

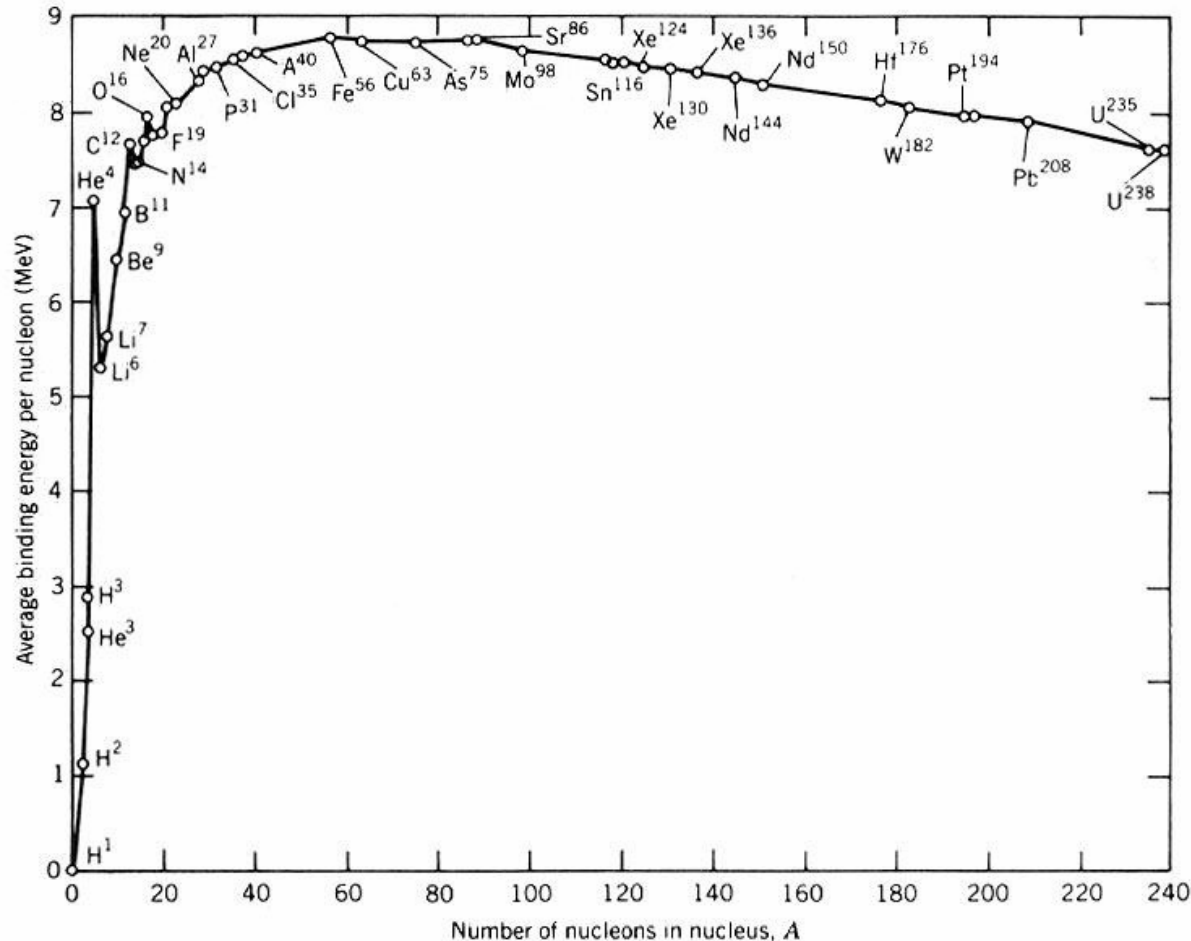
Foolproof systems do not take into account the ingenuity of fools.
- Gene Brown

We know very little, and yet it is astonishing that we know so much,
and still more astonishing that so little knowledge can give us so
much power.
- Bertrand Russell, English philosopher, mathematician

(sodium iodide and surface barrier detectors)

Binding energy is the energy that it takes to pull particles apart.

