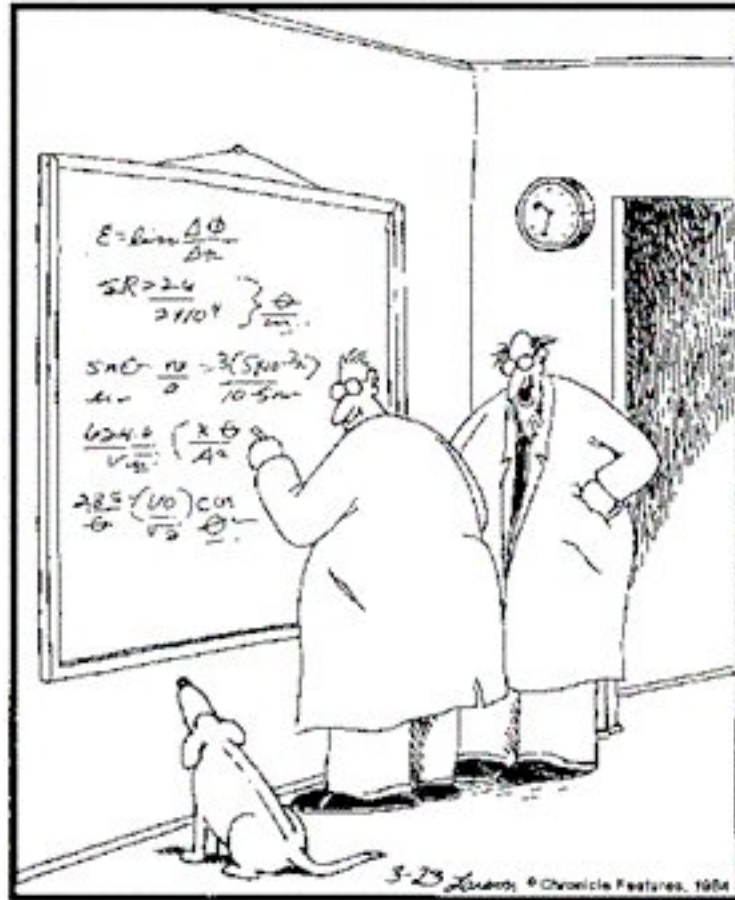


THE FAR SIDE

By GARY LARSON



"Ohhhhhh . . . Look at that, Schuster . . .
Dogs are so cute when they try to comprehend
quantum mechanics."

SPH4UI

Unit 5: Modern Physics

Unit 5 Overview

Lesson	Text Reference	Topic	Questions	Done
1	12.2	Max Planck & the Photoelectric Effect	Pg 624 P#1, 2; Pg 629 P# 1 – 3; Pg 631 Q#1 – 3, 5, 6	
L5.1	--	Determining Planck's Constant	Lab Write-up & Discussion	
2	12.2 & 12.3	Photon Momentum & Matter Waves	Pg 626 P#1 – 3, Pg 631 Q#4; Pg 634 P#1 – 4	
3	12.6	The Bohr Atom	W/S Bohr Model Questions	
4	12.3	Heisenberg's Uncertainty Principal	W/S Heisenberg	
5	11.1	Einstein's Postulates	Pg 579 Q#1, 3, 10	
L5.2	--	Determining the Speed of Light Using Microwaves	Lab Write-up & Discussion	
6	11.2 & 11.3	Consequences of Special Relativity	Pg 585 P#1 – 5; Pg 587 Q#6, 7; Pg 591 P#1 – 3; Pg 597 Q#1, 2	
7	11.3	Mass Dilation & Velocity Addition	W/S Mass Dilation & Adding Fast Speeds	
8	11.3 & 11.4	Mass-Energy Equivalence	Pg 596 P#1 – 4; Pg 602 P#1 – 4; Pg 603 Q#3, 5 – 7, 9, 11	
9	12.6	Particle Physics	W/S – Particle Physics	

Lesson 1 – Max Planck and the Photoelectric Effect

Most of the physics you have learned in both grade 11 and grade 12 is known as *classical physics* – concepts that are largely based on Newtonian Mechanics. As we saw with objects travelling at velocities close to the speed of light, we sometimes need to adjust the laws of classical mechanics to fit with our observations.

As the 20th Century progressed, many experimental and theoretical problems were resolved by the special theory of relativity. But there were many other types of problems that the laws of classical physics could not provide a theoretical answer.

Consider light, for example:

Although it became widely accepted, the classical, or wave theory of light had several problems. Even though it explained many of the properties of light exceedingly well, there were some phenomena it could not account for.

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How then, do we account for these problems? Each of these problems has an explanation in Quantum Physics – the idea or premise that the energy of a given system is quantized into specific values. Over the next few lessons we will investigate each of the above problems.

