Quantum mechanics

Dr P Lawson

The discharging electroscope

- An electroscope has a thin gold leaf attached to a metal stem. When the electroscope is charged, the leaf stands out.
- Use an EHT power supply to charge an electroscope negatively (Figure 18.1). Disconnect the power supply and watch the electroscope for a minute. Does it discharge?
- Repeat the experiment, but this time shine ultra-violet radiation on to the electroscope. Is there a difference?
- Repeat the experiment yet again, but this time put a clean strip of zinc on the top cap (Figure 18.2).
- Experiment with a positively charged electroscope, with strong visible light, and with dull, oxidised zinc.

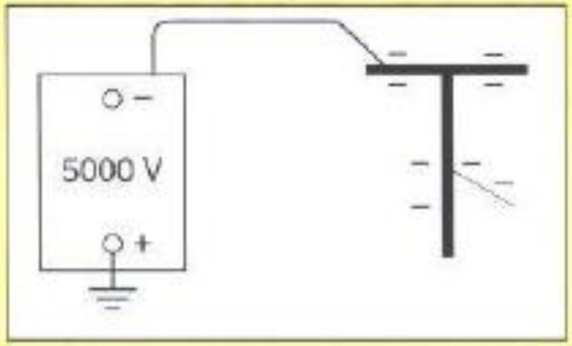


Figure 18.1 Charging an electroscope

ULTRA-VIOLET RADIATION

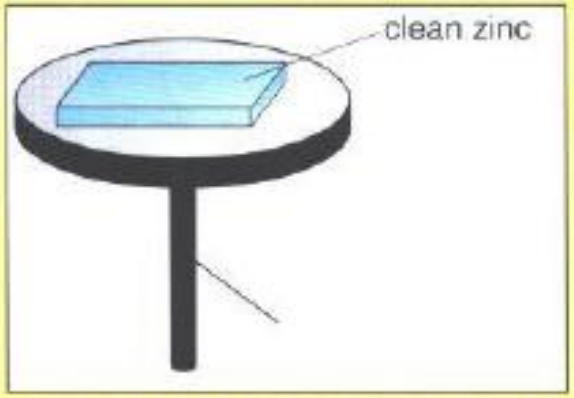


Figure 18.2 Put a cleaned strip of zinc on the electroscope

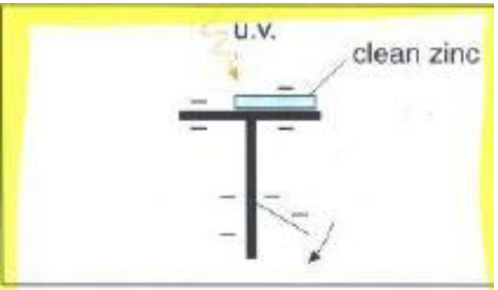


Figure 18.3 The leaf goes down

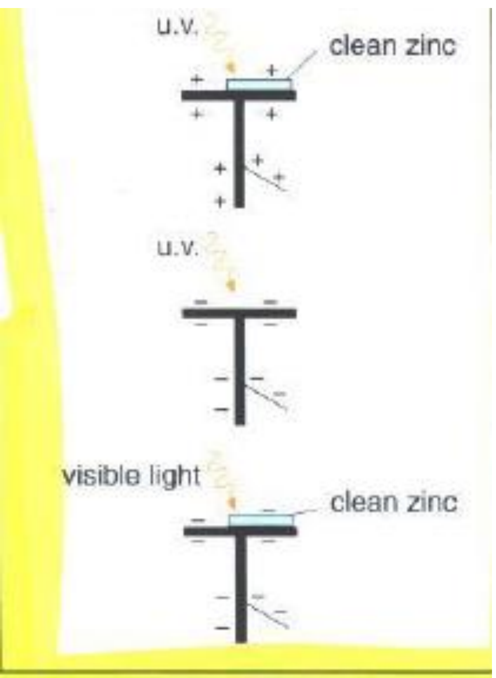


Figure 18.4 The leaf stays up

Photoelectric emission

When you connect the negative terminal of a power supply to an electroscope, some electrons transfer to the electroscope, making it negative too. The leaf on the electroscope then has the same sign of charge as the stem, so the two repel each other and the leaf stands out. The insulation on an electroscope is usually good, so very little charge leaks away and the leaf stays out. But, in certain circumstances, when you illuminate the top cap with the correct kind of radiation, an electroscope with a good insulator can still discharge rapidly.

In the situation shown in Figure 18.3, the leaf goes down, even with nothing touching the electroscope. The leaf discharges only if the zinc is shiny, if the illumination is ultra-violet and if the charge is negative. It does not discharge if the zinc is dull or if there is no zinc, with just bright light, or with positive charge (Figure 18.4).

You might at first think that the ultra-violet light is causing the air around the electroscope to conduct electricity, and so discharge the electroscope. But if so, the electroscope would also discharge if it were charged positively. If ionisation of air were the explanation, why should a zinc plate be necessary? Perhaps the ultra-violet light might be giving positive charge to the electroscope to neutralise it. But if so, why is there discharge when the zinc plate is on the top cap, but no discharge with a chromium top alone?

A likely explanation for the discharge is that ultra-violet radiation is causing the zinc to emit electrons and make itself less negative. This emission is **photoelectric emission** (literally 'emission of electrons by light').

Threshold frequency

Photoelectric emission from zinc only occurs if the radiation illuminating the zinc has a frequency of 1×10^{15} Hz or higher. This is in the ultra-violet region, just outside the visible spectrum. This frequency is called the **threshold frequency** for zinc.

Weak radiation above the threshold frequency will cause photoelectric emission, but radiation below the threshold frequency will not cause photoelectric emission, even if it is powerful. This observation puzzled physicists for some years.

Photons

In 1905, Einstein suggested an explanation for photoelectric emission based on a theory proposed by Max Planck (Figure 18.5). He suggested that electromagnetic radiation – visible light, ultra-violet light, or any other frequency – comes in small packets of energy, rather than in a steady stream. The general name for a small packet of energy is a **quantum**, but a packet, or quantum, of electromagnetic radiation is called a **photon**. The energy of a photon does not depend on the intensity of the radiation, but rather on its frequency.

When the frequency of the radiation is low, the energy of the photons is small; when the frequency is high, the energy of the photons is large.

The electrons in the metal are being bombarded with a stream of photons. An electron is only emitted if it interacts with a photon that has sufficient energy, on its own, to detach the electron from the metal. When photons of lower energy hit the metal, no electrons are emitted.

Figure 18.5. Max Planck (1858–1947). German physicist who proposed that electromagnetic radiation is emitted in quanta

Work function

There is no photoelectric emission from zinc unless it is illuminated with radiation of frequency greater than its threshold frequency of about 1×10^{15} Hz. If you investigate other substances, you find that they each have a different threshold frequency.

Generally, the threshold frequencies are lower for substances that are chemically more reactive. These substances lose electrons more easily both in chemical reactions and photoelectrically. The lower threshold frequency corresponds to photons of lower energy; it means that you do not need photons of such high energy to release electrons from more reactive substances.

The minimum energy needed to remove electrons from a substance is called the **work function**, symbol ϕ (the Greek letter *phi*). The work function for zinc is less than the work function for chromium, which is why the threshold frequency for zinc is lower than the threshold frequency for chromium. This explains why radiation that causes photoelectric emission from the zinc plate does not necessarily cause emission from the chromium cap.

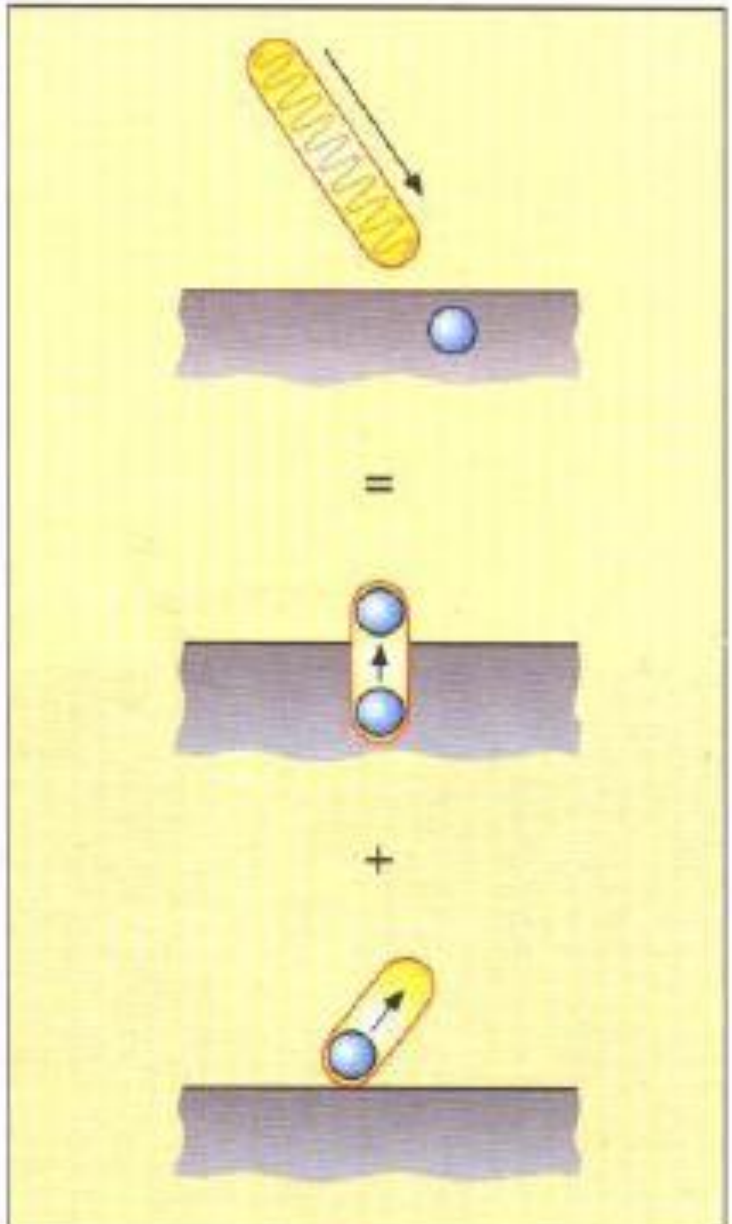


Figure 19.1 *Photon energy = work function + electron kinetic energy*

Measuring the energy of a photoelectron

- The photoelectric cell in Figure 19.2 has two electrodes. Light illuminates the large emitting electrode, which has a low work function. Photons with sufficient energy cause photoelectric emission. If any photoelectrons reach the receiving electrode, the picoammeter indicates a current.
- The battery and potentiometer make the receiving electrode in the photoelectric cell negative. This provides an electrical hill that photoelectrons must run up. The trick is to increase the repelling voltage slowly from zero until the current drops to zero. At this voltage, called the stopping voltage (or stopping potential), the electrical hill is just high enough to stop even the fastest electrons arriving.
- At the stopping voltage, the kinetic energy lost by the fastest electrons is equal to the electrical potential energy they gain going up the hill.
- Shine lights of different known frequencies onto the emitting electrode. For each frequency, measure the stopping voltage.
- Plot a graph of stopping voltage against frequency. What is the relation between them?

