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QUANTUM PHYSICS AND ATOMIC MODELS

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How to Use this File

- Each topic is composed of brief direct instruction

- There are formative assessment questions after every topic denoted by black text and a number in the upper left.

  > Students work in groups to solve these problems but use student responders to enter their own answers.

  > Designed for SMART Response PE student response systems.

  > Use only as many questions as necessary for a sufficient number of students to learn a topic.

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Table of Contents

Click on the topic to go to that section

http://njc.tl/q6

Electrons, X-rays and Radioactivity

Return to Table of Contents

http://njc.tl/q6

Physics by the 19th Century

Newtonian Mechanics.

Maxwell's Equations - unification of electricity and magnetism.

Thermodynamics - heat is another form of energy.

Speed of Light measured - and no stationary reference frame (luminiferous aether) found - helped lead to Einstein's Special Theory of Relativity in 1905.

Many physicists were comfortable that nearly everything had been discovered and explained.

then, things started popping up. Like the electron.

Discovery of the Electron

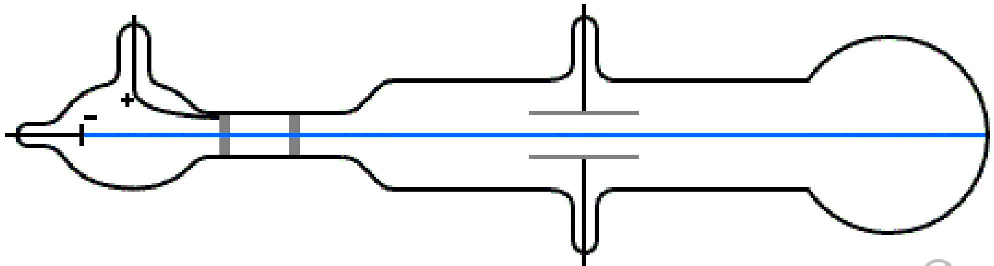
Numerous physicists had worked with passing a current through a tube of rarefied gas. The gas would glow, and the glow intensity would increase as the gas pressure decreased.

Since these rays emanated from the cathode (negatively charged terminal), they were named cathode rays. It was also shown that a magnetic field would change the direction of the rays, showing that they possessed a negative charge.

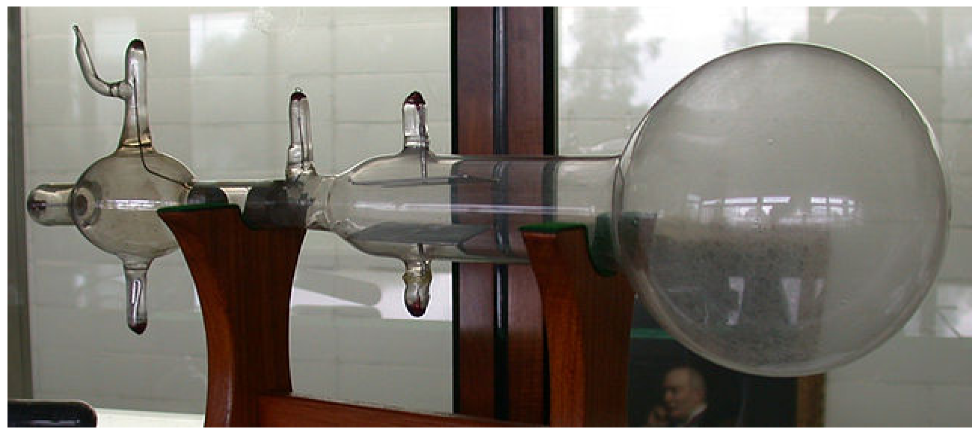
In 1897, J. J. Thomson found that these cathode rays were actually discrete particles, which were then named electrons.

He measured the mass to charge ratio, estimated that the mass was 1/1800 of an Hydrogen atom and stated that all electrons were the same, independent of the material that emitted them.

Discovery of the Electron

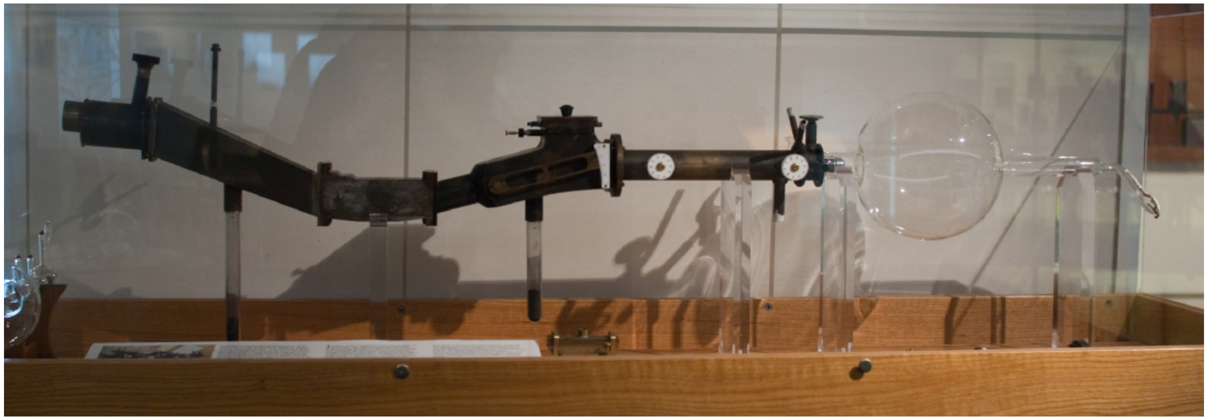


A replica of the Crooke's Tube used by J.J. Thomson at Cambridge University.



Thomson used a Crooke's Tube as shown above. Electrons were emitted from the cathode on the left, and were deflected by an electric field set up in the middle of the apparatus.

Discovery of the Electron



A replica of the third Mass Spectrometer used by J. J. Thomson (you may have seen that in the Magnetism chapter) was used to determine the mass to charge ratio of the electron. It was left to Robert Millikan and Harvey Fletcher to measure the charge, which then gave the value for the mass.

ctrons enter the Spectrometer from the right, into the ocity selector, then through the magnetic field which parates out the particles according to their mass.

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Discovery of the Electron

The electron velocity was set in the velocity selector by adjusting the magnetic field and electric field so that their forces cancelled out - only electrons with the selected velocity would pass into the curved section of the mass spectrometer.

$$\Sigma F = ma$$

$$F_B - F_E = 0$$

$$qvB = qE$$

$$v = \frac{E}{B}$$

Discovery of the Electron

The electrons with velocity v=E/B then entered an area with only a Magnetic Field. This exerted a perpendicular force on the electrons, so they moved in a circle. The radius of the circular path was measured by observing where the electrons struck the side of the tube.

$$\Sigma F = ma$$

$$F_B = m\frac{v^2}{r}$$

$$qvB = m\frac{v^2}{r}$$

$$\frac{q}{m} = \frac{v}{Br} = \frac{E}{B^2 r}$$

Substituting in the set values for E and B, and the measured r:

$$\frac{q}{m} = 1.76x10^{11}\ C/kg$$

Thus, the charge to mass ratio was determined.

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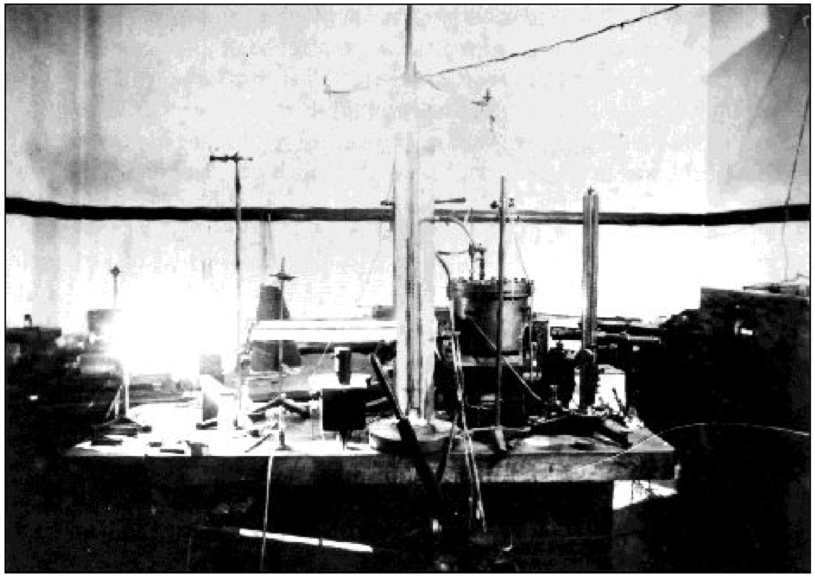
Millikan Oil Drop Experiment



Robert Millikan and Harvey Fletcher determined the charge on the electron by using the experimental setup above.

w that the charge on the electron was known, the mass
ıld be found by using Thomson's determination of the
arge to mass ratio.