Black-body Radiation

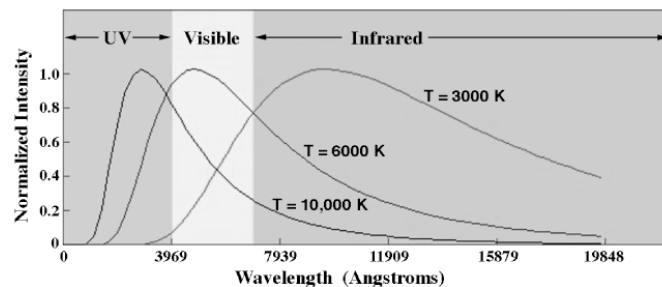
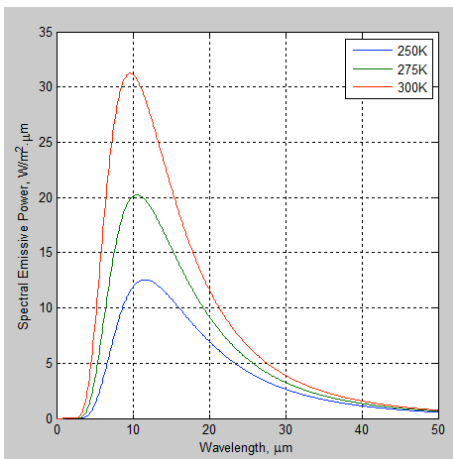
Any opaque object that has a temperature above absolute zero (0 K) gives off radiation. One can feel warm objects without touching them – fire, a stove element, Sun – and this effect is known as **black-body radiation**. The characteristics of this radiation depend on the temperature and properties of the object.

At low temperatures –

As the temperature increases –

At high temperatures –

As the temperature of the object is increased the thermal radiation it emits consists of a continuous distribution of wavelengths from the infrared, visible and ultraviolet portions of the spectrum.



Two important observations:

- 1)
- 2)

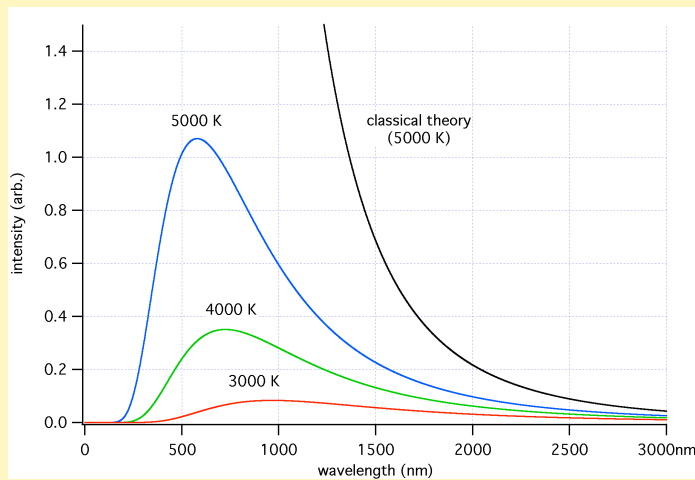
Scientists set out to explain this phenomenon.

The shift in peak wavelength corresponding to different temperatures obeys **Wein's Law** and is given by

$$\lambda_{\max} = \frac{2.898 \times 10^{-3}}{T}$$

λ_{\max} is the wavelength associated with the most common photons (the peak wavelength) in metres and T is the temperature of the black body in Kelvin.

Maxwell, who worked with the premise of electromagnetic waves, said that the radiation originated from the oscillation of electric charges in the molecules of the material. As the temperature increases, the frequency of oscillations increases. This helped explain where the radiation came from but did not predict the spectrum seen.



Lord Rayleigh and James Jean developed a theoretical equation based on Maxwell's work. This became known as the **Rayleigh-Jeans Law** and it correctly predicted the intensity of visible light. However, as the wavelength decreases (for UV light) the theory falls apart because it predicted that the energy of the wave approached infinity.

This became known as the UV catastrophe.

The Origins of Quantum Physics

In 1900, Max Planck derived a formula for black body radiation that was in complete agreement with observation. In his theory he made two assumptions about the nature of the oscillating molecules at the surface of the black body:

1. The molecules can have only *discrete* values of energy E_n , given by

where n is a positive integer called a **quantum number**, f is the natural frequency of oscillation of the molecules, and h is Planck's constant.

$$h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$$

The molecules are only allowed to have certain discrete values of energy, we say that the energy is *quantized* and each energy level represents a different *quantum state* for the molecule.

2. The molecules emit or absorb energy in discrete packets (quanta) that later came to be called **photons**. The molecules emit or absorb these photons by “jumping” from one quantum state to another. If the jump is downward from one state to an adjacent lower state, the molecule emits a photon. The difference in energy between two levels is hf and we find an expression for the energy of a photon:

$$E = hf$$

Also,

Example 1

If a metal bar is heated in a shop so that the peak wavelength in its spectrum is $2.6 \mu\text{m}$ long, determine

- a) its temperature.
- b) the energy in the photons at the peak wavelength, in joules.
- c) in which part of the electromagnetic spectrum are the peak photons found?

The Photoelectric Effect

In 1887, Heinrich Hertz noticed that when light of certain energy was shone on a metallic surface, electrons were ejected.

