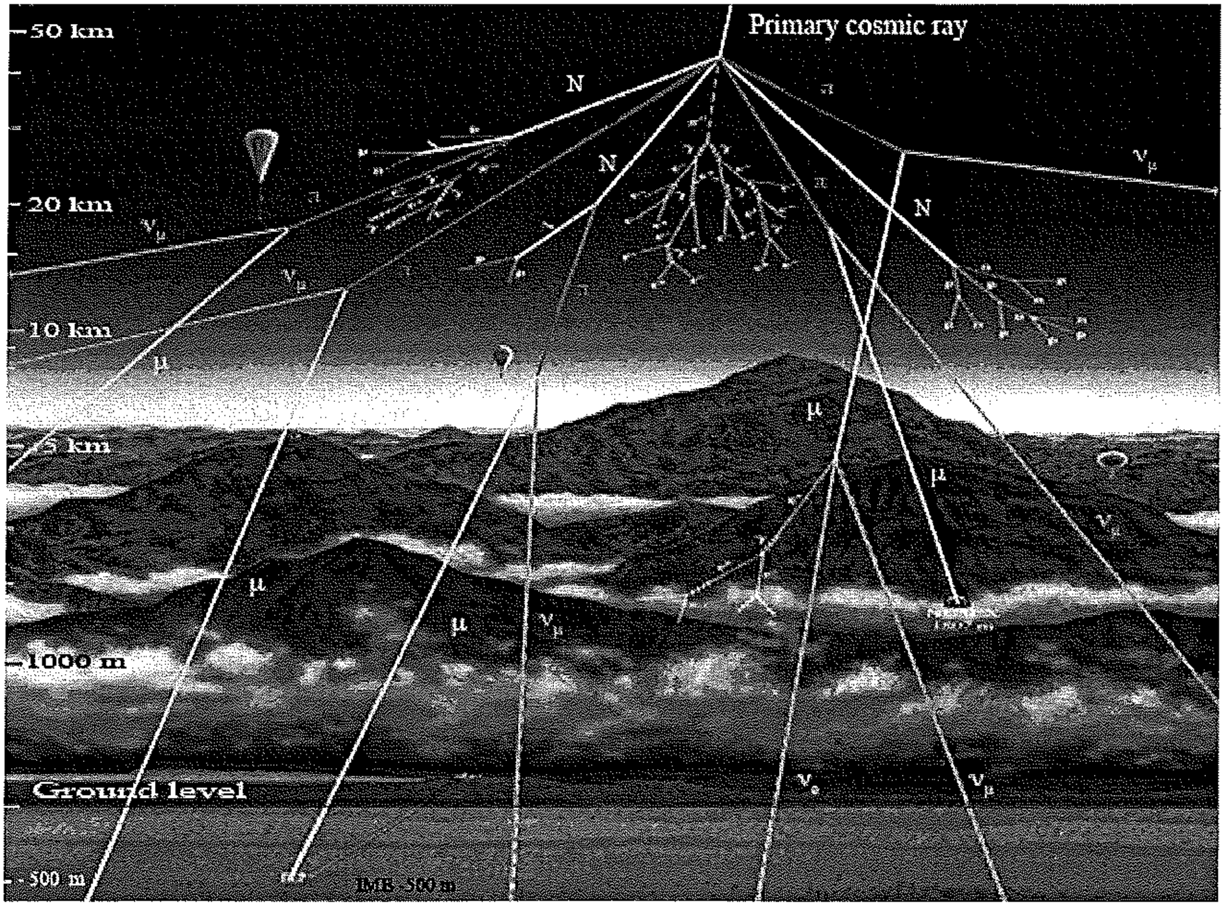
Leptons + hadrons

Sources of high energy particles + discovery of new particles

- cathode ray tubes (1897 Thomson disc. e^-)
- α particles from nuclear decay (1911 Rutherford disc. p)
- van de Graff and Cockcroft-Walton accelerators
- cosmic rays (1912 Victor Hess disc. in balloon flights)
  primarily high energy protons (+ other nuclei)
  from sun (+ elsewhere in galaxy)
  strike gas molecules in upper atmosphere
  creating new (unstable) particles
  [see artists rendition]
- cyclotron (~1950 E. O. Lawrence at Berkeley)
  [see diagram]
  accelerate charged ptls to high energies, collide w/ target.
- linear + circular accelerators
- colliders
  2 beams of particles collide


