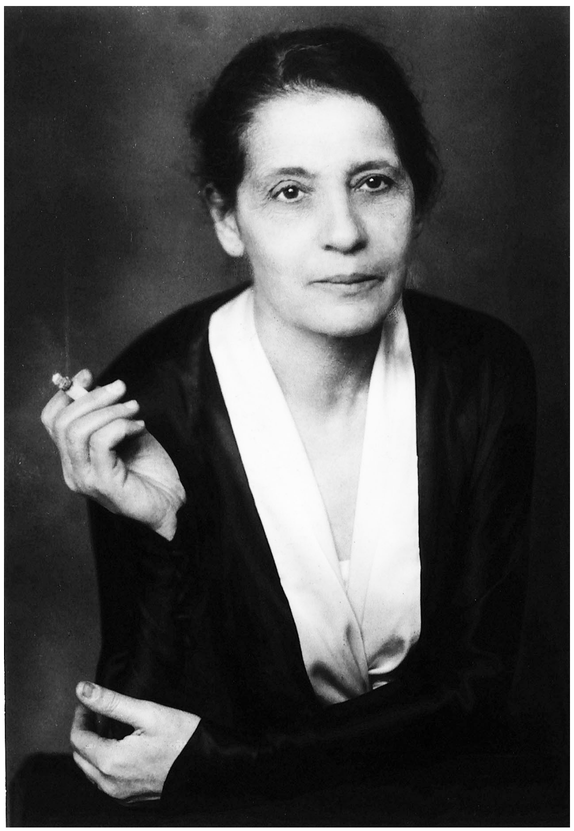
Lise Meitner

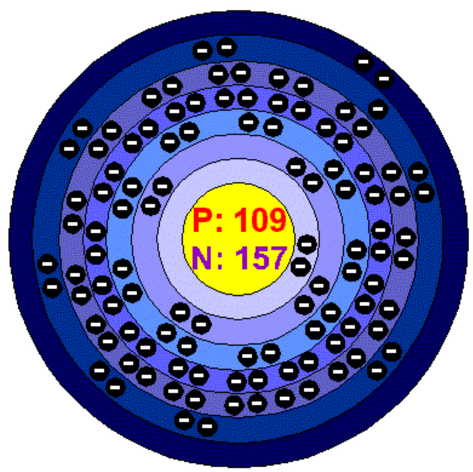


Discoverer of Nuclear Fission

Discovered the reason that no stable elements beyond uranium (in atomic number) existed naturally; the electrical repulsion of so many protons overcame the strong nuclear force.

Her theoretical work correctly predicted the elements created by the splitting (fission) of Uranium

Meitner was the first to realize that Einstein's famous equation: $E=mc^2$ explained the source of the tremendous releases of energy in nuclear fission, by the conversion of rest mass into kinetic energy, popularly described as the conversion of mass into energy.



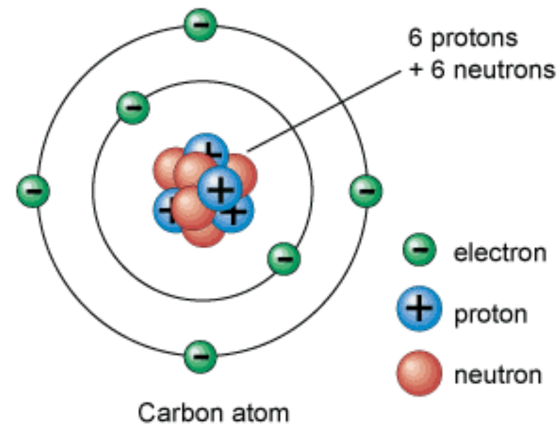
Meitnerium: element 109

30.1 Structure and Properties of the Nucleus

Nucleus is made of protons and neutrons

Proton has positive charge:

$$m_{\mathrm{p}} = 1.67262 \times 10^{-27}\,\mathrm{kg}$$



Neutron is electrically neutral:

$$m_{\mathrm{n}} = 1.67493 \times 10^{-27}\,\mathrm{kg}$$

Neutrons and protons are collectively called nucleons.

The different nuclei are referred to as nuclides.

Number of protons: atomic number, Z

Number of nucleons: atomic mass number, A

Neutron number: $N = A - Z$

30.1 Structure and Properties of the Nucleus

A and Z are sufficient to specify a nuclide. Nuclides are symbolized as follows:

$$^{A}_{Z}X$$

- Where X is the chemical symbol for the element.
- Nuclei with the same Z – so they are the same element – but different N are called isotopes.
- For many elements, several different isotopes exist in nature.
- **Natural abundance** is the percentage of a particular element that consists of a particular isotope in nature.

