[qqq, $q\bar{q}$]

Hadrons: strongly-interacting particles

[so far, only p and n ⇒ comprise all nuclei]
⇒ other hadrons unstable

[shortly after WW II, new hadrons called pions were discovered in cosmic rays]

Cosmic rays: mostly protons + other nuclei from sun and space

[75% H, 25% He in space]

π production

$pp \to pn\pi^+$ $m(\pi^+) = 135$ MeV   [1947: Powell (U. Bristol) Bolivian Andes]

$pp \to pp\pi^0$ $m(\pi^0) = 140$ MeV   [1950]

$pn \to pp\pi^-$ $m(\pi^-) = m(\pi^+)$

Inelastic collisions (KE → rest energy) [HW: calc threshold]

π's nearly degenerate ⇒ isospin triplet: $I = 1$, $I_3 = \begin{cases} 1 & \pi^+ \\ 0 & \pi^0 \\ -1 & \pi^- \end{cases}$

π has $A = 0$ ⇒ "mesons" [not baryons]

[cons of ang. mom ⇒] integer spin ⇒ bosons

expt ⇒ $J = 0$ ⇒ scalar mesons

[Soon after π discovery in cosmic rays, they were created in the Berkeley cyclotron [Lattes, Gardner, 1948]

[HW: compute min K of incident proton]

[Cosmic rays: low event rate, inconvenient]

particle accelerators: van de Graaff [MeV]

E. O. Lawrence — cyclotrons

In a magnetic field, a charged particle moves in a circle w/ angular frequency

$$\omega = \frac{q v B}{p}$$

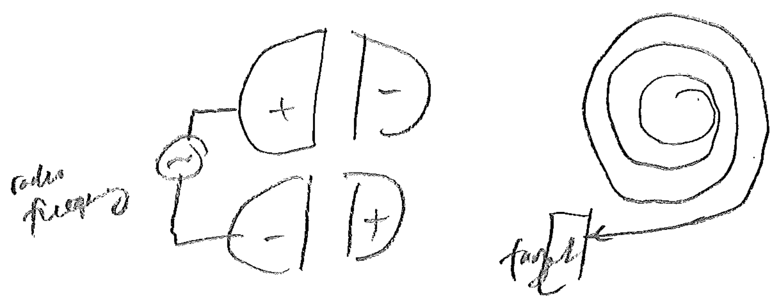
If particle is nonrelativistic: $p = mv \Rightarrow \omega = \frac{qB}{m}$ indep of velocity

(cyclotron frequency)

$B = 1\,T$

$\Rightarrow \omega = \frac{eB}{m_p} = \frac{1.6E-19}{1.6E-27} = 10^8 \frac{rad}{sec} = 15\,MHz$

[fig]



linear collider (SLAC) e^+e^- [2 miles]

Circular colliders (Fermilab, CERN)

SPS $p\bar{p}$

LHC pp

synchrotron radiation

[beamstrahlung]

