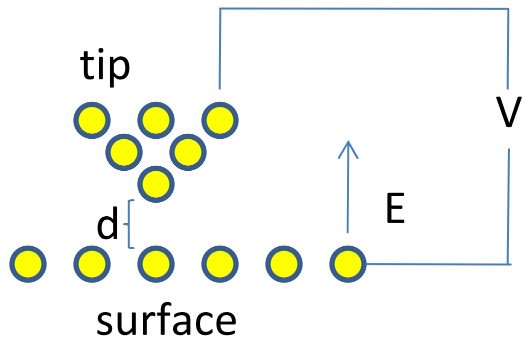
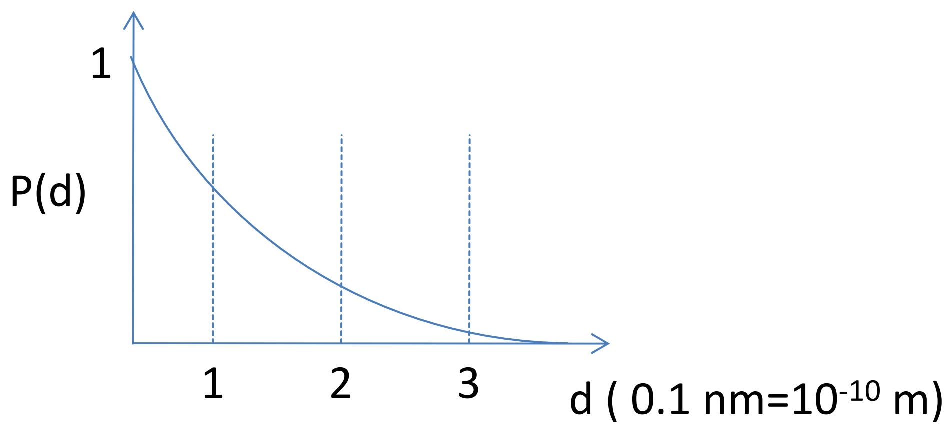
Scanning Tunneling Microscope

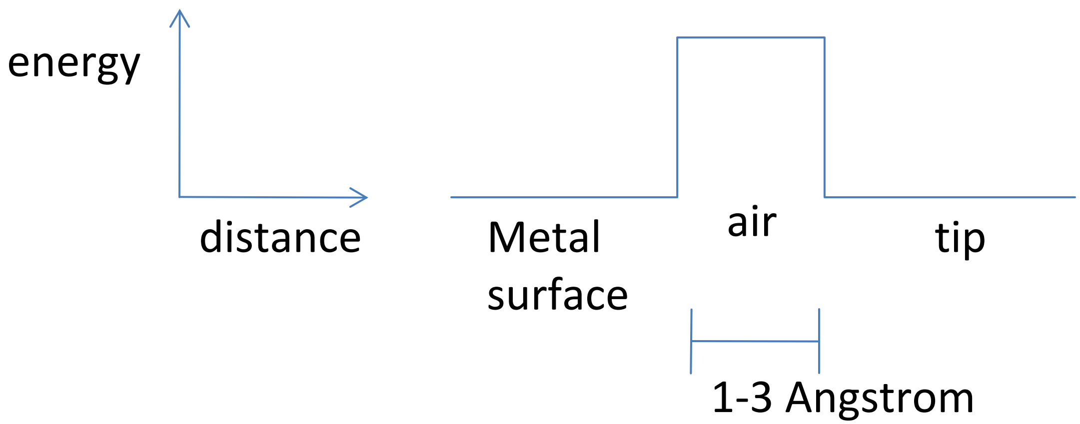


1.) Probability of electron tunneling over ~e^{-d}



Why tunneling? Because the electron cannot escape into air.

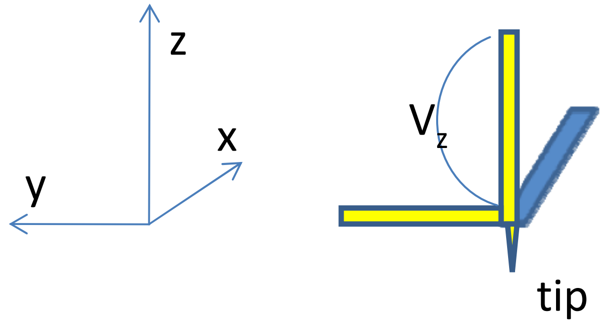
i. Too high energy is needed;
ii. If it could go in the air, then the electrons would have left the surface already;
iii. But: inside the metal tip, the energy is low again. The electron has to tunnel through the high energy region of the air.



They put voltage between the metal surface and the tip to generate a current.
With no voltage equal number of electrons would jump in both directions.

They knew that they observed tunneling when they moved the tip by a distance of the diameter of an atom and the current changed 1000 fold. Only the exponential function can generate such huge changes.

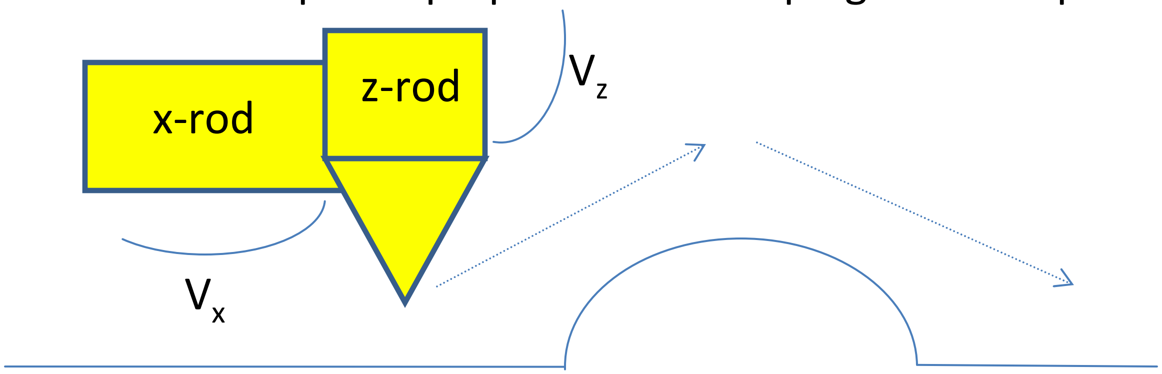
How to keep the tip so precisely so close?



Piezoelectricity
There are materials which contract or expand when you put voltage across them.

