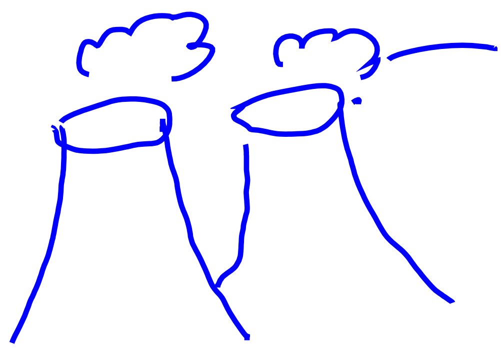
What do you think of when you talk about nuclear technology?



Picture 1

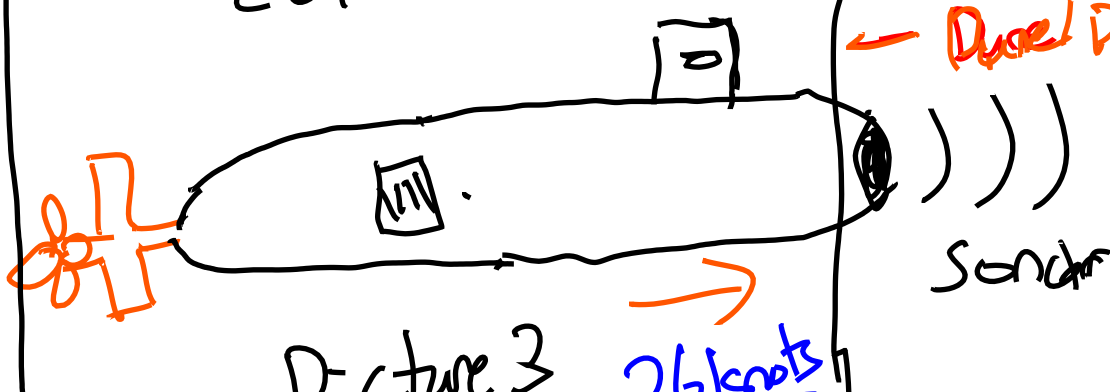
World War II

Picture 2

Gen Y

- Red Alert 2
- Yuri's Revenge
- C & C
  - ↳ Generals
  - ↳ Tiberium Wars
- Starcraft II
- ~~Dune~~ Dune part II
  - ↳ atomics

Cold War

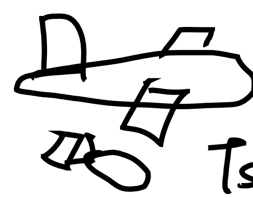


Picture 3

What's in the cold war?

- Nuclear tests
  - ↳ USA
    - ↳ Castle Bravo
    - ↳ Ivy Mike
    - ↳ ~~Operation~~ Baker (Bikini Atoll)
  - ↳ Russia
    - ↳ Tsar Bomba.
  - ↳ China
  - ↳ India
  - ↳ France
  - ↳ UK.

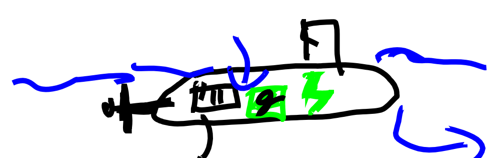
Bloons TD6.



monkey Ace

Tsar Bomba.

U-boats.



above water speed

underwater speed.

Petrol/Diesel.

- Submarines
  - ↳ reactors
  - ↳ mobile missile silo (SLBMs)

U-571

Nuclear Submarine movies.

↳ Hunt for the Red October

↳ Crimson Tide

Pop culture

- Nuclear is dangerous
- Nuclear is scary
- Nuclear is exotic

Nuclear accidents.

↳ Three Mile Island

↳ Chernobyl

↳ Fukushima Daiichi?

↳ check spelling

Nuclear safety.

For next lecture

① Accidents + pop culture

↳ BBC's Chernobyl.

② Nuclear security & cold war arms race

③ Outline of technical stuff.

cold war.

1945 2x atomic bombs plane

1945–1949 US → only major nuclear power

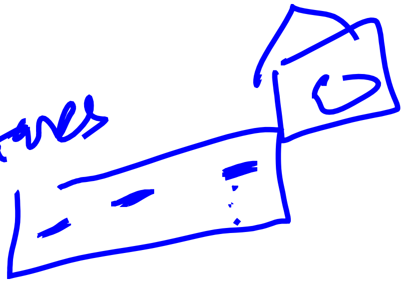
1949 USSR → explodes 1st atomic bomb.

Countervalue

drop bombs on cities

Counterforce

drop bombs to kill opponent's nuclear capability airplanes



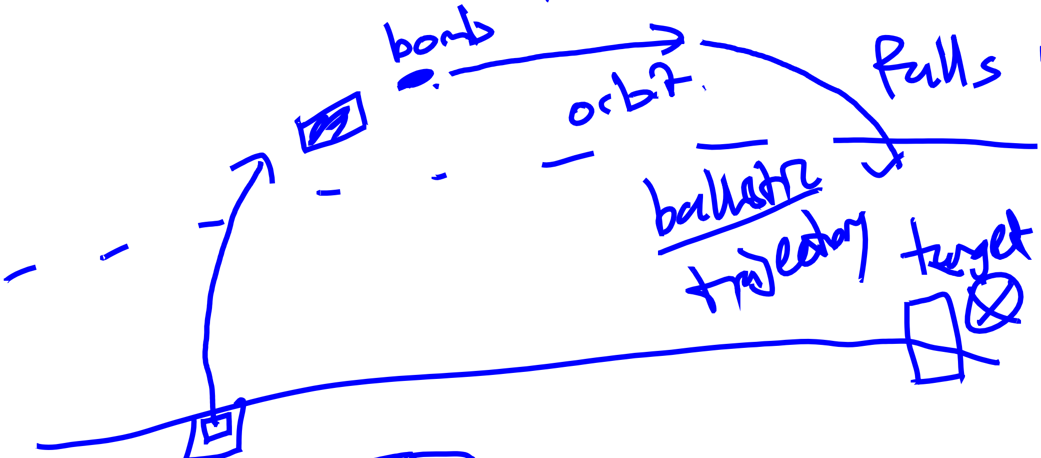
Red Alert

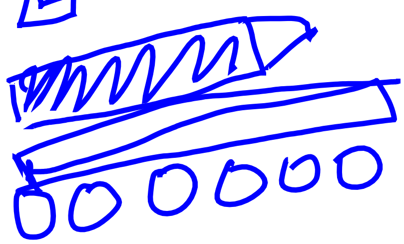
Red Alert 2

ICBMs

missile silos

Intercontinental Ballistic missile (ICBMs)





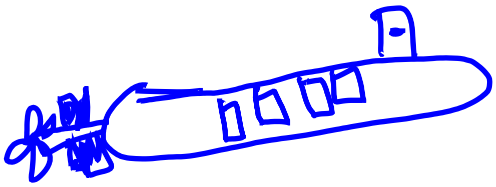
- SR 71 blackbird
- U2

mobile ICBM

nuclear deterrence

mutually assured destruction

MAD



submarine launched ballistic missiles (SLBMs)

accuracy is a big problem for SLBMs.

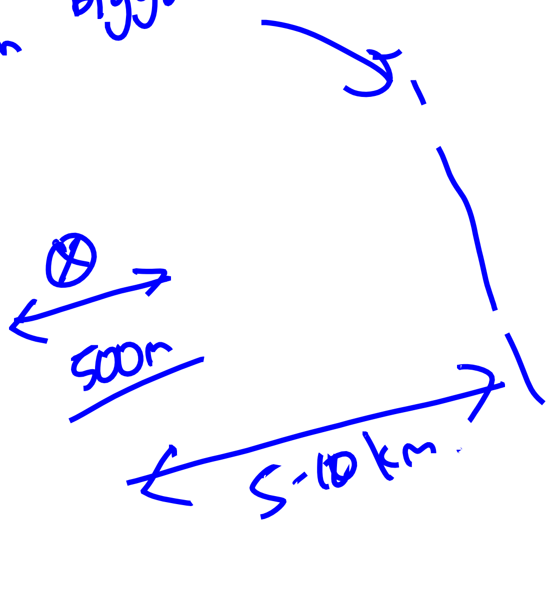
① stay underwater very long

nuclear propulsion ***

H-bomb ***

tech.

