## Sources of high energy particles and discovery of new particles

1896 Becquerel discovers radioactivity ($\alpha$, $\beta$, $\gamma$)

1897 Thomson discovers $e^-$ in cathode ray tubes

$\alpha$-particles used as a tool:

1911 Rutherford disc. p

1932 Chadwick disc n

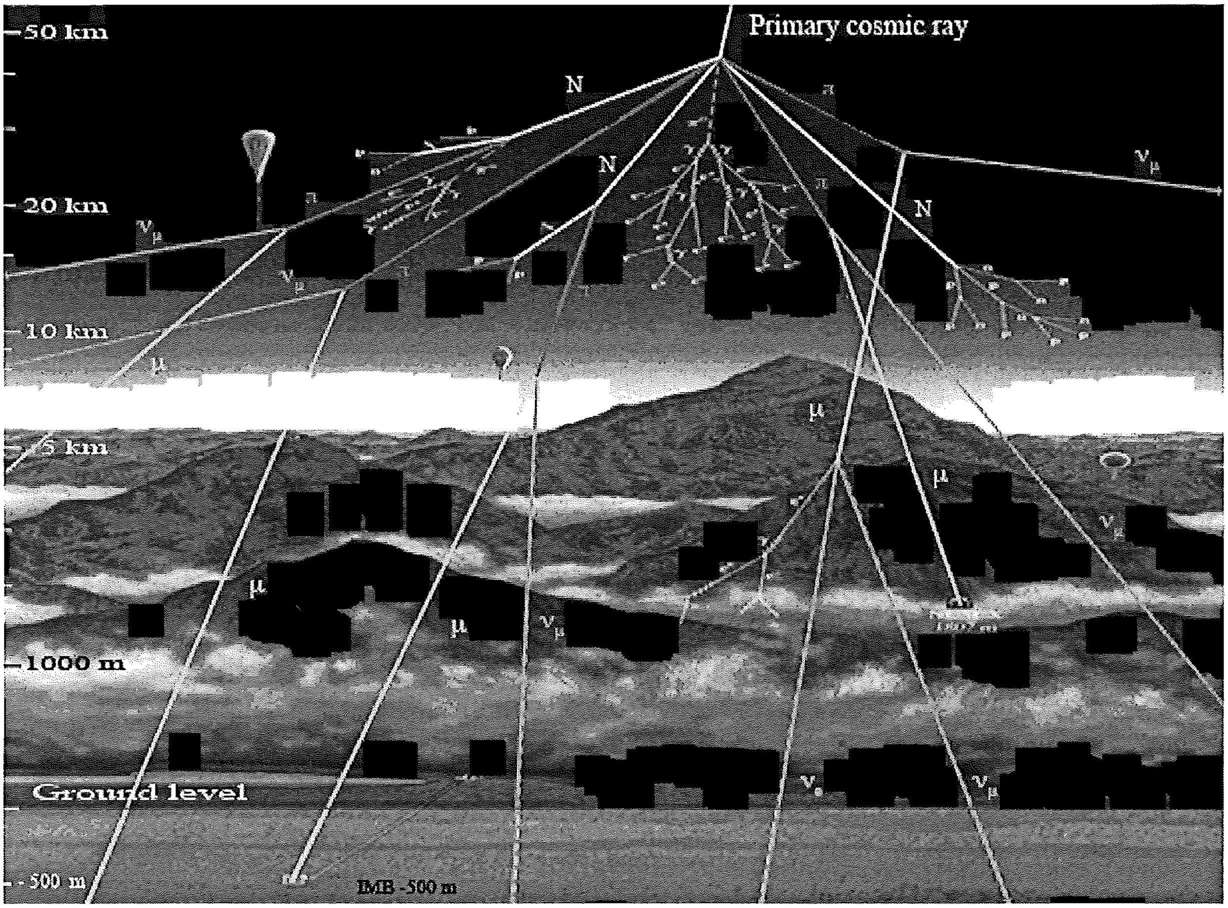
van de Graff & Cockcroft Walton accelerators