Each rod has a voltage applied between its ends.
The z rod contracts if the current increases: this moves the tip up and down.

i. Apply voltage between surface and tip;
ii. Measure the tunneling current of the tunneling electrons;
iii. This current created an induced voltage, which is used to control the location of the tip;
iv. Systematically increase the x-rod voltage—this moves the tip over the surface: “scanning”;
v. If the tip gets close to a bump (atom/structure)—the tunneling current and hence the induced voltage increases;
vi. Apply increased voltage to z-rod. This causes z rod to contract;
vii. Shorter z-rod pulls up tip to avoid bumping into bump.



Today: many variations

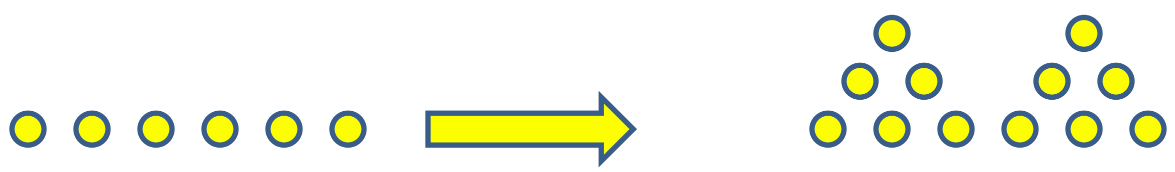
1. STM:
   Scanning Tunneling Microscope
   - i. metal—metal
   - ii. controlled by current

2. AFM:
   Atomic Force Microscope
   - i. insulator—insulator
   - ii. controlled by force, generated by surface, very soft cantilever
   - iii. How do they measure position? [no current in insulator]: put tiny mirror on tip, shine laser on it and analyze reflected laser beam

3. MFM:
   Magnetic Force Microscope
   - i. magnet—magnet
   - ii. the tip is magnetic, controlled by magnetic force between tip and surface

4. Atomic crane:
   - i. pick up atoms one by one
   - ii. move wherever they want to (wrote "IBM")

Surface of silicon—very important for semiconductor/computer industry

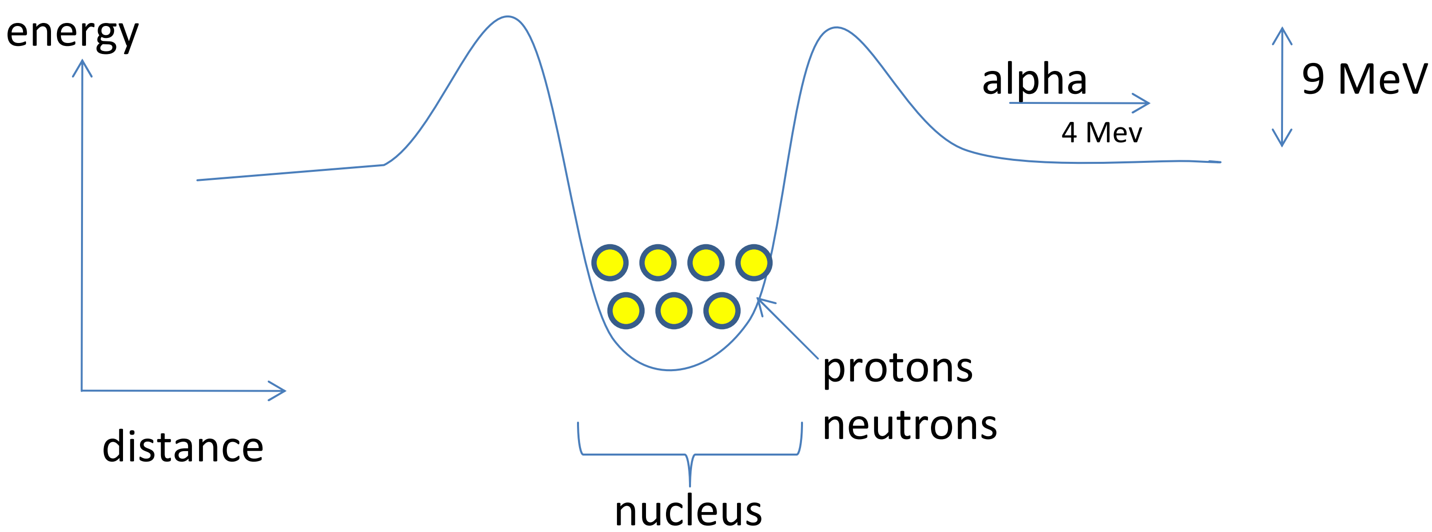


Develops tiny regular mountain structure: "7 atom by 7 atom"

Structure and shape of organic molecules (our department head does this)

Nuclear Physics and α-decay

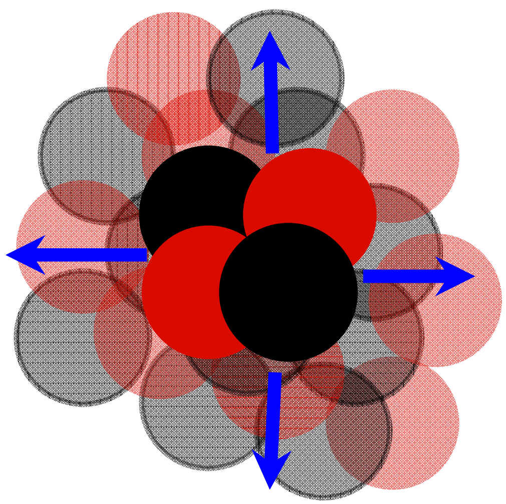
Tunneling in the atomic nucleus: alpha particles in/out of nucleus



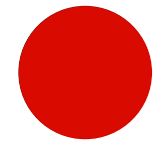
i. To get into nucleus, alpha particles need energy 9 MeV or more
ii. So the energy barrier is probably 9 Mev high.
iii. So if an alpha particle climbs UP the mountain form the inside and then "slides down the other side" its energy is conserved. Thus it should have 9 MeV at least.
iv. Instead, Rutherford found lots of alpha particles with E=4 MeV in the alpha radioactive decay.

