(17) DH-1

[we already discussed leptons; $\mu^{\pm}$ disc. 1937 in cosmic rays] ~~LH 4~~

Hadrons = particles composed of quarks
which therefore interact via the strong force

meson = $q\bar{q}$

baryons = qqq

Nucleons (N) are protons & neutrons

Nucleon - nucleon collision [in cosmic rays or accelerators]

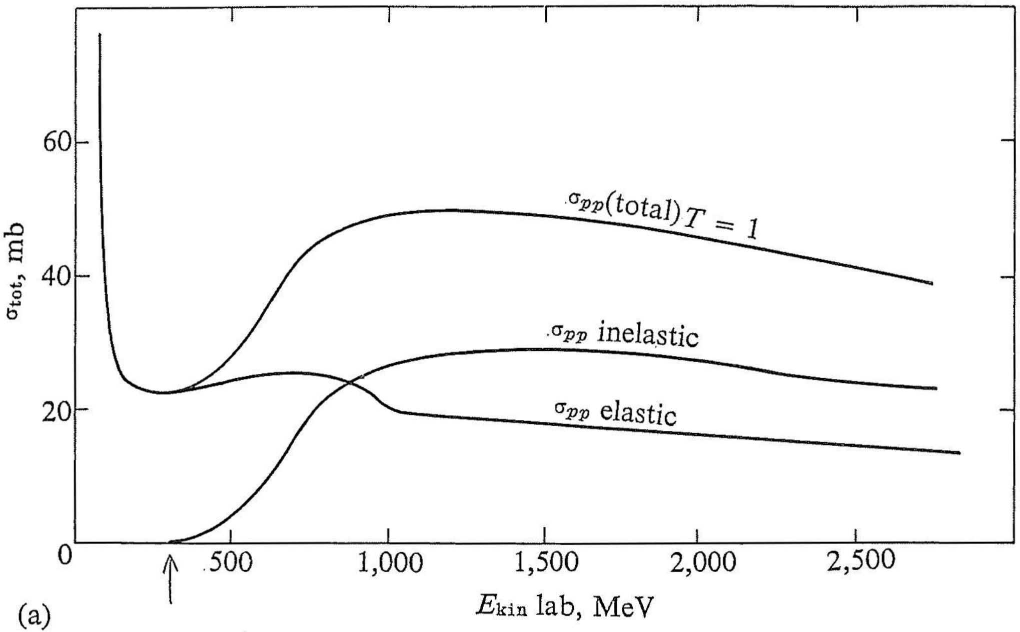
optional

Strong interaction cross section ~ geometric size of nucleon

$\sigma \sim \pi r_0^2 \sim 3 \text{ fm}^2 \sim 0.03$ barns

Typical strong cross-section between 10 - 100 mb
0.01 and 0.1 barns

[see plot]



(a)