30.1 Size of the Nucleus

Because of wave-particle duality, the size of the nucleus is somewhat fuzzy. Measurements of high-energy electron scattering yield:

$$r \approx (1.2 \times 10^{-15}\,\text{m})\left(A^{\frac{1}{3}}\right) \qquad \textbf{(30-1)}$$

Masses of atoms are measured with reference to the carbon-12 atom, which is assigned a mass of exactly 12u. "u" is the unified atomic mass unit.

$$1\,\text{u} = 1.6605 \times 10^{-27}\,\text{kg} = 931.5\,\text{MeV}/c^2.$$

Isotopes of the same element differ by the number of ________ ?

A. Neutrons

B. Protons

C. Electrons

D. Protons and Electrons

E. Neutrons and Electrons

30.1 Structure and Properties of the Nucleus

TABLE 30–1
Rest Masses in Kilograms, Unified Atomic Mass Units, and MeV/c^2

Object	Mass (kg)	Mass (u)	Mass (MeV/c^2)
Electron	9.1094×10^{-31}	0.00054858	0.51100
Proton	1.67262×10^{-27}	1.007276	938.27
$^1_1$H atom	1.67353×10^{-27}	1.007825	938.78
Neutron	1.67493×10^{-27}	1.008665	939.57

Note the difference in Mass of Proton, Neutron, Hydrogen atom

The total mass of a stable nucleus is always less than the sum of the masses of its separate protons and neutrons.

Where has the missing mass gone?

A. Particles with a small mass, such as electrons are emitted when the nucleus forms

B. The lost mass was converted into energy according to $E=mc^2$

30.2 Binding Energy and Nuclear Forces

- The “missing mass” is also called the mass deficit or mass defect.

- It has become energy, such as radiation (usually gamma rays) or kinetic energy, released during the formation of the nucleus.

- Energy released is related to the lost mass by $E=mc^2$

- This difference between the total mass of the constituents and the mass of the nucleus is called the total **binding energy** of the nucleus.

Nuclear Binding Energy

Comparing the mass of Helium to its constituents: (Example 30.3 in Giancoli)

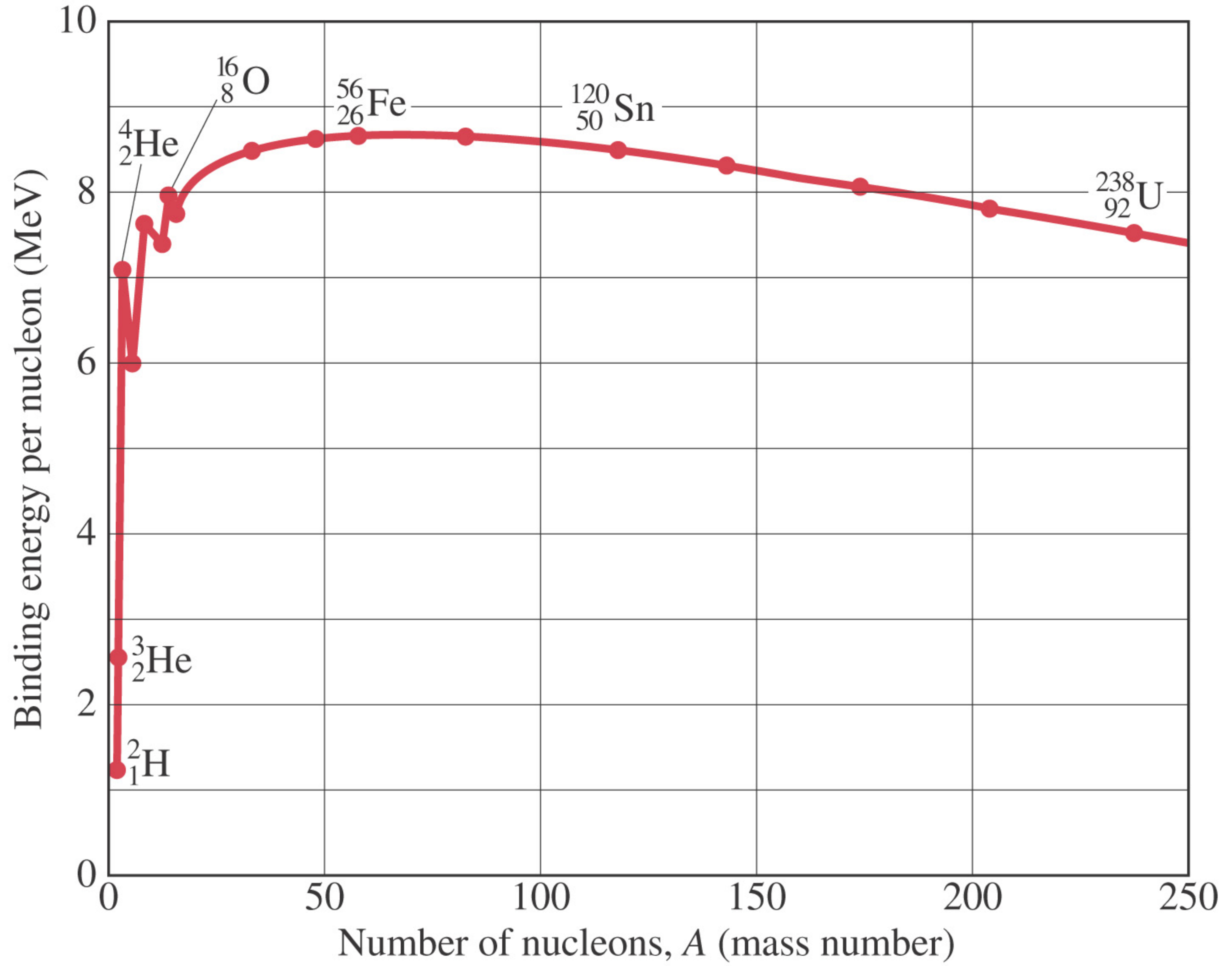
Review this type of calculation as a possible exam question!

