Quantum, Atomic and Nuclear Physics

Introductory Quantum, Atomic and Nuclear Physics Worksheets and Solutions

Workshop Tutorials for Introductory Physics

QI1: **Photons**

A. Review of Basic Ideas:

Use the following words to fill in the blanks:
radiation, reflect, discrete, wave, spectrum, electromagnetic, photons, energy, mass, frequency, same, kinetic, 3×10^8, mass, duality, waves

Light, photons and the electromagnetic spectrum

In the 18th and 19th centuries it was believed that light was a ________. Many experiments provided evidence for the wave model of light since they showed that light could refract, ________ and interfere. However, there were other experiments that couldn't be explained by the wave model of light. In 1900 Max Planck proposed that when light was absorbed or emitted it only came in ________ amounts. The particles of light in this model became known as ________.

These photons have no ________, and no charge, but they do have ________. In fact they can have a huge range of energies, and the light that we can see is only a very small part of the _______. Photons are made up of a combination of an electric field and magnetic field which travel around together, and so we call the entire range the _______ spectrum. Photons are the "particles" associated with electromagnetic ________.

One of the interesting things about photons of a given wavelength is that they always travel at the _______ speed in a given medium, e.g. air. Other particles, like electrons, travel faster or slower depending on how much ________ energy they have, but photons always travel at the speed of light, c = _______ms^{-1} in vacuum or in air.

Even though light behaves like particles, it still behaves like _______! When you do some experiments, the light behaves like particles, while during other experiments it behaves like waves. This is a great mystery. Other particles with _______ like electrons and protons, and even whole atoms, also behave like waves. This is called wave-particle ________, and is one of the biggest mysteries of modern physics. For any wave, there is a relationship between the speed, _______ and wavelength given by $c = \lambda \times f$. Usually you need to know two of these to find the third. However, with light, because the speed is always the same, knowing the frequency will tell you the wavelength and vice versa.

Discussion questions

Give an example of an experiment that shows the particle nature of light. Explain why the experiment shows light to be behaving like a particle.
Give an example of an experiment that shows the wave nature of light. Explain why the experiment shows light to be behaving like a wave.

B. Activity Questions:

1. Wave and particle nature of light 1- interference pattern

Observe the interference pattern produced by the laser light passing through the slits.
Does this experiment show the wave nature or particle nature of light? Explain your answer.

2. Wave and particle nature of light 2- emission spectra

Use the spectroscope to examine the spectral lines of the hydrogen lamp.
Which model of light does this experiment support? Explain your answer.

C. Qualitative Questions:

1. Light is commonly described in terms of brightness and colour. Copy and complete the following table by filling in the quantities in the wave and particle models of light which relate to colour and brightness.

	Wave Model	Particle Model
Brightness		
Colour		

2. Humans only see a small part of the electromagnetic spectrum, the visible region. Some insects, such as bees, can also see in ultraviolet and infrared. Humans can only see from blue (around 400 nm wavelength) to red (around 700 nm).

a. Which have the higher energy, red or blue photons?
b. Which have the higher frequency, radiowaves or X-rays?
c. Why are X-rays used to see inside people, rather than visible light?

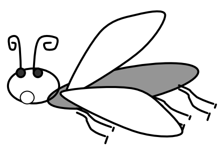
A major environmental issue at the moment is the release of gases which destroy the ozone layer in the upper atmosphere. A hole regularly forms over Antarctica and the layer is thinning elsewhere.

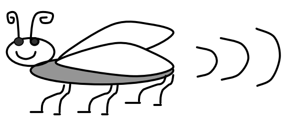
d. Why is the depletion of the ozone layer a concern?
e. Why is ultraviolet light much more dangerous than infrared of the same intensity?

D. Quantitative Question:

An enzyme called luciferase is used by many animals that produce light, for example fireflies. Fireflies produce a yellow light (with wavelength ~500 nm), while many marine organisms produce a green or blue light.

a. What is the photon energy of the light produced by fireflies? Is it greater or less than that produced by jellyfish?
b. If 10 fireflies are radiating light at a combined power of 0.1mW, how many photons per second is each firefly producing?
c. How is the light produced by 10 fireflies different to the light produced by 1 firefly?
d. How would the light be different if a firefly produced higher energy photons?





Workshop Tutorials for Introductory Physics

Solutions to QI1: **Photons**

A. Review of Basic Ideas:

Light, photons and the electromagnetic spectrum

In the 18th and 19th centuries it was believed that light was a **wave**. Many experiments provided evidence for the wave model of light since they showed that light could refract, **reflect** and interfere. However, there were other experiments that couldn't be explained by the wave model of light. In 1900 Max Planck proposed that when light was absorbed or emitted it only came in **discrete** amounts. The particles of light in this model became known as **photons**.

These photons have no **mass**, and no charge, but they do have **energy**. In fact they can have a huge range of energies, and the light that we can see is only a very small part of the **spectrum**. Photons are made up of a combination of an electric field and magnetic field which travel around together, and so we call the entire range the **electromagnetic** spectrum Photons are the "particles" associated with electromagnetic **radiation**.

One of the interesting things about photons of a given wavelength is that they always travel at the **same** speed in a given medium, e.g. air. Other particles, like electrons, travel faster or slower depending on how much **kinetic** energy they have, but photons always travel at the speed of light, $c = \mathbf{3 \times 10^8}$ ms^{-1} in vacuum or in air.

Even though light behaves like particles, it still behaves like **waves**! When you do some experiments, the light behaves like particles, while during other experiments it behaves like waves. This is a great mystery. Other particles with **mass** like electrons and protons, and even whole atoms, also behave like waves. This is called wave-particle **duality**, and is one of the biggest mysteries of modern physics. For any wave, there is a relationship between the speed, **frequency** and wavelength given by $c = \lambda \times f$. Usually you need to know two of these to find the third. However, with light, because the speed is always the same, knowing the frequency will tell you the wavelength and vice versa.

Discussion questions

Photoelectric Effect: Ejected photoelectrons are emitted immediately if they are to be emitted at all. This can be explained if photons are particles having an energy related to their frequency. A wave model of light would suggest that the electrons would be ejected only after some time for low intensity light.

There are many experiments which show the wave nature of light, such as diffraction and interference experiments. An example is the twin slit experiment where light from the two slits interferes to give a pattern of fringes. This is a result of the wave nature of light, allowing it to pass though both slits at once.

B. Activity Questions:

1. Wave and particle nature of light 1- interference pattern

This demonstrates the wave nature of light. A particle could only pass through one slit or the other. However, a wave can pass through both slits simultaneously and interfere with itself.

2. Wave and particle nature of light 2- emission spectra

If you accept that the spectral lines result from transitions of electrons from one energy level to another, then the excess energy of an electron when it jumps down from one energy level to another is released as a photon. These lines have discrete colours (frequencies) and correspond to photons of different energies.

C. Qualitative Questions:

1. Light as a wave and particle.

	Wave Model	Particle Model
Brightness	square of wave amplitude	number of photons (flux density)
Colour	frequency or wavelength	energy of photons

2. Humans see from blue (around 400 nm wavelength) to red (around 700 nm).

a. Blue photons have shorter wavelength, λ, therefore they have higher frequency, f, as $c = \lambda f$ and c is constant (the speed of light). Energy is proportional to frequency, hence blue light has higher energy per photon than red light.

b. X-rays have much higher frequency than radio-waves, and have much higher energy.

c. X-rays have much higher frequency and energy than visible light, and hence are more penetrating. This allows them to be used to see inside things which visible light cannot penetrate, such as the body.

d. The depletion of the ozone layer is a concern because it absorbs a lot of UV light. Without it much more UV will get through.

e. Ultraviolet light is much more dangerous than infrared because it has much higher energy, and is more penetrating. It can break bonds in DNA and that can lead to skin cancer.

D. Quantitative Question:

An enzyme called luciferase is used by many animals that produce light, for example fireflies. Fireflies produce a yellow light (with wavelength ~500 nm) which they flicker and flash to attract a mate. Many marine organisms produce a green or blue light.

a. Use $E=hf$ and $c = \lambda f$.

$f = c / \lambda = 3\times10^{8} / 500\times10^{-9} = 6\times10^{14}$ Hz.

$E = hf = 6.63\times10^{-34} \times 6\times10^{14} = 4.0\times10^{-19}$ J.

Jellyfish produce higher energy (shorter wavelength) photons.

b. 0.1mW = 0.1×10^{-3} J/s. Each photon has 4.0×10^{-19} J.

so they are producing

0.1×10^{-3} Js^{-1} / 4.0×10^{-19} J.photon^{-1} = 2.5×10^{14} photons per second for 10 fireflies.

So each produces 2.5×10^{13} photons per second.

c. The colour (frequency and energy) is the same, but the intensity is greater for more fireflies.

d. Higher energy photons would be shorter wavelength, so green or blue rather than yellow.

Workshop Tutorials for Introductory Physics

QI2: **Atomic Structure**

A. Review of Basic Ideas:

Use the following words to fill in the blanks:
electrons, shape, matter, electronics, quantum, planets, uniform, pudding, discrete, solar, indivisible, nucleus, spectra

The evolving model of the atom

The word "*atom*" comes from Greek, and means indivisible (*a*- not, *tom*- divisible). In about 450 BC Democritus postulated that _____ was made up of tiny individual atoms, and that the _____ of the atoms determined the properties of the material. It took more than another 2 millennia for this theory to be seriously advanced on.