② Big big explosions, much bigger than hiroshima.



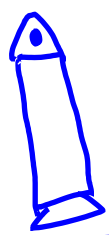
nuclear triad.

Air delivery

triad

SLBMs — ICBMs

Nuclear arms race → space race



rocket technology

- GPS
- Lunar expeditions
- communications networks. — SpaceX
- telescopes → Hubble space telescope
- Advanced science & technology

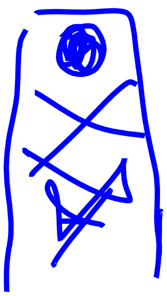
Lecture 3

Manhattan project.

$\boxed{1942}$

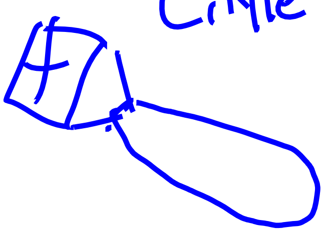
Oppenheimer cooked Nasi Goreng

trinity



Pu-239
New Mexico

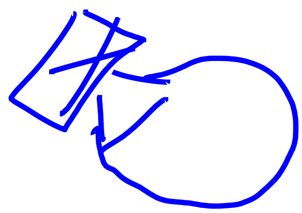
Little Boy



Hiroshima Bomb

U-235

Fat man



Nagasaki

Pu-239

Concepts w/ as little mathematics as possible

Physics

Pu-239

U-233

U-235

A (total no. of neutrons + protons)

$$^{235}_{92}U$$

Z (proton number)

$\boxed{^{1}_{0}n}$

$\circ \longrightarrow$

$\downarrow$ fission

$$^{235}_{92}U + ^{1}_{0}n$$

$\swarrow \quad \downarrow \quad \searrow$

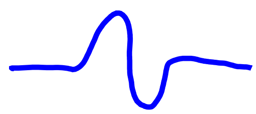
$^{1}_{0}n \quad ^{1}_{0}n \quad ^{1}_{0}n$

$$^{1}_{0}n + ^{238}U \rightarrow ^{239}U \rightarrow \dots \rightarrow ^{239}Pu$$

Quantum Physics

Key Idea of Quantum Physics.

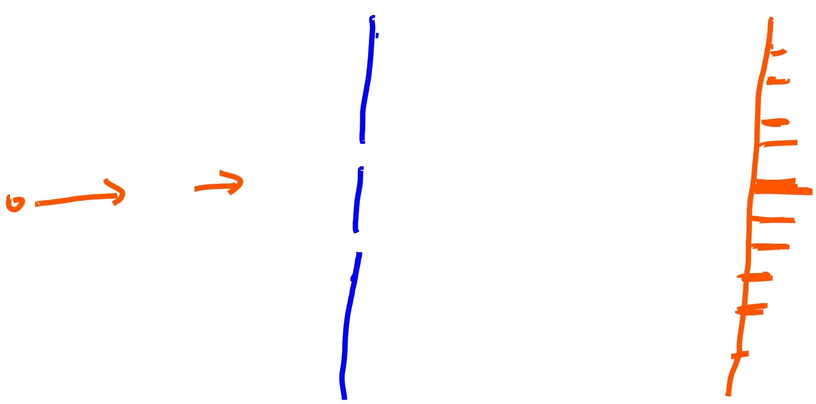
matter (protons, neutrons, electrons)



particle – wave

"billiard balls"

Young's Double Slit experiment.

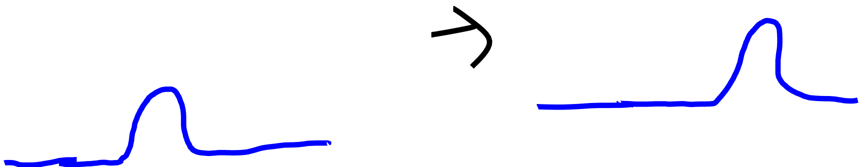


Interference Pattern.

Light → electromagnetic wave.

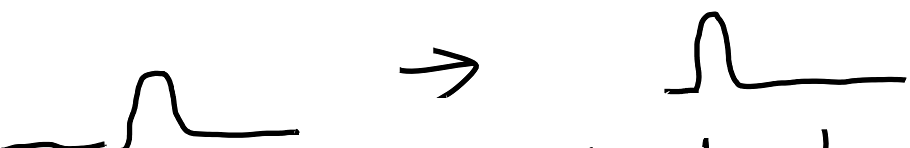
Waves & Superposition

$t=0$ $t=1$



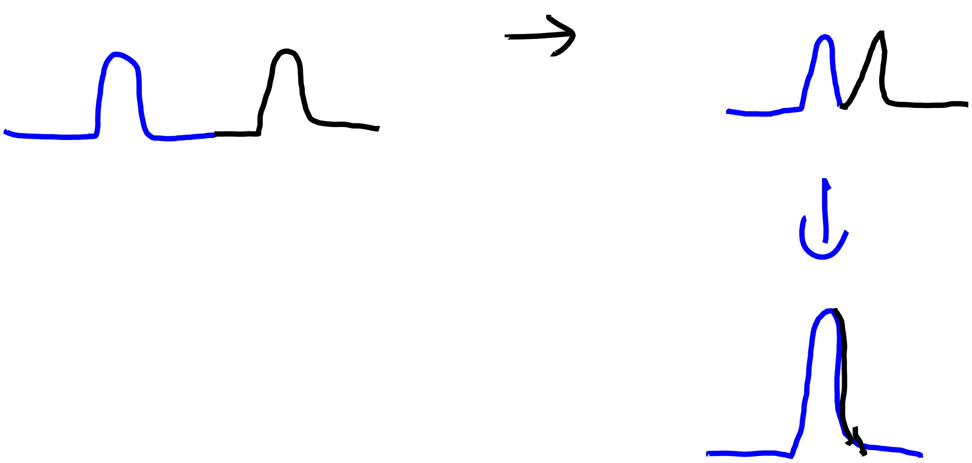
wave is travelling to ē right.

$t=0$ $t=1$



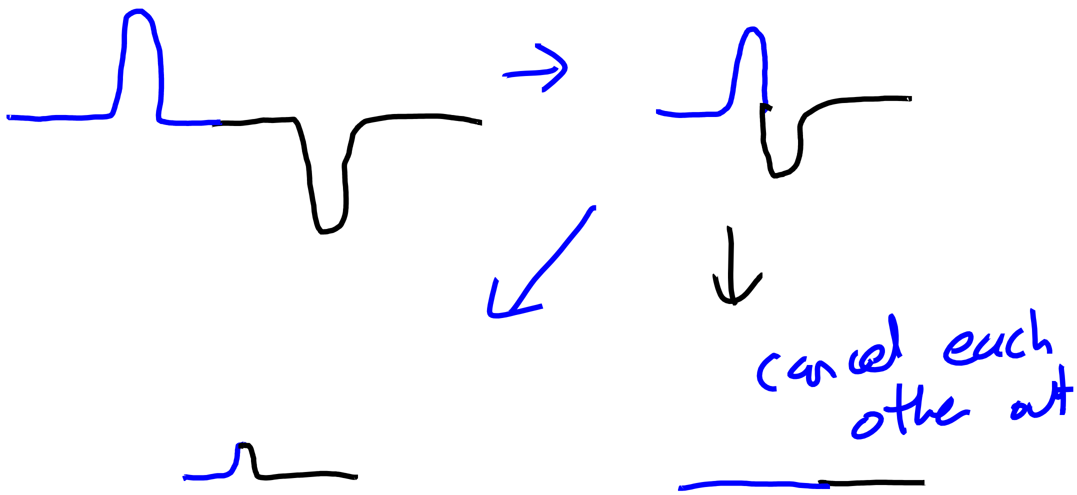
wave is traveling to the left

$t=0$ $t=2.5$?