There are a couple of these in HW 11.

Open the book on Document camera…….

30.2 Binding Energy and Nuclear Forces

To compare how tightly bound different nuclei are, we divide the binding energy by A to get the binding energy per nucleon.



ConcepTest 31.4 Nuclear Fission

How does the total mass of the fission fragments compare to the mass of the original nucleus in a fission reaction?

1) fission fragments have more mass
2) fission fragments have less mass
3) fission fragments have the same mass

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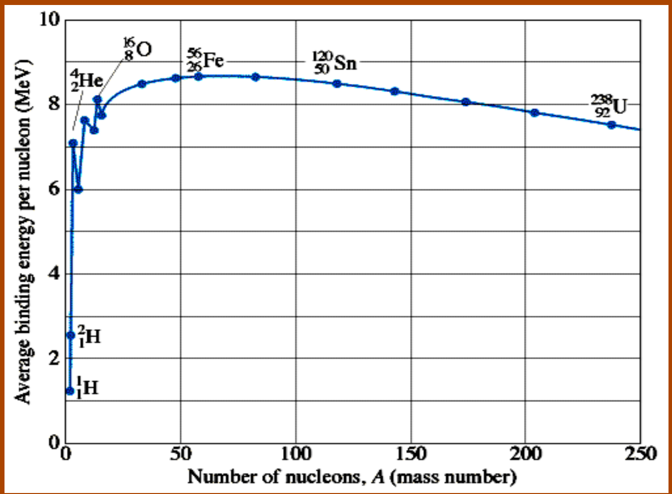
How does the total mass of the fission fragments compare to the mass of the original nucleus in a fission reaction?

1) fission fragments have more mass
2) fission fragments have less mass
3) fission fragments have the same mass

The **fission reaction releases energy**, so the total energy (or mass) of the fission fragments **must be less** than the energy (or mass) of the original nucleus.

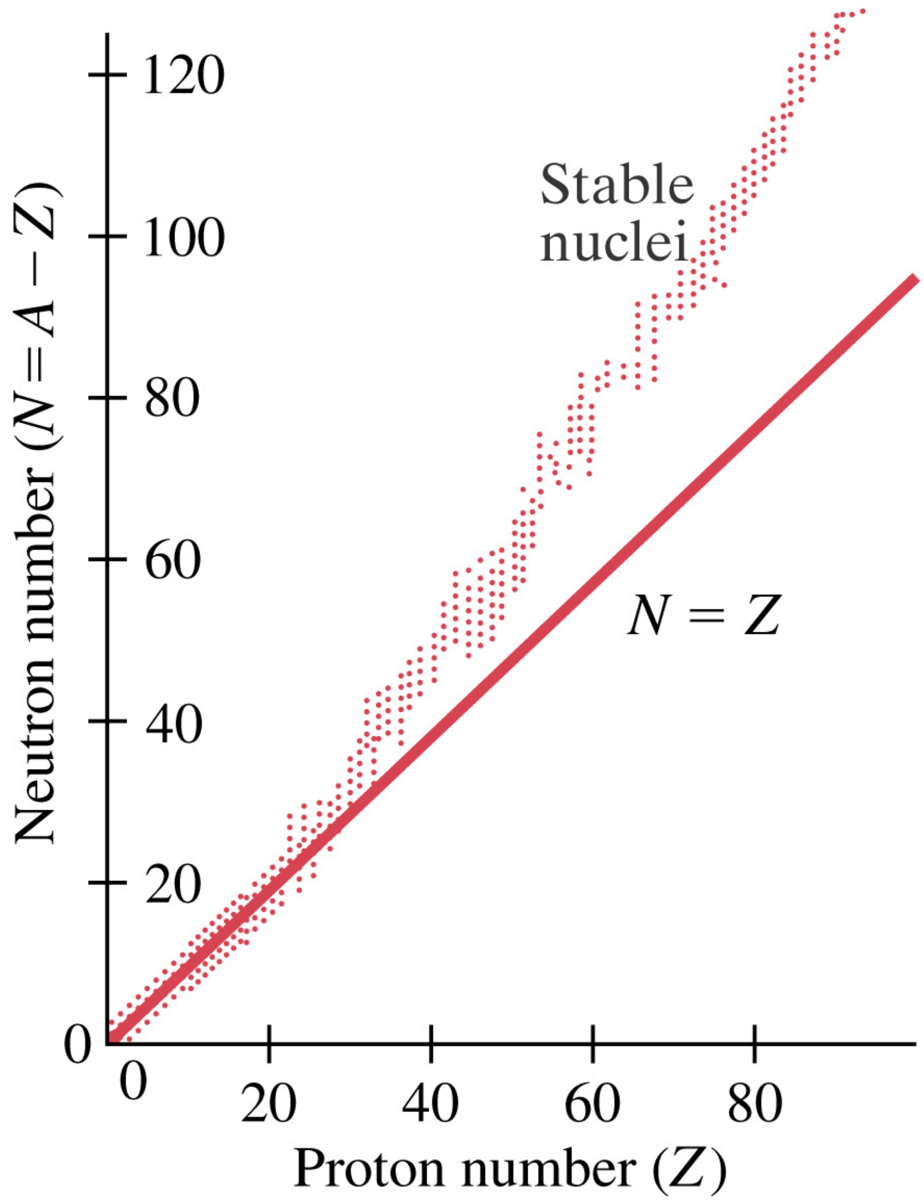
Follow-up: Where are the fission fragments located relative to the original nucleus on the curve of binding energy per nucleon?