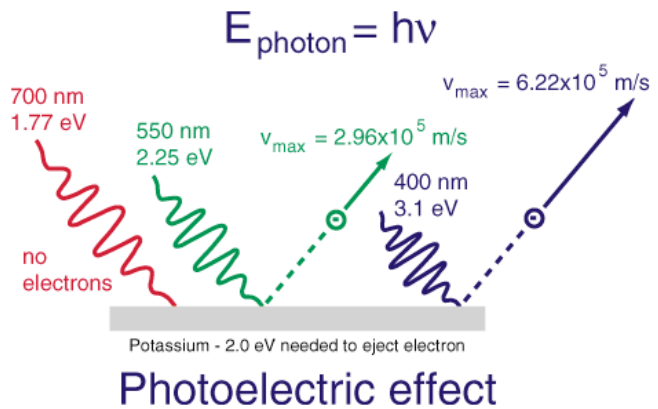
The emitted electrons are called photoelectrons and this phenomenon was called the **photoelectric effect**.

Albert Einstein used Planck's quantum idea to explain the observations Hertz had made. Some of the important findings:

✓

✓

✓



Good to Know

Recall that an electron-volt is another unit for energy. It is often useful when dealing with very small quantities.

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

Einstein suggested that the energy of the light was transmitted in bundles of energy called photons and that the amount of energy in these bundles was dictated by Planck's equation. He went on to reason that each electron near the surface in the metal needed to absorb a photon to escape. Some of the energy would be used to escape, and the rest transferred to the electrons kinetic energy.

$$E_{\text{photon}} = W + E_k$$

Where E_{photon} is the energy of the incident photon, W is the energy with which the electron is held to the surface and E_k is the kinetic energy of the emitted electron. This is known as **Einstein's Photoelectric Equation** and is sometimes written as

$$E_k = hf - W$$

Often, W is referred to as the work function, since work must be done to liberate the electrons from the surface. It is a property of the photoelectric metal. Note that in order for the photoelectric effect to occur, the energy of the incident photon must be higher than the work function of the metal.

Example 2

A material with a known work function of 2.3 eV is shone with incident light of wavelength 632 nm . Will this light cause the metal to exhibit the photoelectric effect and if not, what maximum wavelength will cause the photoelectric effect?

Example 3

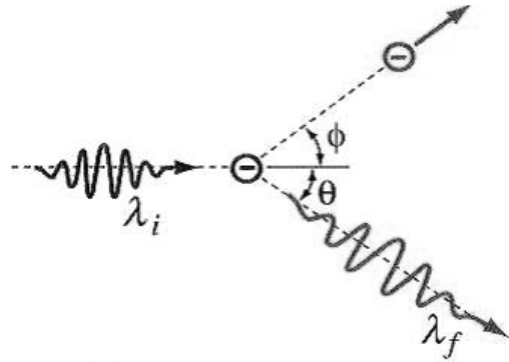
A sodium surface is illuminated with light having a wavelength of 300 nm . The work function for sodium metal is 2.46 eV . Find the maximum kinetic energy of the ejected electrons and the cutoff wavelength for sodium.

Lesson 2 – Photon Momentum & Matter Waves

The Compton Effect

In St. Louis in 1923, Arthur Holly Compton performed a series of different experiments involving the photoelectric effect. He directed high energy x-rays with a known frequency at a thin metal foil. As well as observing ejected electrons due to the photoelectric effect, he also noted that lower energy photons were emitted.

The emitted photons, as it turns out, are simply the original x-rays that have been deflected because of their collision with the electron. This deflection of photons is called **scattering** and the effect is called the **Compton Effect**.



Compton hypothesized that if he treated photons as particles, he could analyze the collisions of the photons and electrons using motion techniques.

Compton proposed

Which is simply the conservation of energy. He also asserted that momentum would also be conserved. But what is the momentum of a photon? It is a bundle of energy with no mass that travels at the speed of light.

In 1905, the same year that he published his analysis of the photoelectric effect, Albert Einstein suggested that mass is another form of energy. He postulated that the decrease in mass of a system should show up as an increase in energy according to his famous equation

$$E = mc^2$$

This equation indicates that a body with energy E has a mass equivalence of

Compton's work showed that photons collide and exchange energy with particles according to the law of conservation of energy, that they possess momentum and that their momentum is conserved during collisions. His work lent support to the idea that light is both a wave and a particle. In 1927 Compton would win the Nobel prize for his contributions.

Example 1

A 25 eV x-ray photon collides with an electron. What is the momentum of the original photon?

Example 2

An 85 eV x-ray collides with an electron. The resultant photon is deflected 60° from the original line of travel and has a wavelength of 214 nm.

- a) Find the momentum of the original and deflected photon.
- b) Find the energy given to the electron and calculate the electrons speed.

Louis De Broglie

In 1924, Louis de Broglie, a French grad student, expanded on Compton's work. He suggested that since photons have a detectable momentum (a property of matter) then it is possible to explain matter in terms of waves. This reversibility would not be a far stretch – the reversibility of electricity and magnetism had already been discovered.