50 km
Primary cosmic ray
N
π
ν_μ
N
20 km
ν_μ
π
π
N
ν_μ
10 km
μ
μ
5 km
μ
ν_μ
μ
μ
μ
ν_μ
1000 m
Ground level
ν_e
ν_μ
- 500 m
IMB -500 m

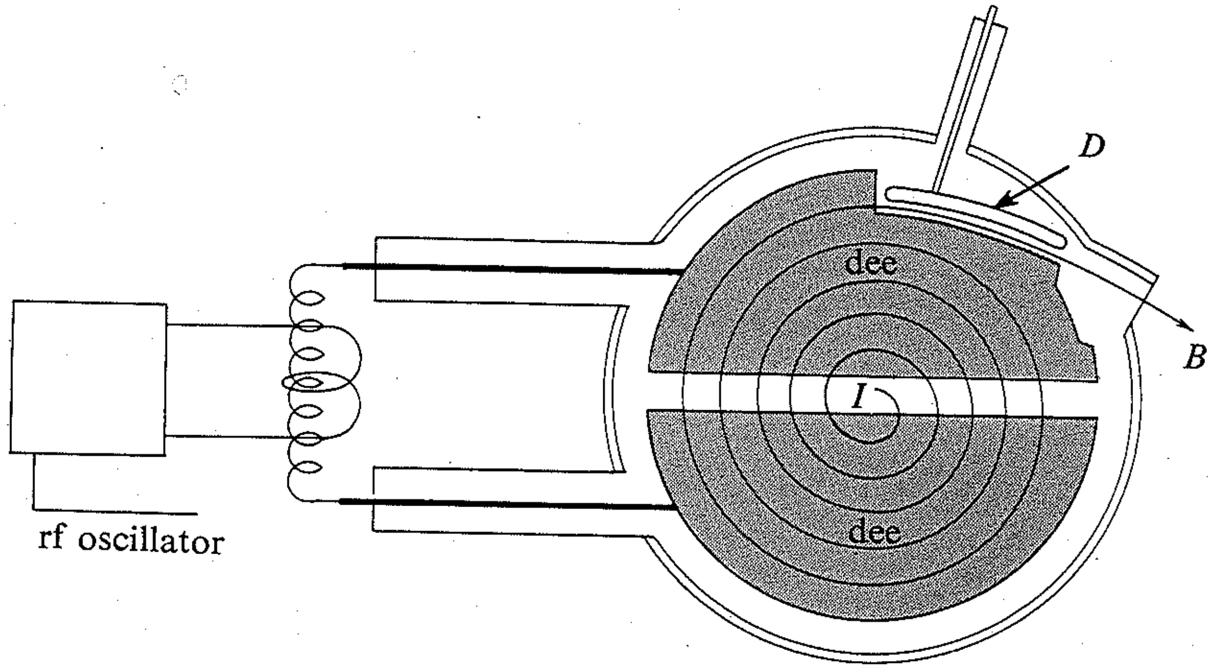


Figure 4-7 Essential parts of a cyclotron (not including the magnet), showing dees (hollow semicircular accelerating electrodes), dee stem insulators, resonant circuit with an rf power source, and deflector plate *D*. The path of the ions from the source at the center *I* to the point of emergence at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

1932 Anderson disc. e^+ from cosmic rays

1937 discovery of μ^+, μ^- from c.r. [Anderson + Neddermeyer,
Street + Stevenson]

"heavy electrons"

$m_\mu \approx 106$ MeV

"Who ordered that?" [Rabi] unnecessary

decays via weak interaction

$\mu^- \longrightarrow e^- \bar{\nu}_e \nu_\mu$ [omit pluses between particles]

$\tau = 2.2 \times 10^{-6}$ s

How far can it travel before decaying?