Big wave is contribution (sum) of two smaller waves.

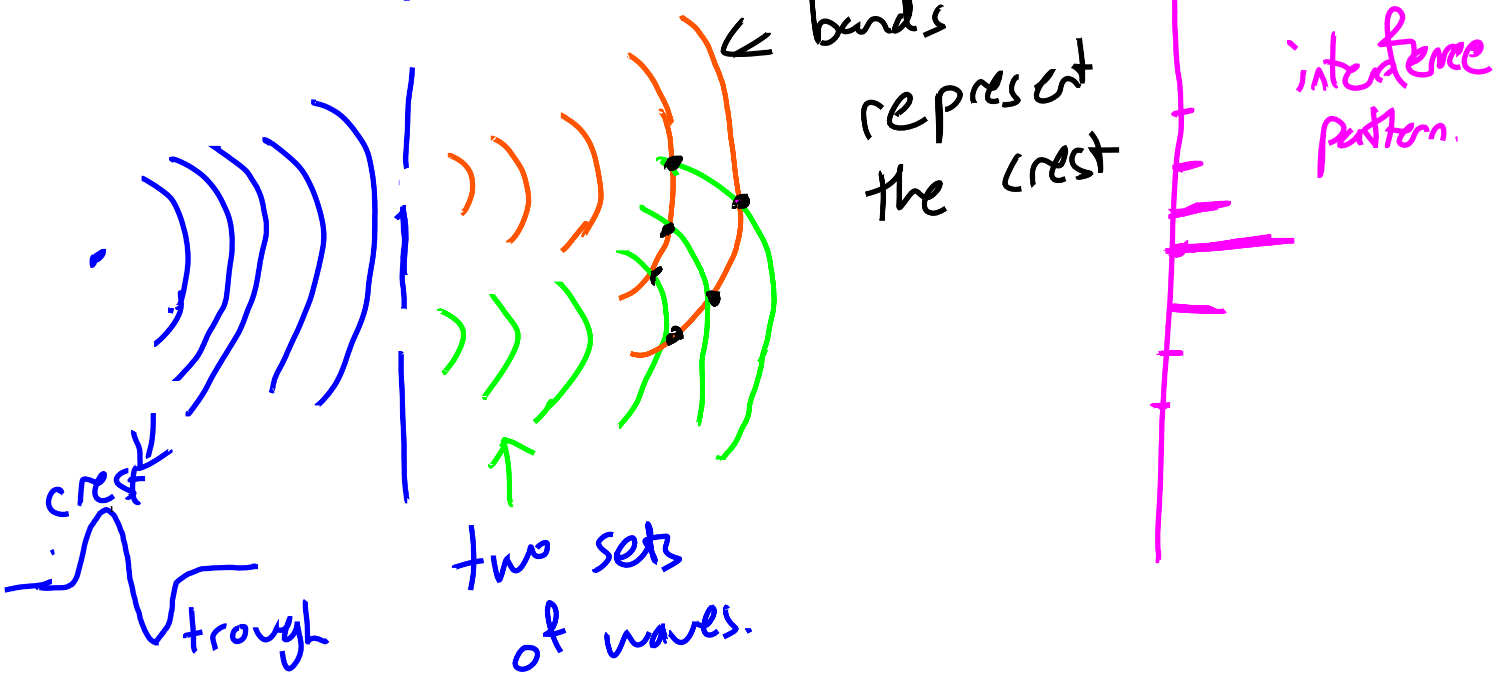
Basic idea of superposition



① when waves build on each other → constructive interference

② when waves cancel each other out → destructive interference.

Double slit



Lecture 4

Lot's of things in nuclear physics can be explained by waves.

---

consequences of wave behaviour

- electrons in atoms have discrete energy levels
- protons & neutrons in the nucleus have discrete energy levels

electrons fired one at a time

in quantum physics, the act of observation changes the experimental results

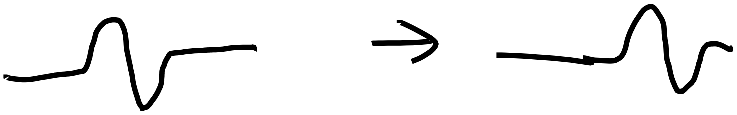
---

Discrete Energy levels

wave behaviour → discrete energy levels.

standing waves.

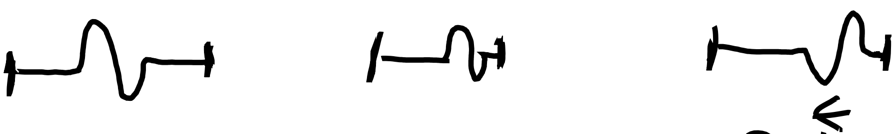
wave on water



"free"

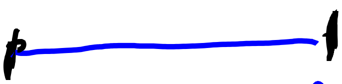
I make the wave "not free"

make the ends "stuck"



wave bounces back & forth & interferes with itself.

Guitar string

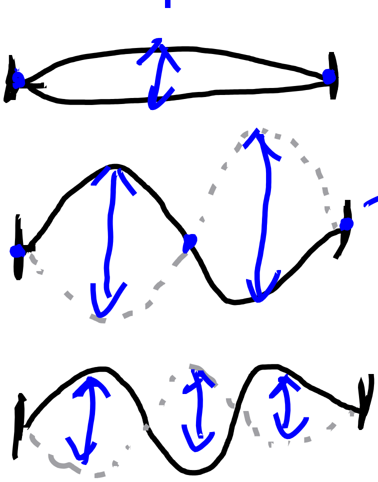


peak & trough → antinodes

n = 1 — 2L

n = 2 — L — nodes

n = 3



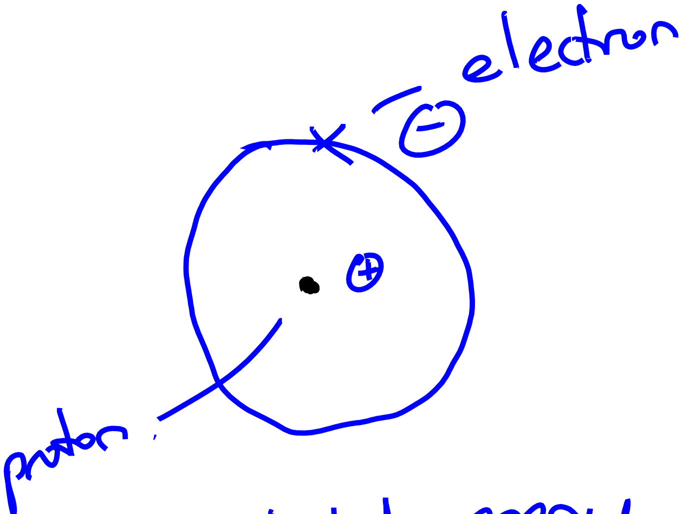
L

You can have a certain number of peaks & troughs.

You can store energy at different frequencies.

$v = f\lambda$

The frequencies (wavelengths) where you can store energy is <u>fixed</u>.



<u>Hydrogen atom</u>

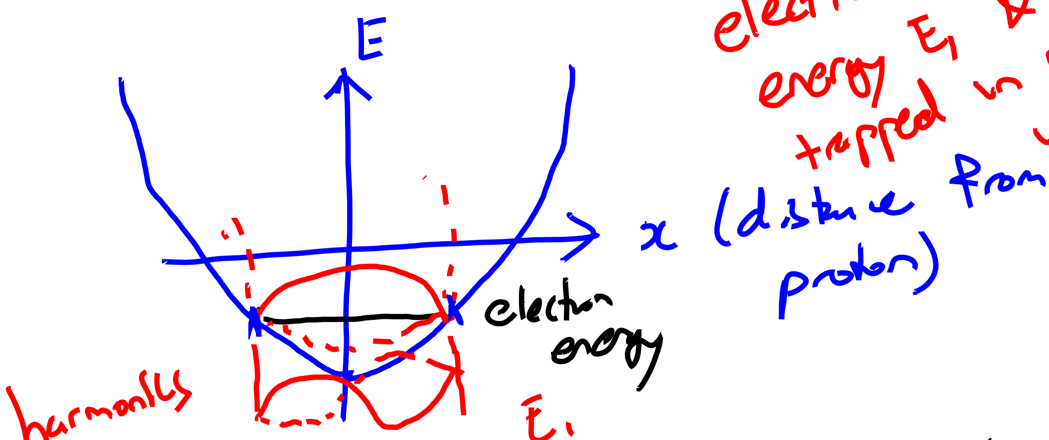
charge of each particle

$$F = \frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$$

distance between particles.

potential energy.

electron has energy E_1 & trapped in potential well



electron's energy is not high enough to escape proton.

