SAND2011-3501C

Review of Research Reactor Physics

Lecture 1

June 6th, 2011

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Principal Member of the Technical Staff

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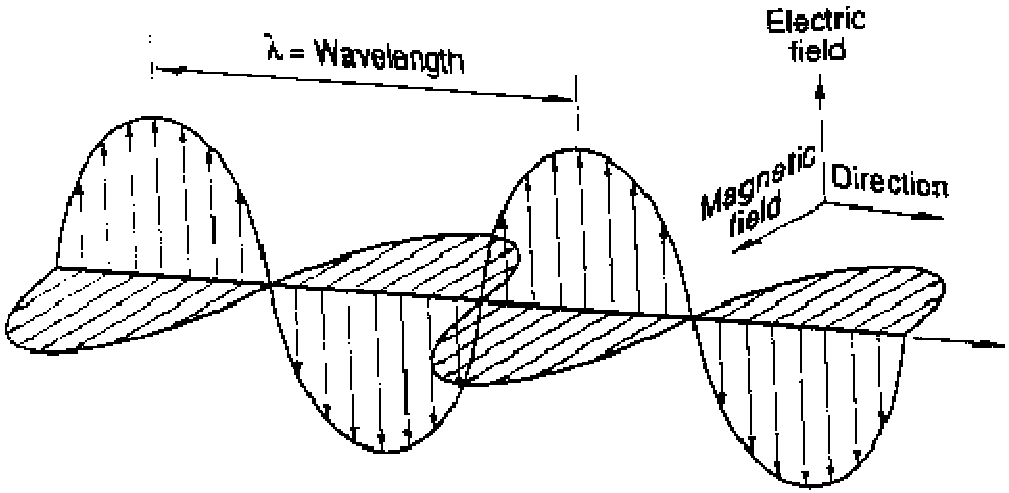
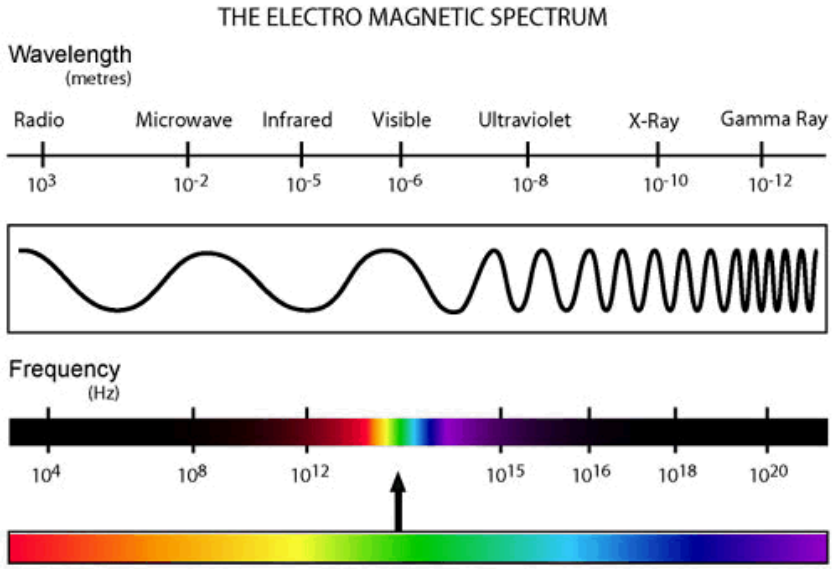
What we are going to cover in this lecture:

- Introduction to photons, electrons, protons and neutrons
- How these basic building blocks effect the form of matter.
- Stable and unstable nuclei
  - How nuclei decay
  - The more common nuclear emissions
  - How those emissions interact with matter
- Fission of the “actinides”

The Atomic Building Blocks of Nature:

The Photon





The photon is a "quanta" of electromagnetic radiation: a traveling electric and magnetic field. It has zero mass and zero charge.

The energy of the photon is inversely proportional to its wavelength.

Source: http://www.fnal.gov/pub/inquiring/more/light/light_page5.html

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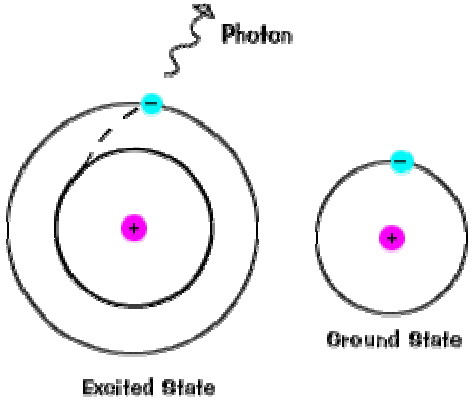
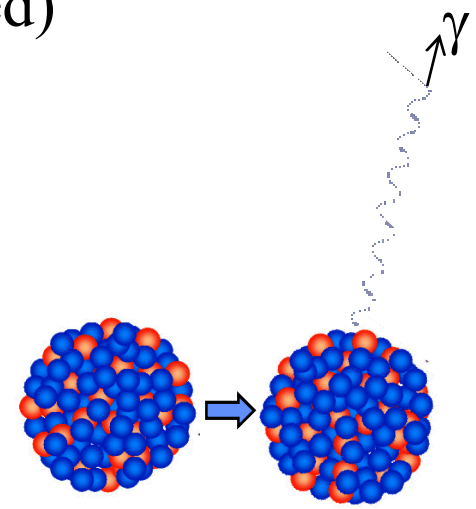
The Atomic Building Blocks of Nature:

The Photon (continued)



Typically, X-rays are emitted when "inner electrons" (inside an atom) make a transition.



Gamma rays (γ) are typically emitted when a nucleus makes a transition.

How these photons interact with matter depends on their energy.

Source: http://imagine.gsfc.nasa.gov/docs/science/how_l2/xray_generation_atom.html

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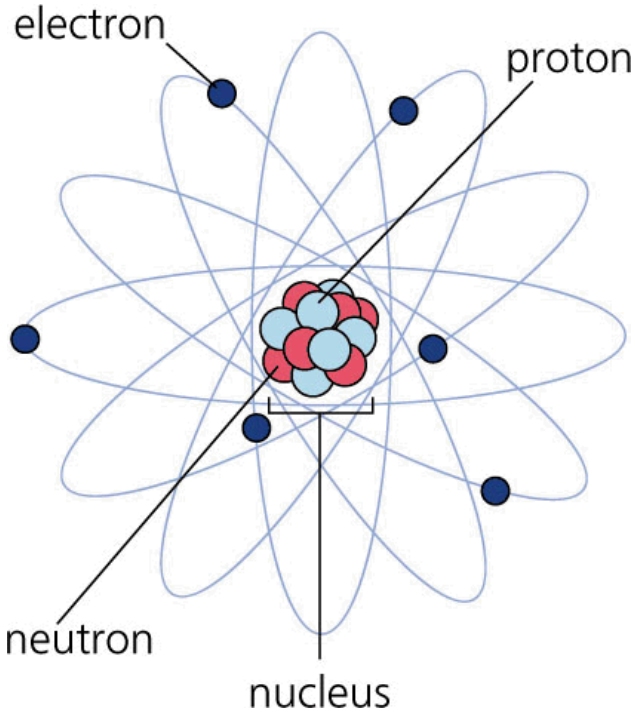
The Atomic Building Blocks of Nature:



The electron:

- Negative Charge
- Very low mass (1/1836 that of the proton)

Electrons are "bound" by their electrical attraction to the positively charged nucleus (or rather the protons inside the nucleus.)

They are usually bound weakly enough that you can easily break them free. Here, static electricity, which can be caused by rubbing your shoes on a carpet, can cause of a spark or the flow of electrons.

Source: http://www.bnl.gov/bnlweb/Museum/Investigate.html

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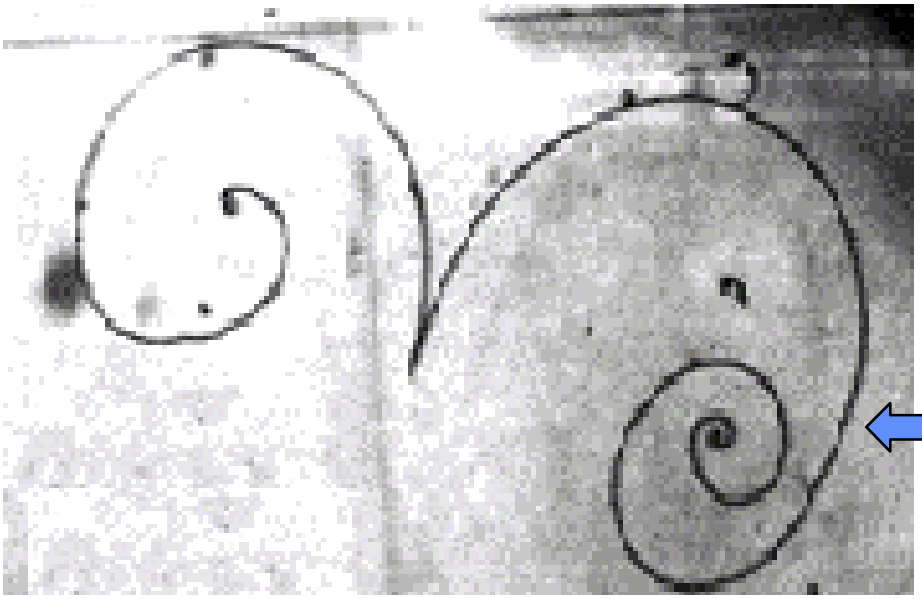
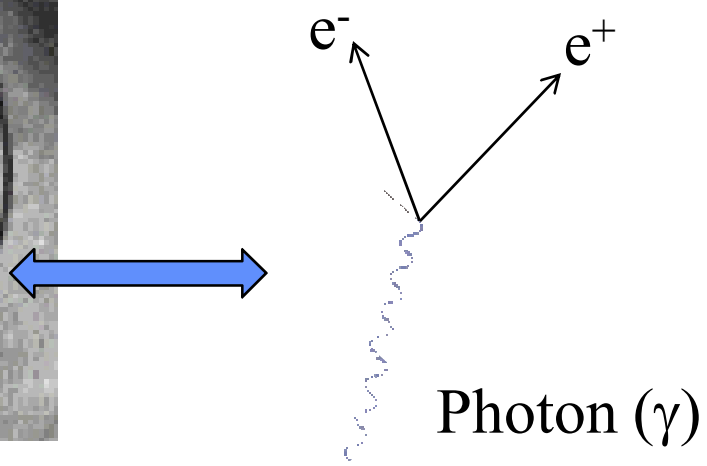
The Atomic Building Blocks of Nature:

The “anti-electron or Positron:





(A magnetic field bends the opposite charges in opposite directions)

The positron has the same mass as an electron but opposite charge.

Source: http://conferences.fnal.gov/lp2003/forthepublic/matter/index.html

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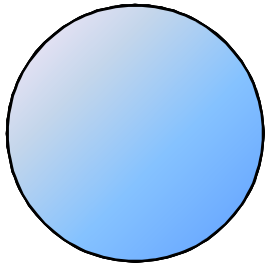
The Atomic Building Blocks of Nature:

The Proton



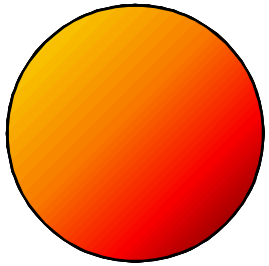
Charge = +1 (the electron charge = -1)

Mass = 938 MeV/c^2 (the electron mass = 0.5 MeV/c^2)

Radius = 0.877 x 10^{-15} meters (the electron radius = 0)

The Atomic Building Blocks of Nature:

The Neutron



Charge = 0 (the proton charge = +1)

Mass* = 940 MeV/c^2 (the proton mass = 938 MeV/c^2)

Radius = 0.886 x 10^{-15} meters
(the proton radius = 0.877 x 10^{-15} meters)

Note that the neutron has slightly more mass than proton; this means that unless the neutron is inside a nucleus, it decays in about 890 seconds!

* Mass outside the nucleus.

