Nuclear Physics

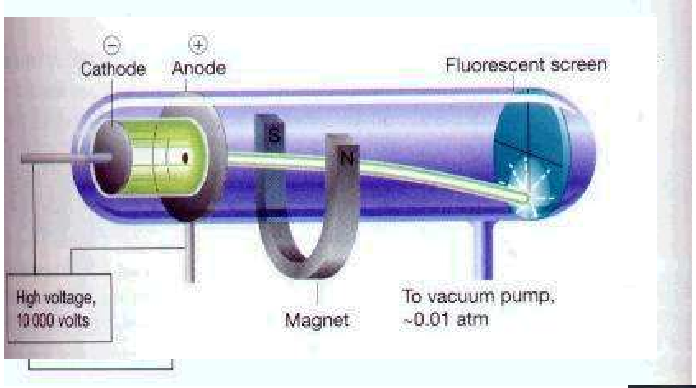
The revolution!

“Creating a new theory is not like tearing down an old barn and erecting a skyscraper in its place. It is rather like climbing a mountain, gaining new and wider views, discovering unexpected connections between our starting point and its rich environment. But the point from which we started out still exists and can be seen, although it appears smaller and forms a tiny part of our broad view gained by the mastery of the obstacles on our adventurous way up.”

Uncuttable?

The Atom

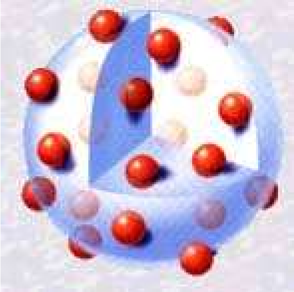
- Thompson proved in 1897 that cathode rays were particles from inside the “a-tomos” or “un-cuttable” atom

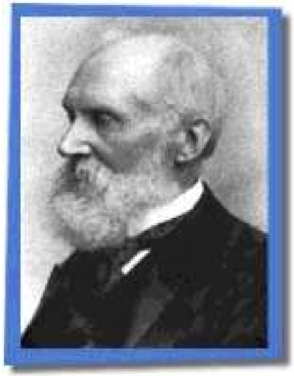


- Nagaoka pictured a planetary model for the atom, with electrons around a central mass

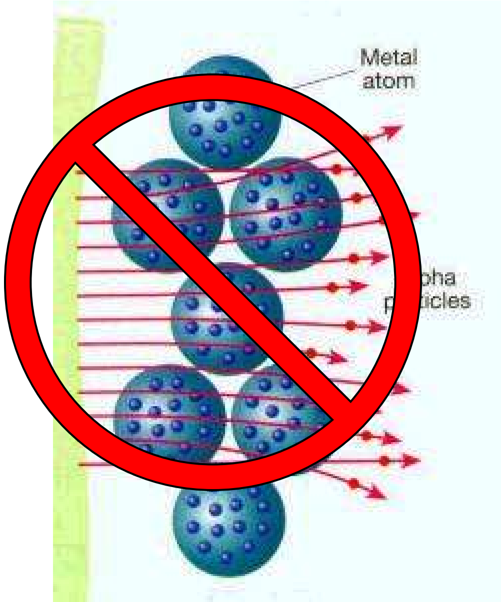
Plum Pudding

- Thompson instead supported Lord Kelvin's suggestion that electrons were embedded in a positively charged "pudding"



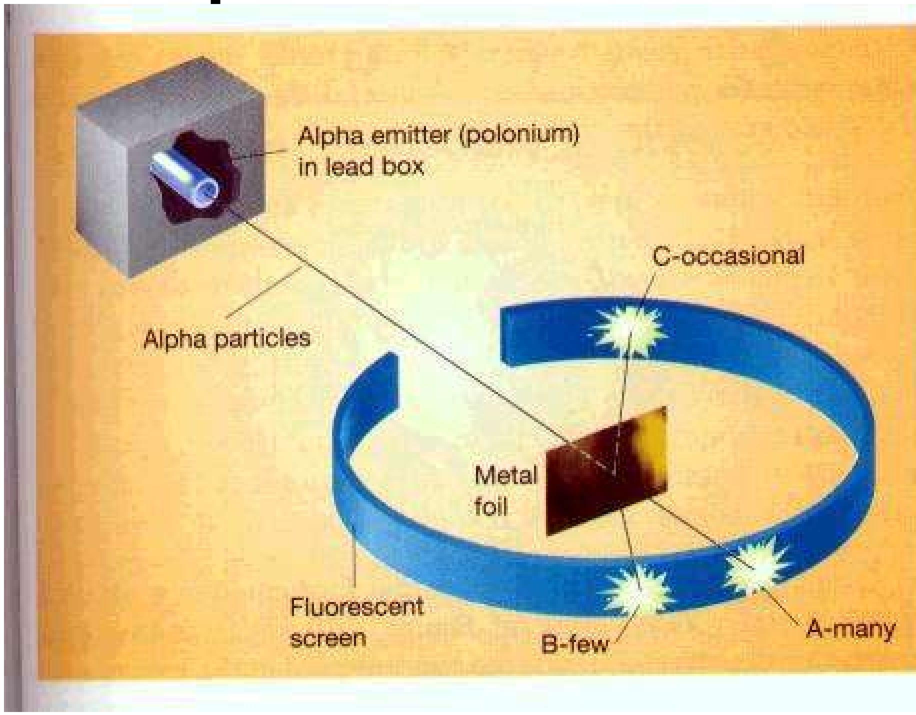


- Rutherford showed Nagaoka was correct by probing the atom with alpha particles

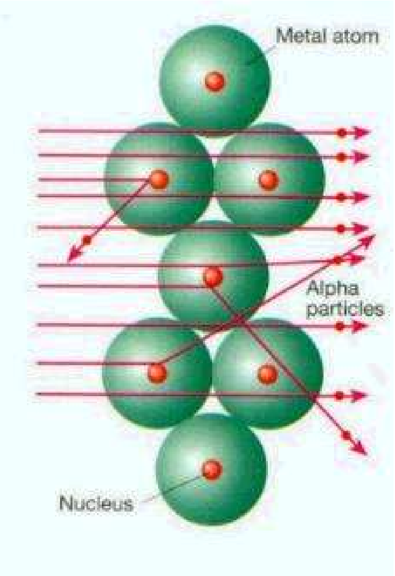


Geiger-Marsden experiment

- Rutherford's results showed the atom is mostly empty space, with a very dense nucleus



- To see why, try firing pennies at water "pudding" then 50g "nuclei" spaced out on your table



Data table for 50 “shots”

Model	# alpha particles	Straight Through	Slight Deflection	Bounce Back
Plum pudding		𝍸	II	
Solar system				

Ex 1: Use the closest approach for 8.2 MeV alpha particles to a gold nucleus (to estimate outer limit of radius of nuclei)

$$\Delta E_p = \frac{kQq}{r} - \frac{kQq}{\infty} \qquad r = \frac{kQq}{\Delta E}$$

$$r = \frac{9E9(79 \cdot 1.6E-19)2 \cdot 1.6E-19}{8.2E6(1.6E-19)}$$

$$r = 2.8 \times 10^{-14} m \approx 10^{-14} m$$

Compare to theoretical radius R:

$$R = R_0 A^{1/3}$$

Where R_0 is the fermi radius, and A is the atomic mass number:

$$R = 1.2 \times 10^{-15} m \left(1^{1/3} \right) = 1.2 \times 10^{-15} m$$

Ex: find the radius of a U-238 nucleus

$$R = 1.2 \times 10^{-15} m \left(238^{1/3} \right) = 7.4 \times 10^{-15} m$$

We can also use diffraction to find D

$$\sin\theta \approx \frac{\lambda}{D}$$

Ex: A beam of 80.0 MeV neutrons are diffracted upon passing through a thin lead foil. The first minimum in the diffraction pattern is measured at 12.6°. Estimate the diameter of the lead nucleus.

SOLUTION: Use $\lambda = h / p$ and $m = 1.67\times10^{-27}$ kg.

- $E_K = (80.0\times10^6 \text{ eV})(1.60\times10^{-19} \text{ J / eV}) = 1.28\times10^{-11}$ J.
- Since $E_K = p^2/(2m)$ we see that

$$p^2 = 2mE_K = 2\times1.67\times10^{-27}\times1.28\times10^{-11} = 4.275\times10^{-38}.$$

- Then $p = 2.068\times10^{-19}$ N·s so that

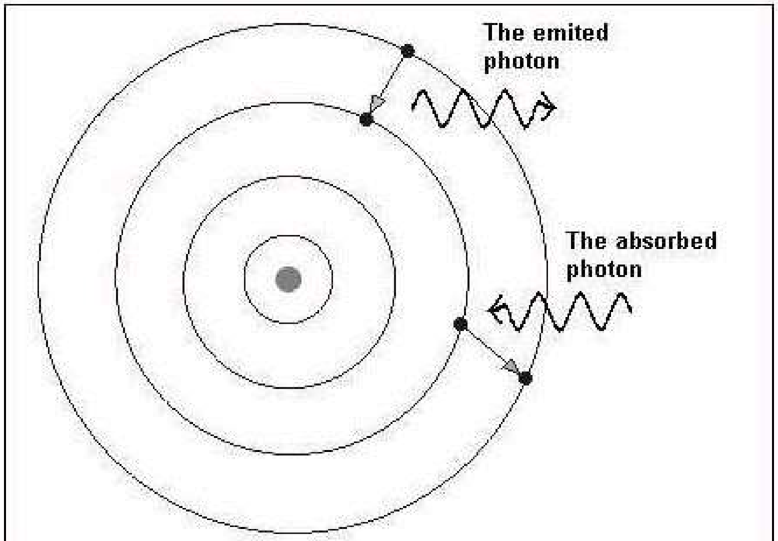
$$\lambda = h / p = 6.63\times10^{-34} / 2.068\times10^{-19} = 3.207\times10^{-15} \text{ m}.$$

- $D = \lambda / \sin\theta = 3.207\times10^{-15} / \sin 12.6°$

$= 1.47\times10^{-14}$ m.

The Bohr Atom

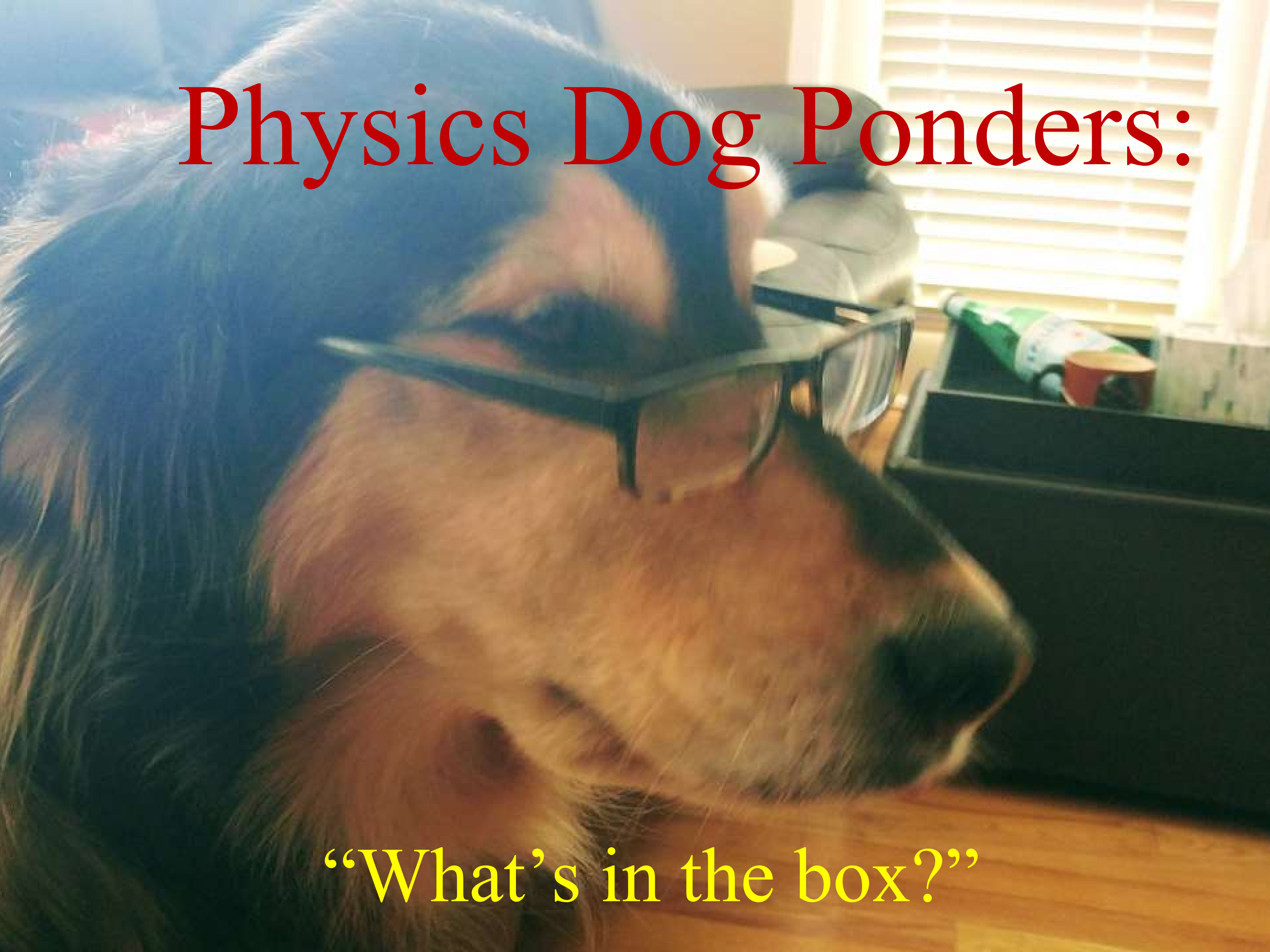
- Nils Bohr demonstrated the electrons in an atom are confined to particular energy levels.
- He called these levels “orbitals”
- Absorbing or emitting energy (a photon) causes the electron to jump between levels



Bohr’s postulates

- Radiation is only emitted when the atom (electron) makes a transition
  from a higher to a lower energy state
- The difference in energy between the two states, $\Delta E = hf$
- The angular momentum of the electron is quantized in units of h/2π (mvr=h/2π)

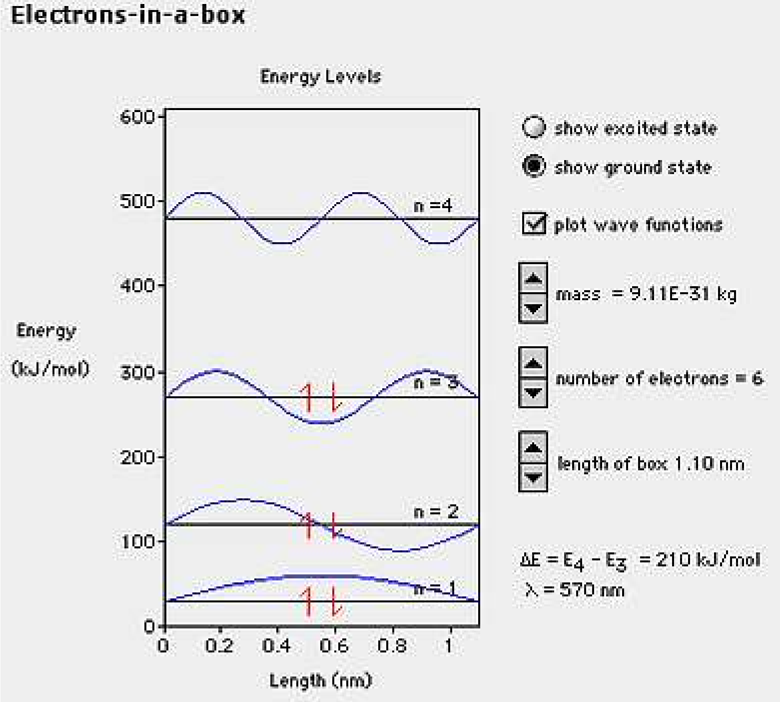
Physics Dog Ponders:



“What’s in the box?”

Electron in a box

$$E_k = \frac{n^2 h^2}{8 m_e L^2}$$



Electrons-in-a-box

○ show excited state

● show ground state

☑ plot wave functions

mass = 9.11E-31 kg

number of electrons = 6

length of box 1.10 nm

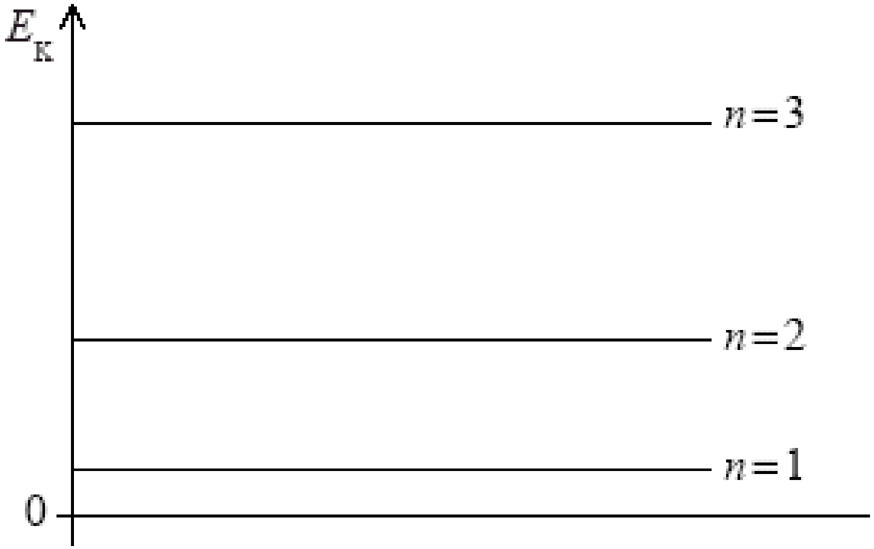
$\Delta E = E_4 - E_3$ = 210 kJ/mol

λ = 570 nm

- For energy level n in a hydrogen atom, where L is the length of the box, aka orbital circumference, m_e is the mass of the electron

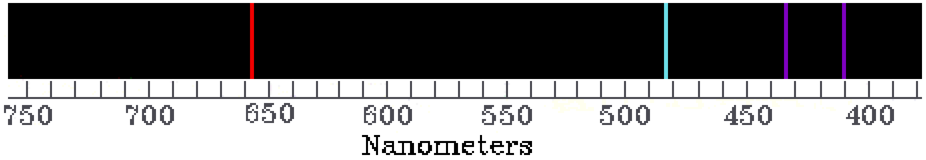
Limitations?

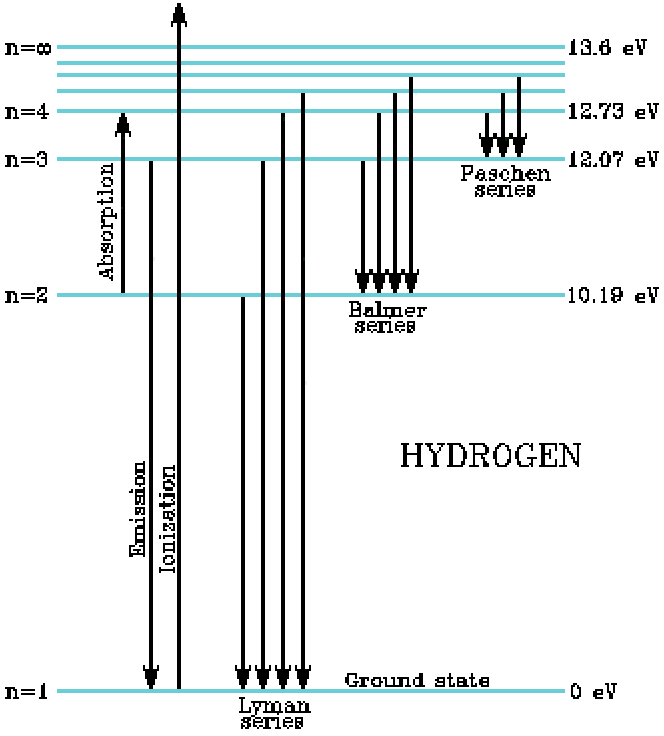
- This model gives confusing spacing of energy levels.

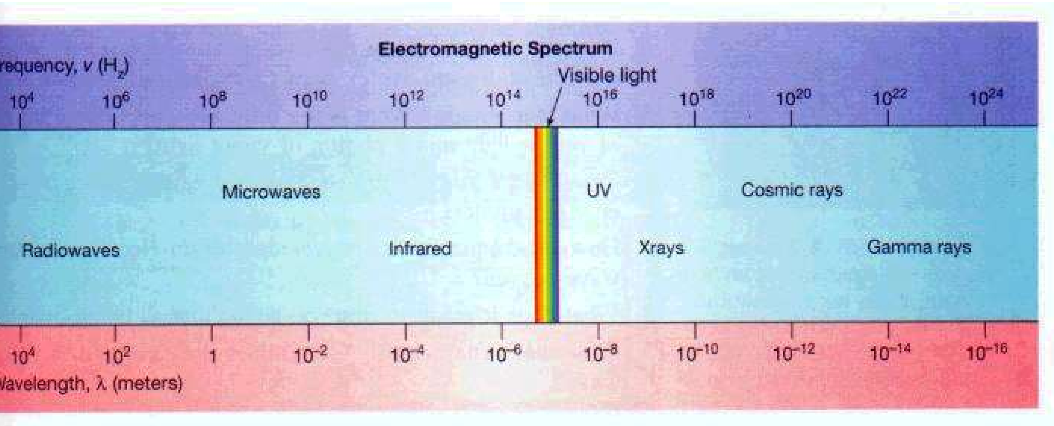


The Bohr does provide an explanation for the spectrum of EM radiation emitted from an excited atom

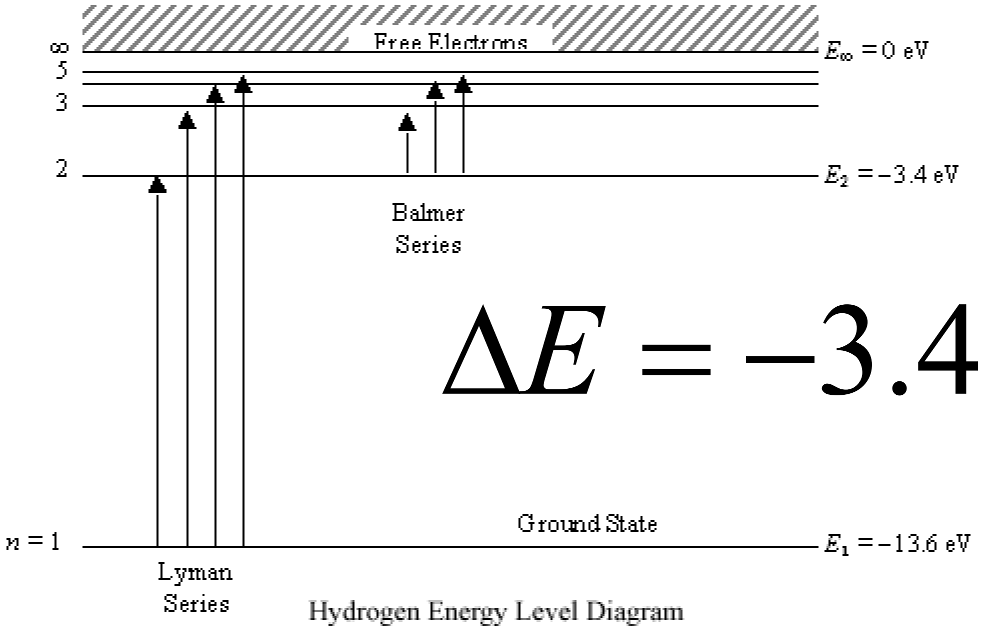
It doesn’t explain the relative intensity of spectral lines







- Ex: find the wavelength of a photon absorbed for an n=1 to n=2 jump



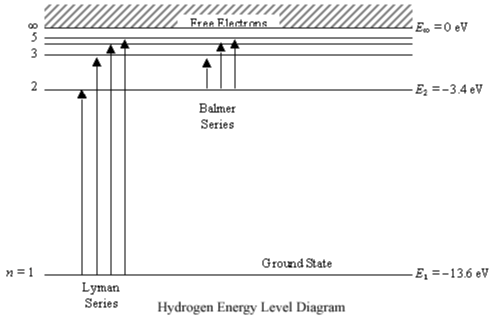
Hydrogen Energy Level Diagram

$$\Delta E = E_2 - E_1$$

$$\Delta E = -3.4eV - (-13.6eV)$$

$$\Delta E = 10.2eV$$

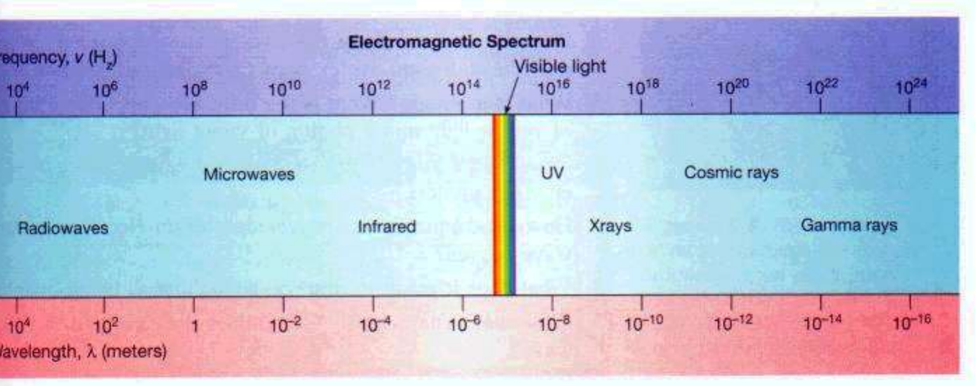
- Ex: find the wavelength of a photon absorbed for an n=1 to n=2 jump