De Broglie stated

This wavelength is known as the de Broglie wavelength for particles. His concept was so radical that his graduate degree was held up for a year. De Broglie was awarded the Nobel prize in 1929 for his work.

Example 3

Find the wavelength of a 1-g steel bearing moving at 10 m/s.

Example 4

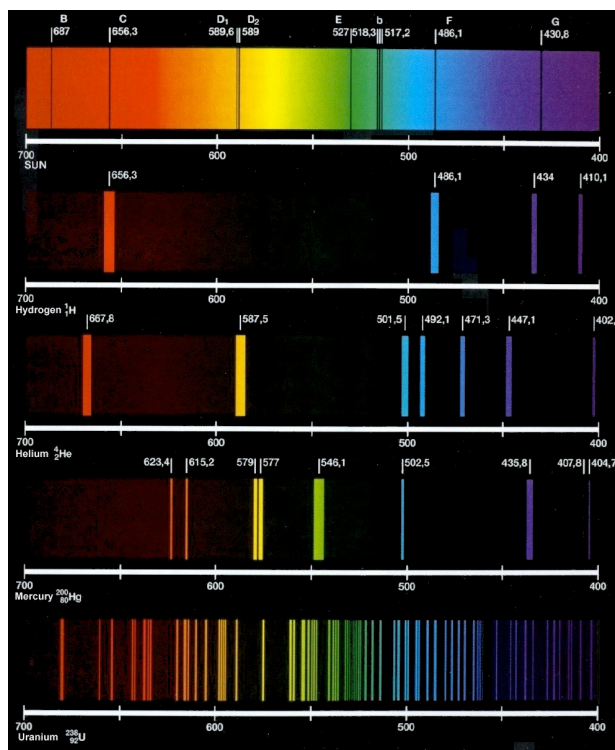
Find the de Broglie wavelength of an electron accelerated from rest through a potential difference of 50 V.

Lesson 3 – The Bohr Atom

Atomic Spectra

We learned in lesson 1 that any object, when heated, gives off a continuous spectrum from the infrared through visible light, to ultraviolet.

But something different happens when we isolate one type of atom, in gas form, and run a current through it. Rather than a continuous spectrum, we obtain a **line spectrum**, a spectrum showing only specific certain colours or specific wavelengths of light.



You can see from the various spectra above that different elements display completely different spectra. In the late 1800s, scientists gathered vast amounts of data on atomic line spectra and in 1885 a Swiss high school teacher named Johann Jacob Balmer found an equation that correctly predicted the four visible emission lines of Hydrogen.

This equation is true for the lines in the visible spectrum of hydrogen and called the Balmer Series. From Balmer's discovery, other spectral lines were found in different ranges of the electromagnetic spectrum – the Paschen Series (infrared) and the Lyman Series (ultraviolet).

It is important to note that Balmer's equation (and those for the Lyman and Paschen series) are empirical – there was no theoretical basis for them; they just worked, so the scientific community used them.

Good to Know

The method of using spectral lines is helpful in determining the composition of stars. The various spectral lines hold the information necessary to determine the presence of gases.

This is how Helium was discovered. Scientists observing the solar atmosphere discovered line spectra of a new element not yet identified.

Interestingly however, in observing distant stars, no elements, other than those on Earth, have been discovered.

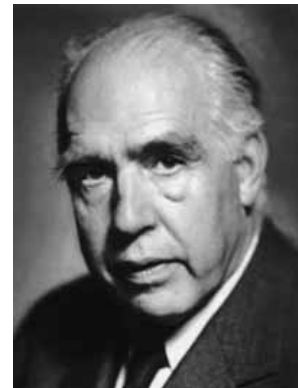
Bohr's Quantum Model of the Atom

Scientists were bothered by two major issues with the classical treatment of the model of the atom.

Inability to Explain SpectraStability of the Atom

In 1913, Danish scientist Niels Bohr introduced a new model of the hydrogen atom, based on Rutherford's planetary model, that explained the spectral lines produced by hydrogen gas and accounted for the observed stability of the atom.

Bohr's model included some aspects of classical physics, Planck's quantum theory, Einstein's photon theory of light and some early models of the atom.



The basic ideas of Bohr's model are as follows:

- 1.
- 2.
- 3.
- 4.

To investigate these basic ideas more in depth, we turn our attention to the conservation of energy and the conservation of angular momentum.

Conservation of Energy

An electron orbiting a nucleus has two kinds of energy –

And we can examine centripetal force as well,

We arrive at a general expression for the total energy of an electron:

Conservation of Angular Momentum

Similar to the momentum of an object travelling in a straight line, we can also describe the momentum of an object that is rotating. We call this angular momentum,

$$L = mvr$$

Where L is the angular momentum of a particle with a mass m , a velocity v and rotating with a radius r . Bohr assumed that angular momentum could be quantized because of its relationship to energy. If energy is quantized, then angular momentum would be as well. Recall from Unit 3 that

$$p = \sqrt{2mE_k}$$

In order to quantize angular momentum, he would need to quantize both velocity and radius and so we modify the above expression:

$$L_n = m v_n r_n$$

Here, n is a positive integer that represents the energy level of the atom. Bohr then suggested that the smallest possible value for L was $h / 2\pi$.