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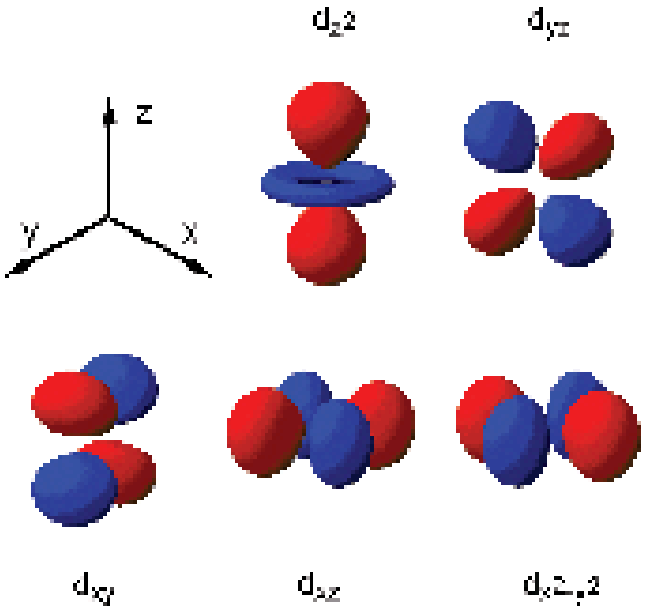
The Structure of Matter

The number of electrons and the shape of their cloud determines the CHEMICAL properties

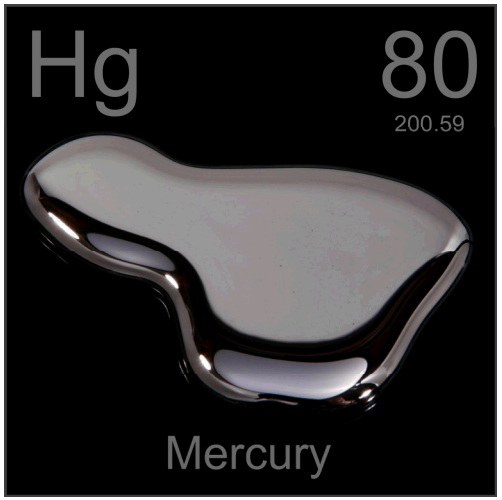
Sulfur

http://www.schools.utah.gov/curr/science/core/8thgrd/sciber8/geology/html/min_id.htm

http://www.nist.gov/pml/data/periodic.cfm



http://www.lanl.gov/orgs/nmt/nmtdo/AQarchive/04spring/VO.html



Source: http://www.dec.ny.gov/chemical/28716.html

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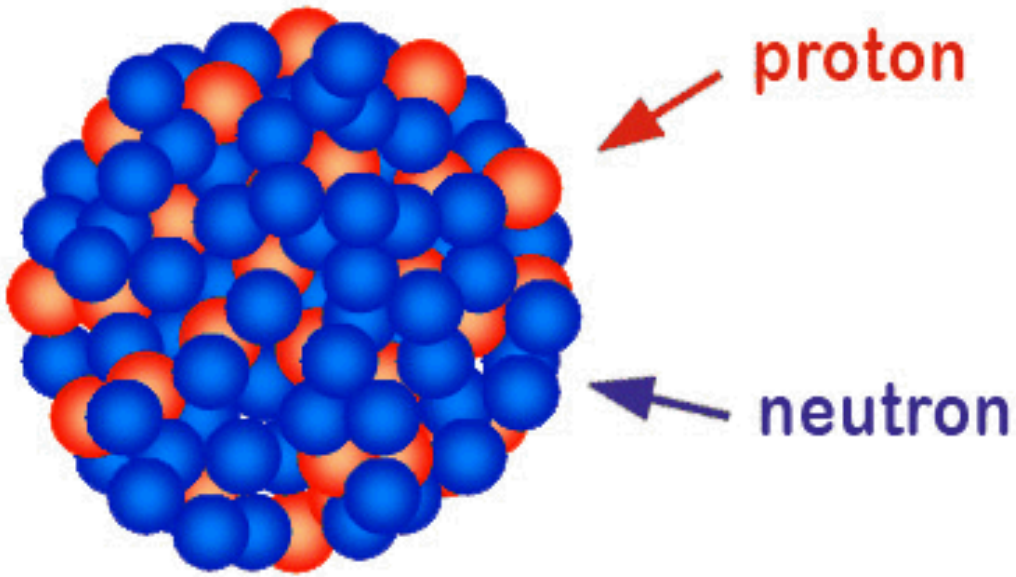
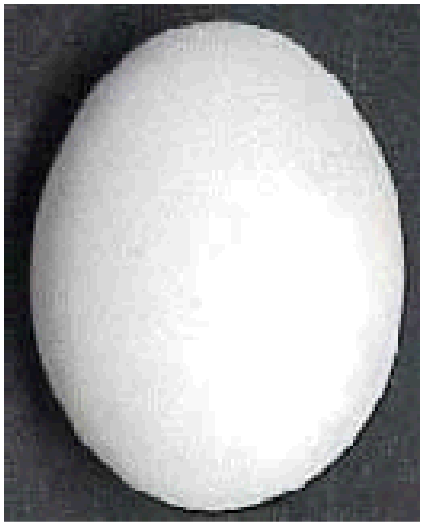
Deep inside the electron cloud lies the nucleus

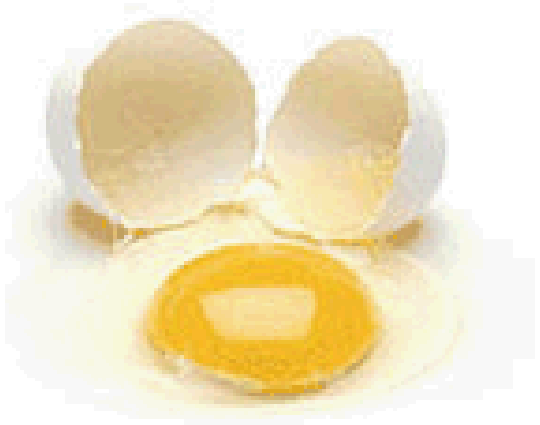


Uranium Nucleus

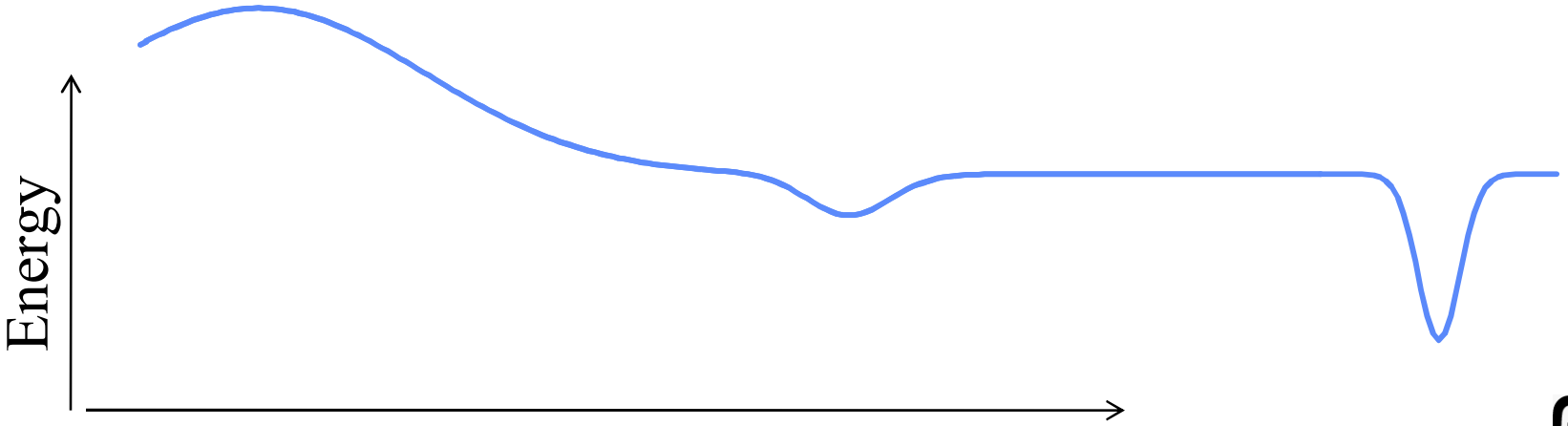
Stable and Unstable Nuclei



http://www.schools.utah.gov/curr/science/core/8thgrd/sciber8/matter/html/chemchng.htm



http://www.ars.usda.gov/is/pr/2005/050322.htm



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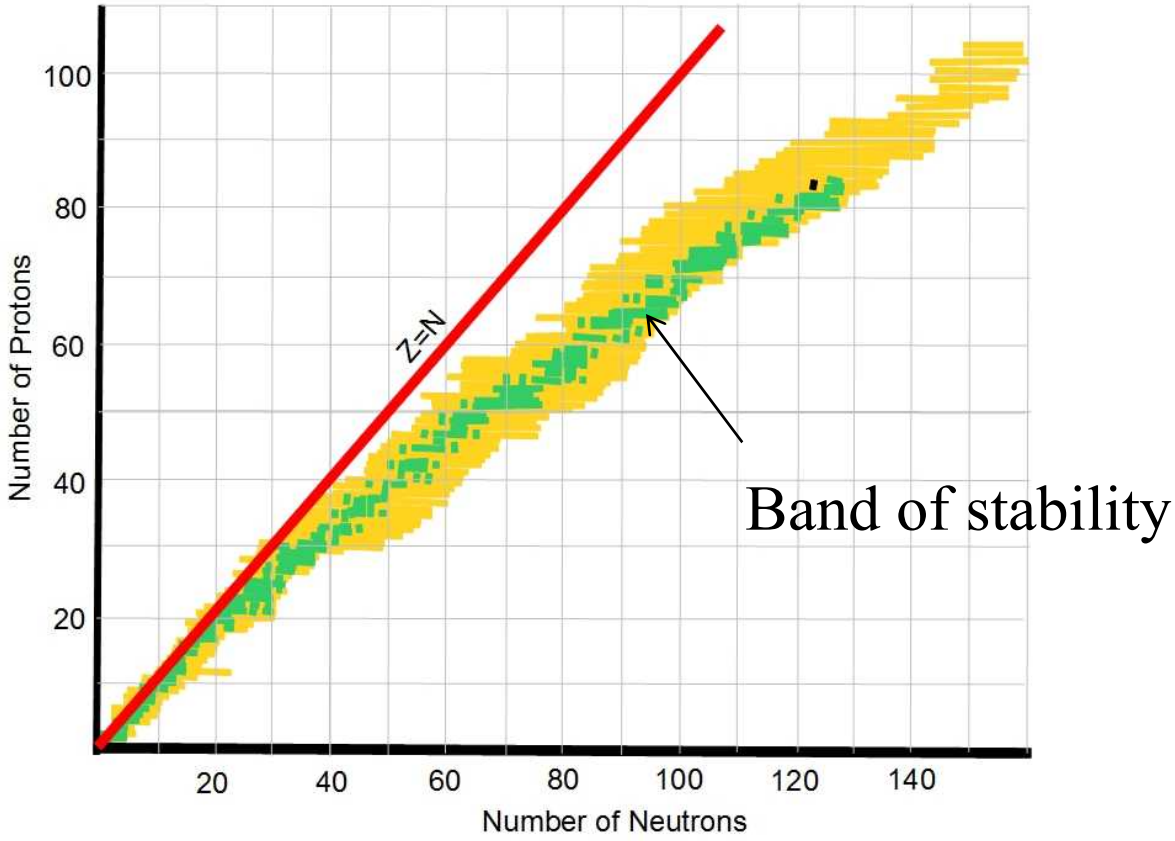
As with the electron cloud, the number of Neutrons and Protons determines the Nuclear Properties



Source: Geoff Forden, based on http://www.phy.ornl.gov/hribf/science/abc/

As the number of protons and neutrons increases, **stable** nuclei have more neutrons than protons