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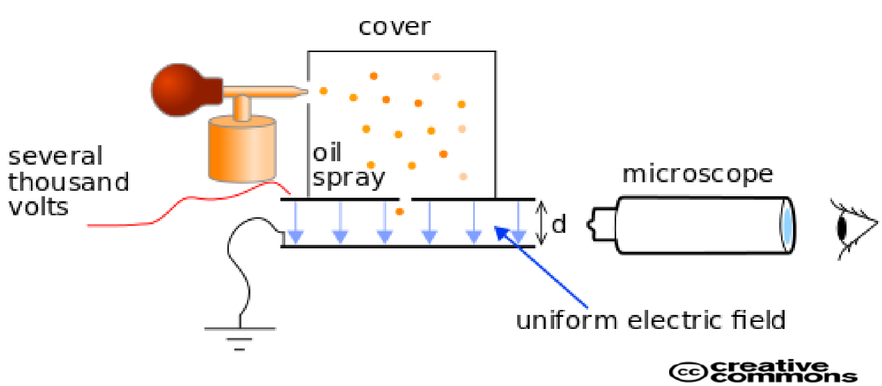
Millikan Oil Drop Experiment



Oil drops were sprayed into a container where they were charged by a high potential source.

The Electric Potential was adjusted so that the drops fell with a constant velocity.

This meant (Newton's Second Law) that the net force on the oil drops was zero.

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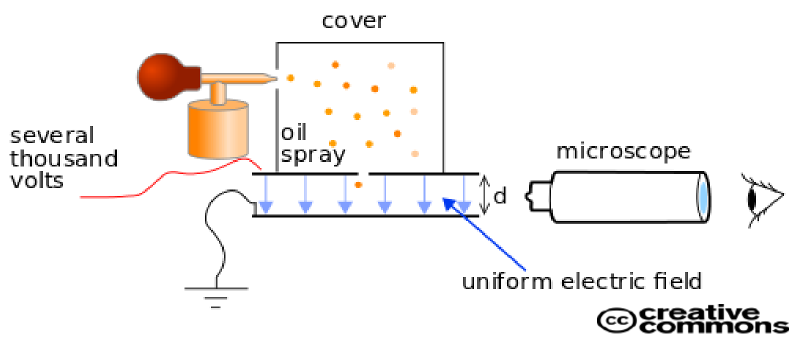
Millikan Oil Drop Experiment



This was a very tedious experiment as thousands of data points were taken, and Millikan's graduate student, Harvey Fletcher, spent days staring into the microscope timing the fall of oil drops.

Using Newton's Second Law, setting the frictional force plus the Electric Field Force equal to the force of gravity, Millikan and Fletcher found that the falling times of all the drops were an integral number of the smallest times.

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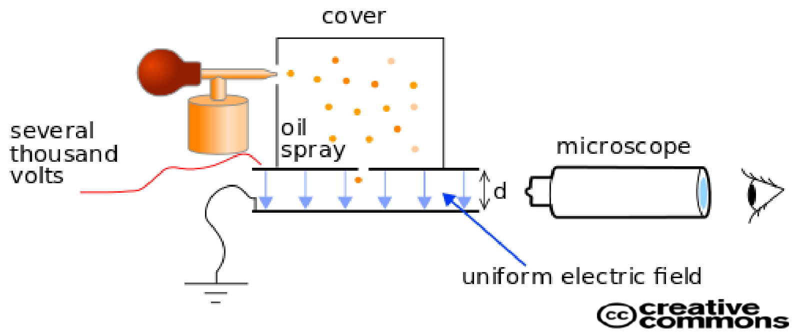
Millikan Oil Drop Experiment



This established the charge of the electron and showed that all charges are integral multiples of the electron charge.

The experiment was repeated many times, with increasing accuracy, by many other groups, and the accepted value of the elementary charge is now 1.602177 x 10^{-19} C.

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1 Which one of the following is not true concerning cathode rays?

- A They originate from the negative electrode (cathode).
- B They travel in straight lines in the absence of electric or magnetic fields.
- C They impart a negative charge to metals exposed to them.
- D They are made up of electrons.

Answer

The characteristics of cathode rays depend on the material from which they are emitted.

http://njc.tl/q7

2 The charge to mass ratio for the electron was determined by:

- A Robert Millikan
- B James Clerk Maxwell
- C J. J. Thomson
- D Harvey Fletcher

Answer

http://njc.tl/q8

3 Which of these values could be the charge of an object?

- A 0.80×10^{-17} C
- B 2.0×10^{-18} C
- C 3.2×10^{-16} C
- D 4.0×10^{-20} C

$$e = 1.602 \times 10^{-19}\ \mathrm{C}$$

Answer

http://njc.tl/q9

4 The charge on an electron was determined by:

- A Cathode Ray Tube experiments by J. J. Thomson.
- B the Rutherford gold foil experiment.
- C the Millikan Oil Drop experiment.
- D Dalton's Atomic theory.
- E the atomic theory of matter.

Answer

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X-rays

The Crooke's Tube that led to the discovery of the electron also was instrumental in the discovery of X-Rays.

William Roentgen noted that a screen placed up to a couple of meters away from an operating Crooke's Tube lit up when it was coated with barium platino cyanide.

He theorized that a radiation was being emitted from the metallic anode when the cathode rays (shown by Thomson to be electrons) struck it.

X-rays

At this time, the dangers of X-rays were not known, and many demonstrations occurred which would not be allowed today.

To the left, is an X-ray photograph of the hand of Roentgen's wife, Anna Bertha Ludwig.

The intensity of the X-rays increased with denser target plates, they penetrated skin, and left images on photographic paper.

It was also discovered that the rays were not affected by electric or magnetic fields - thus they possessed a neutral charge.

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X-rays

Understanding of the nature of X-rays came rapidly.

In 1899, Hermann Haga and Cornelius Wind demonstrated X-ray diffraction through a narrow slit, and estimated the wavelength of X-rays to be 1×10^{-9} m. This indicated a wave nature.

In 1912, Max von Laue showed X-rays diffracting through crystals, which enabled the study of the structure of materials.

Then, in 1923, Arthur Compton showed that X-rays were acting as particles when low intensity X-rays were scattered by electrons.

Radiation

A year after Roentgen discovered X-rays, Henri Becquerel noticed that uranium salts also emitted a type of radiation that exposed photographic paper.

Unlike X-rays, this happened without an external source of energy (the Electric Potential applied to a Crooke's tube).

Marie Curie, and her husband, Pierre Curie, conducted exhaustive experiments and analyses, discovering Radium and Polonium, and coming up with a theory of radioactivity that showed that atoms were not indivisible - they were decaying into other substances.

Curie, Curie and Becquerel were awarded the Nobel Prize in Physics for this discovery in 1903.

http://njc.tl/qb

Radiation

Marie was the first woman to be awarded the Nobel Prize (which she shared with Henri and Pierre), the only person to be awarded the Nobel Prize in two technical disciplines (Physics and Chemistry), and the first woman faculty member at the Ecole Normale Superieure. Sadly, Marie's work led to her early death from radiation exposure.

http://njc.tl/qb

Radiation

Subsequent research by Becquerel, M. Curie, P. Curie, Rutherford, Andrade, Royds, and many others, isolated three types of radiation that were emitted by the soon to be discovered nucleus:

Gamma Rays - a type of high energy (higher than X-rays), high frequency electromagnetic radiation arising from the excitation and deexcitation of protons and neutrons.