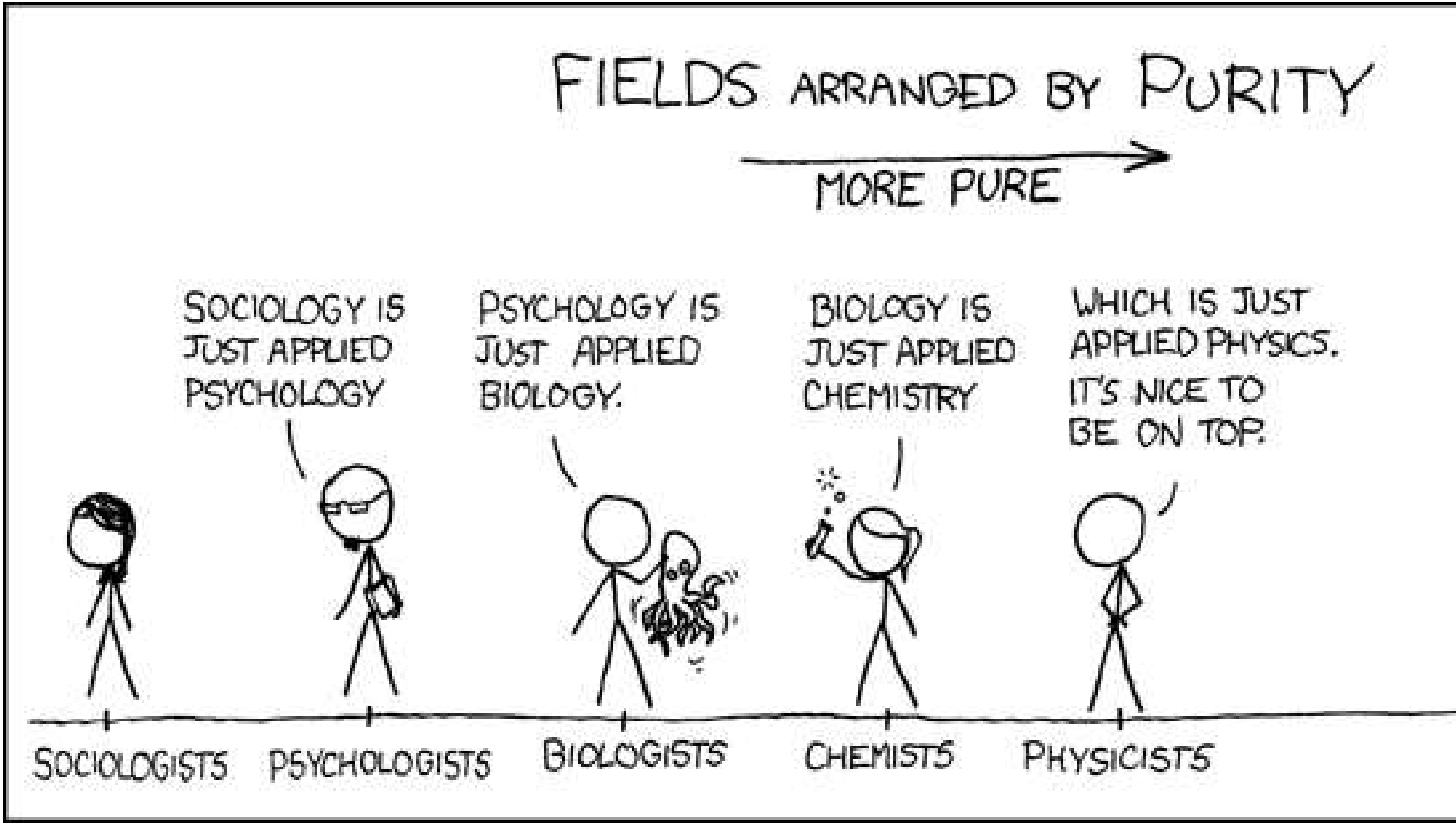
$$\Delta E = 10.2eV\left(1.6\times10^{-19}C\right) = hf$$

$$\lambda = \frac{c}{f} = \frac{hc}{E}$$

$$\lambda = \frac{6.63\times10^{-34}J\cdot s\left(3.00\times10^{8}m\cdot s^{-1}\right)}{1.6\times10^{-18}J}$$

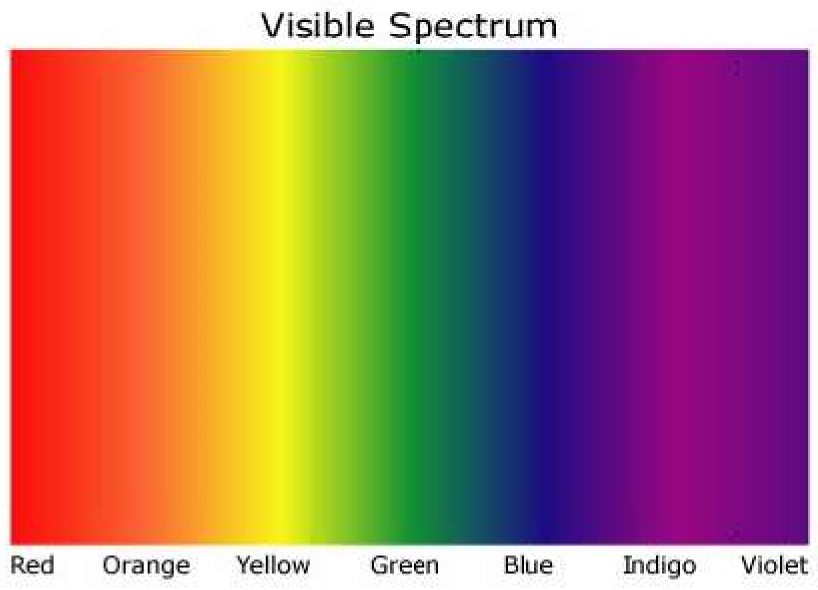


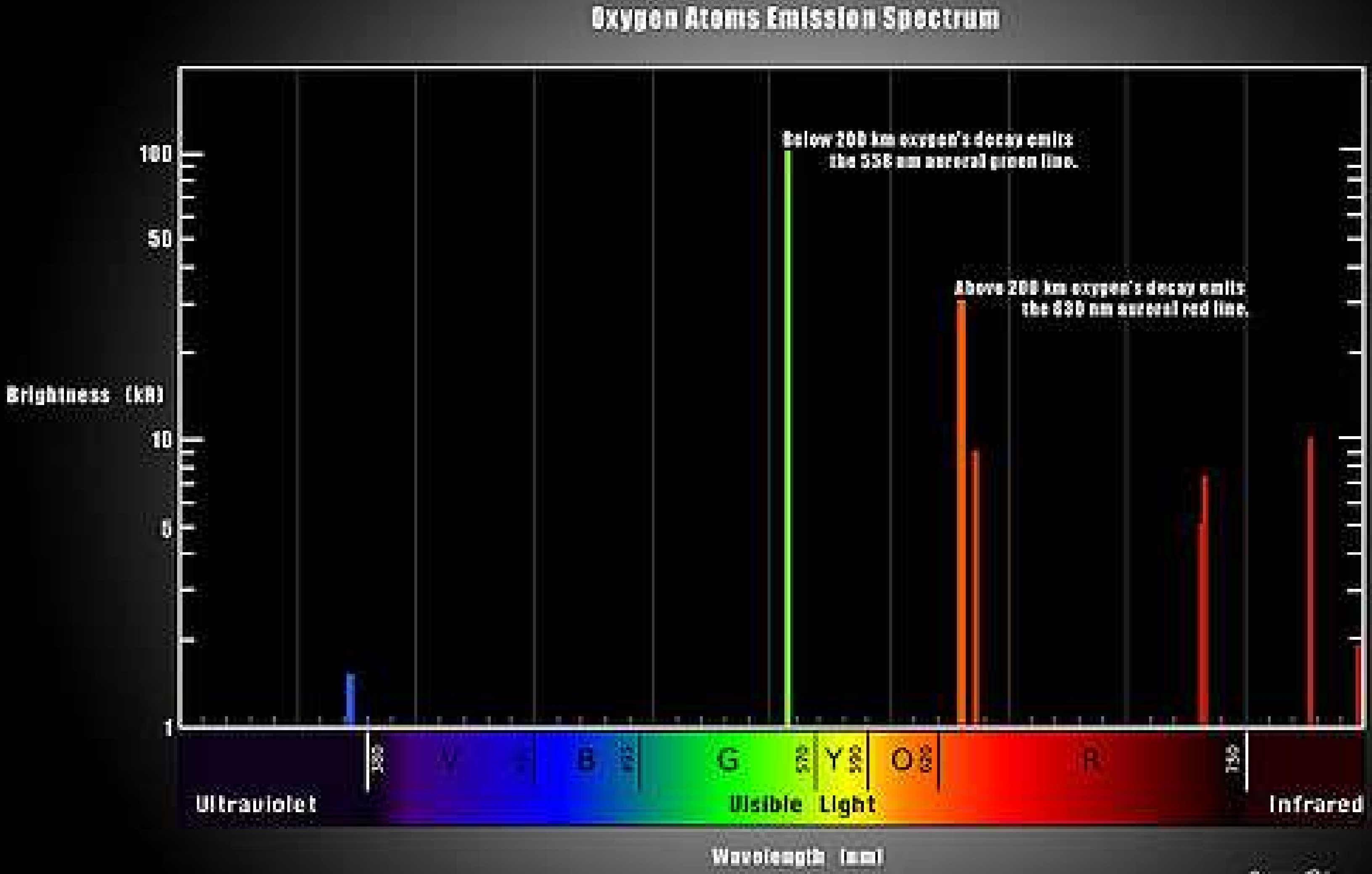
$$\lambda = 1.2\times10^{-7}m$$


FIELDS ARRANGED BY PURITY
MORE PURE
SOCIOLOGY IS JUST APPLIED PSYCHOLOGY
PSYCHOLOGY IS JUST APPLIED BIOLOGY.
BIOLOGY IS JUST APPLIED CHEMISTRY
WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.
SOCIOLOGISTS
PSYCHOLOGISTS
BIOLOGISTS
CHEMISTS
PHYSICISTS

Spectrum activity

- Sketch the spectrum for:
- Incandescent light
- Fluorescent light
- LED light
- Nitrogen
- Neon
- Water



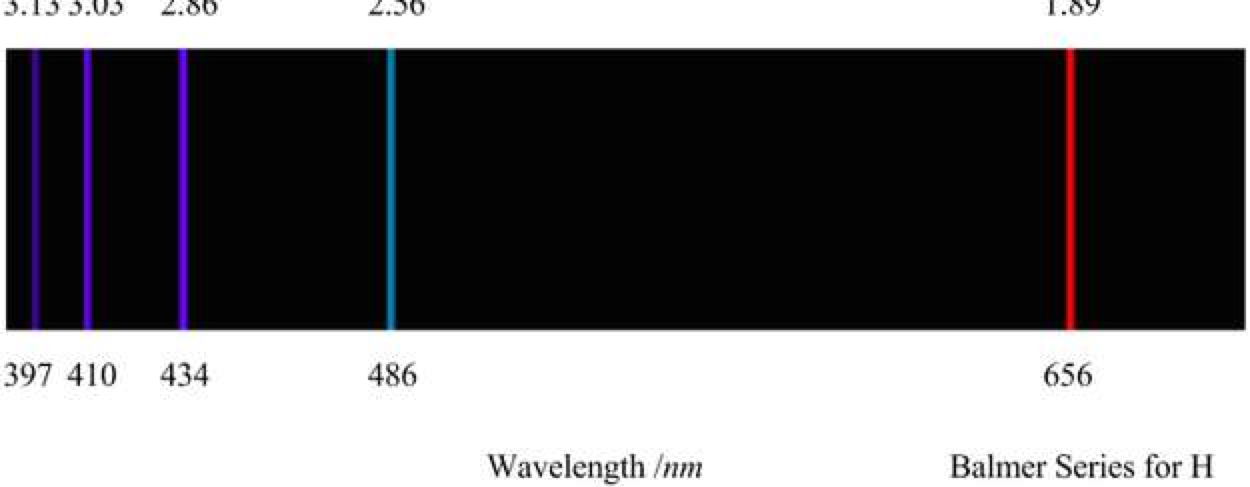


Oxygen Atoms Emission Spectrum

Below 200 km oxygen's decay emits the 558 nm auroral green line.

Above 200 km oxygen's decay emits the 630 nm auroral red line.

Data: NCAR/HAO

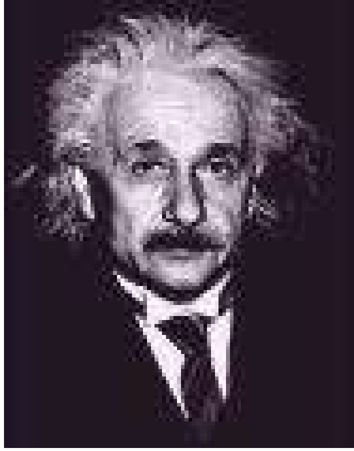


Use these wavelengths to find n=3 given n=2 corresponds to -3.4 eV

$$E = \frac{hc}{\lambda} \qquad E_\alpha = \frac{6.63\times10^{-34}\,J\cdot s\left(3.00\times10^{8}\,m\cdot s^{-1}\right)}{656\times10^{-9}\,m}$$

$$E_\alpha = 3.03\times10^{-19}\,J \;=1.9eV \qquad E_3 = -3.4+1.9 = -1.5eV$$

Einstein



Einstein described light as a stream of particles called "photons," each with an energy defined by their frequency. Photoelectric effect shows:

$$E = hf$$

- Ex 1: Find the energy of a radio photon from NL 610 AM (610 kHz)

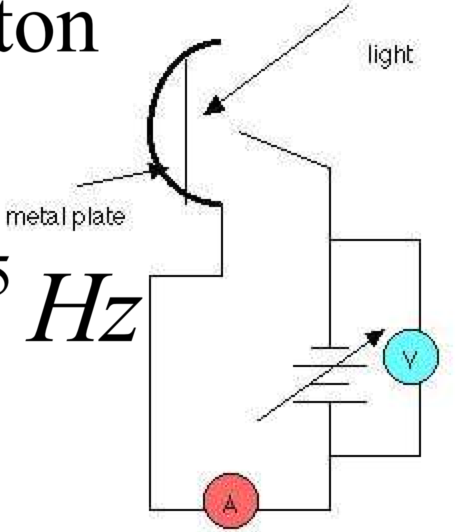


fig. 2: Photoelectric Effect Mea
Plate and Voltage

$$E = hf = 6.63\times10^{-34}\,Js\cdot6.1\times10^{5}\,Hz$$

$$E = 4.0\times10^{-28}\,J \quad = 2.5neV$$

- Physics Dog wants you to find the energy of an Ultraviolet ray photon with frequency 5 x 10^{17} Hz

$$E = hf = 6.63\times10^{-34}\,Js\cdot5.0\times10^{17}\,Hz$$

$$E = 3.3\times10^{-16}\,J \quad = 2.1keV$$

Creation of matter?

Find the minimum frequency for pair production

$$E = hf \qquad mc^2 = hf$$

$$f = \frac{mc^2}{h} = 2.5\times10^{20} Hz$$

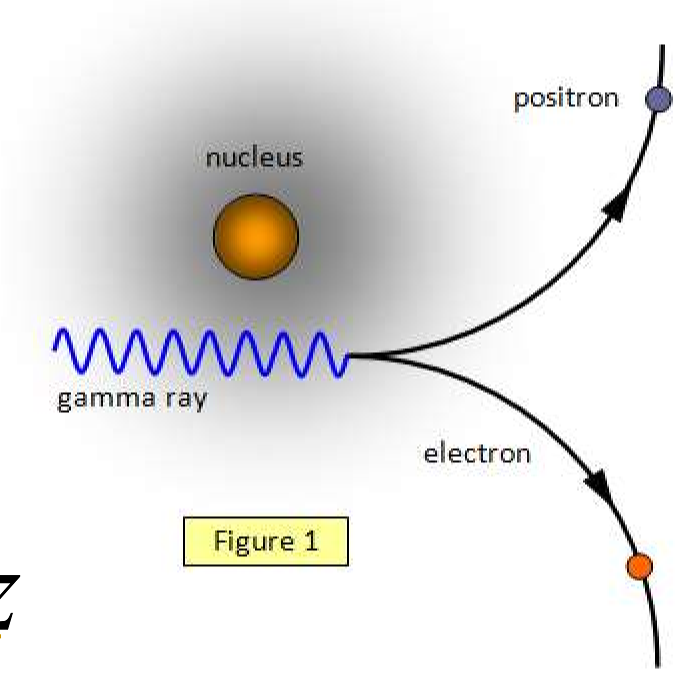
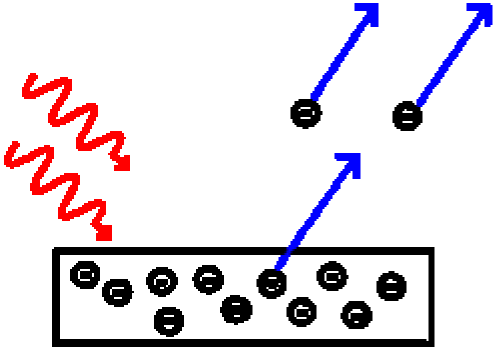
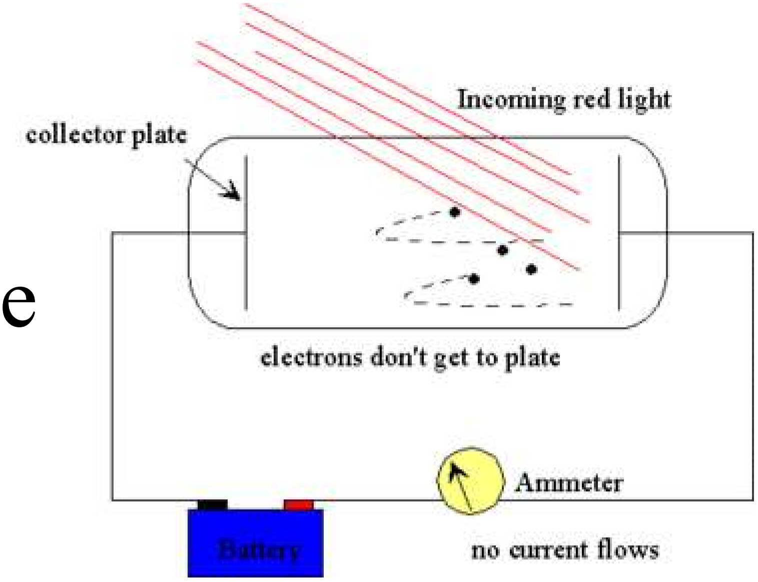


Figure 1

Photoelectric effect

- Photons above threshold frequency cause electrons to be emitted from metal plate
- Stopping potential allows us to measure kinetic energy of electrons





Work Function

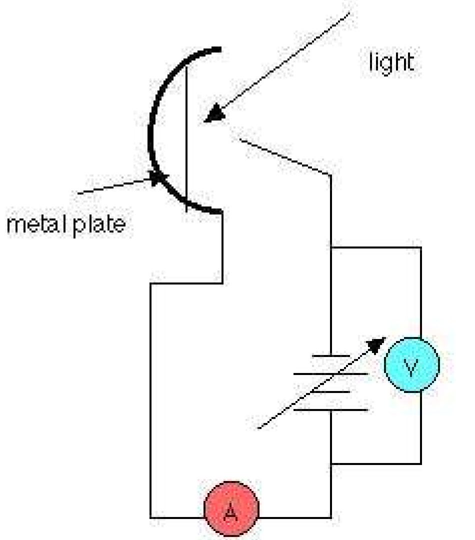


fig. 2: Photoelectric Effect Measured with Plate and Voltage

$$E_{\max} = hf - \phi$$

- Maximum kinetic energy of photoelectron depends on the work function of the metal ϕ

Exercises

1 A sample of sodium is illuminated by light of wavelength 422 nm in a photoelectric tube. The potential across the tube is increased to 0.6 V. At this potential no current flows across the tube. Calculate:

(a) the maximum KE of the photoelectrons
(b) the frequency of the incident photons
(c) the work function of sodium
(d) the lowest frequency of light that would cause photoelectric emission in sodium.

2 A sample of zinc is illuminated by UV light of wavelength 144 nm. If the work function of zinc is 4.3 eV, calculate

(a) the photon energy in eV
(b) the maximum KE of photoelectrons
(c) the stopping potential
(d) the threshold frequency.

3 If the zinc in Question 2 is illuminated by the light in Question 1, will any electrons be emitted?

4 The maximum KE of electrons emitted from a nickel sample is 1.4 eV. If the work function of nickel is 5.0 eV, what frequency of light must have been used?

Ex: #1 p. 231

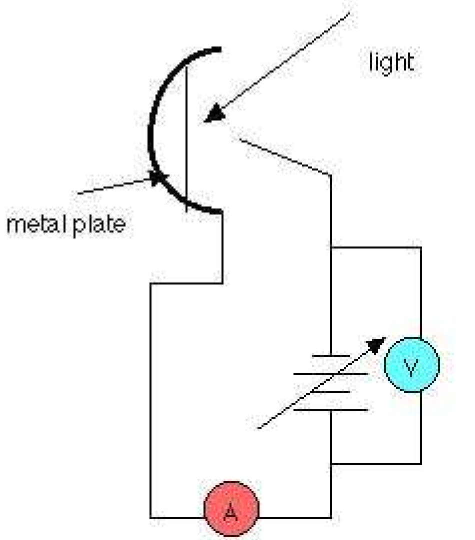


fig. 2: Photoelectric Effect Measured with Plate and Voltage

$$E_{\max} = 0.6eV$$

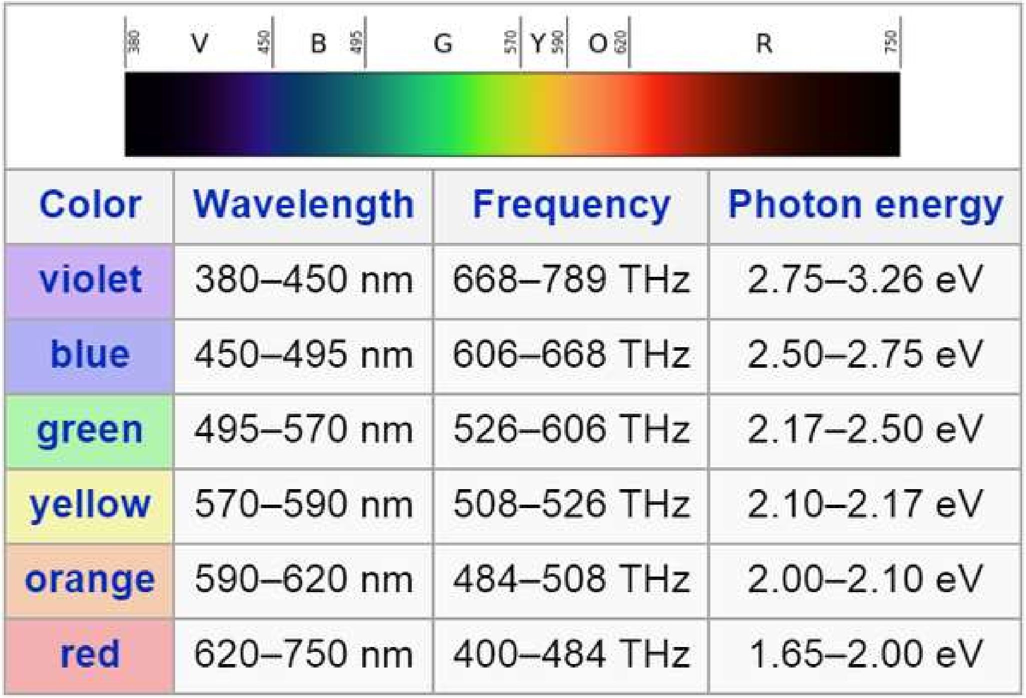
$$E_{\max} = 9.6\times10^{-20}J$$

$$c = f\lambda \quad f = \frac{c}{\lambda} = \frac{3.00\times10^{8}}{422\times10^{-9}}$$

$$f = 7.11\times10^{14}Hz$$

Ex:

$$E_{\max} = hf - \phi$$



Color	Wavelength	Frequency	Photon energy
violet	380–450 nm	668–789 THz	2.75–3.26 eV
blue	450–495 nm	606–668 THz	2.50–2.75 eV
green	495–570 nm	526–606 THz	2.17–2.50 eV
yellow	570–590 nm	508–526 THz	2.10–2.17 eV
orange	590–620 nm	484–508 THz	2.00–2.10 eV
red	620–750 nm	400–484 THz	1.65–2.00 eV

leasured with

$$\phi = 6.63\times10^{-34}$$

$$\phi = 3.75\times10^{-19} J$$

$$hf = \phi \qquad f = \frac{\phi}{h} \qquad = \frac{3.75\times10^{-19} J}{6.63\times10^{-34} Js}$$

$$f = 5.7\times10^{14} Hz$$

Stopping Potential

$$hf = hf_0 + eV$$

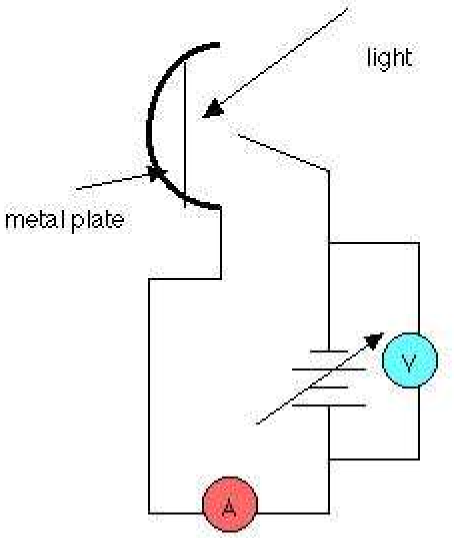


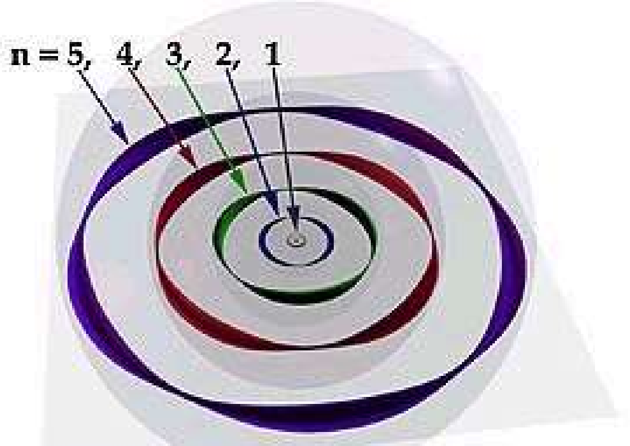
fig. 2: Photoelectric Effect Measured with Plate and Voltage

- Ex: The quantum nature of radiation

LIGHT IS A wave!

de Broglie

- de Broglie explained Bohr’s model by describing the electron as a standing wave
- Only waves that have an even number of wavelengths are allowed
- Schroedinger took this further to describe the electron’s location as a wave equation