→ assign problem abt fixed tgt vs colliding beam

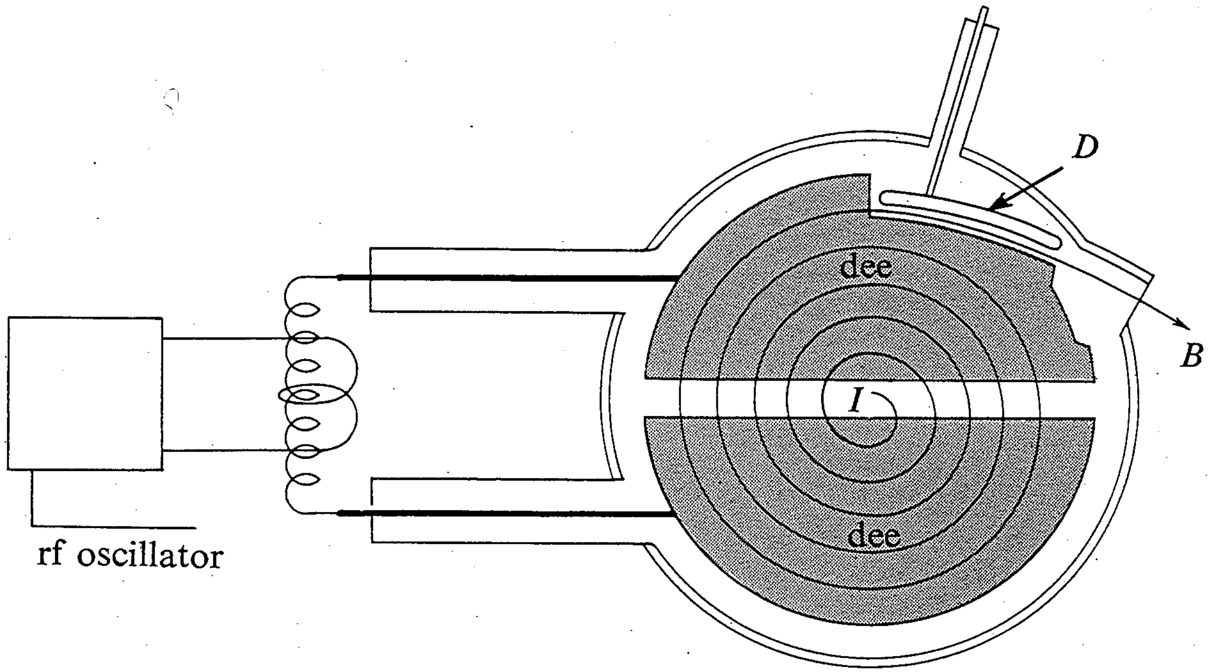


Figure 4-7 Essential parts of a cyclotron (not including the magnet), showing dees (hollow semicircular accelerating electrodes), dee stem insulators, resonant circuit with an rf power source, and deflector plate D. The path of the ions from the source at the center I to the point of emergence at B is shown schematically.

[Since we can produce a beam of protons in cyclotron and aim it at a target, can measure the scattering rate ∴ the cross-section]

$10\,mb = (1\,fm)^2$

10–100mb ~ typical strong interaction cross-section

$\rightarrow \sigma_{pp}$ [show graph Segre 415]

elastic: $pp \rightarrow pp$

$\bar{p} \rightarrow \bar{p}$

inelastic: $pp \rightarrow \begin{cases} pp\pi^0 \\ pn\pi^+ \\ d\pi^+ \\ \vdots \end{cases}$ d = deuteron

Also $pn \rightarrow \begin{cases} pp\pi^- \\ pn\pi^0 \\ d\pi^0 \end{cases}$

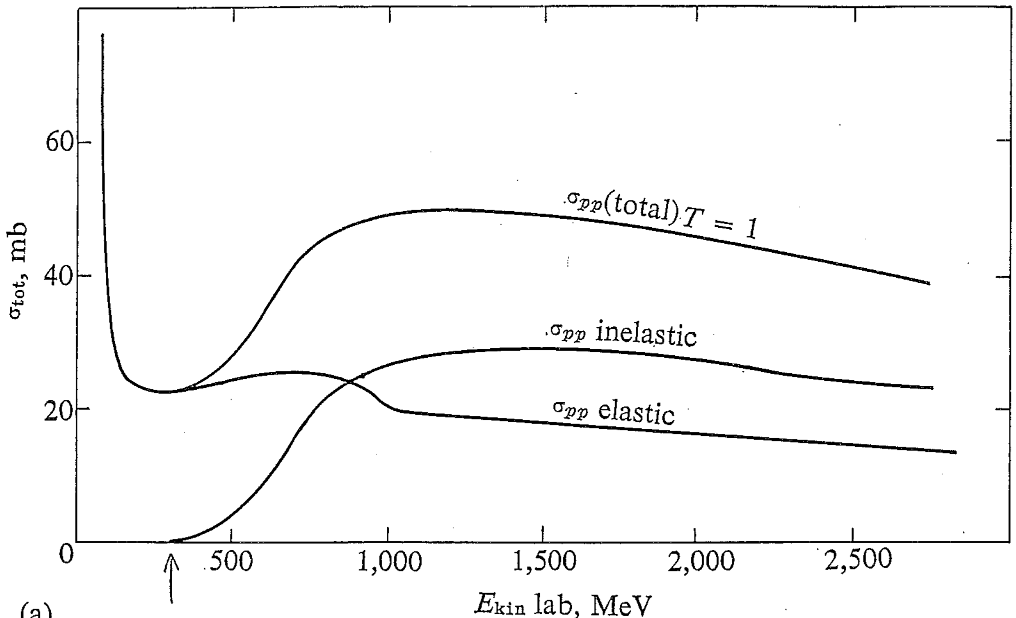
Experiment $\Rightarrow \dfrac{\sigma(pn \rightarrow d\pi^0)}{\sigma(pp \rightarrow d\pi^+)} = \dfrac{1}{2}$ [1957]

Can explain using Iso spin

$\sigma \sim |\text{amplitude}|^2 (\text{phase space factor})$

$\downarrow$

$\mathcal{M} \sim \langle \text{final} | \text{init} \rangle$



(a)

~ 280 MeV threshold

Segre, p. 415

recall $\begin{cases} p, n \text{ have } I = \frac{1}{2} \\ \pi \text{ has } I = 1 \\ d \text{ has } I = 0 \end{cases}$

Isospin is <u>conserved</u> in strong interactions.