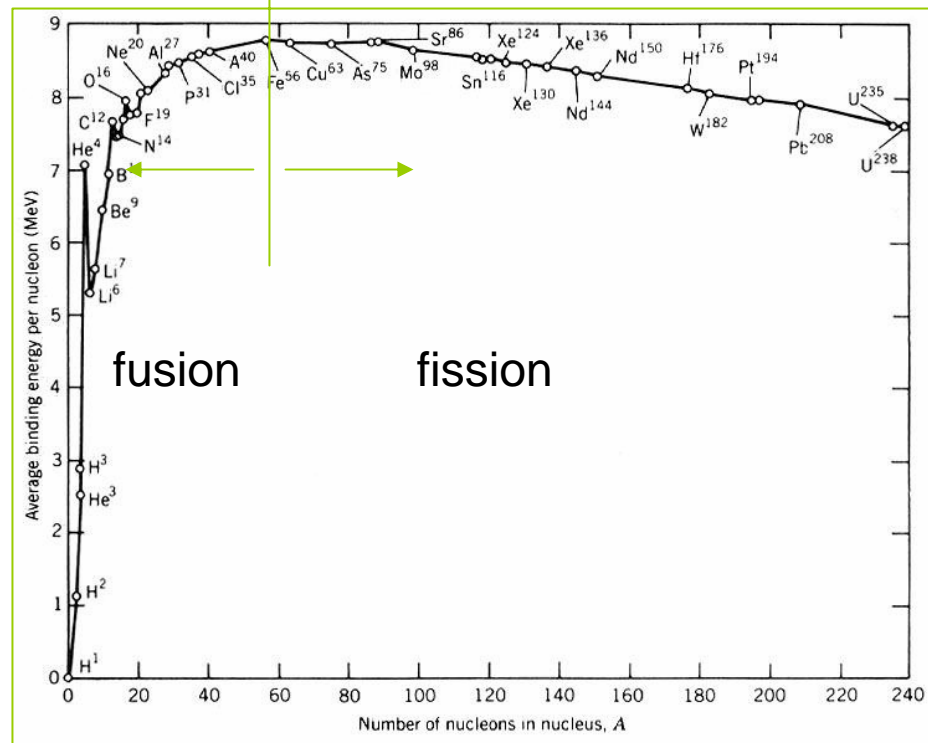
A useful quantity is the average binding energy of a particle in the nucleus, *aka* the binding energy/nucleon.



Why useful? Can tell at a glance whether energy is going to be released if you split a nucleus (*fission*) or combine two nuclei (*fusion*).

If the total binding energy increases, then energy is released.

