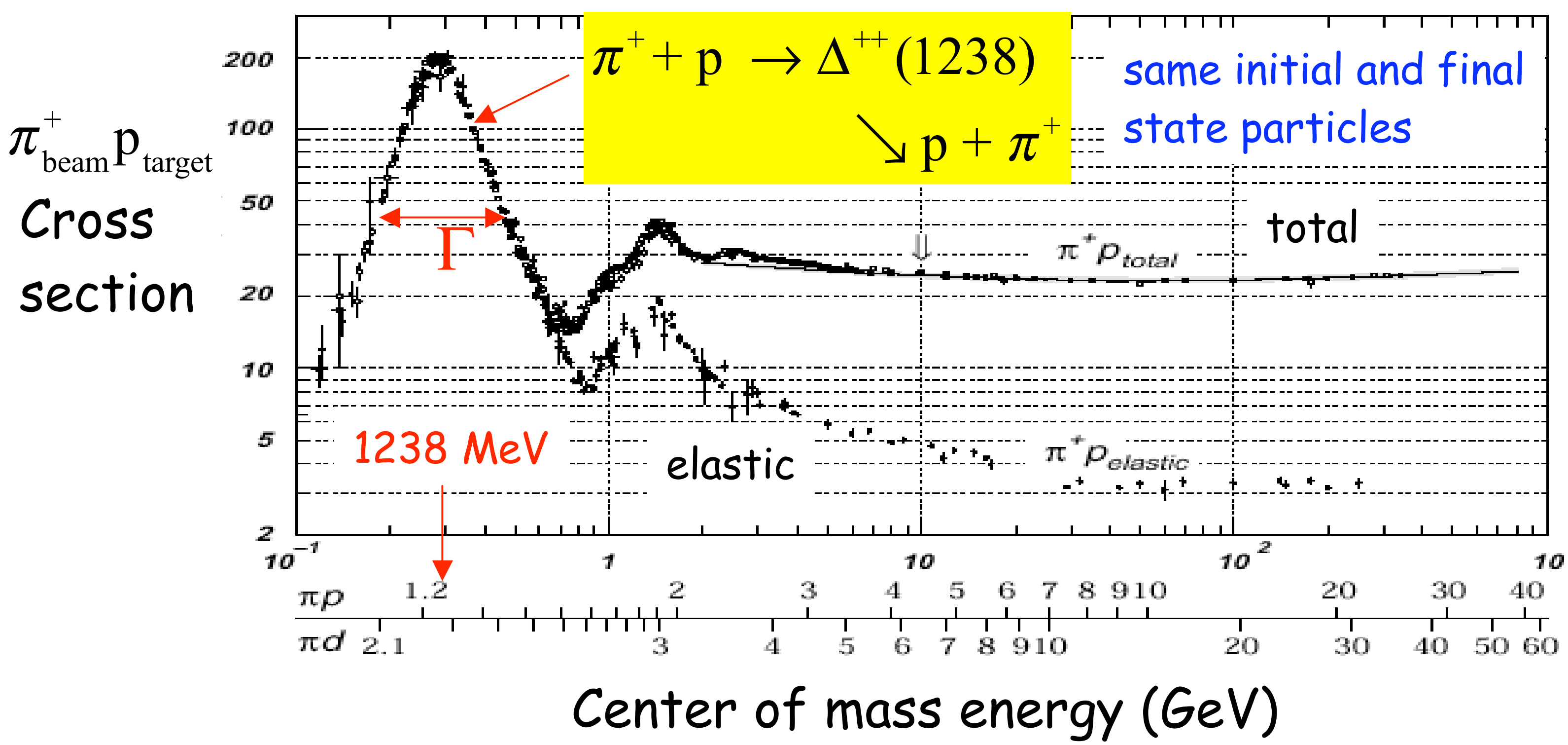
Short lived hadron: Δ^{++}

Produced in $\pi^+ p$ collisions at c.m. energy in range (width Γ) of the particle mass.

$$\left(m_\Delta c^2 - \Gamma/2\right) \lesssim E_{cm} \lesssim \left(m_\Delta c^2 + \Gamma/2\right)$$

Cross section near a resonance mass, m_0, width, Γ .

$$\sigma\left(Mc^2\right) \sim \frac{1}{(M-M_0)^2 c^4 + \Gamma^2/4}$$



Decay of the first hadronic resonance

- Hadronic resonances (lives ~10^{-23} sec)
  - Unstable particles do not have a unique mass:

$$\left(m_0c^2 - \Gamma/2\right) \lesssim M_{res}c^2 \lesssim \left(m_0c^2 + \Gamma/2\right)$$

  - Heisenberg U. P. with $\Delta t = 10^{-23}$s, mass width, Γ = 70MeV

$$\Delta E \leq \frac{\hbar c}{c\Delta t} \approx 70 \text{ MeV}$$

  - Strong decay of hadrons
    - colorless & flavorless quark + anti-quark pair from the vacuum
    - mass(parent) > mass(decay particles)
  - Strong decay prevented if decay particles have a higher total mass. Only weak decays (flavor change)

$$\Lambda^0 \to \mathrm{p} + \pi^-$$

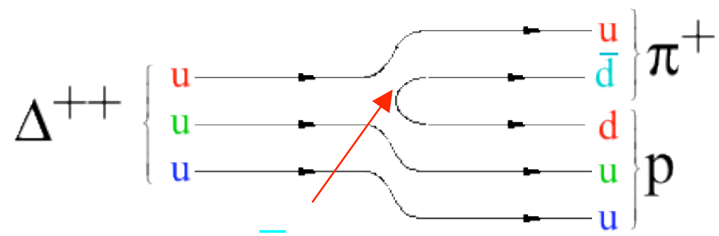
lives ~10^{-10} sec

$$\Delta^{++} \to \mathrm{p} + \pi^+$$

energy OK

$$1238 \text{ MeV} > \left(938 + 140\right)\text{MeV}$$

quarks OK



(d, $\bar{\mathrm{d}}$) pair created from energy

Lambda cannot strong decay

$$\Lambda^0 \to \mathrm{p} + \mathrm{K}^-$$

quarks OK $\left(uds\right) \to \left(udu\right) + \left(\bar{u}s\right)$

Lambda mass too small !

$$1120 \text{ MeV} < \left(938 + 495\right) \text{ MeV}$$