$pp \to d\pi^+$ Initial isospin state $= |\tfrac{1}{2}, \tfrac{1}{2}\rangle |\tfrac{1}{2}\, \tfrac{1}{2}\rangle$
$= |1, 1\rangle$

Final isospin state $= |0, 0\rangle |1, 1\rangle = |1, 1\rangle$

$pn \to d\pi^0$ Initial isospin state $|\tfrac{1}{2}, \tfrac{1}{2}\rangle |\tfrac{1}{2}, -\tfrac{1}{2}\rangle$
$= \frac{1}{\sqrt{2}} [|1, 0\rangle + |0, 0\rangle]$

Final isospin state $= |0, 0\rangle |1, 0\rangle$
$= |1, 0\rangle$

$$\mathcal{M}_{pn \to d\pi^0} \sim \langle 1, 0 | \left[\frac{1}{\sqrt{2}} |1, 0\rangle + |0, 0\rangle\right] = \frac{1}{\sqrt{2}}$$

$$\mathcal{M}_{pp \to d\pi^+} \sim \langle 1, 1 | 1, 1\rangle = 1$$

$$\frac{\mathcal{M}_{pn \to d\pi^0}}{\mathcal{M}_{pp \to d\pi^+}} = \frac{1}{\sqrt{2}}$$

$$\frac{\sigma_{pn \to d\pi^0}}{\sigma_{pp \to d\pi^+}} = \frac{1}{2} \quad \checkmark$$

Although π's are produced by <u>strong</u> interaction,

∃ no lighter hadrons to decay into
So they are "long-lived"

<u>π^0 decay</u>

$\tau = 8.4 \times 10^{-17}$ s [long compared to 10^{-23} s]

$\pi^0 \to \gamma\gamma$ (EM) [nearly 100%]

[$e^+e^-\gamma$ 1.2%
e^+e^- 6.2×10^{-8}]

<u>$\pi^\pm$ decay</u>

$\tau = 2.6 \times 10^{-8}$ s, $c\tau = 7.8$ m

$\pi^- \to \mu^-$ + (1 neutral particle) ⇒ [See photo]

[weak decay because leptons don't feel strong force]

[because μ^- always has same energy] [range: Segre p. 621]

[not γ because no e^+e^- pairs: Segre p. 621] → Hughes p 59, 60

[lepton # suggests $\bar{\nu}_\mu$]

$\pi^- \to \mu^- \bar{\nu}_\mu$ (~100%)

Why not $\pi^- \to e^- \bar{\nu}_e$? [has more phase space]

[perhaps after discussion of Parity]

[ν left handed $\vec{s}\downarrow\vec{p}$
$\bar{\nu}$ right handed $\uparrow\uparrow\vec{s}$]

[$\pi^- \to \pi^0 e^- \bar{\nu}_e$: 10^{-8}, Segre 621]

[At higher energies]

$pp \to pp\,\rho^0$

$\quad \to pn\,\rho^+$

isotriplet ρ^+, ρ^0, ρ^- w/ $J = 1$ (vector meson)

$\rho \to \pi\pi$ (strong) (~100%)

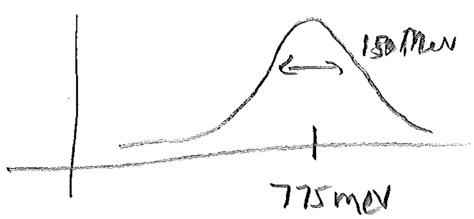
$\rho^+ \to \pi^+\pi^0$ (final state has orbital angular momentum)

$\rho^0 \to \pi^+\pi^-$

$\rho^0 \not\to \pi^0\pi^0$ (cf Clebsch Gordan table)

Track of ρ too short to be measured

Reconstruct mass of ρ from energies of π's



$E_1 + E_2$ (in ρ cm frame)

$m_\rho c^2 = 775$ MeV

$\Gamma = 150$ MeV $\Rightarrow \rho$ "a resonance"

$\tau = \frac{\hbar}{\Gamma} = 5 \times 10^{-24}$ sec (typical strong interaction decay 10^{-23} s)

$c\tau \sim 10^{-15}$ m (width of proton)

Isosinglet mesons $(I = 0,\ A = 0)$

[For my info]

	mc^2	J	Q	τ	decay
η	550 MeV	0	0	5E-19 s	$\gamma\gamma$ (39%) $\pi^0\pi^0\pi^0$ (30%) $\pi^0\pi^+\pi^-$ (22%) ($\pi\pi$ violates P, CP)
η'	960	0	0	3E-21 s	$\pi^+\pi^-\eta$ (44%) $\pi^0\pi^0\eta$ (21%) ($\pi\pi$ violates P, CP)
ω	780	1	0	E-22 s	$\pi^+\pi^-\pi^0$ ($\pi^0\pi^0\pi^0$ violates C) $\pi^+\pi^-$ small
ϕ	1020	1	0	E-22 s	KK

So far, avg electric charge of meson multiplets is zero.