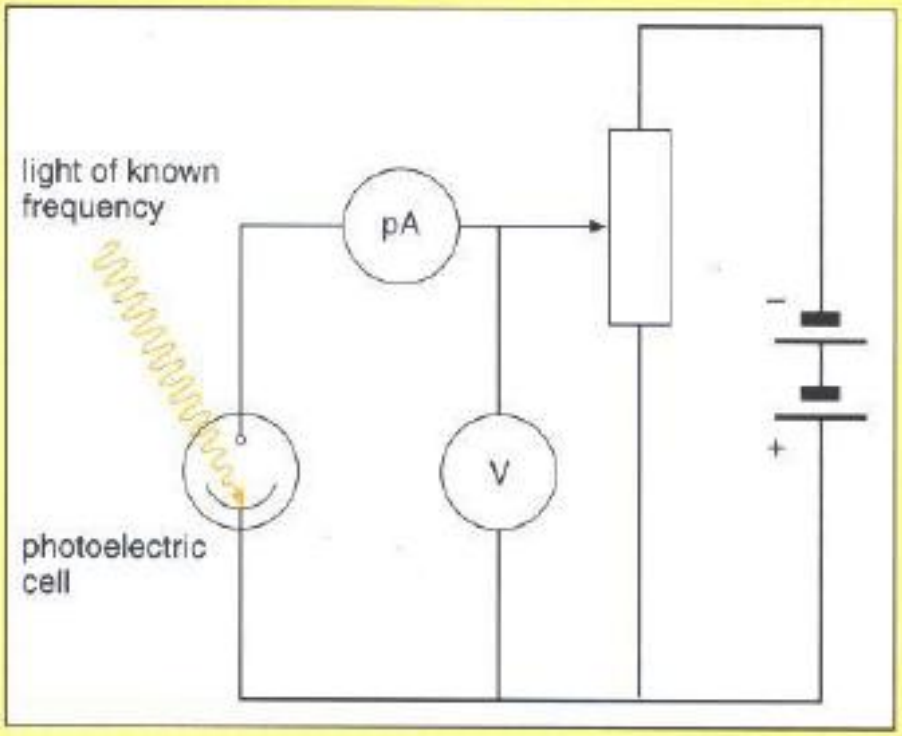
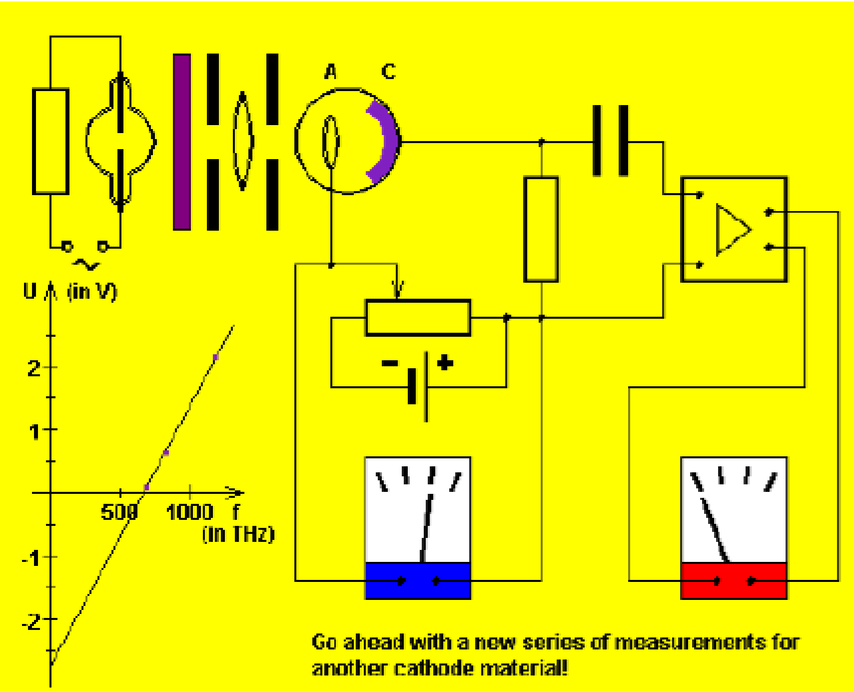


Figure 19.2 The electrons are repelled back to the emitting electrode

ULTRA-VIOLET RADIATION

http://www.walter-fendt.de/ph11e/photoeffect.htm



The evaluation of the three measurement series by means of the diagram will result in three parallel lines. From the slope of these lines the Planck constant (h) can be calculated. In addition you can read the work function of the respective cathode material (in eV, i.e. electron volt) directly from the intersection with the vertical axis.

$$E_{kin} = hf - W$$

If y axis scale is E_{kin} in eV (proportional to stopping potential in V) and we set f =0 then we can find the work function.

$$E_{kin} = 0 - W$$

If we compare the equation with that of a straight line we can calculate planks constant

$$E_{kin} = hf - W$$

$$y = mx + C$$

$$\text{Gradient} = m = h$$

$$E_{kin} = h f - W$$

Calculating photon energy

Einstein accepted Planck's hypothesis that the energy of each photon is proportional to its frequency:

$$E \propto f \qquad \text{or} \qquad E = hf$$

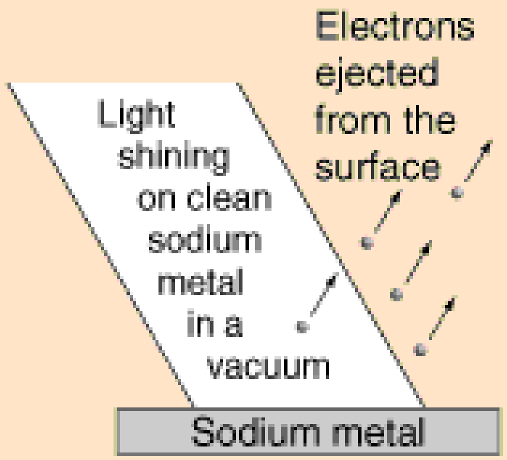
The constant of proportionality h is Planck's constant; it is 6.6×10^{-34} J s. Since

photon energy = work function + kinetic energy of fastest electrons

$$hf = \phi + \tfrac{1}{2}mv^2$$

where ϕ is the work function, and m and v are the mass and speed of the fastest electrons.

The Photoelectric Effect



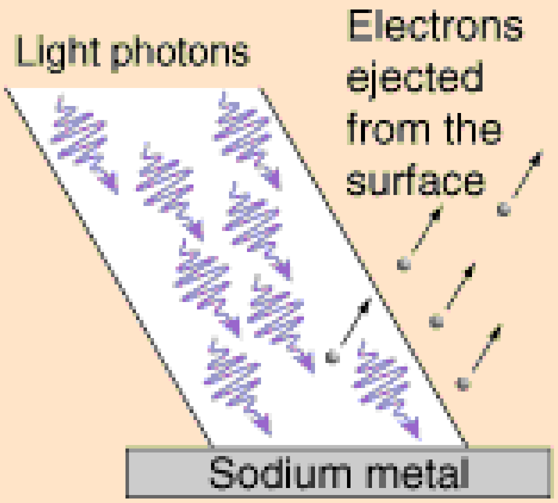
The remarkable aspects of the photoelectric effect when it was first observed were:

1. The electrons were emitted immediately - no time lag!
2. Increasing the intensity of the light increased the number of photoelectrons, but not their maximum kinetic energy!
3. Red light will not cause the ejection of electrons, no matter what the intensity!
4. A weak violet light will eject only a few electrons, but their maximum kinetic energies are greater than those for intense light of longer wavelengths!

The details of the photoelectric effect were in direct contradiction to the expectations of very well developed classical physics.

The explanation marked one of the major steps toward quantum theory.

Photoelectric Effect



Photon energy

$$E = h\nu$$

explains the experiment and shows that light behaves like particles.

Experiment

Analysis of data from the photoelectric experiment showed that the energy of the ejected electrons was proportional to the frequency of the illuminating light. This showed that whatever was knocking the electrons out had an energy proportional to light frequency. The remarkable fact that the ejection energy was independent of the total energy of illumination showed that the interaction must be like that of a particle which gave all of its energy to the electron! This fit in well with Planck's hypothesis that light in the blackbody radiation experiment could exist only in discrete bundles with energy

$$E = h\nu$$

Finding the threshold frequency

Look at the stopping voltage–frequency graph for caesium in Figure 19.3. As you would expect, it is a straight line. As the frequency of the radiation increases, the stopping voltage gets greater, meaning that electrons are emitted with greater energy. As the frequency gets less, the stopping voltage gets smaller, until, when the line cuts the frequency axis, electrons are emitted with zero kinetic energy. This is the **threshold frequency**. Below this frequency, no electrons are emitted.

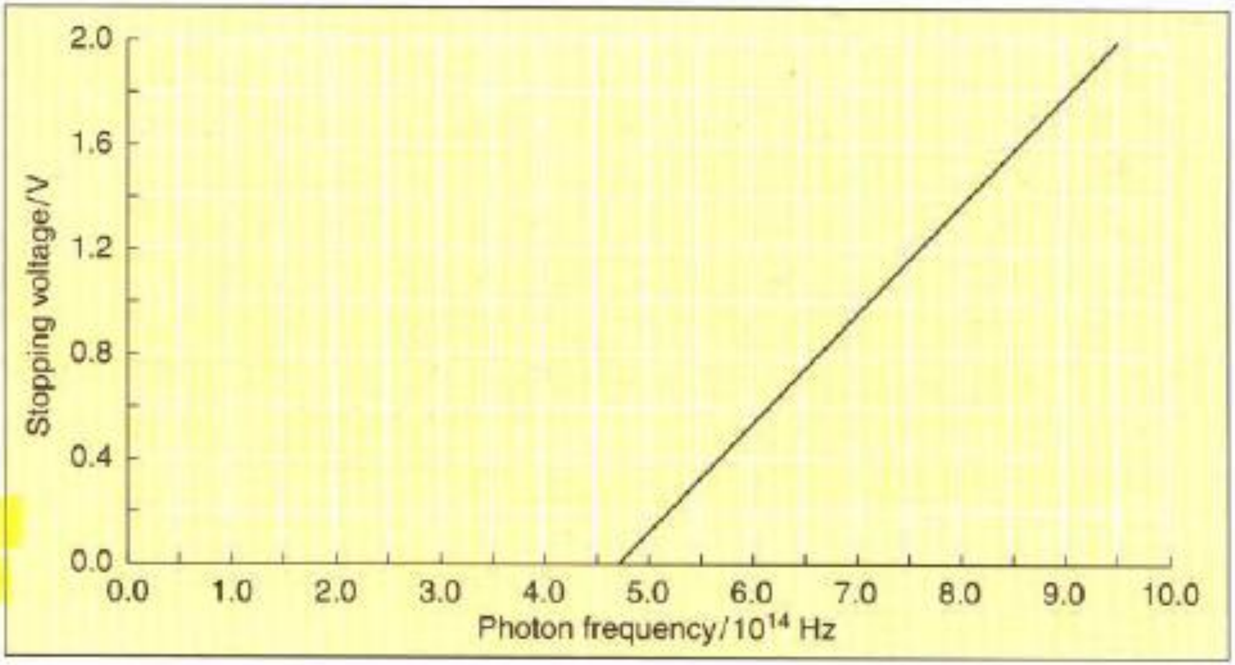


Table 20.1 *Threshold frequency for a number of metals*

	Threshold frequency
Metal	**$/10^{15}$ Hz**
caesium	0.47
sodium	0.57
zinc	0.88
chromium	1.08
iron	1.12
copper	1.13

Table 20.2 *Work function for a number of metals*

	Work function	
Metal	**$/10^{-19}$ J**	**/eV**
caesium	3.11	1.94
sodium	3.78	2.36
zinc	5.81	3.63
chromium	7.10	4.44
iron	7.36	4.60
copper	7.44	4.65

$$\text{work done} = QV = 1.6 \times 10^{-19}\,\text{C} \times 1\,\text{V} = 1.6 \times 10^{-19}\,\text{J}$$

This amount of work, 1.6×10^{-19} J, is called the **electronvolt**. It is the work done when a charge equal to that on an electron moves through a potential difference of 1 V.

