24. FAMILIES OF PARTICLES ; PARTICLE ACCELERATORS

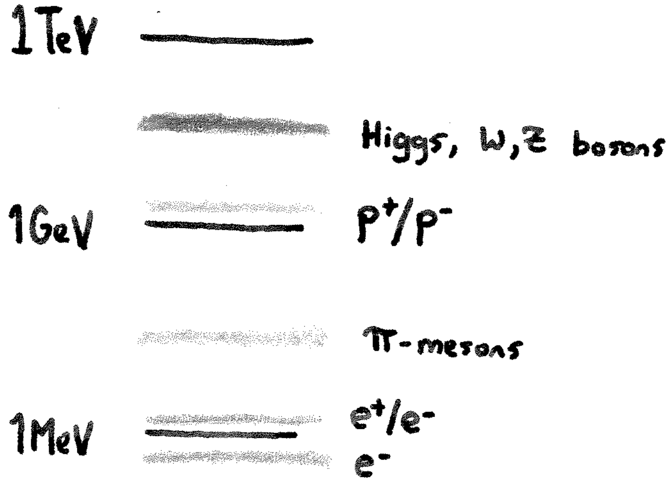
Today we'll talk about the families of particles that are revealed when we collide protons , electrons and their antiparticles with one-another inside accelerators. Why accelerate particles ? Elementary particles might be viewed as the fundamental "vibrations" or notes of the cosmos. If we are to understand the fabric of our cosmos, we need to play these notes – but to do this – we must concentrate energy within the tiniest spaces.

An electron-positron pair requires just over a million electron volts $(2 \times 0.511\,\mathrm{MeV} = 1.022\,\mathrm{MeV})$ for its creation.

However these are the lightest particles we know.*

To create a proton-antiproton pair requires 2000 times more energy ~ roughly 2 Giga electron volts $(2 m_p c^2 = 2 \times 0.938 = 1.876\,\mathrm{GeV})$

To produce the W & Z bosons that carry the weak force requires electron-positron pairs of about 80 or 90 GeV, and the as-yet undiscovered "Higg's" boson is predicted to require proton-antiproton collisions with about 120 GeV of energy.



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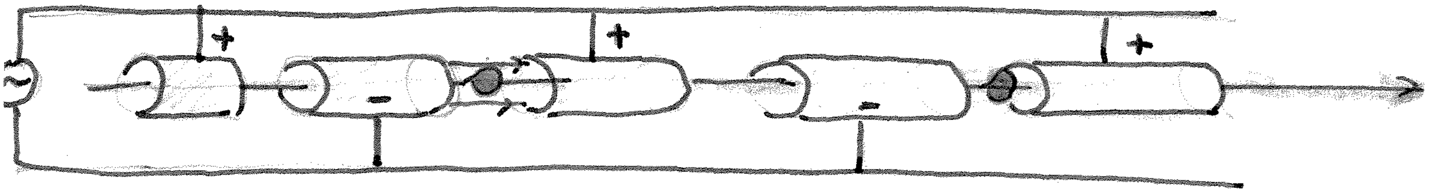
* Lightest charged particles.

Today, the most powerful particle accelerators — the "Tevatron" at Fermi National Lab in Illinois, and the soon-to-be complete "Large Hadron Collider" at the Centre European de Recherche Nucleare (CERN) in Geneva, Switzerland, can achieve collision energies up to a Tera-electron volt (TeV or "tevatron").

44.2 Accelerators

Accelerators are devices that expose particles — typically protons, or electrons, to accelerating electric fields. We'll examine three basic types — the cyclotron, the linear collider (or linac) and the most popular form of accelerator today — the "synchrotron".

LINEAR ACCELERATOR (LINAC)

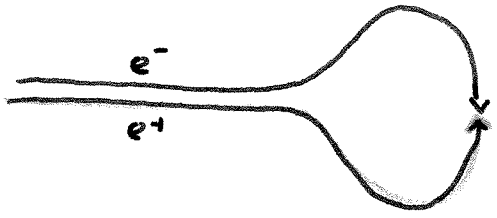


Radio frequency (RF) source creates a "wave" moving to right on which the particles "surf" up to the speed of light.

SLAC : $e^{+/-}$ reach

$\underline{E = 50\,\text{GeV}}$

3km long



e.g Calculate the wavelength of an e^- at 50GeV.

$50\,\text{GeV} \gg m_e c^2 = 0.511\,\text{MeV}$

$$\Rightarrow \quad E = \sqrt{p^2c^2 + (m_e c^2)^2} \approx pc \quad \text{(like a photon)}$$

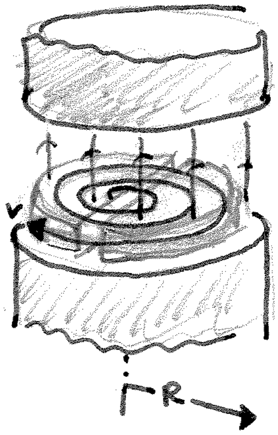
$$= \frac{hc}{\lambda}$$

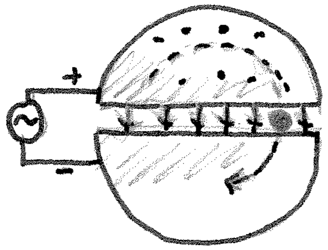
$$\lambda = \frac{hc}{E} = \frac{6.6 \times 10^{-34} \times 3 \times 10^8}{50 \times 10^9 \times 1.6 \times 10^{-19}} = 2.47 \times 10^{-17}\,\text{m}$$

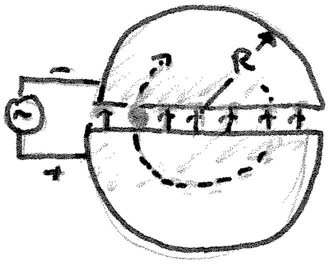
$$\simeq 25\,\text{am} \text{ or } 0.025\,\text{fm}.$$

CYCLOTRON

(1930's, E.O. Laurence + M. Livingston UC Berkeley).







$$Bqv = \frac{mv^2}{r} \Longrightarrow \boxed{\omega = \frac{v}{r} = \frac{qB}{m}}$$ cyclotron frequency.

The max speed attained as protons leave cyclotron

$$\boxed{\begin{aligned} V_{max} &= \omega r = \frac{qB}{m} R \\ KE_{max} &= \frac{1}{2} m v_{max}^2 = \frac{1}{2}\left(\frac{qB}{m}\right)^2 R^2 m \end{aligned}}$$

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e.g. $B = 0.1T$
protons
$R = 1m$

$$\omega = \frac{1.6\times10^{-19} \times 0.1T}{1.67\times10^{-27}\,kg} = 0.96 \times 10^{7} \text{ rad/s}$$

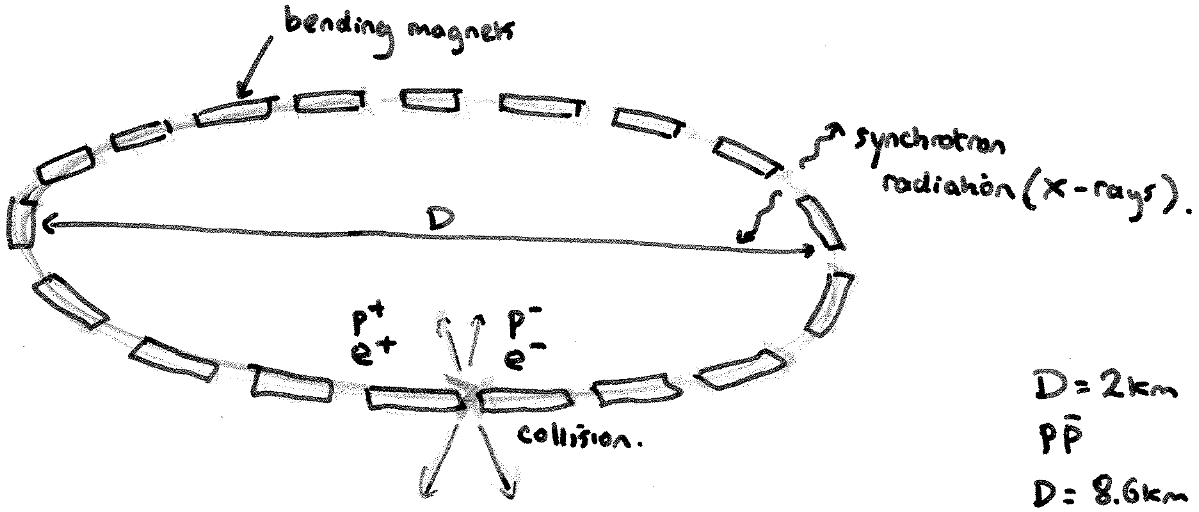
$$V_{max} = 9.6\times10^{6}\,m/s$$

$$E = \frac{1}{2} m v_{max}^2 = 7.66\times10^{-14}\,J \cong 4.8\times10^{5}\,eV$$
$$= \underline{0.48\,MeV}$$

When cyclotrons get too large, $m \rightarrow m\gamma$ increases

$\omega = \frac{qB}{m}\sqrt{1-\frac{v^2}{c^2}}$ is then smaller than the cyclotron frequency.

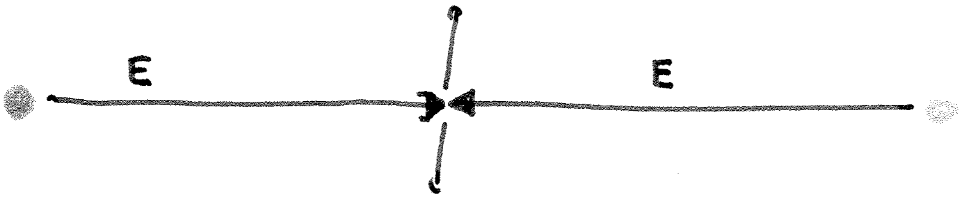
SYNCHROTRON



$D = 2$km Tevatron.
$p\bar{p}$
$D = 8.6$km LHC.

- Large radius minimizes centripetal accn $\frac{v^2}{r}$ and reduces synchrotron radiation.
- In a "collider" particles & antiparticles accelerate in opposite directions around the ring.
- Field in magnets is increased as particles accelerate.

STATIONARY TARGET VS COLLIDERS



collider

$$E_{cm} = E_a = 2E_m$$

stationary target

$$E_{cm} = E_a' = \sqrt{2(E+mc^2)mc^2}$$

$$\frac{E_a}{E_a'} \simeq \sqrt{\frac{2E_m}{mc^2}} \gg 1$$

e.g. p-p collision. How much energy to produce proton-anti-proton pairs via the reaction:

$$p + p \to p + p + p + \bar{p} \quad ?$$

Collider $2E_m > 4mc^2$ $E_m > 2mc^2 = 2\times(0.938) = 1.88$ GeV

Stationary $4mc^2 < \sqrt{2(E+mc^2)mc^2} \Rightarrow E_m > 7mc^2 = 6.57$ GeV.

44.3 FAMILIES OF PARTICLES

FERMIONS "Matter Constituents"

$S = 1/2, 3/2, 5/2 \ldots$

LEPTONS	QUARKS
e^-	u
ν_e	d
μ^-	c
ν_μ	s
⋮	

HADRONS

Quark triplets

BARYONS

$p, \bar{p}, n, \Lambda, \Omega^-$

BOSONS "Force Carriers"

$S = 0, 1, 2, \ldots$

γ
$W^\pm$
Z
$S=1$

graviton $S=2$ *

Higg's $S=0$ *

Quark, antiquark

MESONS

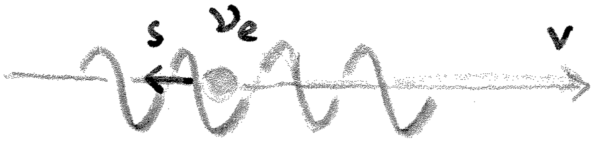
$\pi^+, K^-, \rho^+, B^0, \eta_c$

LEPTONS : Only interact via E & M / weak force.