① Electrons behave as waves

② movement of electron waves is | Standing electron restricted as electron energy < potential energy req'd to escape. | waves.

↳ standing waves consequence

① frequency / wavelength is restricted ✓

② Energy is correlated to frequency

③ Energy levels are therefore restricted. ✓

---

what is true of electrons is also true of the nucleus.

① protons / neutrons behave as waves

② movement of proton / neutron waves restricted by attractive forces in nucleus → strong nuclear force

↳ give rise to fixed energy levels with $\bar{e}$ nucleus.

Energy is "quantized"

↳ fixed energy levels.

If you are interested in the math.

Go read up:

- Schrodinger's equation
- wave function $\boxed{\psi(x)}$ ψ = "psi"

↳ "probability waves"

$|\psi(x)|^2$

↳ $\psi(x) \times \psi^*(x) \Rightarrow$ probability.

Lecture 5

schrodinger's equation

↳ implications

① Guitar string analogy

↳ Infinite square well.

↳ 1 D

↳ "force field" is infinite

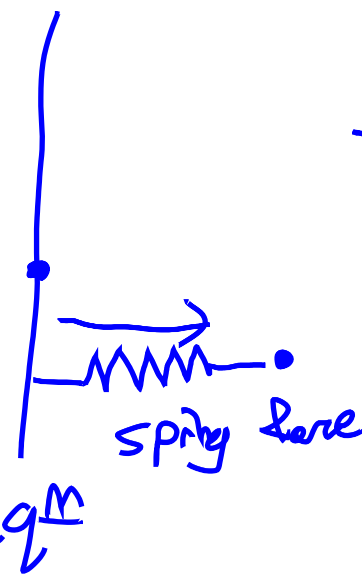
In ~~real~~ real life, force fields are finite

② Finite force fields

↳ 1D

↳ finite force field,
finite well

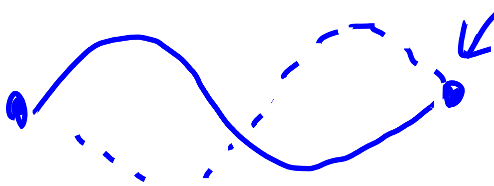
↳ simple harmonic oscillator



- finite force field

- $F = kx$

Guitar string

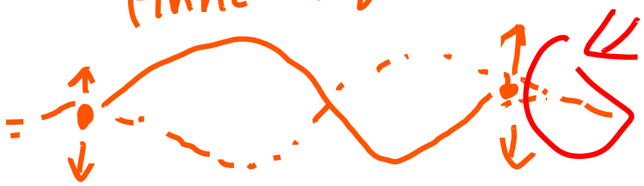


ends are fixed

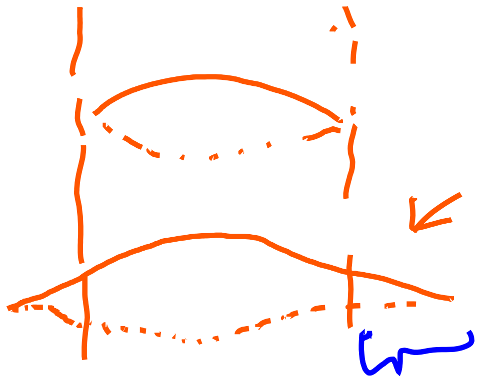
Infinite sq well

Guitar string

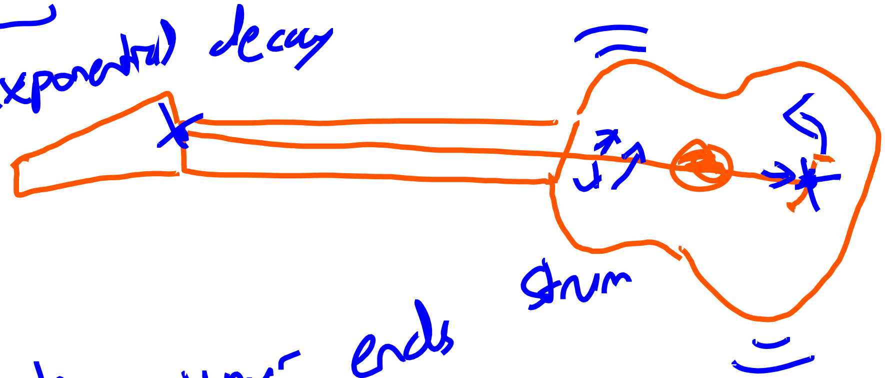
Finite sq well

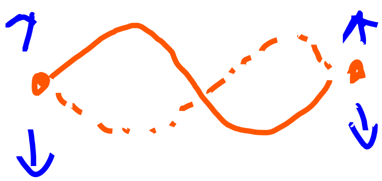


spillover effect



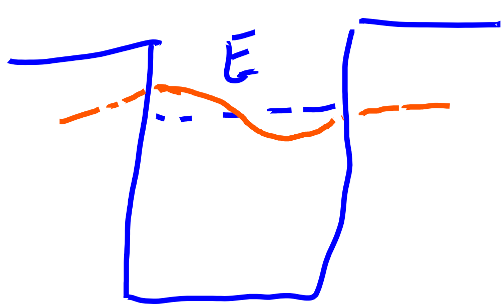
ends "leak out"





In reality, your ends vibrate

What do waves "leaking out" mean?

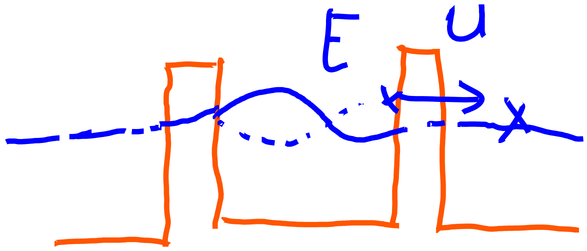


U = potential energy

$E < U$

$E = 1J$

$E < U$ $\quad U = 2J$



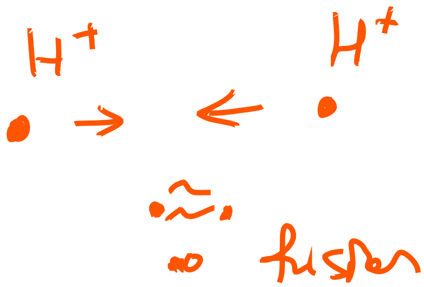
$|\psi(x)|^2 \Rightarrow$ probability

particles leak through barrier

∴ Quantum Tunnelling

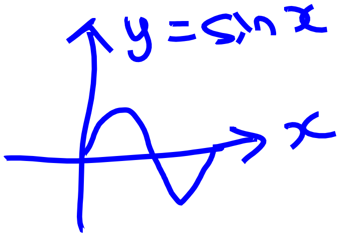
↳ Alpha decay

↳ Fusion process in é sun.



Lecture 6

In previous discussion, we talked about 1D waves, sine & cosine waves, or exponentials



reality : 1D geometry is not representative of an atom or nucleus, we need

3D version.