To convert from joules to electronvolts, divide by $1.6 \times 10^{-19}\,\text{J eV}^{-1}$. For example, the work function of zinc, ϕ(zinc), is

$$\phi(\text{zinc}) = 5.8 \times 10^{-19}\,\text{J} = \frac{5.8 \times 10^{-19}\,\text{J}}{1.6 \times 10^{-19}\,\text{J eV}^{-1}} = 3.6\,\text{eV}$$

Variation of photocurrent with voltage

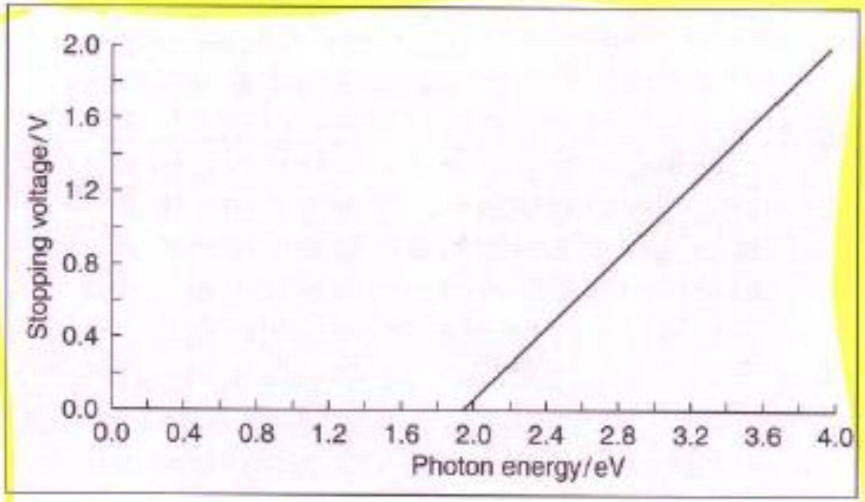


Figure 20.1 Stopping voltage for caesium for a range of photon energies

So far we have discussed varying the frequency of the light illuminating a photocell. If, instead, you keep the frequency constant, you can measure how photocurrent depends on the voltage between the electrodes. Figure 20.2 shows a current–voltage graph for a photocell illuminated with dim red light. As the graph shows, there is a current even when there is no voltage across the cell. The electrons have enough energy when they are emitted to travel across the gap between the electrodes even with no voltage across the cell.

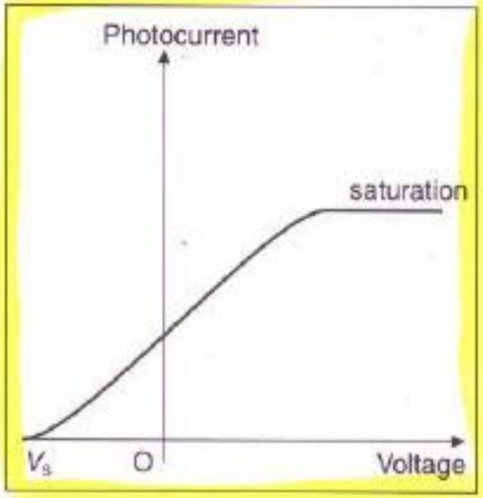


Figure 20.2 Current–voltage graph for a photocell illuminated with dim red light

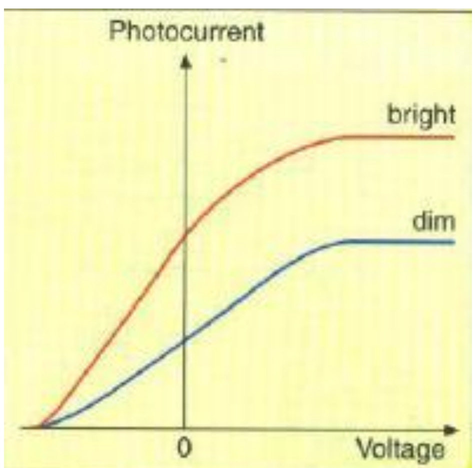


Figure 20.3 Current–voltage graphs for a photocell illuminated with two different intensities of red light

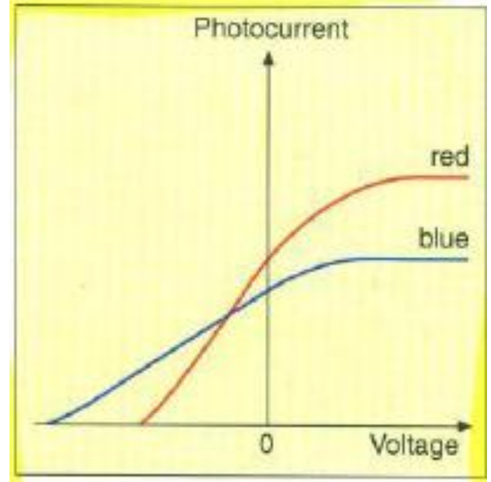
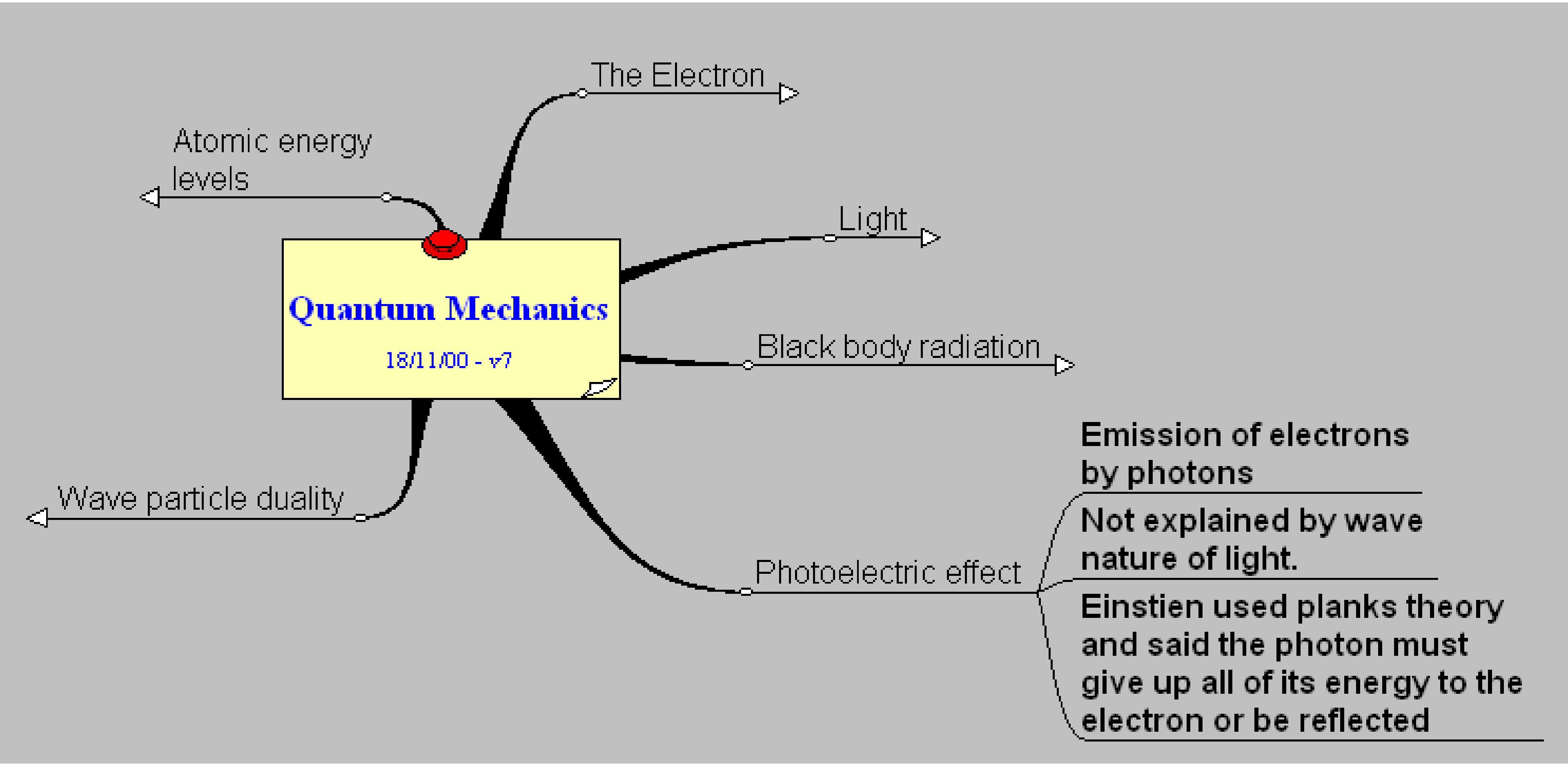


Figure 20.4 Current–voltage graphs for a photocell illuminated with different frequencies of light

Figure 20.4 shows current–voltage graphs for a photocell illuminated by red and blue light of the same intensity. The stopping voltage for blue light is greater than that for red, showing that the photons of blue light have a higher energy than the photons of red.

The saturation current for blue light is less than that for red, showing that there are fewer electrons emitted per second by the blue. Both radiations have the same intensity. The blue light comes as a smaller number of photons, each of which has a larger energy, emitting fewer electrons but with higher energy. The red light comes as a larger number of photons, each of which has a smaller energy, emitting more electrons but of lower energy.



Quantum Mechanics
18/11/00 - v7
The Electron
Atomic energy levels
Light
Black body radiation
Wave particle duality
Photoelectric effect
Emission of electrons by photons
Not explained by wave nature of light.
Einstien used planks theory and said the photon must give up all of its energy to the electron or be reflected