I_3			
1	π^+	ρ^+	
0	π^0	ρ^0	$\eta\ \eta'\ \omega\ \phi$
-1	π^-	ρ^-	

$\Rightarrow \quad Q = I_3$

[not true for p, n!]

[Now that we're producing mesons of masses ~1 GeV, can begin to produce anti baryons]

$$pp \to pp\,p\bar{p} \qquad \text{[1955, Bevatron]}$$

$$\to pp\,n\bar{n} \qquad \text{[1956]}$$

requires $K_{min} \sim 5.6$ GeV

$$\left[\, K_{min} = \frac{m_1 + m_2 + m_{final}}{2m_2}\,|Q| = 3\cdot(2m_pc^2) \,\right]$$

[Now that can create π at well, collimate them into a beam]

$$\pi^\pm \bullet\!\longrightarrow \qquad p$$

measure $\sigma_{p\pi^+}$ and $\sigma_{p\pi^-}$ $\Rightarrow$

[$\pi^- p \to \pi^0 n \to \gamma\gamma n$: use to determine m_{π^0} (Segrè)]

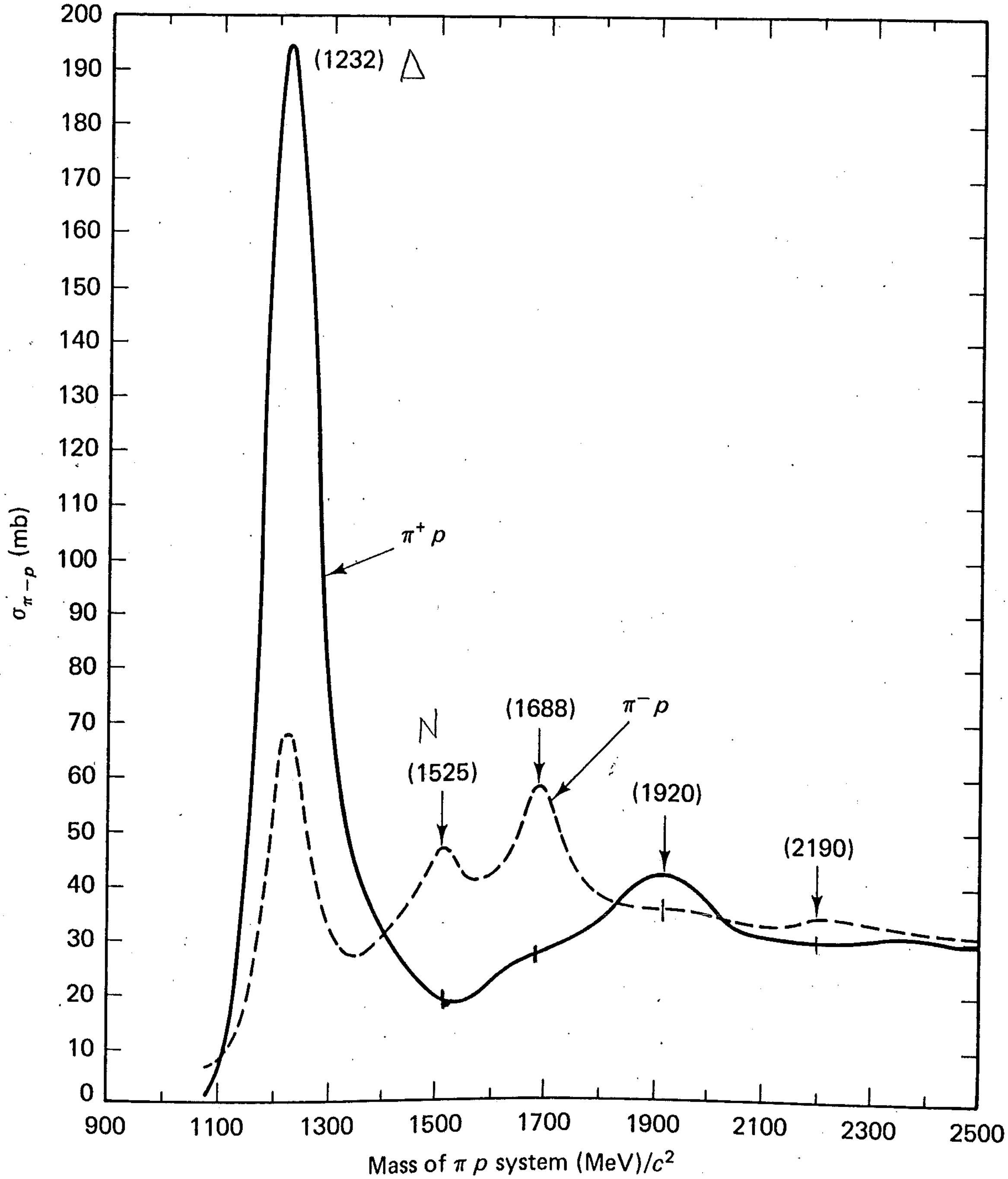


Figure 4.6 Total cross sections for π^+p (solid line) and π^-p (dashed line) scattering. (*Source:* S. Gasiorowicz, *Elementary Particle Physics* (New York: Wiley, copyright © 1966, page 294. Reprinted by permission of John Wiley and Sons, Inc.)

[plots shown] [Enrico Fermi]

resonance : $\pi^+ p \longrightarrow \Delta^{++} \longrightarrow \pi^+ p$

driven harmonic oscillator

$\pi^- p \longrightarrow \Delta^0 \longrightarrow \pi^- p,\ \pi^0 n$

$m(\Delta) = 1232\ \text{MeV},\ \Gamma(\Delta) = 120\ \text{MeV} \Rightarrow \tau = 5\times10^{-24}\,s$

expt $\rightarrow J = \frac{3}{2}$

$\pi^- p \rightarrow N^0 \rightarrow \pi^- p,\ \pi^0 n$ [similar to ρ] [can't see Δ tracks!]

$m(N) = 1520\ \text{MeV}$, similar Γ & τ

expt $\rightarrow \underline{J = \frac{3}{2}}$ [PPB]