--Strange--

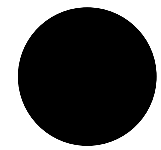
Gamow's theory of α-decay



Key



Proton



Neutron

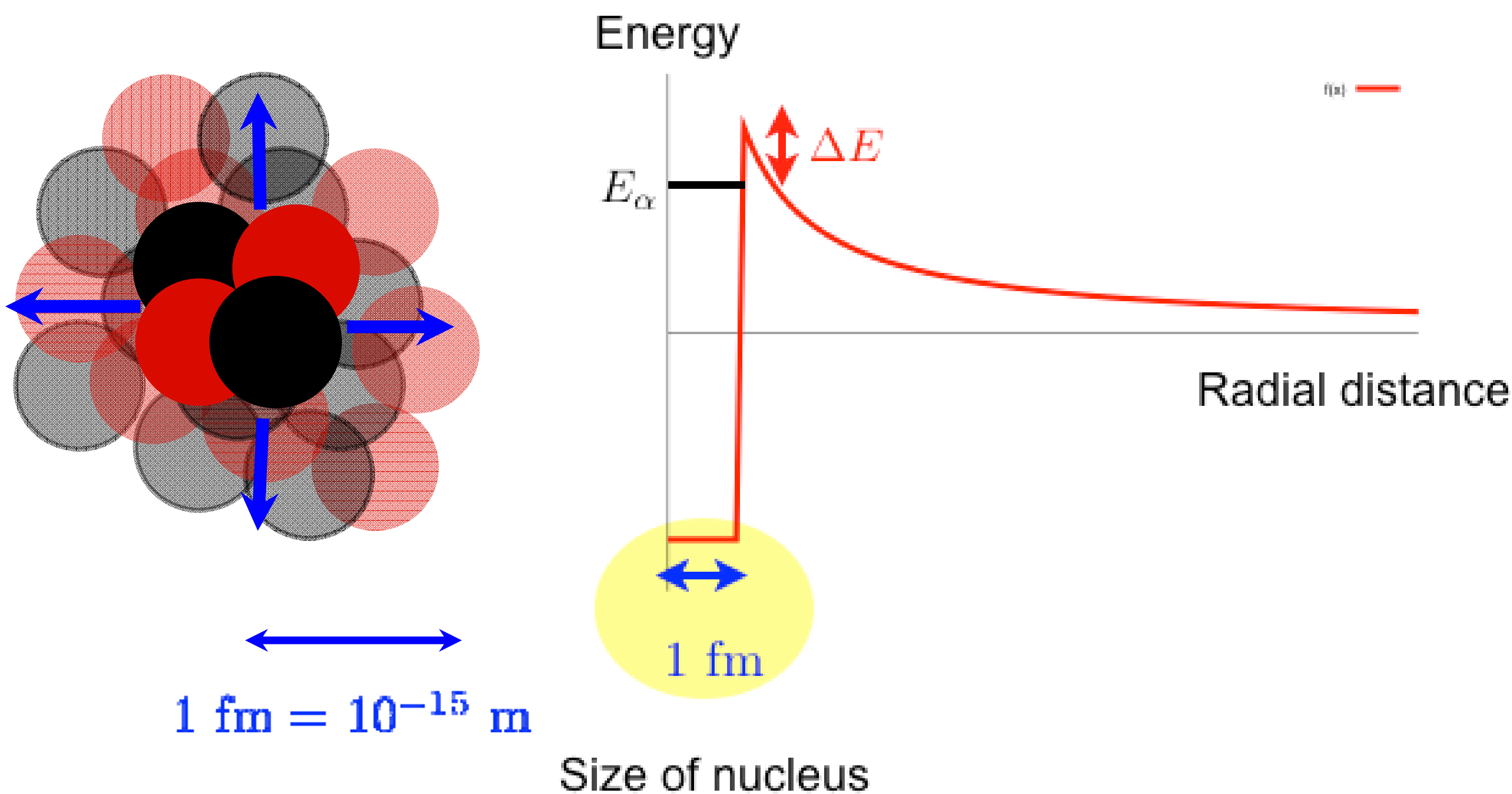
Gamow

α particle (two protons, two neutrons) trapped in the nucleus

Note: nucleus is just a collection of protons and neutrons. Gamow pictured some protons and neutrons binding more strongly into an α particle. The other protons and neutrons "trap" the α particle.

