Light, particles and waves

Introduction to quantum weirdness

Our intuitive view of the "real world" is one in which objects have definite masses, sizes, locations and velocities. But it turns out that once we enter the world of the tiny (atoms and especially the electron), the "common sense" assumptions no longer apply.

Welcome to the quantum world!

The purpose of this unit is to help make you feel more confortable in this strange and counterintuitive space, where the distinction between particle and wave breaks down.

We will then show you how the the ***quantum particle*** behavior of electrons determines the properties of the chemical elements and the structure of the periodic table.

Fasten your seat-belts!

"Anyone who is not shocked by quantum theory doesn't understand it."

Niels Bohr

"I think I can safely say that nobody understands quantum mechanics. ...[its] 'paradox' is only a conflict between reality and your feeling of what reality 'ought to be.' "

Richard Feynman

"The entire universe must, on a very accurate level, be regarded as a single indivisible unit in which separate parts appear as idealisations permissible only on a classical level of accuracy of description."

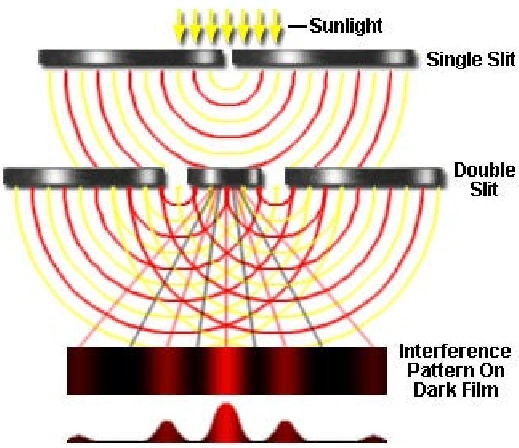
David Bohm

1 The weird behavior of quantum particles

Atoms are far too small to see directly, even with the most powerful optical microscopes. But atoms do interact with and under some circumstances emit light in ways that reveal their internal structures in amazingly fine detail. It is through the "language of light" that we communicate with the world of the atom. This section will introduce you to the rudiments of this language.

Wave, particle... or *what*?

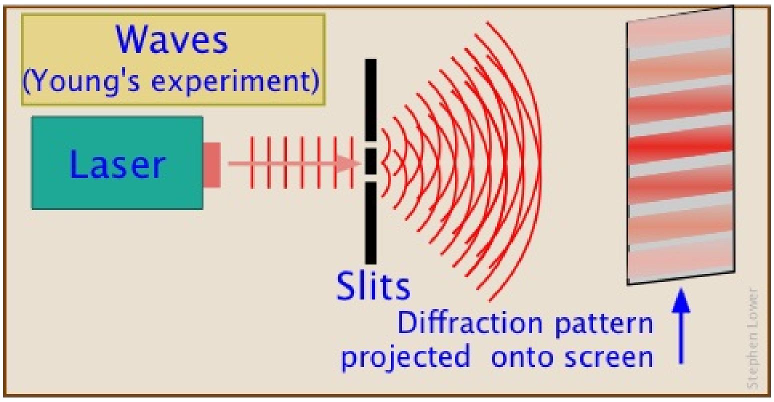
In the early 19th century, the English scientist Thomas Young carried out the famous double-slit experiment which demonstrated that a beam of light, when split into two beams and then recombined, will show *interference effects* that can only be explained by assuming that light is a wavelike disturbance. By 1820, Augustin Fresnel had put this theory on a sound mathematical basis, but the exact nature of the waves remained unclear until the 1860's when James Clerk Maxwell developed his electromagnetic theory.



[New Zealand Institute of Physics]

Young's experiment deconstructed

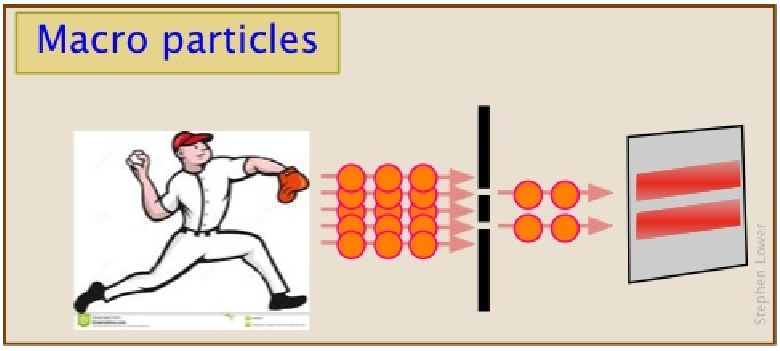
In this



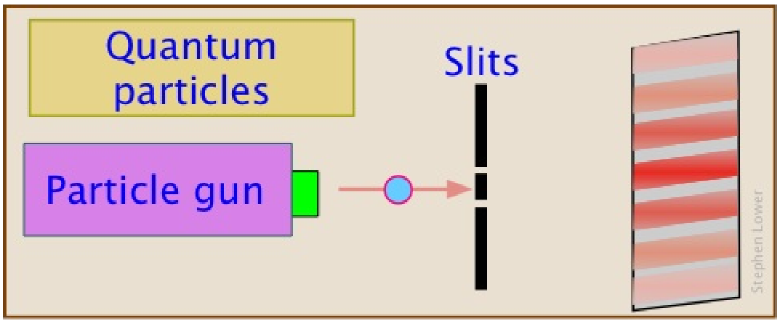
simplified version of Young's experiment, a laser provides a coherent source of plane waves (eliminating the need for the single slit shown at the top of the preceding diagram) directed at the two slits. