

Achievement Standard

Subject Reference	Physics 3.5		
Title	Demonstrate understanding of atoms, photons and nuclei		
Level	3	Credits	3
		Assessment	External
Subfield	Science		
Domain	Physics		

This achievement standard involves knowledge and understanding of phenomena, concepts, principles and/or relationships related to atoms, photons and nuclei, and the use of appropriate methods to solve related problems.

Achievement Criteria

Assessment will be limited to a selection from the following:

Phenomena, concepts and principles of atoms, photons and nuclei:

The Bohr model of the hydrogen atom; the photon; the quantisation of energy; discrete atomic energy levels; electron transition between energy levels; ionisation; atomic line spectra (infrared, visible and ultraviolet); the photoelectric effect; the electron volt; description of the particle/wave duality of light; nuclear binding energy and mass deficit; conservation of mass-energy for nuclear reactions.

Relationships:

$$E = hf$$

$$hf = \phi + E_K$$

$$E = \Delta mc^2$$

$$E_n = -\frac{hcR}{n^2}$$

$$\frac{1}{\lambda} = R\left(\frac{1}{S^2} - \frac{1}{L^2}\right)$$

Achievement	Achievement with Merit	Achievement with Excellence
<ul style="list-style-type: none"> Identify or describe aspects of phenomena, concepts or principles. Solve straightforward problems. 	<ul style="list-style-type: none"> Give descriptions or explanations in terms of phenomena, concepts, principles and/or relationships. Solve problems. 	<ul style="list-style-type: none"> Give explanations that show clear understanding in terms of phenomena, concepts, principles and/or relationships. Solve complex problems.

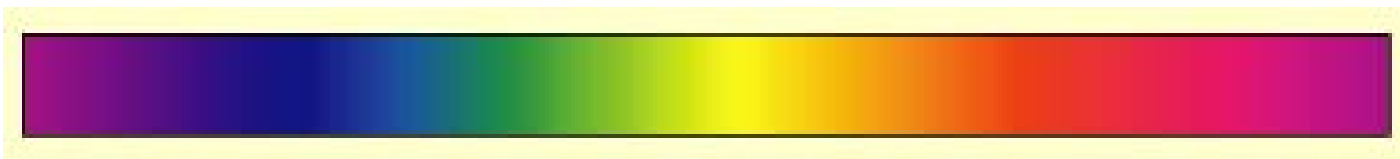
Atomic Spectra

The Problem with Rutherford's Model is that Light and other electromagnetic waves are emitted by accelerating charged particles. The electrons being accelerated in orbit about the nucleus of an atom release a certain amount of energy in the form of electromagnetic radiation.

If an electron gives off energy, then its potential energy, and the radius of its orbit about the nucleus, should decrease. Any radiating electron would give off all its potential energy in a fraction of a second, and the electron would death spiral into the nucleus. The fact that most of the atoms in the universe have not yet collapsed suggests a fundamental flaw in Rutherford's model of electrons orbiting nuclei.

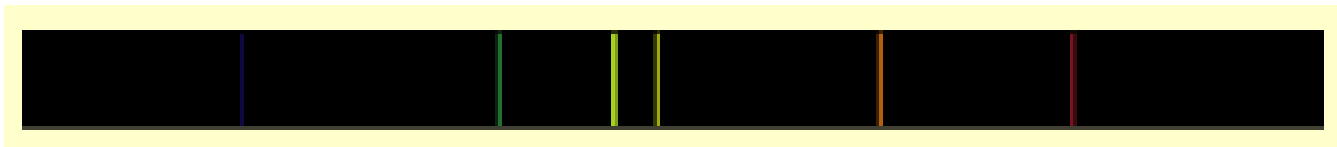
Another puzzling phenomenon unexplained before 1913, is the spectral lines we see when looking through a **spectroscope**. A spectroscope breaks up the visible light emitted from a light source into a spectrum, so that we can see exactly which frequencies of light are being emitted.

Emission Spectra of liquids and solids:



Liquids and Solids produce continuous spectra because electrons are shared between many atoms, giving a huge range of possible frequencies. The hotter a solid or liquid an object is, the higher the limit of the continuous spectra it emits. E.g. “cool” objects emit the spectra up to red light (that is radio waves, microwaves, infra-red and red light). A “hotter” object emits all of these and orange, yellow, green, blue, indigo and violet so appears white hot. An “even hotter” object emits all of these and ultraviolet, x rays and gamma rays. Please note – the ultraviolet catastrophe means that these frequencies are not emitted in equal amounts.

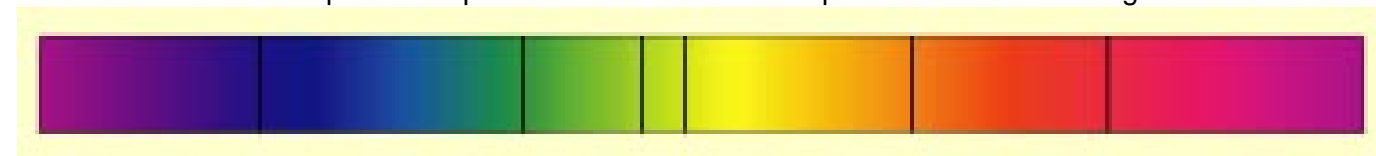
Emission Spectra of gases:



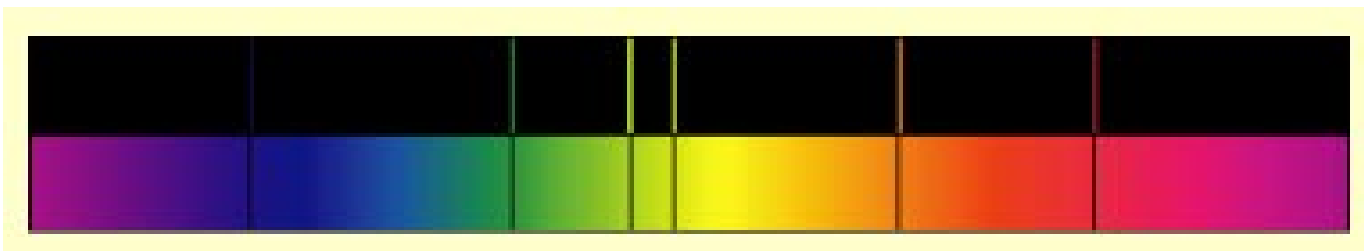
Excited gases emit line spectra due to the excitation of individual electrons (which don't interact with each other).

Absorption Spectra of gases:

Gases can also absorb specific frequencies when continuous spectrum is shone through them.



When photons of light pass through a gas, the photons with the same energy as the energy gaps in the atoms can be absorbed. This causes an absorption spectra.



Because the energy levels are the same, the lines in the emission spectra of an element are in the same position as the lines in the absorption spectra of the same element.

The Rydberg Equation

Johannes Robert Rydberg was a Swedish physicist who devised a formula, in 1888, which can be used to predict the wavelengths of photons emitted by changes in the energy level of an electron in a hydrogen atom.

$$\frac{1}{\lambda} = R \left(\frac{1}{S^2} - \frac{1}{L^2} \right)$$

He devised a series using other scientists to help him:

Series Name	Part of spectrum	S
Lyman	Ultraviolet	1
Balmer	Visible	2
Paschen	Infrared	3

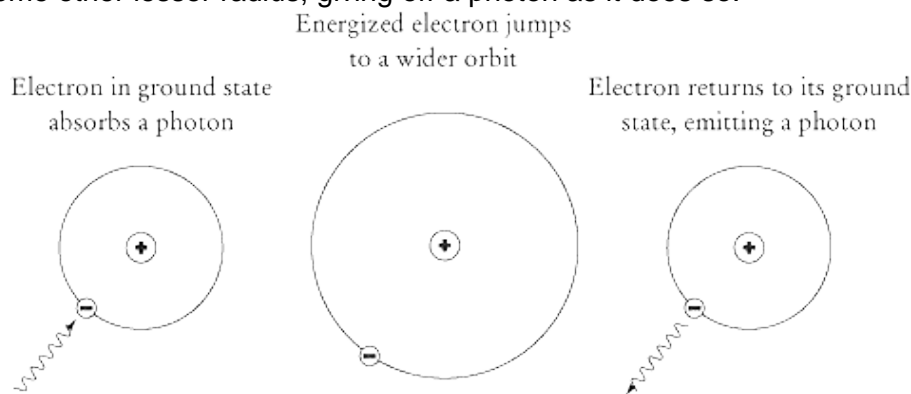
(There are other series not mentioned here)

The Bohr Model of the Atom

Niels Bohr sought to refine both Rutherford and Rydberg theories by suggesting that energy travels only in distinct quanta. He developed an atomic theory that accounts for why electrons do not collapse into nuclei and why there are only particular frequencies for visible light.

