PA2260

Quantum & Relativity : Special Relativity

Lecture 1

History

1676 - Ole Romer calculated speed of light from Jupiter.
light of moons appear faster when closer/approaching.
He calculated 10^{-4} c ($30 kms^{-1}$) too slow!

1849 - Hippolyte Fizeau measured c by reflecting a beam off a distant mirror.

1865 - James Clerk Maxwell unified EM & got $3 \times 10^8 ms^{-1}$

The Principle of Relativity - Galileo.

All velocities are relative

$$\underset{\text{another ref frame}}{\underline{r}_B} = \underset{\text{nonaccelerating ref frame A}}{\underline{r}_A} - \underline{v}t$$

Hence accelerations in each frame are the same:

$$\ddot{\underline{r}}_B = \ddot{\underline{r}}_A$$

So you can't measure absolute velocities, but you <u>can</u> measure absolute acc^n.

Lecture 2

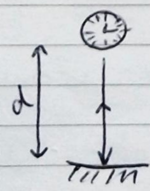
1905 - Einstein's paper extended Galilean Principal. Dispersed "ether" idea.

1. Laws of physics are identical in all non-accelerating inertial frames.

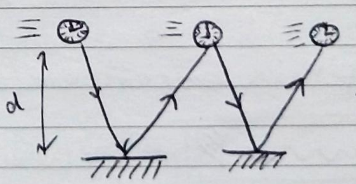
2. C is a constant for observers in inertial frames (in a vacuum). So it appears constant when you're not accelerating.

Time Dilation

if a clock ticks when a photon bounces between it & a mirror



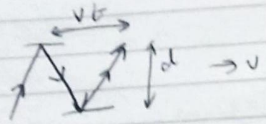
If it moves, the γ needs to travel further => clock runs slower. => clock sees us running slower



the clock won't realise <u>it's</u> slower, it thinks everything else is slower

The passage of time appears relative here.

let's do maths!



so time between a stationary clock:

$$\delta t = 2d/c$$

time between ticks of moving clocks at v $\delta t'$:

$$\delta t' = \sqrt{(2d)^2 + (v\delta t')^2}\ /c$$

$$c^2 \delta t'^2 = (2d)^2 + v^2 \delta t'^2$$

$$(c^2 - v^2)\delta t'^2 = (2d)^2$$

$$\delta t'^2 = (c\delta t)^2 / (c^2 - v^2)$$

so $$\boxed{\delta t' = \frac{\delta t}{\sqrt{1 - \frac{v^2}{c^2}}}}$$

so if $v = 0$ $\sqrt{1 - \frac{v^2}{c^2}} = 1$
if $v = c$ $\sqrt{m} = 0$
so $\delta t / m \Rightarrow \infty$

The Lorentz Factor

$$\gamma \equiv \frac{1}{\sqrt{1 - \beta^2}} \qquad \beta \equiv \frac{v}{c}$$

if $\beta = 0.866$
$\gamma = 2$
he says it too much for me to ignore ‼

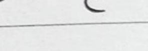
so time dilation can be written as $\delta t' = \gamma \delta t$

Lorentz factor become significant <u>only</u> at high velocities. no relativistic effects in everyday.

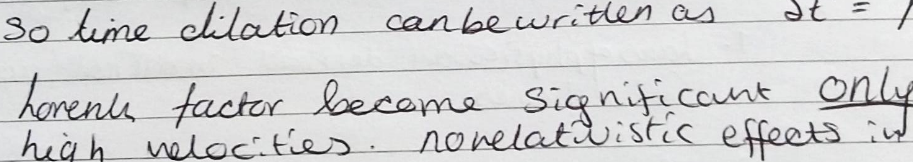
Length Contraction

imagine measuring length by firing a photon to front and back and timing the light

$$2L = ct$$



If this experiment were moving, the mirror would also move



outward part of journey   return back

$$vt_1' + L' = ct_1' \quad ; \quad L' - v_2' = ct_2'$$

$$t' = t_1' + t_2' = \frac{L'}{c-v} + \frac{L'}{c+v}$$

$$= \frac{2L'}{c}\left[\frac{1}{1-v^2/c^2}\right]$$

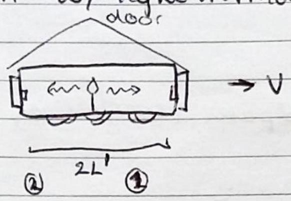
and:
$2L = ct$

observer   experiment.

hence $\Rightarrow$ $\boxed{L' = \frac{ct'}{2\gamma^2} = \frac{ct\gamma}{2\gamma^2} = L/\gamma}$.

Another experiment

Train w/ light in middle, Doors w/ light sensor that open.



beam going forward takes longer to travel. no "momentum" principle, γ don't do that.

All of this is assuming you're omnipresent.

$$vt_1' + L' = ct_1' \quad ; \quad L' - vt_2' = ct_2'$$

$$\Delta t' = t_1' - t_2' = \frac{L'}{c-v} - \frac{L'}{c+v}$$

Difference in time between doors

$$= \frac{L'(2v)}{c^2-v^2} = \gamma^2 \frac{v}{c^2} 2L'$$

Example:

Spaceship 1000m w/ $\beta = 0.866$

① $\gamma = \frac{1}{\sqrt{1-0.866^2}} = 2$ ② Length we see $L' = L/\gamma = 500m$

③ clocks look half speed on ship.