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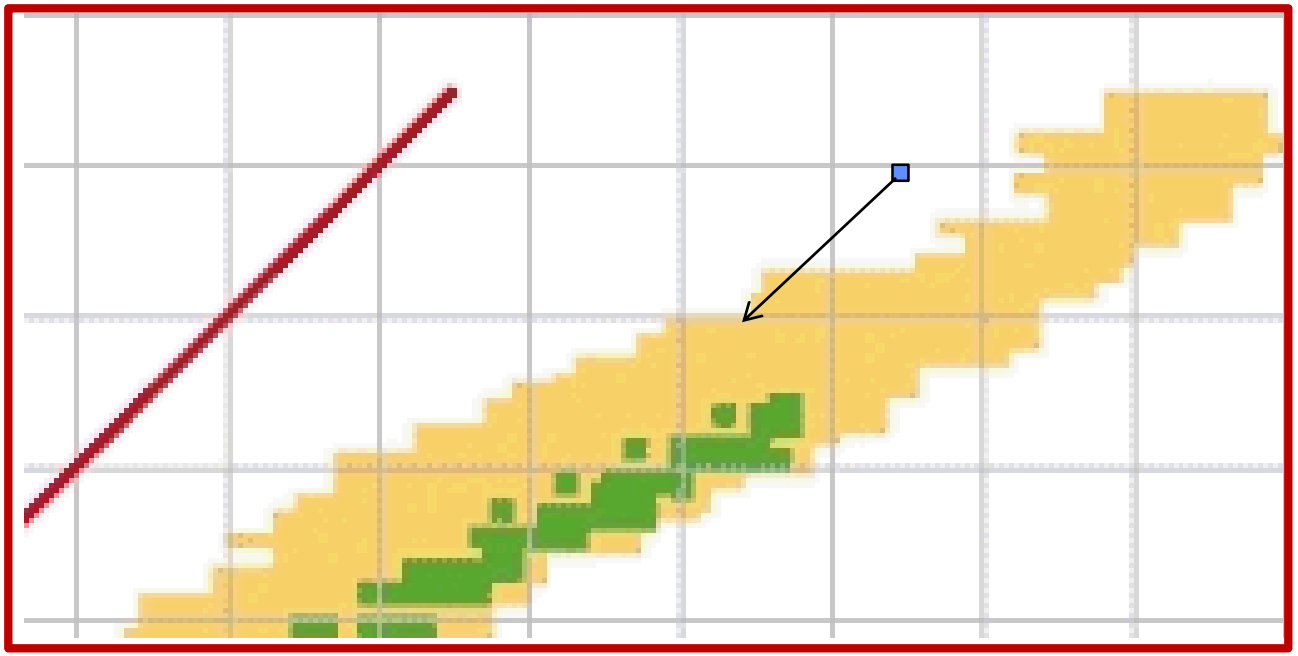
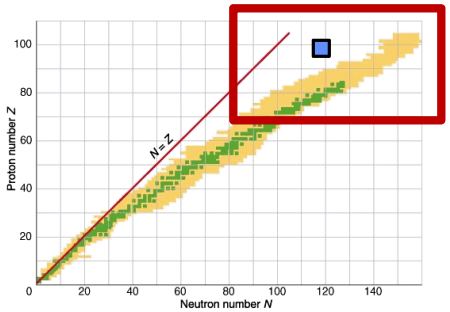
How does an unstable nucleus become stable?



If it is created above the band of stability, it can get rid of equal numbers of neutrons and protons and move to the band of stability.



It does this in “steps” of 2 neutrons and 2 protons at a time:

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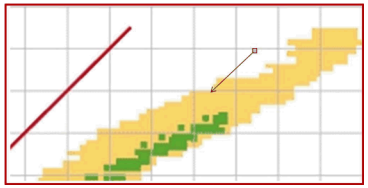
It does this in steps of 2 neutrons and 2 protons (an "alpha" particle) at a time:

$^{228}Th_{90}$

1.9 years



$^{224}Ra_{88}$

3.6 sec.

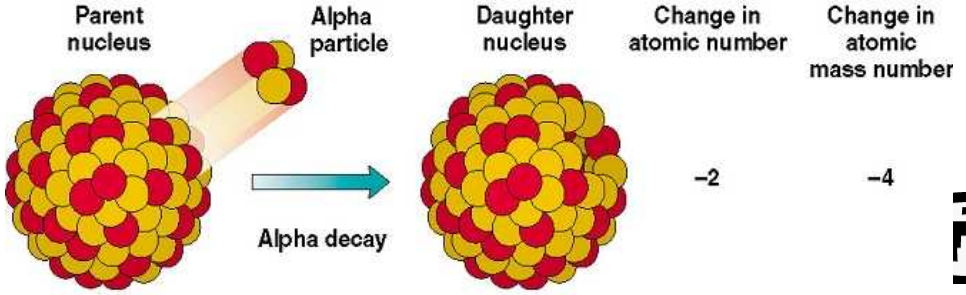
$^{220}Rn_{86}$

55 sec.

$^{214}Po_{84}$

0.15 sec.

Spontaneous Fission



Based on https://www.llnl.gov/str/JanFeb02/Moody.html

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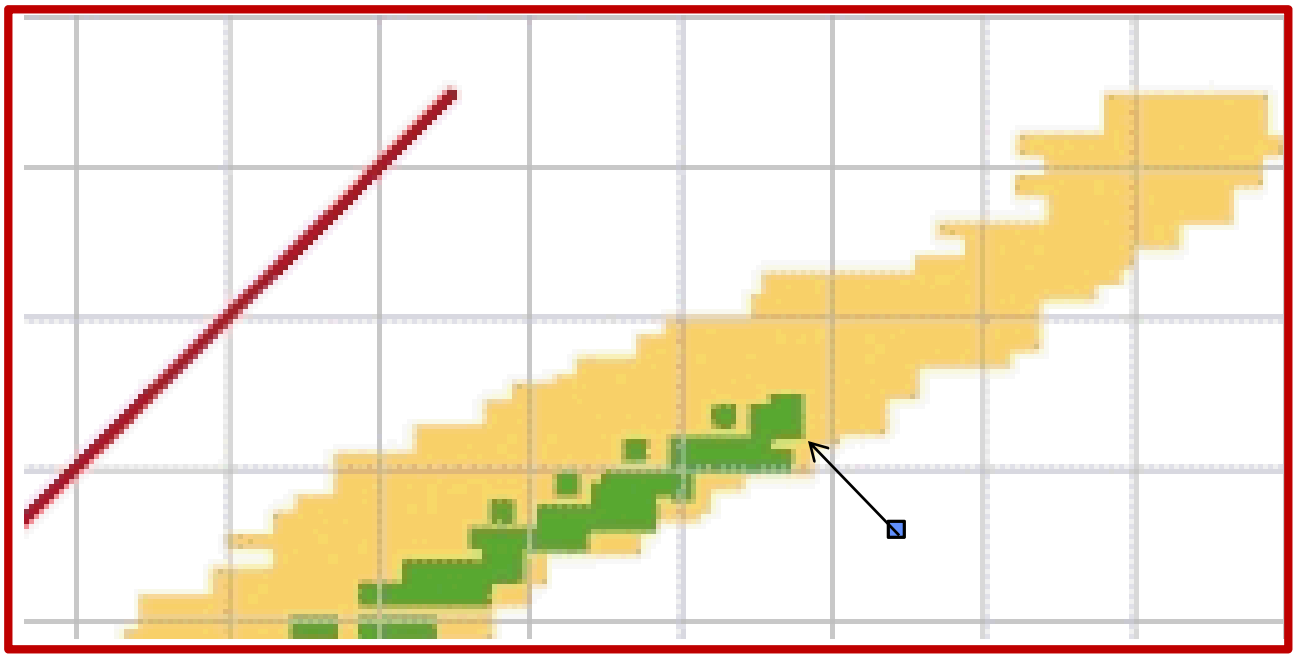
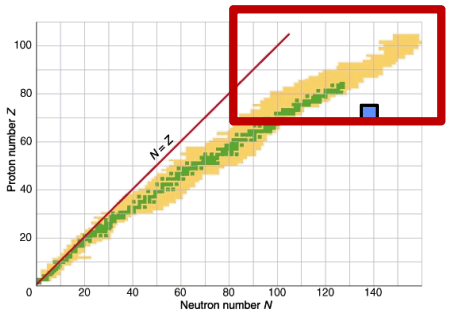
If it is created below the band of stability…



…it can convert an excess neutron to a proton by having a neutron emit an electron:



$n^0 \rightarrow p^+ + e^-$ This is called "beta" decay

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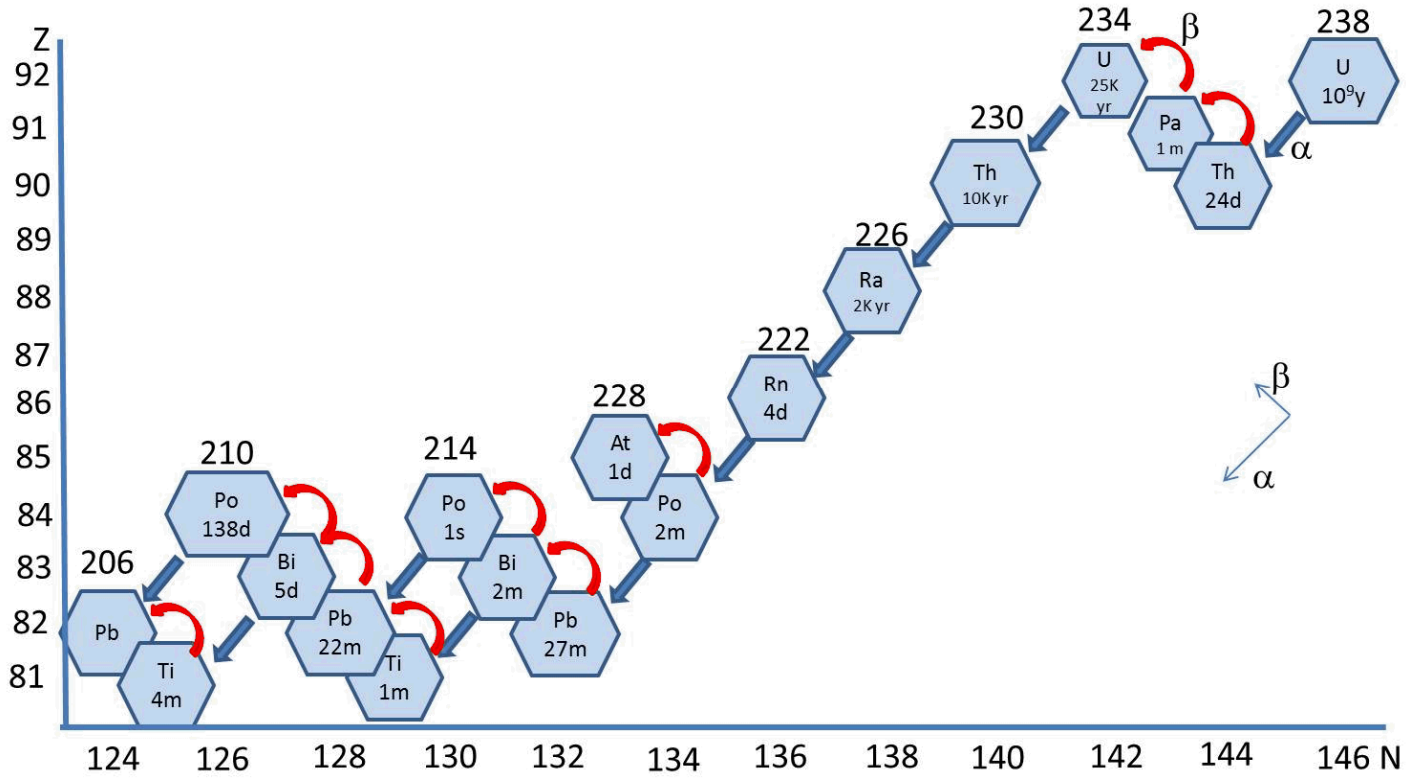
In real life, actual decay paths are a combination of these…



Source: G. Forden based on http://pubs.usgs.gov/of/2004/1050/uranium.htm

Note that some of these decays take a **long** time!

Left to itself, uranium will alpha decay but in **1 billion years**!