Bohr's model was based on the hydrogen atom, since, with just one proton and one electron, it makes for the simplest model.

According to Bohr, the electron of a hydrogen atom can only orbit the proton at certain distinct radii. The closest orbital radius is called the electron's **ground state**. When an electron absorbs a certain amount of energy, it will jump to a greater orbital radius. After a while, it will drop spontaneously back down to its ground state, or some other lesser radius, giving off a photon as it does so.



Because the electron can only make certain jumps in its energy level, it can only emit photons of certain frequencies.

Electronvolts

Because the amounts of energy involved at the atomic level are so small, it's difficult to talk in terms of joules. Instead, we use the **electronvolt (eV)**, where 1 eV is the amount of energy involved in accelerating an electron through a potential difference of one volt.

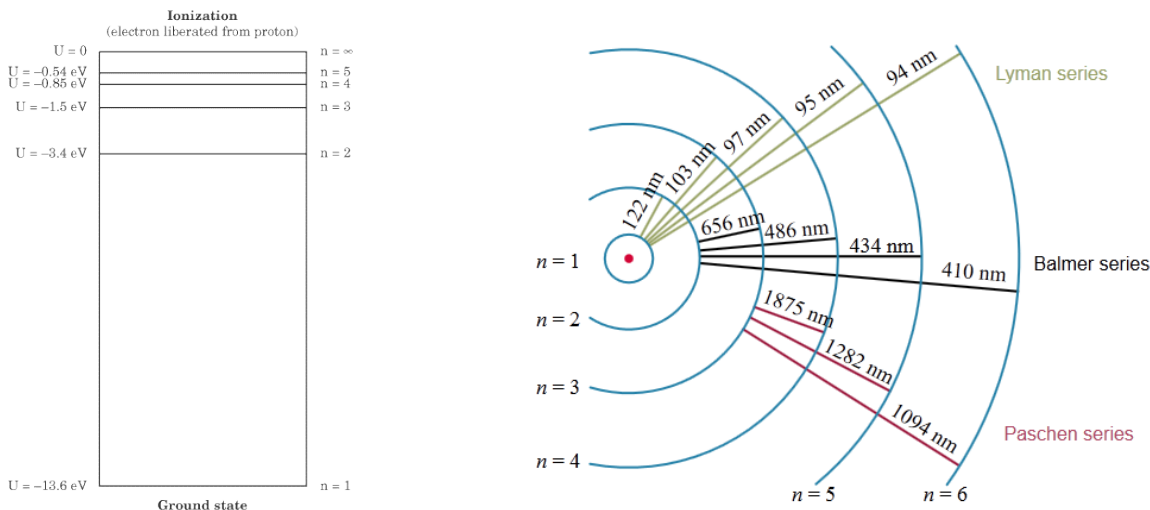
Mathematically, $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ and $1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}$

Electron Potential Energy

The energy of an electron in a hydrogen atom at its ground state (where $n = 1$) is -13.6 eV. This is a negative number because we're dealing with *potential* energy: this is the amount of energy it would take to free the electron from its orbit. It is calculated by the equation:

$$E_n = -\frac{hcR}{n^2}$$

When the electron jumps from its ground state to a higher energy level, it jumps by multiples of n .



Frequency and Wavelength of Emitted Photons

An excited hydrogen atom emits photons when the electron jumps to a lower energy state. For instance, a photon at $n = 2$ returning to the ground state of $n = 1$ will emit a photon with energy, $E = (-3.4 \text{ eV}) - (-13.6 \text{ eV}) = 10.2 \text{ eV}$. Using Planck's formula, which relates energy and frequency, we can determine the frequency of the emitted photon:

$$f = \frac{E}{h} = \frac{10.2 \text{ eV}}{4.14 \times 10^{-15} \text{ eV} \cdot \text{s}} = 2.46 \times 10^{15} \text{ Hz}$$

Knowing the frequency means we can also determine the wavelength:

$$\lambda = \frac{c}{f} = 1.22 \times 10^{-7} \text{ m}$$

This photon is of slightly higher frequency than the spectrum of visible light: we won't see it as it is ultraviolet radiation. Whenever an electron in a hydrogen atom returns from an excited energy state to its ground state it lets off an ultraviolet photon.

