Hadrons

In 2025, I skipped directly
from (14) ν (measure neutrinos)
to (19) WQ (wk intn of qks)
+ then (20) QCD
(omitted eightfold way + isospin)

(15) H-1
(rev. 2025)
(but not presented!)

particles composed of quarks (and gluons)
which therefore interact via the strong force
(as well as other forces)

e.g.

baryons = qqq $\qquad A = 1$

mesons = $q\bar{q}$ $\qquad A = 0$

pentaquarks = $qqqq\bar{q}$

lowest mass baryons:

nucleons $N = \begin{cases} p = uud & (938.3 \text{ MeV}) \\ n = udd & (939.6 \text{ MeV}) \end{cases}$

all hadrons other than p are unstable

but some are more unstable than others

- if decay strongly, then $\tau \sim 10^{-23}$ s

  [~ time taken light to cross a proton: why?]

- if decay weakly, then $\tau \sim 10^{-8}$ s or longer

  [eg neutron 15 minutes]

[Heisenberg asked why are p, n nearly degenerate in mass. Could it be due to some symmetry?]

Symmetry $\xrightarrow[\text{CM}]{}$ conservation laws (Noether's thm)

Symmetry $\xrightarrow[\text{QM}]{}$ degeneracies
i.e. different states have same energy

~~Heisenberg postulated that p, n are nearly degenerate in mass due to isotopic spin symmetry (or isospin)~~

Recall:

Invariance of laws of physics under rotations (principle of isotropy)

$\Rightarrow$ cons of angular moment J
orbital, spin

QM $\Rightarrow$ ~~[illegible]~~ sp. quantized in units of $\frac{\hbar}{2}$

eg proton, neutron $\underline{\underline{J = \frac{1}{2}}}$

Angular momentum

moved to LD

Invariance of laws of physics under rotations (isotropy)

$\Rightarrow$ cons of angular momentum $\vec{J} = (J_x, J_y, J_z)$

[$\vec{J}$ due to motion of particle or intrinsic which it has even at rest]

- orbital
- spin (intrinsic)

QM $\Rightarrow$ J quantized in half integer units of $\hbar$

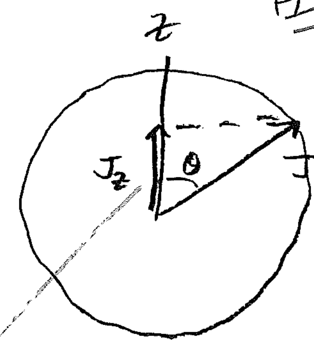
Bosons have integer spin: $J = 0, \hbar, 2\hbar, \ldots$

Fermions have half integer spin: $J = \frac{\hbar}{2}, \frac{3\hbar}{2}, \frac{5\hbar}{2} \ldots$

eg

spin	example: fundamental	composite	
0	Higgs Boson	π meson	"scalar"
$\frac{1}{2}$	quarks, leptons	proton, neutron	"spinor"
1	$\gamma, W^\pm, Z^0$, gluon	ρ meson	"vector"
$\frac{3}{2}$	gravitino?	Δ baryon	"spinor vector"
2	graviton		"tensor"

Spatial quantization



J_z = z-component of spin $= J\cos\theta$

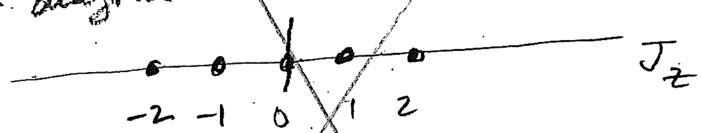
$|J_z| \le J$

QM $\Rightarrow$ J_z is also quantized

Allowed values: $J_z = J, J-1, J-2, \ldots, -J$ (massive)
$J_z = J, -J$ (massless)

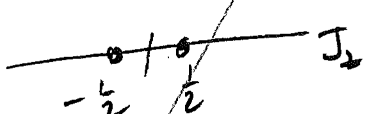
# of allowed values = multiplicity $= \begin{cases} 2J+1 & \text{(massive)} \\ 2 & \text{(massless)} \end{cases}$

weight diagram



set of allowed spin states called a "multiplet"

E.g. spin-$\frac{1}{2}$ particle has 2 spin states: $J_z = \pm\frac{1}{2}$
"doublet"



↑ spin up ↓ down spin

If environment is rotationally symmetric, then particle energy is *independent* of direction of spin
$\Rightarrow$ 2J+1 degenerate states