The first modern model is Thompson's plum _____ model. In this model the atom is described as a lump of material with a _____ positive charge and uniform low density, with little bits of negative charge (_____) speckled throughout. Thompson measured the charge/mass ratio of the electron, the first sub-atomic particle. But even though this showed that the atom wasn't quite _____, atoms weren't renamed "*toms*"

The next big change to the model came from Rutherford. He discovered that the atom wasn't a uniform lump, but actually had a little _____ where the positive charge was, and the electrons were outside this. In fact, he showed that the nucleus was actually really small compared to the size of the atom. He suggested that the atom was like a _____ system, with a nucleus in the middle like a sun, and electrons orbiting around like _____.

There were some problems with this model. But at about the same time Planck and others were developing the _____ theory. Bohr incorporated the quantum theory into Rutherford's model, which solved a lot of the problems and explained not only why atoms show _____, but predicted where the lines for hydrogen would be. Unfortunately it didn't work very well for bigger atoms.

The currently accepted model of the atom is that the electrons exist in clouds around the nucleus, and have _____ energies which can be determined from quantum mechanics, although the calculations can be very difficult. While this model is bound to change a bit, it seems to work pretty well. In fact, all modern _____is based on it. Everything that has a transistor in it, from a digital watch to a computer, is based on quantum mechanics and the quantum model of the atom.

B. Activity Questions:

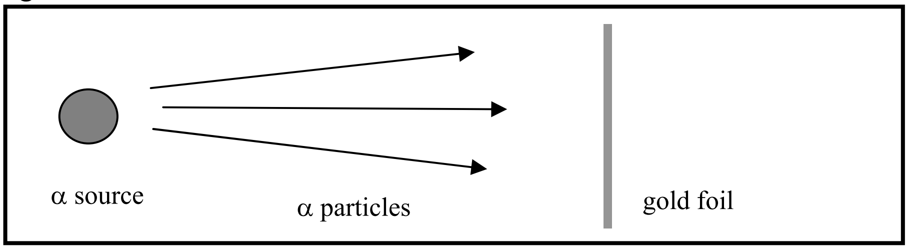
1. Hydrogen Spectrum
The hydrogen lamp has a tube which contains lots of hydrogen atoms, which have been excited so that their electrons occupy different energy levels.
Describe what you see when you look at the lamp. Now look at the lamp through the spectroscope. What do you see? Draw a sketch of the spectrum you observe.

2. Emission spectra
Use the spectroscope to observe light from other sources, including the lamps, fluorescent tubes and sunlight. Why are the spectra from these sources different?
How do you think scientists can tell what stars are made from without actually collecting samples?

3. Identify the element
Use the spectra chart and the spectroscope to identify the element contained in fluorescent lights.

C. Qualitative Questions:

1. In 1911 Ernest Rutherford, a New Zealand physicist and winner of the 1908 Nobel prize in chemistry, had his friend Hans Geiger (of Geiger counter fame), fire alpha particles (helium nuclei) at a very thin sheet of gold.



a. Draw a diagram showing where you expect the majority of alpha particles to go.
b. Where do the remainder go?
Most of the α particles went straight through, but a few bounced back. Given the model of the atom at the time, the plum pudding model, this was a very surprising result.
c. What do these results tell you about the structure of the atom?
d. What would have happened had Geiger accidentally used a neutron source rather than an α source?

2. In 1913 Niels Bohr proposed a modification to Rutherford's atomic model. He envisioned specific discrete energy levels (shells, numbered n=1,2,3…) for electrons bound to a nucleus.
a. What does discrete mean?
b. What else comes in discrete quanta?
c. How do we know that there are discrete energy levels?
d. Would you expect the energy levels to be the same or different for hydrogen and helium?
e. How are the levels distinguished in the current atomic model?

D. Quantitative Question:

The effective radius of a nucleus can be calculated using $R = R_o A^{1/3}$, where R_o = 1.2 fm = 1.2×10^{-15}m, and A is the atomic mass number of the nucleus. The atomic mass number of gold is 197.
a. Calculate the size of a gold nucleus.
b. What is the density of a gold nucleus?
A gold atom has an effective radius of around 2 nm. Imagine making a model of a sheet of atoms with nuclei 1cm in diameter (marbles, for example), and spacing them so that the atoms were just touching.
c. How far apart would the nuclei need to be positioned?
d. How hard would it be to hit the nuclei with thrown marbles from several atomic radii away?

By convention there is colour,
By convention sweetness,
By convention bitterness,
But in reality there are atoms and space.
-Democritus (c. 400 BCE)

Workshop Tutorials for Introductory Physics

Solutions to QI2: **Atomic Structure**

A. Review of Basic Ideas:

The evolving model of the atom

The word "*atom*" comes from Greek, and means indivisible (*a*- not, *tom*- divisible). In about 450 BC Democritus postulated that **matter** was made up of tiny individual atoms, and that the **shape** of the atoms determined the properties of the material. It took more than another 2 millennia for this theory to be seriously advanced on.

The first modern model is Thompson's plum **pudding** model. In this model the atom is described as a lump of material with a **uniform** positive charge and uniform low density, with little bits of negative charge (**electrons**) speckled throughout. Thompson measured the charge/mass ratio of the electron, the first sub-atomic particle. But even though this showed that the atom wasn't quite **indivisible**, atoms weren't renamed "*toms*"

The next big change to the model came from Rutherford. He discovered that the atom wasn't a uniform lump, but actually had a little **nucleus** where the positive charge was, and the electrons were outside this. In fact, he showed that the nucleus was actually really small compared to the size of the atom. He suggested that the atom was like a **solar** system, with a nucleus in the middle like a sun, and electrons orbiting around like **planets**.

There were some problems with this model. But at about the same time Planck and others were developing the **quantum** theory. Bohr incorporated the quantum theory into Rutherford's model, which solved a lot of the problems and explained not only why atoms show **spectra**, but predicted where the lines for hydrogen would be. Unfortunately it didn't work very well for bigger atoms.

The currently accepted model of the atom is that the electrons exist in clouds around the nucleus, and have **discrete** energies which can be determined from quantum mechanics, although the calculations can be very difficult. While this model is bound to change a bit, it seems to work pretty well. In fact, all modern **electronics** is based on it. Everything that has a transistor in it, from a digital watch to a computer, is based on quantum mechanics and the quantum model of the atom.

B. Activity Questions:

1. Hydrogen Spectrum

a. You should see a blue-ish coloured light.

b. You should have seen lines of different colours, due to different electronic transitions. Discrete energies mean that electrons can only make distinct transition, hence they can only change energy by fixed amounts, hence they can only emit (or absorb) photons of particular energy.

2. Emission spectra

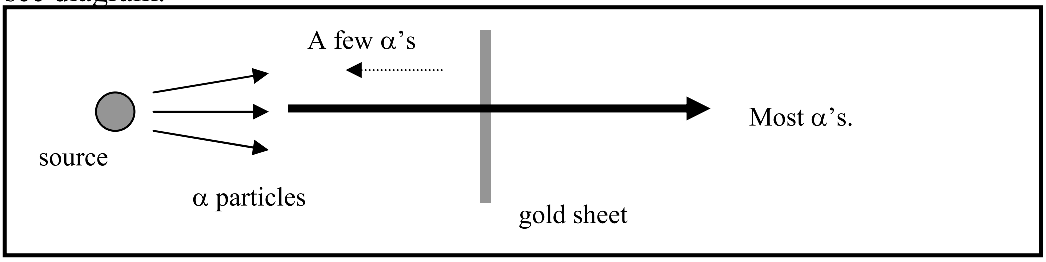
The spectrum of any given element is unique, hence by observing the spectrum of a source, we can tell what elements are present. This is used to identify what elements are in all sorts of things, including stars.

3. Identify the element

The element contained in fluorescent lights is mercury.

C. Qualitative Questions:

1. The Rutherford experiment.
a. and **b.** see diagram.



c. The nucleus is very small compared to the atom, and hence most of the α's pass straight through. Previously (the Thompson model) it was thought that the positive charge was distributed throughout the atom, hence Rutherford's surprise at the scattering of the massive α particles.
d. Had Geiger accidentally used a neutron source there would have been very few particles scattered. Neutrons have no charge and only ¼ the mass of an α particle, hence interact only weakly with matter compared to the α particles.

2.
a. Discrete means that the energy levels can only have certain values, there is not a continuous range of energies possible.
b. Light comes in discrete quanta, called photons, matter comes in discrete amounts, such as electrons and protons and neutrons. Information usually comes in discrete amounts as well, for example letters in words, 0's and 1's in computers and base pairs in DNA.
c. We know that there are discrete energy levels in atoms, because as photons are emitted from a certain atoms they can only have a particular set of wavelengths. The wavelengths are related to the energy of the photons by $E = hc/\lambda$. The energy of the photon is equal to the energy difference between two energy levels.
d. The energy levels for hydrogen and helium would be different because of the different numbers of electrons and also because of the different number of protons in the nucleus which attract the electrons.
e. The current model is the quantum mechanical model which is a mathematical model based on probability waves. This model can be visualised as a cloud of electrons surrounding the nucleus. This cloud gives the probability of finding an electron in a particular area, the densest part of the cloud has the highest probability of finding an electron in that area. The different shape and size of the electron clouds correspond to different energy levels.