30.2 Binding Energy and Nuclear Forces

The higher the binding energy per nucleon, the more stable the nucleus.

More massive nuclei require extra neutrons to overcome the Coulomb repulsion of the protons in order to be stable.



ConcepTest 31.5 Nuclear Fusion

How does the binding energy per nucleon of a fusion product compare to that of the pieces that combined to form it?

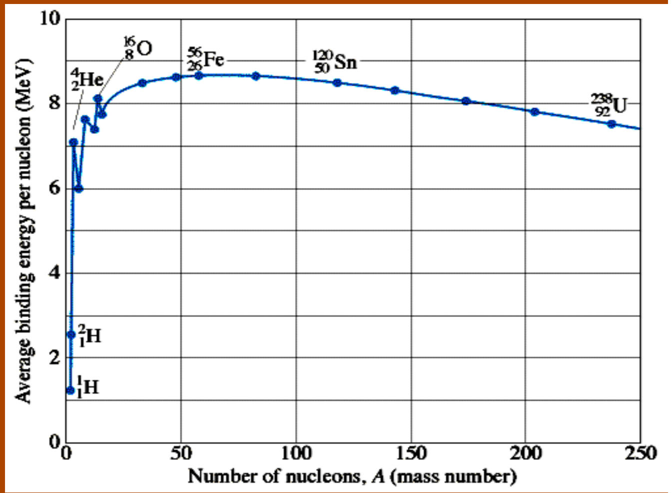
1) product has greater BE than the pieces
2) product has less BE than the pieces
3) product has the same BE than the pieces

ConcepTest 31.5 Nuclear Fusion

How does the binding energy per nucleon of a fusion product compare to that of the pieces that combined to form it?

1) product has greater BE than the pieces
2) product has less BE than the pieces
3) product has the same BE than the pieces

The fusion reaction releases energy, so the product is more tightly bound (more stable) than the separate pieces that combined to form it. This means that the binding energy per nucleon is greater for the fusion product.



Follow-up: Which weighs more: the fusion product or the pieces?

The Strong and Weak Nuclear Forces

The force that binds the nucleons together is called the strong nuclear force.

It is a very strong, but short-range, force.

It is essentially zero if the nucleons are more than about 10^{-15} m apart.

The Coulomb force is long-range.

This is why extra neutrons are needed for stability in high-Z nuclei.

Nuclei that are unstable decay. Many such decays are governed by another force called the weak nuclear force.

The Strong Nuclear Force

- Nuclei contain Positive charge

- Mutually repulsive force between like-charges (coulomb force)

- Yet Something is holding all those protons together.