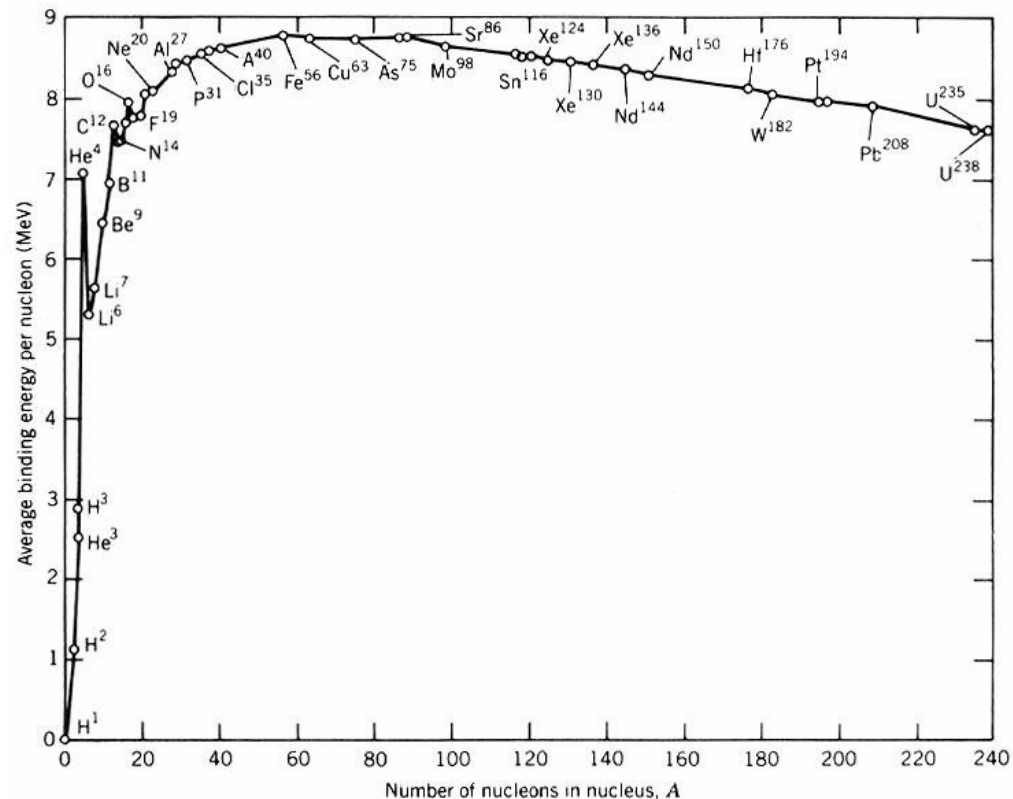
In the reactions considered, total number of nucleons the same before and after, so average binding energy and total binding energy are proportional.



What sets shape of the curve of binding energy?

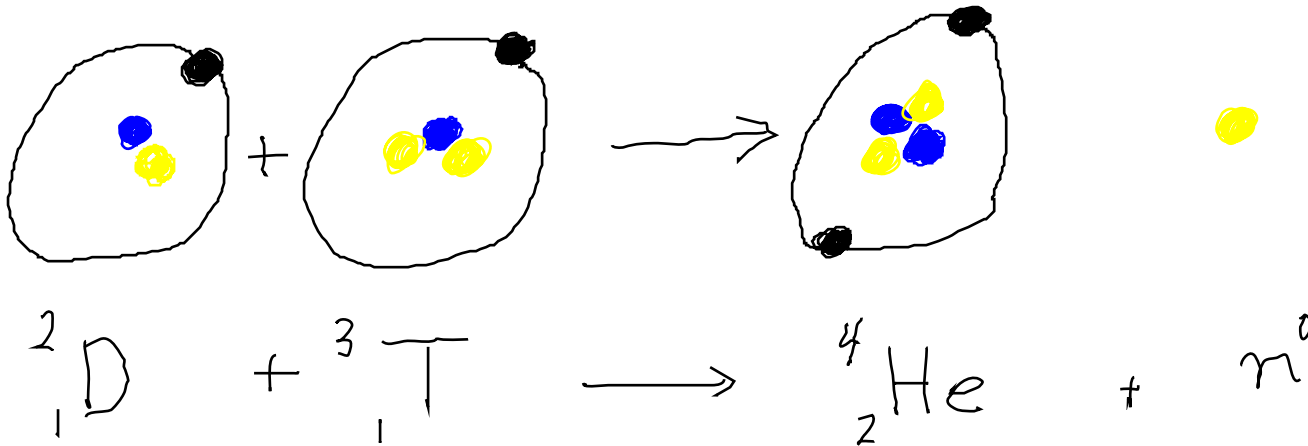
For small nuclei, small number of protons so relatively weak repulsion, small number of nucleons, so relatively weak attraction

For large nuclei, large number of protons so relatively strong repulsion, short range of strong force means saturation of strong force



Ex: D-T (deuterium-tritium) fusion

Combine deuterium ${}^2_1\text{D}$ ($= {}^2_1\text{H}$) and tritium ${}^3_1\text{T}$ ($= {}^3_1\text{H}$) to form ${}^4_2\text{He}$ and a neutron.