Beta Particles - electrons from beta decay in the nucleus (this was the radiation from the Uranium salts).

Alpha Particles - Helium nuclei.

5 X-Rays were first observed when

- A protons impacted upon a metal.
- B neutrons scattered off of a crystal.
- C electrons passed through a double slit.
- D electrons struck a metal target.

Answer

http://njc.tl/qc

6 A difference between X-Rays and Radiation as discovered by Becquerel, M. Curie and P. Curie is:

- A X-Rays were discovered by placing a substance in front of a photographic plate.
- B Radiation occured only when an electric potential was applied to a Crooke's Tube.
- C Radiation was spontaneously emitted from certain substances.
- D All substances emit radiation.

Answer

http://njc.tl/qd

Blackbody Radiation and the Photoelectric Effect

Return to Table of Contents

http://njc.tl/qe

Blackbody Radiation

All objects emit electromagnetic radiation which depends on their temperature: thermal radiation.

A black body absorbs all electromagnetic radiation (light) that falls on it. Because no light is reflected or transmitted, the object appears black when it is cold. However, when black bodies are heated, they emit a temperature-dependent spectrum, [illegible]lackbody radiation.

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Blackbody Radiation

At normal temperatures, we are not aware of this radiation.

But as objects become hotter, we can feel the infrared radiation or heat.

At even hotter temperatures, objects glow red, and at still hotter temperatures, objects will glow white hot such at the filament in a light bulb.

http://njc.tl/qe

Blackbody Radiation

Wilhelm Wien, through experimental observation, determined the following equation that related the color of the light to its temperature:

$$\lambda_{\max} T = 0.28978 x 10^{-2} mK$$

This is Wien's Displacement Law and shows that the higher the temperature, the shorter the wavelength of the peak color of the light. As an object gets hotter, it changes color from red to orange to blue then finally to white (all wavelengths are present in high intensity in the visible spectrum).

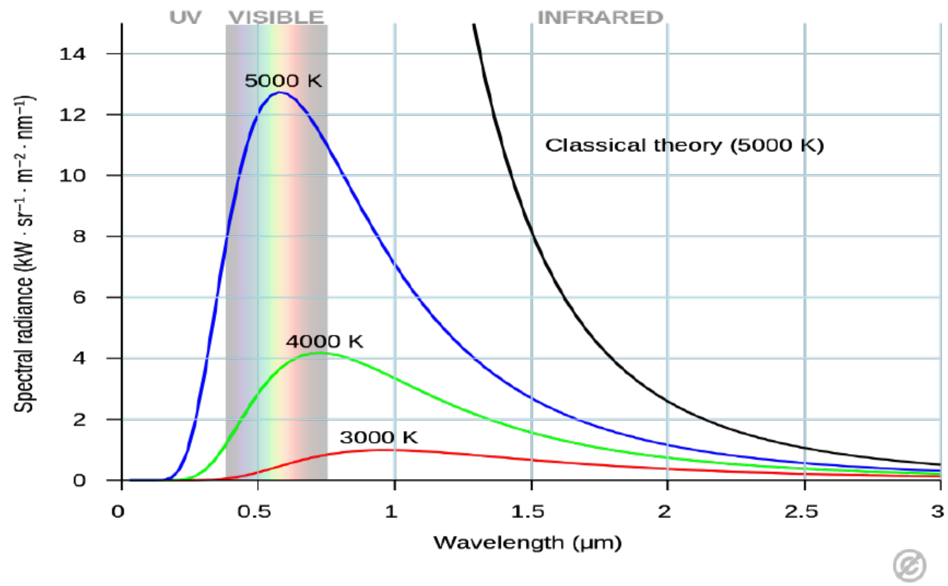
Blackbody Radiation

This figure shows blackbody radiation curves for three different temperatures and the classical prediction of its intensity at 5000 K.

However, classical physics couldn't explain the shape of these spectra - it actually showed that the intensity of the emitted radiation would go to infinity at short wavelengths - this was

' the "Ultraviolet

ophe."



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Blackbody Radiation

In 1900, Max Planck was able to explain the blackbody radiation spectrum by introducing the concept of quantized energy.

He stated that energy associated with the light given off by these radiators could not be emitted with any value. Rather, the energy came in packets, or quanta as they were named later, and it was proportional to the frequency of the light:

$$E = hf$$

E is the energy of the light, h is Planck's Constant and f is the frequency of the light.

Blackbody Radiation

$$E = hf = h\frac{c}{\lambda}$$

Planck continued his analysis to try and make h=0. However, he didn't succeed because it turns out that h is a fundamental constant of the universe and is equal to 6.626×10^{-34} J-s.

This quantum assumption was then confirmed by Albert Einstein when he explained the photoelectric effect - which also brought back Newton's concept of light as a particle!

7 Which of the following colors indicates the hottest temperature of an object?

- A Black.
- B Red.
- C Yellow.
- D Blue.

Answer

http://njc.tl/qf

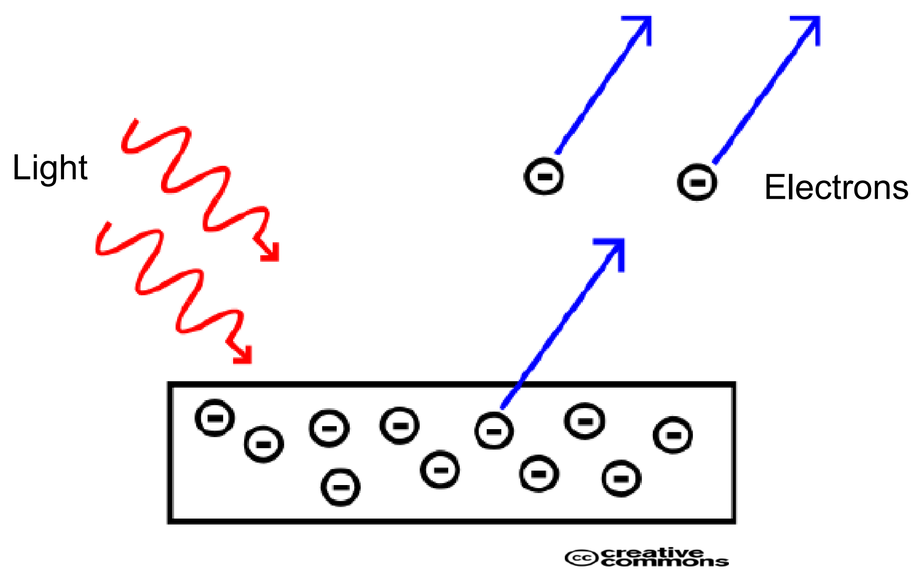
8 What wavelength is the maximum contributor to an object's color at a temperature of 4000.0 K?

Answer

http://njc.tl/qg

Photoelectric Effect

Between 1888 and 1889, Heinrich Hertz, Wilhelm Hallwachs and Philipp Lenard performed experiments that showed light incident upon certain polished metals would emit electrons.



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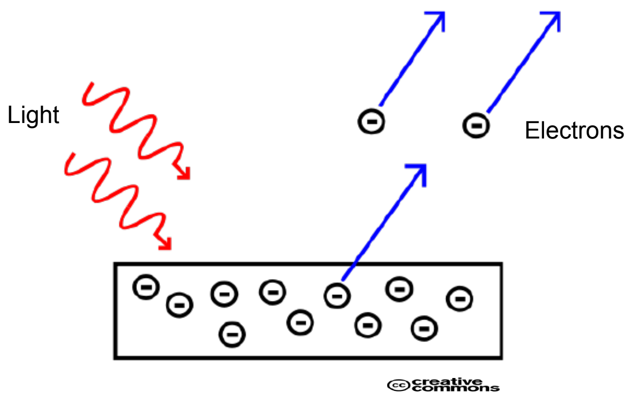
Photoelectric Effect



Below a certain cutoff frequency of the incident light, there were no electrons emitted.

When electrons were emitted, their number were directly proportional to the intensity of the light, but their energy was independent of the light intensity.