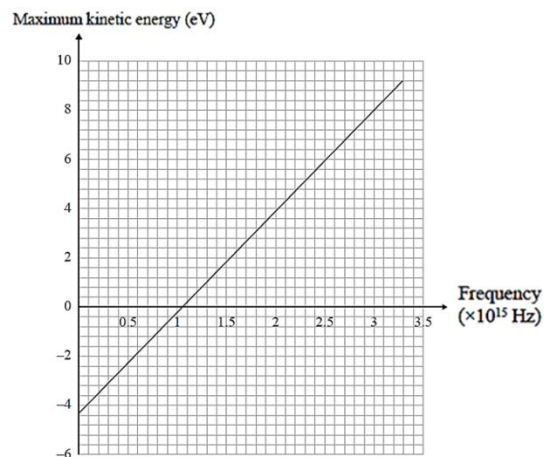
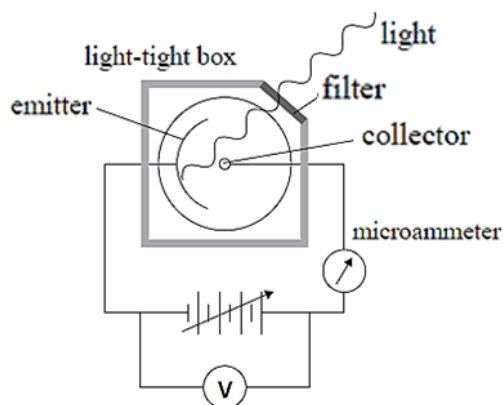
Quantum Physics

It became clear to Physicists that things at the atomic level are totally unlike anything we find on the level of everyday objects. Physicists had to develop a whole new set of mechanical equations, called "quantum mechanics," to explain the movement of elementary particles. The physics of this "quantum" world demands that we upset many basic assumptions—that light travels in waves, that observation has no effect on experiments, etc.—but the results, from digital cameras to microprocessors, are undeniable. Quantum physics is strange, but it works.

The Photoelectric Effect

Electromagnetic radiation transmits energy, so when visible light, ultraviolet light, X rays, or any other form of electromagnetic radiation shines on a piece of metal, the surface of that metal absorbs some of the radiated energy. Some of the electrons in the atoms at the surface of the metal may absorb enough energy to liberate them from their orbits, and they will fly off. These electrons are called photoelectrons, and this phenomenon, first noticed in 1887 by Hertz, is called the photoelectric effect.

This can be investigated using a photoelectric apparatus:



Photoelectric emission is a process during which electrons are ejected from a metal surface by electromagnetic radiation, (e.g. ultraviolet).

- If a clean, **positively charged** zinc plate is exposed to intense white light it will **not** discharge.
- If a clean, **negatively charged** zinc plate is exposed to intense white light it will **not** discharge. No matter how intense the light the plate will **not** discharge, or whether the plate is positively or negatively charged, the plate will **not** discharge.
- If a clean, **positively charged** zinc plate is exposed to an ultraviolet source it will **not** discharge. However, if a clean, **negatively charged** zinc plate is exposed to an ultraviolet source it **will** discharge.
- Only if the plate is negatively charged and the source has a high enough frequency will it discharge. The intensity of the source only affects how long it takes the plate to discharge.

The above points lead to the following conclusions:

- the plate is not being discharged by ionization (the positive one would also discharge)
- the total amount of energy from the source does not determine whether the plate discharges or not

This leads to the theory that the beams of light and ultraviolet are made up of individual units called **photons**.

The kinetic energy of the electrons can be determined by supplying a stopping potential to attract the released electrons back to the metal so $E_k = eV_s$ (but note this is $e \times V_s$ not eV). If a graph of kinetic energy against frequency is drawn then the x-intercept is the threshold frequency, f_0 , the y-intercept is (-) the work function and the gradient is h . A different metal target would produce a very similar graph with a parallel line to that shown since the gradient is a constant.

Einstein's contribution

Albert Einstein accounted for these discrepancies between the wave theory and observed results by suggesting that electromagnetic radiation exhibits a number of particle properties.

Rather than assuming that light travels as a continuous wave, Einstein drew on Planck's work, suggesting that light travels in small bundles, called **photons**, and that each photon has a certain amount of energy associated with it, called a **quantum**. Planck's formula determines the amount of energy in a given quantum:

$$E = hf$$

where h is a very small number, 6.63×10^{-34} Js, called **Planck's constant**, and f is the frequency of the beam of light.