Gamow's theory of α-decay

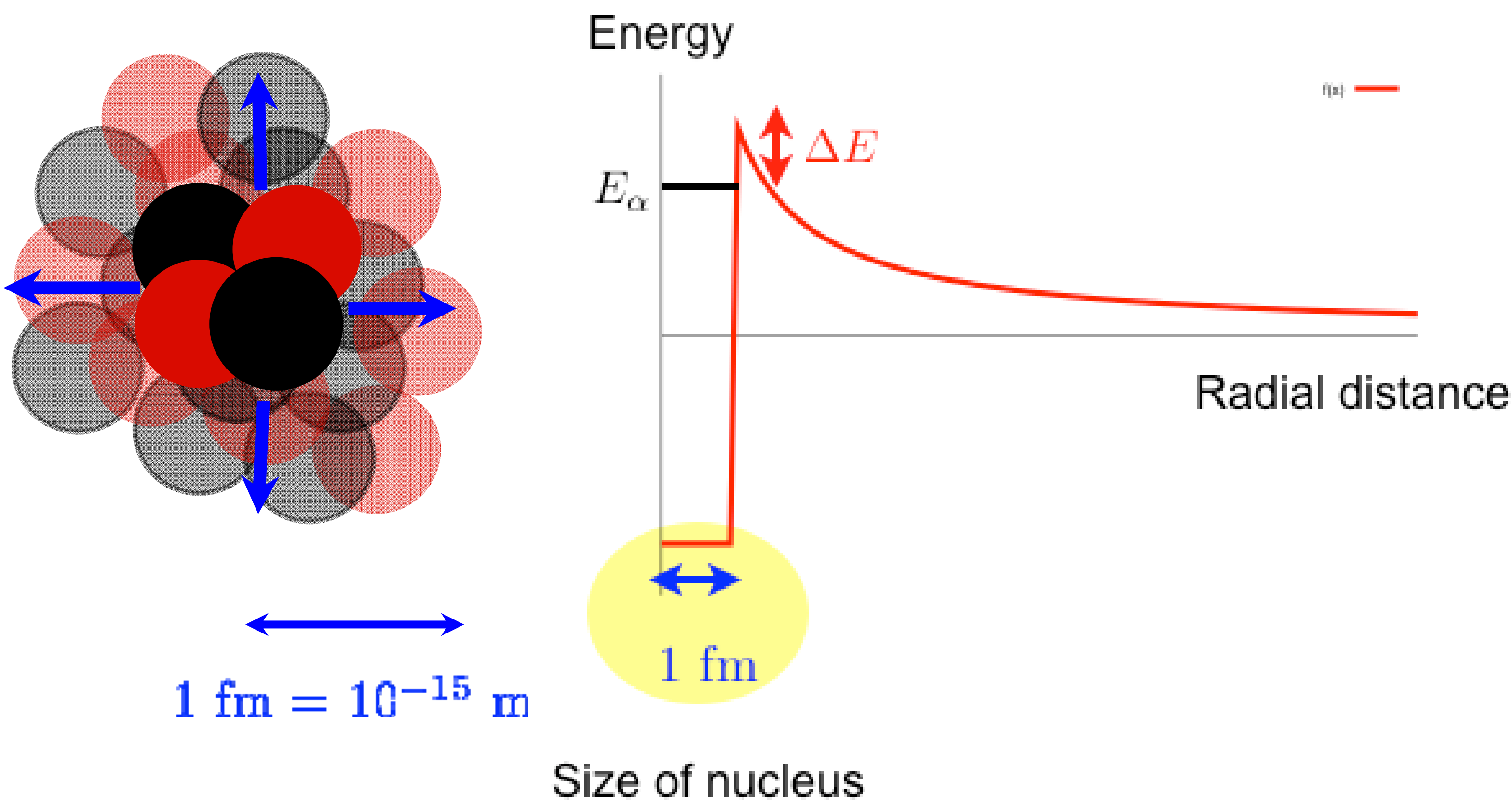
Energy – Classical picture



$E_\alpha < E_{\mathrm{peak}}$: *Classically* the α particle is trapped. For the particle to get out it would need an energy input ΔE

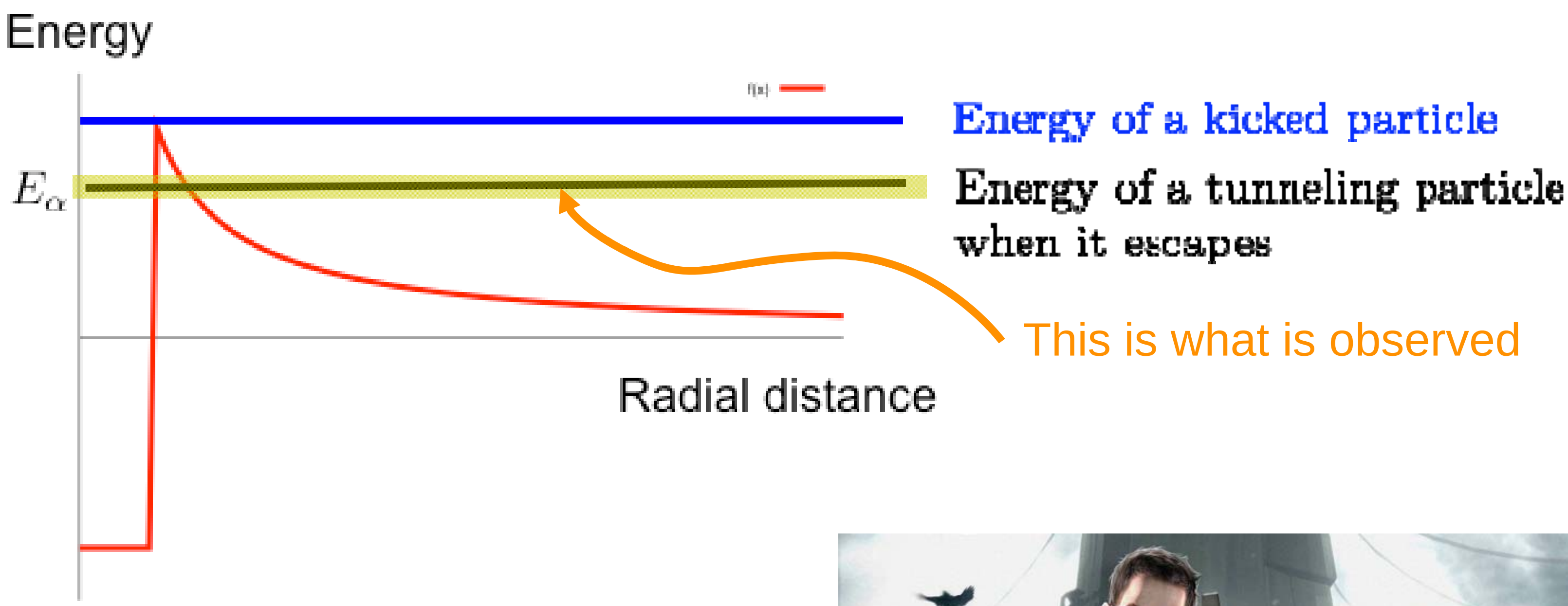
Gamow's theory of α-decay

Energy – quantum picture



Quantum mechanically: Particle can tunnel out with an energy less than ΔE!

Gamow's theory of α-decay

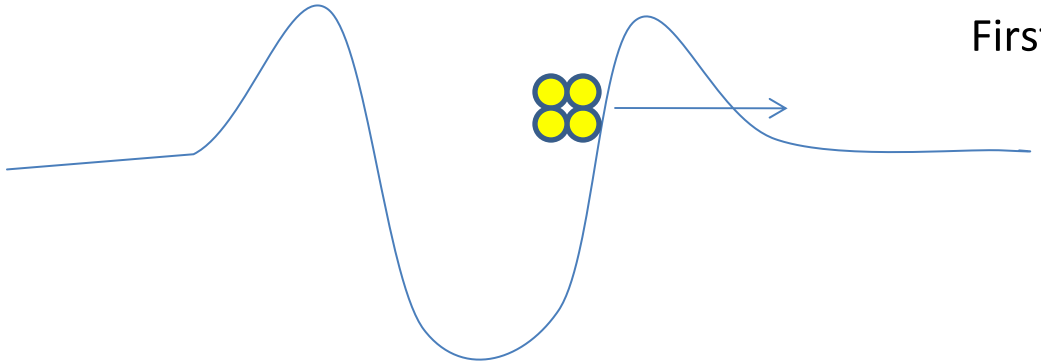


We measure the energy of the alpha particle, and find they really are tunneling!

The height and width of the barrier control the rate at which tunneling occurs. Different barriers means different decay rates -- or halflives!

Gamow's theory of α-decay

i. 2 proton + 2 neutron inside nucleus join into an alpha particle.
ii. This alpha tunnels out from nucleus, instead of climbing over mountain.



First observation of tunneling

Bombardment by particles: sometimes they can tunnel IN, too.