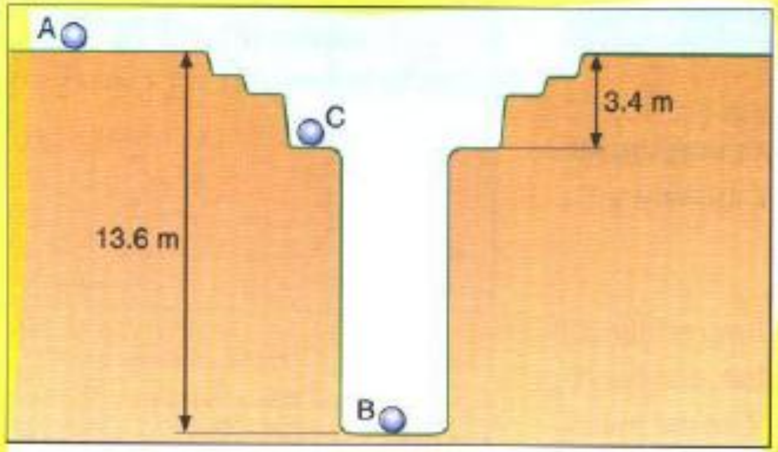


Figure 21.1 The balls have different potential energies

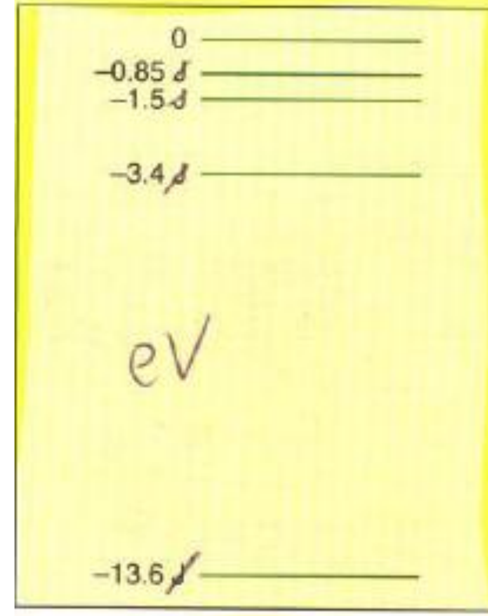


Figure 21.2 Energy level diagram

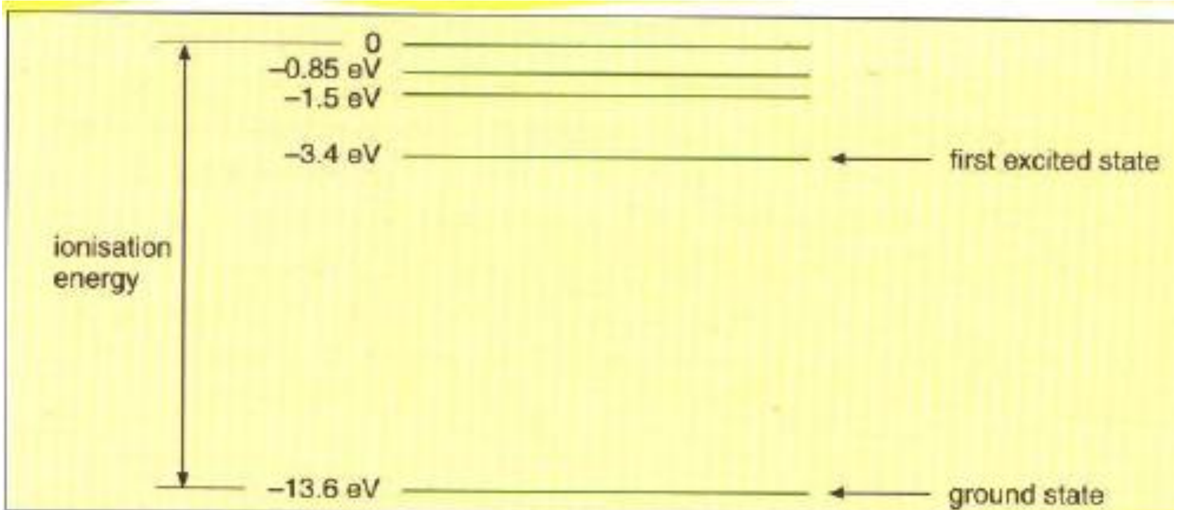


Figure 21.3 The energy levels for a hydrogen atom

Excitation and ionisation

If you give an atom energy to raise the electron above the ground state, the atom becomes **excited**. Energy is required to raise the electron above the ground state. This is **excitation energy**. The electron may remain above the ground state temporarily, but it will usually drop back to the ground state, either directly or via another level, giving out the excitation energy as it does so.

The first excitation energy for hydrogen is 10.2 eV, because it needs 10.2 eV to raise the atom from its ground state to the first excited state.

If you give the atom enough energy, you can free the electron completely from the atom. This is called **ionisation**. The **ionisation energy** is the energy required to free an electron completely, starting from the ground state of an atom. It is 13.6 eV for the hydrogen atom.

$$hf = E_2 - E_1$$

Observing spectra

- Put a slit in front of a hydrogen lamp. Hold a diffraction grating next to your eye and look through it at the slit (Figure 21.4).
- Sketch the pattern of light you see.
- Repeat with lamps containing different elements.

Figure 21.4 Using a diffraction grating to observe an emission spectrum

Emission spectra

You can give an element energy to excite the atoms by heating it. In this way, electrons are continually being given energy to enable them to rise to a higher state, but they then fall down again. The atoms give out the range of frequencies characteristic of that element. This range of frequencies of emitted radiations is called the **emission spectrum** of the atom.

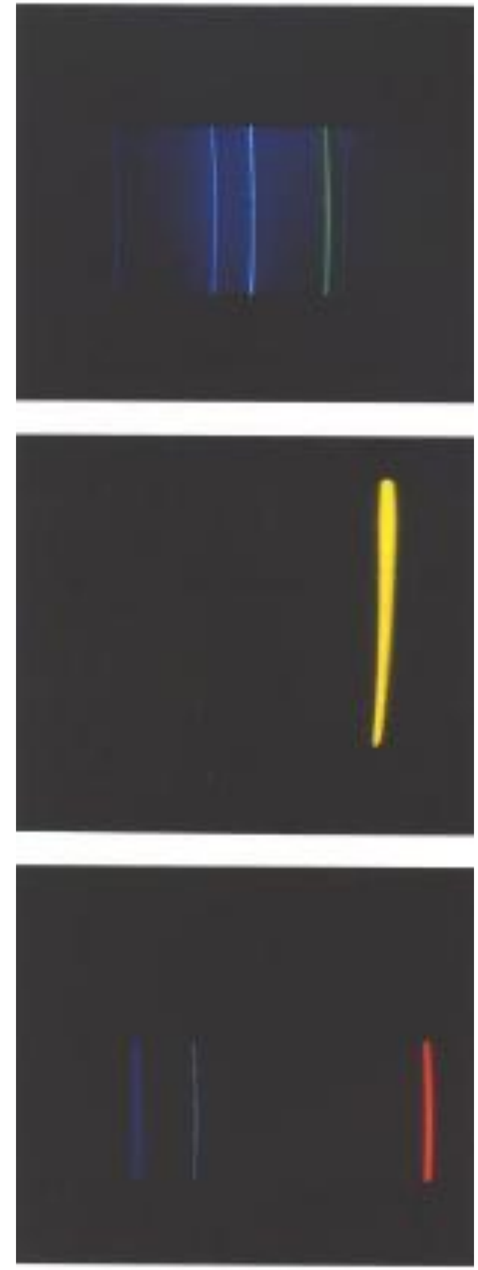


Figure 21.6 Emission spectra from (top) cadmium, (centre) sodium, (bottom) hydrogen

Using a diffraction grating to observe spectra

A diffraction grating works on the same principle as Young's slits (see Chapter 16). But the grating has more slits and they are closer together, so the fringes are brighter and spaced much further apart. You can use a diffraction grating to observe and measure the wavelengths of radiation from an emission spectrum. Figure 21.5 shows how you can observe the fringes that a diffraction grating can produce on the retina of the eye.