④ time dilation between front & back of ship:

$$\Delta t' = \gamma\beta\frac{L}{c} \approx 6\mu s.$$

Lecture 3 **Maths of Spacetime.**

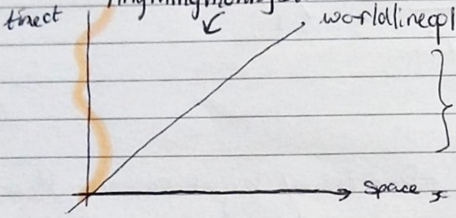
we can set time as the 4^{th} dimesion eg (x, y, z, ct) makes a distance.

All have same units now

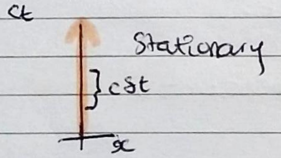
Spacetime diagrams.

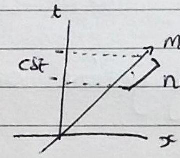
for the purpose of ~~kr~~ repoesentation. we need to lose a dimension or two.

Anything moving slower than c is here



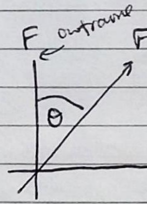
A material body will follow a curved path (worldlines) but never < 45°



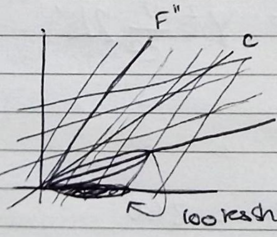


$c\delta t' = \gamma c \delta t$.

Stretched out by Lorenz factor.



$\tan\theta = \beta$ from prev lecture.



reflected F

looks shorter line. follow the diamond grid

search hypersurface

Vectors on the light cone are said to be light like. All events can be contained within. Points outside light cone called space like separated. or light separated.

Special Relativity could be understood in a geometrical way 1908 minkowski

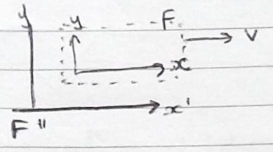
$$\delta s^2 = c^2 \delta t^2 - \delta r^2$$

independent of reference frame. so interval is same for all inertial observers.

spacetime interval, seperated by space & time.

The Lorentz Transformation.

Tells us how separation of time & space change when transferring ref frames. (but no acceleration!)



$$\delta t' = \gamma(\delta t + v\delta x/c^2) \quad \text{or} \quad \delta t = \gamma(\delta t' - v\delta x'/c^2)$$

$$\delta x' = \gamma(\delta x + v\delta t) \quad \delta x = \gamma(\delta x' - v\delta t')$$

$$\left.\begin{aligned} \delta y' &= \delta y \\ \delta z' &= \delta z. \end{aligned}\right\} \text{ v is along x axis.}$$

Consider something stationary on F. $\delta x = 0$ but not $\delta x'$

so $\delta t' = \gamma(\delta t)$ here.

for length contraction, set $\delta t' = 0$ for inverse transformation.

$$\delta x = \gamma \delta x'.$$

we can represent these as matrices.

$$\begin{pmatrix} c\delta t' \\ \delta x' \\ \delta y' \\ \delta z' \end{pmatrix} = \begin{pmatrix} \gamma & \beta\gamma & 0 & 0 \\ \beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c\delta t \\ \delta x \\ \delta y \\ \delta z \end{pmatrix}$$

Velocity Addition Rule.

object in F moving at u. (F moving at v.) in frame F", we'd naively expect it u'

$$u' = v + u \quad \text{not true though!}$$

Actually: $u' = \frac{\delta x'}{\delta t} = \frac{\gamma(\delta x + v\delta t)}{\gamma(\delta t + v\delta x/c^2)}$ $\Rightarrow$ $u' = \dfrac{v+u}{(1 + uv/c^2)}$

this is so if we had 2 F moving at 0.8c & object also 0.8c we don't actually get 1.6c, which is over speed of light!

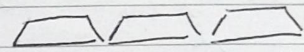
Lecture 4

Twin Paradox.

1 twin stays on Earth w/ a clock, other twin speeds off on rocket w/ a clock. The both appear slow to the other. The twin returns, and the Earth twin should have aged alot.

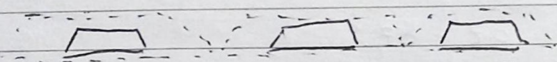
The ship twin hadn't a ... frame because they accelerated. when she turns around and accelerates, she then sees the Earth twin age like crazy.

Bell's Paradox but different



$\Rightarrow a$

3 carriages, self propellent, each behind each other. The drivers at the exact same time accelerate until 0.866c & what do you expect?



they separate.

they contract and stay in same "position" from driver POV, its still together.

from middle POV, front coach looks faster since γ from clock path has been cut since you're accelerating. looks faster, speedy. behind carriage looks slower, you're stretching path for γ from you to them.

Lecture 5

Mass, Energy, Momentum.