Cockroft + Walton (1932)

They shot not too high energy protons into nuclei and sometimes those converted into other types of nuclei.

p + Li $\longrightarrow$ 2 He   Alpha + N $\longrightarrow$ O + p   …

lithium

"splitting the atom" (recall: "atom" means "un-splittable")

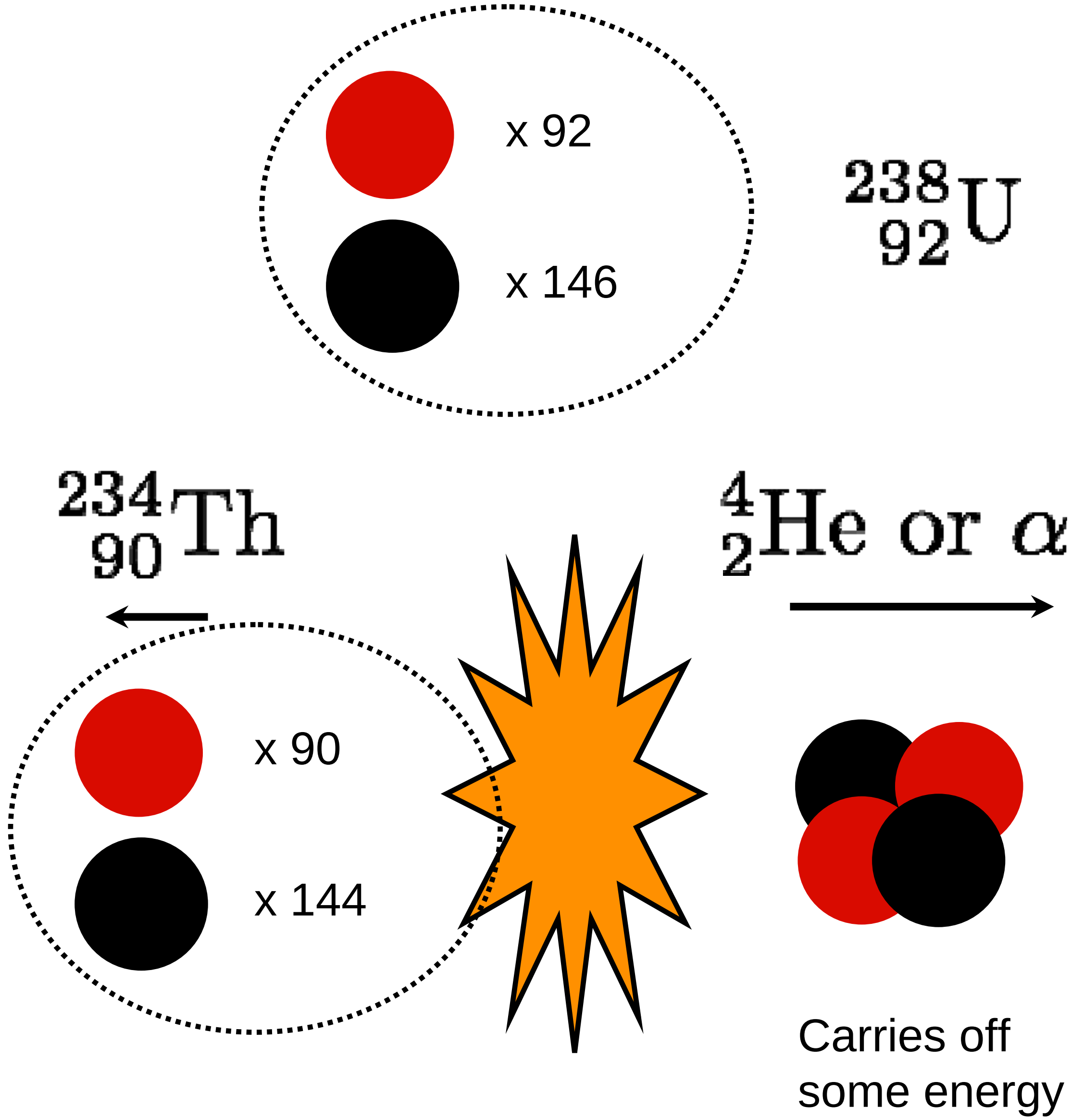
Gamow's theory of α-decay

The α-decay of Uranium:

Initial:
Uranium with 238 nucleons
92 protons
\+ 146 neutrons
----
238 particles in nucleus

Final:
Thorium with 234 nucleons
90 protons
\+ 144 neutrons
----
234 particles in nucleus

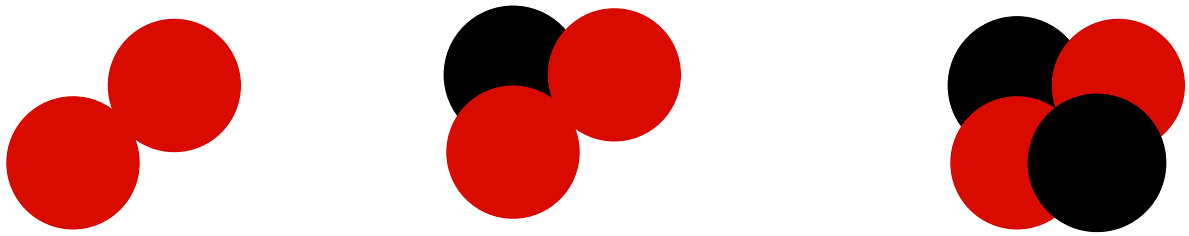
& alpha particle (2 p, 2n)



A bit of chemistry

Number of <u>protons</u> controls the attraction of electron, and hence controls chemistry

Element related *only* to number of protons



(Does not occur) (Most common form)

These nuclei are **ALL** Helium, and have the same chemistry.
Changing the neutrons does not change elements.

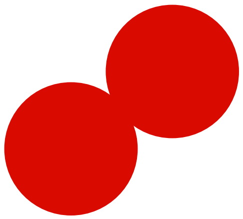
Two nuclei with different number of protons are different **elements**.

The same **element** with different number of neutrons are different **isotopes**.

A bit of chemistry

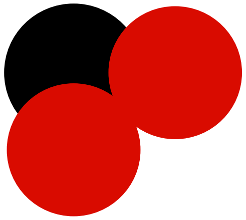
Number of <u>protons</u> controls the attraction of electron, and hence controls chemistry

Element related *only* to number of protons

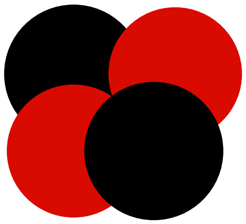


(Does not occur)

$^{2}_{2}\mathrm{He}$



$^{3}_{2}\mathrm{He}$



(Most common form)

$^{4}_{2}\mathrm{He}$

$$^{4}_{2}\mathrm{He}$$

Atomic weight:
- Tells us total number of neutrons + protons.
- Cannot tell element from this number
- The same element can have different atomic weights: these are the isotopes

<u>Atomic number:</u>
- Tells us total number of *protons.*
- Tells us the element
- Carries the *same* information as the name "He"

Where are the “alpha-emitters”?