D. Quantitative Question:

The effective radius of a nucleus can be calculated using $R = R_o A^{1/3}$, where $R_o = 1.2$ fm $= 1.2 \times 10^{-15}$m, and A is the atomic mass number of the nucleus, 197 for gold.
a. $R = R_o A^{1/3} = 6.98\times10^{-15}$m
b. Density = mass/volume = $197 \times 1.66 \times 10^{-27}$ kg / $\pi \times 4/3\ R^3 = 2.3 \times 10^{17}$ kg.m^{-3}, very very dense!
A gold atom has an effective radius of around 2 nm. Imagine making a model of a sheet of atoms with nuclei 1cm in diameter (marbles, for example), and spacing them so that the atoms were just touching.
c. An atom is around $10^{-10}/10^{-15}=10^5$ × bigger than a nucleus. So if the nucleus is 1cm in diameter, the atom should be $10^5\times$ 1 cm = 1 km across!
d. It would be very hard to hit the nuclei with thrown marbles from several atomic radii away!

Workshop Tutorials for Introductory Physics
QI3: **Spectra**

A. Review of Basic Ideas:

Use the following words to fill in the blanks:
discrete, impurity, electromagnetic, excited, spectroscope, ground, photon, Earth, lower, spectrum, emitted, wavelengths, absorption, Spectroscopy, gravitational, spectrum

Spectra

A _____ is a device which uses a prism or a grating to separate light into its component wavelengths and is a valuable tool in discovering what things are made of.

Light emitted by low pressure gases contains only a _____ set of wavelengths, and is called a line spectrum. When atoms are excited, for example by passing a current through them in a discharge tube, their electrons will not all be in the _____ state. Many electrons will be in _____ states. When these electrons move from one energy state to a lower energy state they emit a _____.

In fact it is not really the electron which changes energy, but the whole atom, including the electron. In the same way we talk about the _____ potential energy of a person increasing when they climb up stairs, but in fact it is the system, the person and the earth, which gains potential energy. Without the _____ there, it wouldn't mean much to talk about the person's gravitational potential energy, and without the rest of the atom there, it doesn't make sense to talk about electron energy levels either.

The _____ of an element can tell us about the energy levels of that element. This _____ is unique to an element, and is called an emission spectrum, because the light is _____ by the sample. This is used for identifying contaminants in materials such as silicon which need to be of extremely high purity to make semiconductors. A small sample of the silicon is heated until it starts emitting light, and the spectrum of this light is compared to that of pure silicon. Any extra lines indicate an _____.

Another sort of spectroscopy uses the absorption of light by electrons as they move from _____ to higher energy levels. These spectra look like a rainbow with black lines in them, and are called _____ spectra. Absorption spectra are used to tell what stars are made from. The hot core of a star emits a continuous spectrum of radiation. Atoms in the outer cooler region then absorb some _____, leaving dark lines in the spectrum. This spectrum can be compared to absorption spectra for elements to find out what's in the star.

_____ is used for a vast number of applications, from monitoring blood oxygen levels to identifying contaminants. There are many other sorts of spectroscopy, which use parts of the _____ spectrum other than the visible, and excitations of molecules as well as atoms.

B. Activity Questions:

1. Emission spectra

Use the hand held spectroscopes to "look" at light from different sources, such as sunlight (out the window) and light from fluorescent tubes.
What are the differences in the spectra from the various sources?
Why are the spectra different?

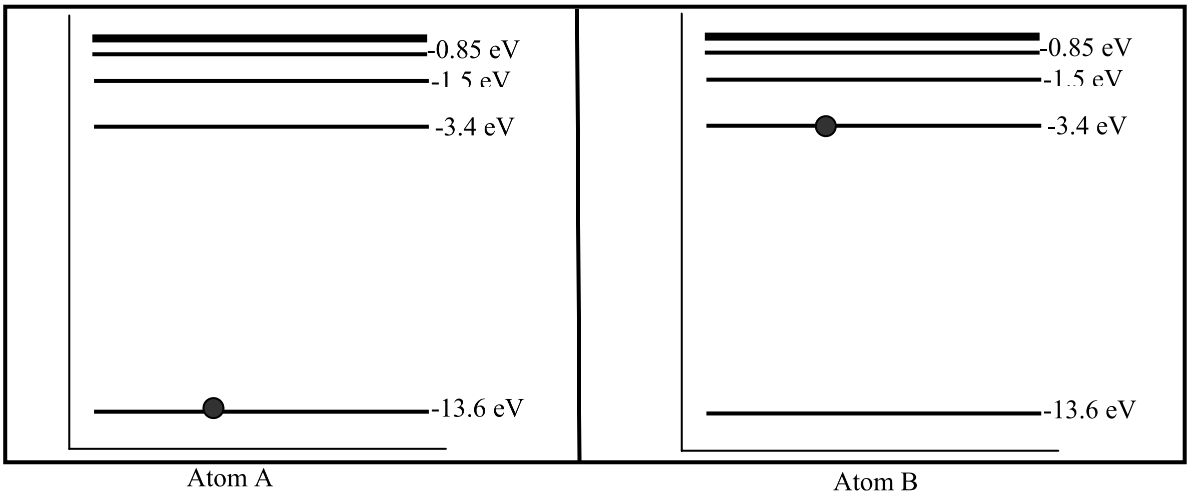
2. Identify the element

Use the spectroscope and the diagrams of various spectra to identify the type of atoms in the lamp.
What would a spectrum from a sample with several elements look like?

C. Qualitative Questions:

1. Some lines in the hydrogen spectrum are brighter than others. Why?

2. The diagram below shows the energy levels of a hydrogen atom. A black blob drawn on an energy level indicates that an electron occupies that energy level.



a. What, if anything, can happen to atom A if a photon of energy 10.2 eV approaches it? What can happen to the photon? If nothing can happen explain why not.
b. What, if anything, can happen to atom B if a photon of energy 10.2 eV approaches it? What can happen to the photon? If nothing can happen explain why not.
c. What, if anything, can happen to atom A if a photon of energy 2 eV approaches it? What can happen to the photon? If nothing can happen explain why not.
d. What, if anything, can happen to atom B if a photon of energy 2 eV approaches it? What can happen to the photon? If nothing can happen explain why not.

D. Quantitative Question:

Consider a hydrogen atom, ${}_{1}^{1}H$, which has one electron. In Bohr's model the electron can be in any one of many discrete energy levels. An electron in the ground state (n=1) energy level of hydrogen has an energy of -13.6eV, and in general $E_n = -13.6\text{eV}/n^2$.
a. Draw an energy level diagram for hydrogen.
Hydrogen has a red, a blue and several violet lines in its spectrum.
b. Which of these lines has photons of the highest energy and which has the lowest?
These lines are part of the Balmer series, which are transitions from n>2 to n=2.
c. Find the energy of the red photons. What wavelength does this correspond to? Mark this transition on your diagram.
d. Given that the visible range is from around 400 nm to 700 nm, to what part of the spectrum do photons from transitions from n>1 to n=1 belong?
e. What is the highest energy photon that an electron binding to a hydrogen nucleus can produce? What wavelength does this correspond to? Show this transition on your diagram.

Workshop Tutorials for Introductory Physics
Solutions to QI3: **Spectra**

A. Review of Basic Ideas.

Spectra

A **spectroscope** is a device which uses a prism or a grating to separate light into its component wavelengths and is a valuable tool in discovering what things are made of.

Light emitted by low pressure gases contains only a **discrete** set of wavelengths, and is called a line spectrum. When atoms are excited, for example by passing a current through them in a discharge tube, their electrons will not all be in the **ground** state. Many electrons will be in **excited** states. When these electrons move from one energy state to a lower energy state they emit a **photon**.

In fact it is not really the electron which changes energy, but the whole atom, including the electron. In the same way we talk about the **gravitational** potential energy of a person increasing when they climb up stairs, but in fact it is the system, the person and the earth, which gains potential energy. Without the **Earth** there, it wouldn't mean much to talk about the person's gravitational potential energy, and without the rest of the atom there, it doesn't make sense to talk about electron energy levels either.

The **spectrum** of an element can tell us about the energy levels of that element. This **spectrum** is unique to an element, and is called an emission spectrum, because the light is **emitted** by the sample. This is used for identifying contaminants in materials such as silicon which need to be of extremely high purity to make semiconductors. A small sample of the silicon is heated until it starts emitting light, and the spectrum of this light is compared to that of pure silicon. Any extra lines indicate an **impurity**.

Another sort of spectroscopy uses the absorption of light by electrons as they move from **lower** to higher energy levels. These spectra look like a rainbow with black lines in them, and are called **absorption** spectra. Absorption spectra are used to tell what stars are made from. The hot core of a star emits a continuous spectrum of radiation. Atoms in the outer cooler region then absorb some **wavelengths**, leaving dark lines in the spectrum. This spectrum can be compared to absorption spectra for elements to find out what's in the star.

Spectroscopy is used for a vast number of applications, from monitoring blood oxygen levels to identifying contaminants. There are many other sorts of spectroscopy, which use parts of the **electromagnetic** spectrum other than the visible, and excitations of molecules as well as atoms.