1923 Compton scattering leads to acceptance of photon as particle

1930 Pauli predicts $\nu$ (to solve continuous $\beta$-spectrum)
not directly detected until 1956

1930 Dirac predicts $e^+$ (from his eqn)

Cosmic Rays (1912 Victor Hess balloon flights)
primarily high energy protons (+ other nuclei)
from sun (+ elsewhere in galaxy)
hit gas molecules → create new unstable particles
(artist's rendition)



50 km
Primary cosmic ray
20 km
10 km
5 km
1000 m
Ground level
- 500 m
IMB -500 m

1932 Anderson discovers $e^+$ from cosmic rays

1937 discovery of $\mu^-, \mu^+$ from cosmic rays
[Anderson + Neddermeyer; Street + Stevenson]

(Pike's Peak, Bolivian Andes)

"heavy electron" $m_\mu = 106$ MeV

"Who ordered that?" [Rabi] unexpected, unnecessary

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

How far does it travel? $v\tau$

At most $c\tau \sim 600$ m?

Time dilation of moving particle

$d = v\gamma\tau$ [HW: if $d = c\tau$, find $v$]

[Track of particle visible in emulsions ⇒ curves]

Weak interaction decay [calc max + min energy of $e^-$]

$\mu^- \to e^- \bar{\nu} \nu$ <u>not</u> $\mu^- \to e^- \gamma$

[because $e^-$ not monoenergetic, must be at 3 body pds, 2 unobserved]

[why $\mu^- \to e^- \gamma$ not allowed theoretically]

Two-neutrino hypothesis

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

Lepton # $L_e$ and $L_\mu$

[1962 Schwartz Steinberger Lederman use $\pi^-$ to create $\bar{\nu}_\mu$
$\bar{\nu}_\mu p \to n \mu^+$ <u>not</u> $n e^+$]

$\pi \rightarrow \mu \rightarrow e$

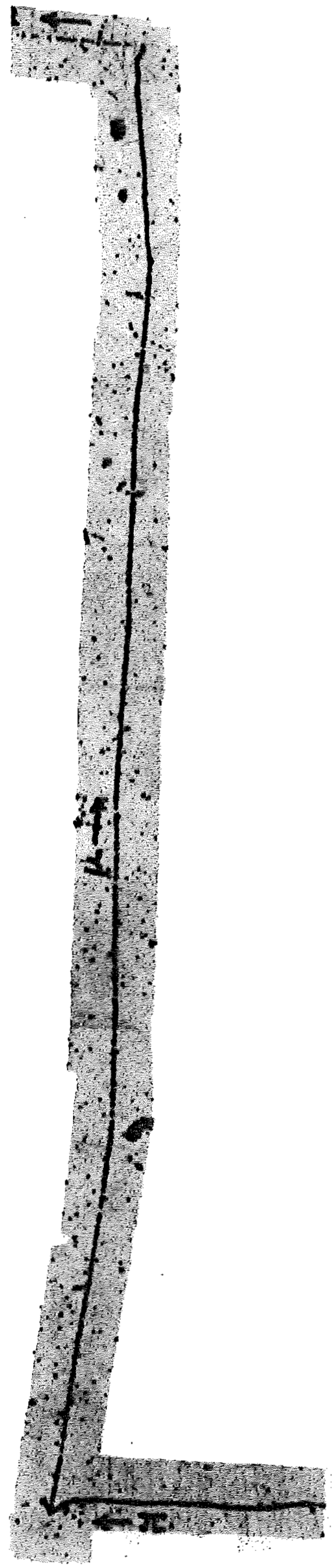


**Figure 1.7** Here, a pion decays into a muon (plus a neutrino); the muon subsequently decays into an electron (and two neutrinos). Reprinted by permission from C. F. Powell, P. H. Fowler, and D. H. Perkins, *The Study of Elementary Particles by the Photographic Method* (New York: Pergamon, 1959). First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

DL-3

other particle disc. in cosmic rays (hadrons)