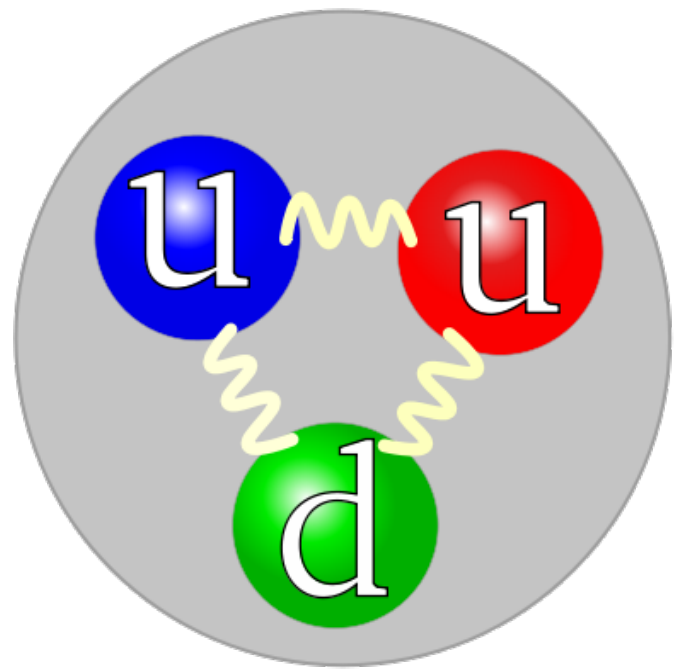
- Nuclei also contain Neutrons

- Stable isotopes of heavy elements all have more neutrons than protons

- The strong force arises from interactions between Quarks

- Each proton or neutron has 3 quarks

- Quark masses are miniscule (like electron)
- Nucleon mass arises from the KE of the quarks ($E=mc^2$)

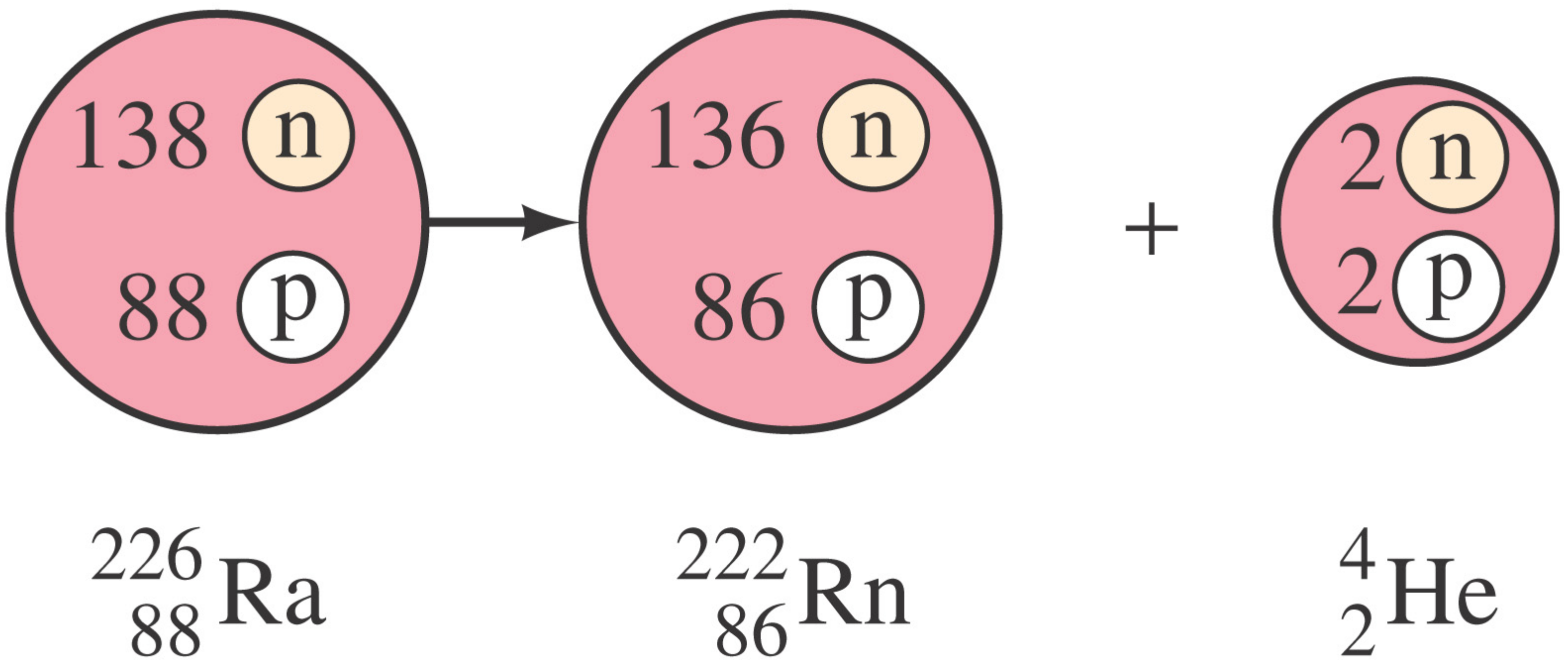


30.4 Alpha Decay

Example of alpha decay:

Radium-226 will alpha-decay to radon-22

$${}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$



30.4 Alpha Decay

In general, alpha decay can be written:

$$^{A}_{Z}\mathrm{N} \rightarrow {}^{A-4}_{Z-2}\mathrm{N}' + {}^{4}_{2}\mathrm{He}$$

Alpha decay occurs when the strong nuclear force cannot hold a large nucleus together. The mass of the parent nucleus is greater than the sum of the masses of the daughter nucleus and the alpha particle; this difference is called the disintegration energy.