Niels Bohr - Louis de Broglie atom, 1924

de Broglie

- Ex: find your wavelength!

$$p = \frac{h}{\lambda} \qquad \lambda = \frac{h}{p}$$

$$= \frac{6.63 \times 10^{-34} Js}{105kg \cdot 10 \, {}^{m}\!/\!_{s}}$$

$$= 6.3 \times 10^{-37} m \cong 10^{-36} m$$

de Broglie

- Ex: find the wavelength of an electron moving at 0.5c

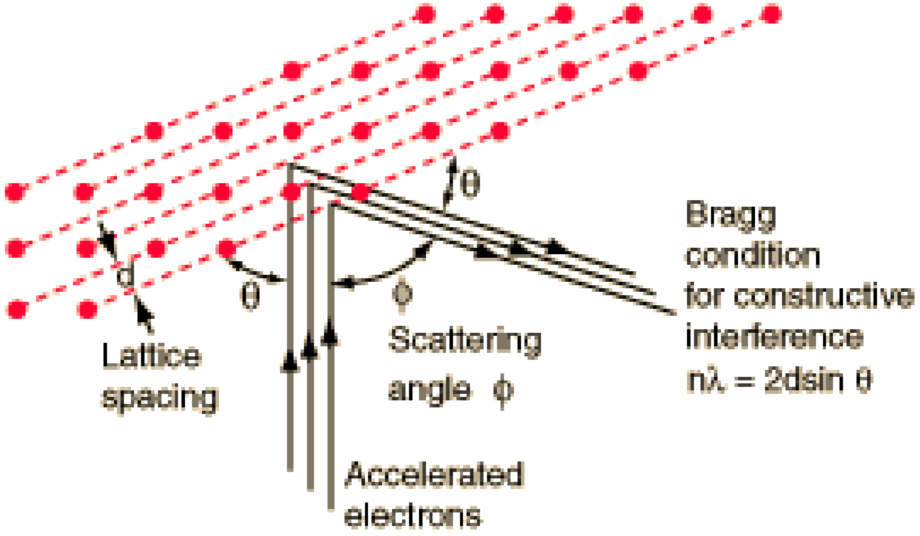
$$p = \frac{h}{\lambda} \qquad \lambda = \frac{h}{p}$$

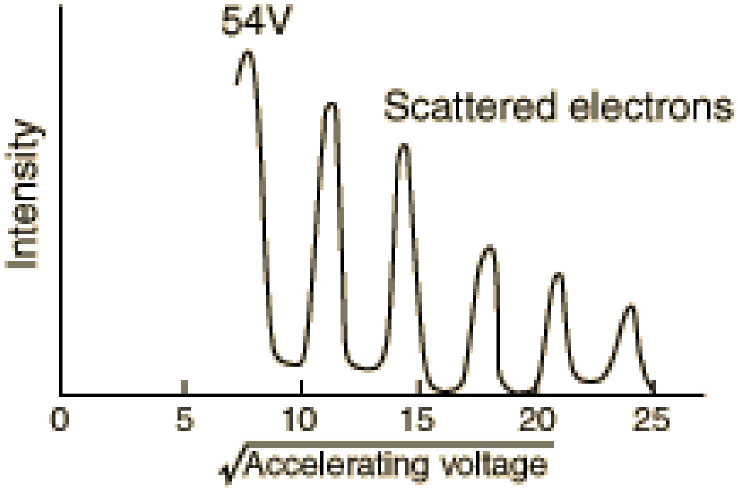
$$= \frac{6.63\times10^{-34}\,Js}{9.11\times10^{-31}\,kg\cdot1.5\times10^{8}\,{}^{m}\!/\!{}_{s}}$$

$$= 4.9\times10^{-12}\,m$$

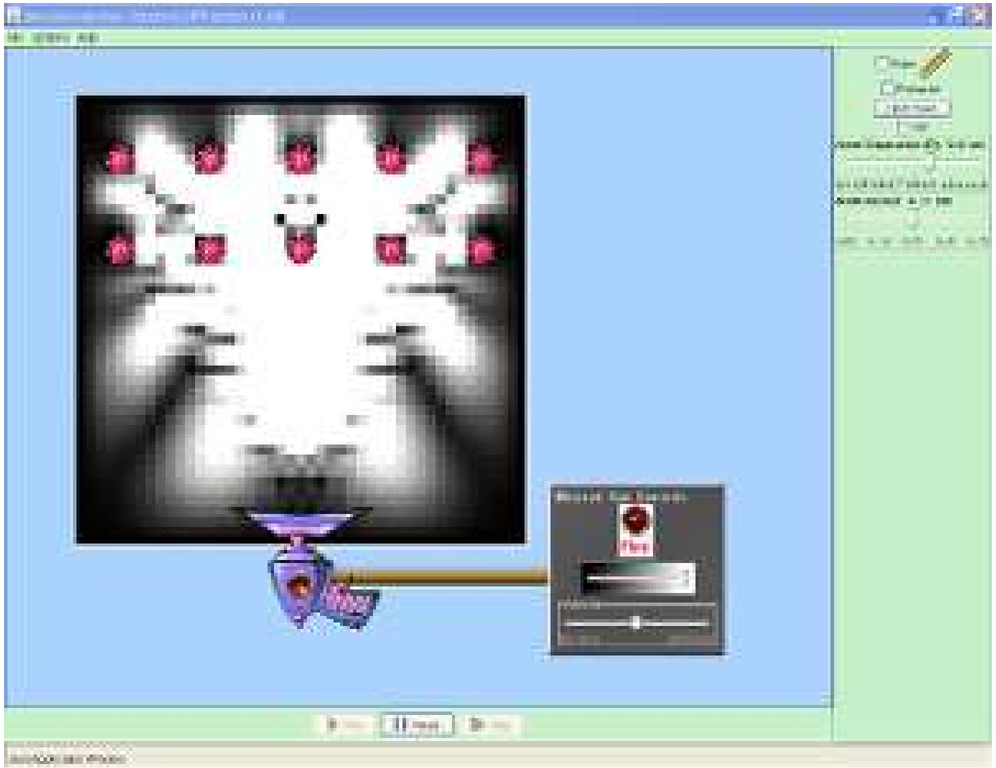
P. 232 #5-8
P. 235 #9-10

Davisson-Germer Experiment





Davisson-Germer PhET



Davisson-Germer

- Experiment to find which of the following affect electron diffraction angles:
  - Velocity
  - Atom Separation
  - Atom Radius

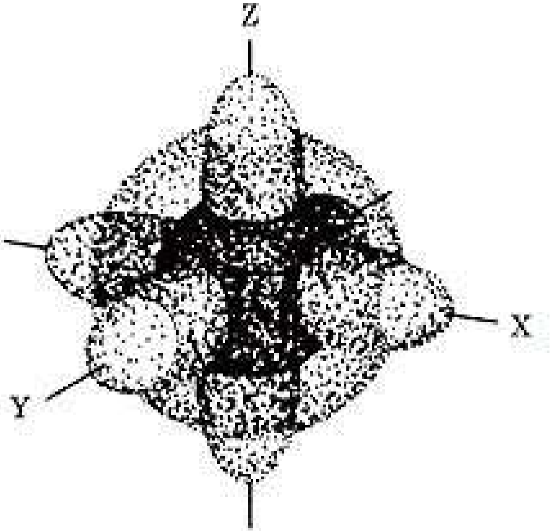
→When you are finished, do #19 p. 244

Davison Germer Example

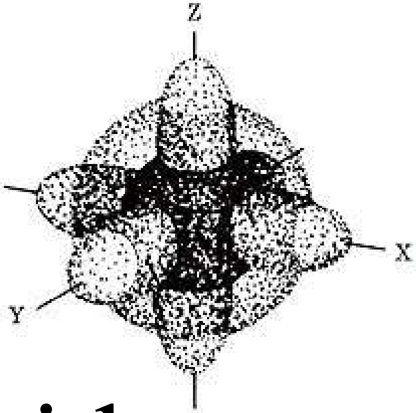
What part of

$$i\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2}+V(x)\Psi(x,t)\equiv\tilde{H}\Psi(x,t),$$

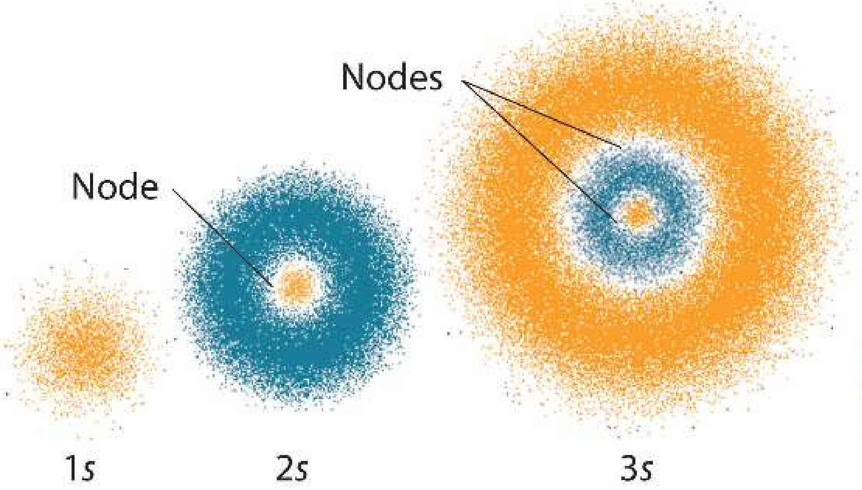
Don’t you understand?



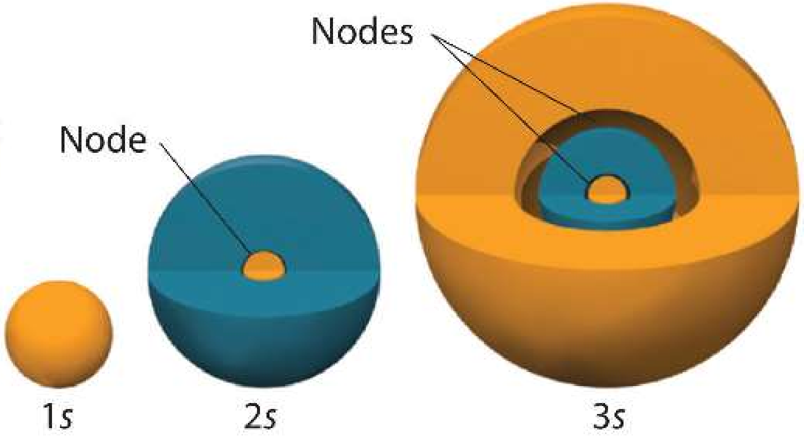
Schrodinger’s model



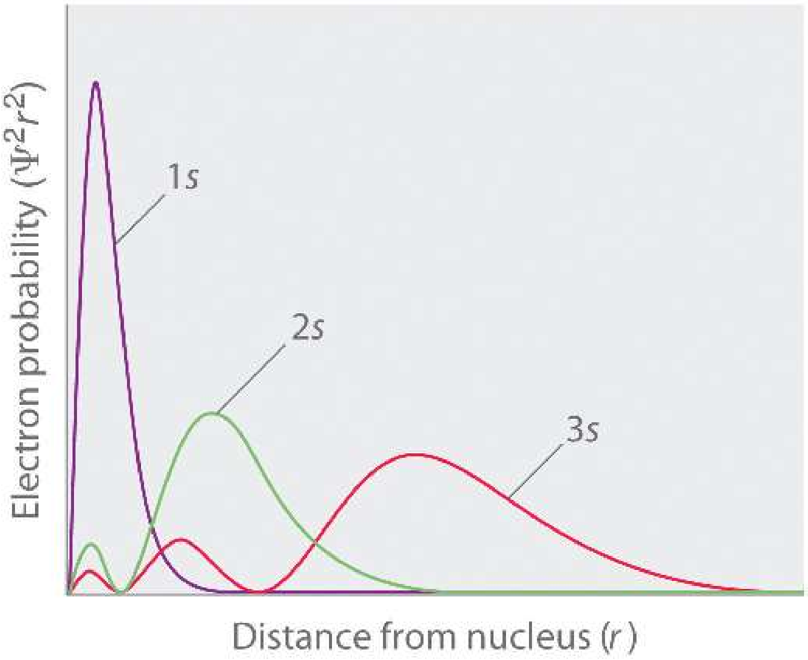
- Electrons are like a wave with only certain wavelengths allowed
- The position is undefined, but a wave function ψ determines the probability of locating it



(a) Electron probability

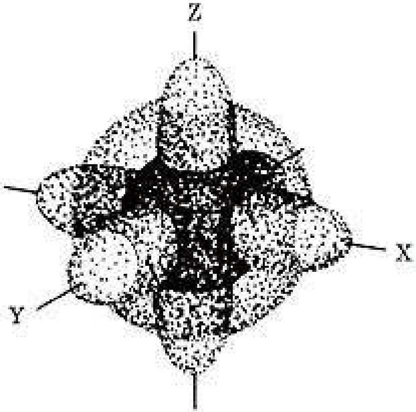


(b) Contour probability



(c) Radial probability

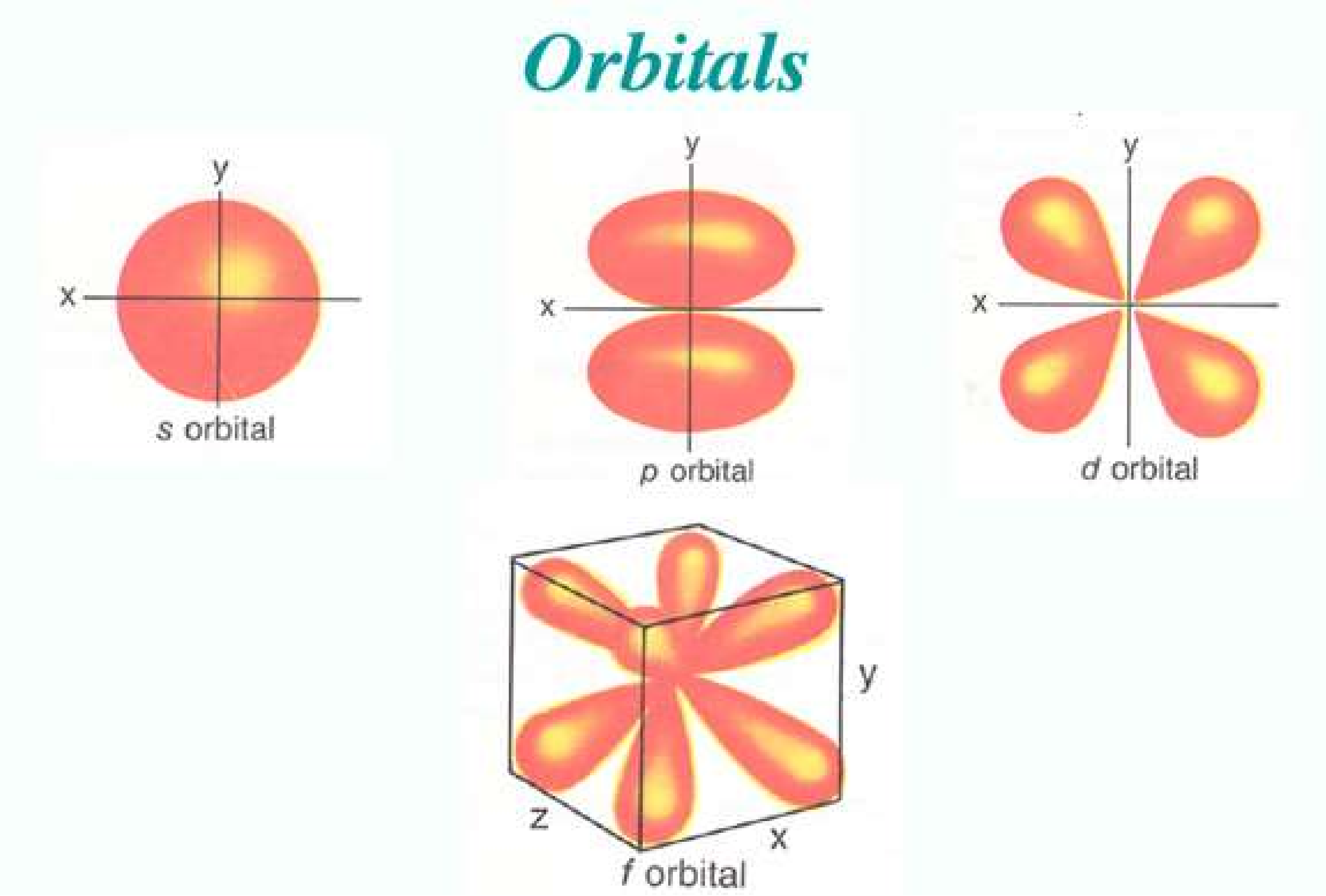
Schrodinger’s cat




science_jokez • Follow
WANTED
DEAD & ALIVE
SCHRÖDINGER'S CAT

SCHRÖDINGER'S CAT IS

Ok, but what does an atom “really” look like?



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P. 239 #11a

Given E=1000N/C find v

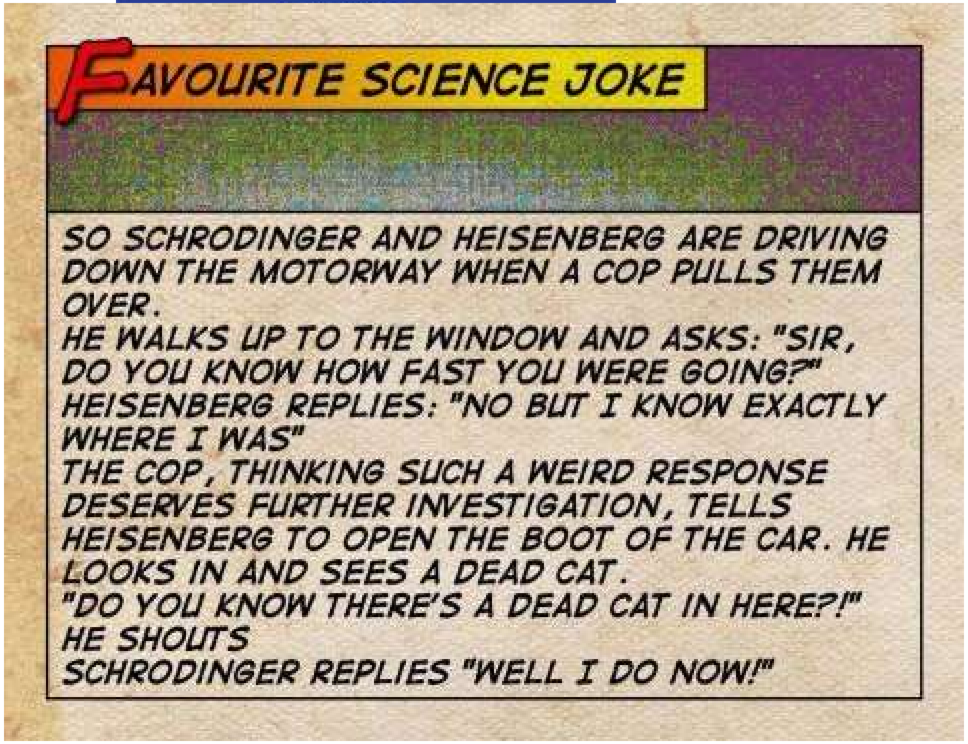
$$qE = qvB \qquad v = \frac{E}{B} = \frac{1000}{0.1} = 10km \cdot s^{-1}$$

#11b find m (in unified amu)

$$qvB = m\frac{v^2}{r} \qquad m = \frac{rqB}{v} = \frac{9.6 \times 10^{-26} kg}{u}$$

$$m = 57.5u$$

No, not that Heisenberg



FAVOURITE SCIENCE JOKE

SO SCHRODINGER AND HEISENBERG ARE DRIVING DOWN THE MOTORWAY WHEN A COP PULLS THEM OVER.
HE WALKS UP TO THE WINDOW AND ASKS: "SIR, DO YOU KNOW HOW FAST YOU WERE GOING?"
HEISENBERG REPLIES: "NO BUT I KNOW EXACTLY WHERE I WAS"
THE COP, THINKING SUCH A WEIRD RESPONSE DESERVES FURTHER INVESTIGATION, TELLS HEISENBERG TO OPEN THE BOOT OF THE CAR. HE LOOKS IN AND SEES A DEAD CAT.
"DO YOU KNOW THERE'S A DEAD CAT IN HERE?!" HE SHOUTS
SCHRODINGER REPLIES "WELL I DO NOW!"

That
Heisenberg

Uncertainty principle

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

- Where Δx is the uncertainty in the position and Δp is the uncertainty in the momentum

Ex 1a: find the uncertainty in momentum

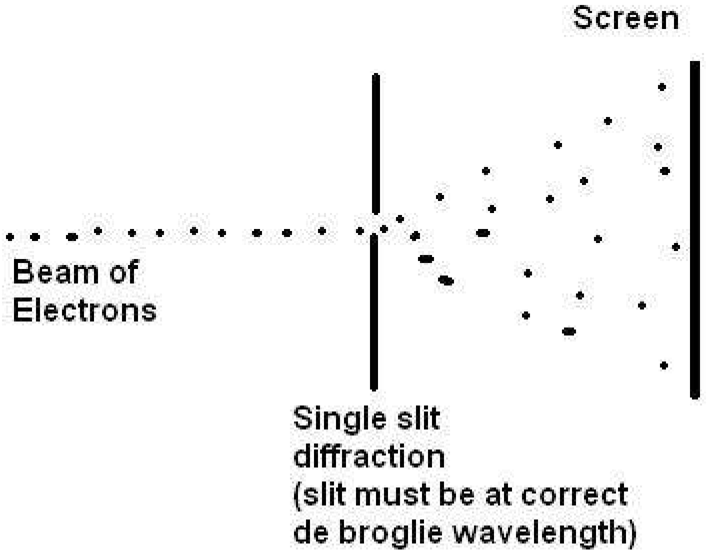
- An electron passes through a thin slit of width Δx = 23μm

$$\Delta x \Delta p \geq \frac{h}{4\pi} \quad \Delta p \geq \frac{h}{4\pi \Delta x}$$

$$\Delta p \geq \frac{6.63 \times 10^{-34} J \cdot s}{4\pi\left(23 \times 10^{-6} m\right)}$$

$$\Delta p \geq 2.29 \times 10^{-30} kg \cdot m \cdot s^{-1}$$

Ex 1b: what direction is the uncertainty in momentum, relative to the original direction of the electron beam?



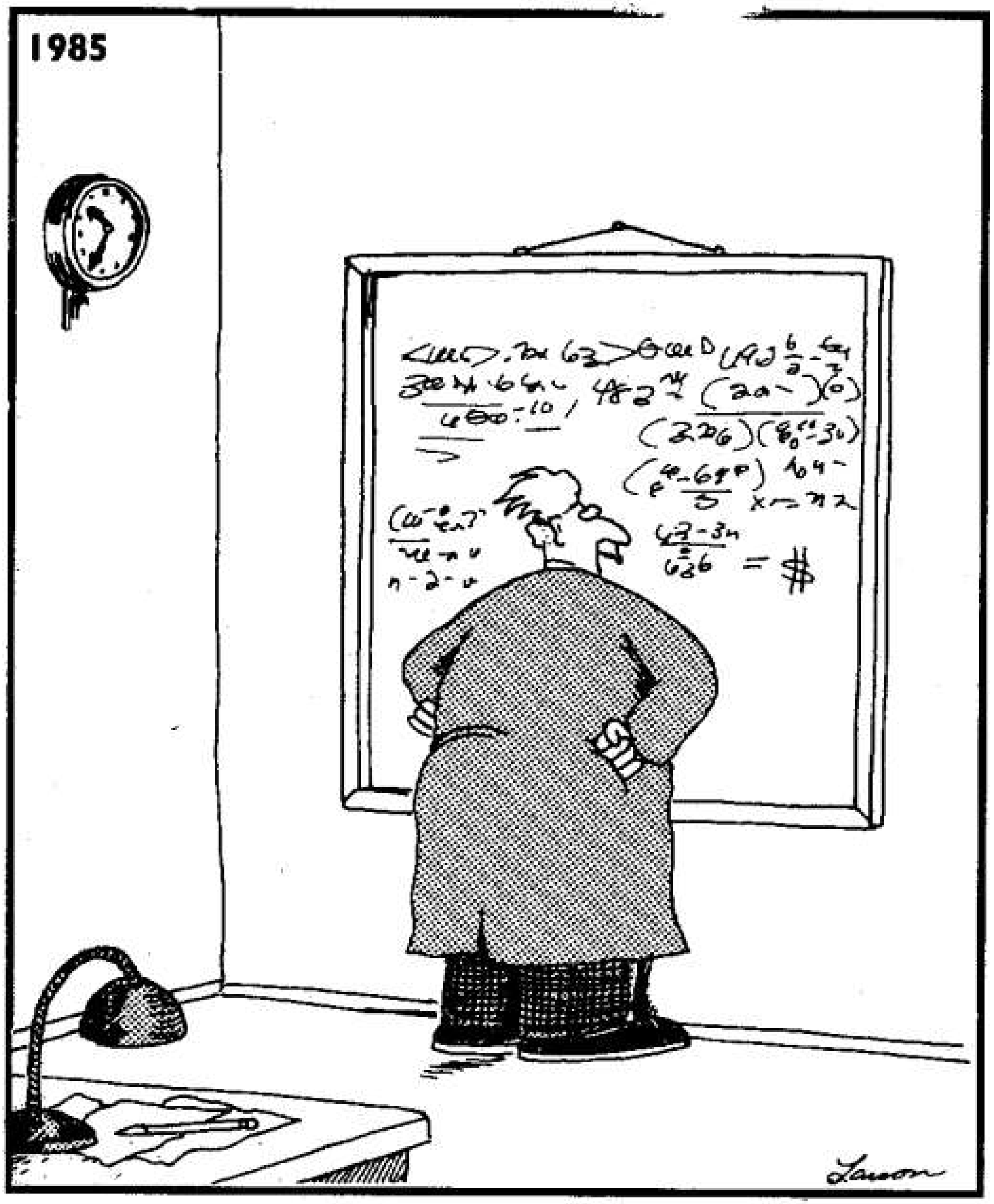
- Perpendicular to beam direction

Uncertainty principle

$$\Delta E \Delta t \geq \frac{h}{4\pi}$$

- Where ΔE is the uncertainty in the change in energy and Δt is the uncertainty in the time that energy change occured

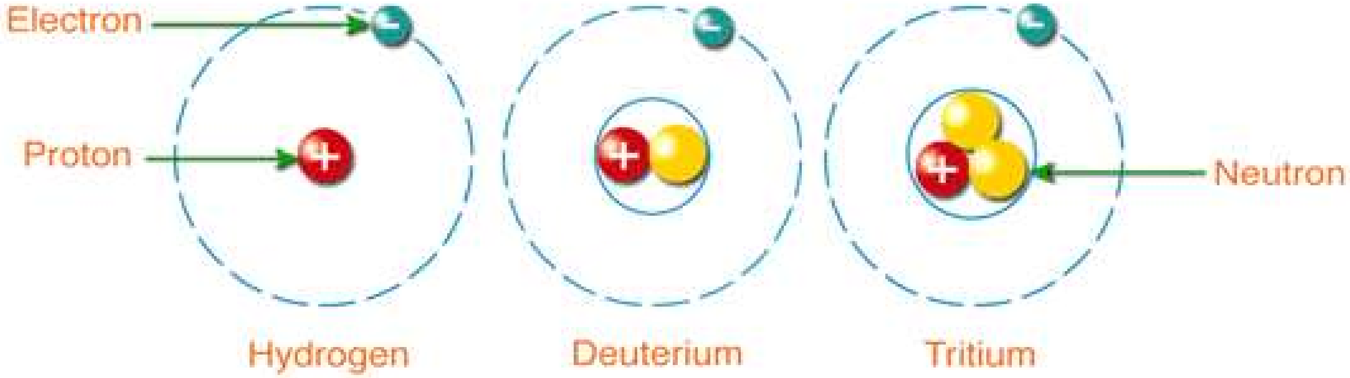
Ex 2: hydrogen atom



Einstein discovers that time is actually money.