This is the reaction used in the *hydrogen bomb*. Also the reaction scientist want to use in *controlled thermonuclear fusion*. Hard to overcome electric repulsion between nuclei. In bomb, use fission to produce fusion.

Can calculate energy released using Einstein's $E=mc^2$:

(data from www.webelements.com)

Mass of deuterium: 2.014101779 amu

Mass of tritium: 3.01604927 amu

Total mass before 5.030151049 amu

Mass of helium-4 4.00260324 amu

Mass of neutron 1.0086649 amu

Total mass after 5.01126814 amu

Change in mass -0.018882909 amu

Energy released $(0.018882909 \text{ amu}) \times (931.5 \text{ MeV/amu}) = 17.59 \text{ MeV}$.

An *electron-volt* (eV) is the kinetic energy an electron acquires in accelerating through an electric potential difference of 1V.

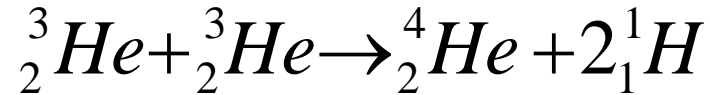
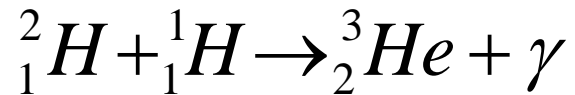
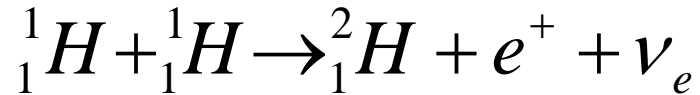
Convenient unit of energy on atomic/nuclear scale.

Typical chemical reaction energy releases are about 1 eV.

Typical nuclear energy releases are about 1 MeV.

Fusion in stars:

Different fusion cycles depending on the phase of life of a star:
the Sun is in the first stage