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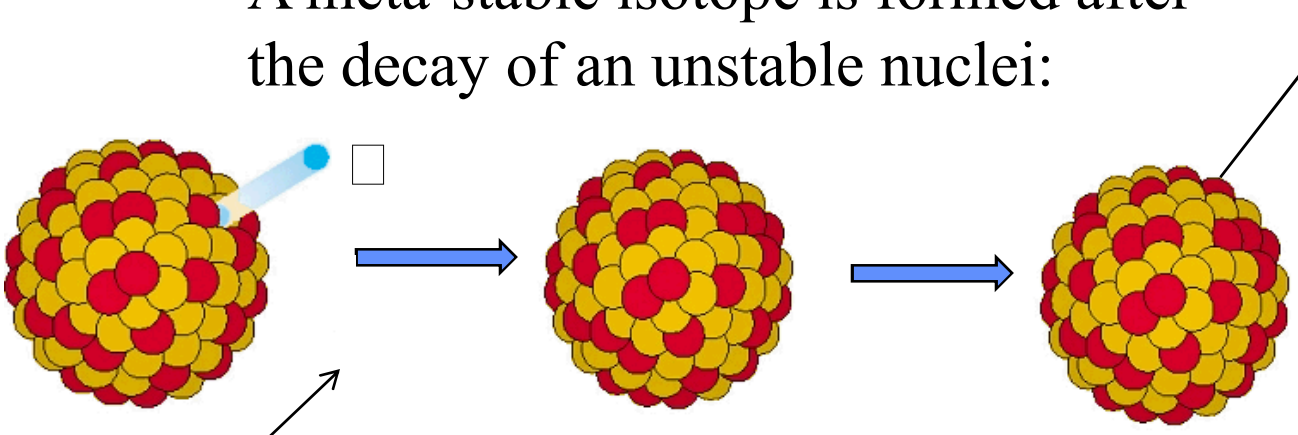
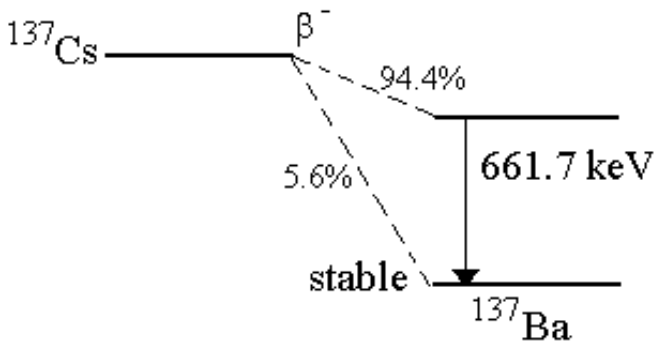
There are other ways for "unstable" nuclei to decay:

A meta-stable isotope is formed after the decay of an unstable nuclei:



The beta decay of Cs^{137} "excites" its daughter nucleus 94% of the time.



http://ie.lbl.gov/radioactivedecay/page2.htm

A gamma ray is like a very high energy X-ray.

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There are other, more exotic, nuclear “decays”…

Electron Capture (EC, K-capture)

Internal Conversion

Double beta decay

Double electron capture

Electron capture followed by proton emission

…

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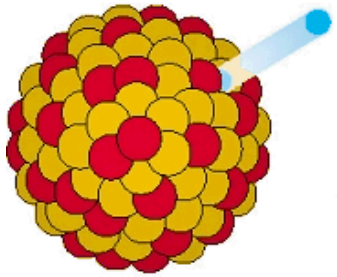
Review: types of decays covered so far:

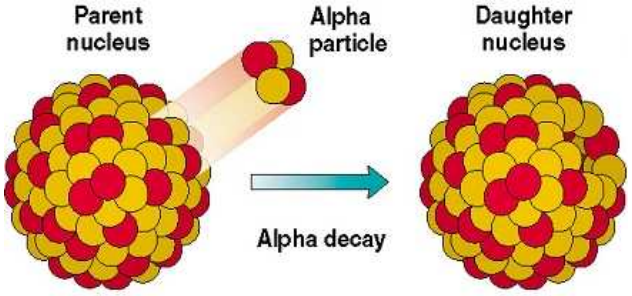
Beta decay:



Where a neutron decays into a proton and an electron:

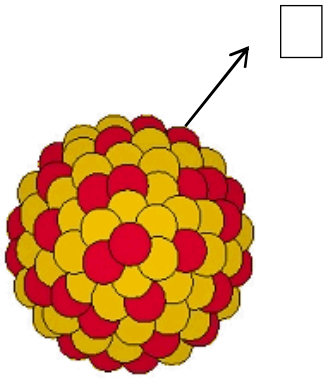
$n^0 \rightarrow p^+ + e^-$

Alpha decay:



A nucleus emits two neutrons and two protons **as a unit** (called an alpha particle)

Gamma decay:



Internal energy, usually left over from a previous decay or reaction, is radiated off as a neutral gamma ray.

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Penetration of Radiation

Source: http://www.nasa.gov/audience/forstudents/k4/stories/F_Keeping_Cool_With_Shadows.html

What are effective barriers?

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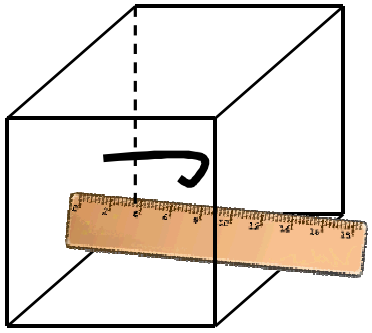
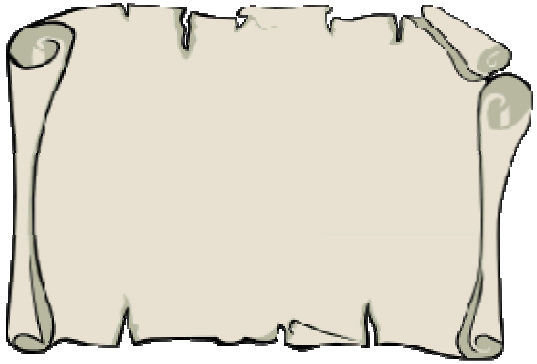
How do Alpha, Beta, and Gammas interact with matter?

These interactions depend on the particle's mass, electric charge, and energy as well as the properties of the materials they are interacting with:

Alphas have a charge of +2 and a large mass:



Alphas penetrate less than 4 cm in air.



Alphas only penetrate a **single** sheet of paper.

They will **NOT** penetrate skin.

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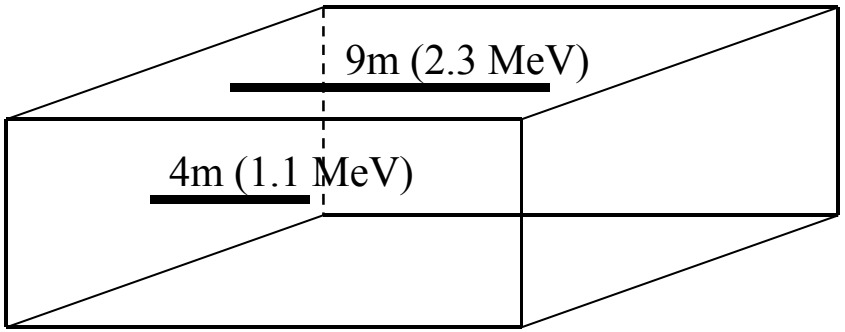
How beta (□) particles interact with matter:

Betas have a charge of -1 and very small mass:

Higher Z (atomic number) materials are better at stopping betas.

Air



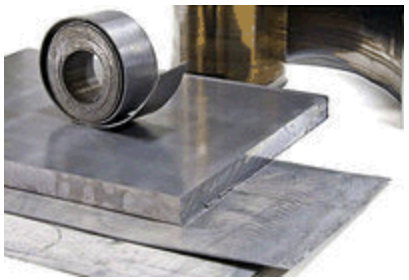
Beta penetration in air depends on the energy, a 1.1 MeV beta penetrates 4 meters and a 2.3 MeV beta penetrates 9 meters.

Aluminum (Z=13)

Max. Ranges:

	2.3 MeV	1.1 Mev
Range=	4.2 mm	2.0 mm

Lead (Z=82)



	2.3 MeV	1.1 Mev
Range=	1.0 mm	0.4 mm

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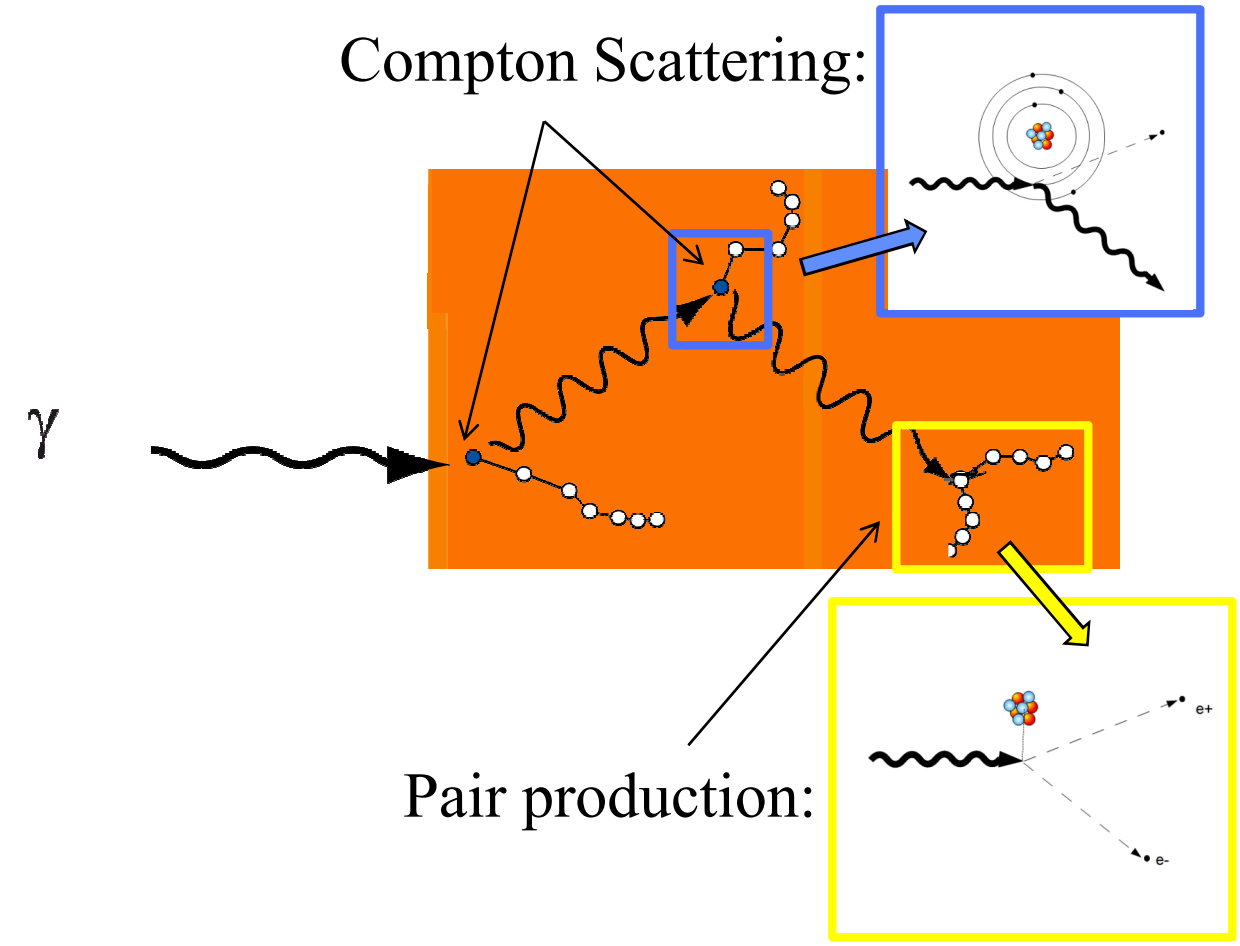
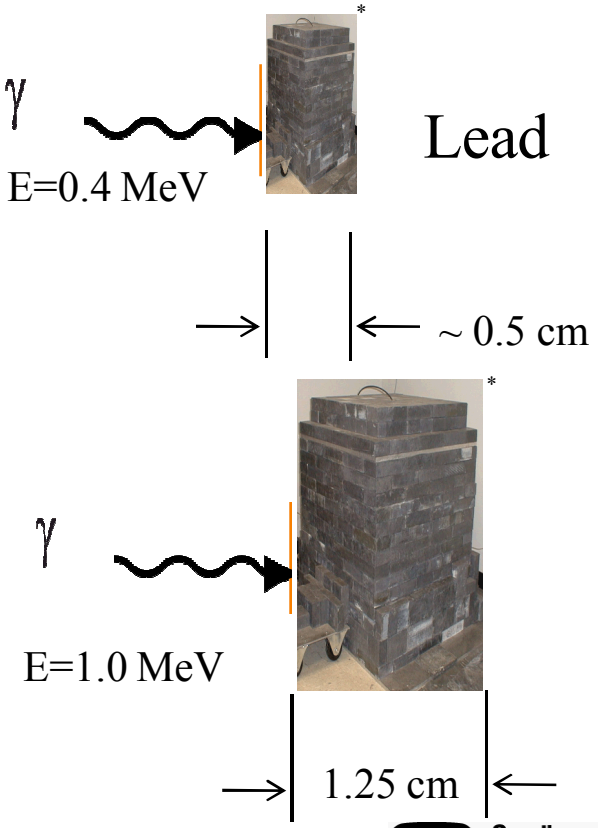
Gamma (γ) ray:

A gamma-ray's interaction with matter depends on the γ's energy:





Source: G. Forden

*source: http://pubs.usgs.gov/of/2003/of03-029/HTML/Photos.html

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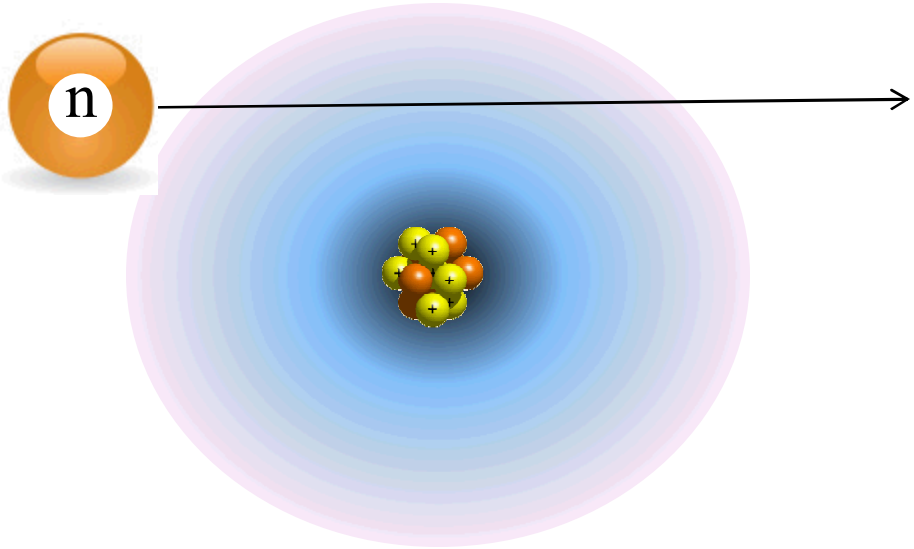
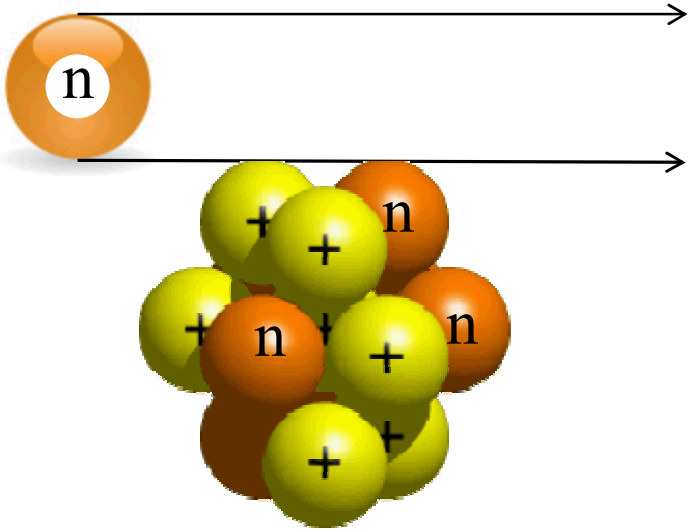
Neutrons have zero electric charge:



They pass undisturbed through the electron cloud surrounding the nucleus.

Neutrons need to essentially "bump" into a neutron or proton in a nucleus before they can interact:



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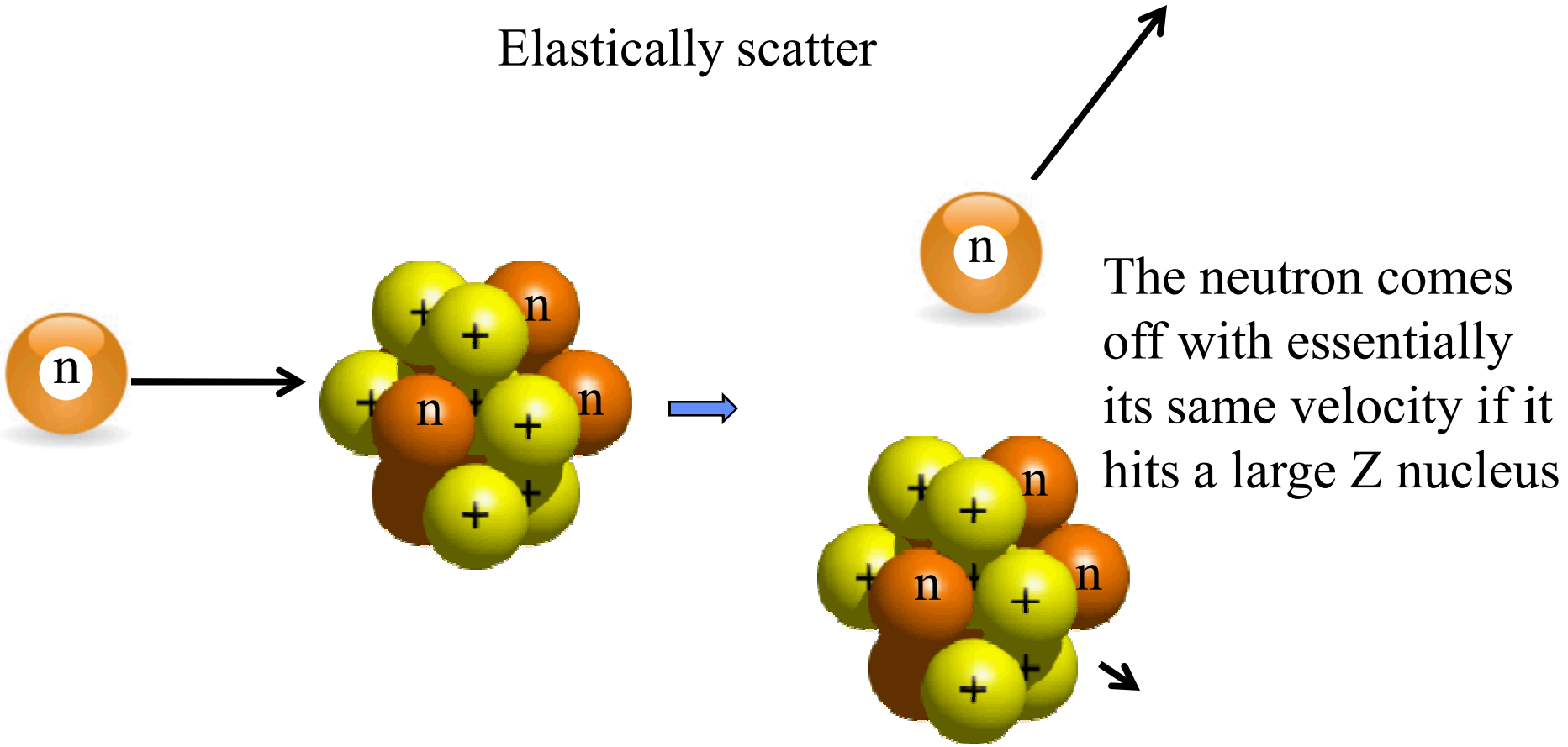
When neutrons do collide with nuclei, they can:

Elastically scatter



The neutron comes off with essentially its same velocity if it hits a large Z nucleus

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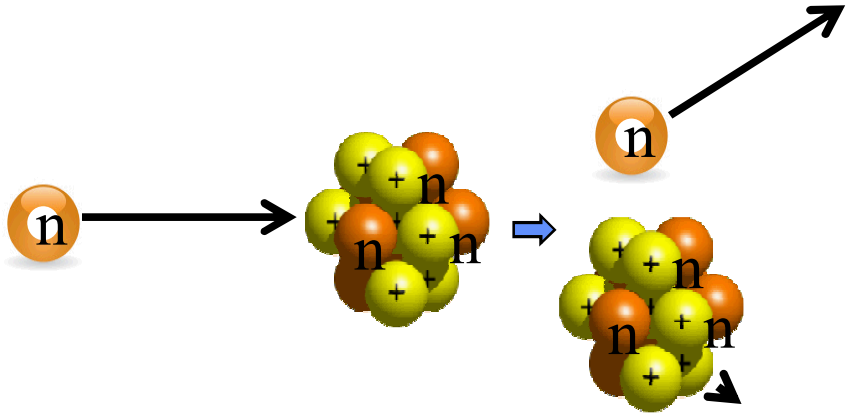
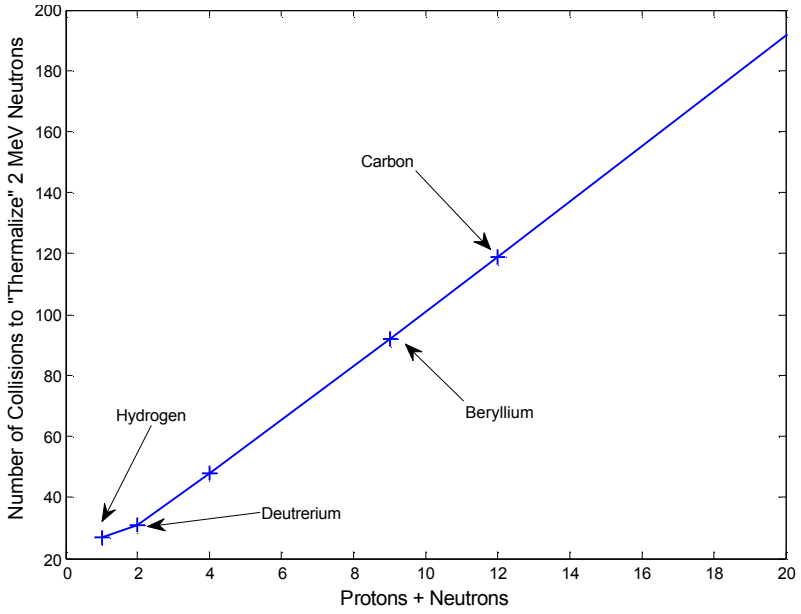
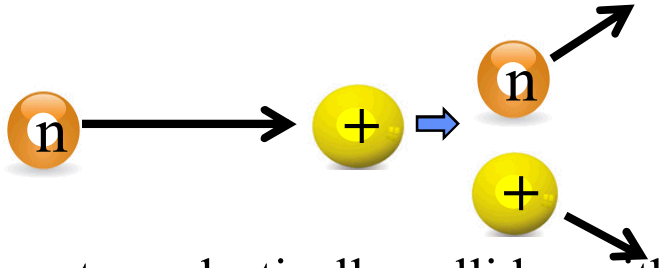
Elastic Collisions (continued)

When a neutron elastically collides with a heavy nucleus, it comes off with essentially all of its original energy.



Source: G. Forden based on information in http://www.lanl.gov/orgs/n/n1/panda/00326407.pdf





If a neutron elastically collides with a light nucleus (a hydrogen for instance) it can transfer a large fraction of its energy.

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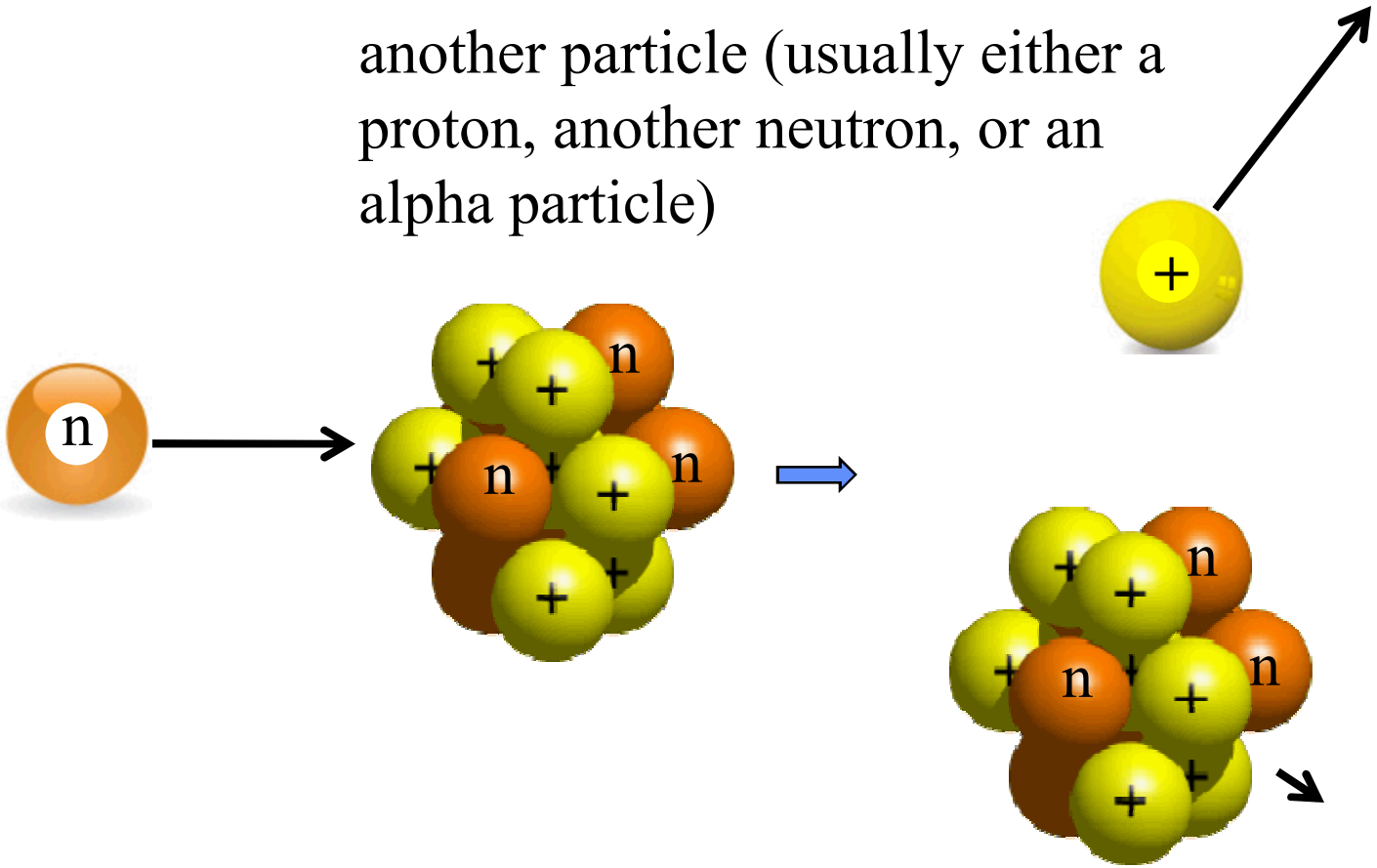
When neutrons do collide with nuclei, they can: be absorbed