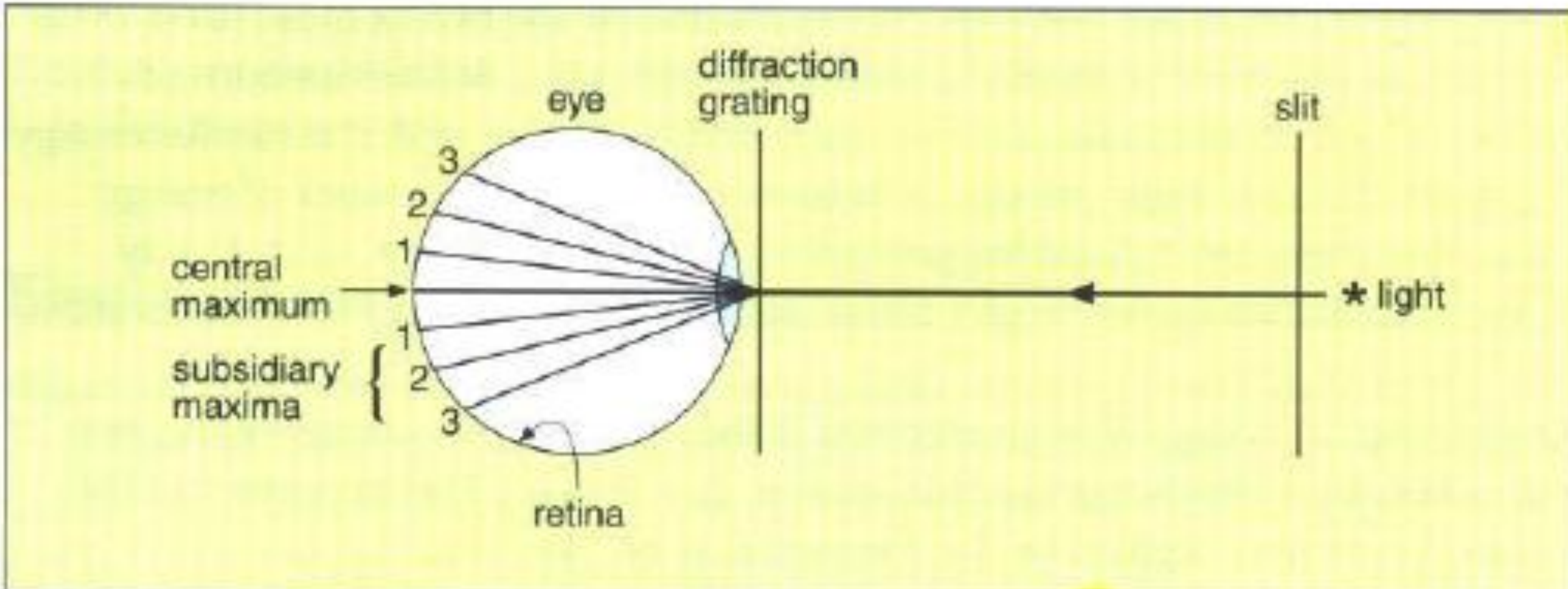


Figure 21.5 Superposition fringes on the back of the eye

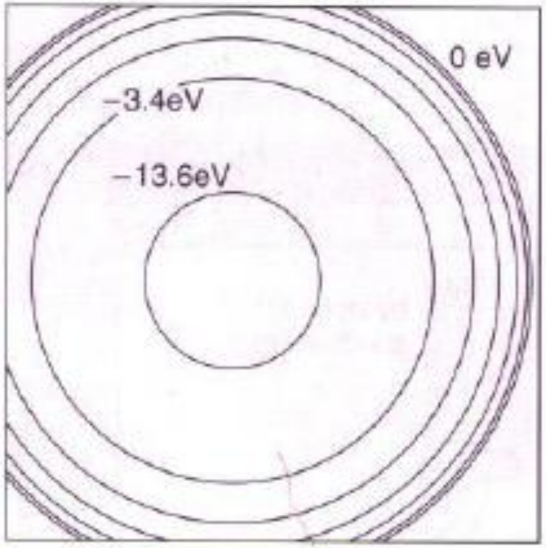


Figure 21.7 Bohr atom

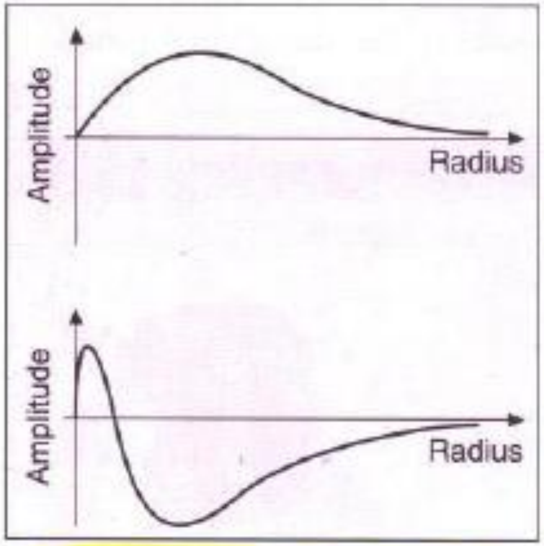
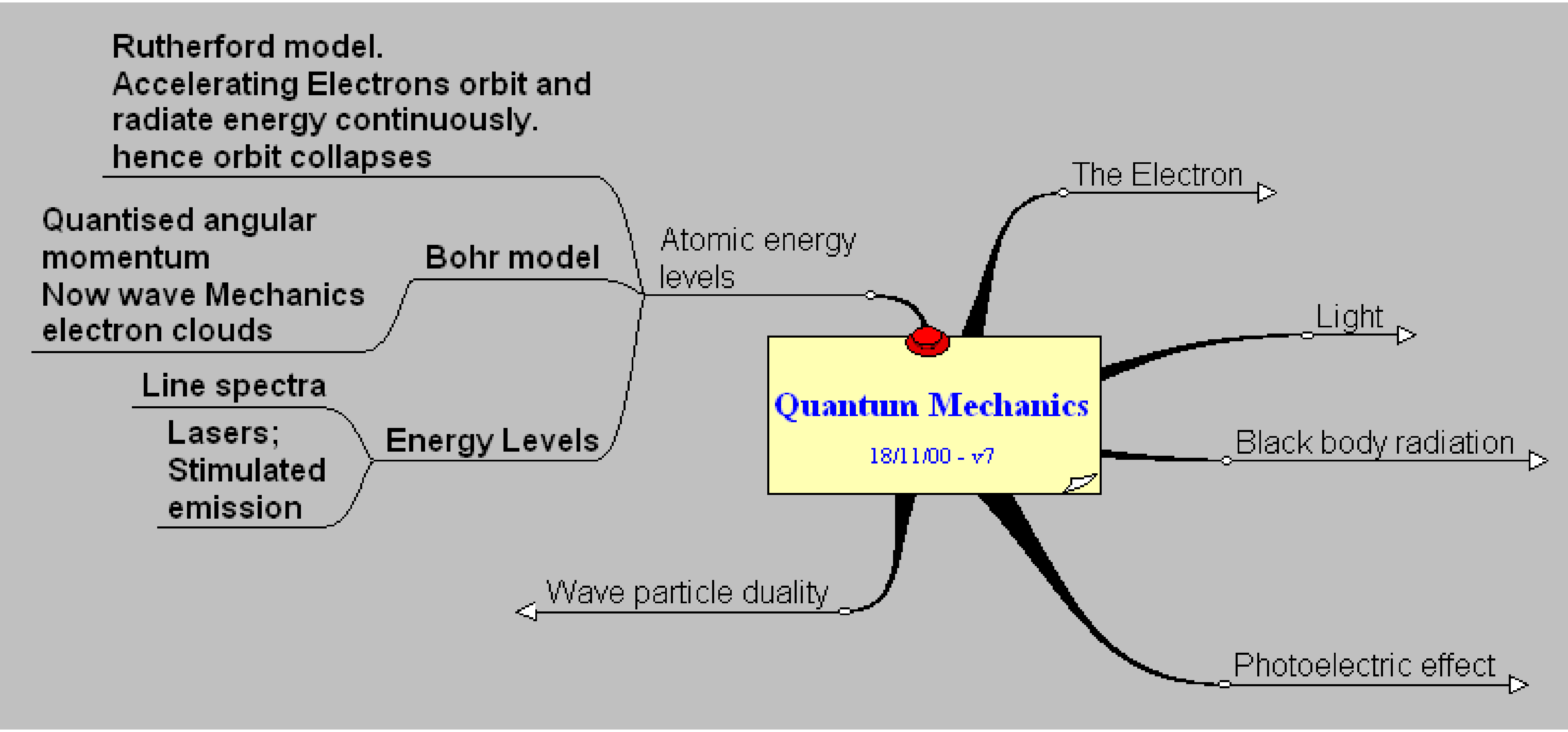


Figure 21.8 Schrödinger atom

Stationary waves in atoms

Neils Bohr suggested that the discrete energy levels in atoms are due to the electrons being allowed to have discrete orbits around the atom, rather like Figure 21.7. The changes in energy correspond to changes in orbit.

Erwin Schrödinger suggested that the energy levels in atoms were due to electrons behaving like stationary waves in the atom, with a profile like the waves in Figure 21.8. Only certain types of wave fit the atom, and these correspond to the fixed energy states.


Rutherford model.
Accelerating Electrons orbit and
radiate energy continuously.
hence orbit collapses
Quantised angular
momentum
Now wave Mechanics
electron clouds
Bohr model
Line spectra
Lasers;
Stimulated
emission
Energy Levels
Atomic energy
levels
The Electron
Light
Quantum Mechanics
18/11/00 - v7
Black body radiation
Wave particle duality
Photoelectric effect

Crossed gratings

- Shine a laser beam into a single diffraction grating and look at the pattern produced on the screen.
- Then use two gratings at right angles and look at the pattern due to that.
- Next put a number of gratings at a range of angles to each other (Figure 23.1) and look at the pattern that this produccces.

LASER BEAM

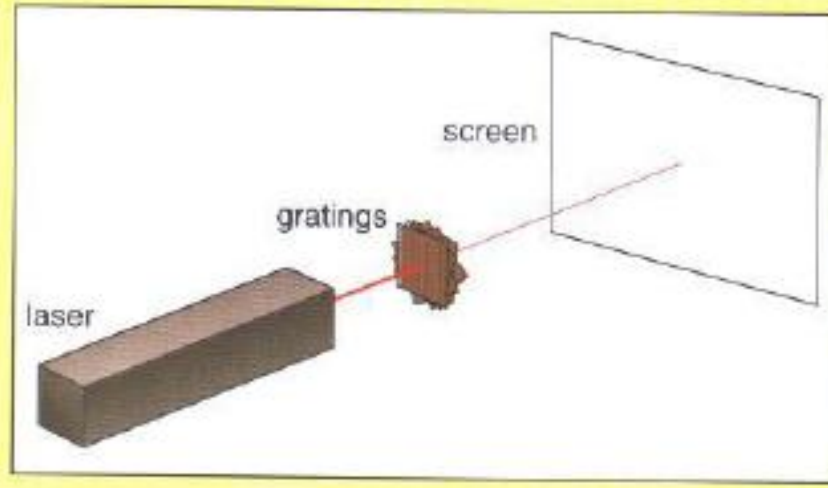


Figure 23.1 Producing superposition patterns from a number of crossed gratings

Figure 23.2 The superposition pattern for one grating

Diffraction patterns

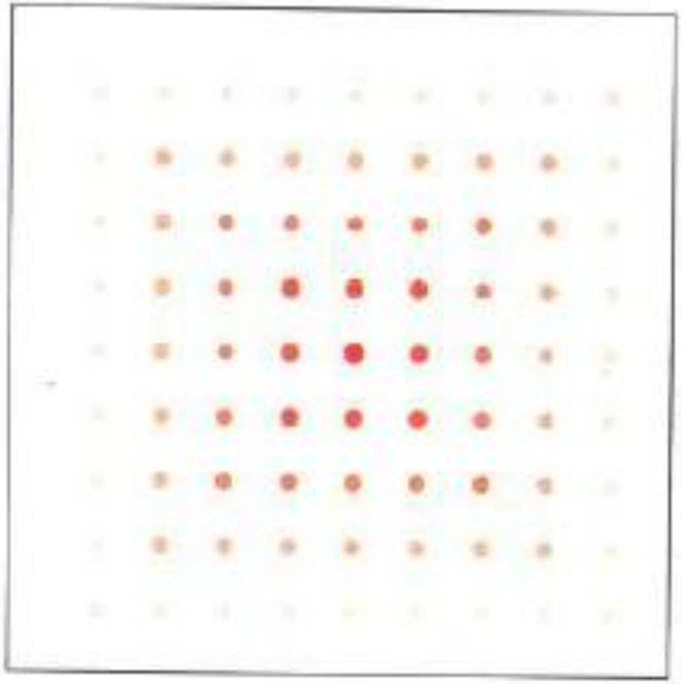


Figure 23.3 The superposition pattern for two crossed gratings

Figure 23.4 The superposition pattern for many gratings at different angles

Firing electrons at graphite

- Figure 23.5 shows an electron beam tube. The low-voltage power supply heats up the cathode and so gives the atoms enough energy for them to emit electrons. You might like to compare this **thermionic emission** with photoelectric emission. The EHT power supply attracts the electrons from the filament to a positive plate, which has a piece of graphite fixed in the middle. The fluorescent screen gives out light whenever it is hit by electrons, and therefore shows what happens after the electrons hit the graphite.
- Observe the pattern produced when the electrons hit the screen. Then change the voltage of the EHT power supply and see how the pattern changes

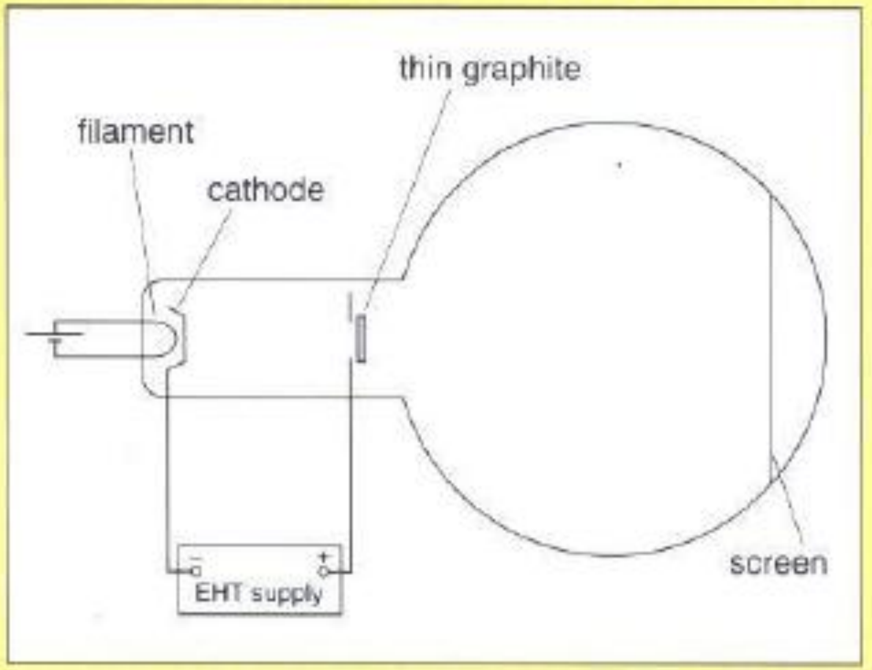


Figure 23.5 An electron diffraction tube

The layers of atoms in graphite produce electron superposition patterns. These layers are 2.1×10^{-10} m apart, and this is equivalent to the Young's slit separation. The screen is 0.14 m from the graphite, and the first subsidiary maximum is at a distance of 12 mm from the centre. So using $\lambda = xs/D$, we get

$$\lambda = (1.2 \times 10^{-2}\ \mathrm{m} \times 2.1 \times 10^{-10}\ \mathrm{m})/0.14\ \mathrm{m} = 1.8 \times 10^{-11}\ \mathrm{m}$$

De Broglie's theorem

The French physicist, Louis Victor de Broglie (pronounced "de Broy') suggested that electrons, like other particles, have wave properties, with a wavelength that is dependent on the momentum of the particle. His equation states that

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

where λ is the wavelength, h is Planck's constant and p is the momentum (found by multiplying the mass by the velocity). We can use this relationship to calculate the wavelength of the electrons producing the superposition pattern shown in Figure 23.6 and compare the result with the value above.