B. Activity Questions:

1. Emission spectra

Some spectra, for example sunlight and incandescent globes, are approximately continuous, and you see a complete rainbow of colours. Others, like the discharge lamps, show discrete line spectra.

The spectra are different because the light sources contain different elements. In the sun, there is both absorption and emission, and many different elements. In a discharge lamp there is mainly emission.

The spectrum of any given element is unique, hence by observing the spectrum of a source, we can tell what elements are present. This is used to identify what elements are in all sorts of things, including stars.

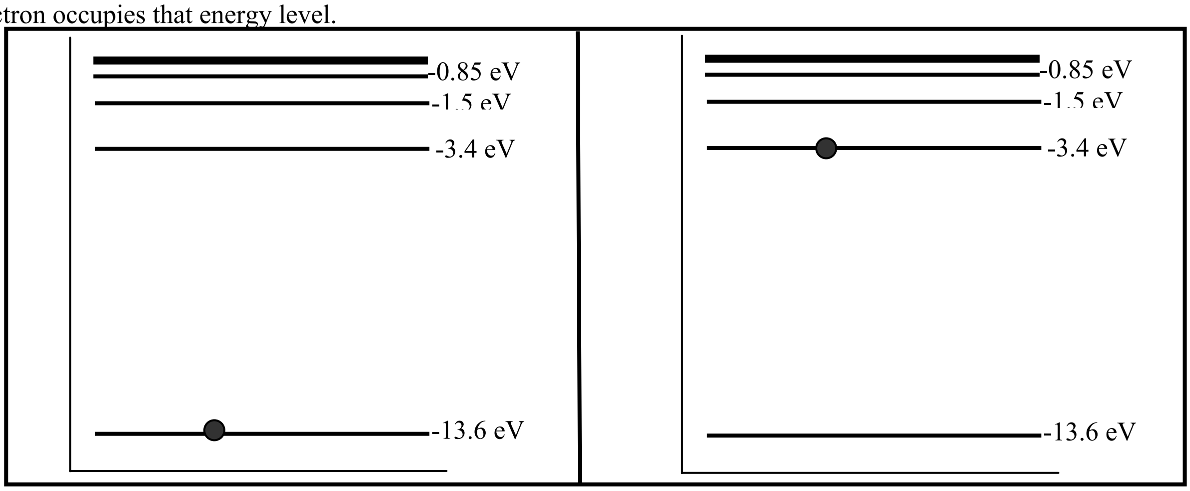
2. Identify the element

The element contained in fluorescent lights is mercury.

C. Qualitative Questions:

1. The colour of a line depends on the energy of the photons. The brightness or intensity of a line depends on the number of photons. The more often a transition happens the more photons are emitted, and the brighter the line corresponding to that transition.

2. The diagram below shows the energy levels of a hydrogen atom. A black blob drawn on an energy level indicates that an electron occupies that energy level.



a. If a photon of energy 10.2 eV approaches atom A it can undergo a transition. The photon can be absorbed and the electron can jump to the next level up.

b. If a photon of energy 10.2 eV approaches atom B the photon can be absorbed and the ataom can be ionised. The electron would escape with the extra energy, (10.2 – 3.4 = 6.8 eV) as kinetic energy.

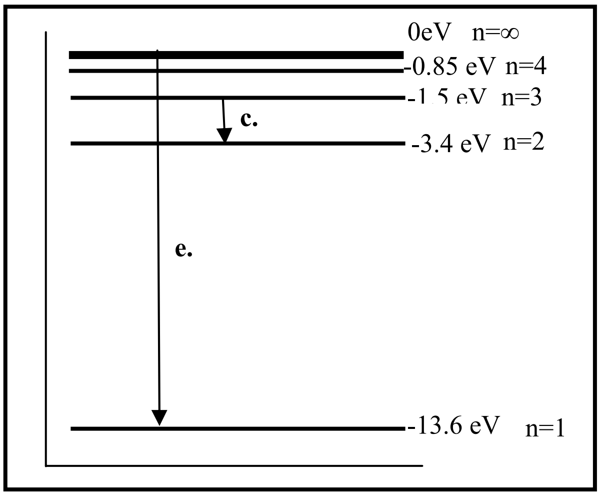
c. If a photon of energy 2 eV approaches atom A nothing will happen. This is not enough energy to excite the electron to a higher level, so the photon will not be absorbed and the atom will not become excited.

d. If a photon of energy 2 eV approaches atom B nothing will happen. This is too much energy to excite the electron to the next level up, and it is not enough to go two levels up, only the exact amount of energy will excite the electron to the next level, so the photon will not be absorbed and the atom will not become excited.

D. Quantitative Question:

Consider a hydrogen atom, ${}^{1}_{1}H$, which has one electron. In Bohr's model the electron can be in any one of many discrete energy levels. An electron in the ground state (n=1) energy level of hydrogen has an energy of -13.6eV, and in general $E_n = -13.6\text{eV}/n^2$.

a. see diagram opposite.
b. The violet lines have the highest energy and the red has the lowest.
c. The red has the lowest energy, hence it must be due to a transition from $n = 3$ to $n = 2$, which is an energy of $E = -1.5 - -3.4 = 1.9$ eV $= 3.0 \times 10^{-19}$J.
The frequency is then $f = E/h = 3.0\times10^{-19}\text{J} / 6.63\times10^{-34}$ J.s $= 4.6 \times 10^{14}$ s^{1}.
Which is a wavelength of
$\lambda = c/f = 3 \times 10^{8}$ m.s^{-1}/ 4.6×10^{14} s^{1}= 650 nm.
d. Transitions from n>1 to n=1 have greater energy than the visible lines, hence they are in the UV part of the spectrum.



e. The shortest wavelength possible corresponds to the highest energy possible, which is from $n = \infty$, with energy 0 eV to n =1, with -13.6 eV, a change of 13.6 eV = 2.18×10^{-18}J.
Again using $f = E/h = 2.18\times10^{-18}\text{J} / 6.63\times10^{-34}$ J.s $= 3.28 \times 10^{15}$ s^{1}
Which has a wavelength of $\lambda = c/f = 3 \times 10^{8}$ m.s^{-1}/ 3.28×10^{15} s^{1}= 91nm. This is in the ultraviolet region.

Workshop Tutorials for Introductory Physics

QI4: **The Nucleus**

A. Review of Basic Ideas:

Use the following words to fill in the blanks:
nucleons, neutrons, Gravity, protons, protons, N, mass, energy, binding, atomic, neutral, nucleus, stable, bigger, defect

The nucleus

The nucleus is made up of _____ and _____, which are collectively called _____. A nucleus can be described by three numbers: N, Z and A. _____ is the number of neutrons in the nucleus, and Z is the number of _____, also called the _____ number. A is the _____ number and is the total number of nucleons which is equal to N + Z.

The neutrons are _____, and the protons are positively charged. So if the only significant force in the nucleus was the Coulomb force, the nuclei would blow apart. _____ is very weak compared to the Coulomb force, so it doesn't hold them together. The force that holds them together is very strong, and acts over short distances between nucleons. Hence it is called the "strong nuclear force".

Because there is a strong force which pulls nucleons together, they have lower potential _____ when they are bound together in a nucleus than if they were free. In the same way, an electron has lower potential energy when it is bound by the Coulomb force to a _____ to form an atom. In the same way that you need to give an electron energy to allow it to escape from an atom, you need to give a nucleon energy to pull it apart from the nucleus. For an electron this is called the ionisation energy, for a nucleon it is called the _____ energy.

The binding energy tells us how _____ a nucleus is, how hard it is to break it apart. This is usually shown in charts as a binding energy per nucleon, which is the amount of energy you need to pull a nucleus completely apart into protons and neutrons, divided by the number of protons and neutrons (A). The _____ this energy, the more stable the nucleus. The binding energy can also be expressed as a mass. The mass of a nucleus is a bit less than the sum of the masses of its protons and neutrons. The difference is called the mass _____ which, using $E=mc^2$, is equivalent to the binding energy.

Discussion questions
What is the Coulomb force? What force holds the earth in its orbit around the sun?
What force holds your nose onto your face and electrons into atoms?
What force holds nucleons into nuclei?

B. Activity Questions:

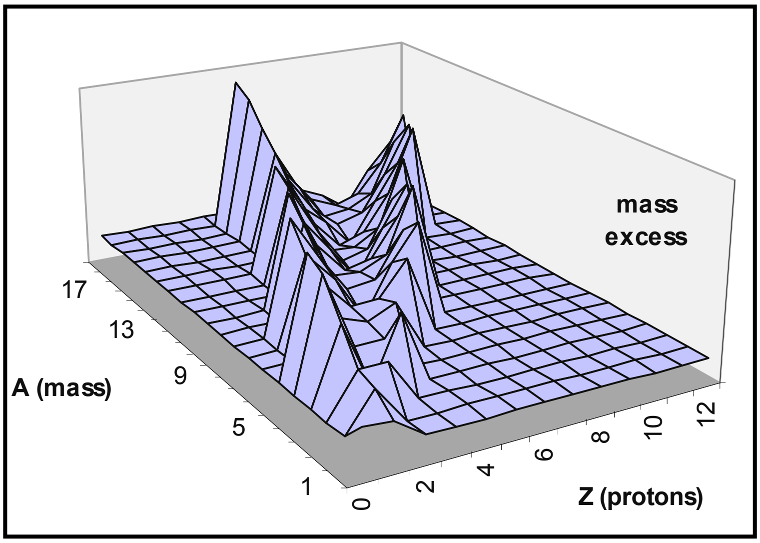
1. Binding energies
Examine the chart of binding energies.
a. What does the diagram represent?
Fission and fusion are opposite processes, when fission occurs a nucleus breaks apart and when fusion occurs two nuclei fuse to form a larger one.
b. How can both these processes release energy?
c. Which nuclei are more likely to undergo fusion? Which will undergo fission? Explain your answer.