$c\tau \sim 600$ m

But can travel much further due to time dilation

$d = v \gamma \tau$

Track of particle visible in emulsions [see photo]

Two distinct varieties of neutrinos

[1962 Schwartz Steinberger Lederman
Use π^- to create $\bar{\nu}_\mu$.
$\bar{\nu}_\mu p \longrightarrow n \mu^+$ but not $n e^+$]

$\pi \to \mu \to e$

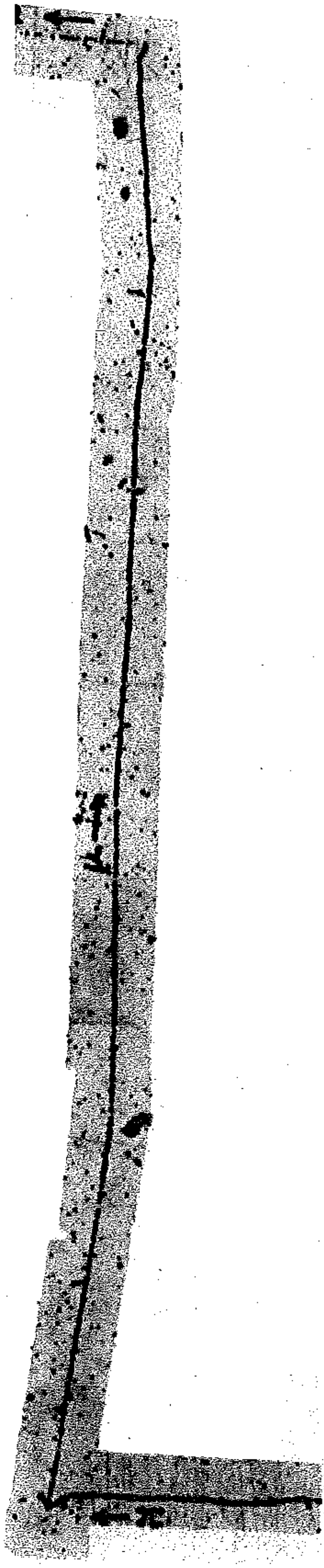


Figure 1.7 Here, a pion decays into a muon (plus a neutrino); the muon subsequently decays into an electron (and two neutrinos). Reprinted by permission from C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (New York: Pergamon, 1959). First published in *Nature* **163**, 82 (1949).

1975 discovery of τ^- in accelerators [Perl]

first 3rd generation particle discovered

$m_\tau = 1777$ meV

$$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau \quad [17\%]$$

$$\to e^- \bar{\nu}_e \nu_\tau \quad [18\%]$$

Conservation of lepton numbers L_e, L_μ, L_τ

	L_e	L_μ	L_τ
e^-	1	0	0
e^+	-1	0	0
ν_e	1	0	0
$\bar{\nu}_e$	-1	0	0
μ^-	0	1	0
etc.			