Consider this

$$dE = F\,dx$$

but $F = v\dfrac{dm}{dt}$ if v is constant.

$$dE = v\frac{dm}{dt}dx = v^2\,dm \qquad \frac{dx}{dt} = v$$

$$E = v^2 \int dm$$

$$= mv^2$$

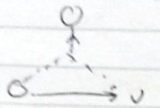
rest mass $= m_0$

m_0 of $\gamma = 0$

$$E = mc^2$$ relativistic mass m_r

$$E_0 = m_0c^2$$

if 2 objects collided, one moving perpendicularly at high speed and the other stationary



to conserve momentum, one must have increased in mass because of time dilation.

$$p = \gamma m_0 v$$

Total energy $\quad E = m_r c^2 = \gamma m_0 c^2$

Squaring gives $\quad E^2 = \dfrac{(m_0 c^2)^2}{1-\beta^2} \Rightarrow E^2 - E^2 \dfrac{v^2}{c^2} = (m_0 c^2)^2$

$$E^2 = (\gamma m_0 v c)^2 + (m_0 c^2)^2 = p^2c^2 + m_0^2 c^4$$

and Kinetic ~~relativistic~~ energy as:

$$T = (\gamma - 1) m_0 c^2$$

Example a clockwork car with $m_0 = 0.1$kg
The car reaches $0.866c$. Assuming no energy lost.

$m_r = ?$ stays 0.1 kg.

$m_0 = ?$ becomes 0.05kg $\quad (m_r c^2 = \gamma m_0 c^2)$

why? when we wound the clock up, we gave it lots of energy $\Rightarrow$ increased its rest mass.

Mass can be expressed in GeV/c^2.

eg $\quad M_p = 1.67 \times 10^{-27}$ kg $= 0.938\ GeV/c^2$

momentum can be written as GeV/c

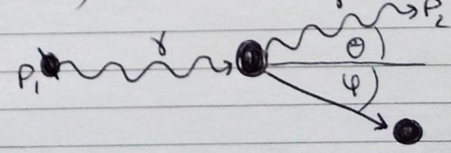
Compton Effect

momentum conservation

$$\begin{pmatrix} P_1 \\ 0 \end{pmatrix} = \begin{pmatrix} P_e \cos\varphi \\ P_e \sin\varphi \end{pmatrix} + \begin{pmatrix} P_2 \cos\theta \\ P_2 \sin\theta \end{pmatrix}$$

energy conservation

$$P_1 c + m_e c^2 = P_2 c + \sqrt{P_e^2 c^2 + m_e^2 c^4}$$



Square and Combine

$$p_1 p_2 (1-\cos\theta) = m_e c (p_1 - p_2)$$

So change in wavelength:

$$\boxed{\Delta\lambda = \frac{h}{p_2} - \frac{h}{p_1} = h \times \frac{p_1 - p_2}{p_1 p_2} = \frac{h}{m_e c}(1-\cos\theta).}$$

Example 2 photons 1 TeV γ ray. (10^{12} eV)

$p_1 = E_1/c$ $\quad\quad$ $p_2 = E_2/c$

what energy would p_1 need for the collision to make a $e^- e^+$ pair?

momentum conserved, so if just sufficient to produce a pair : $2p_e = (p_1 - p_2)$

and energy $(E_1 + E_2)^2 = (2E_e)^2 = (2p_e c)^2 + (2m_e c^2)^2 = (p_1 - p_2)^2 c^2 + 4m_e^2 c^4$

hence $\quad E_1 E_2 = m_e^2 c^4 \quad$ after lots of cancellations!

$$E_1 = \frac{m_e^2 c^4}{E_2} \quad\quad E_2 = 1 \text{ TeV}.$$

$$\approx 0.25 \text{ eV}.$$

One more: inelastic 2 lumps of clay, rest masses $m_0 = 1$kg fired at each other at $0.943c$ ($\gamma = 3$), they stick as they collide, at that moment, M_0 combined = ?

Total energy $= E = 2\gamma m_0 c^2$

$$M_0 = 2\gamma m_0 = 6\text{kg}.$$

Once excess internal energy has radiated away, $M_0 = 2$kg.

Inelastic collisions

Lecture 6

See previous example. KE not conserved here, but in general Energy is always conserved

Further Consequences

1 Test: muon decay. It Takes 30×10^{-6} s to reach ground (10km), but ½ life is 2×10^{-6} so most shouldn't make it. Actually, more than we expect do. γ factor normally 5−10, so lifetimes stretch to $10\text{-}20\times10^{-6}$ s. in terms of length contraction ie muon's POV, distance looks about 1−2km

Doppler Shift

Conventional eq:

$$\frac{\lambda_{obs}}{\lambda_{actual}} = \frac{C+V_s}{C+V_s}$$

← velocity of source relative to medium

← velocity of receiver

Adding Special relativity:

$$1+z = \frac{\lambda_{obs}}{\lambda_0} = \gamma\left(\frac{c+v}{c}\right) \Rightarrow \left(\frac{1+ v/c}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\right) = \sqrt{\frac{(1+\beta)^2}{(1-\beta)(1+\beta)}} = \boxed{\sqrt{\frac{1+\beta}{1-\beta}}}$$

This time-slowing applies whatever direction. Successive wavecrests are delayed. Switch signs for approaching source

Doppler effect reduces luminosity for redshift (γ loses energy by factor $\sqrt{(1+\beta)(1-\beta)}$. Vice versa for blueshift.

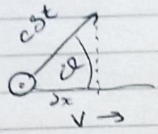
Rate of γ arrival varies with time dilation, by a factor of:

$$\frac{1+\beta}{1-\beta}$$

eg blazar's incoming jet brighter than back jet.

Headlamp Effect

$c\delta t \cos\vartheta = \delta x$ if stationary.



Now Sun's moving at v:

in our frame

$$\cos\vartheta' = \frac{\delta x'}{c\delta t'} = \frac{\gamma(\delta x + v\delta t)}{c\gamma\left(\delta t + \frac{v\delta x}{c^2}\right)}$$

So we see a weird angle.

$$= \frac{\frac{\delta x}{\delta t} + v}{c + \frac{v\delta x}{c\delta t}}$$

use stationary eq.