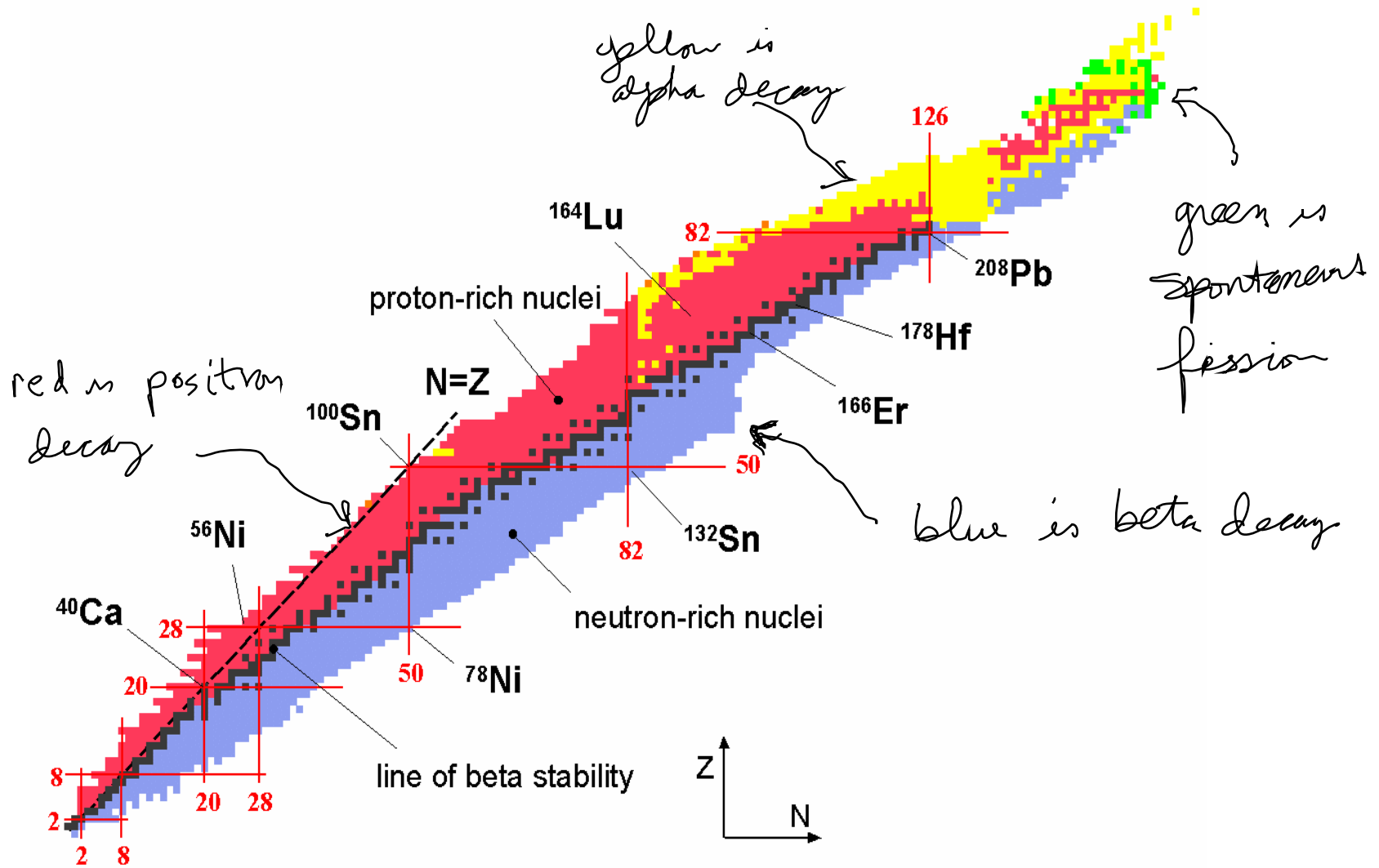


Later stages produce heavier elements, but curve of binding energy limits fusion to create elements only up to iron-56

Supernovas create more massive elements.

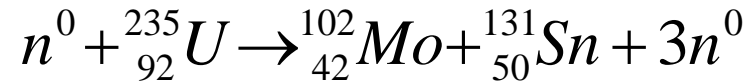
Therefore, Sun is at least second generation star!

Rare solution to problem of too many protons is *spontaneous fission*.



Key to getting energy from fission is *neutron-induced fission*.

E.g.,



Nuclei that can undergo neutron-induced fission are called *fissionable*.