The Periodic Table of the Elements

Iron - most stable element

1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Red elements have some (known) alpha emitter isotopes. Note they are heavier elements

Energy Balance during α-decay

$$p + Li \longrightarrow 2\,He$$

lithium

Cockroft and Walton knew all terms, except the energy of the outgoing He.
They predicted it from this equation to be 8.5 MeV.
Energy of the helium was 1 MeV.
Conservation of energy ?!?

Theory or relativity
Einstein (1905): $E=mc^2$

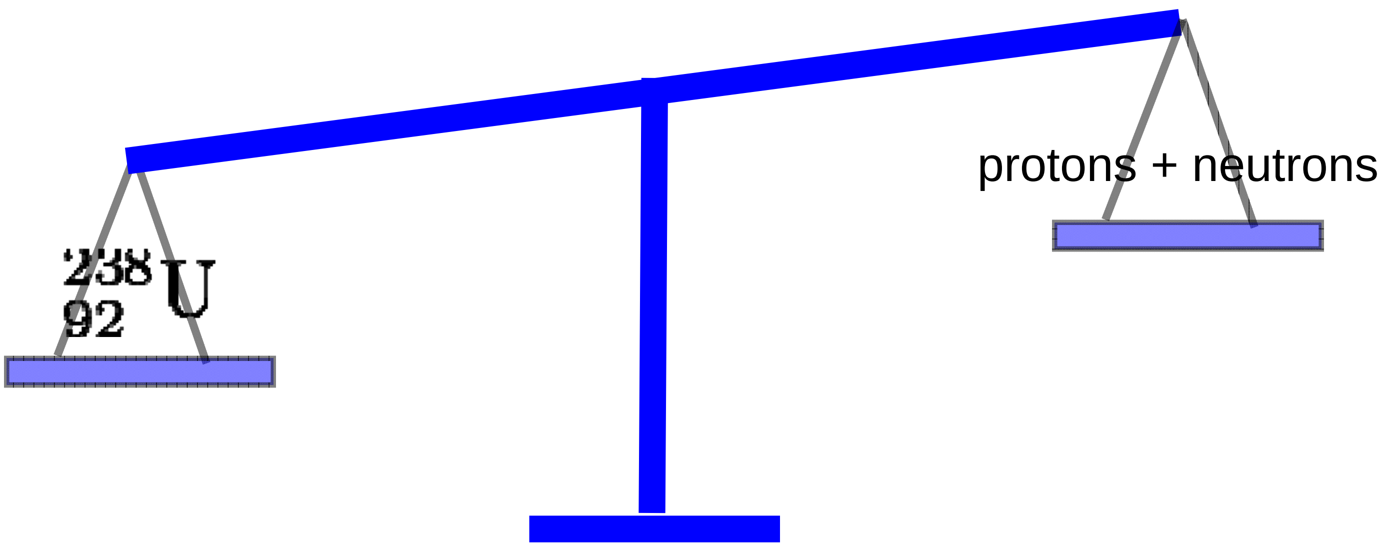
energy = mass * (light speed)^2
kinetic energy of proton + $m_p c^2 + m_{Li} c^2$ = (kinetic energy of 2 He) + $2m_{He}c^2$
We have to include the "energy of the mass," $E=mc^2$

More on the energy

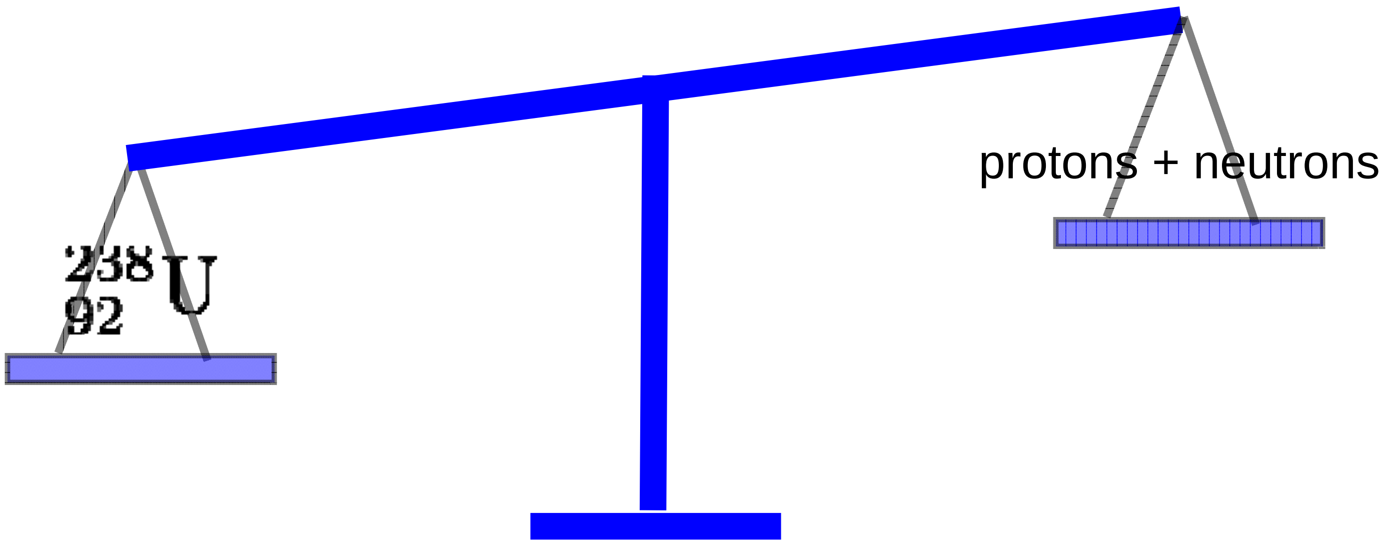
Which has more mass:

$^{238}_{92}\text{U}$ <u>or</u> $92 \times \text{protons}$, $146 \times \text{neutrons}$

(Seperated)