So if $\odot$ $\cos\vartheta = 0$ then

$\cos\vartheta' = \beta$ in ~~c~~ which $=1$.

so $\vartheta' = 0$

Means rapid approach makes lightsource bend towards you

$$\boxed{\cos\vartheta' = \frac{\cos\vartheta + \beta}{1 + \beta\cos\vartheta}}$$

highest intensity occurs when $\vartheta = 90°$ ~~...~~ so already pointing at you.

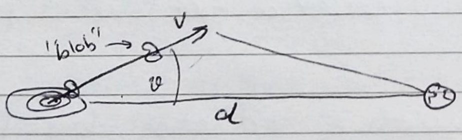
if ϑ' is small $\quad \cos\vartheta \rightsquigarrow 1 - \frac{\vartheta'^2}{2} = \boxed{1 - \frac{\vartheta^2}{2} + \beta.}$

hence $\quad \boxed{\vartheta'^2 \approx \vartheta^2 \frac{1-\beta}{1+\beta}} \quad$ familiar!

Thus there's increase in intensity!

"Superluminal" Motion. (faster than c motion).

eg jets with both doppler boosting + headlamp effects.



if ϑ is small, jets appear to move at superluminal velocity

time of arrival of light to me is d/c and:

time of arrival $= d/c$ and $t_1 + (d - vt_1\cos\vartheta)/c$

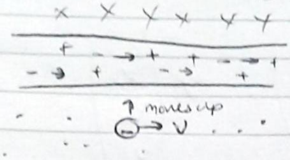
t_1 = time for something to completely transverse the jet.

tangential velocity $\quad u = \frac{vt_1 \sin\vartheta}{t_1 - \frac{v}{c}t_1\cos\vartheta} = \frac{\beta\sin\vartheta}{1 - \beta\cos\vartheta}c$

apparent distance travelled tangentially: vt_1.

Magnetism

eg electron moving parallel to a wire with current I at distance r.



From β^- POV it sees a +ve wire
it's attracted to wire by Coulomb's force.

$$F = \frac{e\lambda(\gamma - 1/\gamma)}{2\pi r \varepsilon_0}$$

p wire POV

$$\approx \frac{\mu_0 e \lambda v^2}{2\pi r}$$ since $\gamma - 1 \approx \beta^2/2$ when β is small

and $c = \sqrt{\varepsilon_0 \mu_0}$

lecture 7

Proper time

time measured by stationary (or accelerated) clock is "proper time".

$$\boxed{\tau = \int \frac{dt}{\gamma(t)}}$$ so $\Delta t = \gamma \Delta \tau$ (Proper time)

the proper time is maximised for non accelerating observers

eg twin paradox

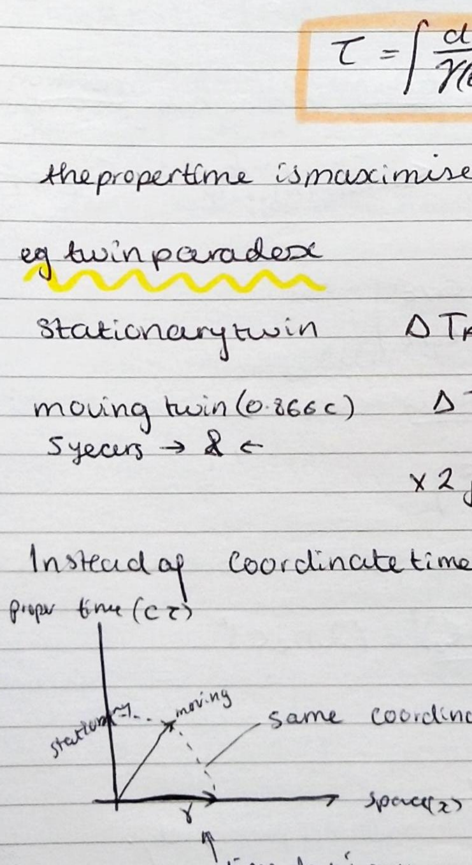
stationary twin $\Delta T_A = \sqrt{(10\text{ years})^2} = 10$ years

moving twin (0.866c) 5 years → & ← $\Delta T_{leg} = \sqrt{5yr^2 - 4.33yr^2} = \sqrt{(6.25yr)^2} = 2.5$ years.

x 2 journeys $= 2\Delta T_{leg} = 5$ years.

Instead of coordinate time, lets plot proper time

As you go faster your angle will tilt towards space axis.



4-Velocity

we can define velocity with 3 space properties & time.

4 velocity is rate of change of 4-position wrt to propertime.

$$\underline{\vec{V}} = \frac{d}{d\tau}\begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} = \gamma \frac{d}{dt}\begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} = \gamma \begin{pmatrix} c \\ v_x \\ v_y \\ v_z \end{pmatrix}$$ Simplified Minkowski space.

magnitude

$$\underline{\vec{V}} \cdot \underline{\vec{V}} = \gamma^2(c^2 - v^2) = c^2\gamma^2\left(1 - \frac{v^2}{c^2}\right) = c^2$$

So think that we're all travelling at c, but some of us is in the time component.