The electrons appeared instantly when illuminated by the proper frequency of the light.

se properties could not be explained with the classical wave ory of light.

http://njc.tl/qh

Photoelectric Effect

Einstein expanded Planck's work on the quantized nature of light. Planck applied his quantum theory only to light trapped within a cavity, and theorized that light was a wave outside the cavity.

Einstein stated that light energy came in discrete packets of energy, that were later named photons, again, with the energy described by Planck. Thus, light is a group of photons - which act like particles.

The quantized nature of light is important because an electron was only emitted when a single photon struck it. All of the energy of the single photon was transmitted to the electron, freeing it from its orbit.

Photoelectric Effect

Because the electrons were bound to their atoms, a minimum amount of energy was required to free them. This energy is called the work function (W), and the equation for the maximum kinetic energy of the emitted electron is:

$$KE_{\max} = hf - W$$

All of the observed properties of the Photoelectric Effect were explained by Einstein's work (for which he received his only Nobel Prize).

9 What is the energy of a photon with a frequency of 5.00×10^{22} Hz?

Answer

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10 What is the wavelength of a photon with an energy of 5.00×10^{-11} J?

Answer

http://njc.tl/qj

11 If the wavelength of a photon is cut in half, what is the new value of its energy in terms of its original energy?

Answer

http://njc.tl/qk

12 The ratio of energy to frequency for a photon is

- A its amplitude.
- B its velocity.
- C Planck's constant.
- D its Work function.

Answer

13 What is a photon?

- A An electron in an excited state.
- B A small packet of electromagnetic energy that acts as a particle.
- C One form of a nucleon - one of the particles that makes up the nucleus.
- D An electron that has been made electrically neutral.

Answer

http://njc.tl/qm

14 The energy of a photon depends on

- A its amplitude.
- B its velocity.
- C its frequency.
- D All of the above.

Answer

http://njc.tl/qn

15 The Photoelectric Effect was explained by treating light as a

- A particle.
- B wave.
- C a wave and a particle.
- D None of the above.

Answer

http://njc.tl/qo

16 A photoelectric cell has a work function of 5.0×10^{-19} J. What is the minimum frequency of the incident light that will eject electrons from its surface?

Answer

http://njc.tl/qp

17 Light, with a frequency of 9.5×10^{14} Hz, is incident upon a photoelectric cell with a work function of 5.0×10^{-19} J. What is the maximum kinetic energy of the ejected electrons?

Answer

http://njc.tl/qq

Atomic Models

Return to Table of Contents

Evolution of Atomic Models

The atom was originally viewed around 400 B.C. by the Greek philosophers as an indivisible object whose shape depended on its macro physical properties. e.g., water "atoms" would be slippery, and iron "atoms" would be very solid and hard.

It wasn't until 1802, when John Dalton, based on experimental research, proposed that elements were made up of specific atoms that would combine with each other - and were indivisible, and could not be altered by chemical means.

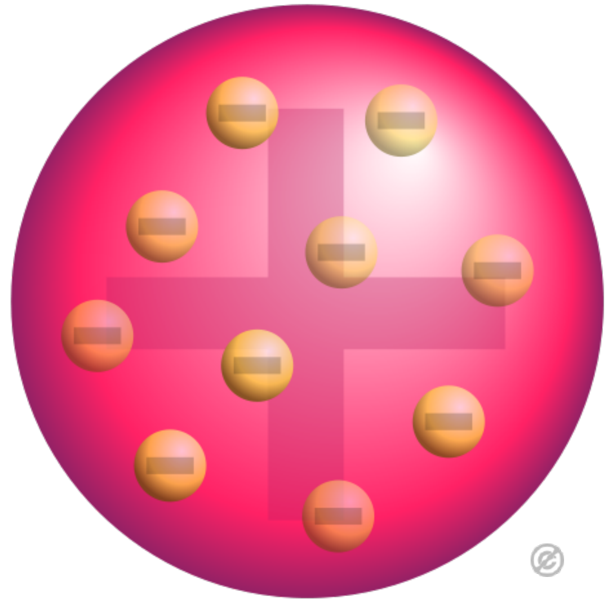
Then models evolved very rapidly, starting with Thomson's discovery of the electron.

Thomson's Plum Pudding Model

Thomson's discovery of the electron was the first evidence that the atom had an underlying structure.

In 1904, he proposed that the electrons moved about within a mass of positive charge - he never really said what the positive charges were.

A plum pudding is an English dessert where raisins (used to be called plums in England) are embedded in an egg, suet and sses mixture, hence the ame.



But, the model could not explain the different wavelengths of light emitted by excited atoms.

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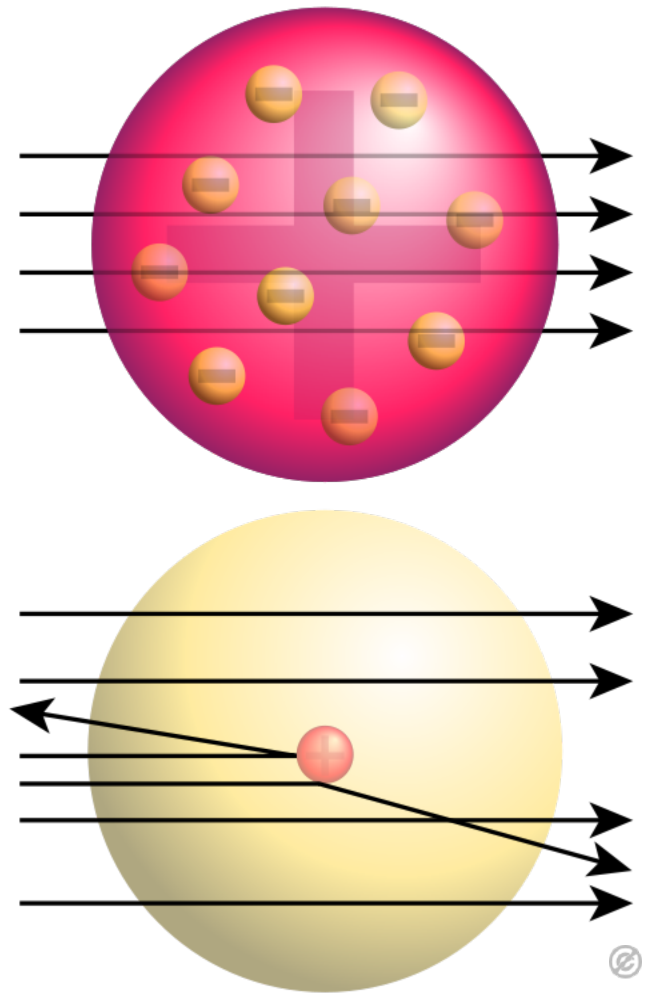
Rutherford Model

The Plum Pudding Model only lasted five years, when work done by one of his students, Ernest Rutherford, and Hans Geiger and Ernest Marsden established that the positive charge was concentrated in a tiny nucleus of diameter 10^{-15} m.