More on the energy

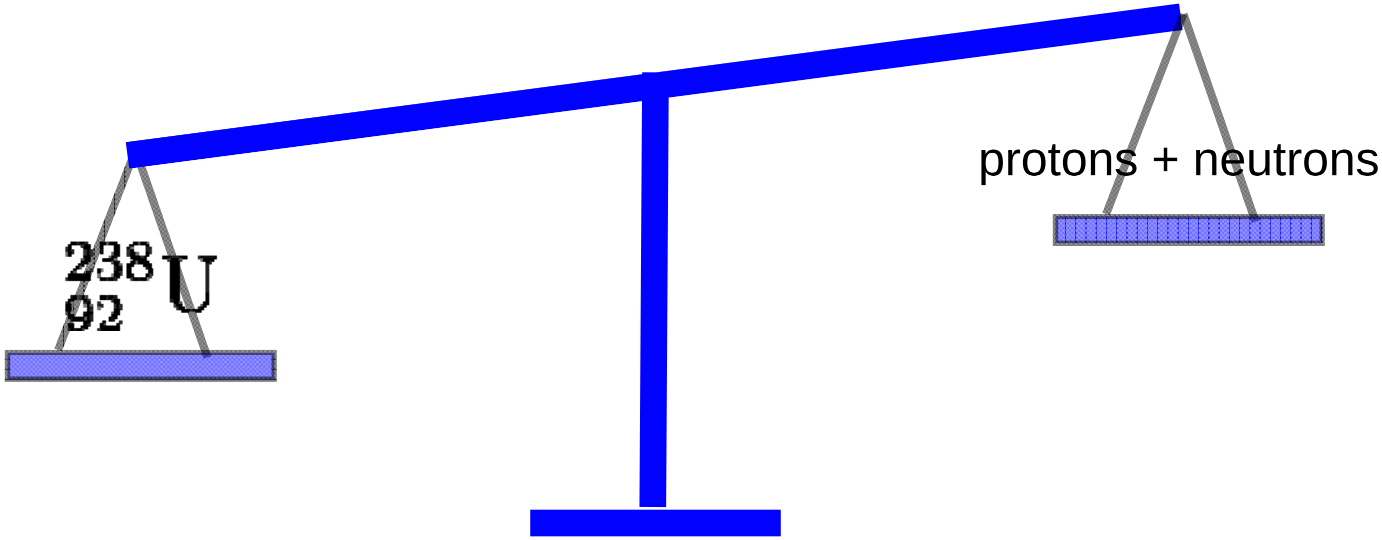


Neutrons + protons inside Uranium are heavier than separately. This mass difference is related to the energy via the famous Einstein formula:

$$E = mc^2$$

Heavy atoms breaking into smaller atoms reduces their energy -- alpha decay.

More on the energy



Break the rules of chemisty: mass is not conserved

$$m_{\text{initial}} = \text{mass of uranium}$$

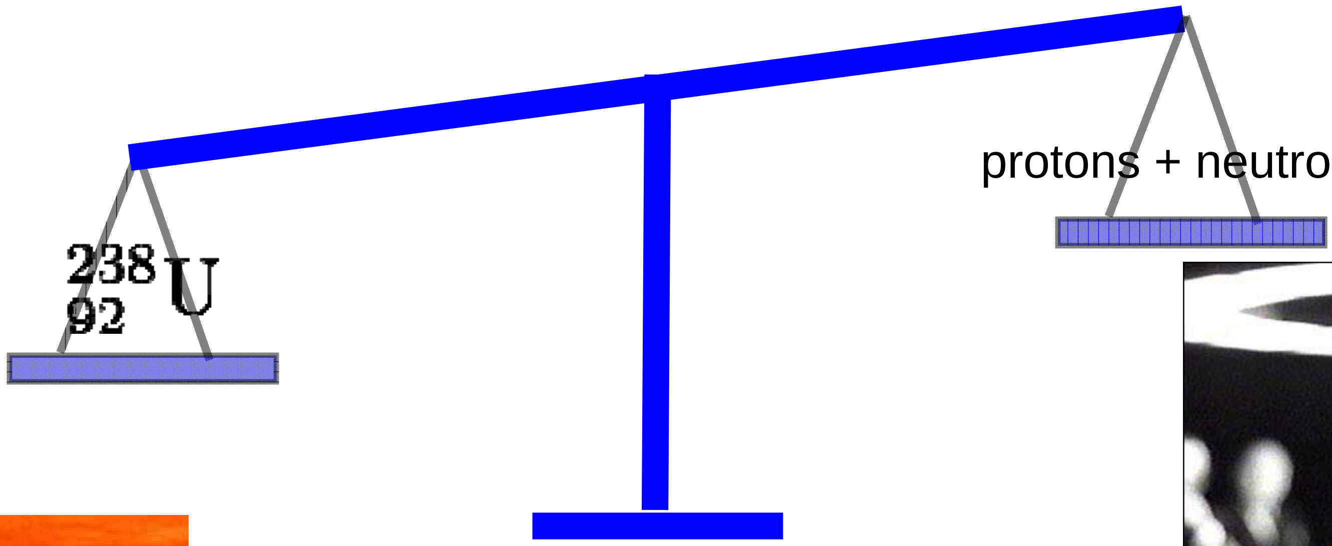
$$m_{\text{final}} = \text{mass of thorium} + \text{mass of } \alpha$$

$$m_{\text{initial}} > m_{\text{final}} \qquad \textbf{NOT EQUAL}$$

$$\text{BUT } m_{\text{initial}}c^2 = m_{\text{final}}c^2 + E_{\text{released}}$$

i.e. “Mass is a form of energy”