The disintegration energy is given by $E=mc^2$

Alpha decay is so much more likely than other forms of nuclear disintegration because the alpha particle itself is quite stable.

30.4 Alpha Decay

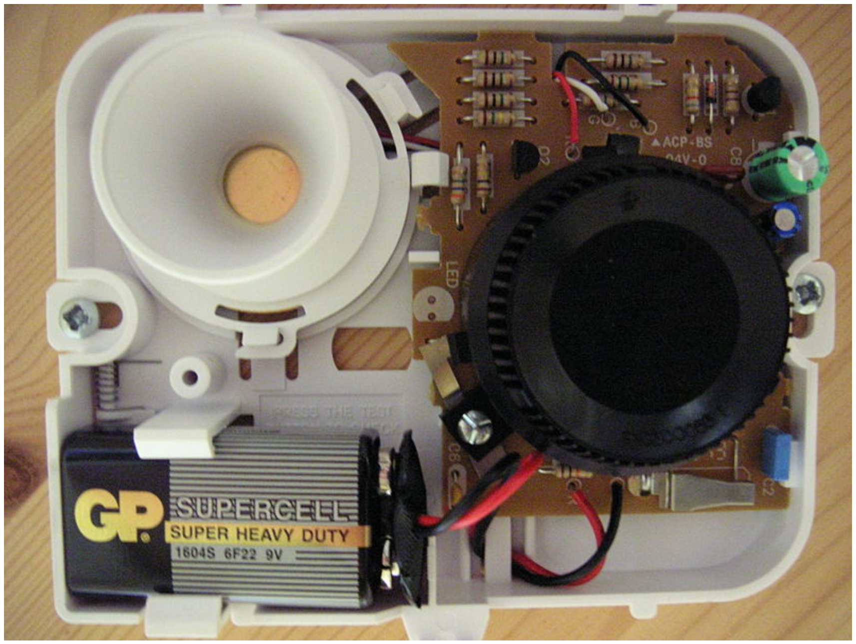
•Many smoke detectors use alpha radiation

• Americium 241

• Alpha particles ionize the air inside a small chamber, allowing an electric current to pass through it.

•Smoke absorbs the Alpha’s, stopping the current.

•A circuit then sounds the alarm



Why α decay ?

Unstable Nuclei generally decay by emitting an α-particle, leaving behind a smaller, more stable nucleus.

Interestingly, nuclei <u>never</u> decay by ejecting a shower of neutrons and protons.

Why?

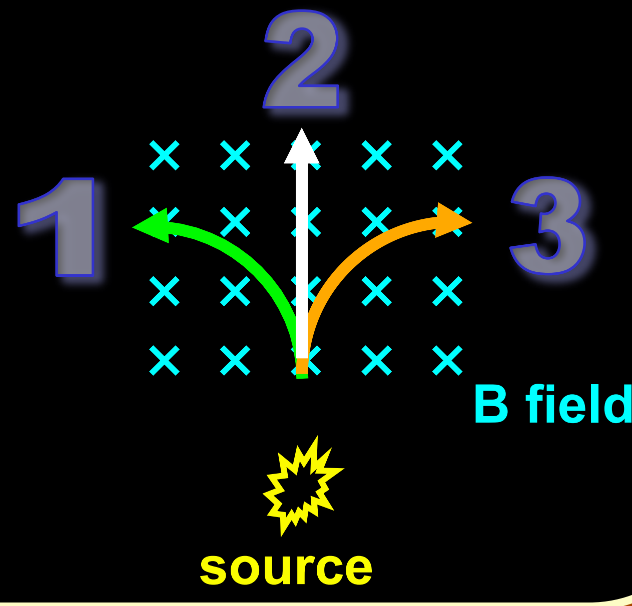
α's appear to be the building block of the nucleus, because their binding energy is so high.

Consider the decay of Radium: $^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + \alpha$

It is energetically impossible for nuclei to split into a shower of particles. The reaction would require an impossibly huge input of energy.

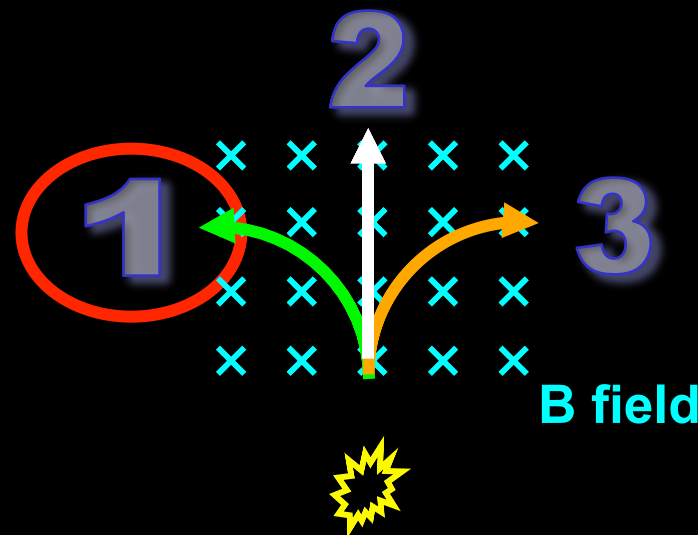
ConcepTest 30.4a Particle Emission I

A radioactive substance decays and the emitted particle passes through a uniform magnetic field pointing into the page as shown. In which direction are alpha particles deflected?