They aimed a beam of alpha particles at gold foil. If the atom were a plum pudding, they expected that the alpha particles would just plow through as shown in the top

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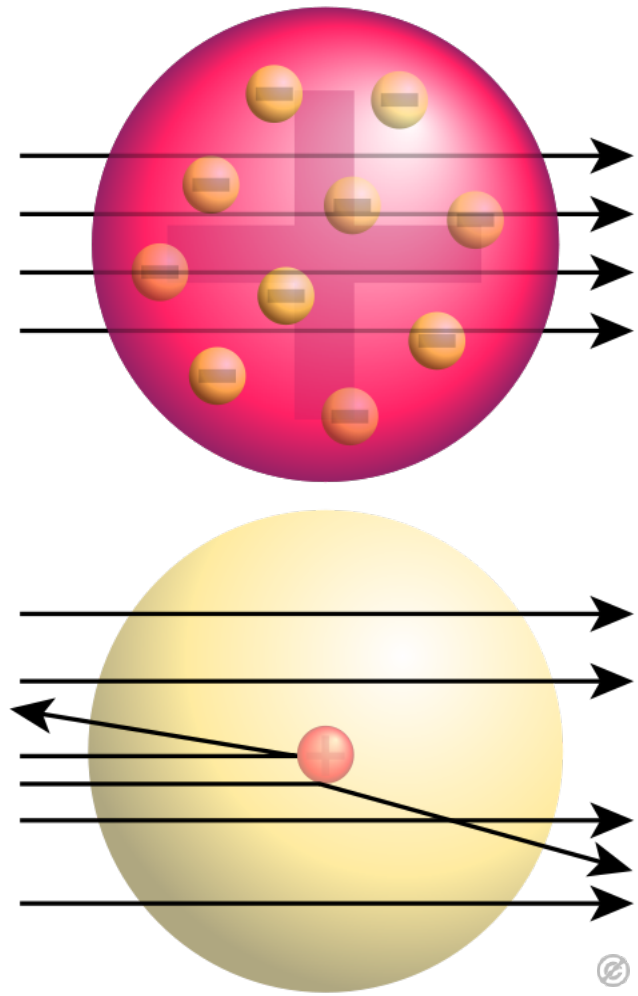
Rutherford Model

But, a very small amount of alpha particles were deflected; some were bounced right back to the alpha source.

As Rutherford said, "It was quite the most incredible event that has happened in my life. It was almost as if you fired a 15-inch shell at a piece of tissue paper, and it came back and hit you."

Hence, the conclusion that the
ve charge was all located
ny region of the atom as
in the lower right.



Rutherford Model

Since all the positive charge of the gold atoms were concentrated in a small nucleus, and most of the atom was just empty space, most of the positively charged alpha particles would not be affected by the positively charged nucleus.

However, for the small percentage of alpha particles that actually struck the nucleus, they would be deflected from their original paths, and in the most extreme case, just bounce right back. Rutherford proposed that the small nucleus was surrounded by electrons in planetary orbits.

Rutherford Model

To emphasize how much of the atom is just empty space - a void - if the nucleus was magnified so that it was the size of a baseball, then the atom would have a radius of 4 km.

The electrons would be the size of the period at the end of this sentence.

The below website presents a great simulation of Rutherford's gold foil experiment.

But, Rutherford could not explain the different wavelengths of light [illegible]ed by excited atoms. That would be left for Niels Bohr.

18 The Plum Pudding model of the atom was important because

- A it was correct in every manner and lasted for many years without any corrections.
- B it confirmed that electrons had a negative charge.
- C it included protons.
- D it was the first model that showed that atoms had an underlying structure.

Answer

19 The gold foil experiment performed under Ernest Rutherford's direction

- A confirmed the plum pudding model of the atom.
- B led to the discovery of the atomic nucleus.
- C was the basis for Thomson's model of the atom.
- D utilized the deflection of beta particles by gold foil.
- E proved the law of multiple proportions.

Answer

http://njc.tl/qt

20 In the Rutherford Nuclear atom model,

- A the heavy part of the atom is very small and is surrounded by electrons.
- B the positive charge in the atom is uniformly spread throughout.
- C the positive charges surround the electrons which are concentrated in the center.
- D the nucleus is physically large compared to the rest of the atom.

Answer

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Bohr Model

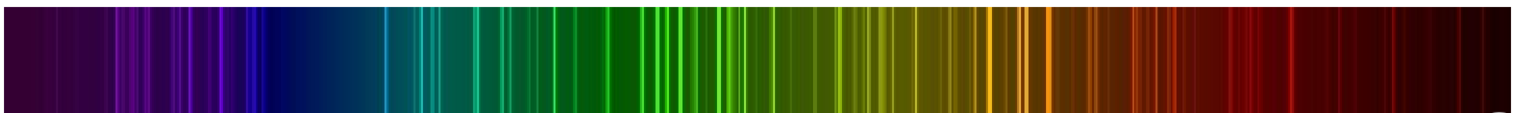
Neils Bohr applied Einstein's (and Newton's!) concept of light as quantized photons to the Rutherford model to explain the optical spectrum for hydrogen like atoms. These are atoms with only one electron such as hydrogen, helium missing one electron, lithium missing two electrons, etc - and obtained good agreement with experimental data.

Despite only having one electron, Hydrogen emits many wavelengths of light when it is excited - and this is what Bohr explained with his model introduced in 1913.

Let's start with these optical spectra.

Optical Spectra

When light is passed through a diffraction grating, interference causes different colors to show up on the detection screen. From the Electromagnetic Waves unit of this course:



With Xenon gas is in a tube, and an electric potential is applied to either end of the tube (like the Crooke's tube), the Xenon gas emits light with frequencies that are unique to Xenon. When this light is passed through a diffraction grating, it results in the above optical spectra.

Rutherford model had no explanation for this.

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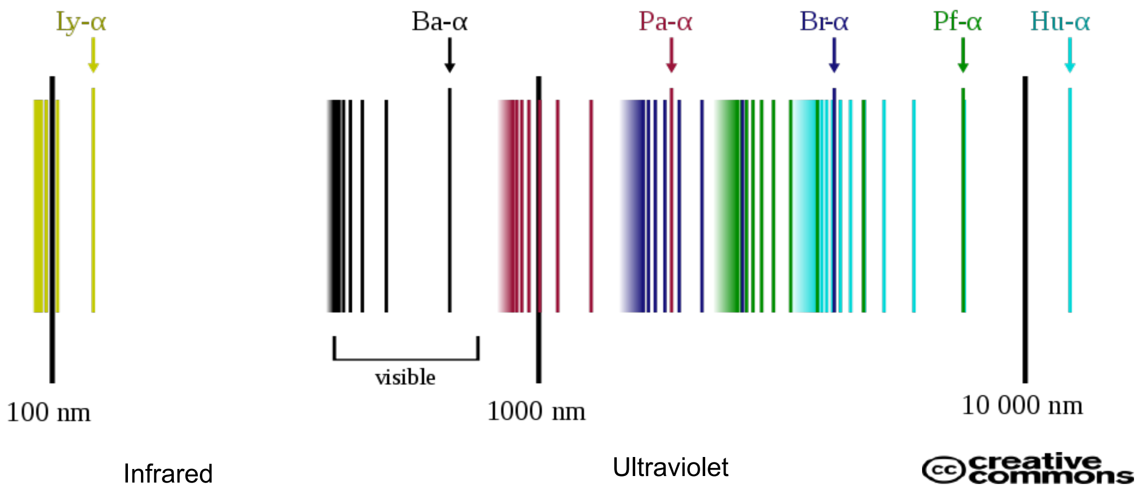
Hydrogen Spectra

Here's the spectrum from ionized Hydrogen gas. This is important because it has been well studied and equations were derived experimentally that would fit this spectra. They will be shown on the next page. What's very interesting is that these empirically derived equations would match Bohr's theory exactly.



Hydrogen Spectra

These equations match exactly where the Hydrogen spectra lines were found by experiment.

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{n^2}\right), \qquad n = 3, 4, \cdots$$

Balmer series

$$\frac{1}{\lambda} = R\left(\frac{1}{1^2} - \frac{1}{n^2}\right), \qquad n = 2, 3, \cdots$$

Lyman series

$$\frac{1}{\lambda} = R\left(\frac{1}{3^2} - \frac{1}{n^2}\right), \qquad n = 4, 5, \cdots$$

Paschen series

$$R = 1.0974 \times 10^7\,\mathrm{m}^{-1}$$

R is the Rydberg Constant

http://njc.tl/qv

Planetary Orbit Problem

Another issue that Bohr needed to address was the "planetary orbits" of the electrons. The electrons in the Rutherford model were kept in orbit by the Coulomb Force providing the centripetal force between the electrons and the positively charged nucleus.

That was good. But, as shown earlier in the 19th century, an accelerating charge would emit electromagnetic radiation, and since the electrons were constantly accelerating (centripetal acceleration), they would lose energy. This loss of energy would cause the electrons to slow down, fall out of orbit and collapse into the nucleus within 10^{-11} s. This doesn't happen, since we're all still here.

http://njc.tl/qv

Bohr's Solution

Neils Bohr made the following assumptions to address the shortcomings of the Rutherford model. It is called a semi classical model as Bohr is combining classical physics with aspects of the emerging quantum world.