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

L_e $\quad 0 = 1 - 1 + 0$ ✓

L_μ $\quad 1 = 0 + 0 + 1$ ✓

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

meson = $q\bar{q}$

baryons = qqq

Nucleons (N) are protons & neutrons

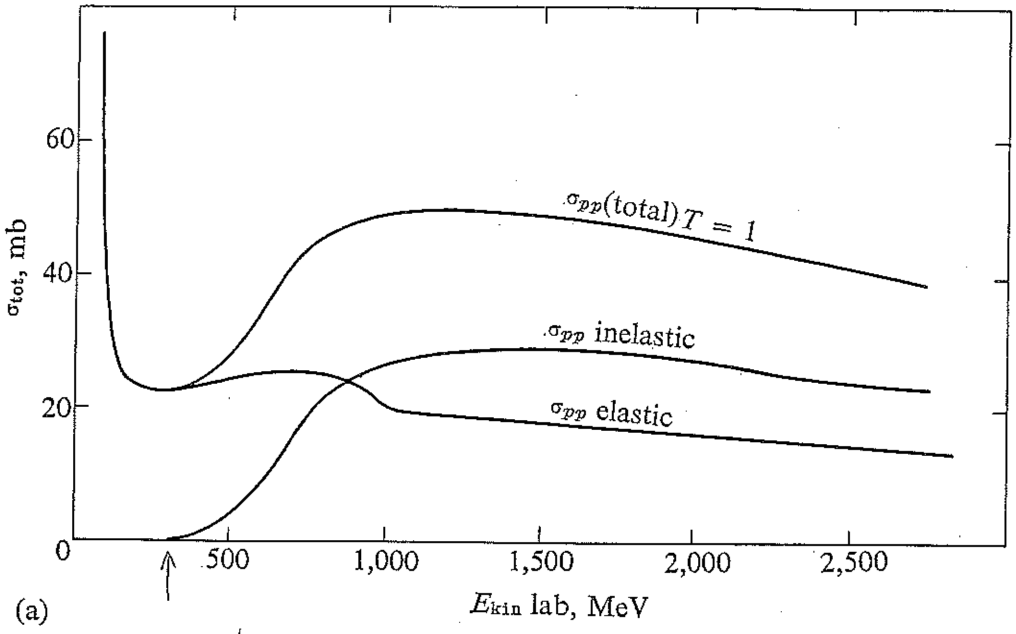
Nucleon - nucleon collision [in cosmic rays or accelerators]

Strong interaction cross section ~ geometric size of nucleon

$\sigma \sim \pi r_0^2 \sim 3$ fm ~ 0.03 barns

Typical strong cross-section between 10 – 100 mb

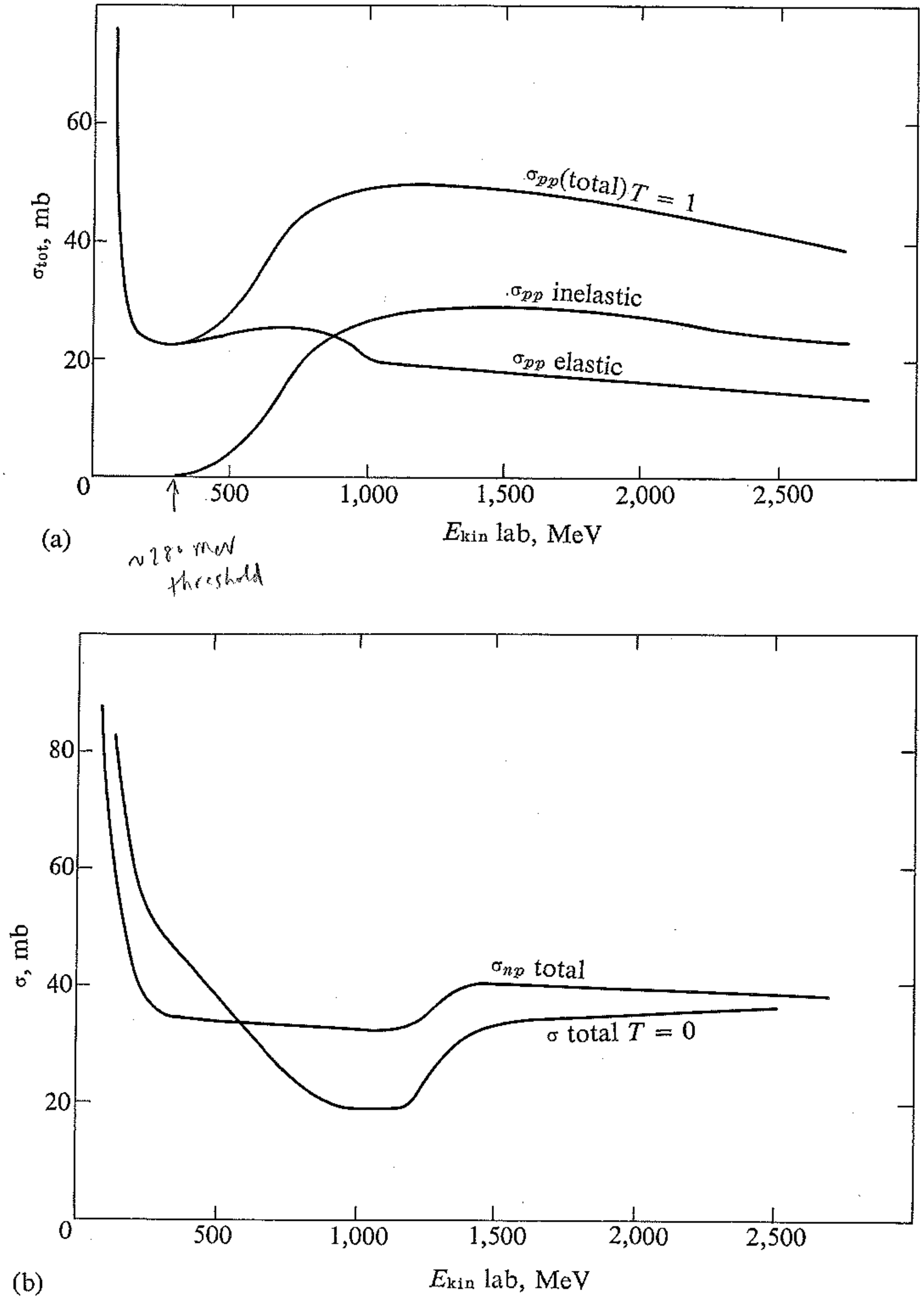
[see plot]