[If $\vec{B}$ field in z-direction, then energy depends on direction of spin (because $\vec{\mu} \propto \vec{S}$, and magnets align w/ $\vec{B}$)]

$\vec{B}$ field breaks rotational symmetry $\Rightarrow$ splits the degeneracy

[Should we do g-factor?, see J-4 in old notes]

Heisenberg postulated that p, n are 2 nearly degenerate states of a single particle N (analogous to spin-up + spin down)

Isotopic spin or isospin $\vec{I} = (I_1, I_2, I_3)$

↳ based on group SU(2)

Like spin, isospin is quantized.

Also components are quantized:

$$I_3 = \underbrace{+I,\ I-1,\ \dots,\ -I}_{2I+1 \text{ states}} = \text{iso multiplet}$$

eg nucleon N has $I = \frac{1}{2}$ + $I_3 = \pm\frac{1}{2}$

$$\left.\begin{array}{l} I_3 = \frac{1}{2} \Rightarrow \text{proton} \\ I_3 = -\frac{1}{2} \Rightarrow \text{neutron} \end{array}\right\} \text{iso doublet}$$

[Same particle w/ isospin up + down, pointing in diff. directions in isospin space (abstract)]

Claim: the strong force is symmetric under rotation in iso space $\Rightarrow$ isomultiplets are degenerate in mass

weak + EM forces break the symmetry so break the degeneracy

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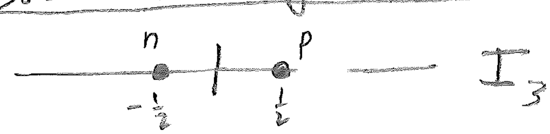
weight diagram



~~H-2~~ ~~H-5~~

H6

[If hadrons are unstable, why do they exist?
created in collisions of cosmic rays or accelerators]

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

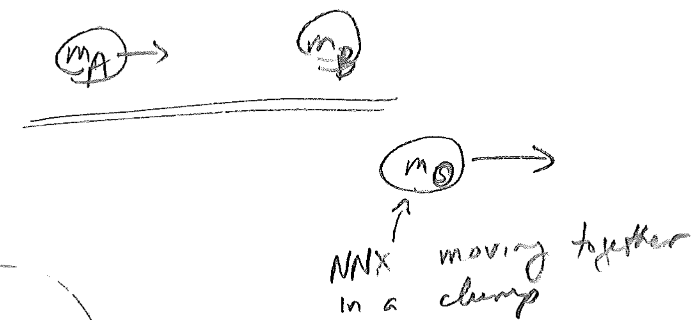
inelastic ($Q < 0$) $\quad NN \longrightarrow NNX$

created particle

$$Q = -m_X$$

How much kinetic energy required to create X?

Recall from problem set:



problem set

$$\frac{T_1}{|Q|} = \frac{m_3 + m_A + m_B}{2m_B}$$

redo

$m_1 = m_2 = m_N$

$m_3 = 2m_N + m_X$

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

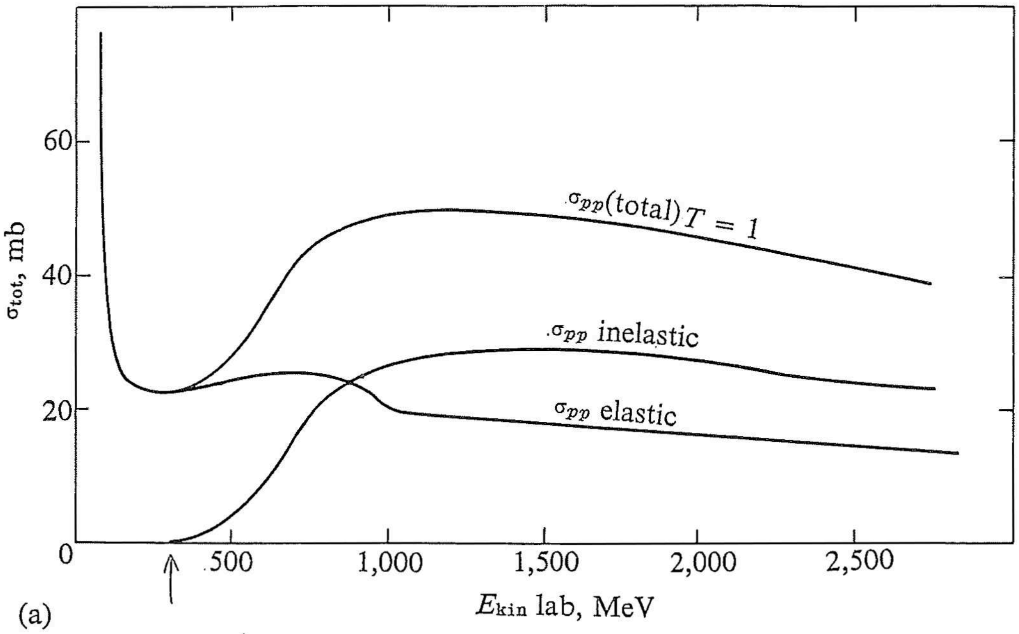
threshold $\displaystyle (T_1)_{min} = \left(2 + \frac{m_X}{2m_N}\right) m_X \approx 2m_X \quad$ if $m_X \ll m_N$