[why Δ peaks for both, but N peak only for $\pi^- p$?]

Isospin

$\pi^+ p \Rightarrow |1,1\rangle\,|\tfrac{1}{2},\tfrac{1}{2}\rangle = |\tfrac{3}{2},\tfrac{3}{2}\rangle$

$\pi^- p \Rightarrow |1,-1\rangle\,|\tfrac{1}{2},\tfrac{1}{2}\rangle = \frac{1}{\sqrt{3}}|\tfrac{3}{2},-\tfrac{1}{2}\rangle - \sqrt{\tfrac{2}{3}}\,|\tfrac{1}{2},-\tfrac{1}{2}\rangle$

Suggests that Δ is an isospin $\frac{3}{2}$ state [Fermi 1951]
N is an isospin $\frac{1}{2}$ state

isoquartet
$\Delta^{++} = |\tfrac{3}{2},\tfrac{3}{2}\rangle$
$\Delta^{+} = |\tfrac{3}{2},\tfrac{1}{2}\rangle$
$\Delta^{0} = |\tfrac{3}{2},-\tfrac{1}{2}\rangle$
$\Delta^{-} = |\tfrac{3}{2},-\tfrac{3}{2}\rangle$

isodoublet
$N^{+} = |\tfrac{1}{2},\tfrac{1}{2}\rangle$
$N^{0} = |\tfrac{1}{2},-\tfrac{1}{2}\rangle$
"excited state of p + n"

$Q - I_3 = 0$ for mesons

Observe: $Q - I_3 = \frac{1}{2}$ for baryons

$\rightarrow Q - I_3 = \frac{1}{2}A$

optional

$$\frac{\sigma_{\pi^+ p \to \Delta^{++}}}{\sigma_{\pi^- p \to \Delta^0}} = \frac{|\mathcal{M}_{\pi^+ p \to \Delta^{++}}|^2}{|\mathcal{M}_{\pi^+ p \to \Delta^0}|^2} = \frac{1}{\left(\frac{1}{\sqrt{3}}\right)^2} = 3$$

$$\frac{\sigma_{\pi^+ p \to N}}{\sigma_{\pi^- p \to N}} = \frac{|\mathcal{M}_{\pi^+ p \to N}|^2}{|\mathcal{M}_{\pi^- p \to N}|^2} = \frac{0}{\left(\sqrt{\frac{2}{3}}\right)^2} = 0.$$

[Total cross-sections so don't need worry about whether $\Delta^0 \to \pi^- p$ or $\pi^0 n$ $\left(\frac{1}{3} \text{ vs } \frac{2}{3}\right)$