↑

~ 280 MeV
threshold

Segre, p. 415

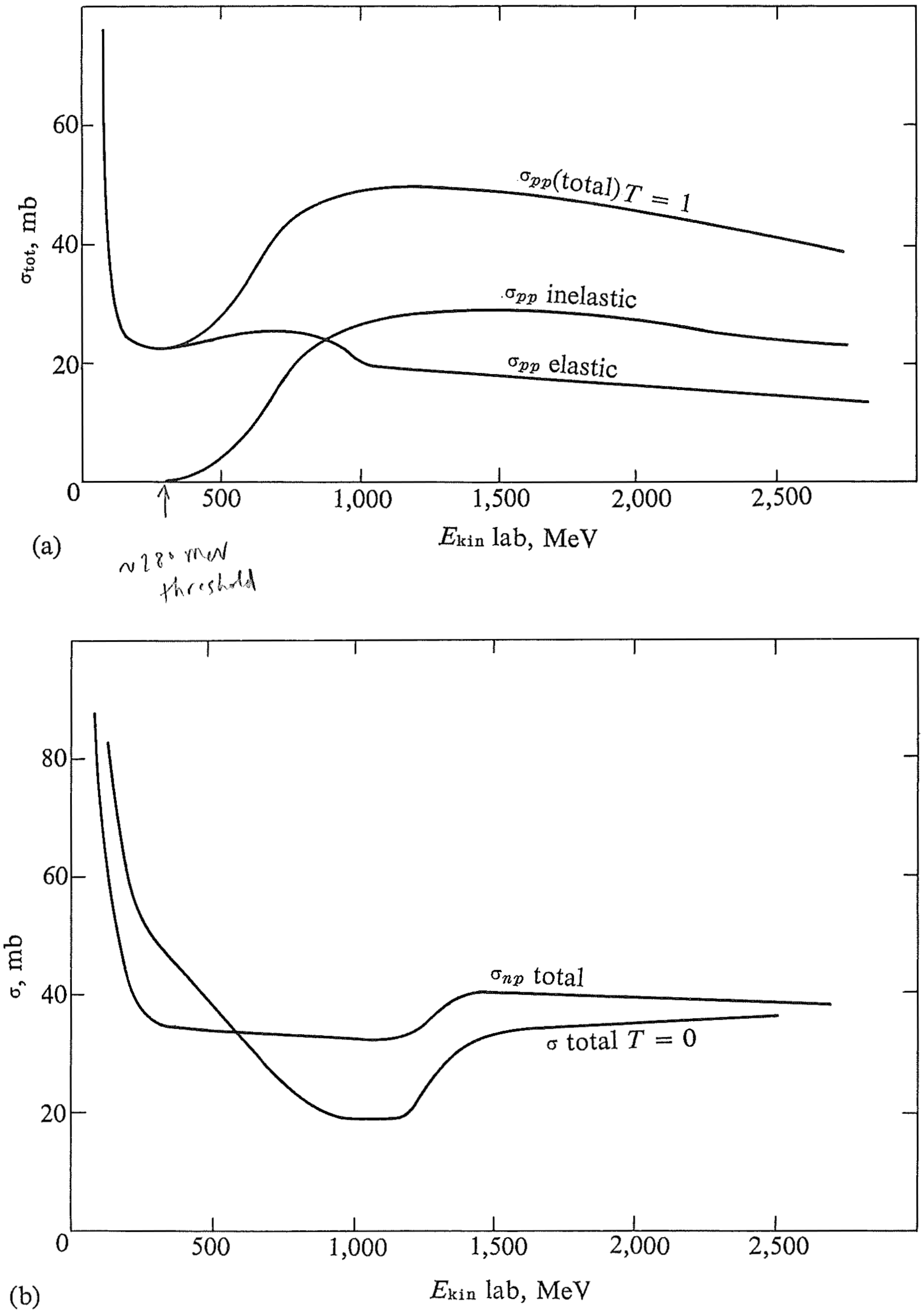


Figure 10-18 The neutron-proton total and the proton-proton total, elastic, and inelastic cross sections as a function of energy. All curves shown are empirical. The inelastic-cross-section curve has been obtained by subtraction of the elastic-cross-section curve from the total cross-section curve. The curves for pure *i*-spin states $T = 1$ and $T = 0$ are shown also. How is the $T = 0$ curve obtained?

DH-2
~~LH~~ 5

elastic $(Q = 0)$ $\quad NN \longrightarrow NN$

inelastic $(Q < 0)$ $\quad NN \longrightarrow NNX$

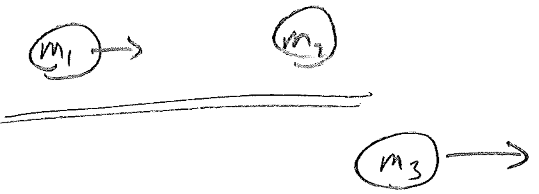
↑ created particle

$Q = -m_X$

[Could omit this]

How much kinetic energy required to create X?