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

Lightest hadron $\Rightarrow$ π meson

[mention $\sigma \sim \pi r_0^2 \sim 0.03$ barns ? see old notes]

$\rightarrow$ typical 10 – 100 mb



(a)

~ 285 MeV
threshold

Segre, p. 415

$pp \to pn\pi^+$ $\qquad m_{\pi^+} \approx 140$ MeV

[first obs. 1947 Powell: Bolivian Andes
1948 Lattes Gardner: Berkeley]

$pp \to pp\pi^0$ $\qquad m_{\pi^0} \simeq 135$ MeV

[1950. Lawrence Berkeley] [computed in problem]

($pn \to pp\pi^-$?)

Also π^- = antiparticle of π^+
π^0 = antiparticle of π^0

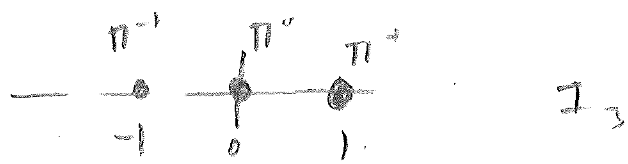
(π^+, π^0, π^-) nearly degenerate $\Rightarrow$ isotriplet

$$I = 1, \begin{cases} I_3 = 1 & \pi^+ \\ I_3 = 0 & \pi^0 \\ I_3 = -1 & \pi^- \end{cases}$$

Experiments reveal π have spin zero ($J=0$)
"scalar mesons"

[pseudoscalar because negative parity]

weight diagram



[Can also create deuterons $pp \to d\pi^+$
$pn \to d\pi^0$

other particle disc. in cosmic rays (~~hadrons~~ mesons)
(π, K, ...)

- cyclotrons (~1950 E. O. Lawrence at Berkeley)

[dgm]

accelerate charged particle to high energies
collide w/ target

- linear + circular accelerators

- colliders : 2 beams of particle collide

(HW: fixed target vs colliders)

$$\boxed{\begin{array}{l} R = \dfrac{p}{qB} \\ \text{or } \omega = \dfrac{v}{r} = \dfrac{p}{\gamma m R} = \dfrac{qB}{\gamma m} \end{array}}$$