4-momentum:

$$\underline{\vec{P}} = \underset{\text{rest mass.}}{m_0}\underline{\vec{V}} = \gamma m_0 \begin{pmatrix} c \\ v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} E/c \\ p_x \\ p_y \\ p_z \end{pmatrix}$$

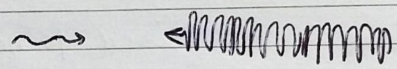
$E = \gamma m_0 c^2$

$E^2 = p^2c^2 + m_0^2c^4$

magnitude

$$\underline{\vec{P}} \cdot \underline{\vec{P}} = \frac{E^2}{c^2} - p^2 = (m_0 c)^2 = \left(\frac{E_0}{c}\right)^2$$ invariant (independent of frame).

Example. remember mega ~~photon~~ electron hitting baby ~~photon~~ positron

$E_1/c = P_1$  $E_2/c = P_2$

using 4 momentum:

$$\underline{\vec{P}} = \begin{pmatrix} E_1/c + E_2/c \\ E_1/c - E_2/c \end{pmatrix} \begin{matrix} \leftarrow \text{time} \\ \leftarrow x \end{matrix}$$

4 momentum of $\gamma\gamma$ pair in <u>their</u> rest frame:

$$\underline{\vec{P}} = \begin{pmatrix} 2m_e c \\ 0 \end{pmatrix}$$

momentum's conserved, so equate before and afters:

$$\frac{(E_1 + E_2)^2}{c^2} - \frac{(E_1 - E_2)^2}{c^2} = (2m_e c)^2$$

expand & simplify

$4E_1E_2 = 4m_e^2c^4$

$E_1E_2 = (m_e c^2)^2$ as found previously.

Intro to General Relativity.

Lecture 8

If a rocket accelerates

Rocket thinks
extra velocity = dv

Earth thinks
already travelling v' so:
$$v' + dv' = \frac{v' + dv'}{1 + v'dv/c^2}$$

but also include time dilation:

$$dt' = \gamma dt$$

Hence observed acceleration:

$$a' = \frac{dv'}{dt} = \frac{1}{dt'}\left(\frac{v' + dv}{1 + v'dv/c^2}\right) = \frac{1}{\gamma dt}\left(\frac{dv - v'^2 dv/c^2}{1 + v'dv/c^2}\right)$$

$$= \frac{a}{\gamma}\left(\frac{1/\gamma^2}{1 + \frac{v'dv}{c^2}}\right)$$

tends to $\Rightarrow \dfrac{a}{\gamma^3}$.

so if they're moving relativistically acceleration looks minimal regardless.

Extra Stuff

Black Holes: redshift

wavelength

$$1 + z = \frac{\lambda_\infty}{\lambda_0} = \frac{1}{\sqrt{1 - R_s/R_0}}$$

seen by super far observer.

Stretching γ till $z = \infty$

time gets slower & slower as you get to R_s.

Unit 2: Elementary Particles.

Lecture 1

Hadron.

2 types: meson & baryon. Not elementary.

meson → 0 spin, mass between e^- and p.

baryon → ½ integer spin, mass ≥ p. → proton, neutron, Σ^{+0-}, λ^0

→ strong interactions

Σ and λ have S = -1

Leptons

weak interaction. 1/2 spin.

Electron (neutrino), muon (neutrino), tauon (neutrino)

Varying mass. τ is 2x mass of p.

Beta decay makes one electron, but to conserve energy it must make a neutrino too.

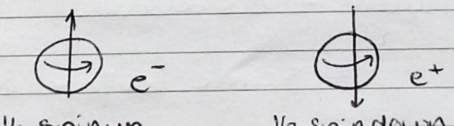
antineutrino

$$ {}^3_1H \Rightarrow {}^3_2He + e^- + \bar{\nu}_e. $$

Electrons had less energy than predicted, so neutrino was found! now e^- and ν_e can share energy in multiple ways.

Spin.

like angular momentum. a fundamental property.



Spin is a quantum property. Don't take these pictures too literally.

½ spin: e^-, p, n, ν, μ, τ have s = ½, 3/2, 5/2 ... Fermions. These obey the Pauli Exclusion Principle.

integer spin: Mesons, bosons. s = 0, 1, 2 ... don't obey PEP.

Pauli Exclusion: Only 2 particles can occupy the same quantum state, one spin up one spin down.

Stops white dwarves & neutron stars collapsing further.

Antimatter

Samparticle but opposite charge and spin
Has a bar on the symbol except e^+ and sometimes p^-.

antimatter always produced in matter antimatter pairs
eg: $2\gamma \Rightarrow e^+ + e^- \Rightarrow 2\gamma$ → photon gets $e_\gamma = m_e c^2$, $P_\gamma = m_e c$.

These get annihilated so quickly!

Lecture 2

Strong Nuclear

10^{-23} s
Hadrons (quarks)
many hadrons are stable
$n = 930s$, $P.\ 10^{30}$ yrs.

Weak Force

10^{-10} s. μ mean lifetime 2.2×10^{-6} s
e^- are very stable

neutrino's don't decay, but can change flavour.

Conservation Laws

Eenergy - total rest mass of decay products < initial mass of particle before decay

Linear momentum - e^- and e^+ must produce 2 γ to conserve and carry momentum

Angular momentum - as above.

Charge - same before & after.

Baryon number - +1 for baryon, -1 for anti baryon, 0 for else.

Lepton number - leptons are conserved, but it needs to be same flavour eg electron number = L_e for e^- & ν_e.

Strangeness - Strangeness stays conserved.

Strange Particles.

family of particles found in 1950s that behave oddly, ie conserved in some strong force, but not weak.