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

[dgm]

accelerate charged particles to high energies
collide w/ target

- linear + circular accelerators

- colliders : 2 beams of particles collide

(HW: fixed target vs collider)

$$R = \frac{p}{qB}$$

$$\text{or } \omega = \frac{v}{r} = \frac{p}{\gamma m R} = \frac{qB}{\gamma m}$$

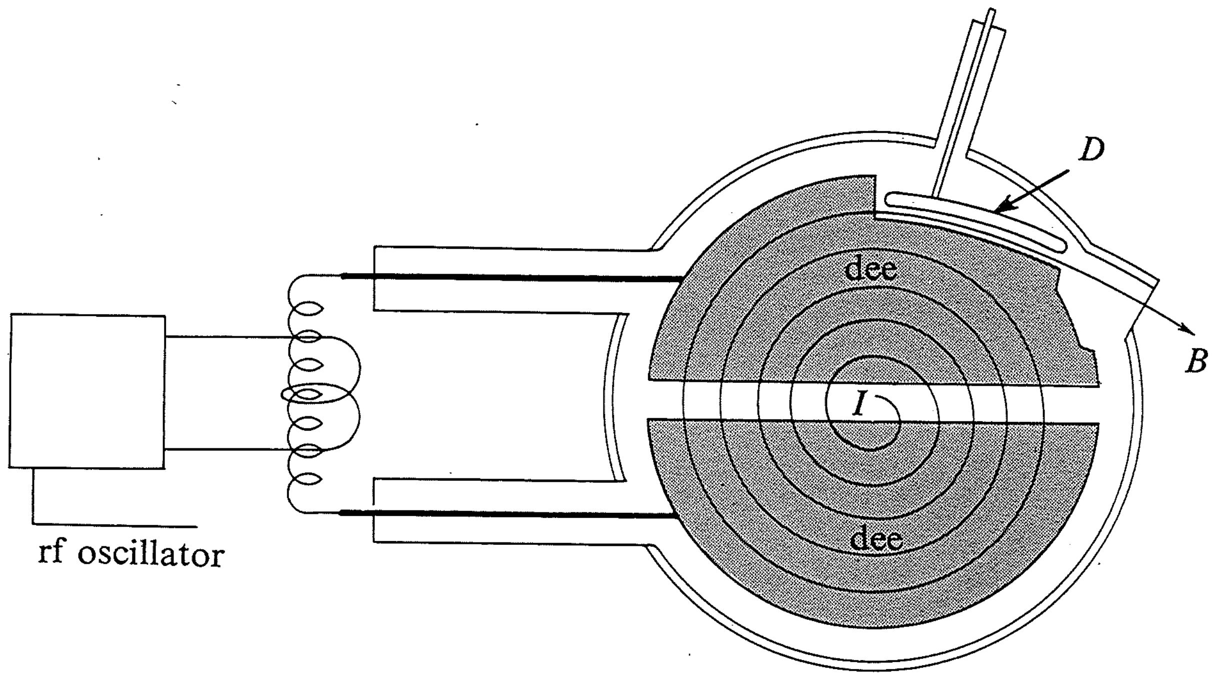



**Figure 4-7** Essential parts of a cyclotron (not including the magnet), showing dees (hollow semicircular accelerating electrodes), dee stem insulators, resonant circuit with an rf power source, and deflector plate $D$. The path of the ions from the source at the center $I$ to the point of emergence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

1975 discovery of $\tau^-$ in accelerators [Perl]

first 3rd generation particle discovered

$m_\tau = 1777$ MeV

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

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

Conservation of lepton numbers $L_e$, $L_\mu$, $L_\tau$

| | $L_e$ | $L_\mu$ | $L_\tau$ |
|---|---|---|---|
| $e^-$ | 1 | 0 | 0 |
| $e^+$ | -1 | 0 | 0 |
| $\nu_e$ | 1 | 0 | 0 |
| $\bar{\nu}_e$ | -1 | 0 | 0 |
| $\mu^-$ | 0 | 1 | 0 |

etc.

| | $\mu^-$ | $\longrightarrow$ | $e^-$ | $\bar{\nu}_e$ | $\nu_\mu$ | |
|---|---|---|---|---|---|---|
| $L_e$ | 0 | = | 1 | − 1 | + 0 | ✓ |
| $L_\mu$ | 1 | = | 0 | + 0 | + 1 | ✓ |