Force fields are spherical in nature : $F \propto \frac{1}{\underline{\underline{4\pi}}\, \varepsilon_0 \underline{\underline{r^2}}}$ ← sphere surf area $= 4\pi r^2$

↳ need a spherical version of the sine wave

Spherical harmonics

↳ 3D spherical version of sine waves

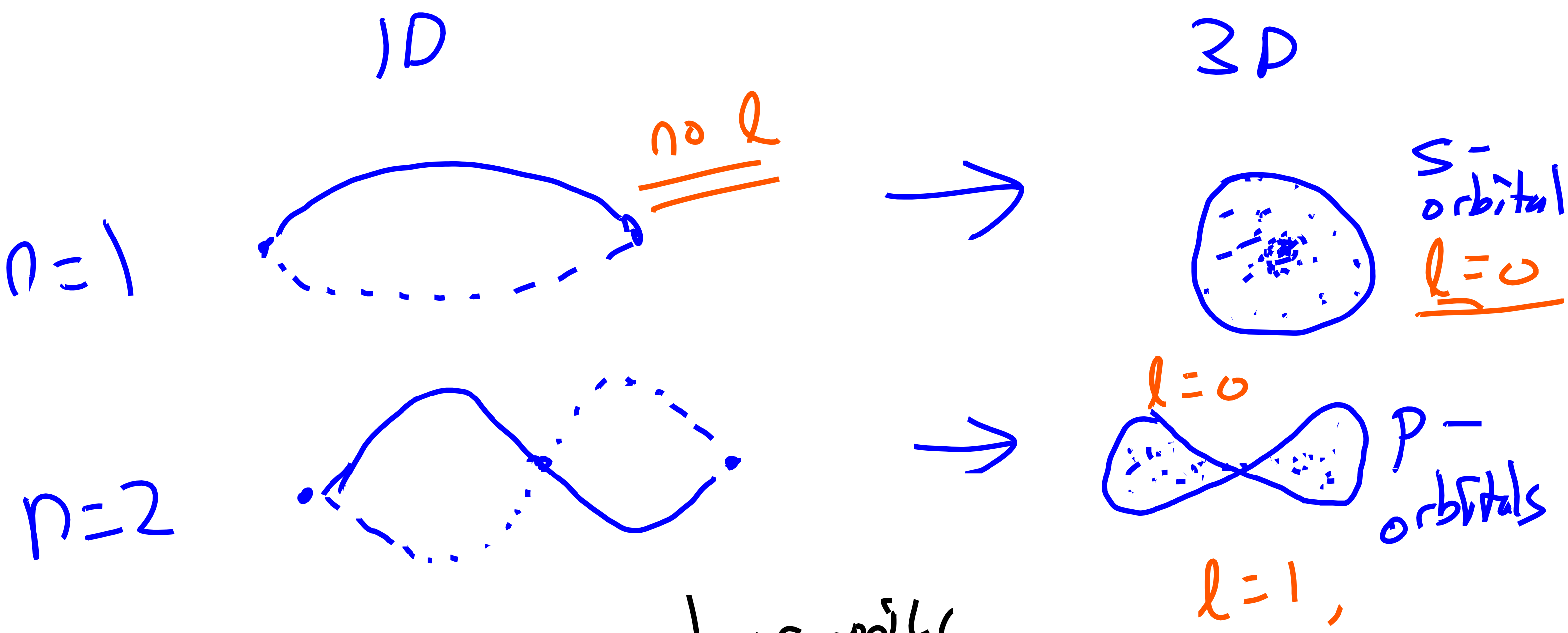
↳ explored in hydrogen atom

3D matter wave
electron 'cloud'

↳ implications of spherical harmonics

↳ angular momentum becomes important (ℓ)

↳ angular momentum projection no. becomes important (m)



In spherical harmonics

↳ $\underline{n, l, m}$ become important

in electrons

↳ same applies to the nucleus.

protons & neutrons

↳ strong nuclear force is responsible for force field rather than electric.

Summary : Implications of Schrodinger equation

① Infinite Sq well

↳ discrete energy levels

② Finite well (Simple harmonic oscillator)

↳ Quantum Tunnelling

③ 1D → 3D spherical harmonics

↳ l (angular momentum) becomes important

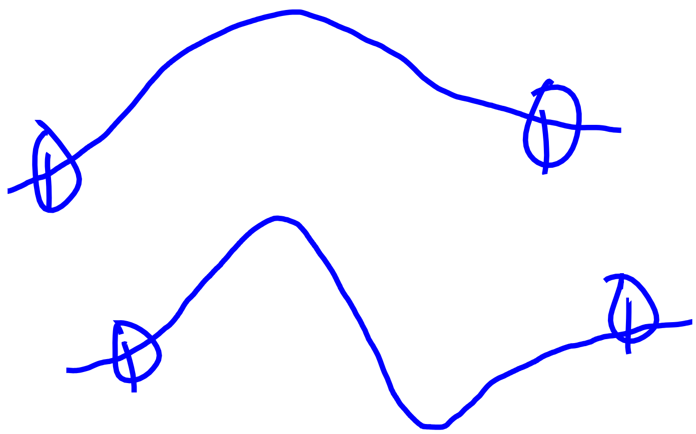
↳ m (angular momentum projection) becomes important

Lecture 7

ψ

$n=1$

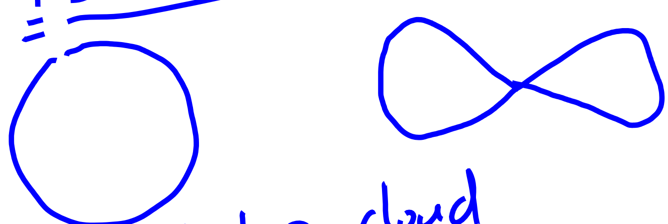
$n=2$



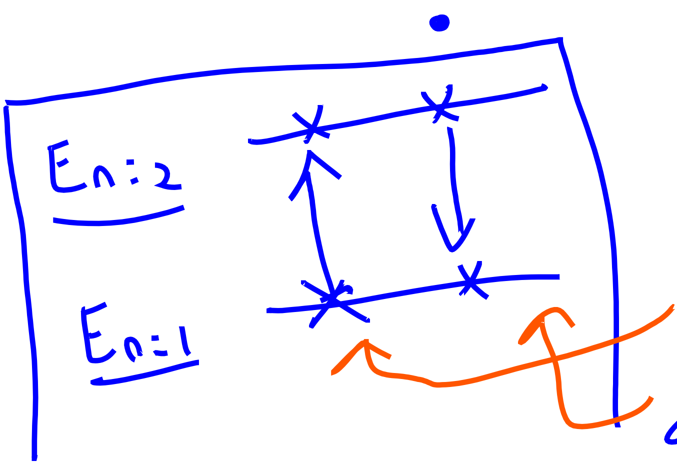
$\leftarrow \lambda_{n=2} < \lambda_{n=1}$

$l=0 \quad \uparrow \quad \lambda = \frac{h}{p} \downarrow$

1s-orbital $\qquad$ 2p-orbital ($l=1$)



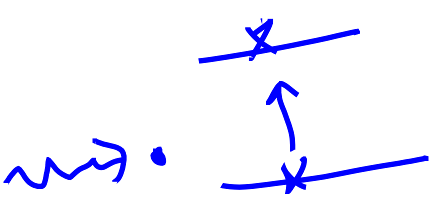
electron cloud



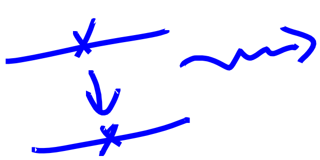
excitation

de-excitation

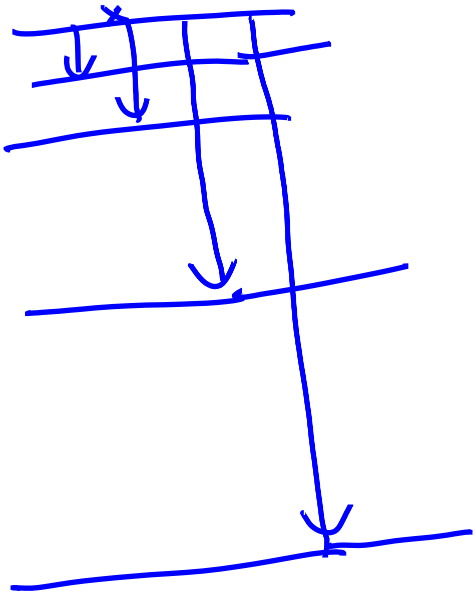
light



excitation



light energy = $E_{n=2} - E_{n=1}$



emitted light from excited Hydrogen atom will have fixed energy

fixed energy → fixed wavelength.