Made in pairs, eg Kaon $K^+ + \Sigma^-$, $K^0 + \Sigma^0$, $K^0 + \Lambda^0$ all from $\pi^- + p$.

but some interactions conserve all laws, but never occur???

$\pi^- + p - \pi^+ + \Sigma^+$ only cause strangeness isn't conserved!

However ⚠

Sometimes a strange particle decays, & strangeness ISN'T conserved.

Particles prefer strong decay, but sometimes strong doesn't allow decay, so they need weak decay:

$\Sigma^+ \rightarrow \pi^0 + p$

$\Lambda^0 \rightarrow \pi^- + p$

So it seems only strong force (+ electro) requires strangeness conservation.

Strong force - conserved

Weak force - may change by ± 1

Example:

$$K^0 \rightarrow \pi^+ + \pi^-$$

$S = +1 \quad 0 \quad 0$ so change of 1, hence could interact weakly

$$\Sigma^0 \rightarrow \Lambda^0 + \gamma$$

$S = -1 \quad -1 \quad 0$ There's a γ, so most likely electromagnetic. However strangeness is conserved, so it prefers strong decay

$$\Xi^0 \rightarrow \pi^0 + n$$

$S = -2 \quad 0 \quad 0$ Impossible!

Lecture3

Quarks

1963 discovery. ½ Spin, and third charges. All have baryon number ⅓.

6 types	Charge	Strangeness	Charm	beauty	truth	Mass
up	+2/3	0	0	0	0	335 MeV
down	−1/3	0	0	0	0	338 "
strange	−1/3	−1	0	0	0	510 "
charm	+2/3	0	1	0	0	1500 "
bottom	−1/3	0	0	−1	0	4750 "
top	+2/3	0	0	0	1	174 GeV.

main: up, down, strange

top: too unstable for hadrons

Mesons. = Quark Antiquark $u\bar{d}$

Baryon = 3 Quark uud

AntiBaryon = 3 Antiquarks $\bar{u}\bar{d}\bar{d}$

Examples:

uud — Bnumber: 1, Charge: +1, Strangeness: 0 } proton

udd — 1, 0, 0 } neutron

uus — 1, +1, −1 } Σ^+

dds — 1, −1, −1 } Σ^-

Strangeness, charm, beauty, truth are conserved in electromagnetic force, but Not in weak force.

Quark Spin

Let's say in a meson: Since all quarks have ½ spin:

↑↑ Spin 1 ($\frac{1}{2} + \frac{1}{2}$) and ↑↓ Spin 0. ($\frac{1}{2} - \frac{1}{2}$.) or ↓↓ Spin −1

In a baryon with uud

↑↑↑ Spin 3/2 ← Δ^+ particle

↑↓↓ Spin ½. ← Proton

↑↑↓ Still spin ½ ← Proton too?

You'd think uud would always mean a proton. wow!

Quark Colour

Ω^- is a baryon SSS. $S=-3$ Spin $=3/2$. Hence

↑↑↑

But Pauli Ex forbids same state sameparticles. identicality! This can work if the quarks have different colour ie RGB.

So in baryons(+antibaryons) colour is arranged so they're colourless. Baryons = RGB = white.
Antibaryon: Magenta, cyan, yellow = white.

In meson = red + antired = white.

Quark Confinement.

Quarks aren't naturally isolated. ever. impossible. Because of it, we infer propertese based on systems, and we can't accurately know mass.

lecture 4

Fundamental Forces

A particle experiences/interacts with a boson if it's charged in that property of the boson.

if we put energy into a system like accelerating a particle, virtual photons get shaken off and become real. All of the bosons can be described this way.

Photon
γ
gluon
g
Z boson
Z^0
W^+, W^-
W

Weak force

- Quarks, leptons
- W^+, W^-, Z^0 bosons
- the "charge" they mediate is flavour.
- Quantum Electrodynamics
- Spin 1
- Charges +/- 1e for W^+/W^-
  0 charge for Z

Strong force

- Quarks, hadrons
- gluon, never observed!
- The "charge" is colour
- Quantum Chromodynamics
- fundamental strong = binds quarks
- residual strong = attracts P to n in nucleus.
- Spin 1
- Charge 0

Gravity

- maybe the graviton!
- the "charge" is mass
- gravitons massless
- Spin 2
- Hypothetical,
- 0 charge.

Electromagnetic

- many particles (electrically charged).
- involves photons γ
- photons "massless"
- Spin 1
- 0 charge

Electroweak Theory.

Bring electromagnetic + weak together. At high energies, >100 GeV electroweak would be carried by $W^+, W^- W^0$ and B^0 bosons. W^0 B^0 can't be observed directly

The W^0 + B^0 combine => Z^0 bosons or γ. At ordinary energies, the symmetry is broken, and electroweak separates.

Higgs Boson

For electroweak to work, we need a Higgs Boson.

The Higgs Field breaks the symmetry. The Boson was found at CERN w/ 126 GeV/c².

Higgs

- Symbol H_0 (not Hubble!)
- no charge, no colour
- Spin 0.

Higgs.
H_0

Higgs field is an energy field. It gives rest mass to particles. It doesn't "create" mass, but "assigns".

Process of giving mass = Higgs effect.

If the field didn't exist, particles have no mass, no gravitational attraction, all travelling at c.

Quarks interact strongly w/ field, leptons interact slightly less, γ don't interact.

The Standard Model

Combination of Quark theory, electroweak and QCD make the Standard Model.

All matter is made of Quarks & leptons, all particles have anti-particle, and every force is due to 4 basic interactions.