2. Coolite Balls
Charge the coolite balls so that they have opposite charges. What happens?
Now charge them so they have like charges and observe what happens. What would happen to nuclei if there wasn't a strong nuclear force to hold them together?

C. Qualitative Questions:

1. Captain Picard and Data have just completed a successful mission on the planet Zog and are beaming back aboard the starship Enterprise (mark III) when there is an error in the transporter circuits!
The transporter de-materialises all their atoms on the planet surface and converts them into information in the circuits of the ship's transporter, and then reconstructs the atoms and puts them back in the right places. However the computer mixes up its N's and Z's so the codes for protons and neutrons are mixed up. When the transporter in the ship reconstructs them all their protons have been exchanged for neutrons and vice versa.
a. What is the effect of this on the carbon, oxygen, nitrogen and hydrogen which make up Captain Picard?
b. What will be the likely effect of this on Captain Picard?
c. What is the likely effect on Data, who is mostly metal (such as copper and iron) beneath his plastic simulated skin?
Hint : you may want to look at a periodic table.

2. The figure below shows the mass excess as a function of A and Z for the first 12 elements.



a. In which region are the nuclei stable?
There are two regions of unstable nuclei, one to the left of the valley, and one to the right.
b. Why are the nuclei to the left unstable?
c. Why are the nuclei to the right unstable?
(Hint: Look at the A and Z numbers.)
The nuclei from each of these regions become stable by different processes.
d. Describe these processes.
e. What happens to N and Z during these processes?

D. Quantitative Question:

A deuteron (a proton and a neutron) has a binding energy of 2.22 MeV = 3.55×10^{-13}J.
a. What is the binding energy *per nucleon* for a deuteron?
b. By how much is a deuteron lighter than a proton plus a neutron?
c. How much energy is released when two hydrogen nuclei and two neutrons fuse to form a helium nucleus in the sun?
d. How much energy is released when uranium232 decays into a thorium228 nucleus and a helium nucleus?
e. Comment on your answers to **c** and **d**.

Particle	proton	neutron	H	He	^{232}U	^{228}Th
Mass (amu)	1.007276	1.008665	1.0107276	4.002603	232.0371	228.0287

1amu = 1.66054×10^{-27} kg.= 931.3 MeV/c^2.

Workshop Tutorials for Introductory Physics

Solutions to QI4: **The Nucleus**

A. Review of Basic Ideas:

The nucleus

The nucleus is made up of **protons** and **neutrons,** which are collectively called **nucleons**. A nucleus can be described by three numbers, N, Z and A. **N** is the number of neutrons in the nucleus, and Z is the number of **protons**, also called the **atomic** number. A is the **mass** number and is the total number of nucleons which is equal to N + Z.

The neutrons are **neutral**, and the protons are positively charged. So if the only significant force in the nucleus was the Coulomb force, the nuclei would blow apart. **Gravity** is very weak compared to the Coulomb force, so it doesn't hold them together. The force that holds them together is very strong, and acts over short distances between nucleons. Hence it is called the "strong nuclear force".

Because there is a strong force which pulls nucleons together, they have lower potential **energy** when they are bound together in a nucleus than if they were free. In the same way, an electron has lower potential energy when it is bound by the Coulomb force to a **nucleus** to form an atom. In the same way that you need to give an electron energy to allow it to escape from an atom, you need to give a nucleon energy to pull it apart from the nucleus. For an electron this is called the ionisation energy, for a nucleon it is called the **binding** energy.

The binding energy tells us how **stable** a nucleus is, how hard it is to break it apart. This is usually shown in charts as a binding energy per nucleon, which is the amount of energy you need to pull a nucleus completely apart into protons and neutrons, divided by the number of protons and neutrons (A). The **bigger** this energy, the more stable the nucleus. The binding energy can also be expressed as a mass. The mass of a nucleus is a bit less than the sum of the masses of its protons and neutrons. The difference is called the mass **defect** which, using $E=mc^2$, is equivalent to the binding energy.

Discussion questions

Matter consists of positively charged protons and negatively charged electrons. Charged particles attract each other if their charge is different and repel each other if the charge is the same. Coulomb measured the force between 2 small charged balls and showed that the force was proportional to the magnitude of the charges and inversely proportional to the square of the distance between them. This is force is known as the Coulomb force.

The gravitational force is an attractive force between two bodies and inversely proportional to the square of the distance between them. It is this force, attraction between the sun and the earth that keeps the earth in orbit around the sun. There is no repulsive gravitational force [yet discovered].

Your nose stays on your face because of the attractive electrical forces (Coulomb forces) in the bonds, which hold matter together. It is this force which also holds the negatively charged electrons around the positively charged nucleus of the atom.

In the nucleus, which comprises the positively charged protons and the neutral neutrons, there is a force acting, called the strong nuclear force. This helps to hold the nucleus together. This force is necessary because of the strong repulsive forces, which exist between the closely packed protons. This force only acts over atomic distances within the nucleus and, if the nucleus becomes too big, it will become unstable and decay.

B. Activity Questions:

1. Binding energies

a. The diagram shows the amount of energy per nucleon that you would need to pull that nucleus into its component protons and neutrons. This is sometimes also expressed as a mass defect, which is the difference between the mass of the nucleus and the sum of the masses of the same number of neutrons and protons.

b. Both fission and fusion can release energy by increasing the mass defect or binding energy of an atom. The lower the binding energy, the less stable the atom.

c. Small nuclei such as hydrogen are more likely to undergo fusion, moving them along the binding energy chart to the right, with increasing binding energy. Large nuclei with small binding energies, those to the far right of the peak, will undergo fission to produce smaller nuclei with higher binding energies. Remember that the binding energy is how much you have to put in to break the nuclei, not how much energy the nuclei have, hence higher is more favourable.

2. Coolite Balls

When the coolite balls have the same charge they repel each other, and when they have opposite charges they attract. If the only force acting on the protons in the nucleus was the Coulomb force, they would repel each other and the nucleus would fall apart.

C. Qualitative Questions:

1. The transporter error.

a. Captain Picard is composed mostly of carbon, oxygen, nitrogen and hydrogen. The most common isotopes of C, N and O all have the same number of protons as neutrons, so it won't make any difference to these atoms. However hydrogen has one proton, one electron and no neutron, so the transporter error which swaps protons for neutrons will leave Picard with lots of extra neutrons, a huge deficit of protons but the same number of electrons.

b. This will be a very negative experience for Captain Picard, and his chemical structure will fall apart as he emits neutrons and the electrons disperse over him.

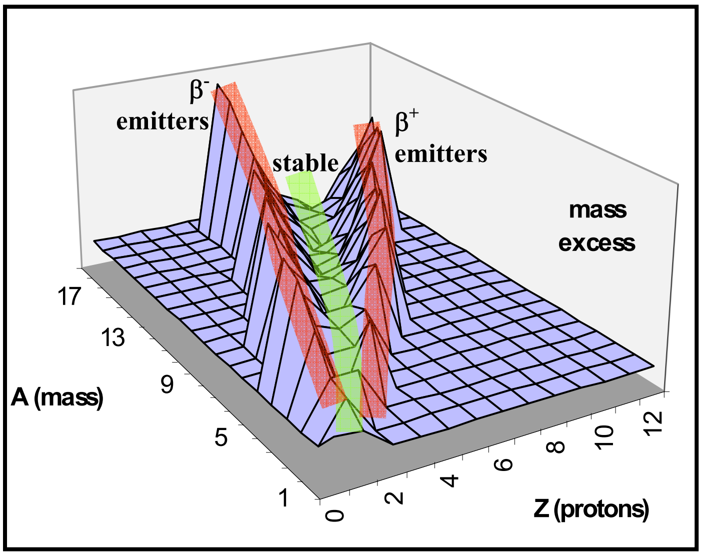
c. Data is mostly metal and most metals such as aluminium, copper and iron have more neutrons than protons to prevent the repulsive Coulombic force from breaking apart the nucleus. Hence the swap will leave the metals with too many protons, which will decay until the metals have stable nuclei again. With too many protons, Data is likely to emit β^+ radiation to convert protons to neutrons.

2. The valley of stability.

a. The region in which the nuclei are stable is in the 'valley' of the graph, called the "valley of stability", where the number of protons and the number of neutrons are approximately equal.

b. The nuclei to the left are unstable because they have too many neutrons for the number of protons, these are called neutron-rich isotopes.

c. The nuclei to the right are unstable because they have too many protons for the number of neutrons, these are called proton-rich isotopes.



d. The neutron rich light elements decay via:

[1] $n \rightarrow p + e^-$ [β^- decay - an electron]

The proton rich light elements decay via:

[2] $p \rightarrow n + e^+$ [β^+ decay - a positron]

Heavy proton-rich elements decay by alpha emission

e. In [1] the atomic number, Z, increases by 1 and the number of neutrons decreases by 1. In [2], Z decreases by one and the number of neutrons increases by 1. In both cases the number of nucleons, A, stays the same.