- Electrons could only revolve around the nucleus in specific circular orbits with fixed angular momentum and energy. The further away from the nucleus, the greater momentum and energy. When in these orbits, the electrons would not radiate electromagnetic energy.

- Energy is emitted from the atom, in the form of light, when electrons move between orbits. And, not a continuous spectrum of energy - the energy would be quantized - only photons of particular energy would be emitted, representing the energy difference between the allowed orbits.

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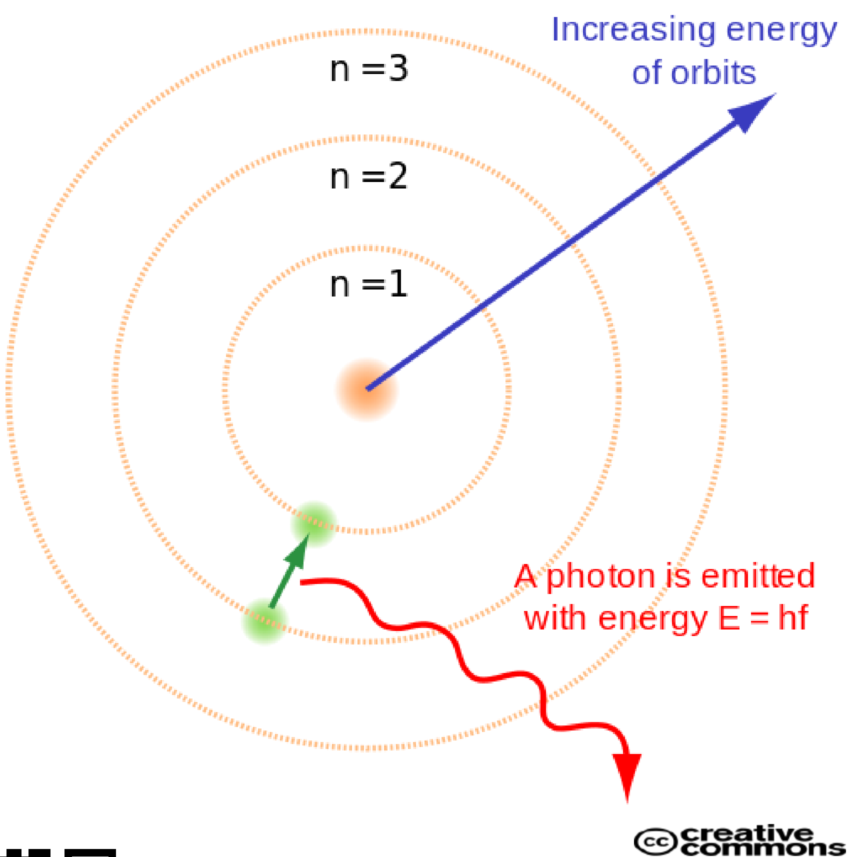
Bohr's Solution



This is a model of electron orbits - there are three orbits (n=1,2 and 3) that the electrons can be in. When an electron falls from a higher energy level (greater n) to a lower energy level, it emits a photon with frequency f proportional to the energy difference between the levels.

http://njc.tl/qv

Bohr's Solution

Here's a quick tour through Bohr's mathematics.

The quantized angular momentum of each level is expressed as (where n is the number of the energy level):

$$L = mvr_n = n\frac{h}{2\pi} \quad n = 1, 2, 3...$$

The Coulomb attractive force between the nucleus of charge Ze and the single electron that provides the centripetal force (remember, Bohr was only calculating orbits for atoms with a single electron):

$$F_E = k\frac{(Ze)(e)}{r_n^2} = k\frac{Ze^2}{r_n^2} = m\frac{v^2}{r_n}$$

http://njc.tl/qv

Bohr's Solution

Combining these two equations, doing a little algebra, and solving for the radius of each quantum level, we get:

$$r_{Z,n} = \frac{n^2 h^2}{4\pi^2 mkZe^2}$$

By using classical equations for the kinetic energy, potential energy, angular momentum, Coulomb's Law, Newton's Second Law, and Bohr's quantum assumption, the energy of the quantum levels in hydrogen like atoms is determined to be:

$$E_{Z,n} = -\frac{1}{8}\frac{mZ^2e^4}{\varepsilon_0{}^2 n^2 h^2}$$

http://njc.tl/qv

Bohr's Solution

Using the radius equation from the previous slide, the Bohr radius (a_0) is defined as the electron orbital radius for the ground state (n=1) of the Hydrogen atom (Z=1):

$$a_0 = 5.29x10^{-11} m$$

Radii of other Hydrogen like atoms are expressed as:

$$r_{Z,n} = \frac{n^2}{Z} a_0$$

And, by substituting in the values of the constants in the Energy equation, it is found that:

$$E_{Z,n} = -(13.6eV)\frac{Z^2}{n^2}$$

Where 1 eV (electron-volt) is a unit of energy used for atomic and clear energy levels and is equal to 1.6 x 10^{-19} J. The negative n indicates that the electrons are bound to the nucleus.

http://njc.tl/qv

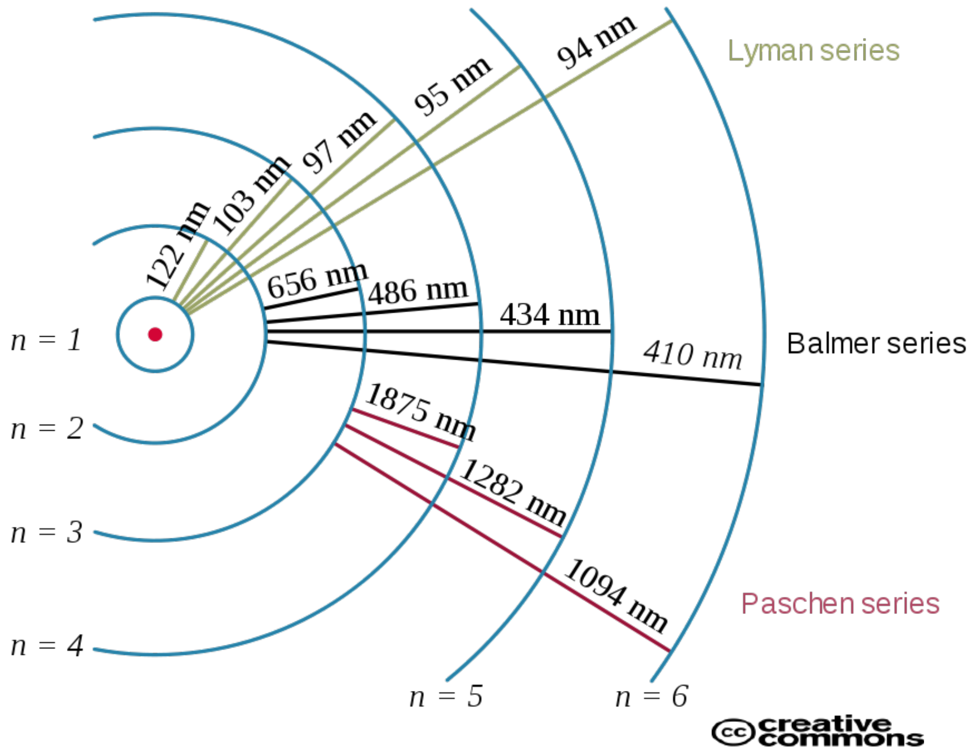
Bohr's Solution

These calculations from Bohr are in excellent agreement with the optical spectra showed earlier.

The next slide shows the various transitions between quantum levels - and have been named for the physicists who first observed them.

The Balmer series of orbital transitions are the only ones that are in the visible spectrum.

Bohr's Solution



http://njc.tl/qv

ohr's model exactly matched the observed spectra and the
xperimentally determined equations shown earlier.