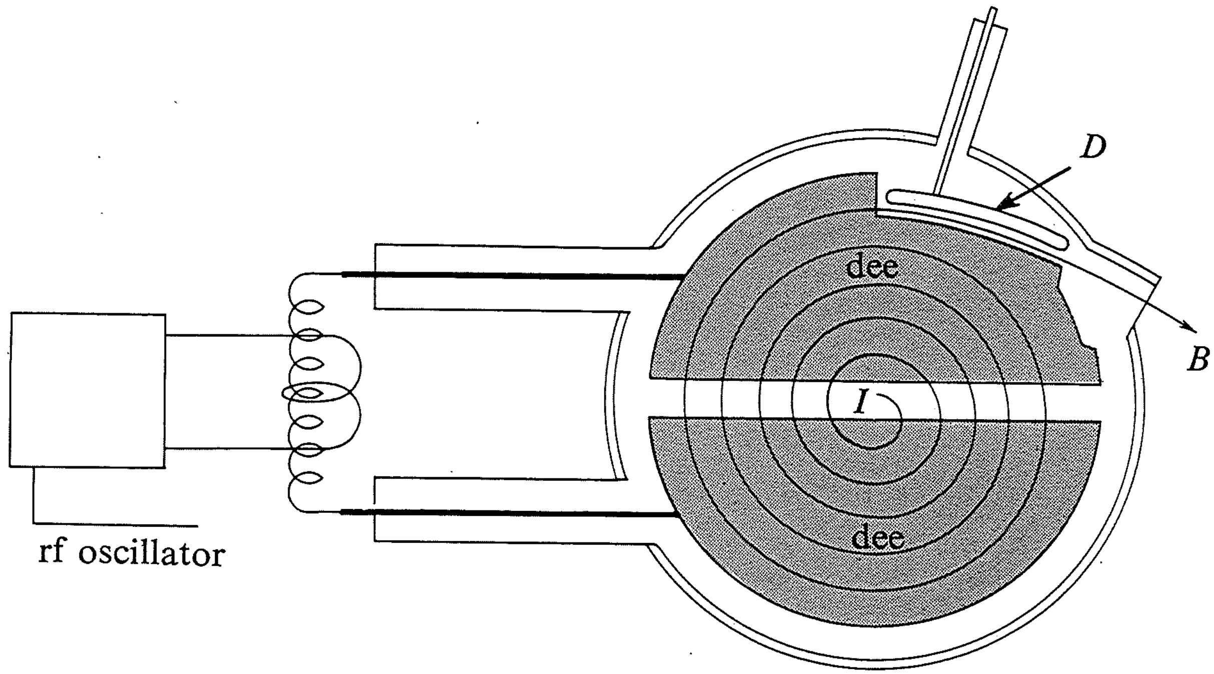


Figure 4-7 Essential parts of a cyclotron (not including the magnet), showing dees (hollow semicircular accelerating electrodes), dee stem insulators, resonant circuit with an rf power source, and deflector plate D. The path of the ions from the source at the center I to the point of emergence at B is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

How do π decay?

Not into other hadrons, because they are lightest.

So must decay into lighter non hadrons

$\pi^0 \longrightarrow \gamma\gamma$ (electromagnetic)

[conserves all qu nos because they are all their own antiparticles & have no qu. nos]

$\tau \sim 10^{-16}$ s [fast but not as fast as strong]

$\pi^+ \longrightarrow \mu^+ \nu_\mu$ (weak)

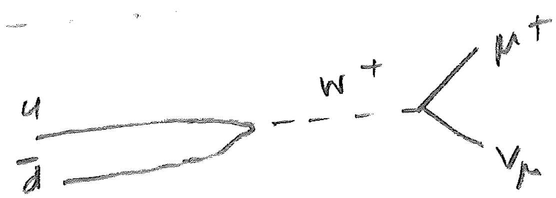
[conserves A, L, charge]

$\tau \sim 2.6 \times 10^{-8}$ s

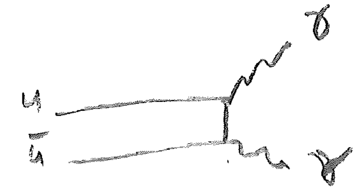
$c\tau \sim 8$ m [so can see π^+ track before it decays]

→ show photo

Sneak peek: $\pi^+ = u\bar{d}$



$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$



At higher energies

$$NN \longrightarrow NN\rho \qquad m_\rho \approx 775 \text{ MeV}$$

or 770?

ρ^+, ρ^0, ρ^- nearly degenerate ("isotriplet") $(I=1)$

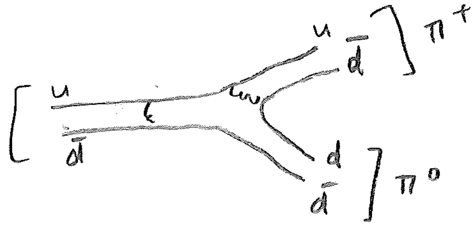
Experiments reveal ρ have spin one $(J=1)$
"vector mesons"

How do ρ decay? strongly!