This gives us the quantization of v , which in turn can be substituted into our previous equation for centripetal force.

The final expression for r is the theoretical radius of the orbit of an electron in metres and n is the quantum number.

Example 1

What are the energy and radius for an electron in a hydrogen atom in the fourth energy level?

Photon Wavelength

Based on the discoveries above, we can now determine the wavelength (and corresponding energy) of the escaping photons. This will provide the characteristic spectrum observed in gas discharge tubes.

We again look to the conservation of energy:

This provides a meaningful and straightforward way to find the wavelength of a photon emitted when an electron ‘jumps’ down an energy level.

Example 2

The electron in a hydrogen atom makes a transition from the $n = 2$ energy state to the ground state ($n = 1$). Find the wavelength and frequency of the emitted photon.

Wave-Particle Duality of Light

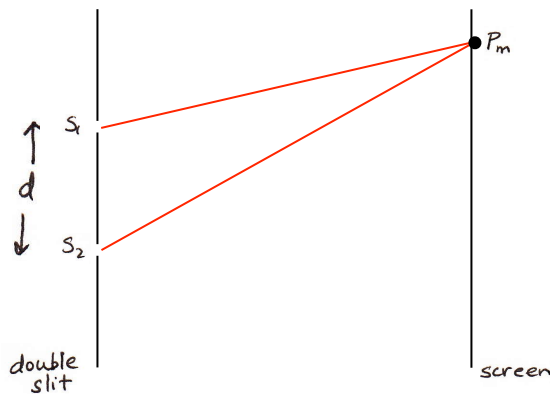
As you have seen in the previous two units, light is a strange subject. It has properties of both waves and particles. We cannot conclude that light is either or, but rather, that it is both. And this combination is not something we can visualize. This premise is known as the **wave-particle duality** of light. Bohr suggested that to understand a given experiment, we must use either the wave or the photon theory of light, but not both – and to fully understand light we need to be aware of both models. He called this the **principle of complementarity**.

Lesson 4 – Heisenberg’s Uncertainty Principle

Probability Waves

Unfortunately, light and other tiny particles (electrons, protons or neutrons for example) are invisible to humans. So to *observe* the behaviour or motion of these particles is impossible. Due to this uncertainty, we must rely on probability in order to describe the motion of tiny particles.

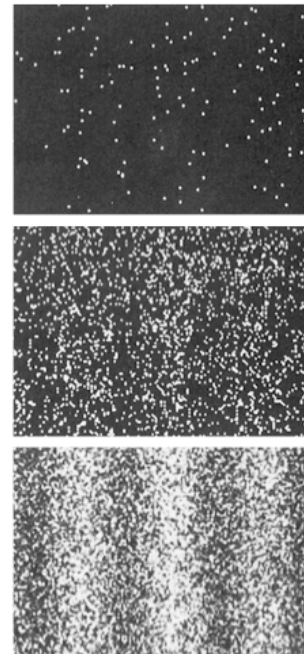
Probability is a very important concept in quantum mechanics. Lets revisit Young’s double slit experiment to illustrate this importance. We need to be able to explain the observed interference pattern using quantum theory.



The answer is that we don’t know – and more specifically, that we *can’t* know. Consider, for a moment, what we would use to measure this effect – light. We know that photons will interact with other photons.

What we are measuring is comparable in size to *what we are attempting to measure with*. This concept is known as **determinacy**.

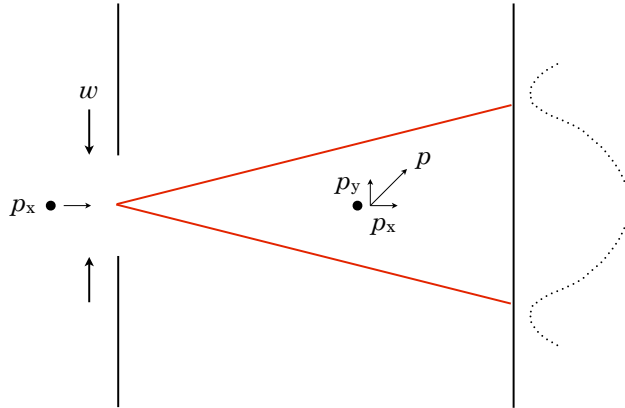
Thought Experiment



Because of indeterminacy, we cannot know what happens in between the source and the screen. We can only look at the screen and predict the probability of where the photons will end up, that is the photon's **probability distribution**.

Heisenberg

In order to develop Heisenberg's Uncertainty Principle, let's consider a simple model of single slit diffraction as applied to photons.



This can also be applied to energy considerations if we use the ideas of Planck and de Broglie.

The Uncertainty Principle

If we know the position of a particle, we cannot know its momentum and vice versa. Similarly, if we know the energy of a particle, we cannot know the length of time it has that energy and vice versa.

Question: Why isn't this observed with macroscopic objects?

Example 1

In a diffraction pattern, an electron is deflected with a speed of 1000 m/s in the y direction. How precisely do we know its position in the slit?