Standard model has problems eg gravity.

Grand Unified Theory

Attempt to unify everything, gravity, GR etc...

One idea is Quarks & leptons are two aspects of a single class of particle. Early universe idea. Another idea is that protons decay, in standard model this doesn't occur.

The Big Bang.

- All fundamental forces unified.

matter wins out over antimatter

- at 10^{-43} s / 10^{32} K / 10^{19} GeV Gravity condenses out
- at 10^{-27} s / 10^{27} K / Strong force condenses out.
- at 10^{-6} s / 10^{13} K most hadrons from destroyed.

Quarks start to bind

- at 10^{-4} s antimatter annihilation creates γ and leptons
- at 10s, $e^- e^+$ annihilation removes e^+.

dominated by γ and n

- minutes in, H^2, H', He fuses.
- 300'000 yrs. mass domination. atoms created.

2.7K era, end of opaque universe

lecture 5 The rest mass of decaying particles must ALWAYS be more than the products eg $\Sigma \rightarrow n + K^-$ cannot occur!

Examples:

1) i) $\mu^+ + \mu^- \rightarrow e^+ + e^-$

L_μ $1 - 1 \rightarrow 0$ ✓

L_e $0 \rightarrow -1 + 1$ ✓

Q $1 - 1 \rightarrow 1 - 1$ ✓ possible!

ii) $\tau^- \rightarrow e^- + \nu_e$

L_τ $1 \rightarrow 0$ x Not possible!

L_e $0 \rightarrow 1 + 1$ x

2)

a)	Meson w/	$S=-1$	$Q=1$	not possible
b)	Baryon w/	$S=-1$	$Q=-1$	sdd $= \Sigma^-$
c)	Baryon w/	$S=-3$	$Q=-1$	$sss = \Omega^-$ ~~not possible (PauliEx)~~
d)	Hadron w/	$S=0$	$Q=0$	neutron udd, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$...
e)	Hadron w/ $Q=3$			not possible

$\bar{s}$ strangeness $s=1$

lecture 6 **Particle Accelerators & Colliders.**

Particle Accelerators, needed to get charged particles close together. High energies overcome electrostatic repulsion. & Shortens particle deBroglie wavelength. Makes higher resolution results.

momentum $p = \frac{h}{\lambda}$ $\quad p = \frac{h}{mv}$ $\quad \lambda = \frac{hc}{E_k}$

Tevatron Fermilab uses 1 TeV, wavelength $\approx 1.24 \times 10^{-18}$ m.

Feedback Matt calls it de Brog-lee, it's actually de "Broy".

First accelerators use constant P.D to accelerate protons.

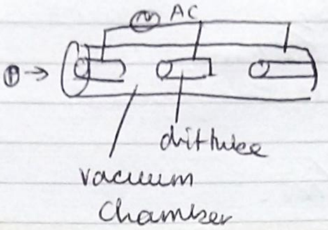
$V_{output} = 2NV_P$

# of stages Peak Voltage.

Many design flaws, couldnt go over ~ MeV otherwise hardware breakdown eg Insulators.

Linear Accelerator LINAC

beam travels through hollow electrodes. in AC Vsupply
As they cross through electrodes, they're accelerated by B field



electromagnets keep tubes suspended.

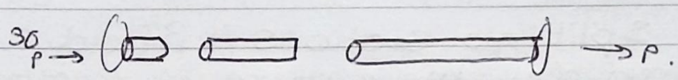
$t/2$ = half period of AC voltage.

length of drift tube of particles speed v = $L_n = vt/2$

$$\boxed{KE_n \text{ of particles} = neV_0 = mv^2/2}$$

n = gaps, V_0 = voltage.

$L_n = (neV_0/2m)^{1/2} t$. so L_n must increase as $n^{1/2}$



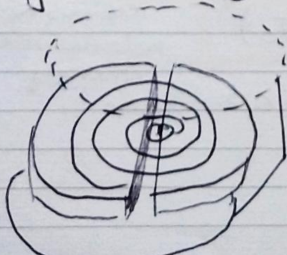
but if particles speedy, L_n is roughly the same throughout.

Cheap, don't need big magnets, no high voltages.

High energies need very long LIANCS. KE is hence very limited.

Cyclotrons.

Particles start in centre. B field bends path in spiral.
2 metal semicircular chambers, called Dees, connected to AC Voltage. feels no electric field in Dee, but in the gap between there's an accelerating voltage
gain in KE



$F = BqV = mv^2/r$

$r = mv/Bq = p/Bq$. increases v, so radius increases.

one rotation takes $t = 2\pi r / v$

$$t = 2m\pi / Bq \quad \text{not dependent on speed!}$$

frequency $\nu = 1/t = Bq / 2\pi m$ cyclotron frequency.

the velocity increases as it spirals.

$$V_{max} = Bq\, R/m.$$

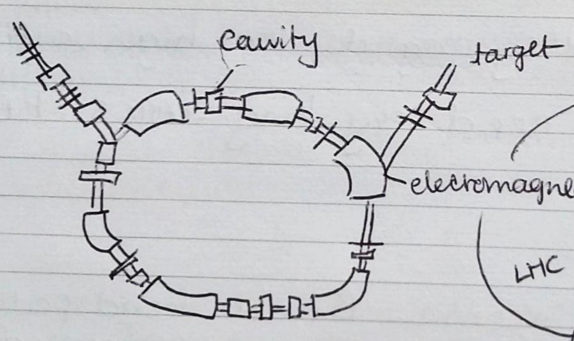
$$KE_{max} = \tfrac{1}{2} m v_{max}^2 = q^2 B^2 R^2 / 2m.$$

Small. useful for medical stuff.