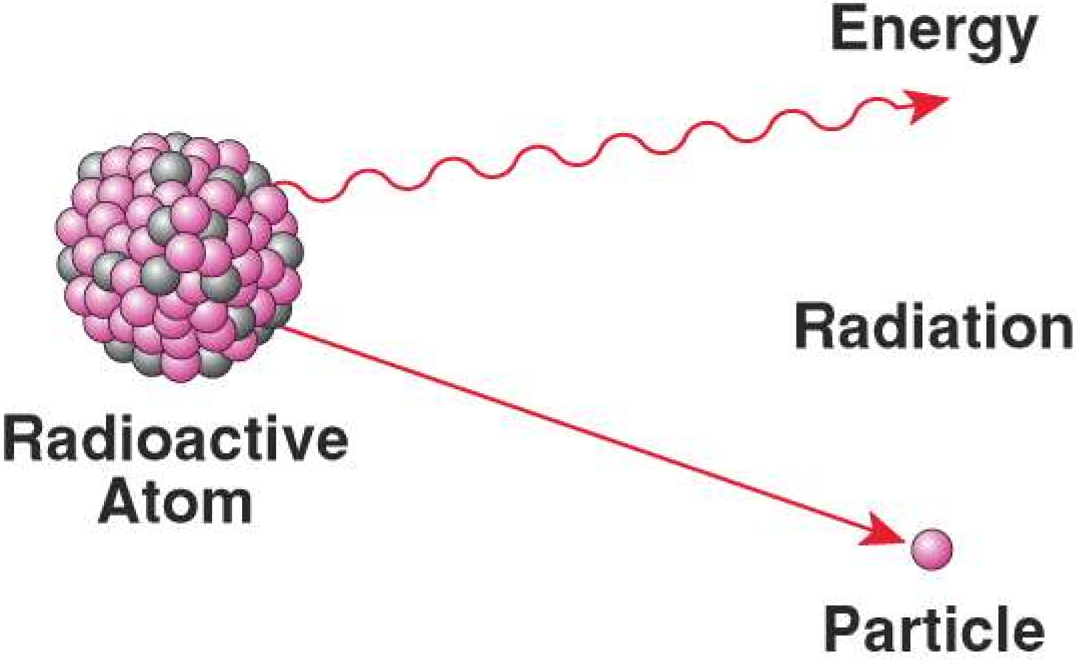
Isotopes

- Elements have a characteristic number of protons,
  - e.g. Hydrogen always has one proton
- They may have different numbers of neutrons
- Neutrons help to glue together the nucleus of mutually repulsive protons



Radioactivity

- Marie and Pierre Curie discovered that some isotopes are unstable: they spontaneously decay and give off radiation



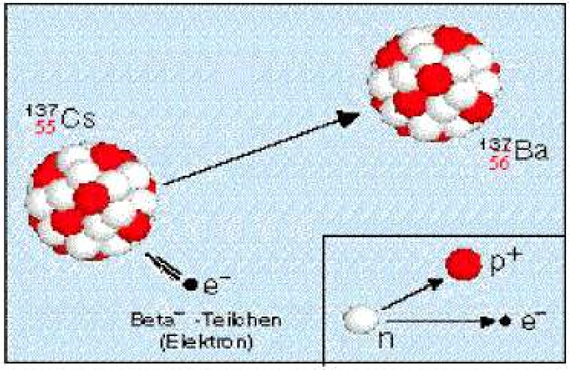
What are the effects of radiation?

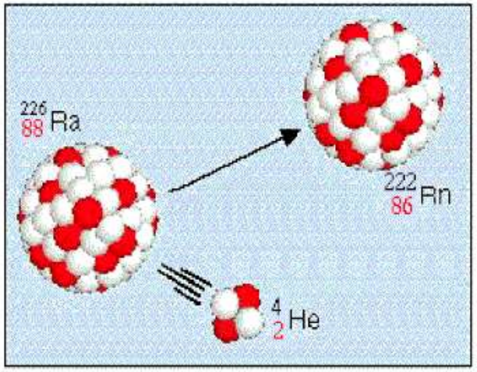
Up and Atom!

You wouldn’t like me when I’m angry...

Radiation

- Radiation from the nucleus comes in three flavors:
  - α (Alpha): massive, “slow”, blocked by paper. He^{2+}
  - β (Beta): fast, low mass, blocked by >10 sheets of Al foil. e^-
  - γ (Gamma): high energy E-M radiation AKA “light”. Gamma ray photon. Blocked by thick lead





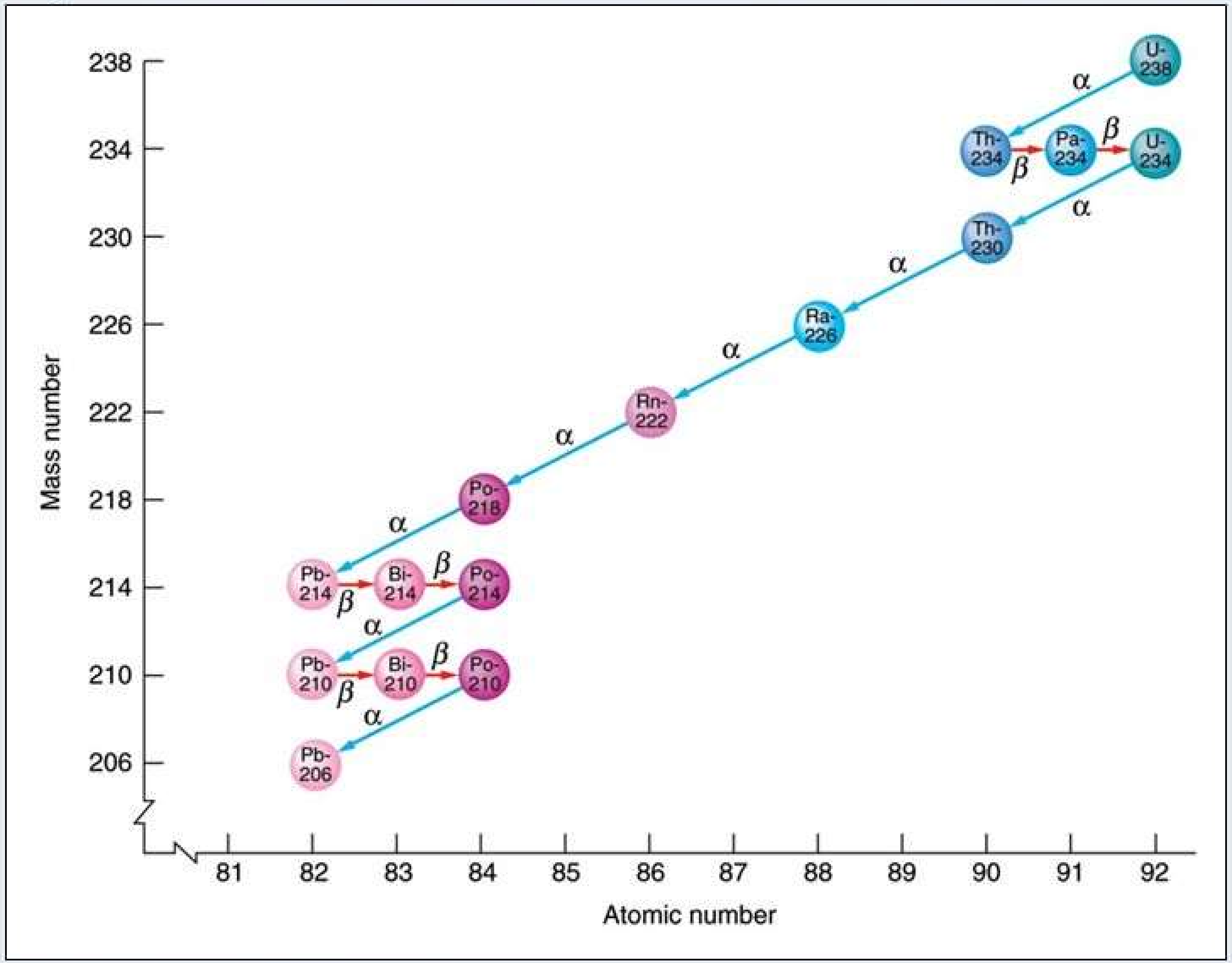
Nuclear equations

- Balance charge, then mass
- Ex: write the equation for the alpha decay of U-238

$$ {}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha $$

- Nuclear energy levels are quantized, so the alpha particles typically have a kinetic energy of 5 or 8 MeV. Also, we often get gamma radiation following alpha

Decay Series of Uranium-238 to Lead-206



- Ex: write the equation for the beta decay of C-14

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}\beta + \overline{\nu}$$

- Beta energy levels are also quantized, but we don’t see discrete beta energies, since the antineutrino carries away some of the energy

- Ex: write the equation for the beta+ decay of Na-22

$$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + ^{0}_{1}e^{+} + \nu$$

- Ex: write the equation for the beta decay of Th-231

$$ {}^{231}_{90}Th \rightarrow {}^{231}_{91}Pa + {}^{0}_{-1}e^{-} + \overline{\nu} $$

- Ex: write the equation for the alpha decay of Pu-239 and find the energy released in MeV

$$ {}^{239}_{94}Pu \rightarrow {}^{235}_{92}U + {}^{4}_{2}\alpha $$

- Pu-239=239.052156
- U-235=235.043923
- Alpha particle = 4.002602
- Mass defect = 239.052156-235.043923-4.002602
- = 0.005631*931.5MeV
- =5.24MeV

Up to P. 250 #23

Ex: #18 p. 235

- U-233 has 92 protons, 141 neutrons
- 92(1.007276u)+141(1.008665u)=234.9u
- 234.9u-233.0=1.9u
- 1.9u(931.5MeV)=1.77GeV
- 1.77 GeV/233 nucleons=7.6MeV per nucleon

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

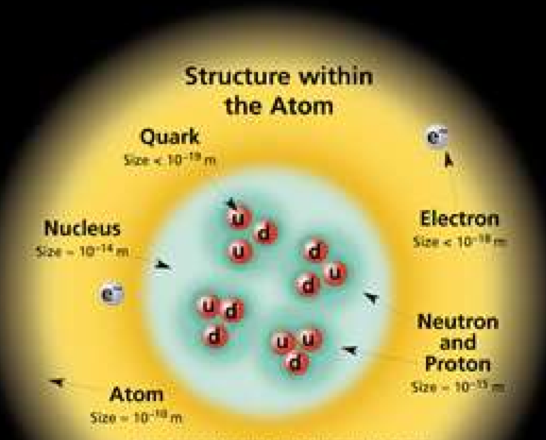
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

Structure within the Atom



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

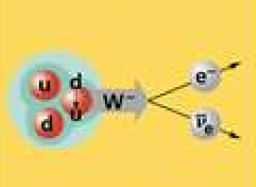
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

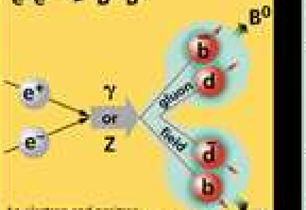
These diagrams are an artist's conception of physical processes. They are *not* exact and have **no** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



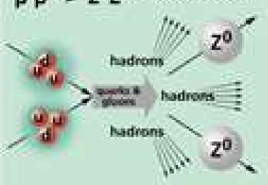
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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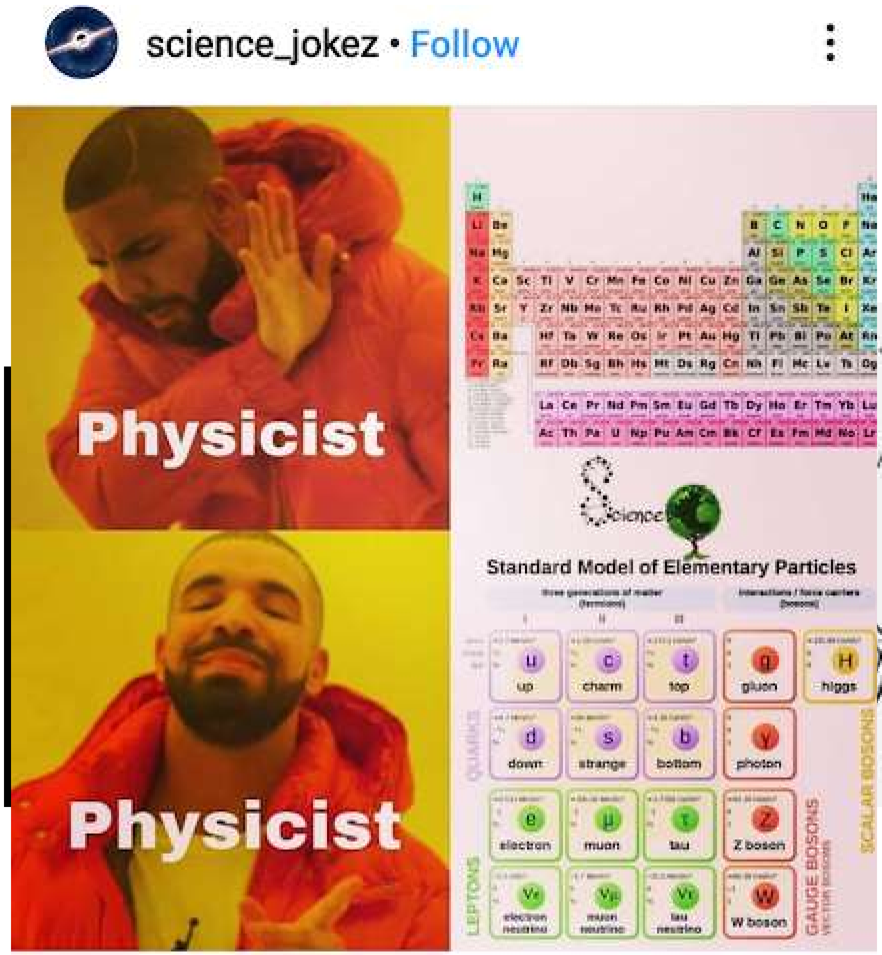
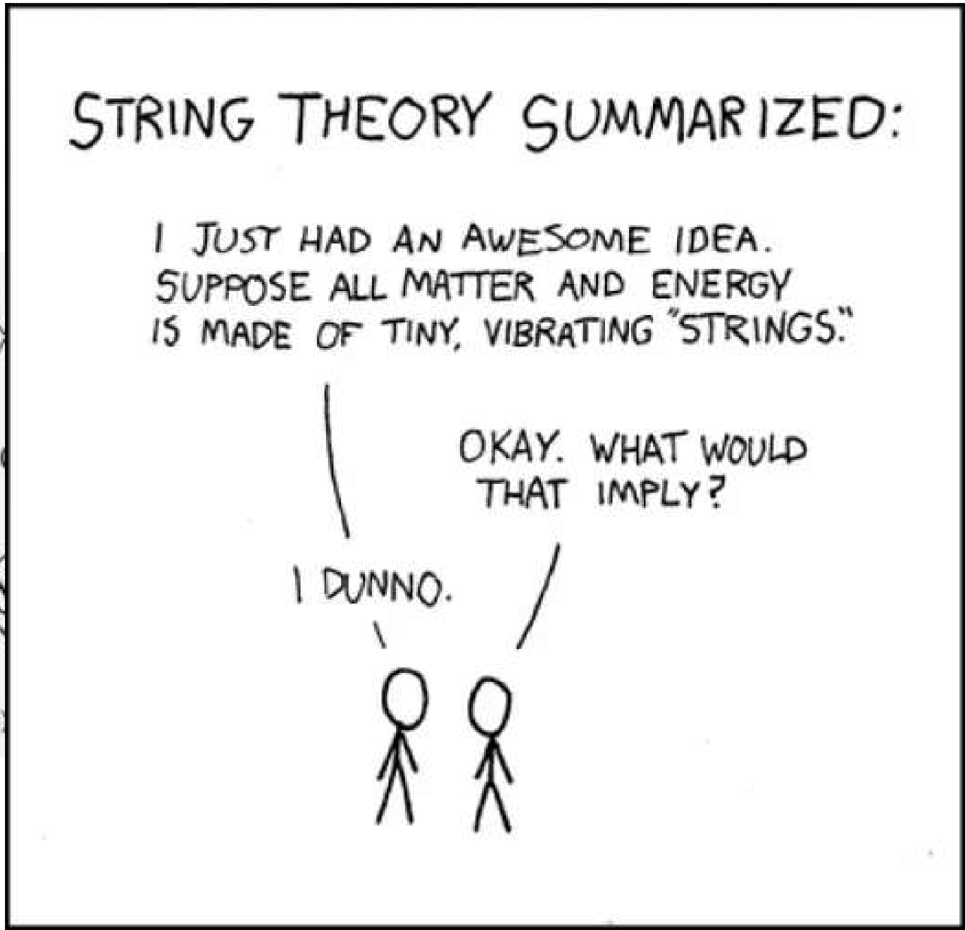
http://CPEPweb.org

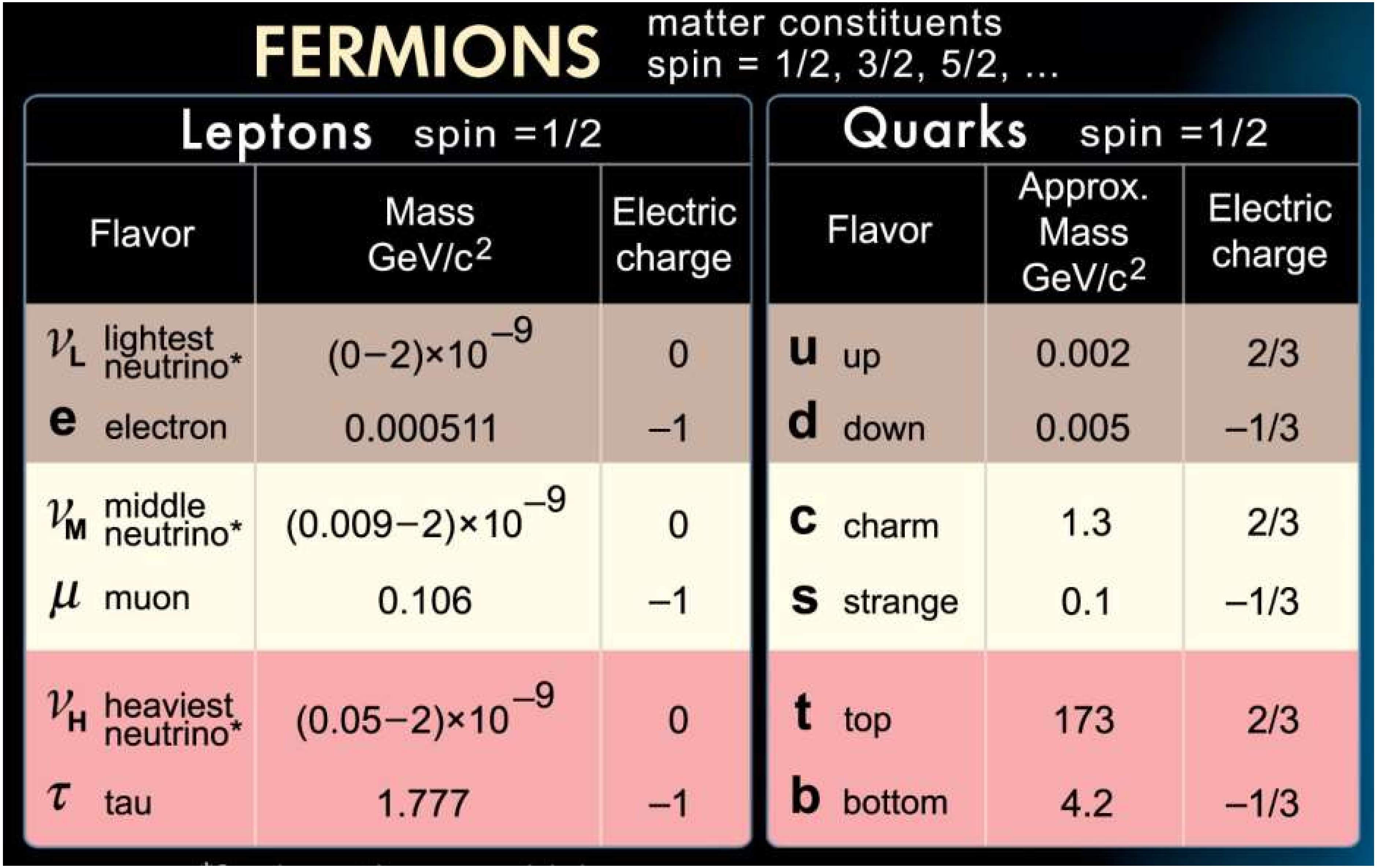
Why so many particles?

- Could there be another underlying fundamental structure?





Standard Model. *flavor?



FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

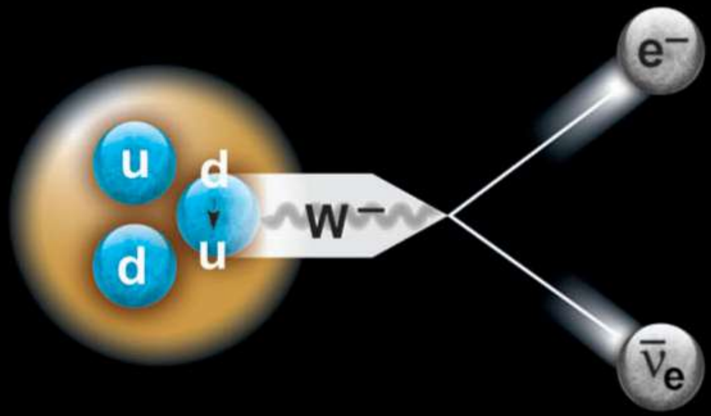
Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Particle Processes

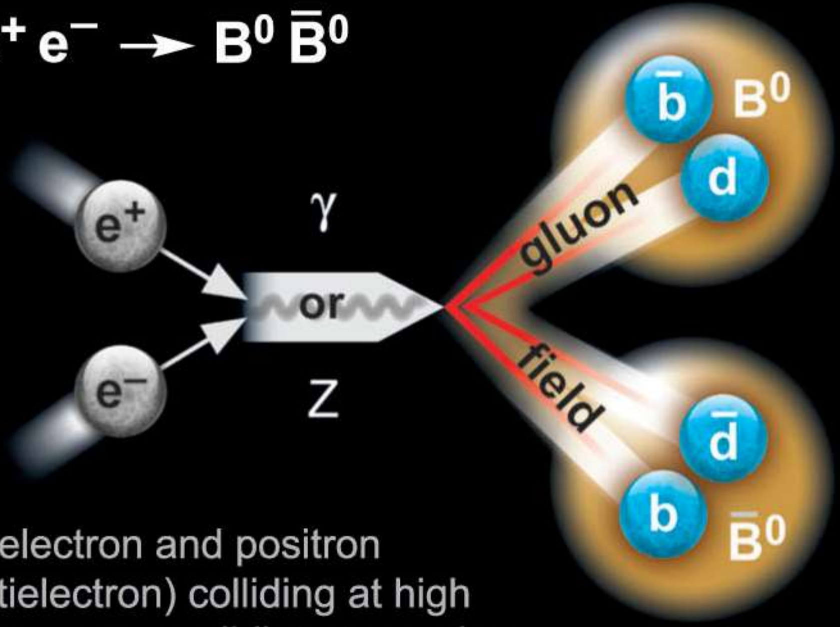
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$$n \rightarrow p\, e^- \,\bar{\nu}_e$$