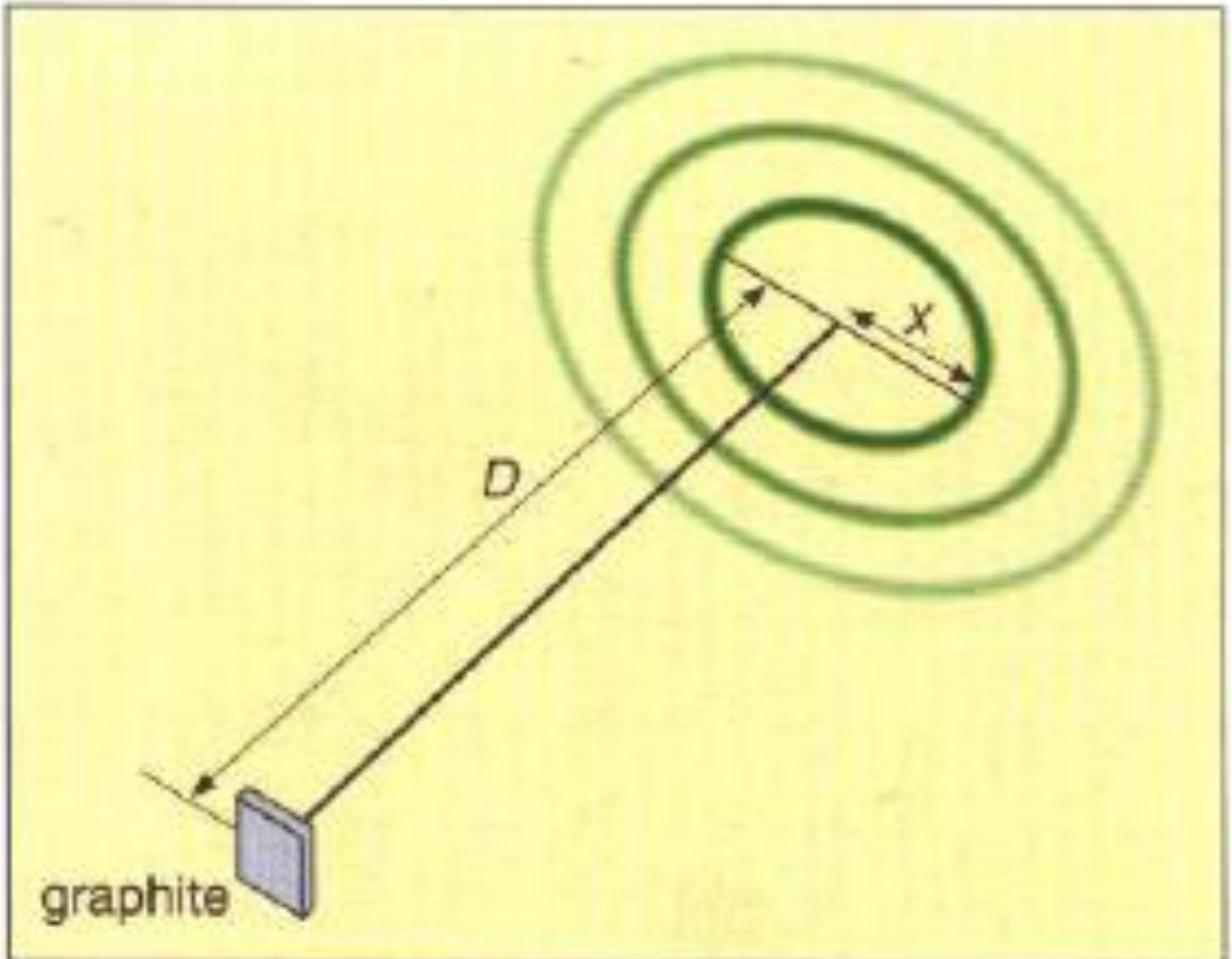


Figure 23.6   Ring geometry

Two-slit diffraction with electrons

Figure 23.7 shows how you can demonstrate two-slit superposition with electrons. This arrangement is just like Young's slits for light, but the superposition is harder to demonstrate. The wavelength even for very fast electrons is small, so the slits need to be very close for fringes to be observable.

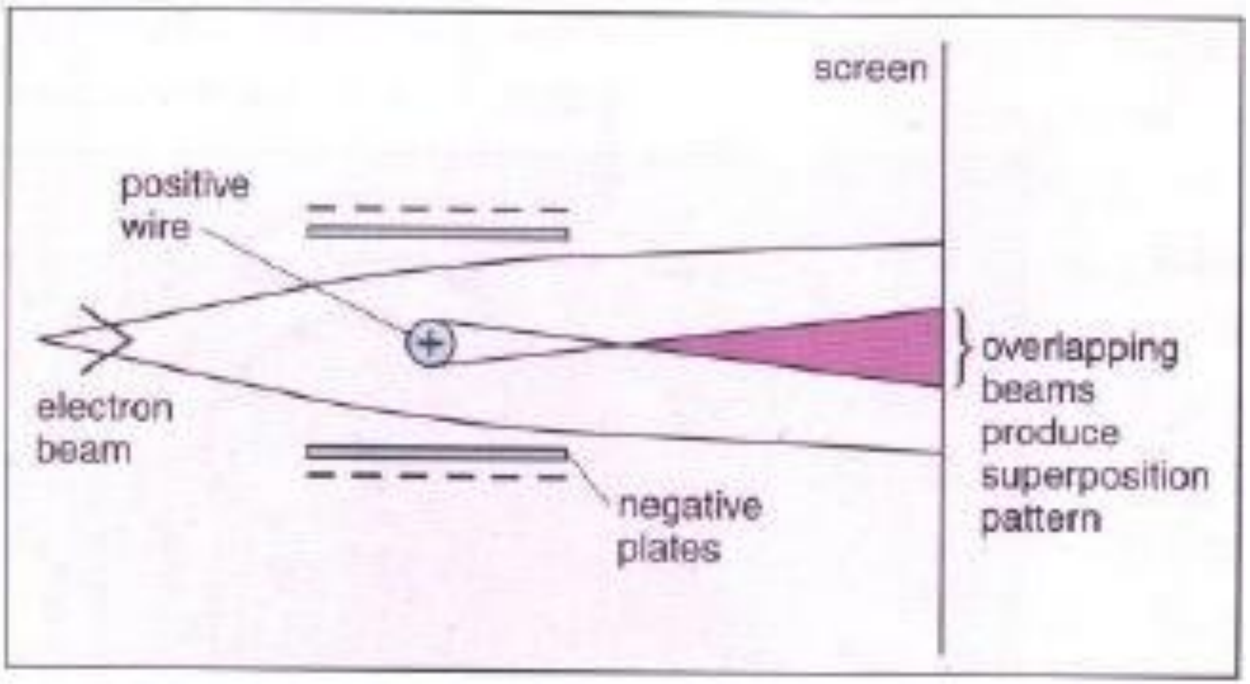
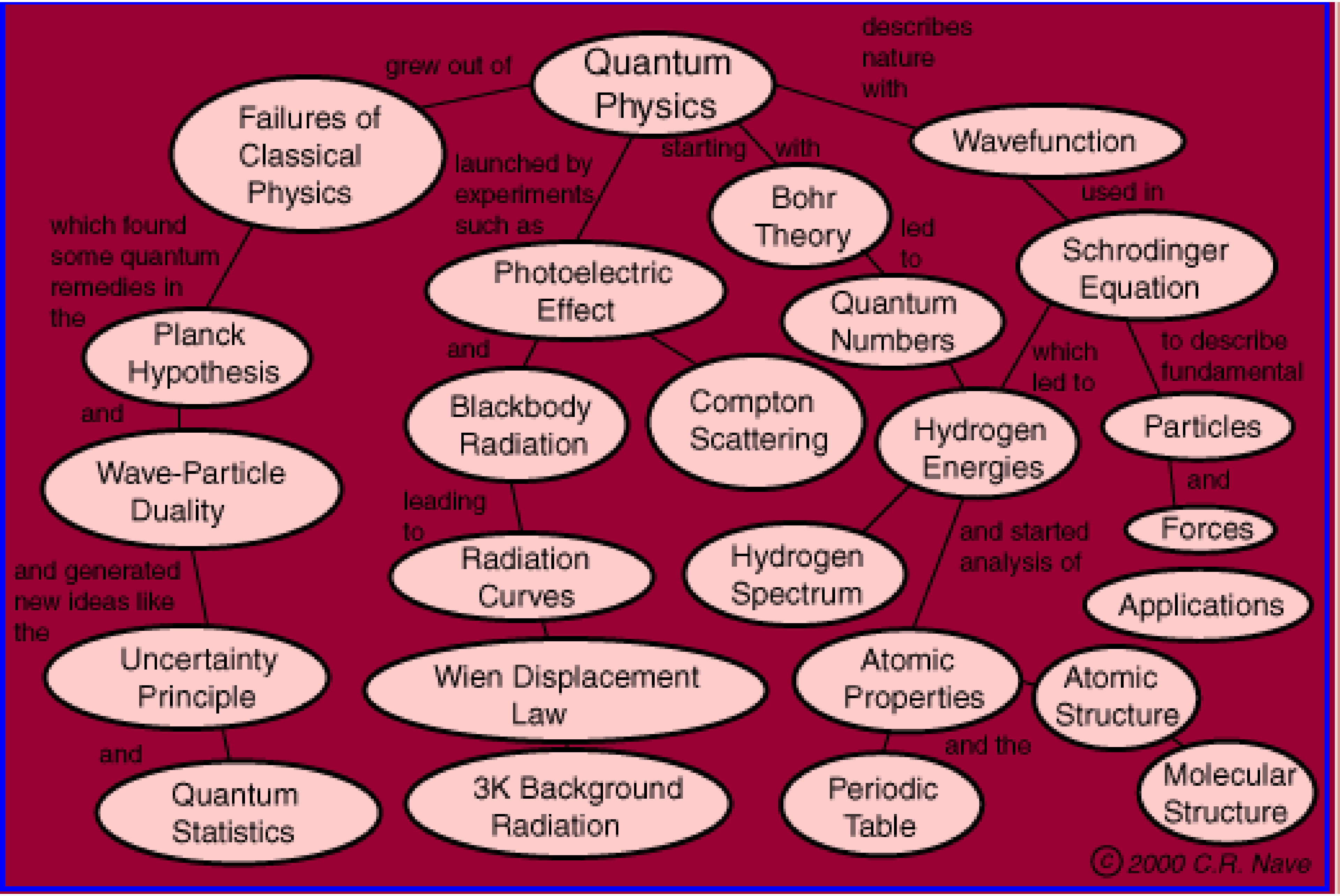


Figure 23.7 Two-slit superposition with electrons

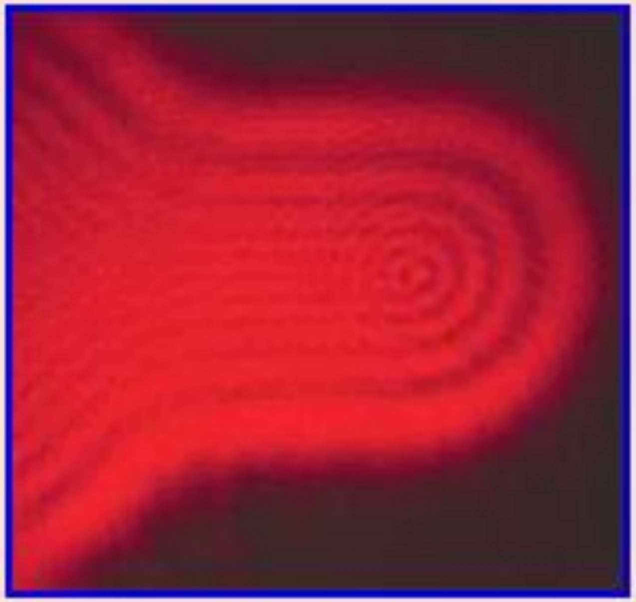
De Broglie's theory about the wave properties of particles applies to all particles, even large ones like people. The theory suggests that particles are indeed separate particles and that the wave that is associated with them (called their *wave function*) describes the probability of finding the particle in a particular place. Practice question 23.5 invites you to calculate the wavelength of a creeping bacterium. Even for that small particle, the wavelength is much smaller than the length of the bacterium, so the wave effects are simply not observable. Wave properties are only significant for particles of the size of an atom or smaller.