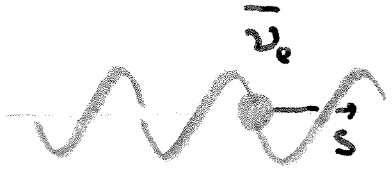
	MeV/c²	L_e	L_μ	L_τ	Lifetime
e^-	0.511	+1			STABLE
ν_e		+1			
μ^-	105		+1		2.2×10^{-6}
ν_μ			+1		STABLE
τ^-	1777			+1	2.9×10^{-13}
ν_τ				+1	STABLE.

24.10

The spin of a neutrino/antineutrino is anti parallel/parallel to its velocity



Left-handed



Right-handed.

Lepton numbers of each generation, L_e, L_μ, L_τ are conserved

(although neutrino oscillations recently observed show that this is an approximation – only total L is conserved).

	$\mu^+ \longrightarrow$	$e^+ +$	$\nu_e +$	$\bar{\nu}_\mu$
L_μ	-1	0	0	-1
L_e	0	-1	1	0

	$n \longrightarrow$	$p +$	$e^- +$	$\bar{\nu}_e$
L_e	0	0	1	-1

	$\tau^- \longrightarrow$	$e^- +$	$\bar{\nu}_e +$	ν_τ
L_e	0	1	-1	0
L_τ	1	0	0	+1

24.11

HADRONS

BARYONS : Quark triplets (qqq) $p, \bar{p}, n, \bar{n}, \overbrace{\Lambda, \Sigma}^{\text{"strange"}} \ldots$

$S = \frac{1}{2}, \frac{3}{2}$.

MESONS : Quark - antiquark pairs. $(q\bar{q})$ $\pi^{0,\pm}, \underbrace{K^{+-}}_{\text{"strange"}}, \eta^0 \ldots$

- Baryons : $B = +1$ particles ; $B = -1$ antiparticles

- Baryon # is conserved.

$$\overset{1}{n} + \overset{1}{p} \rightarrow \overset{1}{n} + \overset{1}{p} + \overset{1}{p} + \overset{-1}{\bar{p}}$$

$$\underset{1}{n} + \underset{1}{p} \not\rightarrow \underset{1}{n} + \underset{1}{p} + \underset{-1}{\bar{p}}$$

- The "Strange" particles are always produced in pairs.

  ⇒ Conserved quantum number dubbed "STRANGENESS"

$$p + \pi^- \rightarrow \underset{+1}{\Sigma^-} + \underset{-1}{K^+}$$

$$\underset{0}{p + \pi^-} \not\rightarrow p + \underset{-1}{K^-}$$

$$p + \pi^- \rightarrow \underset{+1}{\Lambda^0} + \underset{-1}{K^0}$$

	S
K^0, K^+	+1
$\bar{K}^0, K^-$	-1
Σ^+	-1
Σ^0	-1
Σ^-	-1
Λ^0	-1

"Strangeness" is conserved by the strong force, but changes by up to one unit in weak decay processes.

$$\Sigma^+ \longrightarrow n + \pi^+ \qquad \Delta S = +1$$

$$\Lambda^0 \longrightarrow p + \pi^- \qquad \Delta S = +1$$

$$K^- \longrightarrow \pi^+ + \pi^- + \pi^- \qquad \Delta S = +1 .$$

CONSERVATION LAWS

"Strangeness" is an example of a conditional conservation law — conserved by one type of interaction but not another.

QUANTITY	CONSERVED	NOT
E (Energy)	✓	—
P (Momentum)	✓	—
L (Angular M.)	✓	—
Q (Charge)	✓	
B (Baryon number)	✓	
S (Strangeness)	STRONG, E.M.	Weak
I (Isospin)	Strong	E.M, weak
Parity	Strong, E.M	Weak

(p: $I_3 = +1/2$
n: $I_3 = -1/2$)