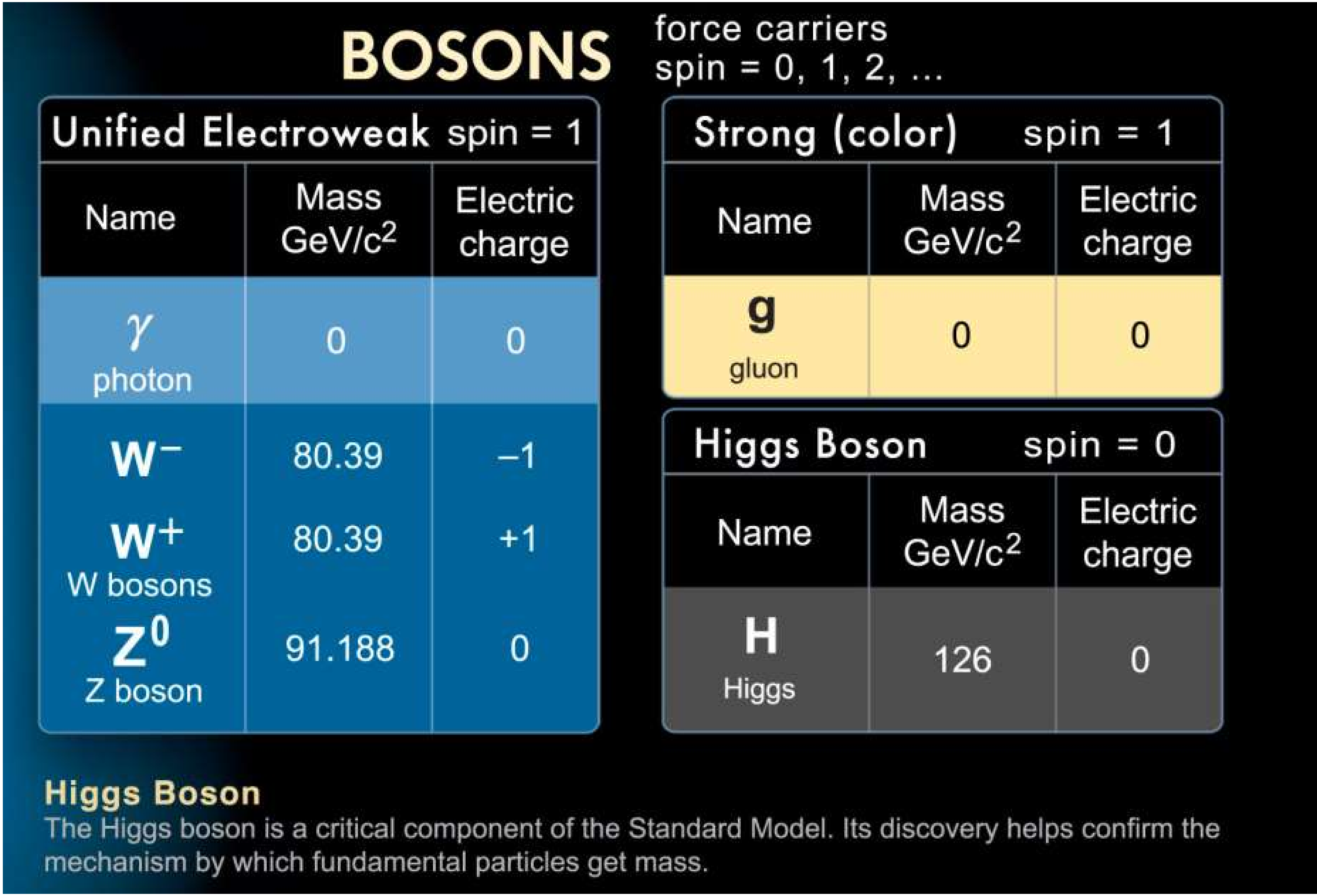


A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$$e^+ e^- \rightarrow B^0 \bar{B}^0$$



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.39	–1
W$^+$ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

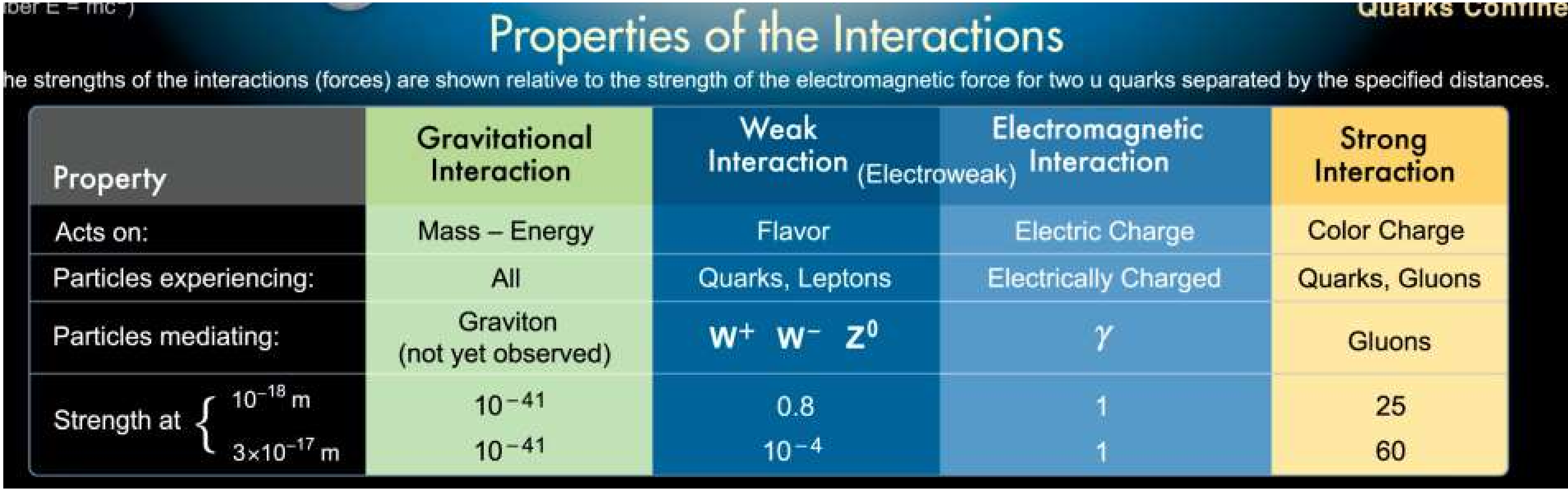
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.



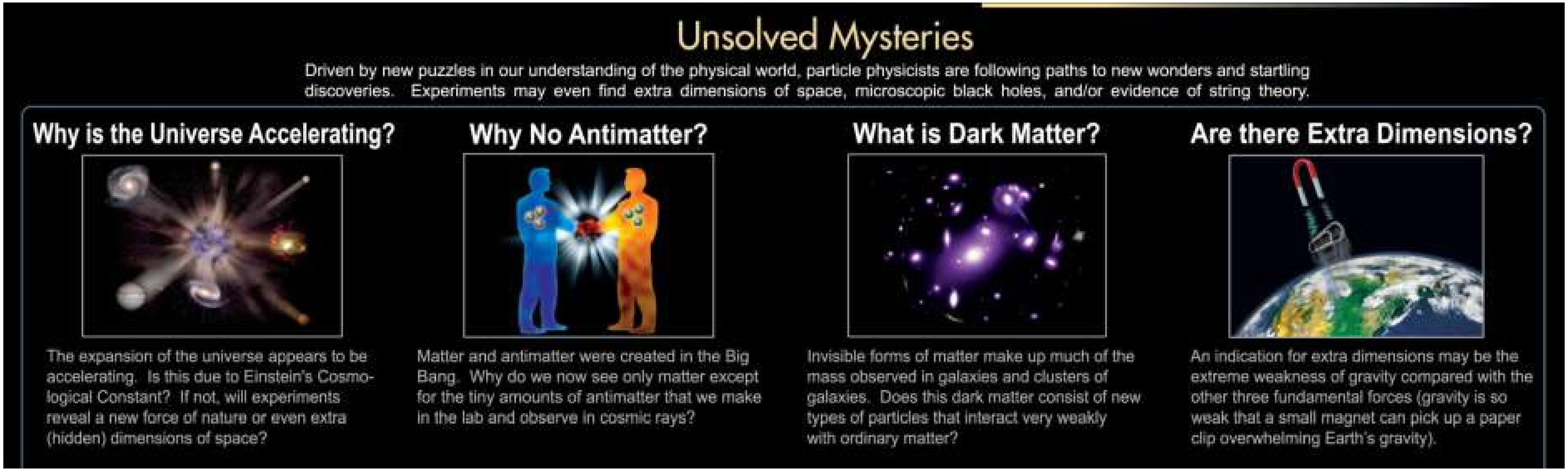
ber E = mc^2)

Quarks Confine

Properties of the Interactions

he strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

		(Electroweak)		
Property	**Gravitational Interaction**	**Weak Interaction**	**Electromagnetic Interaction**	**Strong Interaction**
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60



Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

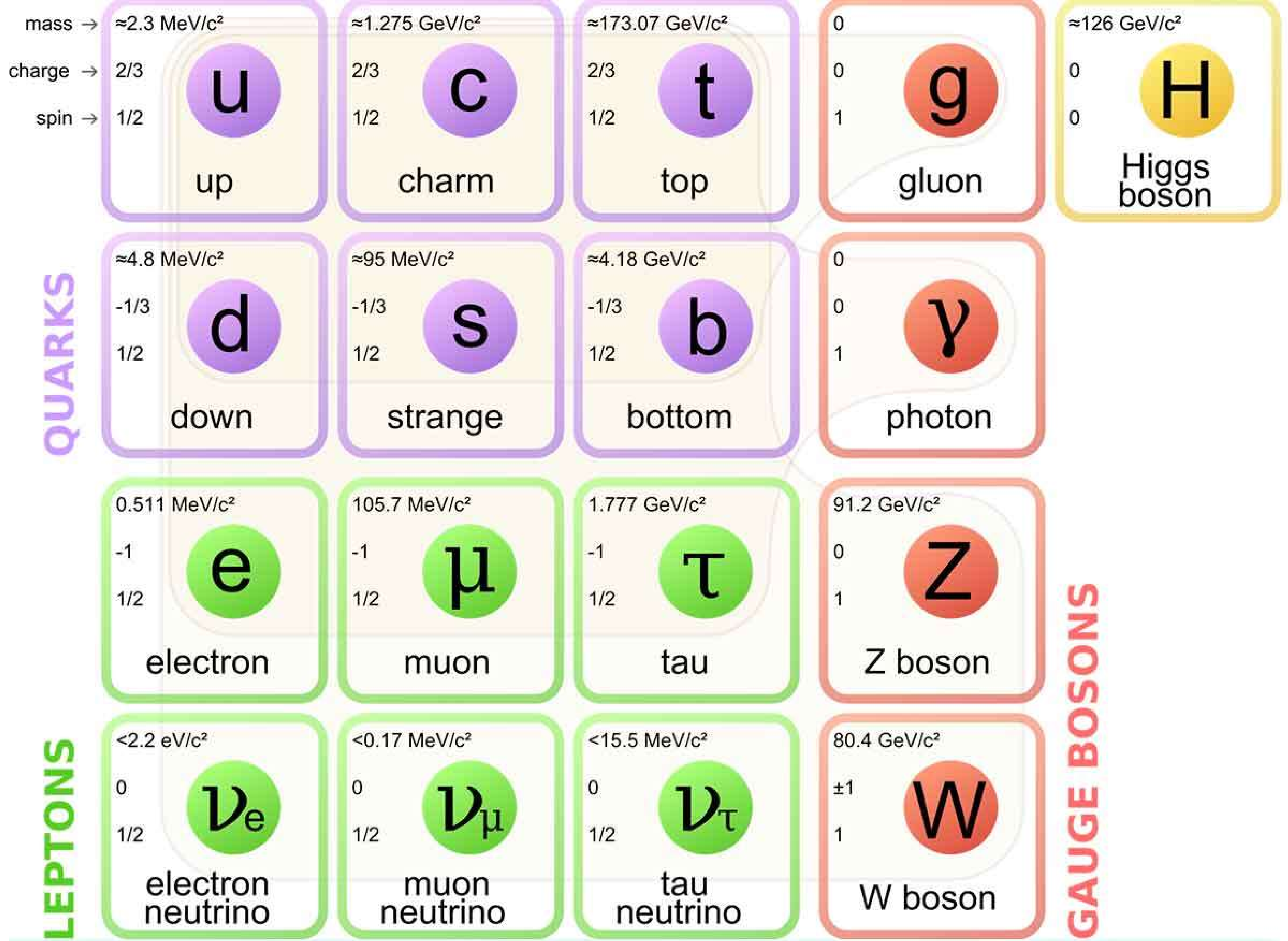
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

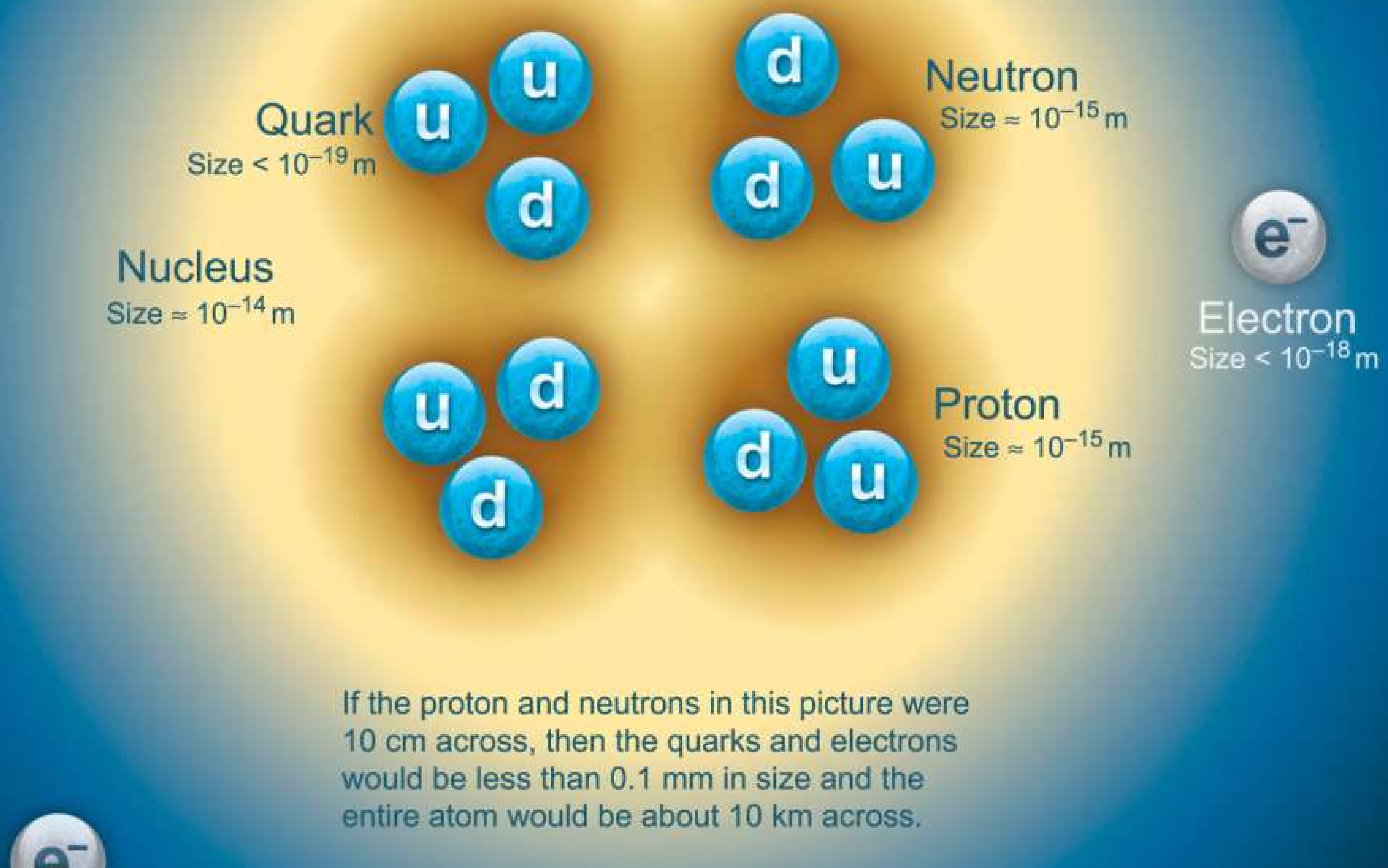
An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

Elementary Particles

Structure within the Atom



Atom
Size ≈ 10^{-10} m

Quark
Size < 10^{-19} m

Nucleus
Size ≈ 10^{-14} m

Neutron
Size ≈ 10^{-15} m

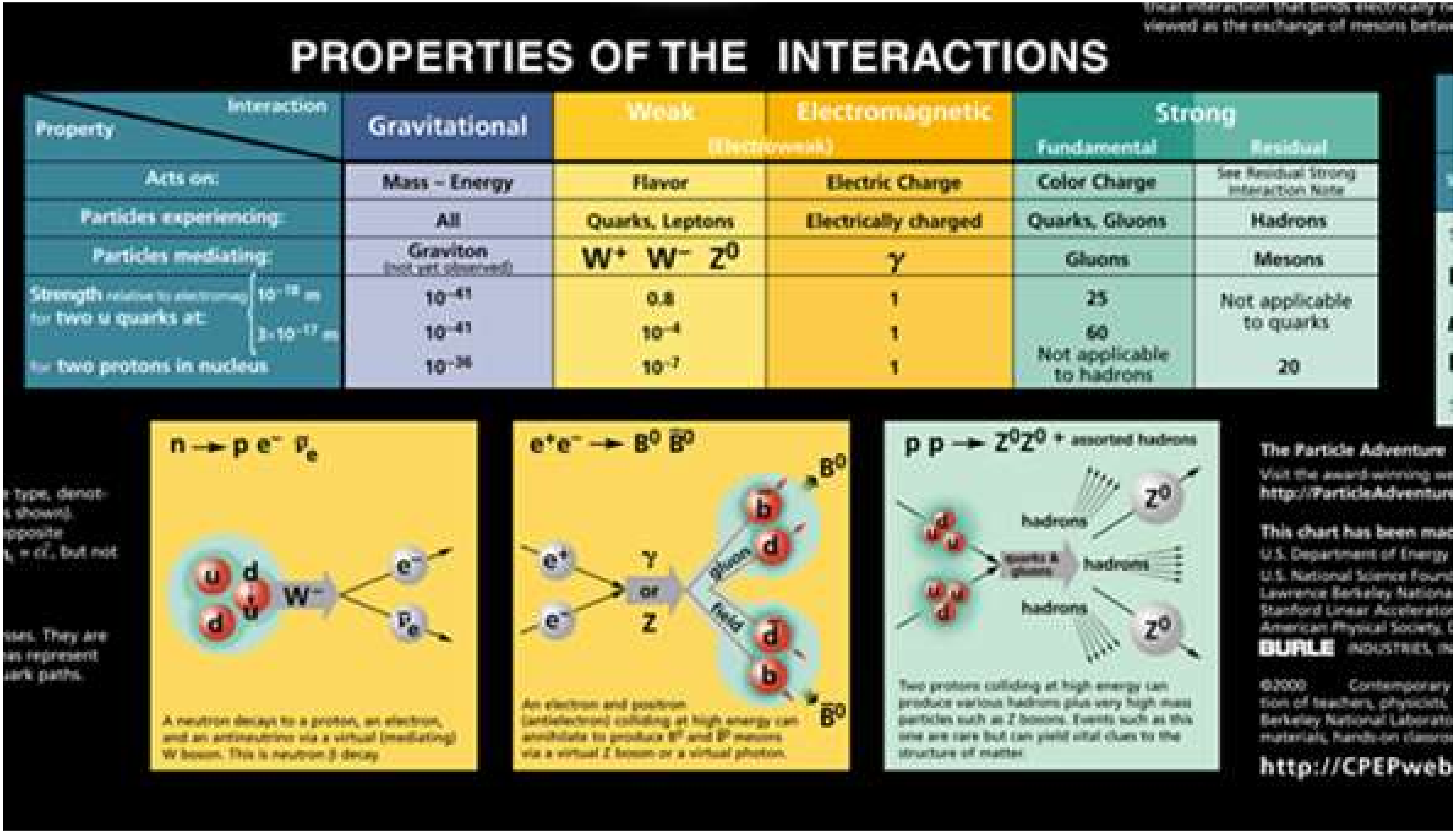
Proton
Size ≈ 10^{-15} m

Electron
Size < 10^{-18} m

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Activate the Radioactivity Activity

- Team alpha, beta and gamma
- Design a procedure to test the penetrating power of alpha, beta, and gamma radiation
- Record your results



tical interaction that binds electrically n

viewed as the exchange of mesons betw

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
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for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

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$e^+e^- \rightarrow B^0 \bar{B}^0$

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0Z^0$ + assorted hadrons

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

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q, = cc̄, but not

sses. They are
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The Particle Adventure

Visit the award-winning we
http://ParticleAdventure

This chart has been mad

U.S. Department of Energy
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American Physical Society, (
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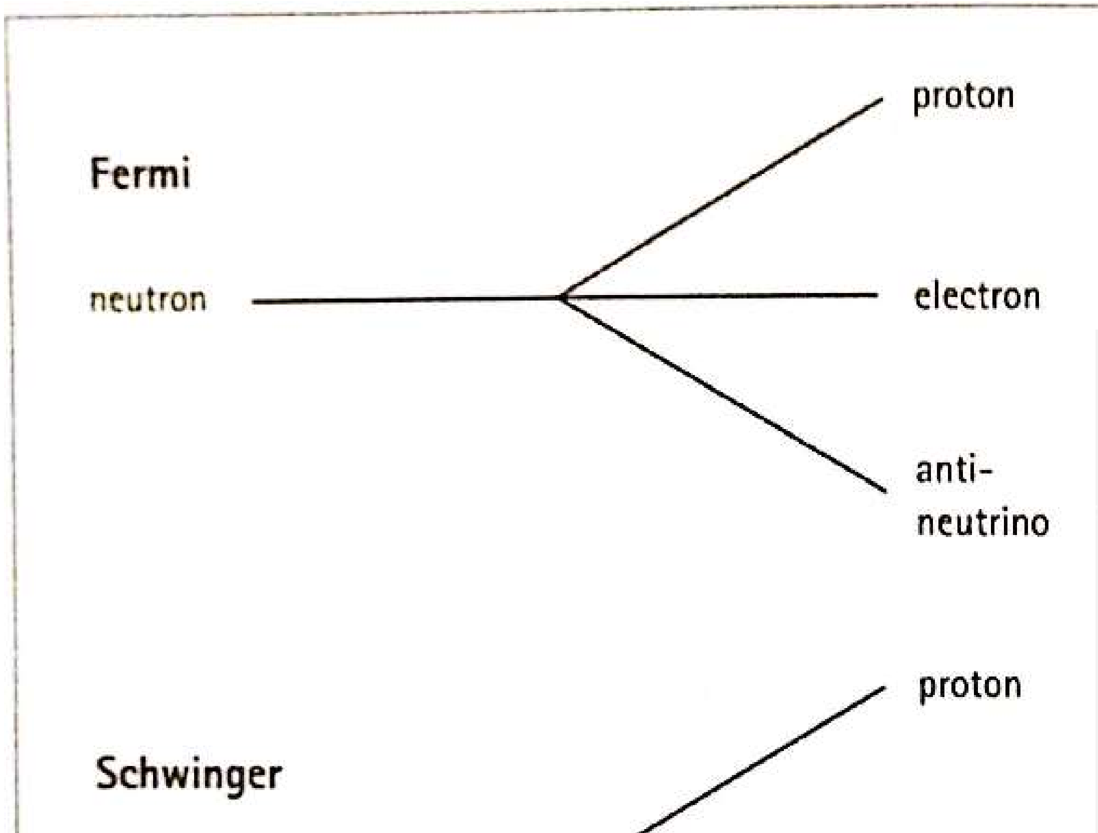
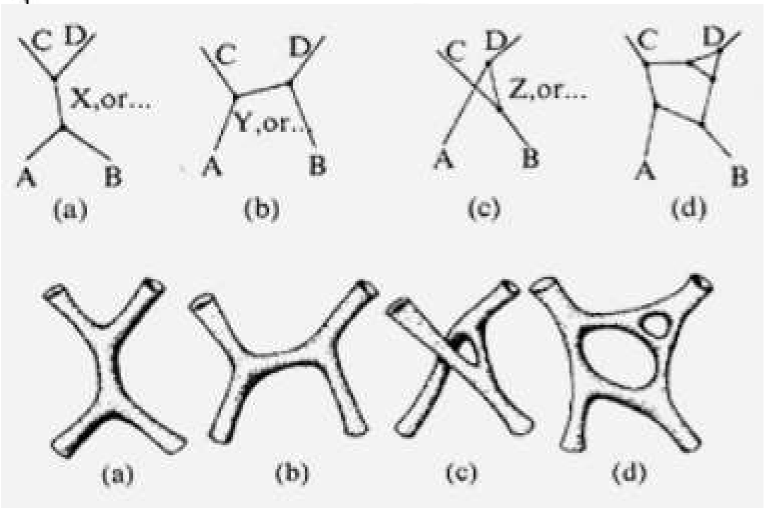
tion of teachers, physicists,
Berkeley National Laborato
materials, hands-on classro

http://CPEPweb

TOK connection: which is the best model?