Recall from problem set:



NNX moving together in a clump

$$\frac{T_1}{|Q|} = \frac{m_1 + m_2 + m_3}{2m_2}$$

$m_1 = m_2 = m_N$

$m_3 = 2m_N + m_X$

$$\frac{T_1}{|Q|} = \frac{4m_N + m_X}{2m_N} = 2 + \frac{m_X}{2m_N}$$

threshold $(T_1)_{min} = \left(2 + \frac{m_X}{2m_N}\right) m_X \approx 2m_X$ if $m_X \ll m_N$

Plot shows $(T_1)_{min} \approx 300$ MeV $\Longrightarrow$ $m_X \approx 150$ MeV

Lightest hadron $\Rightarrow$ π meson

DH-3
~~LH-6~~

strong interaction processes

$pp \rightarrow p n \pi^+$ $m_{\pi^+} = 140$ MeV

[1947 Powell (Bolivian Andes)
1948 Lattes Gardner (Berkeley)]

$pp \rightarrow pp\pi^0$ $m_{\pi^0} = 135$ MeV

[1950 Lawrence (Berkeley)]

All π have baryon #: 0. $\Rightarrow$ "mesons" (medium weight)

π must decay weakly or electromagnetically because there are no lighter hadrons

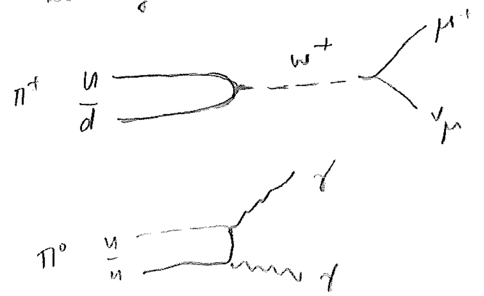
$\pi^+ \xrightarrow{\text{weak}} \mu^+ \nu_\mu$ $\tau = 2.6 \times 10^{-8}$ s

$c\tau = 8$m [detected via tracks in emulsions or bubble chambers]

$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu$

$\pi^0 \xrightarrow{\text{EM}} \gamma\gamma$ $\tau \sim 10^{-16}$ sec

[It already did weak [illegible] + QED



]

PH4
~~L117~~

π^+, π^0, π^- constitute a (nearly) degenerate isotriplet

$$I = 1 \qquad \begin{array}{l} |1,1\rangle = \pi^+ \\ |1,0\rangle = \pi^0 \\ |1,-1\rangle = \pi^- \end{array}$$

Experiments reveal π has spin 0 $(J=0)$
"scalar" meson

At high energies, other mesons are created

$$pp \to pp\,\eta \qquad m_\eta \sim 550 \text{ MeV}$$

η is a neutral, scalar $(J=0)$, iso singlet $(I=0)$

$$NN \to NN\rho \qquad m_\rho \sim 775 \text{ MeV}$$

ρ^+, ρ^0, ρ^- is a vector $(J=1)$. isotriplet $(I=1)$

ρ decays strongly to π's $\qquad \left[\rho^+ \to \pi^+\pi^0,\ \rho^0 \begin{array}{l} \to \pi^+\pi^- \\ \not\to \pi^0\pi^0 \end{array}\right]$

$$pp \to pp\,p\bar{p} \qquad [\text{disc } 1955]$$
$$\to pp\,n\bar{n} \qquad [\text{disc } 1956]$$

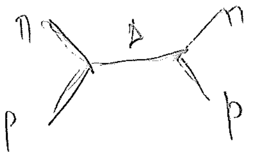
Bevatron (6 GeV)

$$\left\{ \begin{array}{l} \dfrac{T_1}{|Q|} \simeq \dfrac{m_1+m_2+m_3}{2m_2} \approx 3, \quad |Q| = 2m_p \\ \\ T_1 = 6\,m_p \end{array} \right.$$

Other baryons?