Work Function and Threshold Frequency

An electron needs to absorb a certain amount of energy before it can fly off the sheet of metal. That this energy arrives all at once, as a photon, rather than gradually, as a wave, explains why there is no time lapse between the shining of the light and the liberation of electrons.

Every material has a given **work function**, ϕ , which tells us how much energy an electron must absorb to be liberated. For a beam of light to liberate electrons, the photons in the beam of light must have a higher energy than the work function of the material. Because the energy of a photon depends on its frequency, low-frequency light will not be able to liberate electrons. A liberated photoelectron flies off the surface of the metal with a kinetic energy given by using the equation:

$$hf = \phi + E_K$$

Wave-Particle Duality

The photoelectric effect shows that electromagnetic waves exhibit particle properties when they are absorbed or emitted as photons.

Young's double-slit experiment, where light forms areas of constructive and destructive interference suggests that electromagnetic radiation travels in waves. However, the wave theory of electromagnetic radiation makes a number of predictions about the photoelectric effect that prove to be false:

	Predictions of the wave theory	Observed result
Intensity	The intensity of the beam of light should determine the kinetic energy of the electrons that fly off the surface of the metal. The greater the intensity of light, the greater the energy of the electrons.	The intensity of the beam of light has no effect on the kinetic energy of the electrons. The greater the intensity, the greater the number of electrons that fly off, but even a very intense low-frequency beam liberates no electrons.
Frequency	The frequency of the beam of light should have no effect on the number or energy of the electrons that are liberated.	Frequency is key: the kinetic energy of the liberated electrons is directly proportional to the frequency of the light beam, and no electrons are liberated if the frequency is below a certain threshold.
Material	The material the light shines upon should not release more or fewer electrons depending on the frequency of the light.	Each material has a certain threshold frequency : light with a lower frequency will release no electrons.

Nuclear Physics

Atomic Number, Neutron Number, and Mass Number

An element is defined by the number of protons in the nucleus. For instance, a nucleus with just one proton is hydrogen, a nucleus with two protons is helium, and a nucleus with 92 protons is uranium, the heaviest naturally occurring element. The number of protons in an atomic nucleus determines the **atomic number**, Z . In an electrically neutral atom of atomic number Z , there will be Z protons and Z electrons.

The number of neutrons in a nucleus determines the **neutron number**, N . Different nuclei of the same atomic number—that is, atoms of the same element—may have different numbers of neutrons. For instance, the nuclei of most carbon atoms have six protons and six neutrons, but some have six protons and eight neutrons. Atoms of the same element but with different numbers of neutrons are called **isotopes**. Electrons weigh very little compared to protons and neutrons, which have almost identical masses. The sum of the atomic number and the neutron number, $Z + N$, gives us the **mass number**, A .

Atomic Masses

Because objects on the atomic level are so tiny, it can be a bit unwieldy to talk about their mass in terms of kilograms without a calculator. Sometimes the **atomic mass unit** (amu, or sometimes just u), which is defined as one-twelfth of the mass of a carbon-12 atom, is used. $1 \text{ amu} = 1.605 \times 10^{-27} \text{ kg}$. We usually express the mass of the elementary particles in kilograms (but sometimes atomic mass units):

Particle	Mass (kg)	Mass (amu)
Proton	1.6725×10^{-27}	1.0073
Neutron	1.6747×10^{-27}	1.0086
Electron	9.11×10^{-31}	5.4863×10^{-4}

The mass of electrons is pretty much negligible when calculating the mass of an atom.

Einstein's Famous Equation

$$E = \Delta mc^2$$

This equation shows us that mass and energy can be converted into one another.

Chemical reactions result in very small amounts of mass being converted to energy, the fission of large nuclei has a much greater conversion and the fusion of light particles even larger amounts of mass are converted to energy.

Reaction	Fuel	Mass converted	Energy created	Equivalent Energy
Chemical	1 kg of coal	$4 \times 10^{-10} \text{ kg}$	$3.6 \times 10^7 \text{ J}$	0.00000036 TJ
Fission	1 kg of Uranium 235	$1 \times 10^{-4} \text{ kg}$	$9 \times 10^{12} \text{ J}$	0.09 TJ
Fusion	1 kg of Hydrogen	$6.4 \times 10^{-3} \text{ kg}$	$5.76 \times 10^{14} \text{ J}$	576 TJ

Nuclear fission was used in the original atomic bomb, and is the kind of reaction harnessed in nuclear power plants. To produce nuclear fission, neutrons are made to bombard the nuclei of heavy elements—often uranium—and thus to split the heavy nucleus in two, releasing energy in the process. In the fission reactions used in power plants and atomic bombs, two or more neutrons are freed from the disintegrating nucleus. The free neutrons then collide with other atomic nuclei, starting what is called a **chain reaction**.