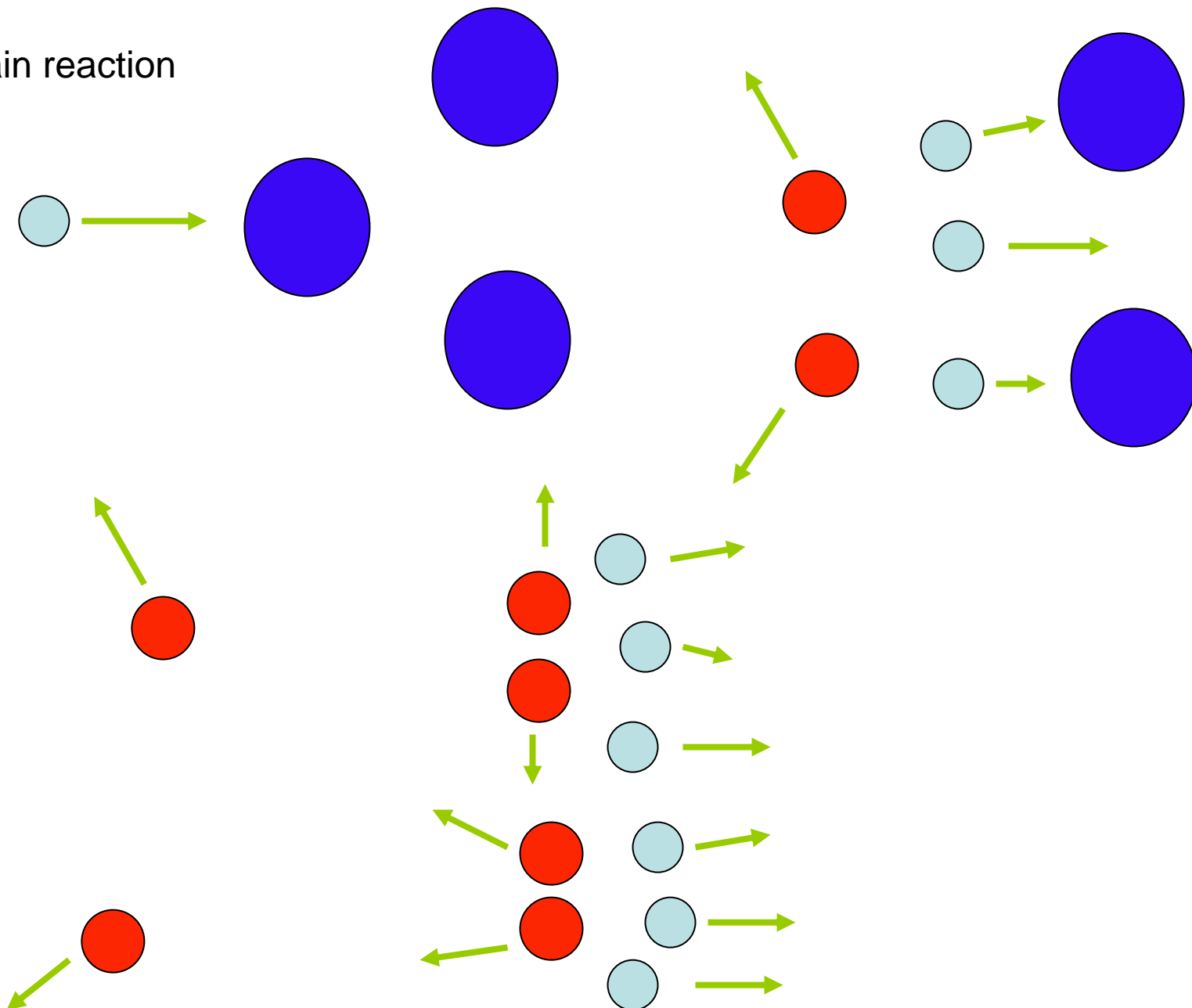
But key distinction: most fissionable nuclei require energetic neutrons (*fast neutrons*) in order to fission. Turns out, hard to create sustained reaction with these nuclei.

But some nuclei will fission with even low energy neutrons (*slow neutrons*) and these nuclei are called *fissile*.

Key fact: Only three! (${}_{92}^{233}\text{U}$, ${}_{92}^{235}\text{U}$, ${}_{94}^{239}\text{Pu}$) Only one naturally occurring!

Others can be produced in nuclear reactors.

Chain reaction



Energy release in “typical” fission reaction

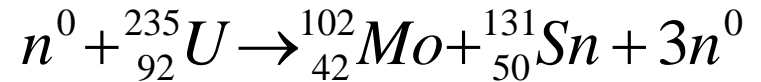
Mass of neutron 1.0086649 amu
Mass of U-235 235.0439242 amu

Total mass before 236.0525891 amu

Mass of Mo-102 101.9102972 amu
Mass of Sn-131 130.9169191 amu
Mass of neutrons 3.0259947 amu

Total mass after 235.853211 amu

Change in mass -0.1993781 amu



Energy released = (0.1993781 amu)x(931.5 MeV/amu) = 185.7 MeV

Reaction products neutron rich