D. Quantitative Question:

a. The binding energy per nucleon for a deuteron:

Deuteron *B.E.* = 2.22 MeV and there are two particles, hence *B.E.* = 2.22 MeV / 2 nucleons = 1.11 MeV / nucleon

b. Mass of proton = 1.007276 amu, Mass of neutron = 1.008665 amu, total = 2.015941 amu.

Mass of deuteron = 2.014102 amu

Δm = 2.015941 - 2.014102 = 0.001849 amu

c. Fusion of 2 H nuclei and 2 neutrons to form a He nucleus:

2 H = 2.014552 amu and 2 n = 2.017330 amu; total = 4.031882 amu

mass of He atom =4.002603 amu

$\Delta m = [2m_p + 2m_n]$ - [mass He] = 0.030377 amu

And we can use $E = \Delta mc^2$:

As Δm is in u and ΔE is in MeV we can use the conversion factor between amu and MeV- (1 amu = 931.3 MeV)

E =[0.030377 u] c^2 [931.3 MeV/amu c^2] = 28.3 MeV.

d. The amount of energy released in the fission of ^{235}U to ^{228}Th + ^{4}He

[U] 232.0371 → [Th] 228.0287 + [He] 4.0026 = 232.0313 amu.

Δm = 0.0058 amu so ΔE = [0.0058 amu] c^2 [931.3 MeV/amu.c^2] = 5.4 MeV

e. The answers to **c** and **d** illustrate that more energy is released in the process of fusion than fission.

Workshop Tutorials for Introductory Physics

QI5: **Radioactivity**

A. Review of Basic Ideas:

Use the following words to fill in the blanks:
photon, nuclides, radionuclides, decay, medicine, strongly, random, radiation, electron, charged, helium, 4, β^-, positively, large, half-life, nuclei

Radiation
Most species of nuclei, or ________, are stable, but some are not. Those that are unstable can become stable by emitting _______. This process is called radioactive decay. The unstable nuclei are called radioactive nuclides, or ________.

There are three types of radiation which can be emitted when a radionuclide decays. It can emit an α particle, which is the same as a ________ nucleus. This is the heaviest and most highly ________ of the nuclear radiations, it has a mass number of ________ and a positive charge of $2e$. These particles interact ________ with matter.

The next heaviest are the β particles. There are two types of β particle, a β^+ and a _____. The β^- is the same as an ________, it has a negative charge, and a small mass. A β^+ particle is a _____ charged electron, also known as a positron. These particles don't interact as strongly with matter as the α particles.

The third type of radiation is γ radiation. A γ particle is a _____. It has no mass and no charge, but may have a lot of energy. A γ particle is emitted from an excited nucleus. They are also often emitted along with a β or α particle during radioactive ________.

Radioactivity has some very useful applications. The emitted particles can be used to track where the radioactive material is, such as in nuclear imaging in ________. Another application is radioactive dating. Although radioactive decay is a ________ process, so that it's impossible to predict when a given nucleus will decay, it does obey statistics. The behaviour of a ________ number of nuclei is, on average, predictable. For example, we can say that half of the nuclei, on average, will decay in a given period of time. This time is called the ________. If we know the half-life of a material, and how many ________ there were to start with, then we can calculate how old the material is.

Discussion questions

1. A particular ^{238}U nucleus was created during a massive stellar explosion, perhaps 10^{10} years ago. It suddenly decays by α emission while you are observing it. After all those years, why did it decide to decay while you were watching?

2. Complete the following equations:

$^{218}_{84}Po \rightarrow \_\_\_\_ + \alpha$

$^{11}_{6}C \rightarrow {}^{11}_{5}B + \_\_\_\_$

$^{12}_{6}C^* \rightarrow \_\_\_\_ + \gamma$

$\_\_\_\_ \rightarrow {}^{101}_{47}Ag + \beta^+ + \nu$

B. Activity Questions:

1. Colleen's Cubes

Shake the bag containing the nuclei (cubes) and pour them into the tray. Write down the number of cubes with dots showing on top, remove those cubes and replace the rest in the bag. How many cubes are left of the original 100?

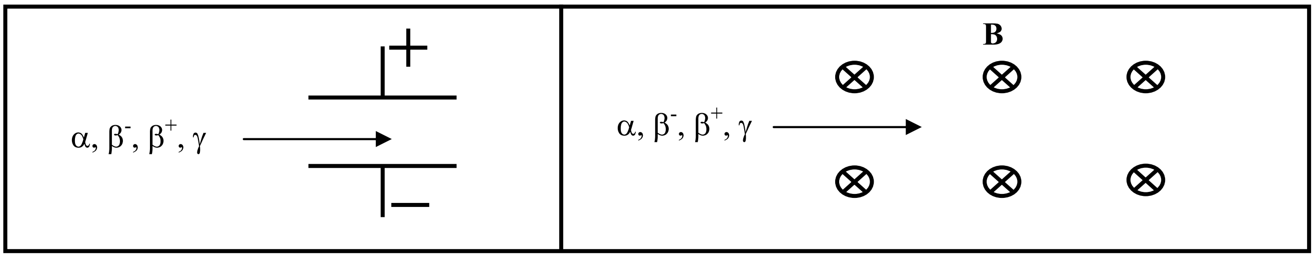
Repeat 10 times. Sketch the number of cubes removed (the activity) as a function of number of throws. Sketch the number of cubes remaining in the bag as a function of number of throws.

2. Smoke detector

Examine the smoke detector. It contains a radioactive source, ^{241}Americium, an α emitter. The α particles ionise air molecules between two charged plates. The positive ions go to the negative plate, the negative ions to the positive plate, which gives a current.
Use the circuit diagram to locate the main components of the detector.
How does smoke disrupt the current?

C. Qualitative Questions:

1. Beams of α, β^- and γ radiation of approximately the same energy pass through electric and magnetic fields as shown below.



a. Show the path taken by each particle in the two fields. Why do they follow these paths?
b. How are β^-, β^+ and electrons different?
c. How are x-rays, γ rays and photons different?

2. Carbon dating has been used to date many archeological finds, including the Dead Sea scrolls.
The scrolls are mostly made of animal skins or papyrus, but one is made of copper. Carbon-14 dating of samples from the scrolls has dated the scrolls at 1950 years old.
a. Describe how the decay of ^{14}C can be used to tell how old things are.
b. Why is it not possible to date the copper scroll in this way?
c. Carbon-14 has a half-life of 5,730 years. Why is carbon dating not used to date things over around 50,000 years old?

D. Quantitative Question:

Many processes and systems follow exponential decay over time. For example; the rate of cooling of a cup of coffee, the improvement in your time at completing a puzzle, the number of members of a population under environmental stress, the charge in a discharging capacitor and the number of radioactive atoms in a sample. The following example illustrates an exponential decay process.
Consider a street with 200 houses. In 1980 every household had one car, which ran on super (leaded) petrol. Every year, one tenth of households, on average, replace their car with one that runs on unleaded fuel.
a. How many cars from this street ran on unleaded fuel in 1982?
b. Draw a graph of number of cars using leaded petrol in this street as a function of time.
c. Draw a graph of number of cars replaced each year as a function of time.
d. What is the "half life" of a leaded-petrol car in this street?
Radioactive decay works in exactly the same way. The number of remaining nuclei, N, at time t is given by $N(t) = N(0)\ e^{-kt}$ where $k = \ln 2$ / half-life.
e. Write an equation of this form which gives the number of leaded-petrol cars as a function of time.
f. What is the number of remaining cars analogous to in radioactive decay? What is the number of cars replaced each year analogous to?

Workshop Tutorials for Introductory Physics
Solutions to QI5: **Radioactivity**

A. Review of Basic Ideas:

Radiation
Most species of nuclei, or **nuclides**, are stable, but some are not. Those that are unstable can become stable by emitting **radiation**. This process is called radioactive decay. The unstable nuclei are called radioactive nuclides, or **radionuclides**.

There are three types of radiation which can be emitted when a radionuclide decays. It can emit an α particle, which is the same as a **helium** nucleus. This is the heaviest and most highly **charged** of the nuclear radiations, it has a mass number of **4** and a positive charge of $2e$. These particles interact **strongly** with matter.

The next heaviest are the β particles. There are two types of β particle, a β^+ and a β^-. The β^- is the same as an **electron**, it has a negative charge, and a small mass. A β^+ particle is a **positively** charged electron, also known as a positron. These particles don't interact as strongly with matter as the α particles.

The third type of radiation is γ radiation. A γ particle is a **photon**. It has no mass and no charge, but may have a lot of energy. A γ particle is emitted from an excited nucleus. They are also often emitted along with a β or α particle during radioactive **decay**.

Radioactivity has some very useful applications. The emitted particles can be used to track where the radioactive material is, such as in nuclear imaging in **medicine**. Another application is radioactive dating. Although radioactive decay is a **random** process, so that it's impossible to predict when a given nucleus will decay, it does obey statistics. The behaviour of a **large** number of nuclei is, on average, predictable. For example, we can say that half of the nuclei, on average, will decay in a given period of time. This time is called the **half-life**. If we know the half-life of a material, and how many **nuclei** there were to start with, then we can calculate how old the material is.