Radioactivity

- When a radioactive isotope decays, the amount remaining can be described by an exponential relation:

$$N = N_0 e^{-\lambda t}$$

- Where λ is the decay constant (s^{-1})
- Ex: use this to find λ from half life

$$\frac{N}{N_0} = e^{-\lambda t}$$

$$\frac{1}{2} = e^{-\lambda T_{1/2}}$$

$$\ln\left(\frac{1}{2}\right) = \ln\left(e^{-\lambda T_{1/2}}\right)$$

$$\ln\left(2^{-1}\right) = -\lambda T_{1/2}$$

$$\lambda = \frac{-\ln 2}{-T_{1/2}}$$

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

- Activity: start with a petri dish full of popcorn kernels. Shake and decay once every 10 s. A kernel has decayed if it is pointing down after the shake. Compare % remaining after “40s” with theoretical:

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{\ln 2}{10s} = 0.069$$

$$N = N_0 e^{-\lambda t} = 100\% e^{-0.069(40)} = 6.3\%$$

Decay rate λ

- Show that decay rate

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

$$N = N_0 e^{-\lambda t}$$

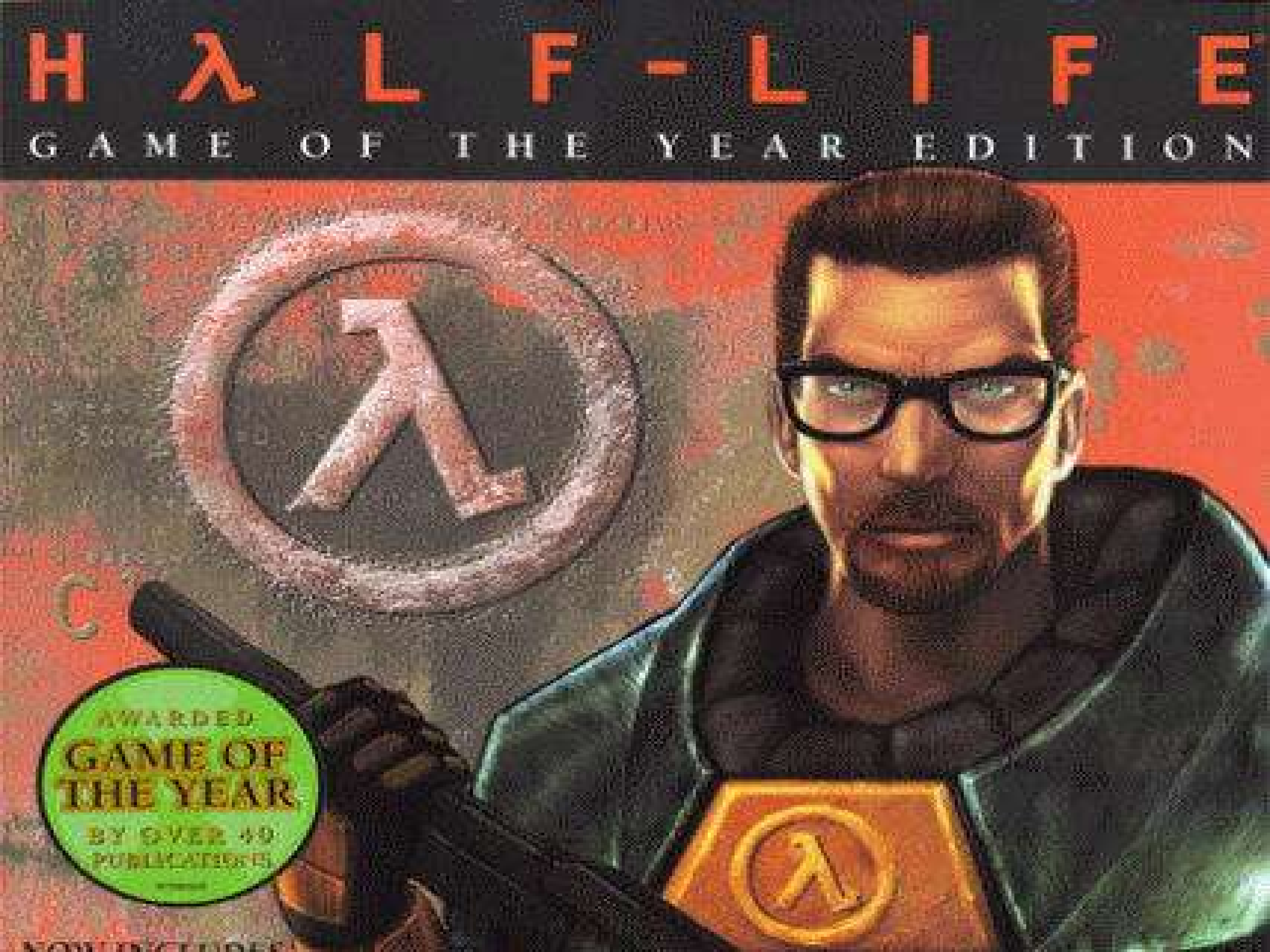
$$\frac{N}{N_0} = e^{-\lambda t}$$

$$\ln\left(\frac{N}{N_0}\right) = \ln\left(e^{-\lambda t}\right)$$

$$\ln\left(\frac{1}{2}\right) = \ln\left(e^{-\lambda T}\right)$$

$$\text{-}\ln(2) = -\lambda \mathrm{T}$$

$$\lambda = \frac{\ln 2}{T_{1/2}}$$


HλLF-LIFE
GAME OF THE YEAR EDITION
AWARDED
GAME OF THE YEAR
BY OVER 40
PUBLICATIONS

Half Life $T_{1/2}$

- When a radioactive isotope decays, the amount remaining can be described by a half life relation:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

- Ex 1: find the decay constant for Po-211, if it has a half life of 0.51s

$$\lambda = \frac{\ln 2}{T_{1/2}} = 1.36s^{-1}$$

Activity Level

- Ex: find the activity level after 2.0s if we start with 99 atoms of Po-211

$$A = \lambda N_0 e^{-\lambda t}$$

$$A = 8.9 decays / s = 8.9 Bq$$

Instantaneous Activity Level

- Ex: find the activity level for 2350 atoms of Po-211

$$A = \lambda N_0 e^{-\lambda t} = \lambda N$$

$$A = 1.36(2350)$$

$$A = 3200 Bq$$

- Ex 1: find the amount remaining of 55kg of plutonium in the year 3018, if it has a half life of $8\text{x}10^7$a

$$\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{8\times10^7\times3.16\times10^7}$$

$$N = N_0 e^{-\lambda t} = 55e^{-2.74\times10^{-16}\times3.16\times10^{10}}$$

$$= 54.9995kg$$

Try Exercises p. 253 #24-26

f(x)=100(0.5)^x

% Remaining vs. Half-lives elapsed

- Ex 2: Exponential decay
  - Cesium 137 has a half life of 30 years. If 2.5 kg is left for 20 years, what mass will be left?

- Ex 2: Exponential decay
  - Cesium 137 has a half life of 30 years. If 2.5 kg is left for 20 years, what mass will be left?

$$\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{30\times 3.16\times 10^{7}}$$

$$N = N_0 e^{-\lambda t}$$

$$A = 1.57kg$$

- Ex 3: Radioactive dating
  - Cesium 137 has a half life of 30 years. If we start with 2.5 kg how much time passes until 0.32 kg remain?

$$\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{30 \times 3.16 \times 10^7}$$

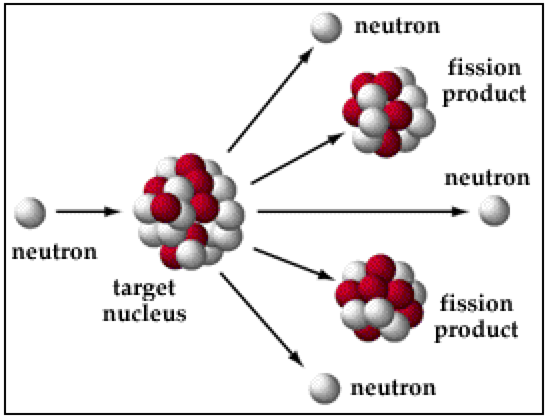
$$N = N_0 e^{-\lambda t} \qquad t = \frac{\ln\left(\frac{0.32}{2.5}\right)}{-7.31 \times 10^{-10}}$$

$$t = 89a$$

Try Exercises p. 255 #27-31

Nuclear reactions

- Atoms can be broken up (fission) or combined (fusion)



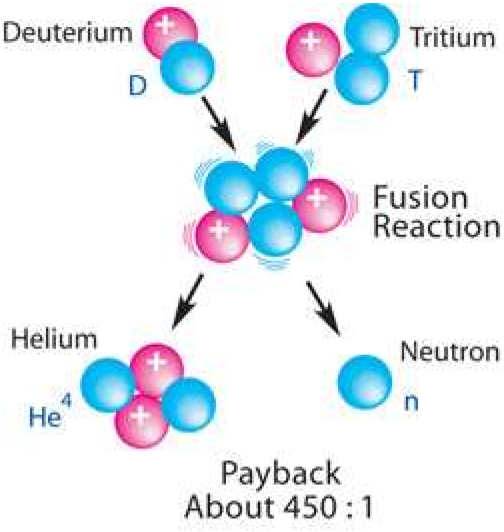
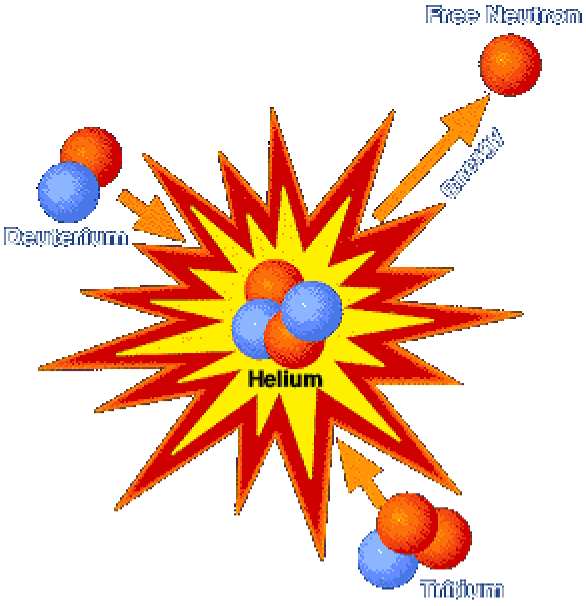


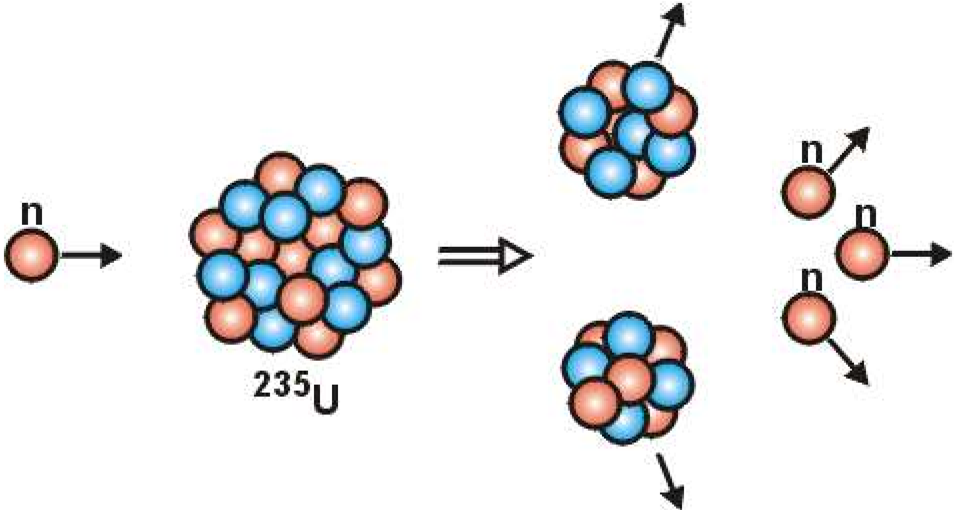
Diagram of deuterium-tritium reaction.

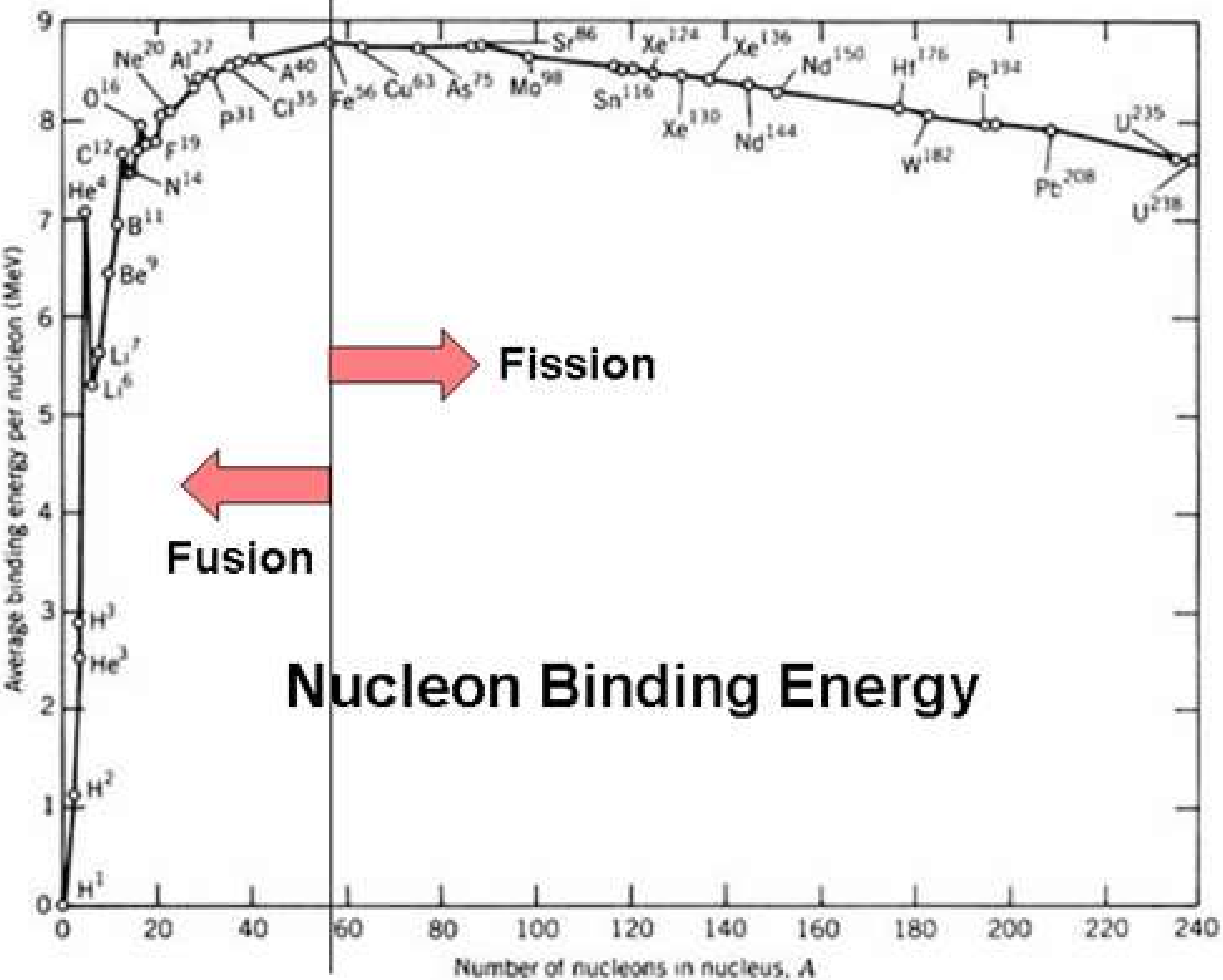
$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}n + energy $$

Fission and Fusion

- We can release nuclear energy by fusing together lighter nuclei
- Or by breaking apart heavier elements







- Ex: find the energy released by the fission reaction of U-235

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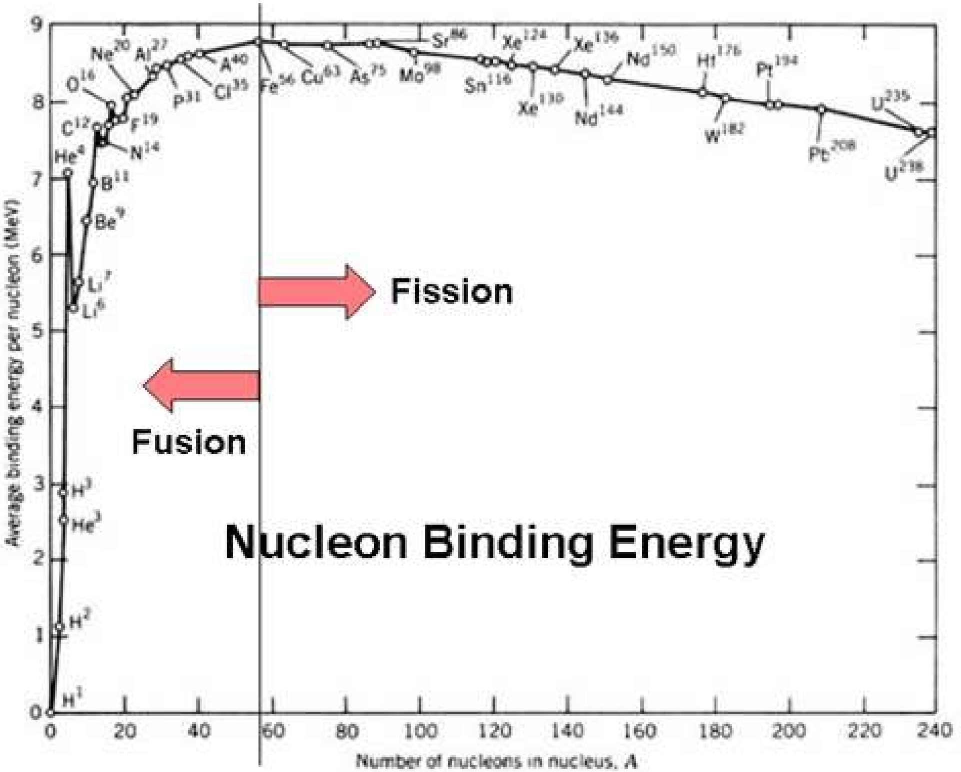
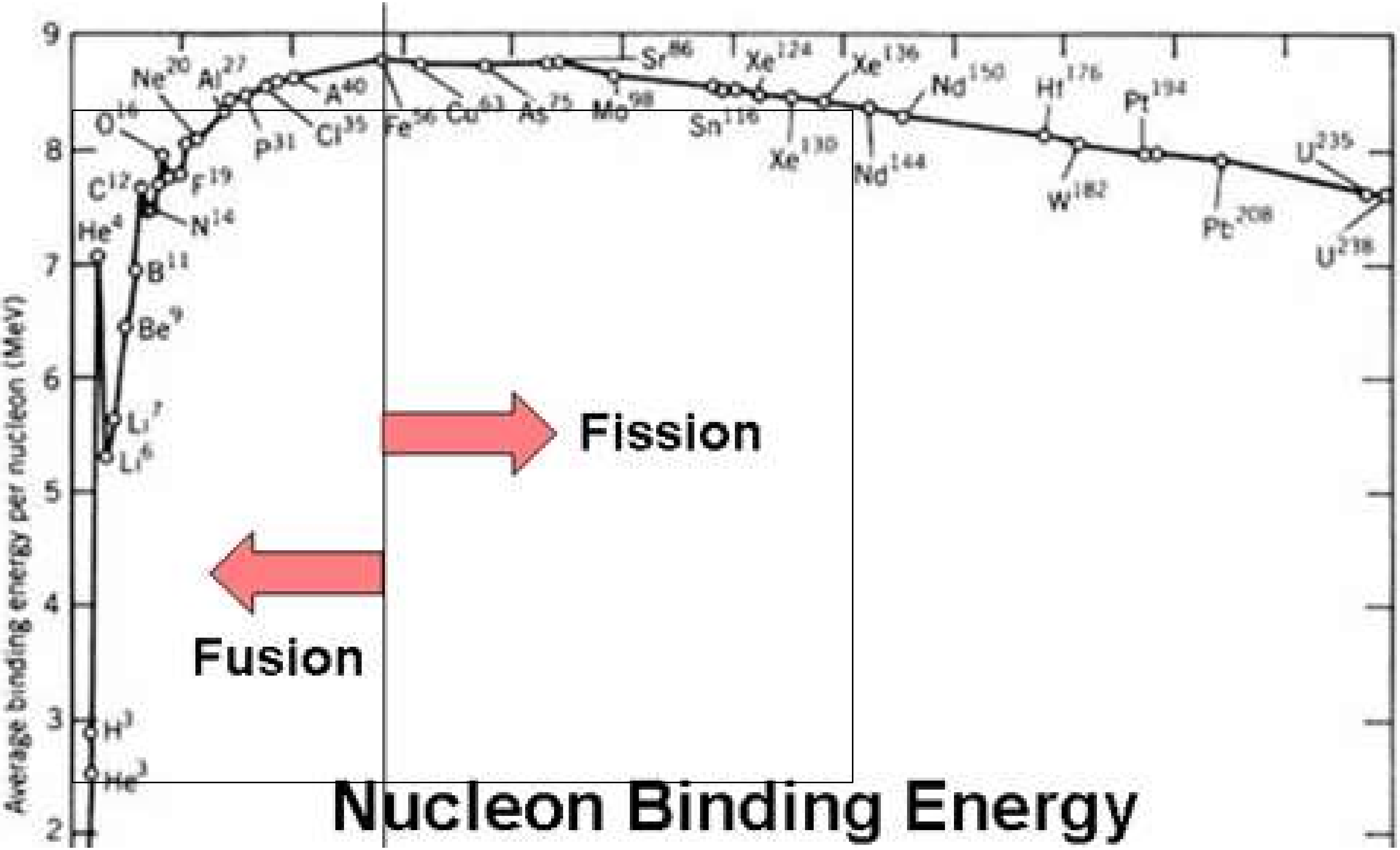


$$ {}_{0}^{1}n + {}_{92}^{235}U \longrightarrow {}_{36}^{92}Kr + {}_{56}^{141}Ba + 3({}_{0}^{1}n) $$

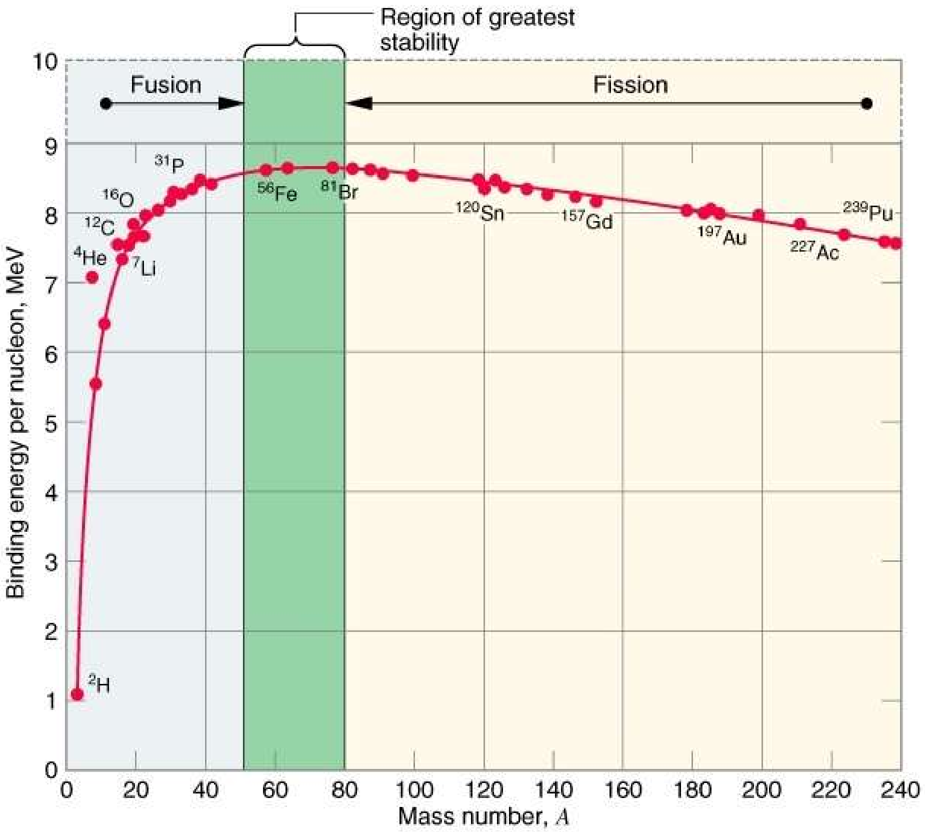


Fission

Fusion

Nucleon Binding Energy

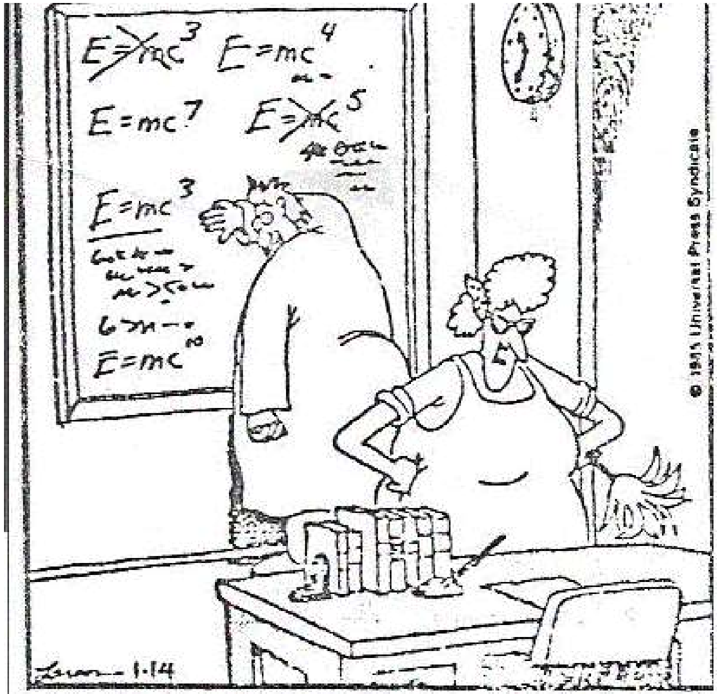
- Ex: find the energy released by the fission reaction of U-235



$$0+7.6\frac{MeV}{nucleon}\longrightarrow 8.6\frac{MeV}{nucleon}+8.3\frac{MeV}{nucleon}+3(0)$$

$$7.6(235)\longrightarrow 8.6(92)+8.3(141)$$

$$1786-(791.2+1170.3)=180MeV$$

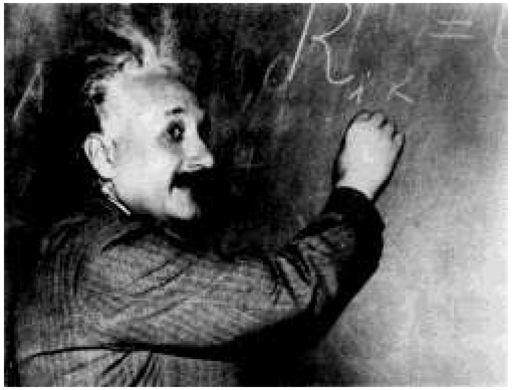


"Now that desk looks better. Everything's squared away, yessir, squaaaaaared away."

Where does the energy come from?

- Einstein showed that in a nuclear reaction, some of the mass is converted into pure energy according to:

$$E = mc^2$$



- Ex 1: how much energy is generated from 0.5g of Uranium?
- Ex2: how much energy is generated when 1kg of matter meets 1kg of antimatter?