→ characteristic spectrum that Hydrogen atom will have when de-exciting

Different atoms have diff electric field (force fields) → Energy level is diff

→ Wavelength/spectra is different.

In the nucleus, strong nuclear force is several orders of magnitude **stronger** such that the energy level difference is about ~1 million times **more**.

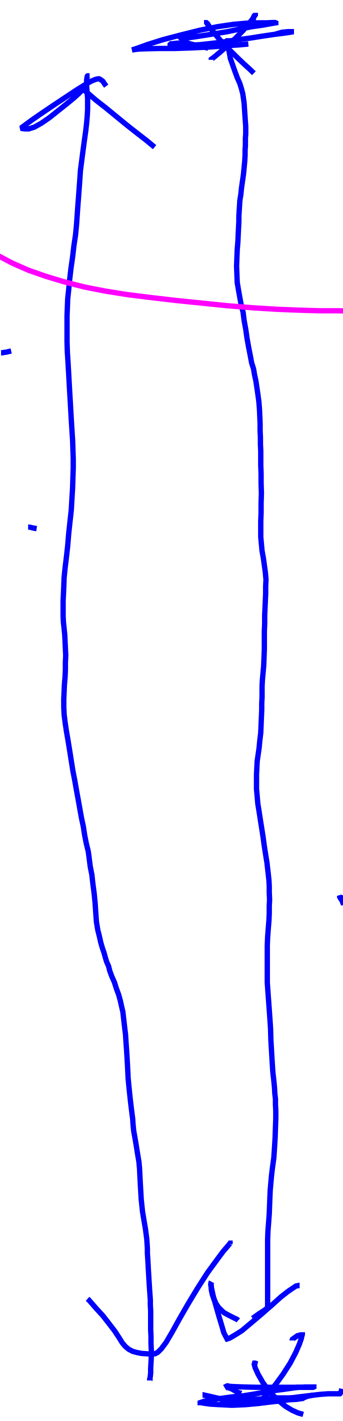
$1\,eV = 1.602 \times 10^{-19}\,J$

nuclear transitions

H electron transitions

13.6 eV ↕ = 91nm

protons 30-100x



keV.

~ MeV. $\underline{\underline{}}$ 10^6

not to scale

γ-decay.

light ~ γ-rays

how many pages wld we need to draw this to scale?

100 x 10,000 page

$10^2 \times 10^4$

nuclear energy is 1 million times more dense than electron energy chemical bonds

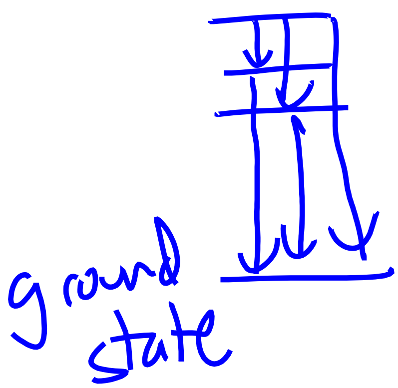
↳ fossil fuel

↳ battery

Nuclear energy is super dense.

Lecture 8

nucleus* → nucleus + γ

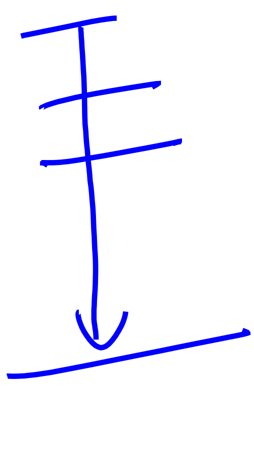


$\boxed{\text{Individual proton transitions}}$

"orbiting"

p γ →

2p
4n



3p
4n
^{7}Li

Main ways for nuclei to have

Excited states (Gamma decay)

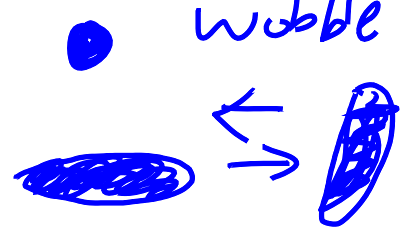
1. • Individual protons excited

2. collective motion.

$$^{238}U \to {}^{238}U^{*}$$

$\gamma \nearrow$ $\uparrow p$

"nuclear wobble"



"vibration wave"

"liquid drop"

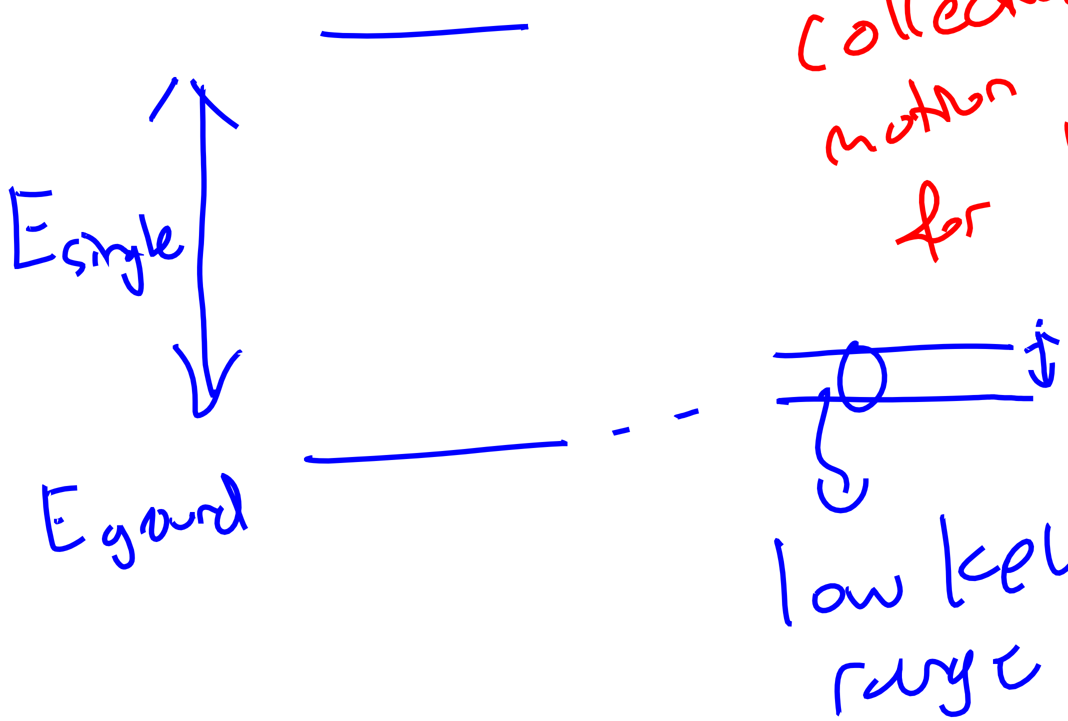
→ "shaking"

→ "spinning"

Individual particle excited states

energy > collective vibration excited state energy

collective ? usually motion for large nuclei



How do nuclei get excited?

① photon absorption

② inelastic collision.