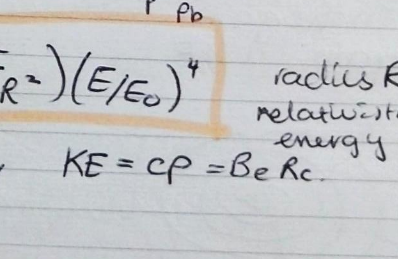
High velocity makes particle mass to increase. makes radius larger. Charges start to arrive too late to be accelerated across gap. Hence 1 GeV is limit.

Synchotrons

Rings split into sections. B field increases as particles move through ring multiple times.



CERN is made of loads of these. Proton/particle will go through some depending on experiment



Synchotron radiation
~~Net energy of proton = BeRc~~

$$\boxed{P = \left(\frac{e^2 c}{6\pi\varepsilon_0 R^2}\right)(E/E_0)^4}$$

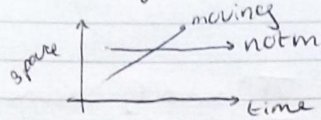
radius R
relativistic energy E.

If for a particle is $\gamma >> 1$, $KE = cp = BeRc$.

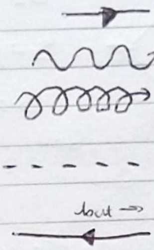
lecture 7

Feynman Diagrams.

A 2D image plotted on spacetime, sometimes time x space.



particle key:



matter particle

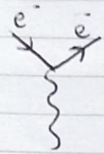
photon

gluon

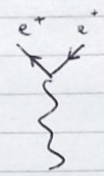
Z^0, W^+, W^- boson

but →

antimatter

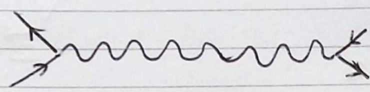


e^- emits γ and keeps going



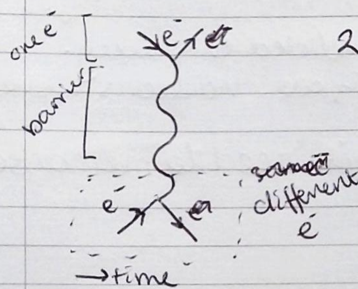
e^+ absorbs γ and keeps going

e^+e^- annihilation & "creation"



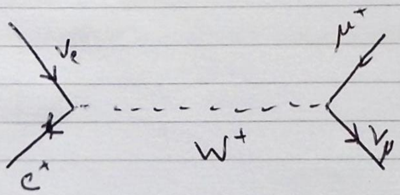
→ time γ doesn't travel much.

⚠ Although they look like they're hitting at an angle, but they're hitting head on.



2 electrons repelling each other. So electro magnetic force keeps them apart. Hence the diagram orientation.

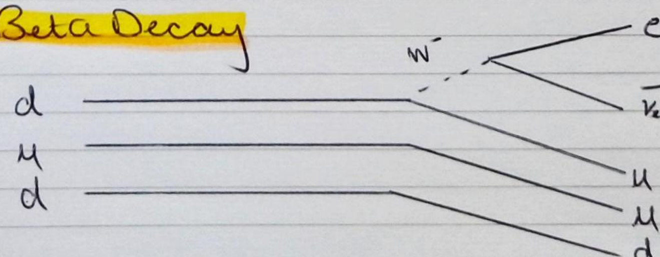
Virtual photon.



allowed

L numbers conserved
the left → W^+ → the right.

Beta Decay



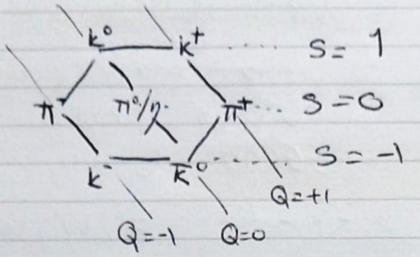
neutron → proton.

$n \to p + e^- + \bar{\nu}_e$

Lecture 8 **The Eightfold Way.**

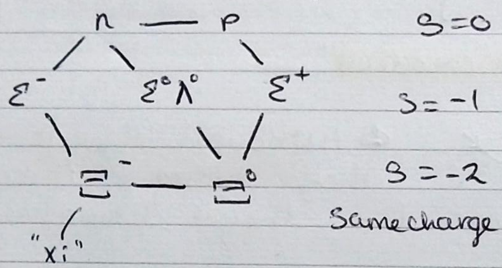
A way to organise hadrons and predict them.

Here is the meson octet

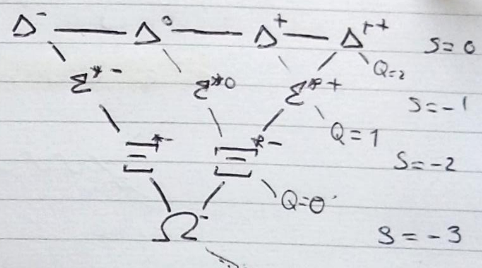


π^0 and η share a place. There's also η' etaprime, Q=0, S=0 but the digram is a bit stupid

Here's the Baryon Octet
spin $1/2$ particles



desuplet (spin-3/2)



The Omega$^-$ (sss) was predicted this way.
These paths occur naturally if all hadrons were made of only u, d, s.

You don't need to memorise these!