(a)

~ 280 MeV threshold

Segre, p. 415



~280 MeV
threshold

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?

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

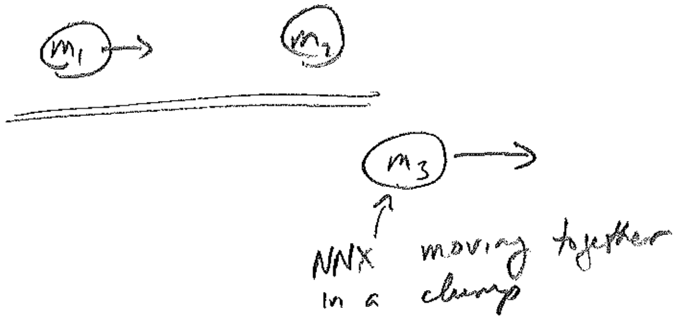
inelastic $(Q < 0)$ $\qquad NN \longrightarrow NNX$

↑ created particle

$$Q = -m_X$$

How much kinetic energy required to create X?

Recall from problem set:



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

$m_1 = m_2 = m_N$
$m_3 = 2m_N + m_X$

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

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 $\Rightarrow$ $m_X \approx 150$ MeV

Lightest hadron ⇒ π meson

$pp \rightarrow pn\pi^+$ $m_{\pi^+} = 140$ meV

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

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

[1950 Lawrence (Berkeley)]

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

$\pi^0 \xrightarrow{EM} \gamma\gamma$ $\tau = 10^{-16}$ s

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

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

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

$I = 1$

$$|1,1\rangle = \pi^+$$
$$|1,0\rangle = \pi^0$$
$$|1,-1\rangle = \pi^-$$

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

At higher energies, other mesons are created

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

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

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

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

$$\left[\rho^+ \rightarrow \pi^+\pi^0,\ \rho^0 \rightarrow \pi^+\pi^- ,\ \not\rightarrow \pi^0\pi^0\right]$$

$pp \rightarrow pp\,p\bar{p}$ [disc 1955] Bevatron (6 GeV)
$\rightarrow pp\,n\bar{n}$ [disc 1956]

$$\begin{cases} \dfrac{T_1}{|Q|} \simeq \dfrac{m_1 + m_2 + m_3}{2m_2} \approx 3, \quad |Q| = 2m_p \\ T_1 = 6\,m_p \end{cases}$$

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

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

[Look at graph]