- momentum conserved
- kinetic energy conserved

$\downarrow$

"no friction"

elastic collision

$\boxed{\frac{1}{2} m v_1^2}$

$\overrightarrow{v_1}$

$P_1 \rightarrow P_2$

rest

$\overrightarrow{v_1}$

$P_1 \quad P_2$

rest

$\boxed{\frac{1}{2} m v_1^2}$

inelastic collision → "friction"

$\boxed{KE_1}$

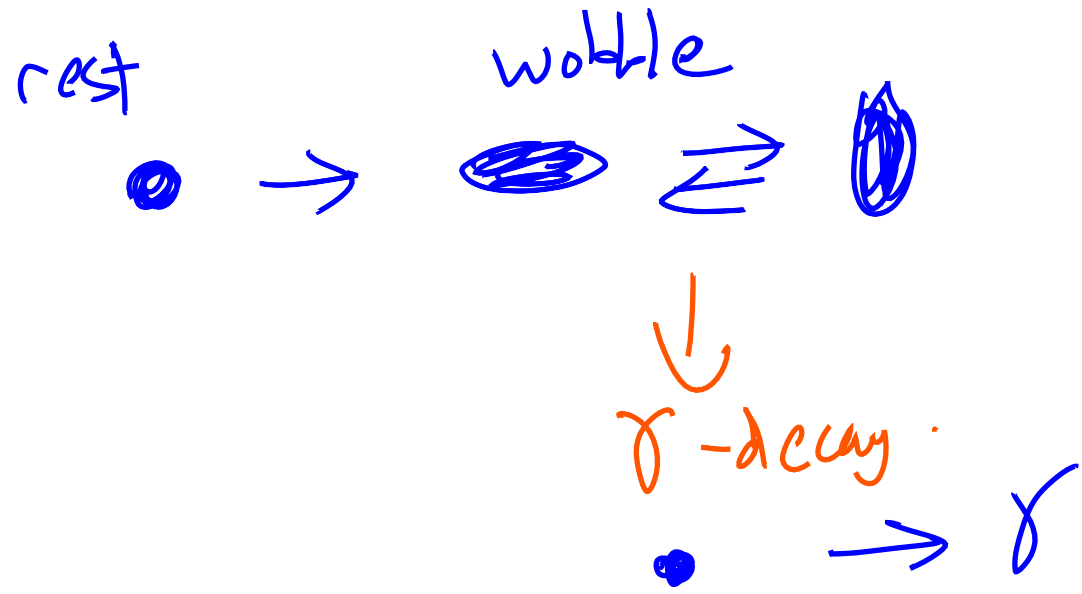
$n \rightarrow {}^{238}U$

KE_2

KE_3

$$KE_1 > KE_2 + KE_3$$

where did the energy go?



③ nuclear reactions

$$^{1}_{0}n + {}^{238}U$$

$\downarrow$ "fuse"

neutron absorption

$$^{239}U^{*}$$

excited U-239

$\downarrow$

$$^{239}U + \gamma$$

gamma photon.

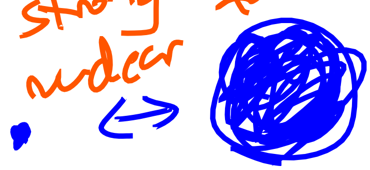
(n, γ) reactions → Important

Why did neutron absorption result in excited state?

↳ boils down to forces.

strong force. → attractive.

nuclear

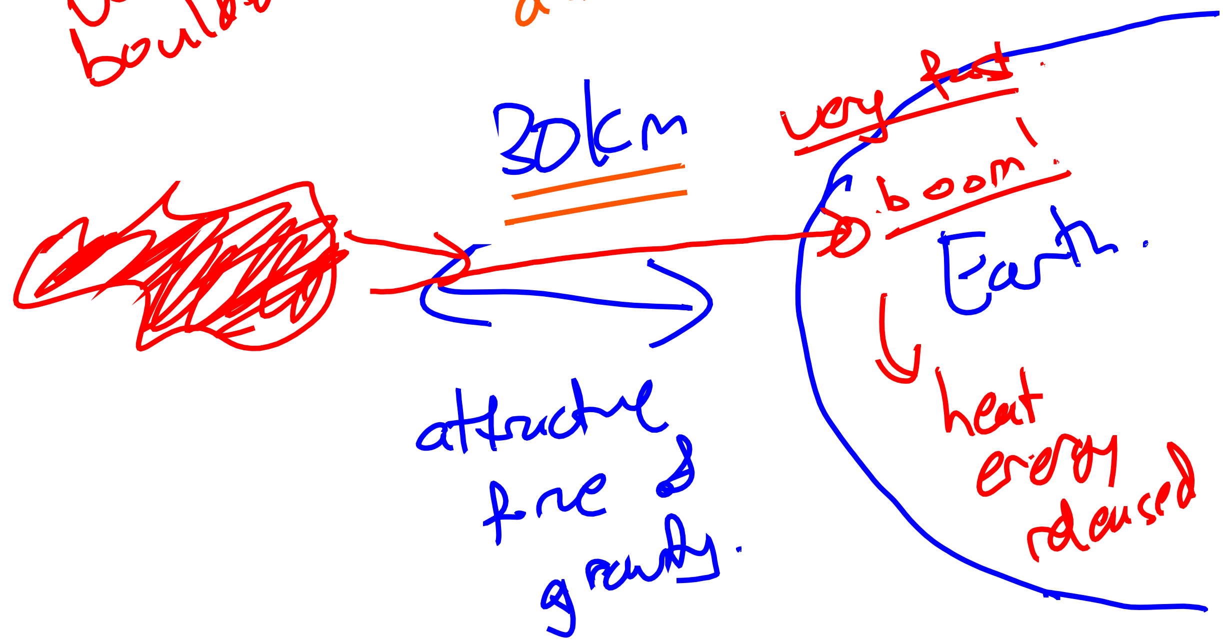


$^{1}_{0}n$ ^{238}U

attractive force + separating distance

50 km wide boulder

separating distance



$^{238}U \rightarrow {}^{4}_{2}He + {}^{234}Th$.

$\boxed{\alpha\text{-decay}}$.

^{137m}Ba.

$^{137}Cs \xrightarrow{\beta^-} {}^{137}Ba^* \rightarrow \gamma$-rays

$\downarrow$

^{137}Ba.

$\boxed{\alpha\text{-decay}}$

schrodinger's eq^n

$$^{238}U \rightarrow {}^{4}_{2}He(\alpha) + {}^{234}Th$$

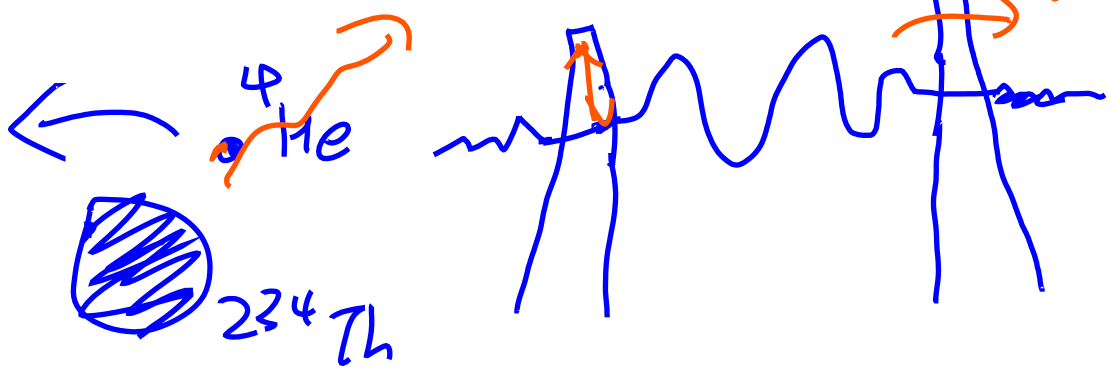
schrodinger's eq^n

$\boxed{\beta\text{-decay}}$

$\boxed{\gamma\text{-decay}}$

$$^{137}Cs \rightarrow {}^{137m}Ba^{*} \rightarrow {}^{137}Ba + \gamma$$

Quantum Tunneling.



Beta decay is special

↳ relies on weak nuclear force.

β - decay & weak nuclear force

electron cloud.

- electrons Quarks are not affected by attractive force (strong nuclear force) in the nucleus.