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

[isospin forbids $\rho^0 \to \pi^0\pi^0$]

Sneak peek: $\rho^+ = u\bar{d}$



$$\tau \sim 10^{-23} \text{ sec}$$

Iso singlet mesons are also created $(I=0)$

$pp \to pp\eta$ $\qquad m_\eta = 550$ MeV

$\to pp\eta'$ $\qquad m_{\eta'} = 960$ MeV

η, η' are both spin zero $\Rightarrow$ Scalar mesons

$m_\omega = 780$ MeV

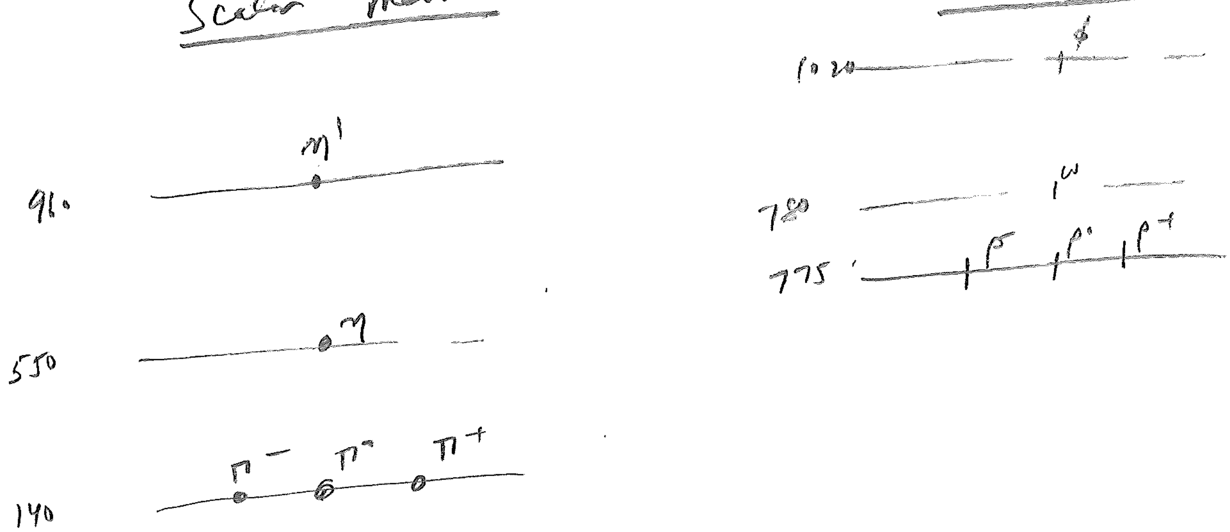
$pp \to pp\omega$ $\qquad m_\phi = 1020$ MeV

$\to pp\phi$

ω, ϕ are spin one, $\Rightarrow$ vector mesons

All these decay strongly into other mesons [$\eta \to \gamma\gamma$ also (40%)]

Scalar mesons $(J=0)$ $\qquad$ Vector mesons $(J=1)$



Observe that for mesons $q = I_3$.

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

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

$$\frac{T_1}{|Q|} \simeq \frac{m_1 + m_2 + m_3}{2m_2} \approx 3$$

$$|Q| = 2m_p \Rightarrow T_1 = 6m_p$$

How about heavier baryons?

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

$Q = 154$ MeV

$$\pi N \xrightarrow[\text{strong}]{} \Delta \longrightarrow \pi N$$

$m_{\Delta} \sim 1230$ MeV
(Fermi, 1951)

$\downarrow$
Computed in problem
$\downarrow$
requires
$T_{\pi} = 190$ MeV

Δ decays almost as soon as created

$$\tau \sim \frac{1}{2}(10^{-23}\,s) \Rightarrow c\tau = \frac{3}{2}\text{ fm}$$

$$\Gamma = \hbar R = \frac{\hbar}{\tau} = \frac{197\text{ MeV fm}}{\frac{3}{2}\text{ fm}} = 120\text{ MeV}$$