Create, collect, collimate + accelerate $\pi^{\pm}$ into a beam

$$\pi^+ p \xrightarrow{\text{strong}} \Delta \xrightarrow{\text{strong}} \pi^+ p$$



Δ decay by strong interaction almost as soon as it is created

$\tau \sim 10^{-23}\,s \Rightarrow c\tau \sim 1\,fm$ (too short to see track)

$$\longrightarrow \Gamma = \hbar R \cdot \frac{\hbar}{\tau} \quad \frac{\hbar c}{c\tau} \approx \frac{197\,MeV\text{-}fm}{fm} \approx 200\,MeV$$

[Look at graph]

already discussed Breit Wigner

Peak in σ curve indicates transitory existence of a particle w/ $M_\Delta \approx E_\pi + E_p = E_{cm}$

Because the Δ only survives for $\tau \sim 10^{-23}\,s$ its energy (mass) is uncertain

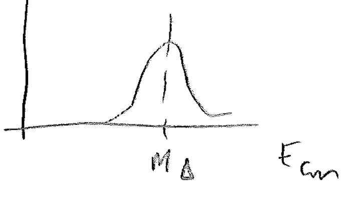
$$\Delta E\, \Delta t \sim \hbar$$

$$\Rightarrow \Delta E \sim \frac{\hbar}{\tau} = \frac{\hbar c}{c\tau} = \frac{(200\,MeV\text{-}fm)}{(1\,fm)} \sim 200\,MeV$$

Width of peak in σ, $\Gamma \sim 200\,MeV$

$$\frac{1}{(E_{cm} - m_\Delta)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