Example 2

An alpha particle (ionized helium nucleus) is emitted from the decay of U^{238} . If this particle has an energy of 34 keV, what is the uncertainty in its position?

Developments in Quantum Mechanics

The study of quantum physics extends well beyond Heisenberg's Uncertainty Principle. Increasing in complexity, various concepts become more dependent on calculus and involved mathematics, and as such, our study of the subject ends here.

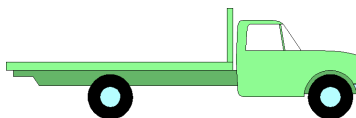
In general however, the next steps in learning quantum mechanics have a great deal to do with describing tiny objects (photons or electrons, for example) as waves. Matter waves, as illustrated by deBroglie, are described by complex-valued wave functions, given the symbol ψ . The wave function contains all the information that is known about the particle and is related to the probability of finding the particle at a specific point in time.

The wave function for deBroglie waves must satisfy the famous **Schrödinger Equation**. One very common task in quantum mechanics is to determine a solution to the equation and then determine the allowed wave functions and energy levels for the system in question.

$$\frac{\partial^2 \psi}{\partial x^2} = -\frac{2m}{\hbar^2} (E - U) \psi$$

Lesson 5 – Einstein's Postulates

All motion is relative depending on your frame of reference.



In the truck's frame of reference, the pitcher and catcher would agree on the speed of the baseball. As viewed from the ground however, an observer would see the baseball travel at a different speed.

The First Postulate

In general, there are two different types of reference frames:

Inertial Frame of Reference

Non-Inertial Frame of Reference

In thinking about these frames of reference, Einstein proposed a theory that boldly changed the way we look at space and time.

The Principle of Relativity

Consider now, an example of the truth of Einstein's first postulate.

Example 1

A physics student, Alphonse, is sitting at the dinner table when his 6.0 kg turkey suddenly explodes into two equal pieces. One piece moves 2.0 m/s [L], while the other moves 2.0 m/s [R]. At this very moment, Beauregard walks by the table moving at 2.0 m/s [L]. Determine the change in Kinetic Energy of the turkey from both A and B's point of view.

Example 1 *continued*

What makes this postulate so bold is that it asserts that **all** the laws of physics – those dealing with mechanics, electricity and magnetism, optics, thermodynamics, and so on – are the same in all reference frames moving with constant velocity relative to one another.

The Second Postulate

In grade 11, we learned that sound is a wave and travels at different velocities depending on the medium. We also saw evidence from the Doppler Effect that sound changes depending on certain conditions. As we will learn in the coming units, light is a very unique subject. It has properties of both particles and waves. In fact, light is different than sound in many ways and a few revolutionary experiments taught us that light does not require a medium to propagate.

Consider this...

You and a friend are outside on opposite ends of the football field.

If your friend calls out to you, how might the sound change if there is a strong wind towards your friend?

Based on this and his conviction that the laws of physics are the same in all inertial frames of reference, Einstein developed his second postulate of special relativity.

The Constancy of the Speed of Light

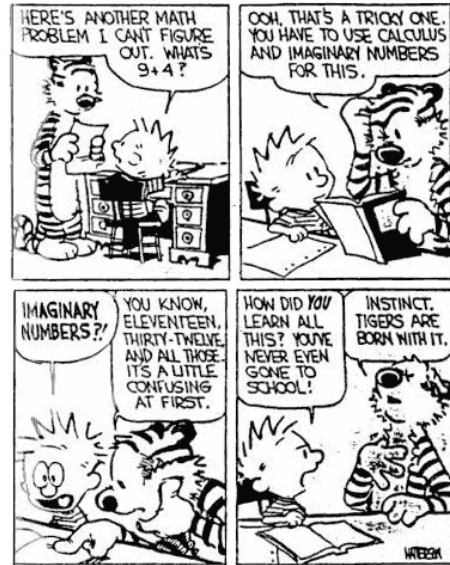
Lesson 6 – Consequences of Special Relativity

If we are to accept the Einstein's theory of Special Relativity, we must conclude that relative motion (as we know it) is not important when measuring the speed of light. We also have to do away with our common sense notion of space and time. This can be difficult, especially considering that most (if not all) of our experience deals with objects moving no where near the speed of light. Get ready to experience the bizarre effects of moving close to the speed of light.

Time Dilation

Moving clocks run slow. This is one effect of the theory of special relativity. Using

Einstein's two postulates and Pythagoras, we can show that the measurement of time depends on your speed.



Consider this... *Thought Experiment 1*

Alphonse is in a boxcar travelling at a speed v . He performs the following experiment: a pulse of light is transmitted from the floor up toward the ceiling, where it hits a mirror and is reflected back to the floor.

Beauregard, observing Alphonse's experiment from the ground as he rides by, notices something different than Alphonse. From Beauregard's point of view, the light travels up to the ceiling while the boxcar moves sideways. She notices the light travels farther than Alphonse does and she measures a time t greater than t_0 .