Quantum Physics
grew out of
Failures of Classical Physics
describes nature with
Wavefunction
launched by experiments such as
starting
with
Bohr Theory
used in
Schrodinger Equation
which found some quantum remedies in the
Photoelectric Effect
led to
Quantum Numbers
Planck Hypothesis
and
which led to
to describe fundamental
and
Blackbody Radiation
Compton Scattering
Hydrogen Energies
Particles
Wave-Particle Duality
and
leading to
Forces
and started analysis of
Radiation Curves
Hydrogen Spectrum
Applications
and generated new ideas like the
Uncertainty Principle
Wien Displacement Law
Atomic Properties
Atomic Structure
and
and the
Quantum Statistics
3K Background Radiation
Periodic Table
Molecular Structure
© 2000 C.R. Nave

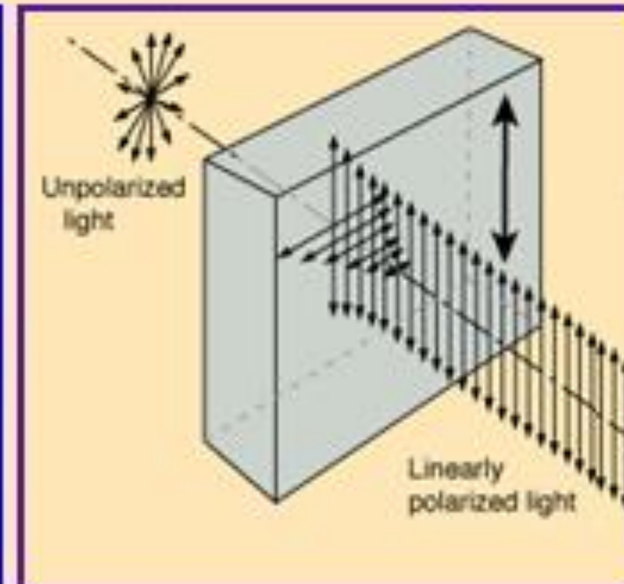
Wave-Particle Duality: Light

Does light consist of particles or waves? When one focuses upon the different types of phenomena observed with light, a strong case can be built for a wave picture:

Interference



Diffraction



Polarization

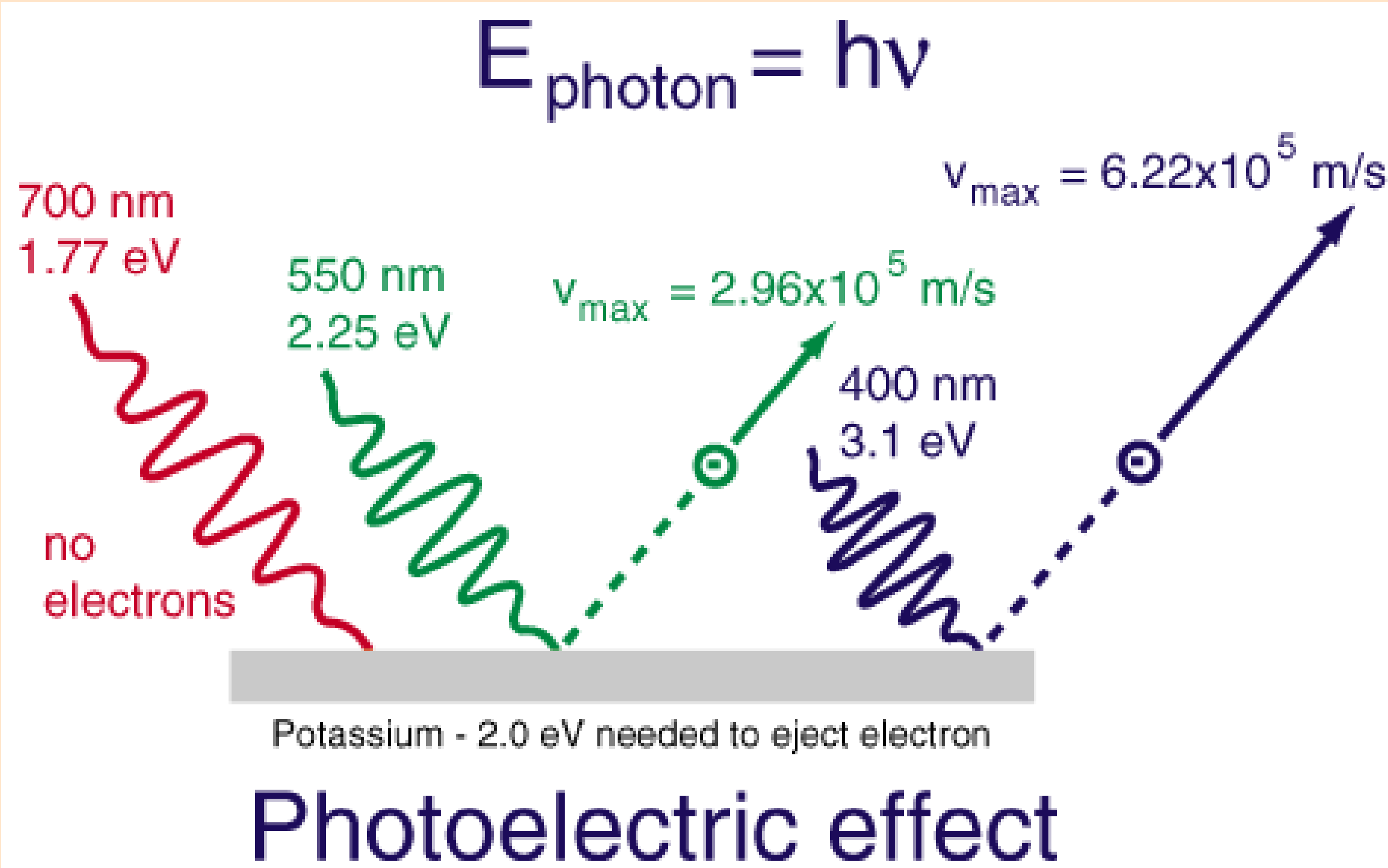
By the turn of the 20th century, most physicists were convinced by phenomena lke the above that light could be fully described by a wave, with no necessity for invoking a particle nature. But the story was not over.

By the turn of the 20th century, most physicists were convinced by phenomena lke the above that light could be fully described by a wave, with no necessity for invoking a particle nature. But the story was not over.

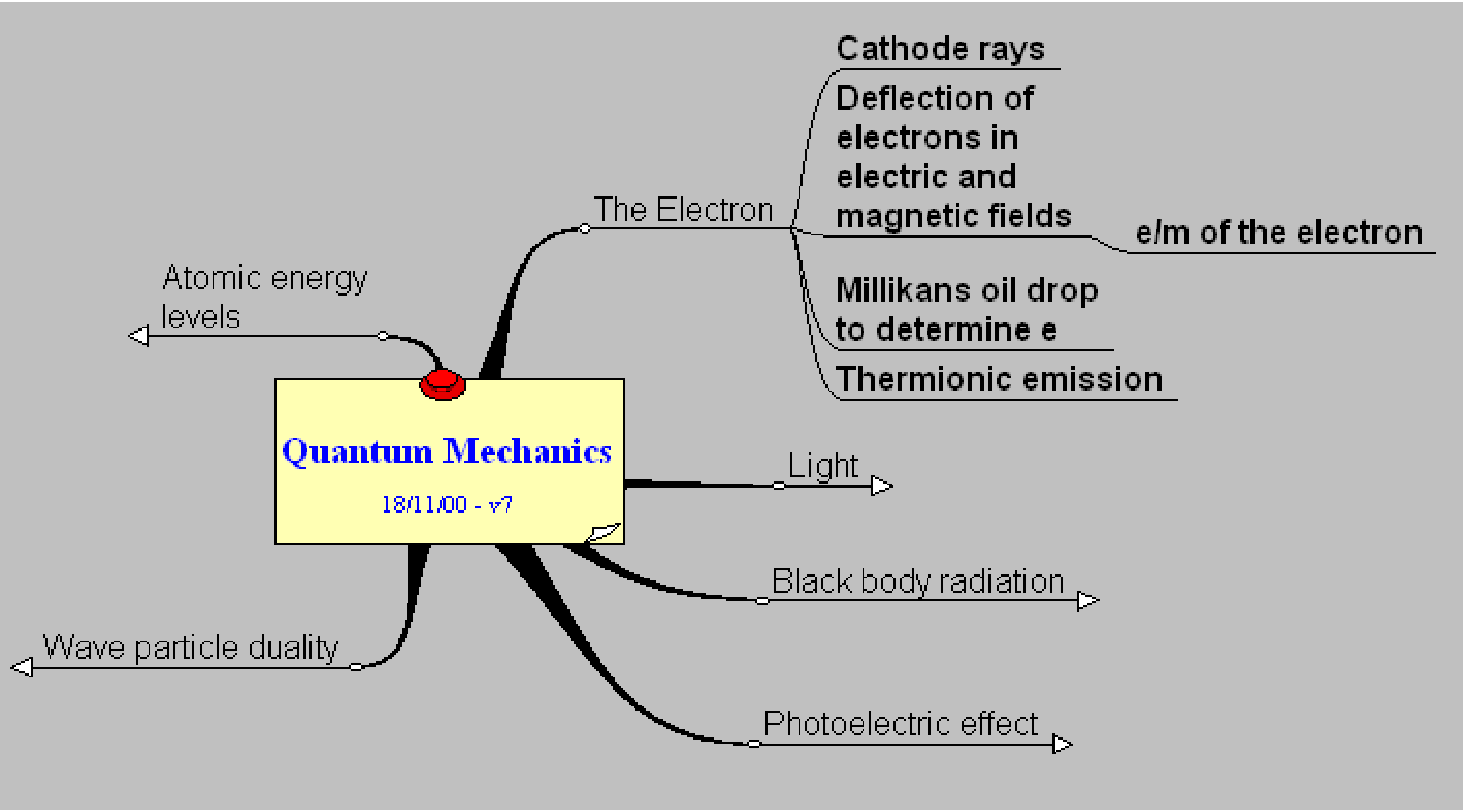
Phenomenon	Can be explained in terms of waves.	Can be explained in terms of particles.
Reflection	✓	✓
Refraction	✓	✓
Interference	✓	⊗
Diffraction	✓	⊗
Polarization	✓	⊗
Photoelectric effect	⊗	✓