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

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

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

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

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

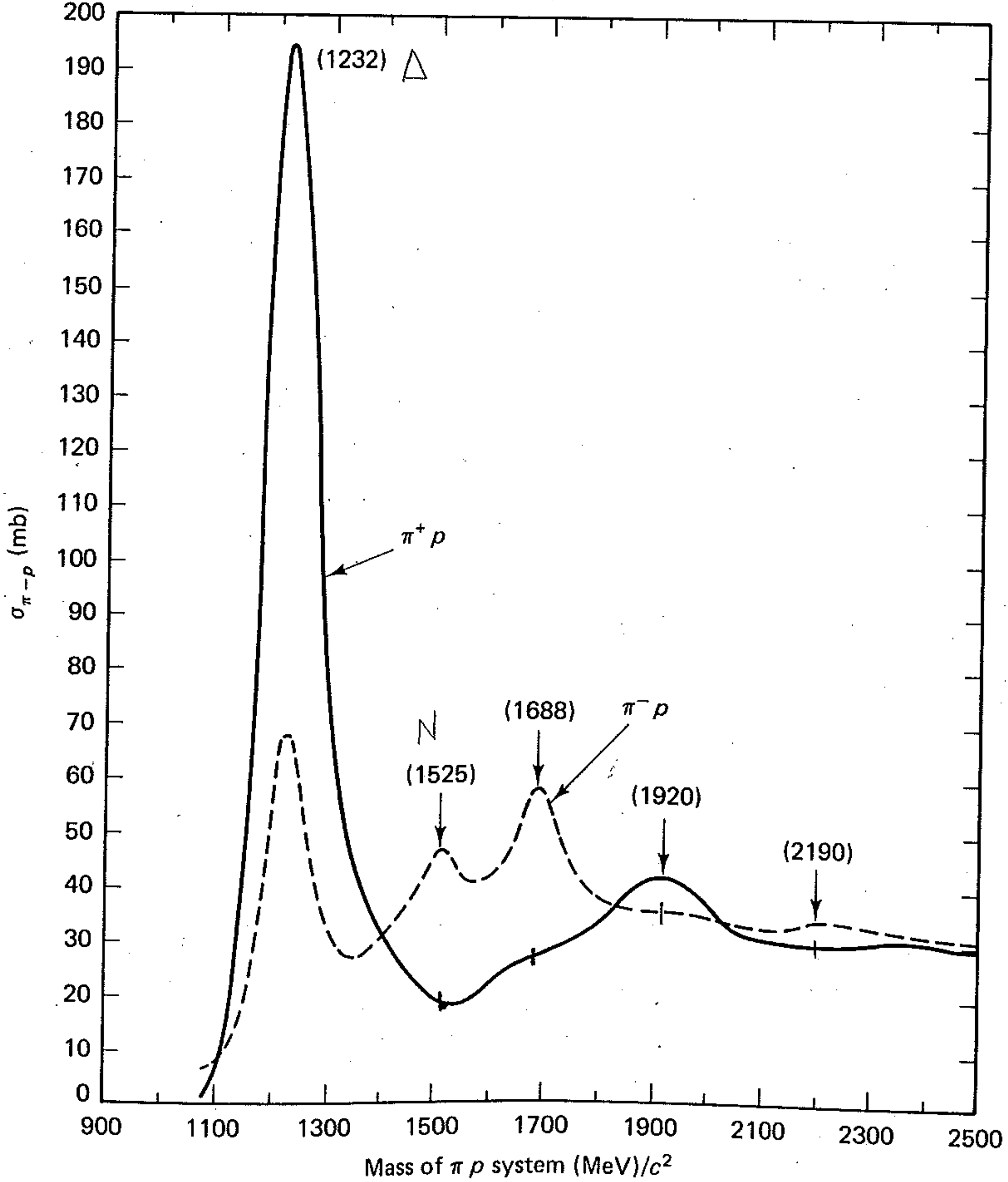


Figure 4.6 Total cross sections for π^+p (solid line) and π^-p (dashed line) scattering. (*Source:* S. Gasiorowicz, *Elementary Particle Physics* (New York: Wiley, copyright © 1966, page 294. Reprinted by permission of John Wiley and Sons, Inc.)

[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? $\overset{\pi}{\underset{\sim}{3}} \otimes \overset{N}{\underset{\sim}{2}} = \underset{\sim}{4} \oplus \underset{\sim}{2}$

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

[Plot also shows]

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

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

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

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

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

Baryon isoquartet

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

[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				
	$\pi^{+}, \pi^{0}, \pi^{-}$	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 resonances

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

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

$$q = \tfrac{1}{2} A + I_3$$

[use q, not Q = energy released]