If the laws of Physics must be the same for both A's and B's inertial frames of reference (first postulate) and light travels at c (second postulate) in both frames, A and B **must** measure a different time for the experiment!

Time, measured by Beauregard, is given by the equation

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Where t is relativistic time, measured in a frame of reference where the beginning and end of the experiment occur *at two different points in space*; and t_o is proper time, measured in a frame of reference where the beginning and end of the experiment occur *at the same point in space*.

Example 1

The period of a pendulum is measured to be 3.0 s in the reference frame of the pendulum. What is the period when measured by an observer traveling at speed of $0.95c$ relative to the pendulum?

Length Contraction

Moving objects appear shorter. This is another affect of the special theory of relativity. As we noted above, time is relative, and using this relationship we can show that length measurements are also relative.

Consider this... *Thought Experiment 2*

Clyde is travelling on a spaceship from Earth to Mars and moving with a speed v . We will assume that Earth and Mars are at rest relative to each other and located a distance L_o apart.

For Delilah, an observer on Earth, the time taken for this trip is $t = \frac{L_o}{v}$. **Proper length**, L_o is the length measured in a reference frame in which the *observed object is at rest* (in this case, the distance between the planets).

For Clyde, proper time t_o (measured on the clock in his spaceship) is less because time dilates. Clyde sees himself at rest, with Mars approaching and Earth receding. Putting these things together we can calculate the **relativistic length** of Clyde's trip.

A general formula for relativistic length is given by

$$L = L_o \sqrt{1 - \frac{v^2}{c^2}}$$

Example 2

A spaceship is measured to be 120.0 m long while at rest relative to an observer. If the spaceship flies by the observer at $0.99c$, what length does the observer measure?

The Twin Paradox

A paradox is a situation in which people reach contradictory conclusions using valid deductions from premises that are acceptable to everyone. The twin paradox is one of the most famous in relativity.

A set of twins named Eunice and Francisco reach an age of 20 years old. Eunice, who is more adventurous, sets out on an epic journey to the planet X, located 20 light-years from Earth. Furthermore, her spaceship is capable of reaching speeds of $0.95c$, relative to the inertial frame of her brother back home. After reaching the Planet X, Eunice becomes homesick and immediately returns to the Earth at the same speed $0.95c$. Upon her return, Eunice is shocked to discover that Francisco has aged 42 years and is now 62 years old. Eunice on the other hand, has only aged 13 years.

Example 3

Verify the final ages of the twins in the situation described above.

But here is the paradox: which twin was actually the traveller? From Francisco's frame of reference, it was he who stayed home while his sister Eunice travelled at a high speed. From Eunice's frame of reference, she was at rest while her brother was on the high-speed journey.

What is the problem with the Twin Paradox?

Lesson 7 – Mass Dilation & Velocity Addition

Mass Dilation

Combining circular motion and the Coulomb force along with the notion of length contraction, we can easily arrive at an expression for mass dilation. Consider an electron in circular motion around a proton. The Coulomb force of attraction provides the centripetal force and we arrive at the following:

Isolate the term for mass and we have

Now for very fast electron speeds, the radius of the orbit is contracted due to relativistic effects,

And we make a substitution for rest mass, m_0

Example 2

Find the dilated mass of a cosmic pion of rest mass 2.5×10^{-28} kg if it is moving at a speed of $0.99c$.

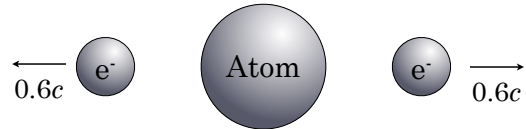
Example 3

An electron travels at $0.69c$ in a circle perpendicular to a uniform magnetic field of strength 2.0 T. Find the radius of the circle and compare it to the radius calculated without considering mass dilation.

Velocity Addition at High Speeds

We know that Einstein's second postulate states that the speed of light is absolute. If we were to use classical physics to find the relative speed of two fast moving objects, a contradiction could occur.

Consider for example, two electrons being repelled by a large positive charge.



To find the relative velocity of the electrons,

Here we have violated Einstein's second postulate and thus the answer cannot be accepted. We need a new way to add velocities; it must be able to handle the concerns of Einstein's second postulate, but should also give the classical answer when operating at low speeds.

The result is not exceeding difficult to derive, but has been provided here in the interest of time.

$${}^A\vec{v}_C = \frac{{}^A\vec{v}_B + {}^B\vec{v}_C}{1 + \frac{{}^A\vec{v}_B \cdot {}^B\vec{v}_C}{c^2}}$$

Example 4

Two galaxies are seen to be receding from Earth due to their red shifts. Galaxy A is farther and moves with a speed of $0.8c$. Galaxy B is in line with A, but moves at a slower speed of $0.41c$. How fast is Galaxy A moving with respect to Galaxy B?

Lesson 8 – Mass-Energy Equivalence

Due to the fact that we have switched our view of space, time and mass from classical physics to relativistic physics, we must change the way we think about momentum and energy. Specifically because momentum has to do with **mass** and energy has to do with **distance**.