[Now do either uncertainty principle
or use Breit-Wigner curve

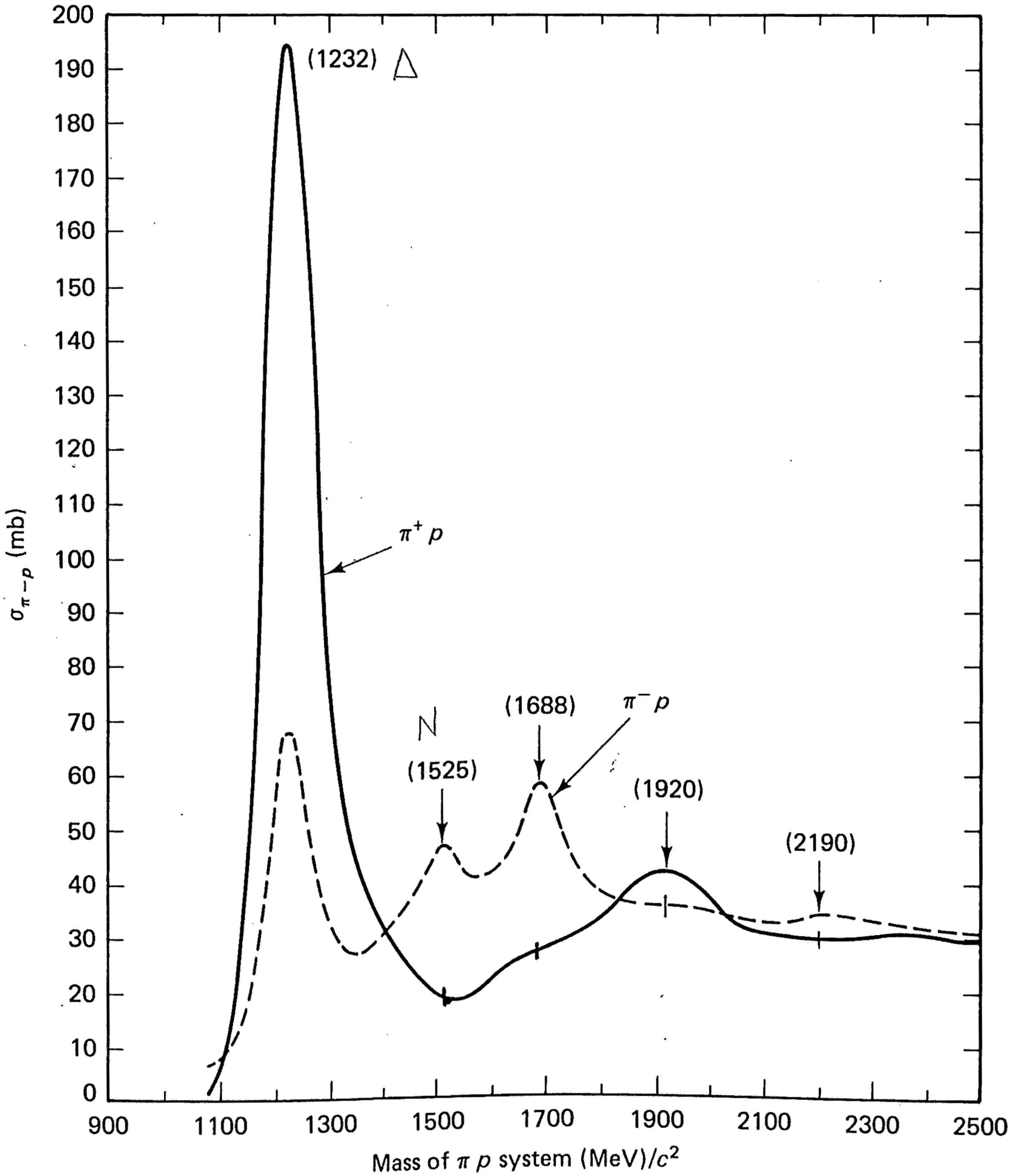


Figure 4.6 Total cross sections for π^+p (solid line) and π^-p (dashed line) scattering. (*Source:* S. Gasiorowicz, *Elementary Particle Physics* (New York: Wiley, copyright © 1966, page 294. Reprinted by permission of John Wiley and Sons, Inc.)

Plot shows

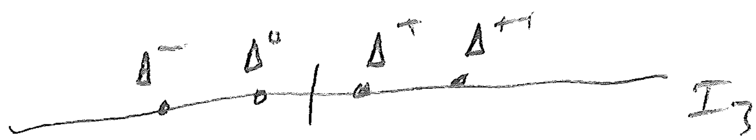
$$\pi^+ p \longrightarrow \Delta^{++}$$

$$\pi^- p \longrightarrow \Delta^{0}$$

[ratios determined by isospin]

$\exists$ also Δ^+, Δ^-

$\Delta^{++}, \Delta^+, \Delta^0, \Delta^-$ form an isoquartet $\Rightarrow I = \frac{3}{2}$



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expt reveals Δ has $J = \frac{3}{2}$

$(\Delta^{++} = uuu)$

Note for baryons $q = I_3 + \frac{1}{2}$

Altogether $\boxed{q = I_3 + \frac{1}{2} A}$