  ↳ not all particles are affected by strong nuclear force

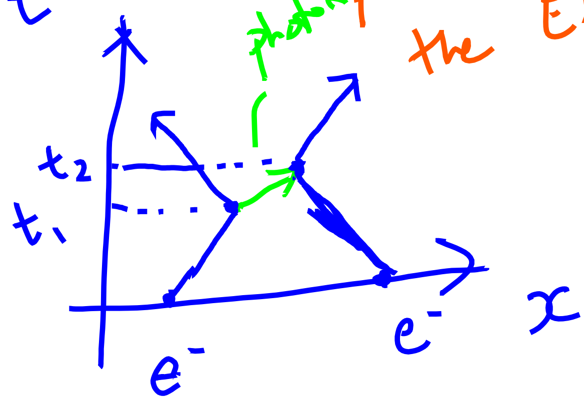
  ↳ affected by strong nuclear force = Quarks

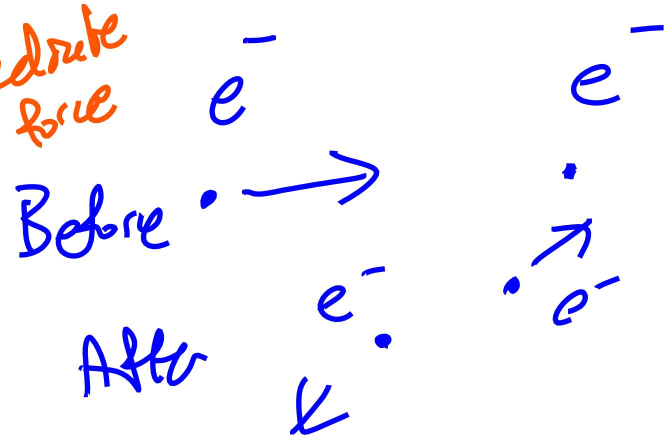
Weak nuclear force

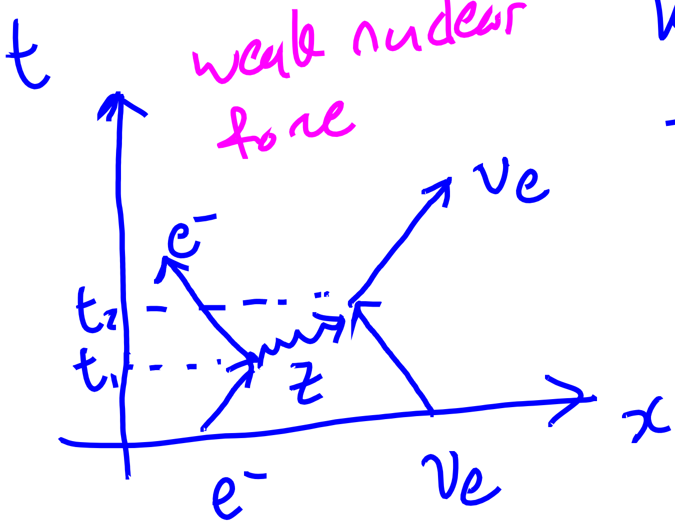
CM = "Centre of mass" frame of

Feynman Diagram

photons mediate the EM force





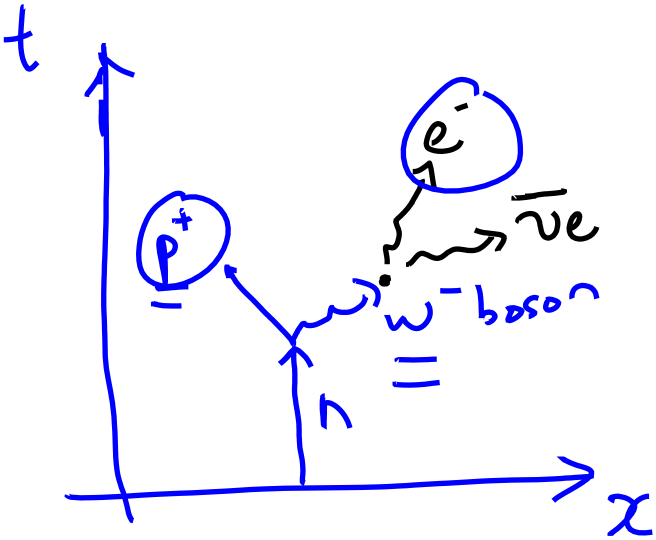


weak nuclear force

- bosons carrying force
- W^-, W^+, Z
- photon is a boson

- neutrinos are ν_e, neutral charge, affected only by gravity & weak nuclear force

- electrons collide w/ neutrons cos of weak nuclear force



W^- boson

(1) neutron splits in two.
→ proton (+)
→ W^- boson (−)

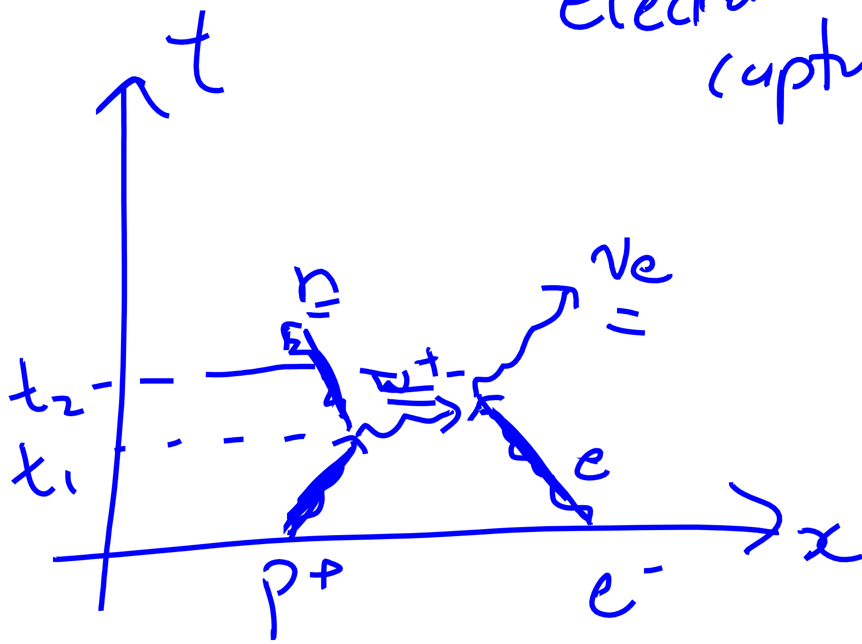
β^--decay.

(2) W^- boson decays into e^- & $\bar{\nu}_e$

- lone neutrons are unstable
↳ $t_{1/2} \sim 10.5$ mins.

- neutron can also decay in unstable nuclei eg. Cs-137.

electron capture.



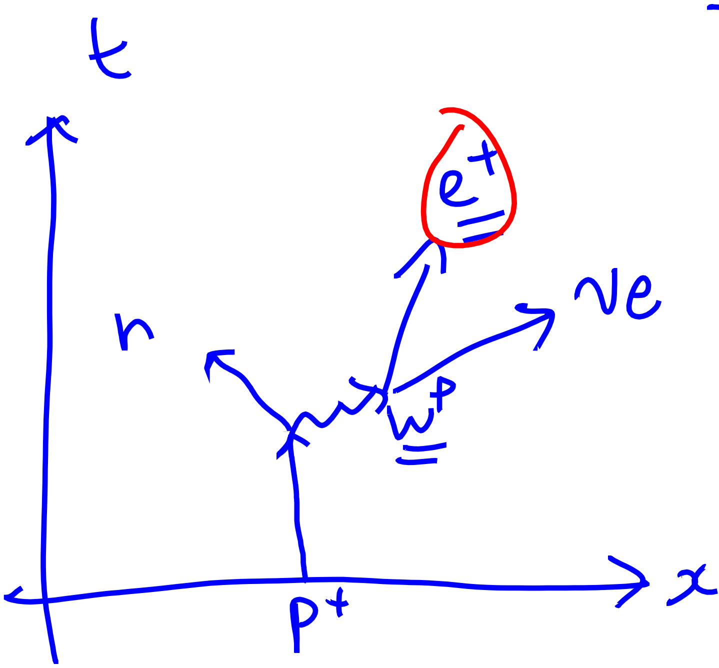
$\underline{\underline{W^+}}$ boson.

e^+ is missing.

needs a lot of energy.

β^+ decay.

$\underline{\beta^+ \text{ decay}}$.



$e^+ + e^-$

$\downarrow$

2γ rays.

(photons)

$\underline{511 \text{ keV}}$.

positron emission tomography

(PET).

Some unstable nuclei can supply energy for β^+ decay.

binding energy