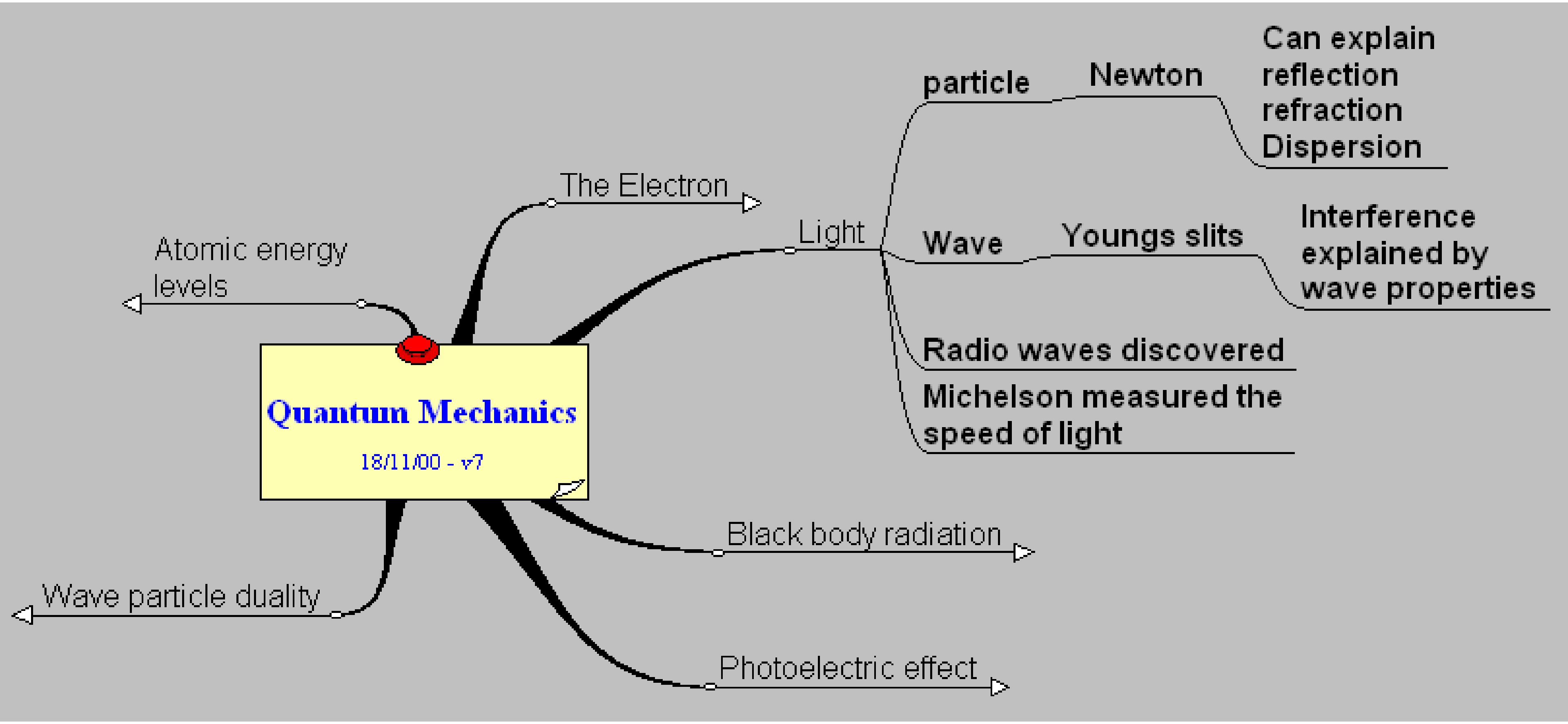
Most commonly observed phenomena with light can be explained by waves. But the photoelectric effect suggested a particle nature for light. Then electrons too were found to exhibit dual natures.

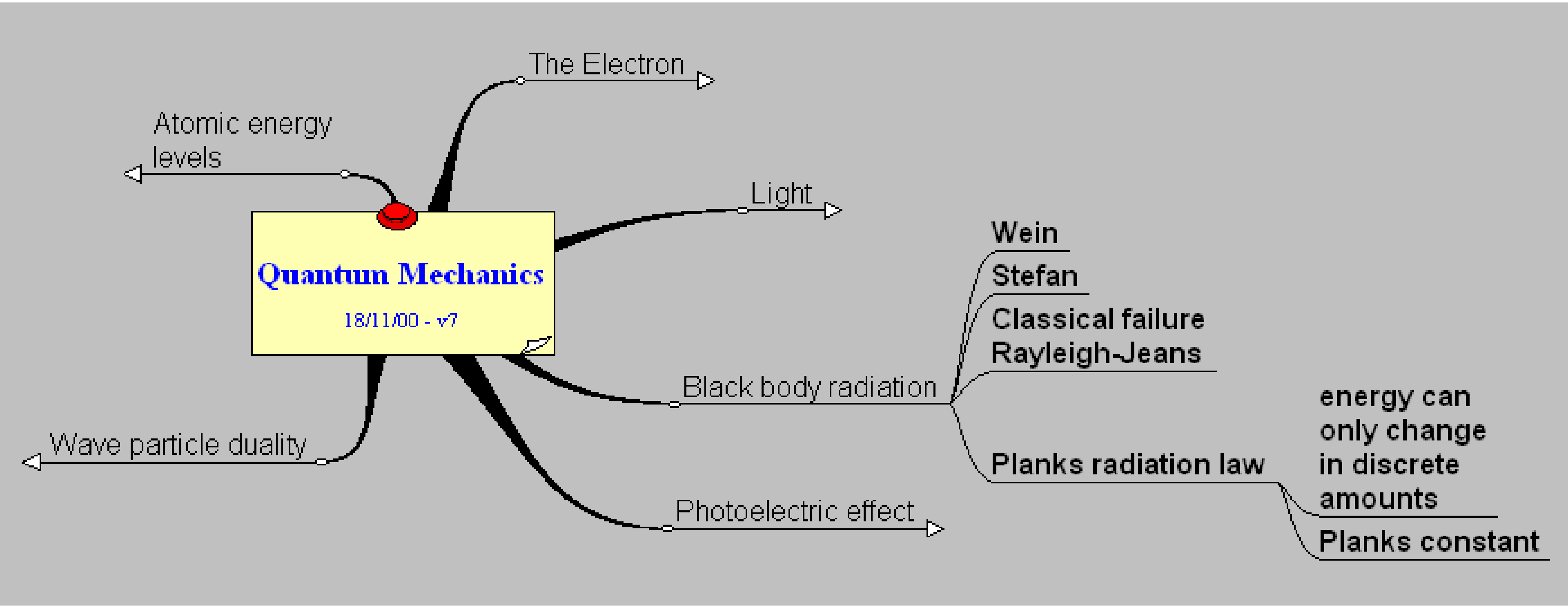
Photoelectric Effect

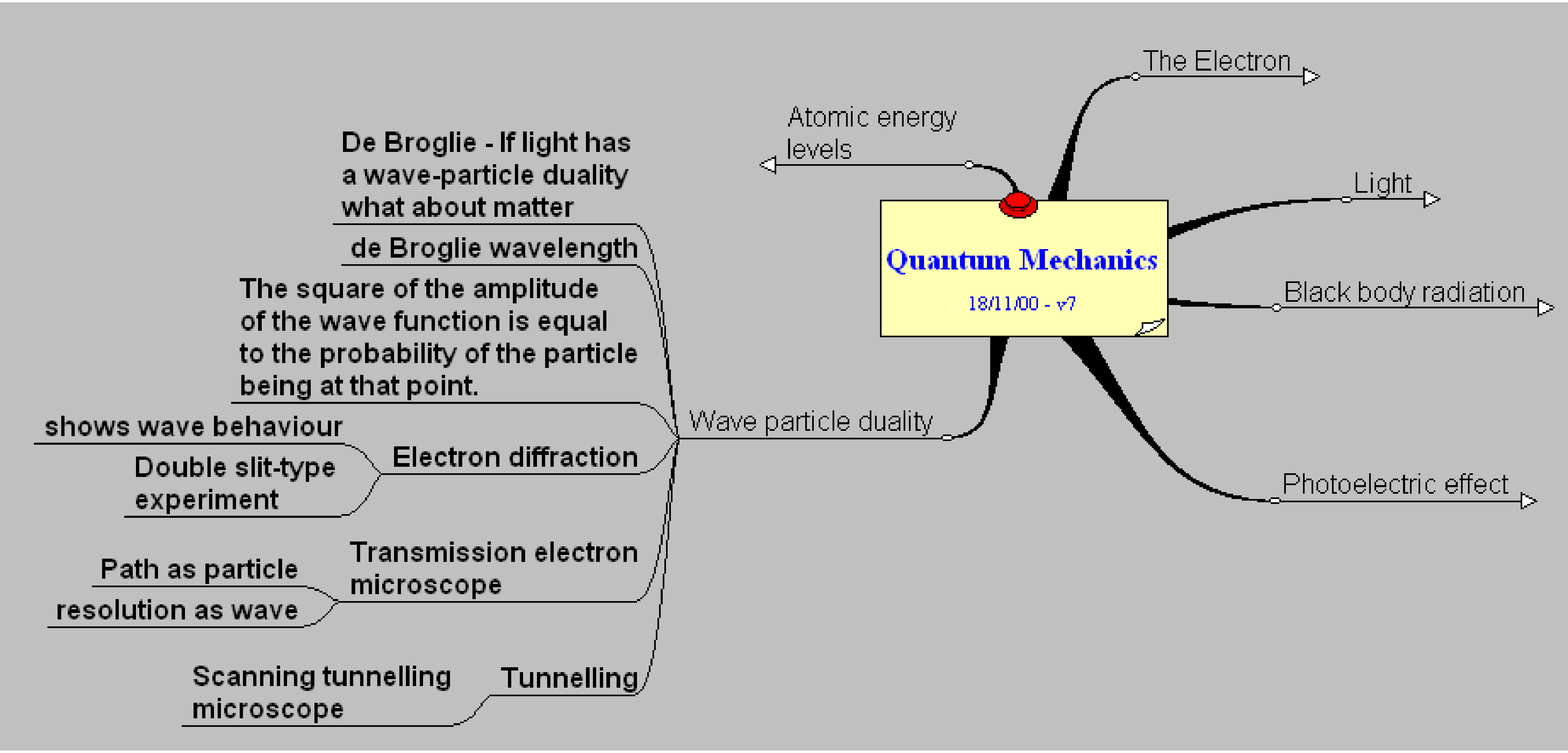


Most commonly observed phenomena with light can be explained by waves. But the photoelectric effect suggested a particle nature for light.


Quantum Mechanics
18/11/00 - v7
The Electron
Cathode rays
Deflection of electrons in electric and magnetic fields
e/m of the electron
Millikans oil drop to determine e
Thermionic emission
Atomic energy levels
Light
Black body radiation
Wave particle duality
Photoelectric effect


Quantum Mechanics
18/11/00 - v7
The Electron
Atomic energy levels
Light
particle
Newton
Can explain reflection refraction Dispersion
Wave
Youngs slits
Interference explained by wave properties
Radio waves discovered
Michelson measured the speed of light
Black body radiation
Wave particle duality
Photoelectric effect


Quantum Mechanics
18/11/00 - v7
The Electron
Atomic energy levels
Light
Wein
Stefan
Classical failure Rayleigh-Jeans
Black body radiation
energy can only change in discrete amounts
Planks radiation law
Planks constant
Wave particle duality
Photoelectric effect


Quantum Mechanics
18/11/00 - v7
The Electron
Atomic energy levels
Light
Black body radiation
Photoelectric effect
Wave particle duality
De Broglie - If light has a wave-particle duality what about matter
de Broglie wavelength
The square of the amplitude of the wave function is equal to the probability of the particle being at that point.
Electron diffraction
shows wave behaviour
Double slit-type experiment
Transmission electron microscope
Path as particle
resolution as wave
Tunnelling
Scanning tunnelling microscope