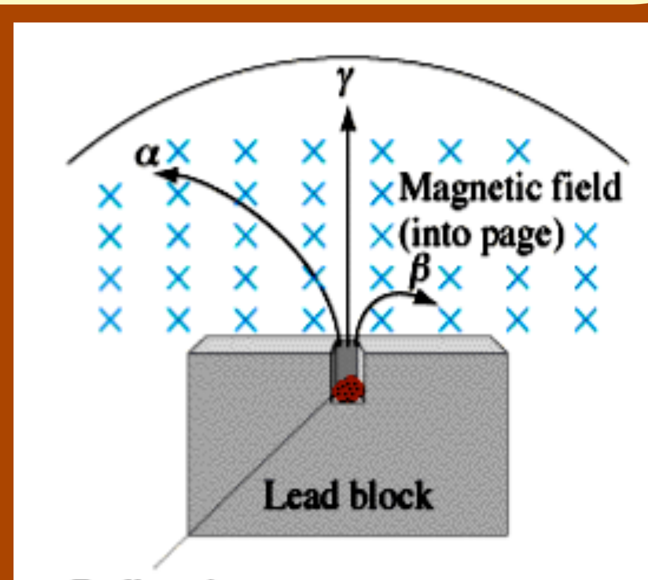


ConcepTest 30.4a Particle Emission I

A radioactive substance decays and the emitted particle passes through a uniform magnetic field pointing into the page as shown. **In which direction are alpha particles deflected?**



Using the right-hand rule, we find that **positively** charged particles (**alpha particles**) are deflected **to the left**.



30.5 Beta Decay

Beta decay occurs when a nucleus emits an electron (or positron). An example is the decay of carbon-14:

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + e^{-} + \text{a neutrino} $$

The nucleus still has 14 nucleons, but it has one more proton and one fewer neutron.

This decay is an example of an interaction that proceeds via the weak nuclear force.

30.5 Beta Decay

The electron in beta decay is not an orbital electron; it is created in the decay.

The fundamental process is a neutron decaying to a proton, electron, and neutrino:

$$n \rightarrow p + e^{-} + \text{a neutrino.}$$

The need for a particle such as the neutrino was discovered through analysis of energy and momentum conservation in beta decay – it could not be a two-particle decay.

30.5 Beta Decay

Neutrinos are notoriously difficult to detect, as they interact only weakly, and direct evidence for their existence was not available until more than 20 years had passed.

The symbol for the neutrino is the Greek letter nu (*v*); using this, we write the beta decay of carbon-14 as:

$$^{14}_{6}C \rightarrow \, ^{14}_{7}N + e^{-} + \bar{\nu}.$$

ConcepTest 31.3 Beta Decay Products

What element results when ^{14}C undergoes beta decay?

1) ^{15}C
2) ^{15}N
3) ^{14}C
4) ^{14}N
5) ^{15}O

$^{A}_{Z}X$

ConcepTest 31.3 Beta Decay Products

What element results when ^{14}C undergoes beta decay?

1) ^{15}C
2) ^{15}N
3) ^{14}C
4) ^{14}N
5) ^{15}O

The reaction is: $^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \text{neutrino}$

Essentially, a neutron turns into a proton (emitting a β^{-} particle), so the atomic number Z of the nucleus must increase by one unit, but without changing the atomic mass A.

$$^{A}_{Z}X$$

Anti-matter, reverse Beta decay, and what a neutron is NOT

Beta decay can occur where the nucleus emits a positron rather than an electron:

^{11}C -> $^{11}B + e^{+} + \upsilon$ + 0.96MeV (used in PET scan)

And a nucleus can capture one of its inner electrons (reverse beta decay):