Be absorbed with the emission of another particle (usually either a proton, another neutron, or an alpha particle)



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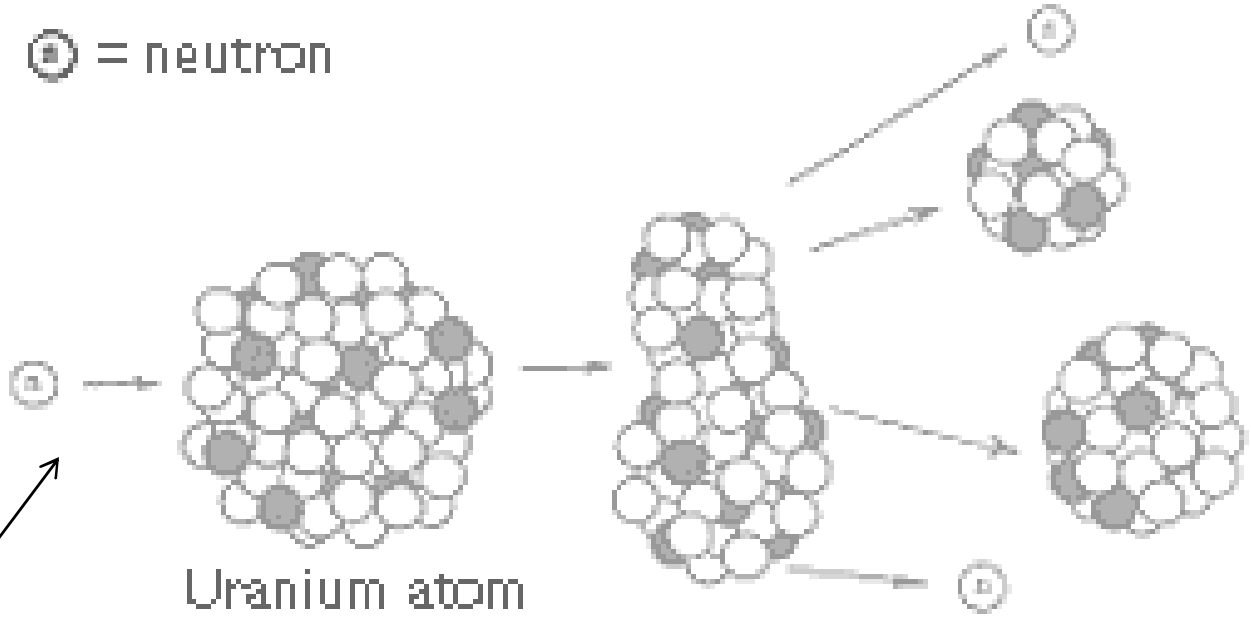
When neutrons do collide with nuclei, the nuclei can: fission

They can also cause massive disruptions to the nucleus:



Source: http://www.bnl.gov/bnlweb/history/BGRR.asp

A neutron strikes a uranium atom, exciting it into a meta-stable state.

Instead of radiating a gamma ray, this excited uranium vibrates until it splits into a number of pieces.

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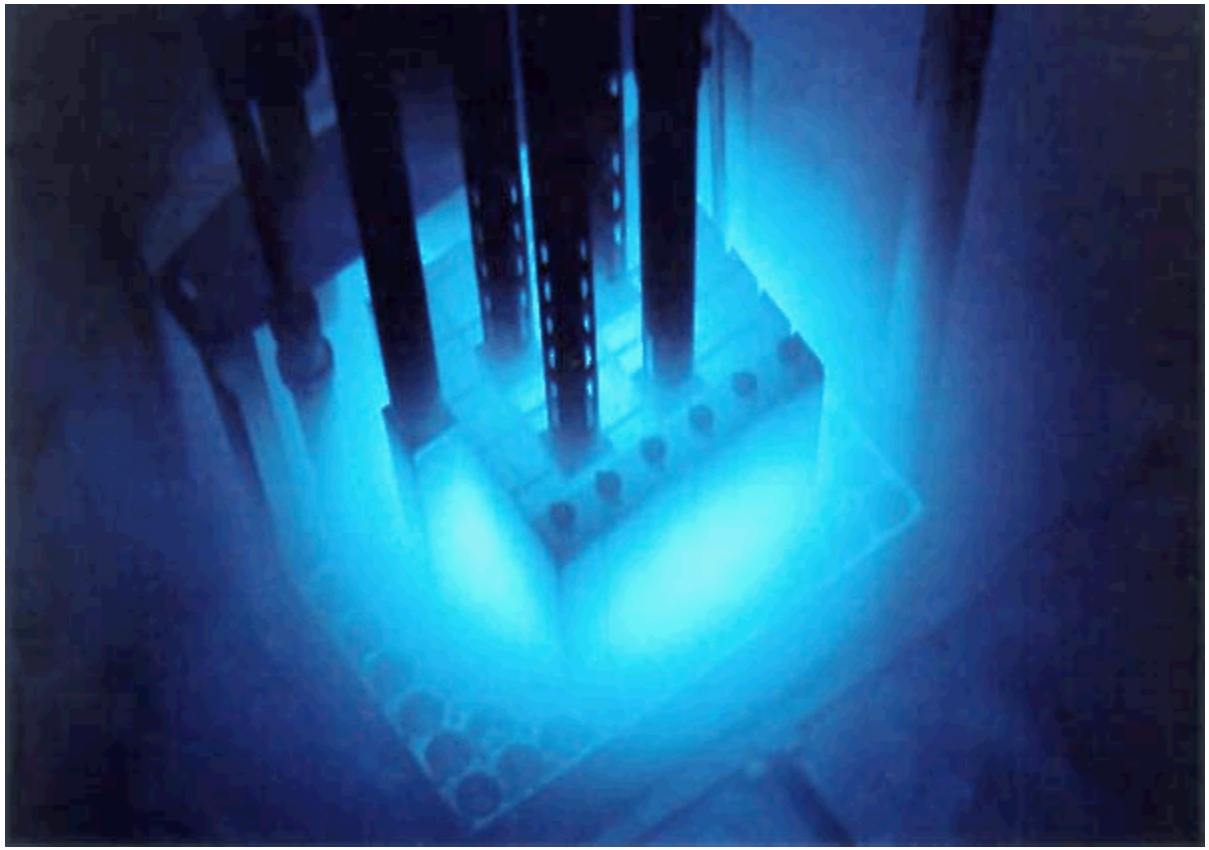
Fission, Fissionable, Fertile



https://engineering.purdue.edu/NE/Research/Facilities/reactor.html

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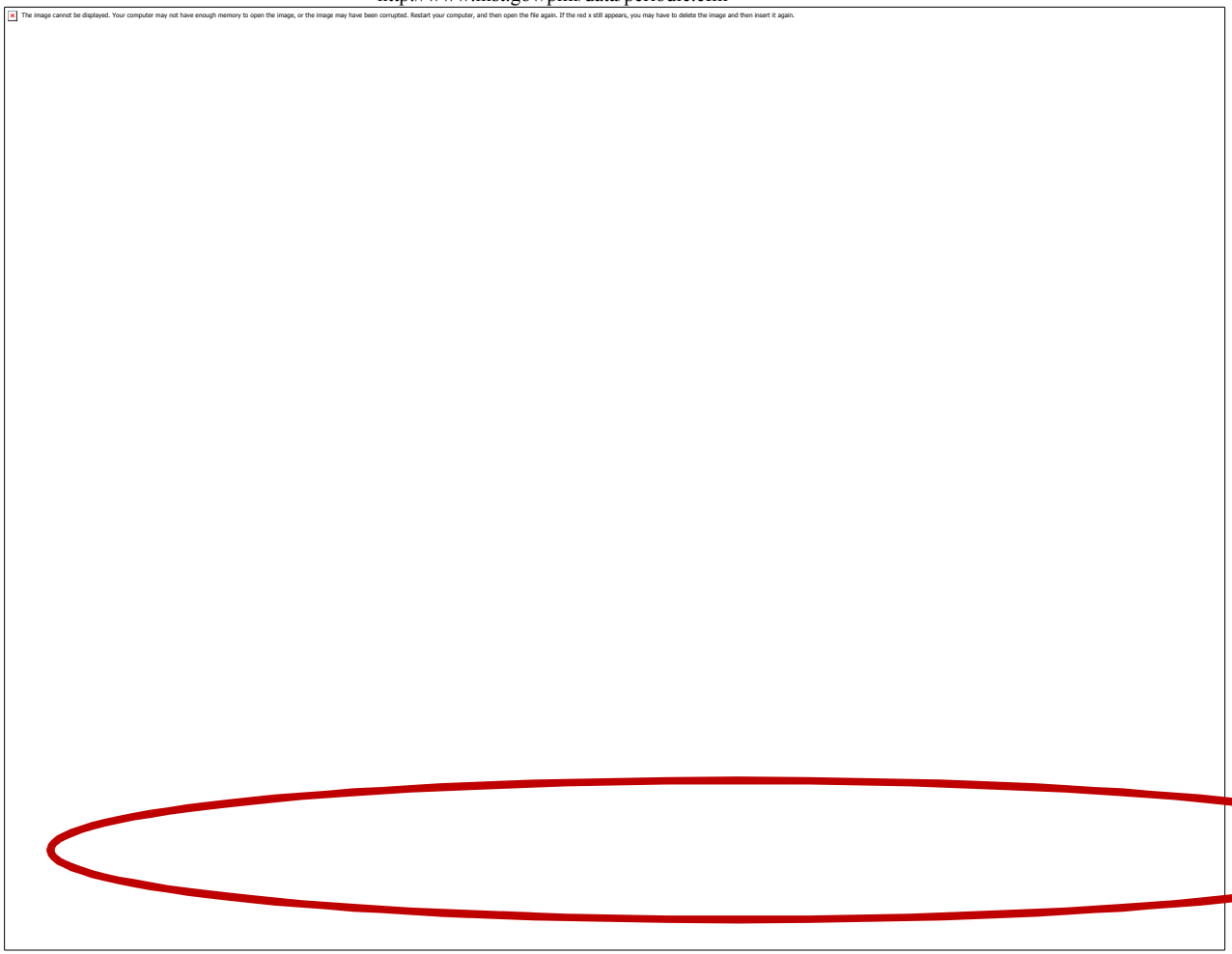
Not all nuclides are “fissile”:

http://www.nist.gov/pml/data/periodic.cfm



Only the actinides have isotopes capable of fissioning…

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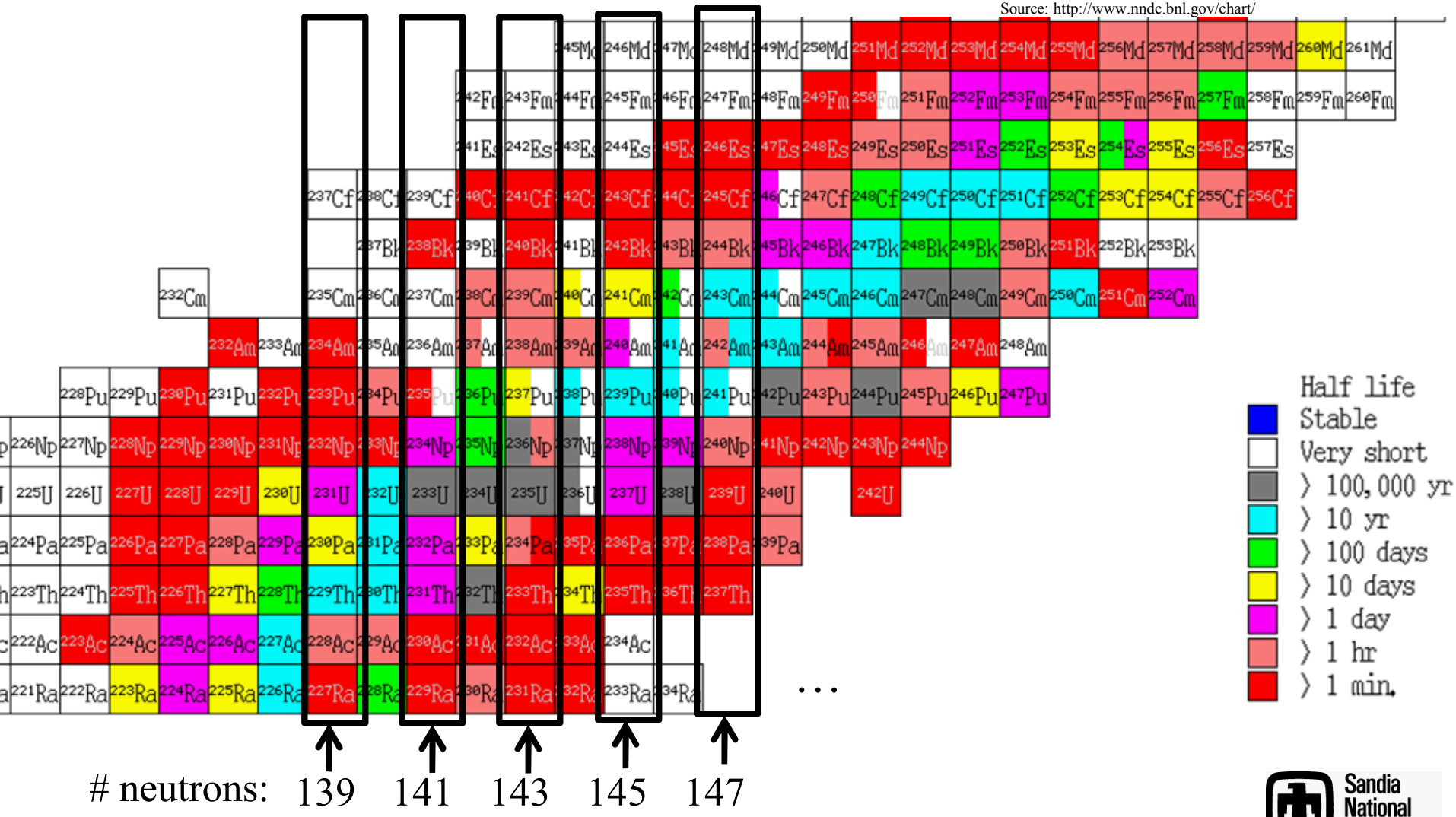
Some definitions:

Fissile material: a nuclei that is capable of fission if a **"slow"** neutron hits it.

Fissionable material: a nuclei that fissions if a "**fast**" or "**slow**" neutron hits it.

Fertile material: a nuclei that can become fissile material if it absorbs a neutron first.

…and only those actinides with an odd number of neutrons.



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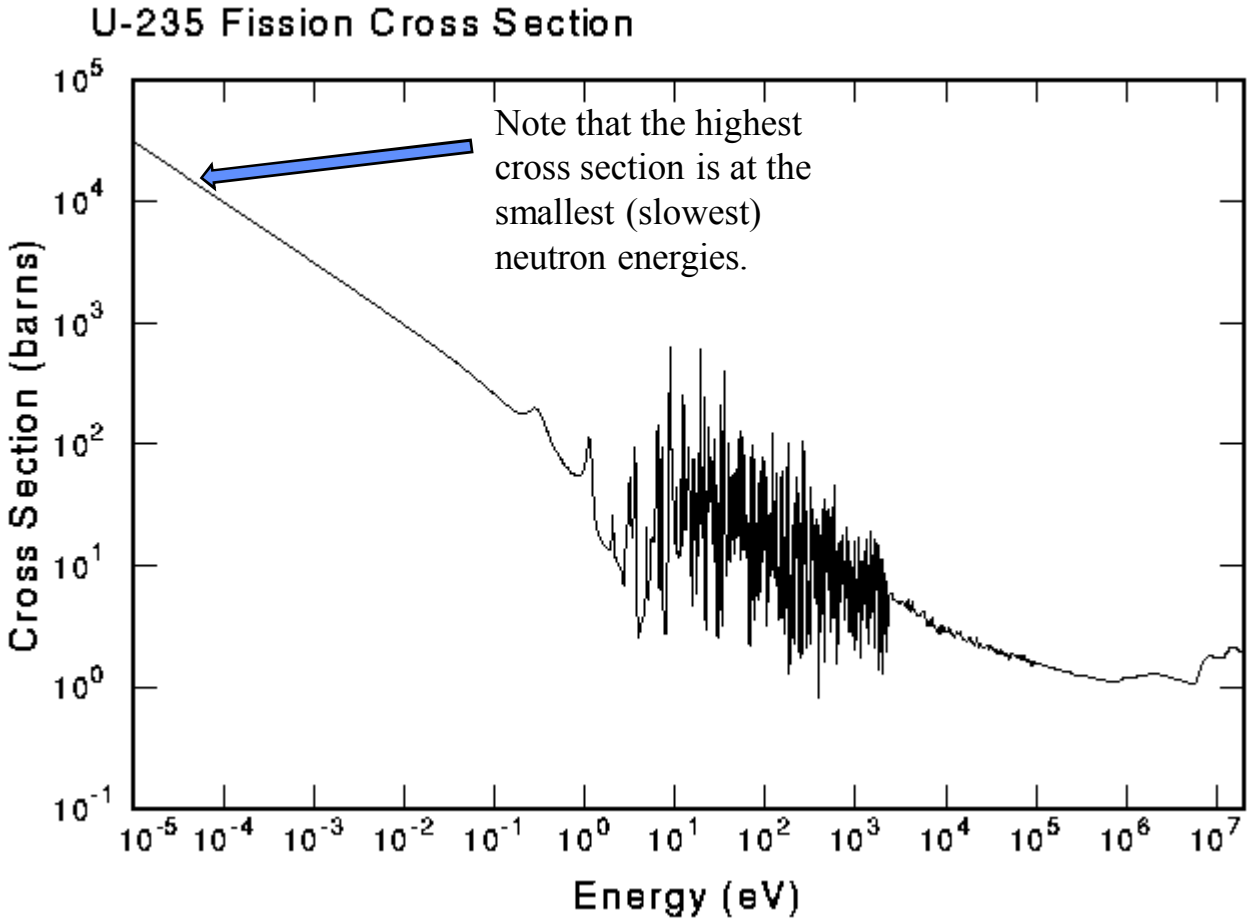
As with other interactions with matter, neutron fission depends on energy as well:



Source: http://t2.lanl.gov/tour/sch002.html

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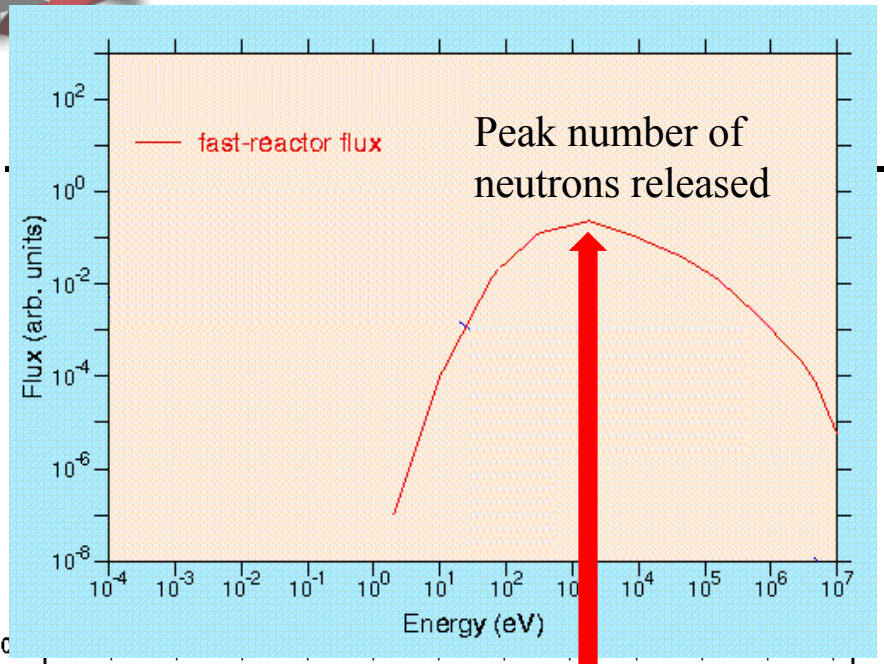
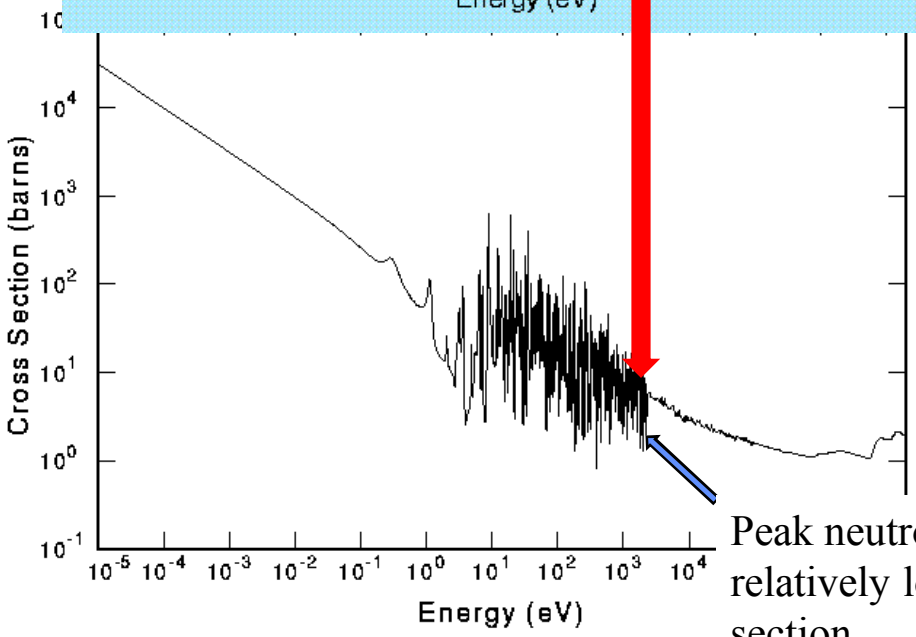
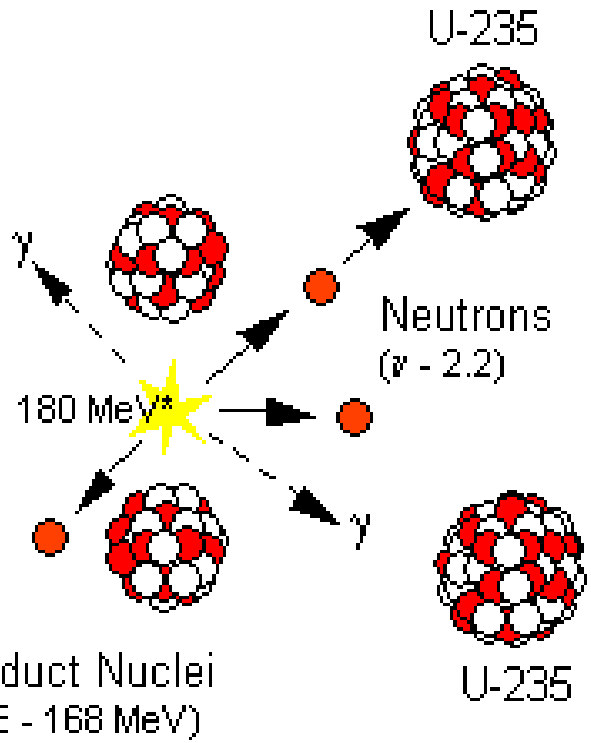
How do we use this process?