Discussion questions

1. Large numbers of nuclei behave in statistically predictable ways, but individual nuclei do not. Nuclear decay is unpredictable, and a single nucleus may decay at any time.

2. ${}^{218}_{84}Po \rightarrow {}^{214}_{82}Pb + \alpha$, ${}^{11}_{6}C \rightarrow {}^{11}_{5}B + \beta^+$, ${}^{12}_{6}C^* \rightarrow {}^{12}_{6}C + \gamma$, ${}^{101}_{48}Cd \rightarrow {}^{101}_{47}Ag + \beta^+ + \nu$

B. Activity Questions:

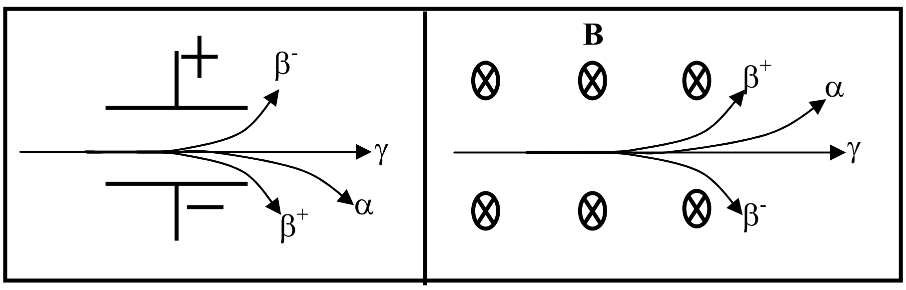
1. Colleens Cubes
You should have come up with an exponentially decreasing curve for both the number of cubes remaining, and the number of cubes removed at each throw. Many physical processes follow this pattern.

2. Smoke detector
When smoke enters the space between the plates the ions attach themselves to the heavy smoke particles and the flow of current is disrupted, setting off the alarm.

C. Qualitative Questions:

1.

a. The charged particles are deflected and follow a curved path in an electric or magnetic field. The γ particles are uncharged and hence are not affected. The α's are charged, but are very heavy and are less deflected than the βs.



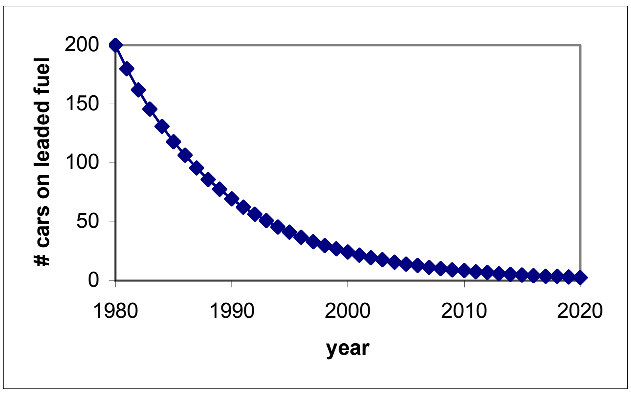
b. β^-s and electrons are exactly the same, they were named βs before it was known that they were electrons. β^+s are positrons, or positively charged electrons. They have the same mass as an electron, and the same magnitude of charge, but are positive.
c. x-rays and γ rays are both photons, they have no charge and no mass. γ rays have higher energy (and higher frequency) than x-rays, and both are higher energy than photons of visible light.

2.
a. There is a constant exchange of Carbon between the body and the environment for all living things. In this way the proportion of ^{14}C is kept approximatley the same in the body as in the atmosphere. When an organism dies this exchange stops, and the proportion of ^{14}C gradually decreases due to decay without being replenished. We know the proportion of ^{14}C in the atmosphere, and how long it takes to decay, hence we can measure how much is left in a sample and work out from this when it stopped exchanging C with the environment, and hence how old it is.
b. Copper is not organic, hence it was never exchanging C with the atmosphere. However the ink used was organic and hence the scroll could be dated that way.
c. Carbon-14 has a half-life of 5,730 years After 50,000 years there is not enough ^{14}C left in the sample to date it accurately.

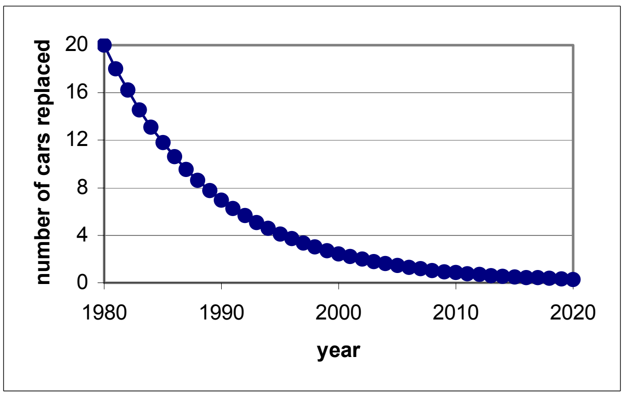
D. Quantitative Question:

Every year one tenth of 200 households replace their car with one that runs on unleaded fuel.
a. In 1981 10% of the cars = 20 cars were replaced, leaving 180 cars. In 1982 10% of this 180, = 18 cars, were replaced, giving a total of 38 cars on unleaded fuel.

b.



c.



d. The "half life" of a leaded-petrol car in this street is the time taken for the number of cars on leaded fuel to reduce to 100 cars, from the graph this is approximately 6 years. We can check this using
$N_{cars}(t) = N_{cars}(0) \times 0.9^{t}$ where t is the number of years since 1980.
Putting in $t = 7$ gives $N_{cars} = 200 \times 0.9^7 = 96$ cars.
Or we can find the half life more precisely:
$N_{cars}(t) = N_{cars}(0) \times 0.9^{t}$ and putting in the values for N:
$100 = 200 \times 0.9^t$ so $0.5 = 0.9^t$ and taking ln of both sides:
$\ln 0.5 = \ln 0.9^t = t \ln 0.9$ from which we get $t = \ln 0.5 / \ln 0.9 = 6.58$ years.
e. Using the analogy with radioactive decay, we could write an exponential equation:
$N_{cars}(t) = N_{cars}(0)\, e^{-kt}$ where the decay constant $k = \ln2/\text{halflife}$.
f. In radioactive decay the number of cars remaining is analogous to the number of nuclei not yet decayed. The number of cars replaced in a year is analogous to the number of decays per time period.

Workshop Tutorials for Introductory Physics
QI6: **Radiation and the Body**

A. Review of Basic Ideas:

Use the following words to fill in the blanks:
brain, atmosphere, lead, radiation, X-raying, radioisotopes, 10 km, inhaled, cosmic, charge, background, exposure, radon, γ, ultraviolet, energy, positron, annihilate, radioactive, photons

Radiation and the body

Everybody is exposed to _____ all the time, from radioactive materials in the ground, the air, and inside us, and _____ radiation from space. This naturally occurring radiation is called _____ radiation. The normal dose from the background radiation is very low, and not dangerous.

However some people are exposed to more background radiation than others. For example airline pilots and stewards spend a lot of time 10 km above the earth. Normally the _____ shields us from a lot of cosmic background radiation, but when you're _____ up, the background level is somewhat higher. Smokers also have a higher _____ to radiation than non-smokers. When tobacco leaves are dried they accumulate small amounts of the _____dust which settles on them. The radon an its daughter products are then _____ by the smoker.

People who work with radiation may also be exposed to higher levels of radiation than the normal background. People working with _____ may wear lead aprons to protect them from radiation, and carry a badge which senses the amount of radiation they are exposed to. The sorts of safety precautions used depend on the type of radiation present.

The most difficult radiation to shield against is _____ radiation. The high energy photons have no mass or ____, and hence are highly penetrating. Dentists and radiologists who use X-ray machines have to be careful to use _____ shielding. Even _____ radiation from the sun can be dangerous, which is why it's important to wear sunscreen if you're outside for any length of time. It is this penetrating nature of high energy photons that makes them so useful for imaging, such as _____.

Other sorts of radiation are also used for imaging. A PET (_____ emission tomography) scan uses β^+ radiation. The patient is injected with a radioisotope which emits positrons. When a positron is emitted it will not travel very far before it encounters an electron. A positron is the anti-matter particle of an electron, so when the two collide they _____ each other and some _____ is released. The energy is released as two _____ of a specific energy (the mass energy of the particles, from $E = mc^2$), which move off in opposite directions. By recording where the photons come out, we can work out where they must have come from, and hence where the original decay occurred. If the positron was emitted from _____ glucose, for example, we can tell which parts of the body are most active and hence using the most energy. This is extremely useful for looking at the _____, which only uses glucose for energy.

Discussion question
The radiation levels inside the reactor building of the HIFAR research reactor at Lucas Heights are lower than those outside the building. How is this possible?

B. Activity Questions:

1. X-ray pictures
Examine the X-ray films.
Why are some areas light and others dark? In which areas are more X-rays absorbed?
Why are more X-rays absorbed in these regions?

2. Measuring Radiation

Several different means of measuring radiation are shown.
Explain how they work.
Which ones would be suitable monitoring devices for persons working in a radiation area?

C. Qualitative Questions:

1. There are three main types of radiation, α, β and γ.

a. Of these three types of radiation, which particle is the most penetrating? Explain your answer.
b. Which has the greatest ionising power?
c. Why are α emitters not considered dangerous unless inhaled or ingested?
d. Why are dense materials, such as lead, the best materials for shielding against radiation?
e. Nuclear reactors produce a lot of neutrons. How do you think the penetrating and ionising power of a neutron compares to α and β radiation?