21 What is the energy of the second excited state (n=3) of the Hydrogen atom?

Answer

http://njc.tl/qw

22 What is energy of the fifth excited state (n=6) of the Hydrogen atom?

Answer

http://njc.tl/qx

23 What is the frequency of the photon emitted when an electron falls from the n=6 level to the n=3 level?
(h = 4.14×10^{-15} eV-s)

Answer

http://njc.tl/qy

Limitations of the Bohr Model

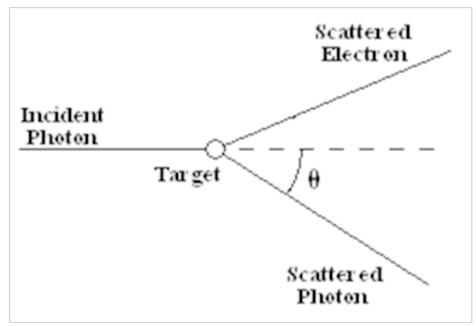
1. The model is applicable only to hydrogen like atoms (single electron).
2. The model is based on an assumption that accelerating charges do not emit electromagnetic radiation if they are in specific orbits.
3. The model predicts the frequencies of the photons that are emitted when an electron changes orbits, but does not predict their intensities.

It would now be left for the Quantum Model of the atom to more completely explain what is happening.

Compton Effect

In 1923, Arthur Compton scattered X-rays off of a graphite surface and observed that the wavelength of the scattered X-rays increased - the Compton shift.

He postulated that the photon, acting as a particle, with an energy E=hf, collided elastically with the electron. Since momentum and kinetic energy are conserved in an elastic collision, the scattered photon would have less energy after the collision; some of its energy would be transferred to the electron. This would be observed by the scattered electron having a longer wavelength.



Compton Effect

To derive the equation for how much the photon's wavelength is shifted, Einstein's equation for the relativistic energy of a particle is used so that a momentum can be assigned to the photon:

$$E^2 = p^2c^2 + m^2c^4$$

And, since the mass of a photon is zero:

$$E = pc$$

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

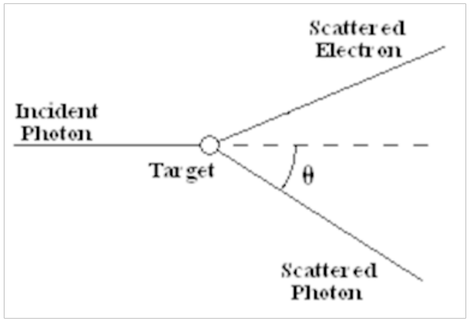
This equation also shows that a massless particle (a photon) still [illegible] momentum.

http://njc.tl/qz

Compton Effect

After solving the conservation of energy and momentum equations (using the relativistic versions as photons move at the speed of light), the following angular dependent equation was derived. It shows how much the photon's wavelength is shifted when it collides with an electron.

$$\Delta\lambda = \lambda_f - \lambda_i = \frac{h}{m_e c}(1-\cos\theta)$$



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Neutron

With all these incredible theories and experiments in the first twenty five years of the 20th century, it's interesting that the neutron's existence was not proven until James Chadwick demonstrated its properties in 1932.

Ernest Rutherford, in 1920, proposed that a neutral particle with a mass on the order of the proton existed to account for the atomic mass measurements of atoms.

Experiments were performed before Chadwick that actually found neutrons, but they were mistakenly believed to be gamma rays or even protons.

Neutron

Chadwick placed a small quantity of radioactive Polonium in an evacuated chamber, where it decayed by emitting alpha rays (Helium nuclei) that then struck a beryllium target.

Neutrons were emitted from this reaction and were found to have the correct mass and a neutral charge.

Neutrons (and protons) provide the strong nuclear force that keep nuclei together by balancing the repulsive Coulomb Force between the positively charged protons.

24 The Compton Effect showed that photons act as

- A light rays.
- B particles.
- C both light rays and particles.
- D None of the above.

Answer

http://njc.tl/r0

25 What is the wavelength for a photon of wavelength 3.0000×10^{-9} m (X-ray) that hits an electron, undergoes a Compton shift and scatters at an angle of 45^0?

$$m_e = 9.11x10^{-31} kg$$

Answer

http://njc.tl/r1

26 Neutrons have a

- A neutral charge and a mass approximately equal to an electron.
- B neutral charge and a mass approximately equal to a proton.
- C negative charge and a mass approximately equal to a proton.
- D positive charge and a mass approximately equal to an electron.

Answer

http://njc.tl/r2

Waves and Particles

Return to Table
of Contents

Light described as a Particle and as a Wave

Newton first described light as a group of corpuscles (particles) and was able to explain reflection, refraction and dispersion.

Thomas Young and others found a wave like description was the only way to explain diffraction phenomena.

James Clerk Maxwell described light as perpendicular magnetic and electric fields moving as a wave.

Einstein brought back the particle model to describe the Photoelectric Effect.

ur Compton used the particle model to explain the uency shift of scattered photons off of electrons.

http://njc.tl/r3

Light described as a Wave

Since light had been described both as waves and particles, Louis de Broglie, in 1924, proposed that particles could be described as waves, with a wavelength equal to:

$$\lambda = \frac{h}{p}$$

This is the same equation that Compton used to determine the momentum of a photon.

Thus, all particles, and by extension, objects like baseballs and bowling balls have a de Broglie wavelength associated with their motion! But, since h is so very small, the wavelength ociated with large objects is vanishingly small.

http://njc.tl/r3

Light described as a Wave

However, for small particles, like electrons, their wavelengths are comparable to their physical size, so one might expect that they could experience wavelike effects like diffraction and interference.

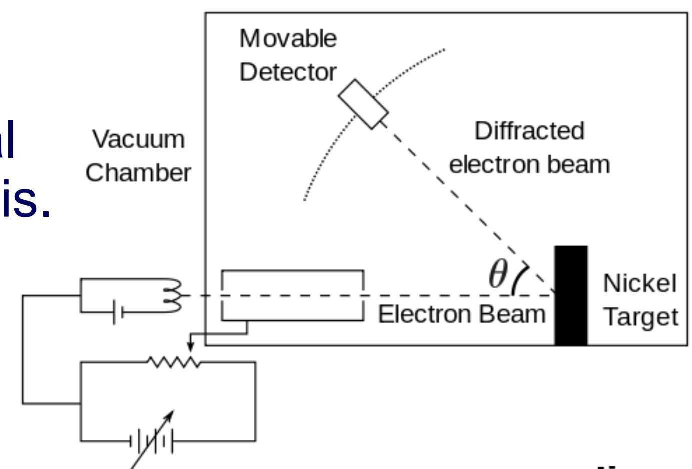
de Broglie proposed that an interference experiment be set up with crystals and electrons to validate his theory. But no one tried until decades later.

Light described as a Wave

In 1927, Clinton Davisson and Lester Germer were studying how electrons bounce off a nickel surface. During the experiment, an accident occurred that resulted in the scarring of the nickel surface, making it act like a three dimensional diffraction grating.

They were startled to find an interference pattern in the scattering! Electrons were diffracting as if they were waves.

This was the first experimental proof of de Broglie's hypothesis.



http://njc.tl/r3

27 What is the de Broglie wavelength of a 0.145 kg baseball moving at 40.0 m/s?

Answer

http://njc.tl/r4

28 What is the de Broglie wavelength of an electron moving at 2.50 x 10^7 m/s?

$m_e = 9.11x10^{-31} kg$

Answer

http://njc.tl/r5

Quantum Mechanics

Return to Table
of Contents

http://njc.tl/r6

Heisenberg Uncertainty Principle

The pieces were now in place for a new way to rationalize all these seemingly contradictory wave and particle behaviors of light and matter.

A driving force behind physics has been the criticality of making accurate measurements of physical phenomena, and making predictions based on these measurements.

This still holds for Quantum Physics, but with a twist - there are times when the more accurate a measurement that you make of one quantity, the less accurate a measurement you can make of a complementary quantity.