Nuclear fusion is ultimately the source of all energy on Earth: fusion reactions within the sun are the source of all the heat that reaches the Earth. These reactions fuse two or more light elements—often hydrogen—together to form a heavier element. As with fission, this fusion releases a tremendous amount of energy. Fusion reactions can only occur under intense heat. Humans have only been able to produce a fusion reaction in the hydrogen bomb, or H-bomb, by first detonating an atomic bomb whose fission produced heat sufficient to trigger the fusion reaction. Scientists hope one day to produce a controllable fusion reaction, since the abundance of hydrogen found in this planet's water supply would make nuclear fusion a very cheap and non-polluting source of energy.

Binding Energy

Atomic nuclei undergo radioactive decay so as to go from a state of high energy to a state of low energy. Atomic nuclei in high-energy states may spontaneously rearrange themselves to arrive at more stable low-energy states.

Mass Defect

The mass of a proton is 1.0073 amu and the mass of a neutron is 1.0086 amu. Curiously, though, the mass of an alpha particle, which consists of two protons and two neutrons, is not $2(1.0073) + 2(1.0086) = 4.0318$ amu, as one might expect, but rather 4.0015 amu. In general, neutrons and protons that are bound in a nucleus weigh less than the sum of their masses.

We call this difference in mass the **mass defect**, Δm , which in the case of the alpha particle is $4.0318 - 4.0015 = 0.0202$ amu.

A small amount of the matter pulled into the nucleus of an atom is converted into a tremendous amount of energy, the **binding energy**, which holds the nucleus together by throwing the energy away.

In order to break the hold of the strong nuclear force, an amount of energy equal to or greater than the binding energy must be exerted on the nucleus. For instance, the binding energy of the alpha particle is:

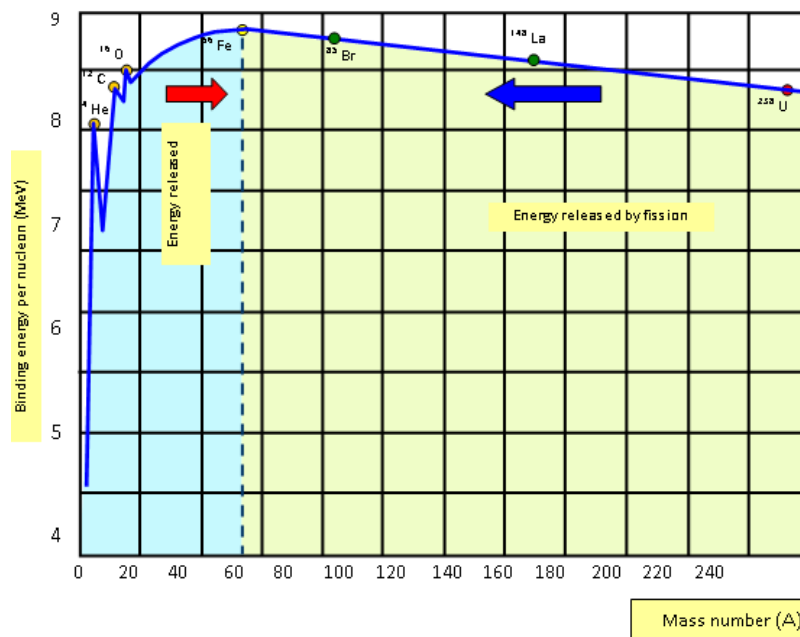
$$E = mc^2 = (3.354 \times 10^{-29} \text{ kg})(3.0 \times 10^8 \text{ m/s})^2 \\ = 3.0 \times 10^{-12} \text{ J}$$

Note that you have to convert the mass from atomic mass units to kilograms in order to get the value in joules.

Often we express binding energy in terms of millions of electronvolts, MeV, per nucleon. In this case, $3.0 \times 10^{-12} \text{ J} = 18.7 \text{ MeV}$.

Because there are four nucleons in the alpha particle, the binding energy per nucleon is $18.7/4 = 4.7 \text{ MeV/nucleon}$.

The binding energy per nucleon determines the stability of a nucleus and predicts whether energy will be given out during fission and fusion.



Iron is the most stable nuclei as it has the most binding energy per nucleon of any known element.