More on the energy

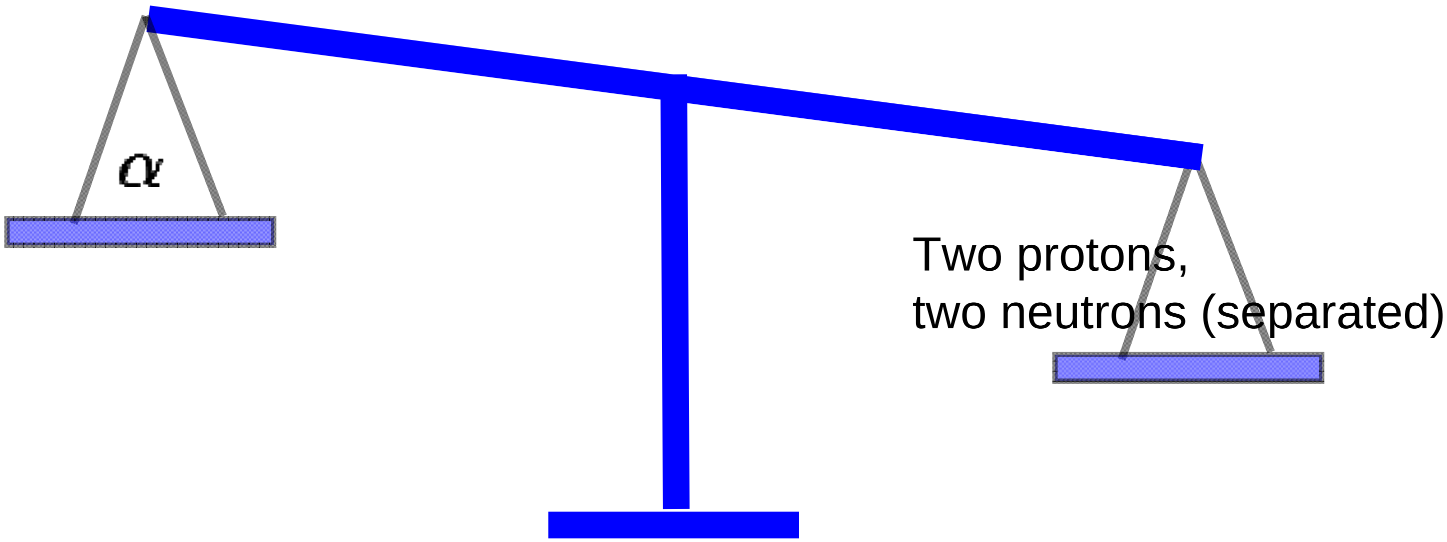


Energy is released by the atom splitting apart!

<u>NUCLEAR FISSION</u>

Are atoms <u>always</u> more (massive) than "the sum of their parts"? Do they always split to release energy?

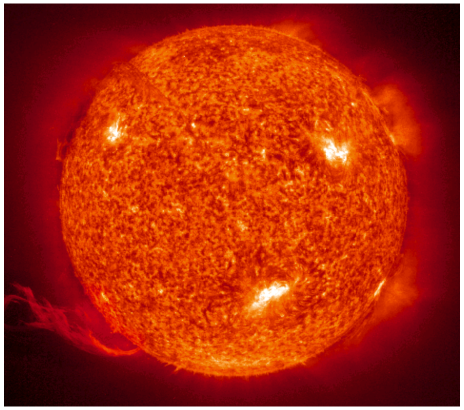
Fusion vs. Fission



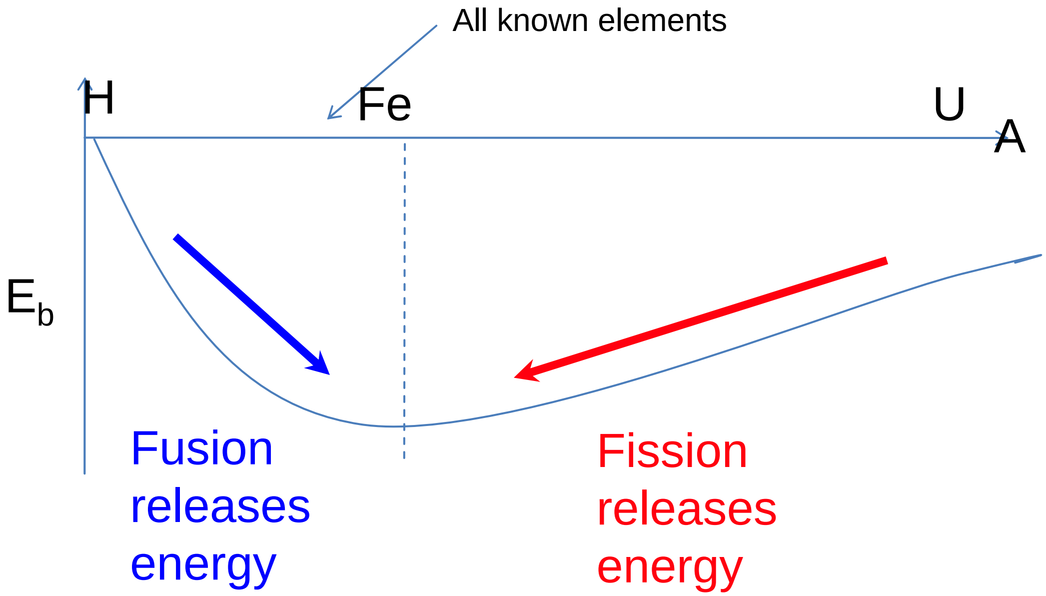
Sometimes the whole is **<u>less</u>** than the "sum of its parts"

e.g. alpha is "lighter" (less energy) than 2 protons, 2 neutrons

Joining (**<u>fusing</u>**) the protons and the neutrons releases energy. Called **nuclear fusion**.



Fusion vs. Fission



Upside down from book
This makes more sense to me

Iron (Fe) stable against
either fusion or fission.

This is why most meteorites are made of iron

Forces inside the Nuclei

i. Charges interact by <u>electric forces</u>. They act <u>long range</u>.
Neutrons: neutral—do not feel it
Protons: positive—repel each other ["Coulomb force"]
So, why does a nucleus remain together if there is so much repulsion? A second type of force explains it.

ii. <u>Strong Force</u>

All particles inside nucleus—protons and neutrons (nucleons)—attract
This force is very strong, and only acts at very <u>short</u> distances: essentially neighbors only.

When # of protons increases, nucleus is held together by strong force—only from neighbors: doesn't change much from light elements to heavy elements. But # of protons increases: All protons repel each other.
In heavy nuclei, protons would dissolve nucleus.
Nature's solution:

-put protons farther apart
-how?
-by butting more neutrons in between

Indeed, this happens: success of theory

Nuclear Forces: Summary

- Heavy elements (heavier than **Fe**) release energy by fission (splitting).
- Light elements (lighter than **Fe**) release energy by fusing (joining)
- Mass is not conserved in nuclear reactions! The "missing mass" gets transformed into energy: $E = mc^2$
- **Protons and neutrons held together by a strong force, which overcomes the repulsion of the nucleus.**
- **The same force traps the alpha particle "inside" the nucleus. Alpha decay (fission; releasing an alpha particle) is an example of tunneling!**

Alpha decay transforms one element into another:
The ancient dream of **ALCHEMY** is real!

Lead -> Gold? Stimulus package!

We will see other decays later to explain beta- and gamma-radiation. These <u>cannot</u> be explained by tunneling because particles change identities (e.g. neutrons become protons!)