Will see later: Breit Wigner curve



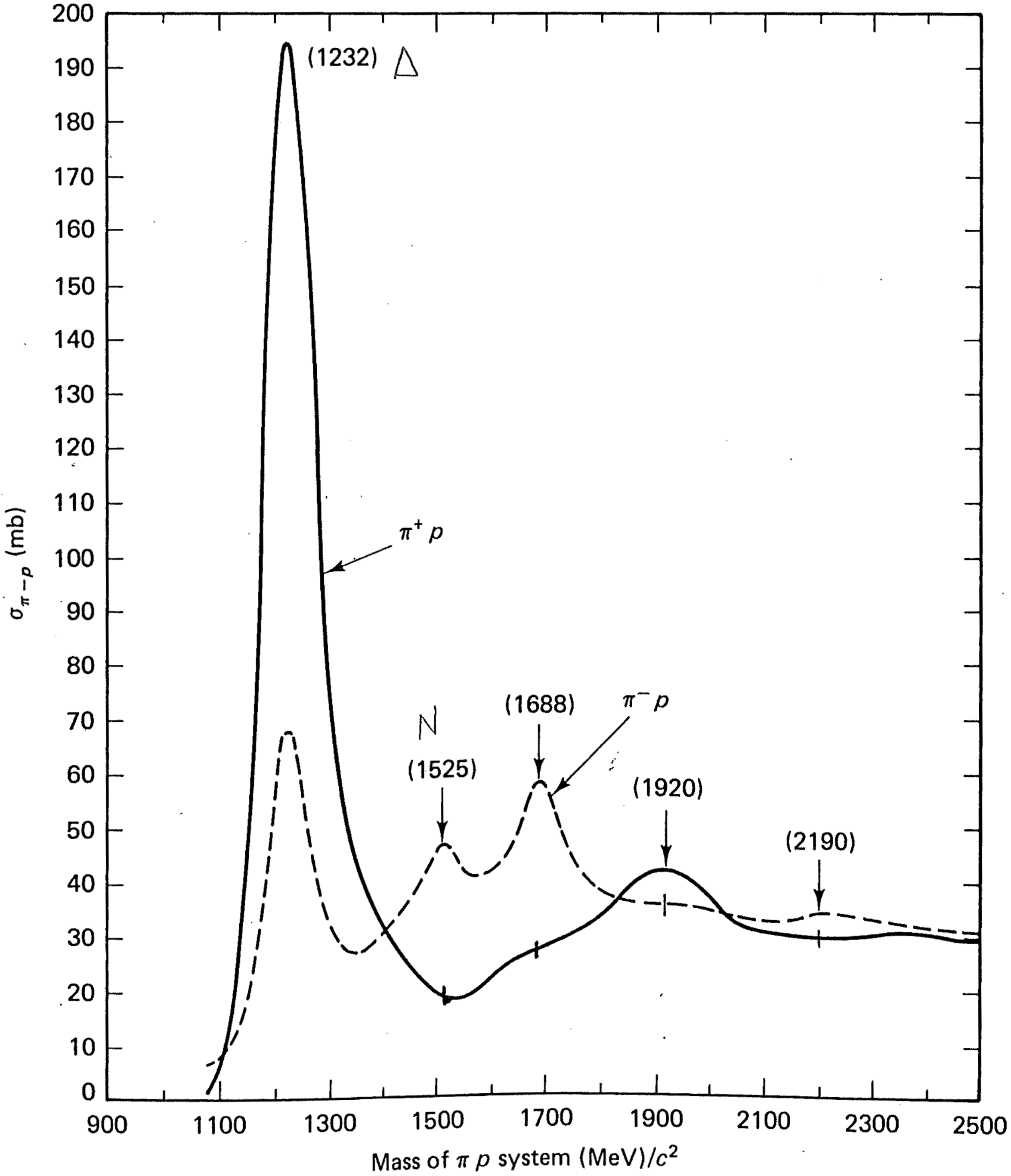


Figure 4.6 Total cross sections for π^+p (solid line) and π^-p (dashed line) scattering. (*Source:* S. Gasiorowicz, *Elementary Particle Physics* (New York: Wiley, copyright © 1966, page 294. Reprinted by permission of John Wiley and Sons, Inc.)

Isospin of Δ?

$$\begin{matrix} \pi & \otimes & N & & & & \\ \underset{\sim}{3} & \otimes & \underset{\sim}{2} & = & \underset{\sim}{4} & \oplus & \underset{\sim}{2} \end{matrix}$$

pH 6

~~LH 9~~

[see plot]

$m \sim 1230$ MeV, $\Gamma \sim 120$ MeV $\Rightarrow \Delta$ [PPB]

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

~~What is isospin of Δ?~~ ~~$\underset{\sim}{3} \otimes \underset{\sim}{2} = \underset{\sim}{4} \oplus \underset{\sim}{2}$~~

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

[Plot also shows]

$\pi^- \quad p \longrightarrow \Delta^0$

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

If Δ^0 is $|\tfrac{3}{2}, -\tfrac{1}{2}\rangle$ then

$$\frac{\sigma(\pi^- p \to \Delta^0)}{\sigma(\pi^+ p \to \Delta^{++})} \quad \frac{\left(\frac{1}{\sqrt{3}}\right)^2}{(1)^2} = \frac{1}{3}$$ agrees w/ plot

Baryon isoquartet

$|\tfrac{3}{2}, \tfrac{3}{2}\rangle = \Delta^{++}$

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

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

$|\tfrac{3}{2}, -\tfrac{3}{2}\rangle = \Delta^{-}$

[HW: $\Delta^0 \to \pi^- p$
$\to \pi^0 n$
what is BR?]

[Fermi 1951]

Experiment reveals Δ has $J = \frac{3}{2}$

Summary (so far)

Baryons	I	J	m (MeV)	decay
$N = p, n$	$\frac{1}{2}$	$\frac{1}{2}$	~940	stable, weak
$\Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-}$	$\frac{3}{2}$	$\frac{3}{2}$	~1230	strong

	Mesons				
	π^+, π^0, π^-	1	0	~140	weak, EM
	$\rho^+ \rho^0, \rho^-$	1	1	~775	strong
electrically neutral	η	0	0	~550	strong, EM
	η'	0	0	~960	strong
	ω	0	1	~780	strong
	ϕ	0	1	~1020	strong

All strongly decaying particles have short τ, large Γ
appear only as resonance

All weakly decaying particles have "long" τ
can be detected by tracks

Observe: average charge in a multiplet $= \frac{1}{2} A$

electric charge $q = \frac{1}{2} A + I_3$

[use q, not Q = energy released]