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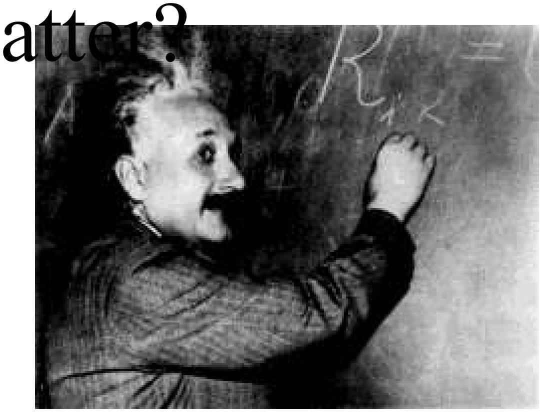


$$E = mc^2$$

$$E = 0.0005kg\left(3.0\times10^8 \, {}^{m}\!/\!{}_{s}\right)^2$$

$$E = 4.5\times10^{13} J$$

$$E = mc^2$$

$$E = 2.0kg\left(3.0\times10^8 \, {}^{m}\!/\!{}_{s}\right)^2$$

$$E = 1.8\times10^{17} J$$

Harnessing Nuclear Power

- WWII arms race
- Oppenheimer: Manhattan Project
- Gadjet: test bomb July 16th
- Little Boy: Enriched U-235 bomb: detonated over Hiroshima Aug. 6, 1945.
  - Eq: 18 kT TNT (4.2x10^9 J per ton)
  - cf May 1945 Germany
- Fat Man: Plutonium: detonated over Nagasaki Aug. 9, 1945

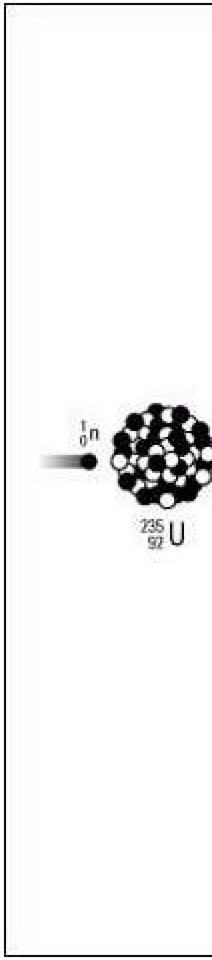
Modern thermonuclear weapons

- Thermonuclear weapons use a fission reaction to trigger a fusion bomb at the core
- This briefly reproduces the temperature and pressure conditions at the sun's core
- The highest yield is for hydrogen isotopes fusing to make helium, hence "H bomb"
- Soviets 1953 test bomb
- US 1954: 15 MT

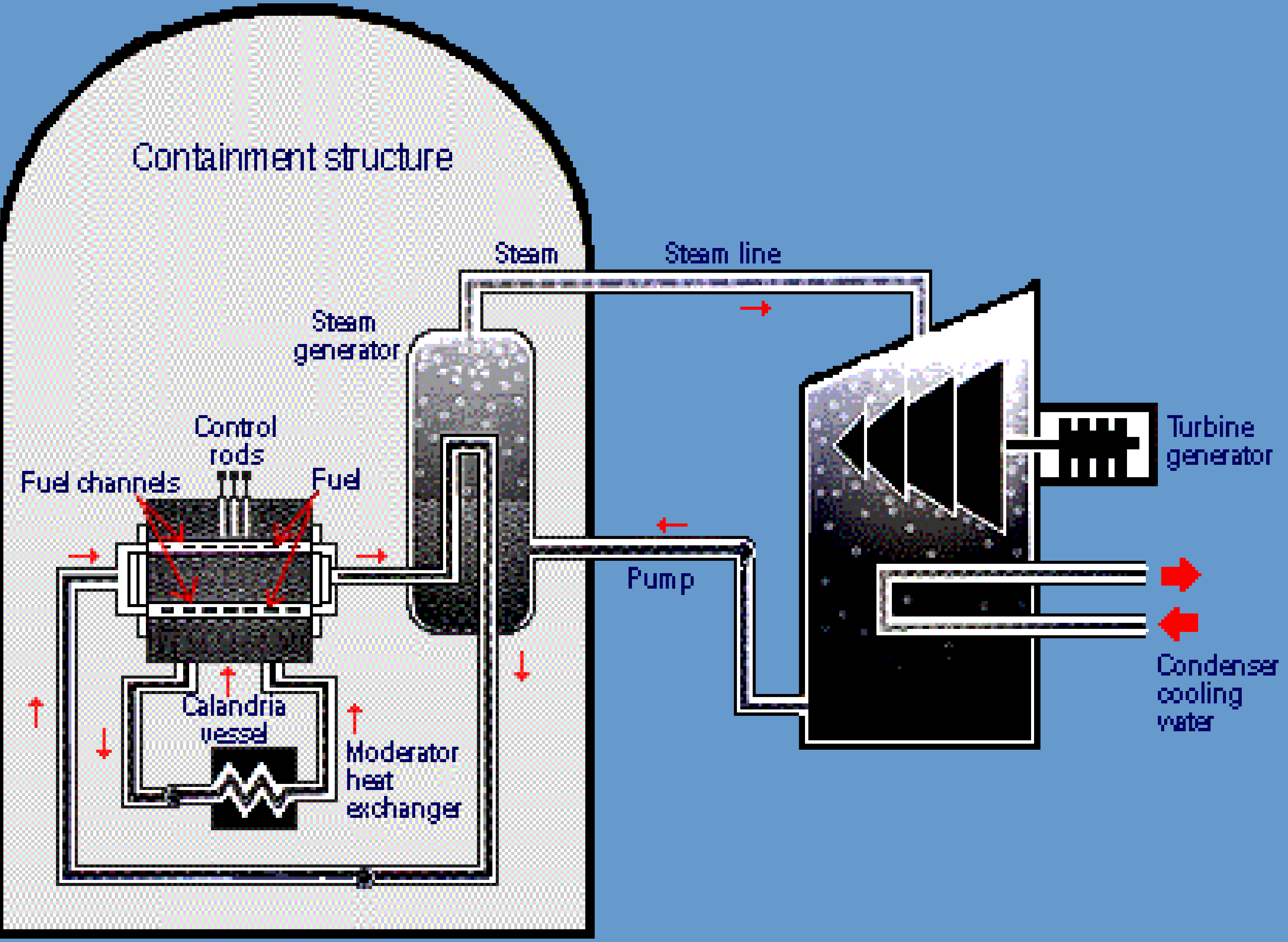
"So, Foster! That's how you want it, huh? ...
Then take this!"

Nuclear Fission Reactors

- To get safe, useful energy, we need:
  - A chain reaction
    - nb critical mass (50 kg Uranium, 16 kg Plutonium)
  - A moderator to slow the neutrons down
  - Control rods to control the rate of the chain reaction, or stop it if necessary

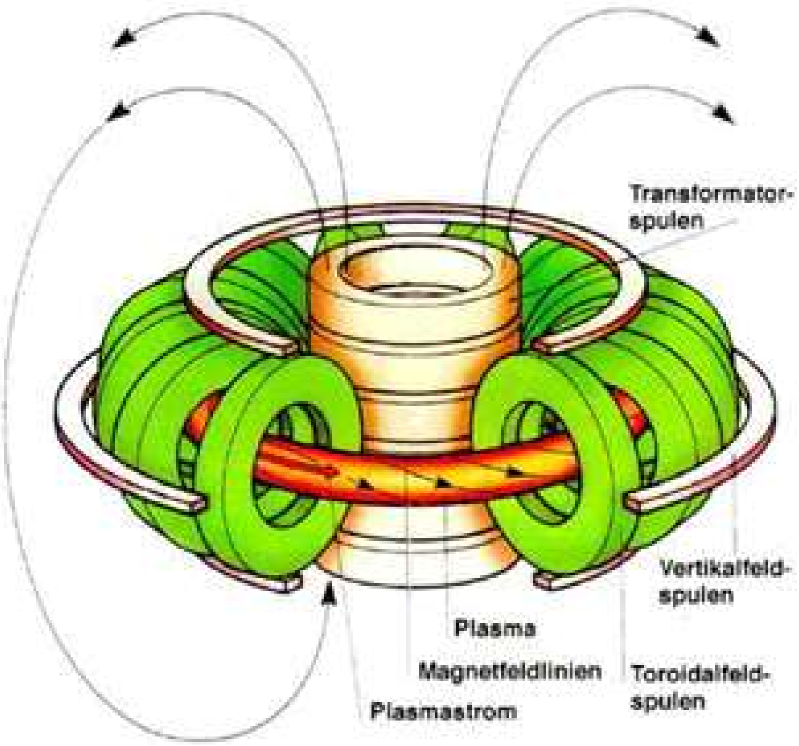


- The CANDU reactor uses:
  - Natural uranium instead of enriched (more U-235)
  - Heavy water D_2O as a moderator
  - Cadmium control rods

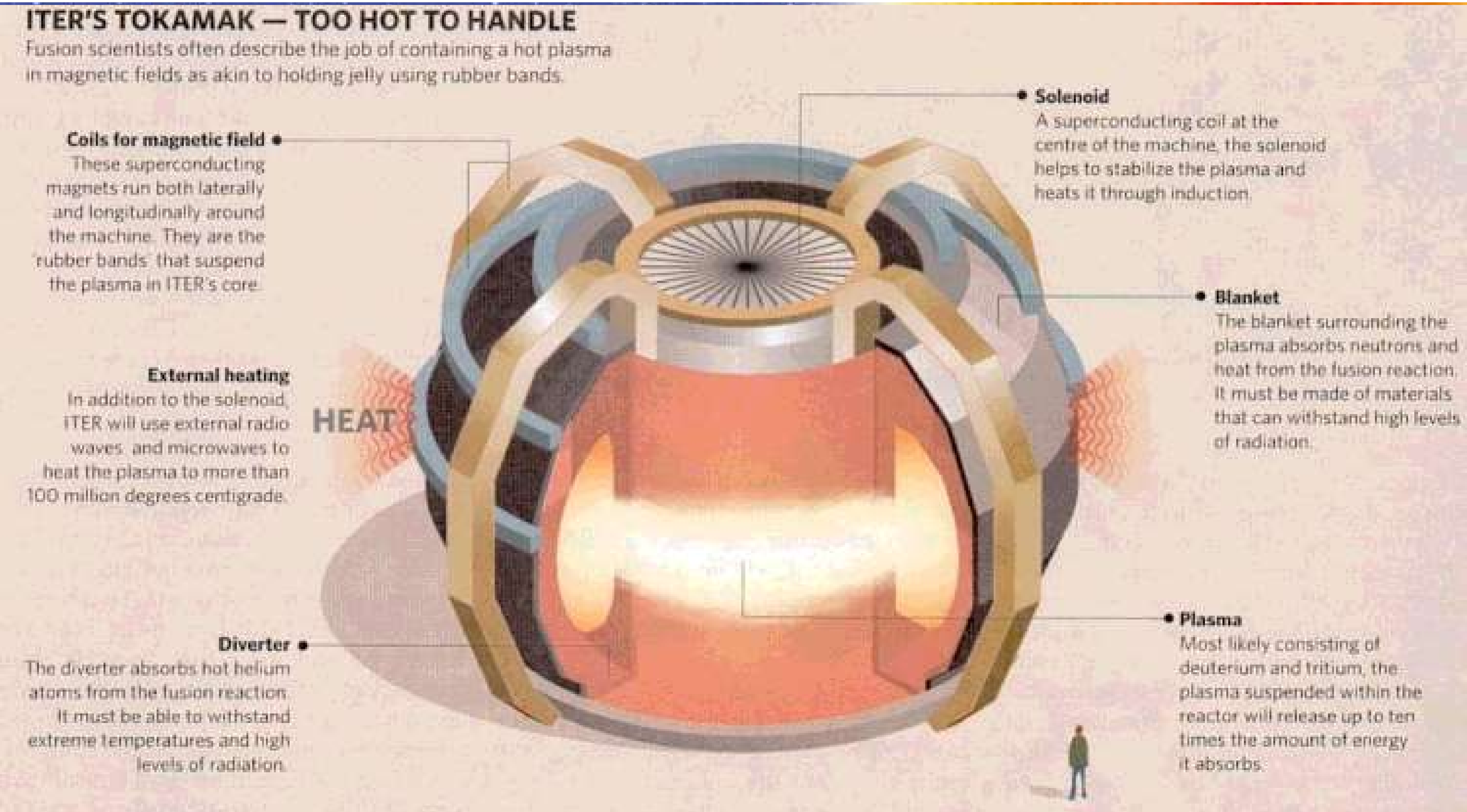

Containment structure
Steam
Steam line
Steam generator
Control rods
Fuel channels
Fuel
Turbine generator
Pump
Condenser cooling water
Calandria vessel
Moderator heat exchanger

Fusion Reactor?

- Nuclear fusion is more powerful, and cleaner: no radioactive fuel or waste!
- Fusion reactions are difficult to contain
- The Tokamak reactor uses magnetic fields to contain a plasma and generate fusion reactions
  - Still not a stable energy producer



ITER: *International Thermonuclear Experimental Reactor*



ITER'S TOKAMAK — TOO HOT TO HANDLE

Fusion scientists often describe the job of containing a hot plasma in magnetic fields as akin to holding jelly using rubber bands.

Coils for magnetic field
These superconducting magnets run both laterally and longitudinally around the machine. They are the 'rubber bands' that suspend the plasma in ITER's core.

Solenoid
A superconducting coil at the centre of the machine, the solenoid helps to stabilize the plasma and heats it through induction.

Blanket
The blanket surrounding the plasma absorbs neutrons and heat from the fusion reaction. It must be made of materials that can withstand high levels of radiation.

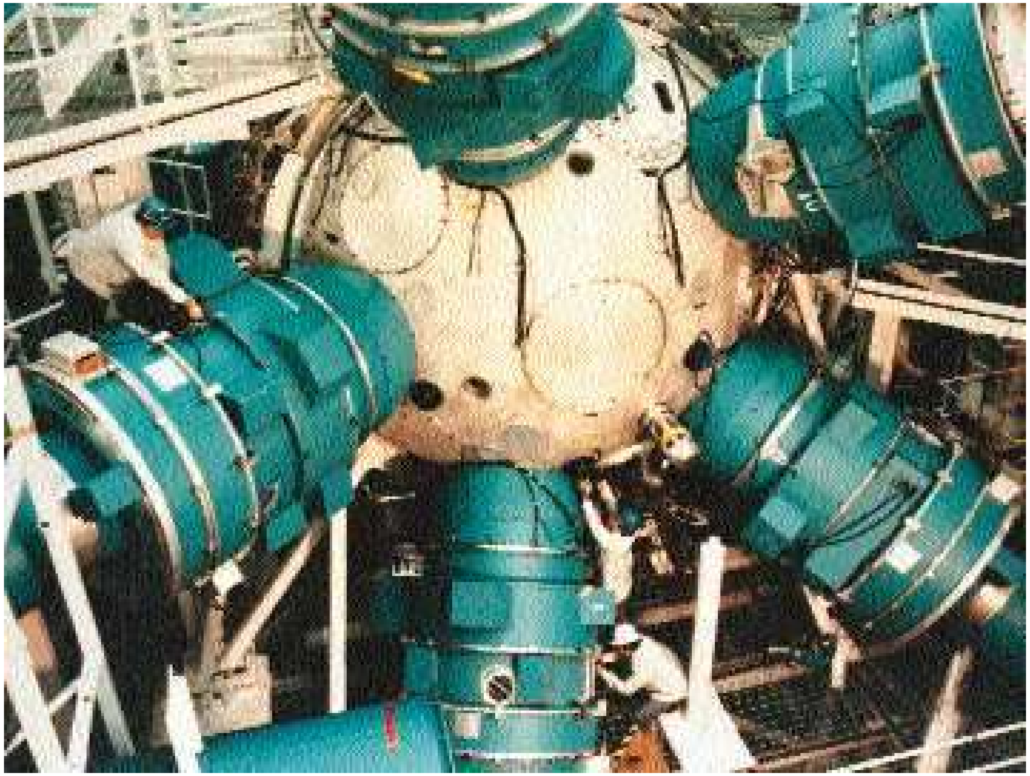
External heating
In addition to the solenoid, ITER will use external radio waves and microwaves to heat the plasma to more than 100 million degrees centigrade.

Diverter
The diverter absorbs hot helium atoms from the fusion reaction. It must be able to withstand extreme temperatures and high levels of radiation.

Plasma
Most likely consisting of deuterium and tritium, the plasma suspended within the reactor will release up to ten times the amount of energy it absorbs.

Another option?

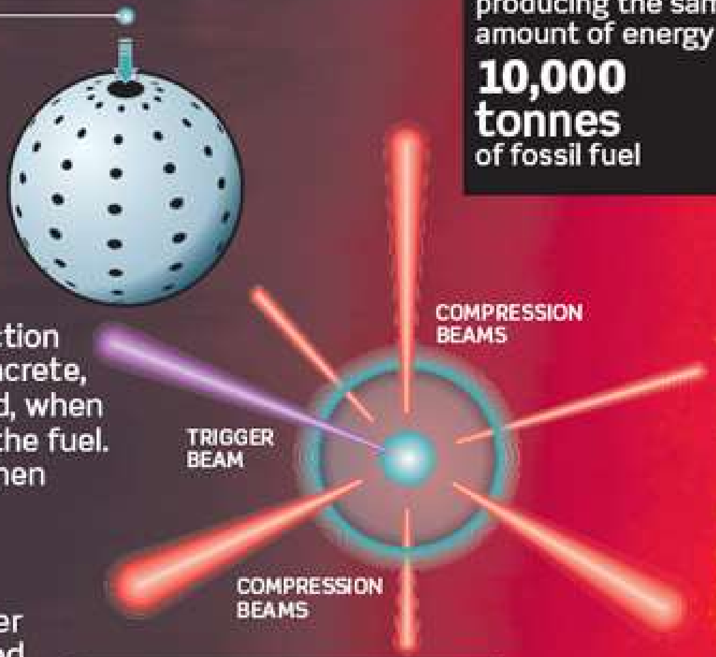
- We can use a "LASER" to heat up the hydrogen and ignite the fusion reaction



CREATING A REACTION

1 A fuel pellet* the size of a pea is made from heavy forms of hydrogen found in sea water called deuterium and tritium, as used in a hydrogen bomb

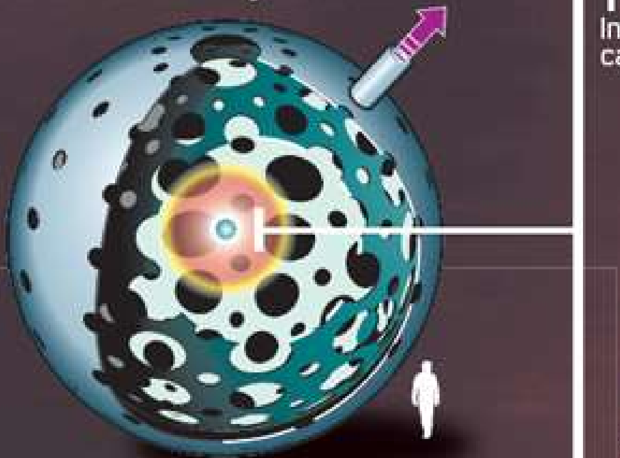
2 Fuel is dropped into a 33ft high reaction chamber made from lithium and concrete, reaching the centre in a split second, when first laser beams fire, compressing the fuel. Another, higher power laser beam then "sparks" fusion reaction.



2lb of fusion fuel is capable of producing the same amount of energy as **10,000 tonnes** of fossil fuel

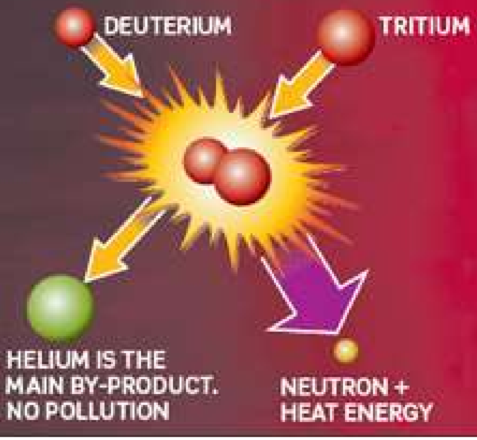
Lasers use power **10,000** times greater than **entire National Grid**, but delivered in a fraction of a second

3 The fusion reaction heats water flowing in tubes around the chamber to produce steam which can be used to drive electricity turbines



THE FUSION REACTION

Intense pressure and energy causes the atoms to fuse together



100m

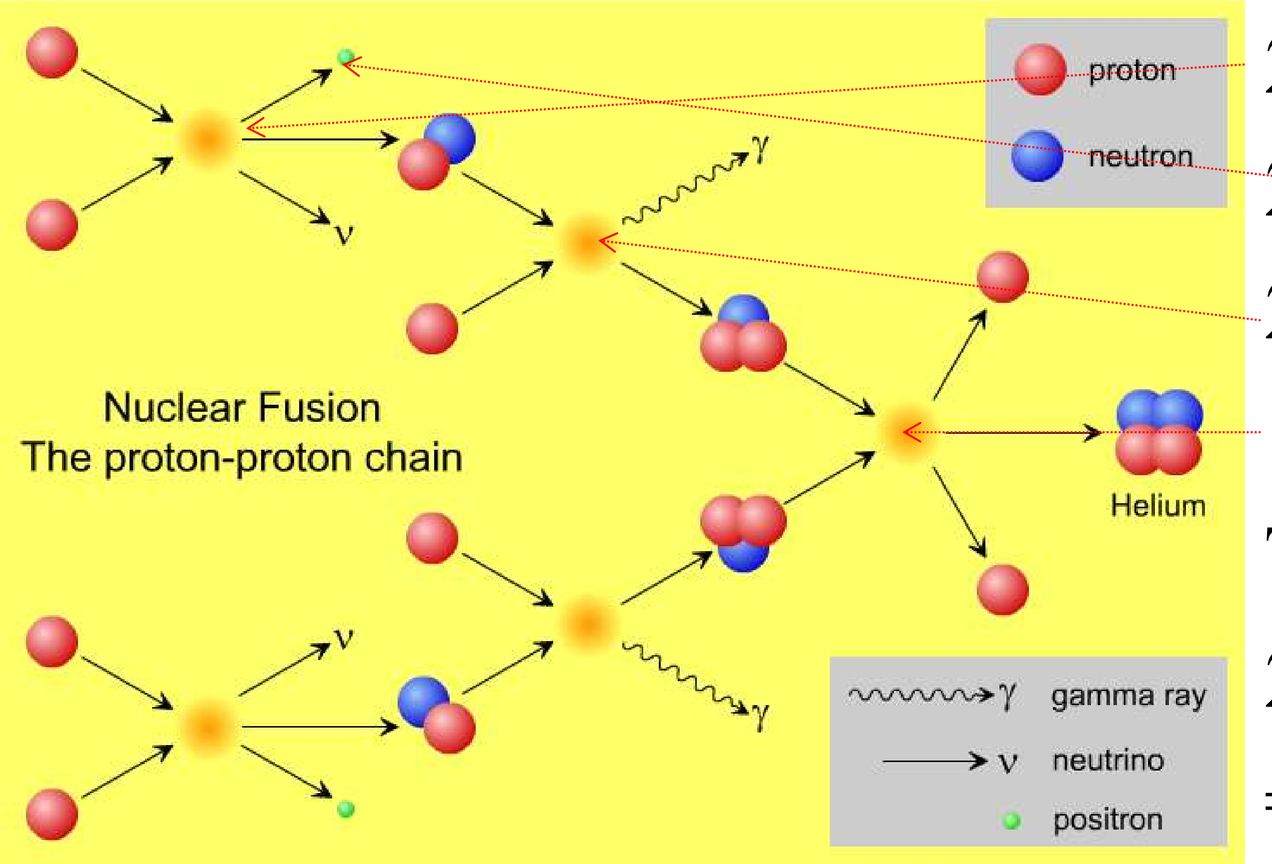
Degrees Celsius. Temperatures produced in nuclear fusion reactor

GRAPHIC: STEF BAYLEY

*WEIGHT NOT AVAILABLE

SOURCE: HIPER-LASER.ORG

Proton-proton chain



2x0.42MeV

2x1.02MeV

2x5.49MeV

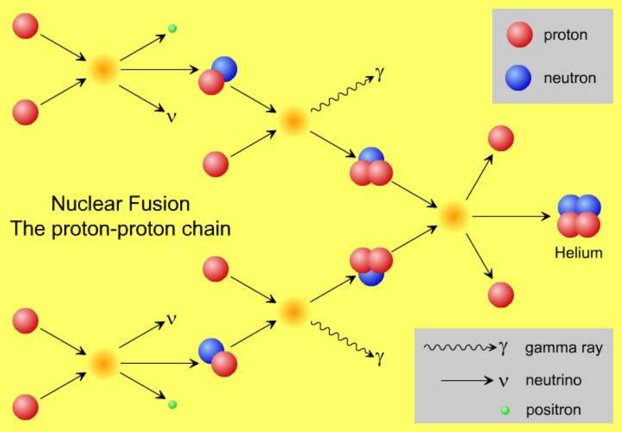
12.86MeV

Total

26.72MeV

$=4.3\times10^{-12}$J

What should our neutrino flux be?



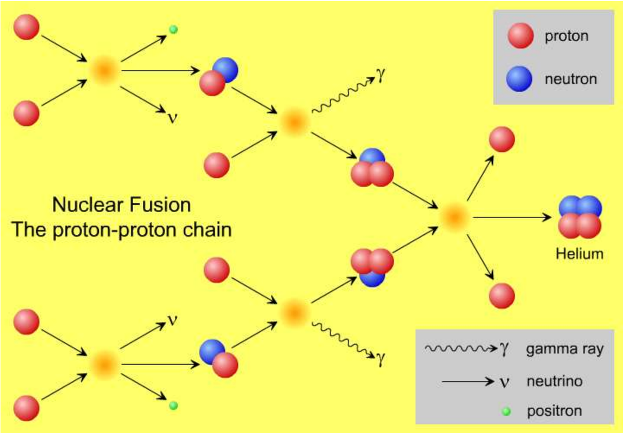
2 neutrinos for every 4.3x10^{-12}J

3.85x10^{26}J/s total output

$$\frac{3.85\times10^{26}\,J\cdot s^{-1}}{4.3\times10^{-12}\,J(2\eta)^{-1}}$$

$$=1.8\times10^{38}\,\eta\cdot s^{-1}$$

What should our neutrino flux be?