This is expressed in the Heisenberg Uncertainty Principle, established by Walter Heisenberg in 1927.

http://njc.tl/r6

Heisenberg Uncertainty Principle

The first two quantities that cannot both be measured precisely at the same time are momentum and position - the more accurately that momentum can be observed, the less sure you are of where the particle (photon, electron, neutron, etc.) is located. This imprecision, or uncertainty, is represented by Δp_x for momentum in the x direction, and Δx for the position in the x direction. Here's the equation:

$$\Delta p_x \, \Delta x \geq h$$

Planck's constant sets the limit for how accurate the measurements of momentum and position can be at the same time.

http://njc.tl/r6

Heisenberg Uncertainty Principle

$$\Delta p_x \Delta x \geq h$$

This expression helps explain why electrons remain in their orbits and do not spiral down to collapse into the nucleus. Neils Bohr theorized that if an electron is in a quantized orbit, it does not radiate EM waves, so it does not lose energy.

Heisenberg's Principle predicts that if you try and move the electron very close to the nucleus, then Δr (there's nothing special about x, y, z or r here - it just represents a distance, and if we're talking about orbits, the radius is what we're interested in) gets very small.

This implies that Δp_r gets very large, and the electron will e a larger momentum which will prevent it from getting ser to the nucleus.

http://njc.tl/r6

Heisenberg Uncertainty Principle

$$\Delta E \, \Delta t \geq h$$

There's another version of the Uncertainty Principle relating Energy and time as shown above.

Fortunately, for physicists making measurements at levels that we can all see, this principle does not affect these measurements due to the very small value of Planck's constant.

29 If you measure the diameter of a baseball to be 74.2 mm with a precision (uncertainty) of ±0.5 mm, how precise can you measure its momentum, at the same time, according to Heisenberg's Uncertainty Principle?

Answer

30 An electron is measured to have a momentum of 2.5×10^{-28} kg m/s with an uncertainty of 2.5×10^{-32} kg m/s. How precisely can we determine where it is?

Answer

http://njc.tl/r8

Schrodinger's Wave Equation

To explain the seeming contradictions between particle and wave behavior and the impossibility of measuring certain quantities simultaneously with perfect accuracy, Erwin Schrodinger developed the wave function,Ψ, in 1926.

Significant work was also done by Paul Dirac, and the two gentlemen shared the Nobel Prize for Physics in 1933.

In classical physics, if all the forces on an object are known, all other quantities, such as position, momentum, acceleration, etc., can be found.

Ψ performs a similar function in Quantum physics - with the major difference that you can find the probabilities of a ...rticle's position, energy, momentum, etc.

...e key word is PROBABILITY, not EXACTLY.

http://njc.tl/r9

Schrodinger's Wave Equation

An example of the use of ψ is in the double slit experiment for electrons. Young's experiment using monochromatic light incident upon two slits showed a unique interference pattern

Electrons showed the same pattern! This leads to a key property of ψ - it is used to represent all the knowledge we have about an electron in this case. And, if a stream of electrons are incident on the double slits, the wave functions of each particle will interfere with the other particles' wave functions.

Thus, the interference patterns are explained by analyzing the wave functions and their interractions.

Schrodinger's Wave Equation

To find the probability of where a particle is, the wave function, Ψ, is squared. This was first suggested by Max Born.

Just to show the beauty of the Wave Equation, here it is for one specific problem:

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},\,t) = -\frac{\hbar^2}{2m}\nabla^2\Psi(\mathbf{r},\,t) + V(\mathbf{r})\Psi(\mathbf{r},\,t)$$

Solving this equation for Ψ, will enable you to understand every thing there is to know about the particle. But, this is College level physics - even beyond AP.

Schrodinger's Wave Equation

The solutions to the Wave Equation show how the periodic table, electron orbitals, atoms, molecules, chemical bonds work. It describes the microscopic world - which is so different and counter intuitive to what we see at our level.

The Uncertainty and Probability concepts contradict what can be seen at the macroscopic level where we know, pretty exactly, where things are and how they're moving.

But - that's how nature works.

http://njc.tl/r9

31 The Schrodinger Wave Equation is used to

- A describe exactly where a particle is at any specific time.
- B calculate the exact momentum of a particle at any time.
- C calculate the probability of a particle being at a certain point at a certain time.
- D calculate only the probability of properties belonging to electrons.

Answer

http://njc.tl/ra

32 How is the probablility of a particle being in a certain position calculated from the wave function?

- A The wave function is the probability of where a particle is located.
- B Divide the wave function by 2.
- C Triple the wave function.
- D Square the wave function.

Answer

*Theory Unification

Return to Table of Contents

http://njc.tl/rc

Physics Status

This unit started by discussing how physicists at the end of the 19th century were pretty comfortable with what they had explained. Electricity and Magnetism had been unified, and Mechanics and Thermodynamics were well understood.

Then Quantum Physics hit and the rest of the 20th century was spent explaining the physics of very tiny particles and objects that moved very fast.

And now, with the dark energy and matter hypothesis, it turns out that we've only been looking at 5% of the universe. There is much more to discover.

This unit will summarize some of the key developments after Quantum Physics started in the first decade of the 20th century.

Quantum Electrodynamics

This discipline provided an integrated explanation of relativity, quantum mechanics and electrodynamics that describes how light and matter interact and has made phenomenally accurate predictions that have been verified by experiment.

Paul Dirac and Hans Bethe introduced the concept, and Sin-Itiro Tomonaga, Julian Schwinger and Richard Feynman were awarded the Nobel Prize for completing the work.

Feynman summarizes this complex theory with three points:

- Photons move from one place in time and space to another.
- Electrons move from one place in time and space to another.
- Electrons emit or absorb protons.

Drawings of these interactions, called Feynman Diagrams, enable complex calculations to be made.

Electroweak Interaction

This theory integrated the descriptions of Electromagnetism and the Weak Force (that is responsible for the radioactive decay of nuclei).

These forces are very different at low energy, but at energies greater than 100 GeV, they are one force - the Electroweak force.

Abdus Salam, Sheldon Glashow and Steven Weinberg were awarded the Nobel Prize for their work in this area.

Quantum Chromodynamics

The proton and neutron have an underlying structure. Each nucleon is actually made up of three quarks. This is the field of Quantum Chromodynamics which explains the Strong Nuclear force.

Quarks are attracted to each other by exchanging gluons, and the further Quarks get from each other, the more strongly they are attracted (unlike gravity and electromagnetism - but analogous to a spring force).

Murray Gell-Mann, Kazuhiko Nishijima, Eugene Wigner and George Zweig were key contributors to this field.

Standard Model

This model explains the electromagnetic, weak and strong nuclear interactions and has 61 elementary particles - particles that have no underlying structure, such as quarks, photons, electrons, neutrinos, muons, W bosons, etc. Note that protons and neutrons are not considered elementary particles as they are made up of quarks.

Many of these particles can only be seen by colliding particles, such as protons, with each other at extremely high energies and then measuring what comes out. This makes the experiments very complex and expensive. The Large Hadron Collider that was built on the border of France and Switzerland cost approximately $5 Billion.

:ure is making it harder for physicists to more completely
›lain the microscopic world!

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Grand Unified Theory

The Unified Theory comes out of the Standard Model, and is still not completely explained.

The Grand Unified Theory seeks to add the Gravitational force to the three other forces covered by the Standard Model.

To date, there is no satisfactory Grand Unified Theory. Gravity is such a small force compared to the other three (an order of 10^{25} smaller than the Weak Force). And, it has not been successfuly integrated with Quantum Physics.

String Theory

Many physicists are unhappy with the Standard Model, as it has so many elementary particles, and it does not include all four fundamental forces.

String Theory is an attempt to fix these problems, by stating that all particles are made up of tiny vibrating strings, and the way they vibrate gives rise to different properties such as mass and charge which are evidenced as different particles.

It is very theoretical, mathematically beautiful, unifies all four forces and requires the use of multiple dimensions and parameters to explain the universe (and allows for the possibility of multiple universes).

Since it has not made any predictions that can be tested yet, other physicists consider it more of a philosophy than physics.

Dark Energy and Dark Matter

The universe has been expanding ever since the Big Bang.

However, it is not only expanding, its expansion is accelerating - which it should not be if gravity was the only force affecting the expansion. The expansion should be slowing down or remaining the same as gravity is an attractive force.

To explain this, physicists have proposed the existence of dark matter and dark energy, which comprise 95% of the universe and cannot be observed, but is accelerating the expansion of the universe.