$$^{7}_{4}\mathrm{Be} + e^{-} \rightarrow\ ^{7}_{3}\mathrm{Li} + \nu$$

Note a Neutron is NOT a Proton + Electron

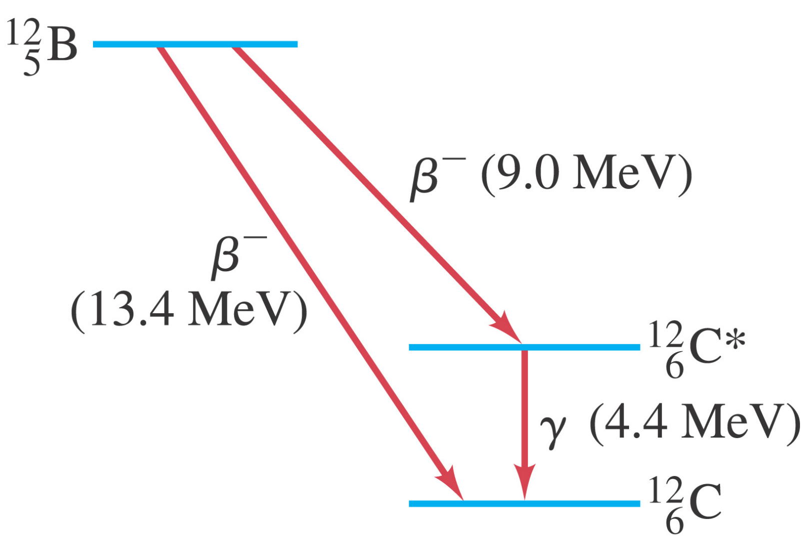
Mp + Me = $1.6726\times10^{-27} + 9.11\times10^{-31}$ kg = 1.67351×10^{-27} kg

Mn = 1.6749×10^{-27} kg (I.e. much heavier)

Rather the Proton and Neutron are composed of different Quarks

30.6 Gamma Decay

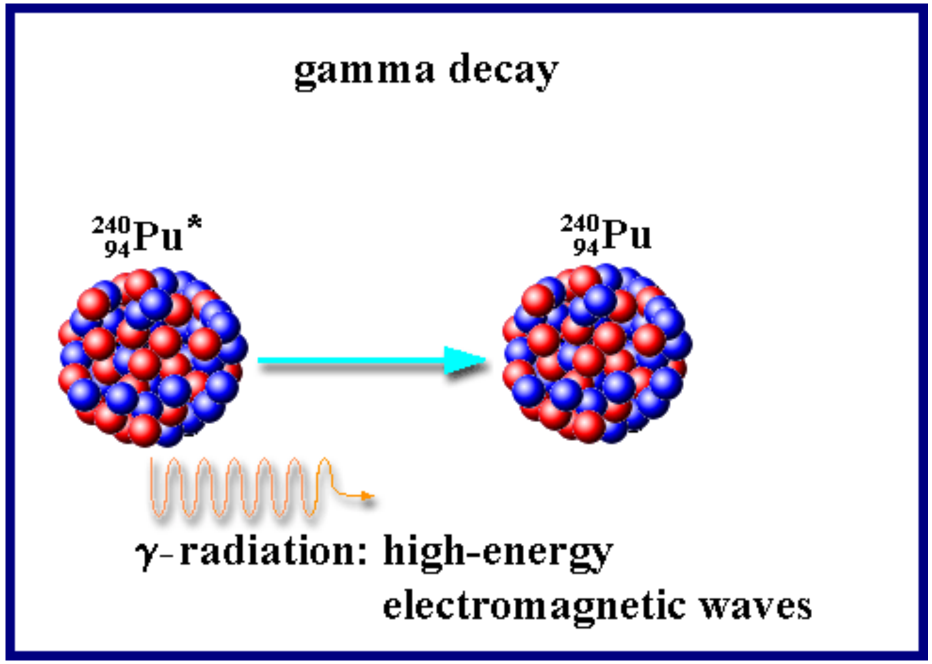
Gamma rays are very high-energy photons. They are emitted when a nucleus decays from an excited state to a lower state, just as photons are emitted by electrons returning to a lower state.



Many α and β decays are accompanied by γ emission as the "new" element settles into its ground state configuration.

Typically some of the binding energy is dissipated as γ, and some as KE

Gamma Decay



- The composition of the nucleus is unchanged!
- The protons & neutrons rearranged into a more stable configuration
- Additional binding energy is released as a single high energy photon

30.7 Conservation of Nucleon Number and Other Conservation Laws

TABLE 30–2 The Three Types of Radioactive Decay

α decay:	
	${}^{A}_{Z}\mathrm{N} \rightarrow {}^{A-4}_{Z-2}\mathrm{N}' + {}^{4}_{2}\mathrm{He}$
β decay:	
	${}^{A}_{Z}\mathrm{N} \rightarrow {}^{A}_{Z+1}\mathrm{N}' + e^{-} + \bar{\nu}$
	${}^{A}_{Z}\mathrm{N} \rightarrow {}^{A}_{Z-1}\mathrm{N}' + e^{+} + \nu$
	${}^{A}_{Z}\mathrm{N} + \mathrm{e}^{-} \rightarrow {}^{A}_{Z-1}\mathrm{N}' + \nu\ [\mathrm{EC}]^{\dagger}$
γ decay:	
	${}^{A}_{Z}\mathrm{N}^{*} \rightarrow {}^{A}_{Z}\mathrm{N} + \gamma$

† Electron capture.

* Indicates the excited state of a nucleus.

A new law that is evident by studying radioactive decay is that the total number of nucleons does not change.

Neutrons can change into protons and vice versa

But these particles are not destroyed