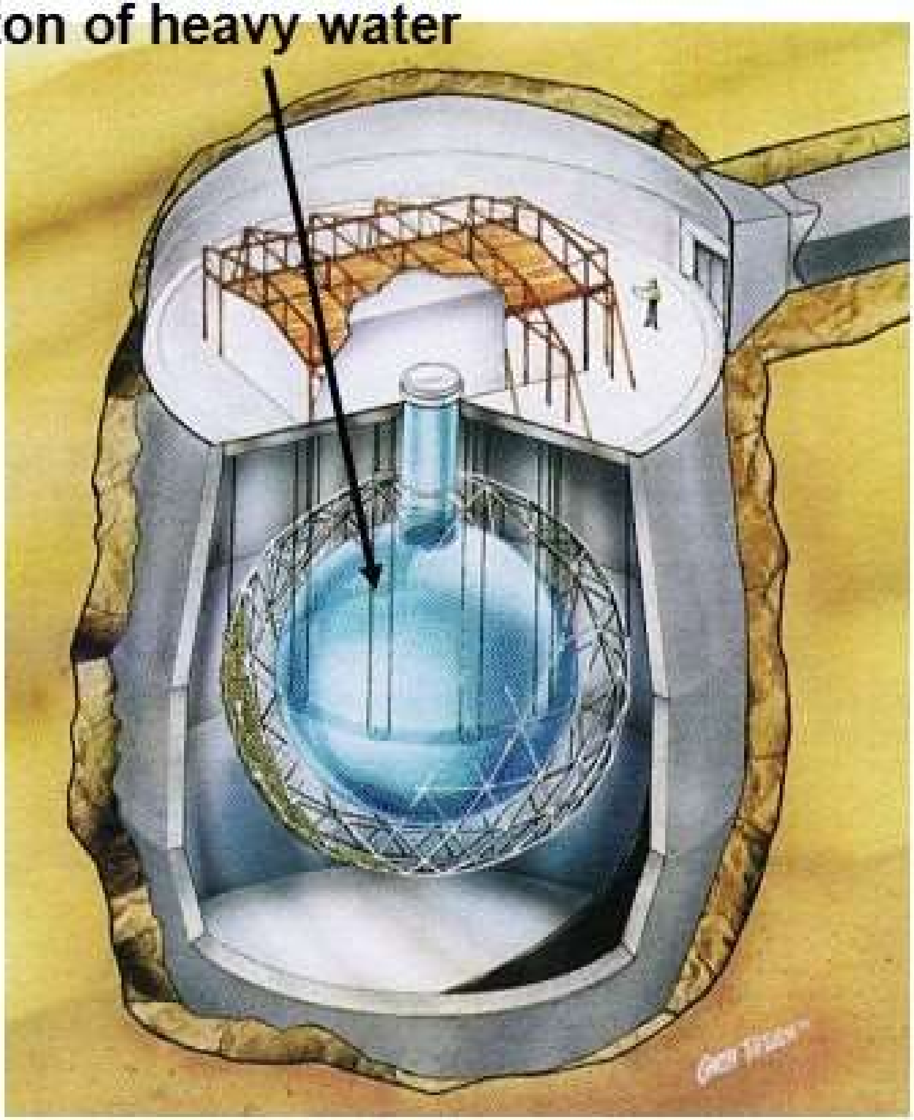
2 neutrinos for every 4.3x10^{-12}J

3.85x10^{26}J/s total output

$$b = \frac{L}{4\pi d^2}$$

$$b = \frac{1.8\times10^{38}}{4\pi(1.5\times10^{11})^2} = 6.3\times10^{14}\nu\cdot m^{-2}\cdot s^{-1}$$

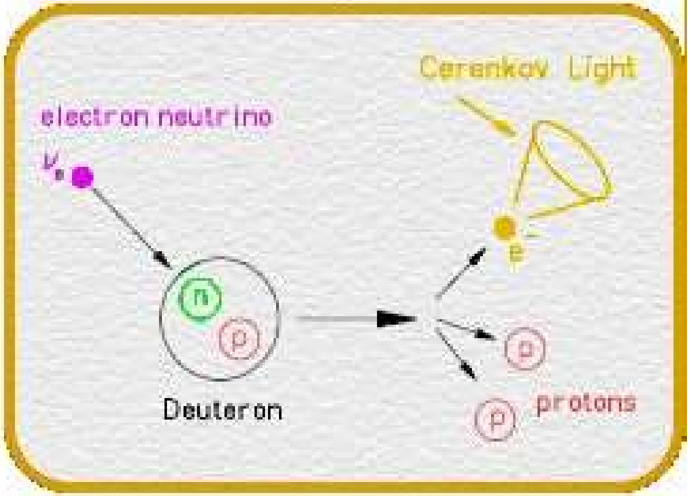
The SNO Experiment



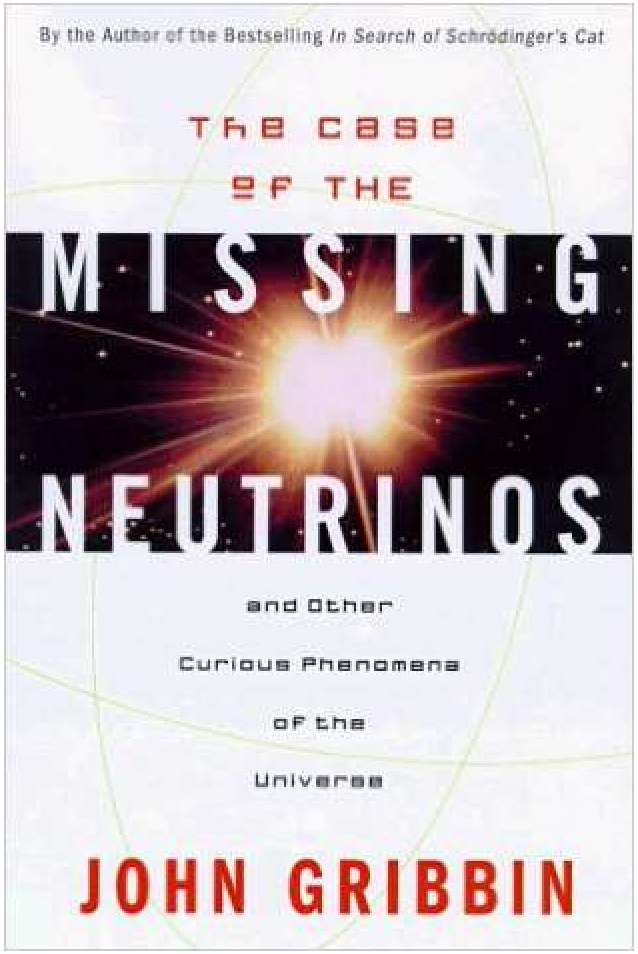
1kton of heavy water

Charged current interaction (through W)

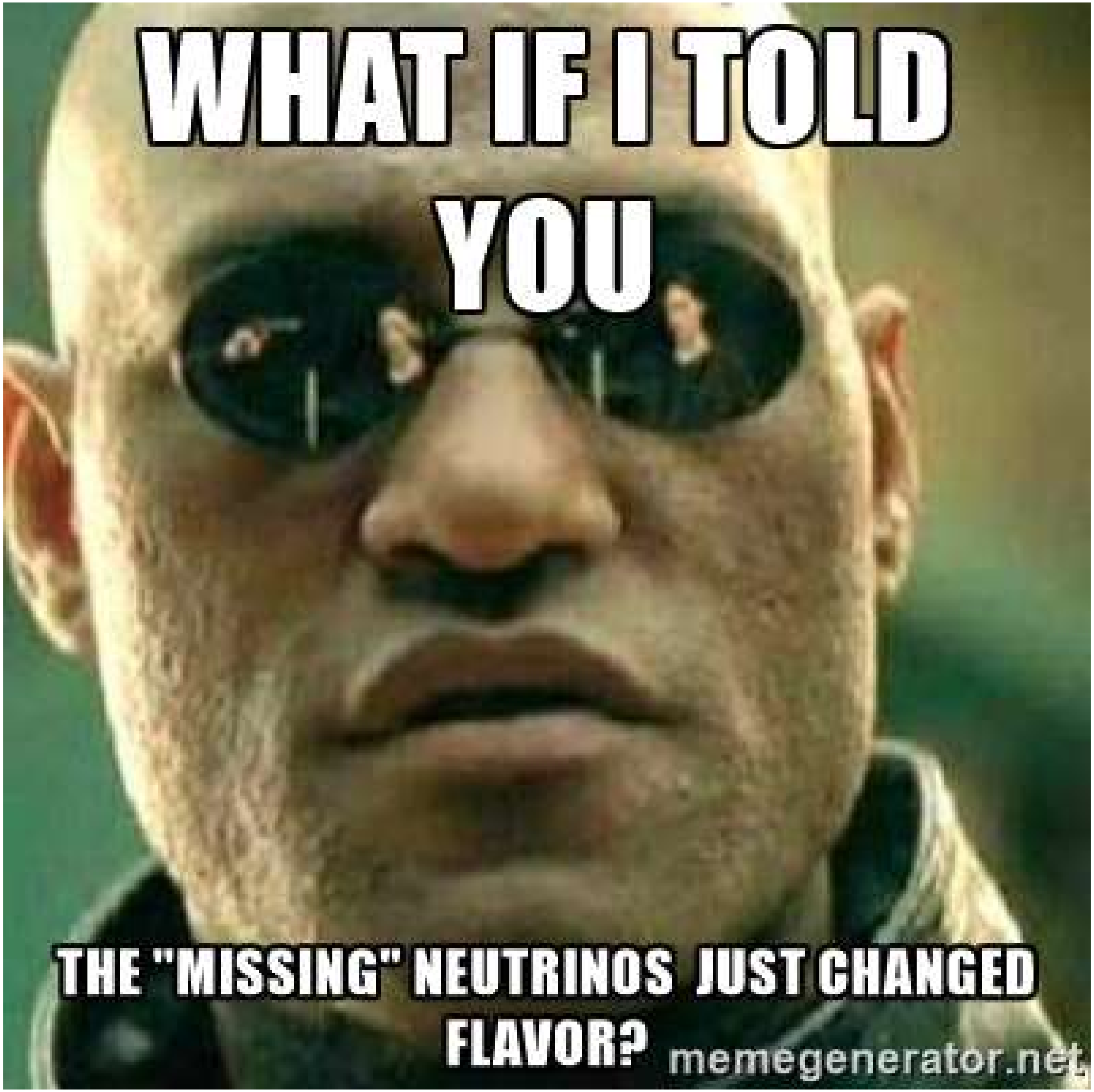
Sensitive to ν_e



Where are the missing neutrinos?

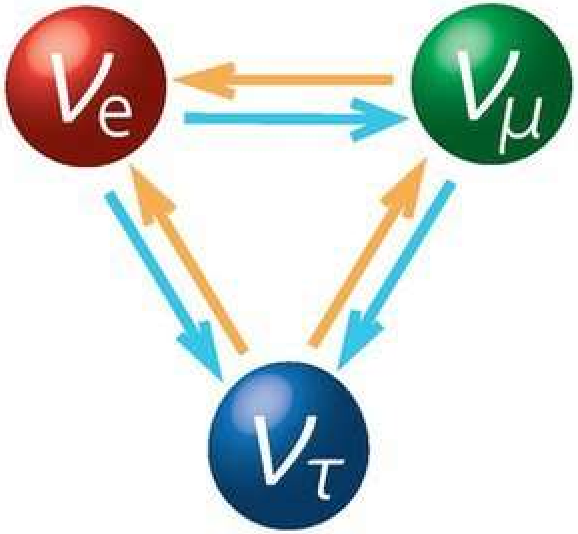


- When measuring solar neutrino flux, we only observe ~1/3 the predicted amount


WHAT IF I TOLD YOU
THE "MISSING" NEUTRINOS JUST CHANGED FLAVOR?
memegenerator.net

What’s your flavorite?

- McDonald found that neutrinos are like Timbits that change flavour on the way here from the Sun.



Try Exercises p. 256-9 #32-36

Ex: 34a

- Find the energy released in MeV:

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$$

2.014101u+2.014101u=3.016029u+1.008665u+?

0.003509u x 931.5 MeV/u = 3.27 MeV

Ex: 34b

- Find the energy released in MeV:

$$ {}_{1}^{2}H + {}_{1}^{2}H \rightarrow {}_{1}^{3}H + {}_{1}^{1}p $$

2.014101u+2.014101u=3.016049u+1.007276u+?

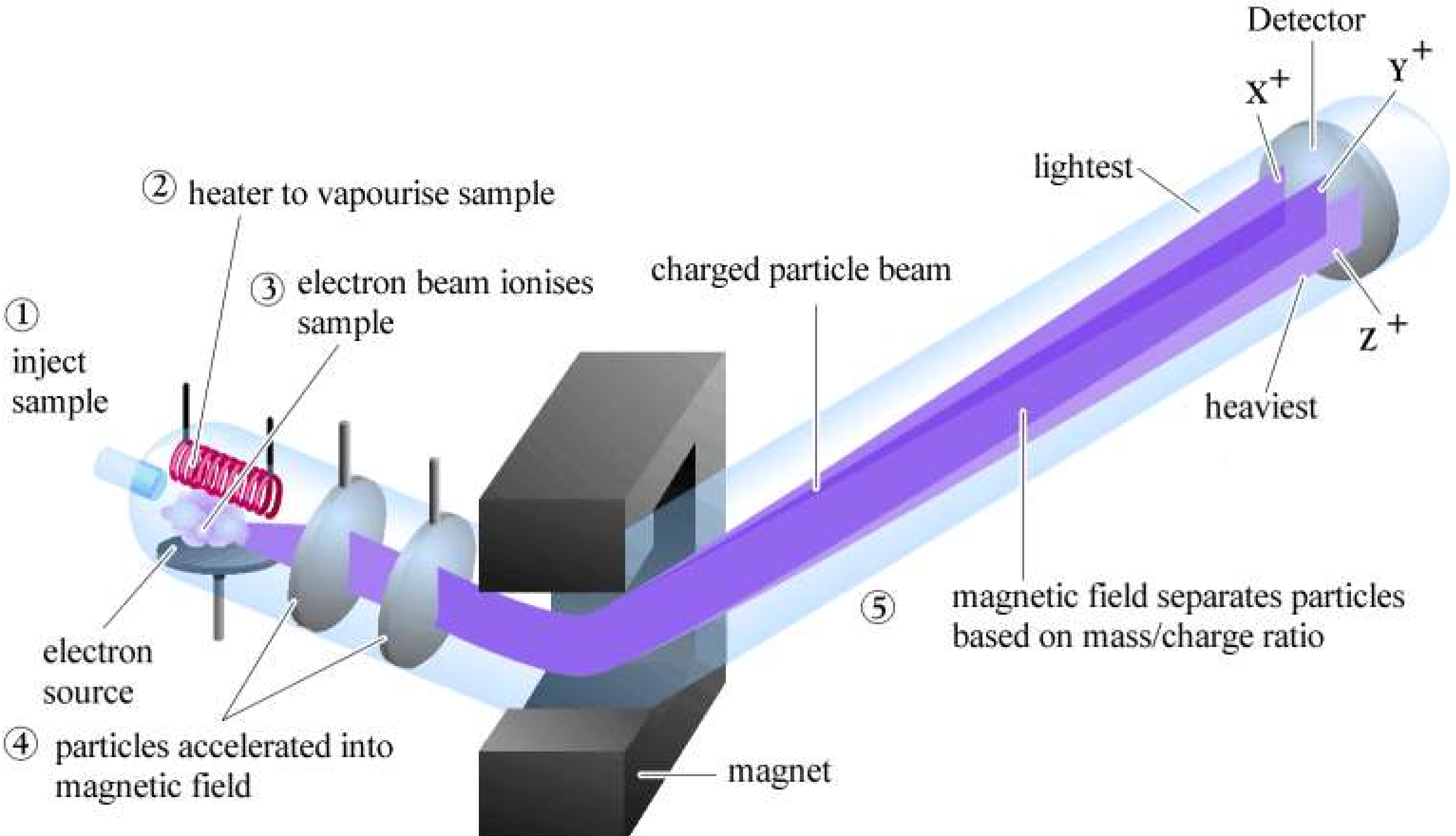
0.004877 u x 931.5 MeV/u =4.543 MeV

To be nuclear or not nuclear…

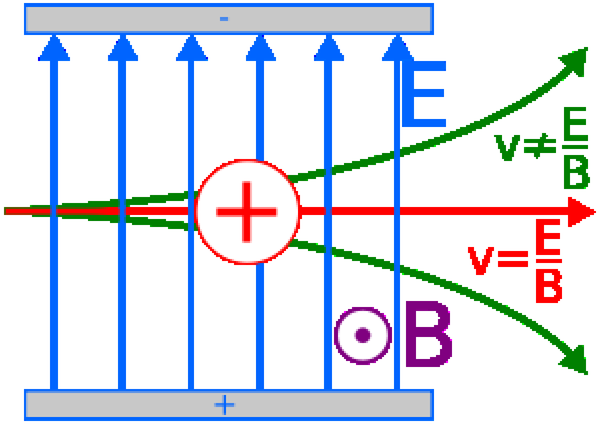
- Create a presentation supporting your viewpoint
- Include pros and cons in terms of the ethical, financial, and environmental issues associated with nuclear energy

Mass Spectrometer

- Use the electric and magnetic forces to select a mass



First: Velocity Selector



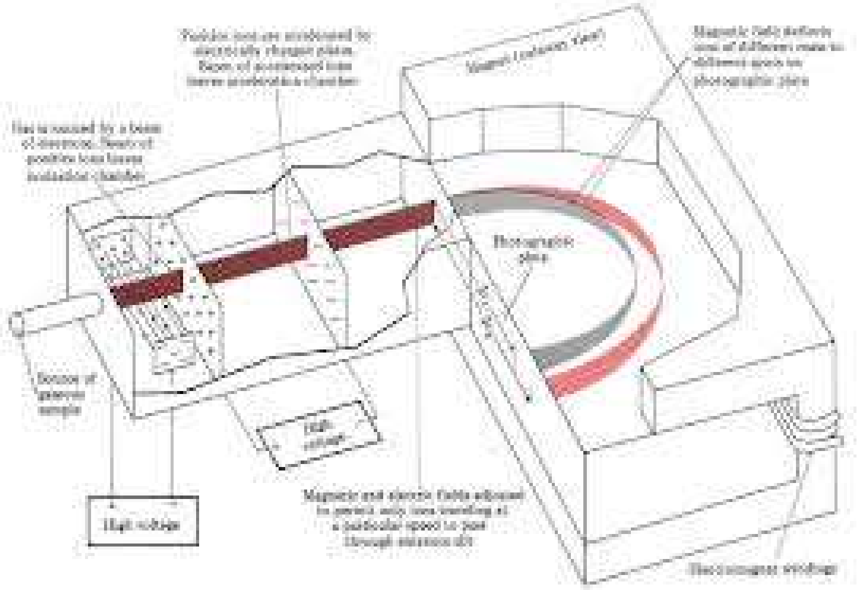
$$F_e = F_B$$

$$qE = qvB$$

$$v = \frac{E}{B}$$

- Only particles with the correct velocity continue to the next stage

Next: mass spectrometry



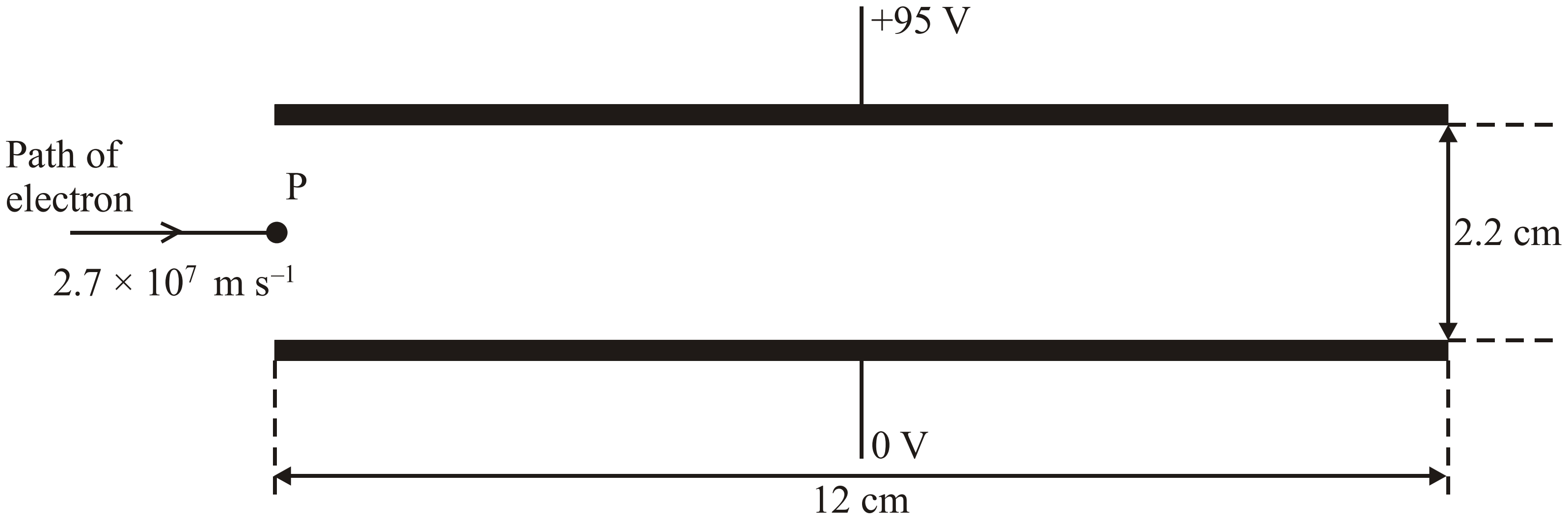
$$F = ma$$

$$qvB = \frac{mv^2}{r}$$

$$m = \frac{qBr}{v}$$

- We can use this to separate isotopes

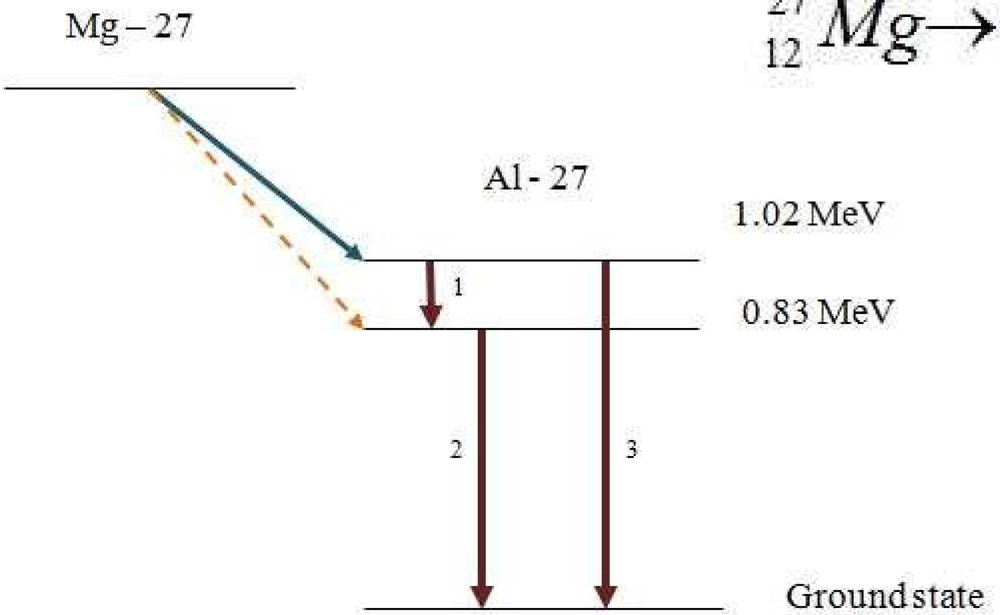
Ex: Mass spectrometry question



- An electron is accelerated from rest in a vacuum through a potential difference of 2.1 kV. b)Deduce that the final speed of the electron is 2.7×10^7 m s^{-1}.c)

Nuclear quantization

$$ {}^{27}_{12}Mg \rightarrow {}^{27}_{13}Al + {}^{0}_{-1}e - + \overline{\nu_e} $$



- The excited Al-27 can release this energy as gamma photons either 1&2 or 3. Ex: find λ for 1

$$\Delta E = 0.83 - 1.02 MeV = -0.19 MeV$$

$$E = 0.19 \times 10^{6} \left(1.6 \times 10^{-19}\right) J$$

$$E = 3.04 \times 10^{-14} J = hf$$

$$\lambda = {}^{c}\!/_{f} = \frac{ch}{E}$$

$$\lambda = \frac{3 \times 10^{8} \left(6.63 \times 10^{-34}\right)}{3.04 \times 10^{-14}}$$

$$\lambda = 6.54 \times 10^{-12} m$$

See me putting in the hard work now,
Momma doesn't have to call work now,
I decide when I start work now,
Problems hit the gym, they all work out

1. This question is about nuclear decay and ionization.

(a) A nucleus of radium-226 ($^{226}{}_{88}$Ra) undergoes alpha particle decay to form a nucleus of radon (Rn).

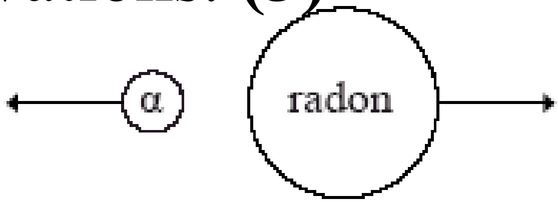
Identify the proton number and nucleon number of the nucleus of Rn.

Proton number: ....

Nucleon number: ....**(2)**

(b) Immediately after the decay of a stationary radium nucleus, the alpha particle and the radon nucleus move off in opposite directions and at different speeds.

(i) Outline the reasons for these observations. **(3)**



(ii) Show that the ratio $\frac{\text{initial kinetic energy of alpha particle}}{\text{initial kinetic energy of radon atom}}$

is about 56. **(3)**

(c) The initial kinetic energy of the alpha particle is 4.9 MeV. As the alpha particle passes through air, it loses all its kinetic energy by causing the ionization of 1.7×10^5 air molecules.

(i) State what is meant by ionization. **(1)**

(ii) Estimate, in joules, the average energy needed to ionize an air molecule. **(2)**

(d) Outline why a beta particle has a longer range in air than an alpha particle of the same energy. **(3)**

(Total 14 marks)

1. (a) (i) *proton number:* 86;*nucleon number:* 222

(b) (i) momentum conserved; so different speeds as different masses; opposite directions because momentum zero initially;

(ii) $k.e._{\alpha} \div k.e._{Rn} = m\alpha v_{\alpha}{}^{2} \div m_{Rn}v_{Rn}{}^{2}$ / sensible ratio formed; = $(m_{\alpha}v_{\alpha})^{2}m_{Rn} \div (m_{Rn}v_{Rn})^{2}m_{\alpha}$ / cancellation of momentum terms; = $m_{Rn} \div m_{\alpha}$ = (= 55.5);

(c) (i) removal (addition) of electron from atom/molecule; (ii) $\frac{4.9\times10^{6}\times1.6\times10^{-19}}{1.7\times10^{5}}$;

4.6×10^{-18} J;

(d) beta have smaller mass / smaller / have greater speed than alpha; beta have smaller charge than alpha; therefore less likely to interact with air molecules;