Relativistic Momentum

In classical physics, the linear momentum of a particle is given by the expression $\vec{p} = m\vec{v}$. At speeds close to c however, mass is dilated and we need a new expression for momentum. Making a substitution for the dilated mass,

We use this law whenever the concept of momentum, or its conservation, concerns relativistic speeds.

Example 1

An electron moves with a speed of $0.750c$. Find its momentum and compare this with the value calculated from the classical expression.

Relativistic Energy

We know that a change in the mechanical energy of a system is called work. And that if we do work on an object by applying a force we can change the object's kinetic energy. Thus, when working with relativistic speeds, we need to modify our equation for energy as well.

The true derivation of this expression is more complex than we are ready to handle. We will deal with a derivation that while valid (assuming certain facts and avoiding unnecessary mathematics) is less elegant.

Due to the fact that mass is dilated at high speeds, it might be tempting to simply correct our expression for kinetic energy similar to how we handled momentum. Instead however, we will utilize Einstein's equation for mass-energy equivalence

$$E = mc^2$$

We can make a substitution for the dilated mass,

And then use a binomial expansion to expand:

We have then,

Einstein called the term m_0c^2 the energy that an object has while it is at rest, or **rest energy**. The total energy is the sum of the rest energy and the kinetic energy.

$$\text{total energy} = \text{rest energy} + \text{kinetic energy}$$

Example 2

An electron in a television picture tube typically moves with a velocity of $0.250c$. Find its total energy and kinetic energy in electron volts.

Lesson 9 – Particle Physics

Matter

As you have learned in previous science courses, our thoughts about matter have evolved. As you have discovered, our understanding of the atom has changed significantly from the early model of the Greeks, to the current accepted notion that the atom is arranged into a nucleus (containing protons and neutrons) surrounded by negative electron clouds. This lesson is dedicated to explaining some of the current theories that explain many lingering questions. We'll investigate matter first, then forces.

The Standard Model

The Standard Model of fundamental particles and interactions is the latest model of matter and forces. It answers questions about how the nucleus is held together and why certain elements experience nuclear decay. The model describes matter as being composed of smaller, more fundamental particles called *leptons* and *quarks* rather than the more widely recognized protons and neutrons.

Leptons

The electron is a member of a family of particles called leptons. These particles are so basic that they are thought to not contain any internal structure. They have specific characteristics: spin, charge, and mass.

Particle	Symbol	Antiparticle	Mass (MeV/c ²)	Charge	Spin
Electron					
Electron neutrino					
Muon					
Muon neutrino					
Tauon					
Tauon neutrino					

These particles are not affected by the strong nuclear force, rather they interact through the weak nuclear force. They are grouped into pairs, each pair has a charged particle and a neutrino, which has no charge.

Neutrinos have an extremely small rest mass and travel very close to the speed of light. They are nearly impossible to detect even though billions of them are passing through us every second. In the recent past, neutrinos have become very popular as a small group of researchers feel they may have found evidence that they travel faster than the speed of light, although this finding remains to be duplicated.

Muons and Tauons –

Evidence also suggests that each lepton has an antiparticle. Antiparticles carry the same names and are equal in every way but have the opposite charge.

Quarks

In 1964, M. Gell-Mann and G. Zweig proposed that all matter not classified as leptons is made up of quarks. Physicists have given colourful names to each type of quark that help to remember their interaction properties.

Name	Mass	Symbol	Charge
Up			
Down			
Strange			
Charm			
Bottom			
Top			

Hadrons

Hadrons are subatomic particles that are made up of quarks. There are two types of hadrons: baryons and mesons. All baryons are made up of three quarks. There are close to 120 different baryons, made up of different combinations of quarks. The proton and the neutron are two of these 120.

Mesons all consist of one quark and one antiquark. There are about 140 different mesons. One example of a mesons is the pion (π^+)

$$\pi^+ = u\bar{d}$$

Example 1

Calculate the total charge on a pion ($u\bar{d}$) and on a proton (uud).

Fundamental Forces

The four fundamental forces of nature are the gravitational force, the electromagnetic force, the strong nuclear force and the weak nuclear force. All other forces we have encountered are caused by one of these four forces.

We've examined a few of these forces by examining fields, but in terms of quantum mechanics and the Standard Model, force is thought to be carried out in the process of interactions between fundamental particles and the exchange of

force-carrying particles. These special force-carrying particles are known as **bosons** and are constantly exchanged between masses and charges. Each of the four fundamental forces has an associated boson.

Force	Particle	Relative Strength	Symbol
Gravity			
Electromagnetic			
Strong			
Weak			

As an analogy, it is thought that a cloud of swarming bosons, which determine various interactions, surrounds each subatomic particle. Electrons can be considered to be surrounded by virtual photons that mediate the electromagnetic force.

Boson Exchange

In order to illustrate the exchange of virtual particles (particles that cannot be detected because of their short lifespan), Richard Feynmann developed a visual way to explain these interactions. In spacetime diagrams, time is on the y -axis and space is on the x -axis.

Example 2

Describe the interactions that are taking place in the following Feynmann diagram.