2. After the Chernobyl nuclear accident, which gave off significant amounts of the radioactive isotope ^{90}Sr, many European countries immediately imposed a ban on the sale of milk, why was this?

D. Quantitative Question:

The proportion of radiation penetrating a material decreases exponentially with the thickness of the material. A shielding material is rated according to its attenuation coefficient, $\mu = \ln2/HVL$. The HVL is the half-value layer, which is the thickness which stops one half of the incident radiation. This thickness depends on the material, and also on the radiation. It will be greater for more penetrating radiation.

a. Write an equation which gives the radiation level at a distance *d* through some material.
b. Sketch the intensity of the radiation as a function of distance.
c. Name another process which follows this form.

There are several isotopes of potassium which are radioactive. They emit γ and β radiation. The half value layers for the γ radiation from ^{40}K for several materials are shown below.

material	HVL (cm)
Lead	1.2
Iron	1.8
aluminium	5.0
water	12
air	10,000
concrete	5.6

d. By what fraction would the radiation be decreased by 25 cm of aluminium?
e. How much lead would you need to reduce exposure by 75%?
f. How much air would you need to reduce exposure by 75%?

Workshop Tutorials for Introductory Physics

Solutions to QI6: **Radiation and the Body**

A. Review of Basic Ideas:

Radiation and the body

Everybody is exposed to **radiation** all the time, from radioactive materials in the ground, the air, and inside us, and **cosmic** radiation from space. This naturally occurring radiation is called **background** radiation.

Normally the **atmosphere** shields us from a lot of cosmic background radiation, but when you're **10 km** up, the background level is somewhat higher. Smokers also have a higher **exposure** to radiation than non-smokers. When tobacco leaves are dried they accumulate small amounts of the **radon** dust which settles on them. The radon and its daughter products are then **inhaled** by the smoker.

People working with **radioisotopes** may wear lead aprons to protect them from radiation, and carry a badge which senses the amount of radiation they are exposed to.

The most difficult radiation to shield against is γ radiation. The high energy photons have no mass or **charge**, and hence are highly penetrating. Dentists and radiologists who use X-ray machines have to be careful to use **lead** shielding. Even **ultraviolet** radiation from the sun can be dangerous, which is why it's important to wear sunscreen if you're outside for any length of time. It is this penetrating nature of high energy photons that makes them so useful for imaging, such as **X-raying**.

Other sorts of radiation are also used for imaging. A PET (**positron** emission tomography) scan uses β^+ radiation. The patient is injected with a radioisotope which emits positrons. A positron is the anti-matter particle of an electron, so when the two collide they **annihilate** each other and some **energy** is released. The energy is released as two **photons** of a specific energy (the mass energy of the particles, from $E = mc^2$), which move off in opposite directions. If the positron was emitted from **radioactive** glucose, for example, we can tell which parts of the body are most active and hence using the most energy. This is extremely useful for looking at the **brain**, which only uses glucose for energy.

Discussion question

The radiation levels inside the building are lower than those outside because the building is well shielded. It has two layers of shielding – one around the reactor itself, and one enclosing the entire building. The natural radiation from cosmic rays and other sources outside cannot get into the building, and the radiation from the reactor inside the building is shielded also, so what remains is lower than the natural levels outside the building.

B. Activity Questions:

1. X-Rays

These are photons in the range of 10^{-10} m. X-rays come about because of atomic processes induced by the energetic electrons shot at the metal target in an x-ray machine. Because of their short wavelength they can pass through objects which are opaque to ordinary light. They can penetrate most tissue, but are absorbed well by bone and can be recorded on photographic film. The different levels of 'greyness' is due to the different abilities of the various tissues to absorb x-rays, the greater the absorption the fewer X-rays get through, and the lighter the film.

2. Measuring Radiation

Two methods of monitoring radiation are the film badge and the Geiger counter.

a. Film Badge: Film badges contain exactly what their name implies -- a piece of photographic film and several types of thin metal strips, which act as absorbers and allow for detection of various energies of radiation. Eg. the attenuation of beta rays depends only on the density of the medium through which it travels and plastic filters of low atomic number can be used to assess beta radiation dose. Cadmium can be used to assess a neutron dose. As the gamma radiation emitted, when neutrons are captured by the cadmium atoms, will blacken the film underneath the cadmium filter. If the radiation beam is only gamma rays then the blackening will be the same under a tin-lead filter and under a cadmium-lead filter. However, the presence of neutrons will produce excess film blackening under the cadmium-lead filter. The amount of exposure to the film determines the amount of radiation exposure that the individual received during that period.

b. A Geiger counter is a device used to detect radiation from a radioactive source. It detects and records the number of radioactive particles. The Geiger counter consists of metal tube filled with a gas at low pressure, such as argon. A wire runs down the centre of the tube and is maintained at a high positive voltage compared with the outer tube, which is negatively charged. The voltage is not sufficient to ionise the gaseous atoms in the tube. When a particle enters the window at one end of the tube it ionises a few gas atoms. The freed electrons are attracted to the central positive wire and ionise other gas atoms as they accelerate towards the wire. A large number of electrons is quickly produced and these produce a voltage pulse at the wire. This pulse is transferred to an electronic counter or to a loudspeaker to be heard as a clicking sound. Counters enable radioactive tracers to be followed as they make their way through complex organisms such as the human body. They are used also to follow radioactive isotopes in chemical reactions.

C. Qualitative Questions:

1. There are three main types of radiation, α, β and γ.

a. The γ particle is the most penetrating because it has neither mass nor charge, hence it interacts relatively weakly with matter.

b. Alpha particles [He nuclei] are very large, but unable to penetrate the human body. Their danger lies in being inhaled or ingested as once inside, they are strongly ionising. They are stopped by air due to collisions with oxygen and nitrogen molecules. In each collision they lose some energy in ionising the air molecules.

c. α emitters are not considered dangerous unless inhaled or ingested because they have very little penetrating power and can usually be stopped by clothing or the air.

d. γ rays are absorbed by interactions with electrons, so heavy elements, like lead, which have a lot of electrons make good shields against γ rays.

e.

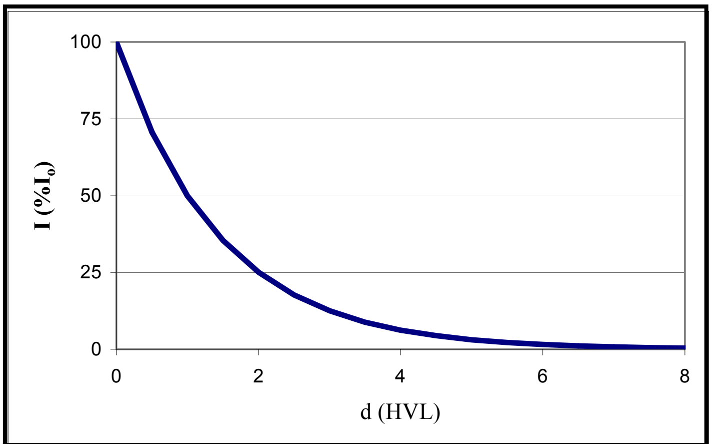
PARTICLE	IONISING ABILITY	PENETRATING ABILITY
Alpha [He nucleus]	Ionises by direct contact with atoms.	Stopped by a few cm. of air or paper. Unable to penetrate the skin because of its large size.
Beta [electron]	Ionise by interaction with atomic electrons in tissue	Because of small mass can penetrate about 1 cm.
Neutron	Does not directly ionise, but transfers their energy to collisions with protons, which then go on to ionise atoms	Very penetrating because of its uncharged nature. Travels hundreds of metres in air.

2. Following the Chernobyl accident the sale of milk was banned. This was because of the fall-out of radioactive isotope ^{90}Sr. This is a reactive metal in the same periodic group as calcium. ^{90}Sr has a relatively long ½ life and is dispersed in varying concentrations throughout the earth's atmosphere and soil. It is readily taken up in the tissues of plants and animals and may enter the human food supply through milk. It is particularly dangerous for growing children as it is easily deposited in the bones and is believed to induce bone cancer.

D. Quantitative Question:

a. The intensity at distance d is $I(d) = I_o\, e^{-\mu d}$.

b. See diagram opposite.



c. Many processes follow this form, such as radioactive decay as a function of time, cooling, and population decay.

d. Each HVL decreases the intensity by 50% or ½. The HVL for Aluminium is 5.0 cm, so 25 cm is 5 HVLs. The reduced intensity is therefore
$\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = (\frac{1}{2})^5 = 1/32$ or 3%,
a reduction of 97%.
You can also do this using
$I(25\text{cm}) = I_o e^{-\mu\, 25\text{cm}} = I_o e^{-\,0.028\times 25\text{cm}} = 0.03\, I_o$.

e. To reduce the intensity by 75% (reducing to 25% or ¼) using any material you need to use $d = 2 \times$ HVL for that material (½ × ½ = ¼). For lead this is 2 × 1.2 cm = 2.4 cm.

f. To reduce the intensity by 75% using air only (no shielding) you would need 2 × HVL = 200 m of air.

material	HVL (cm)
Lead	1.2
aluminium	5.0
air	10,000