Source: http://t2.lanl.gov/tour/sch007.html



Source: http://t2.lanl.gov/tour/sch002.html



Source: http://science.nasa.gov/science-news/science-at-nasa/2002/03sept_spacepower/

Peak neutrons occur at a relatively low cross section

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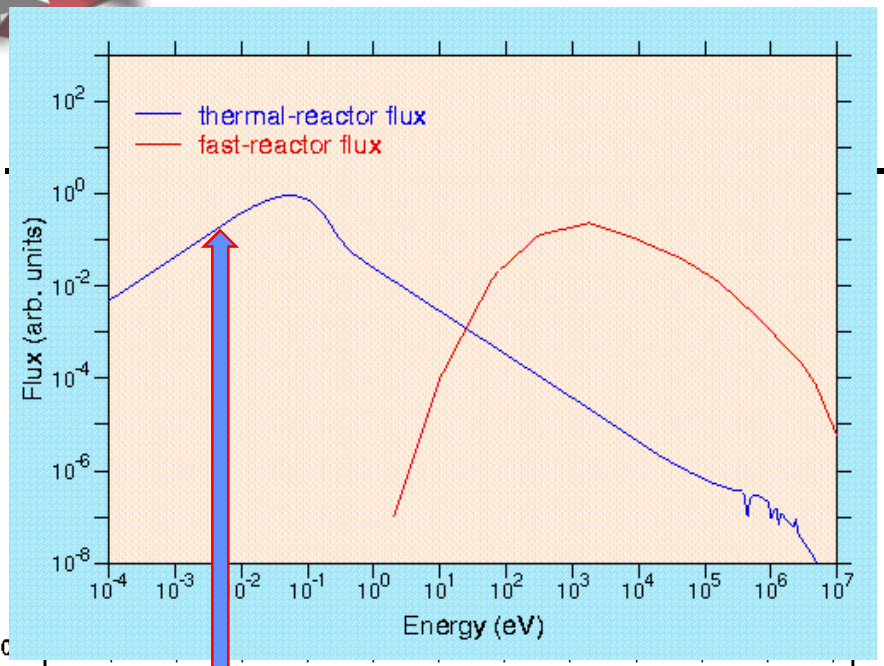
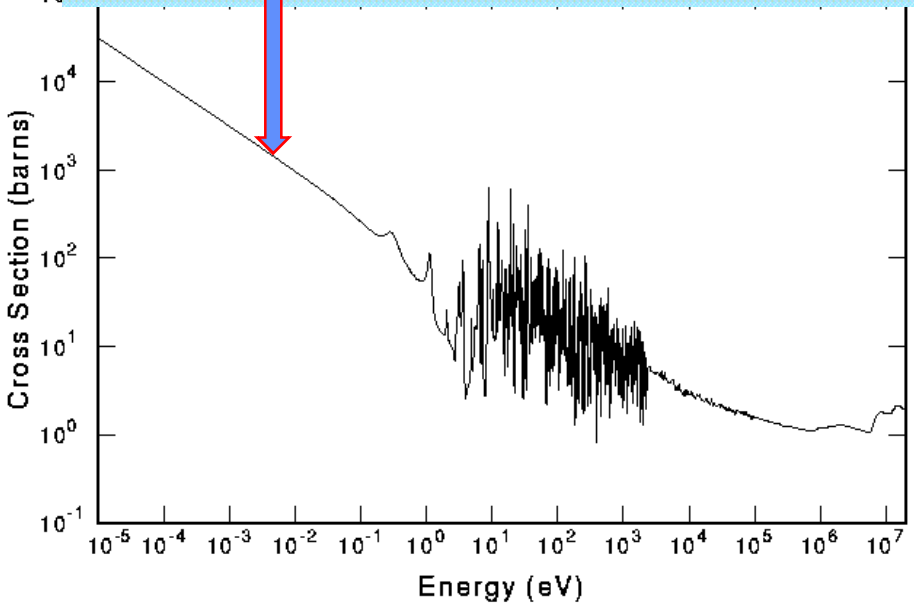
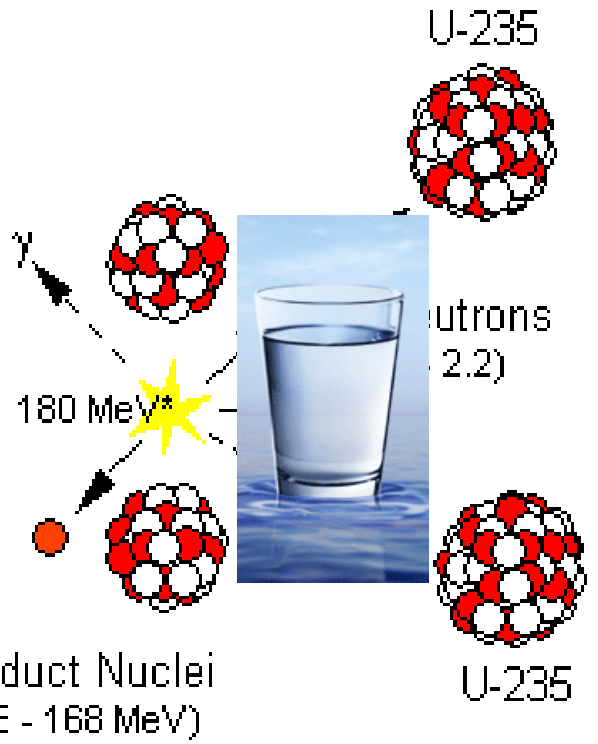


Source: http://t2.lanl.gov/tour/sch007.html



Source: http://t2.lanl.gov/tour/sch002.html



Source: http://science.nasa.gov/science-news/science-at-nasa/2002/03sept_spacepower/

Placing a "glass of water" between initial fission and the daughter fissions increases the odds of fission a hundred fold

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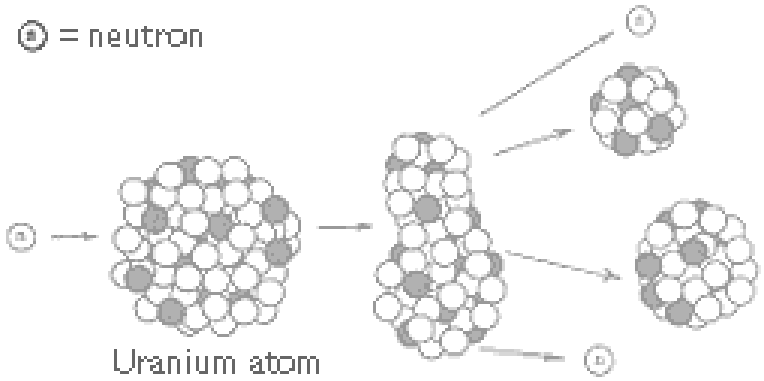
Why do we care about fission?

Because there is a lot of energy released!



Source: http://www.bnl.gov/bnlweb/history/BGRR.asp

These fission products carry off, on average, 181 MeV in kinetic energy for each fission. (Another 22 MeV is released in delayed decays).

It takes 7 *micro*-grams of Uranium to boil 1 cup of water.

Source: http://blogs.nasa.gov/cm/newui/blog/viewpostlist.jsp?blogname=ISS%20Science%20Blog

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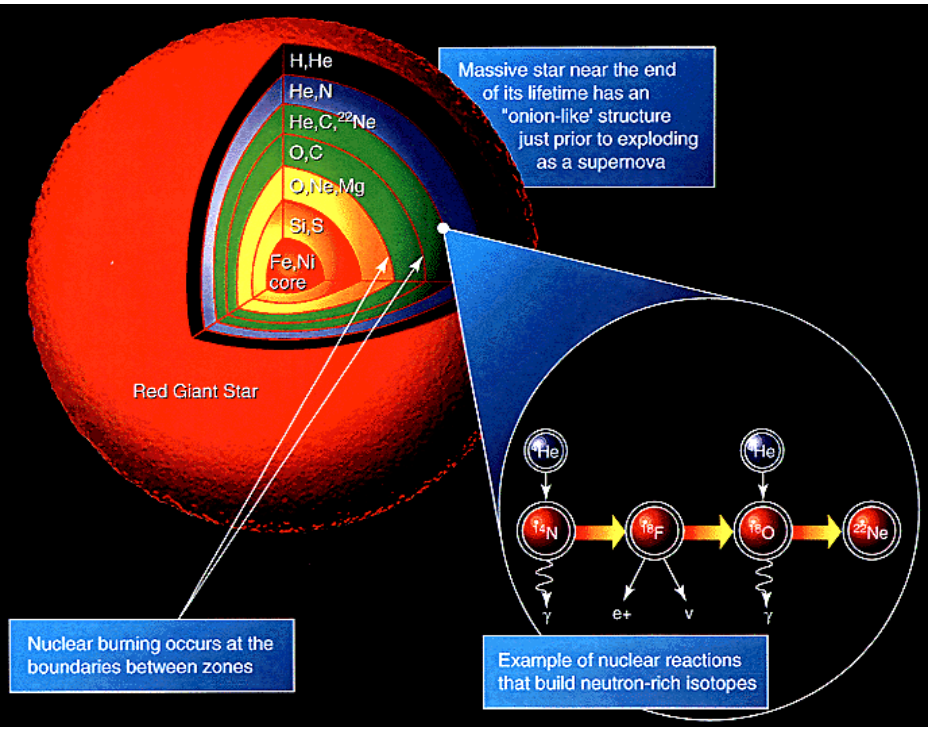
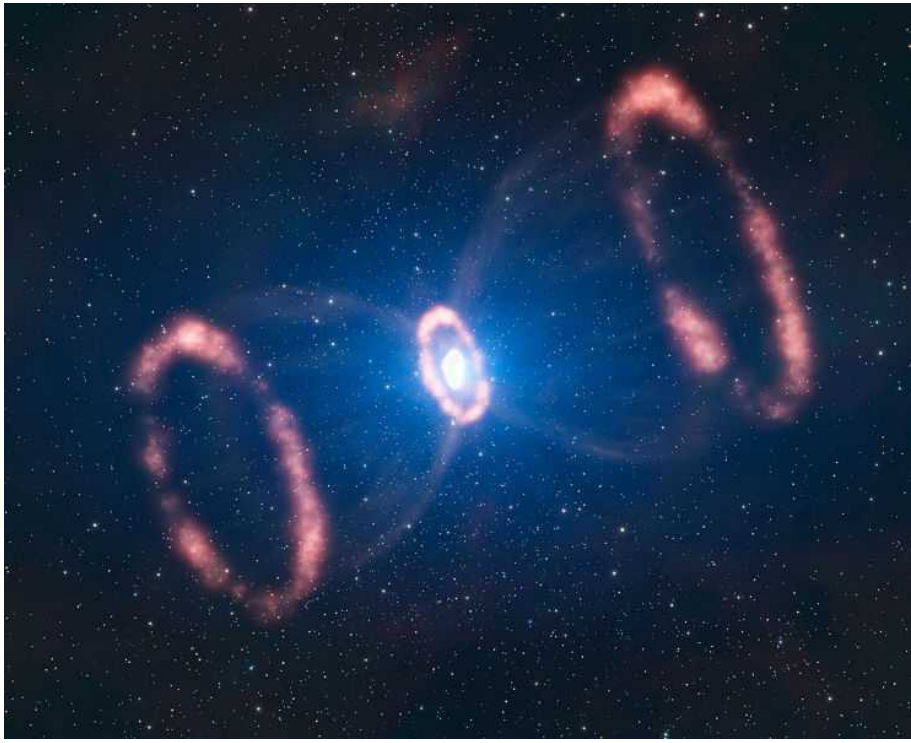
Where did this energy come from?

The energy stored in Uranium is a “fossil” fuel from stellar evolution:





Elements up to iron are “built up” in normal stars; each reaction **releases** energy.

Source: http://helios.gsfc.nasa.gov/onion.html

Energy is **stored** in the higher elements (like uranim) during stellar explosions.

Source: http://www.ornl.gov/info/library/ornlnews/images/eso1032a.jpg

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Questions?

Thank you for your attention!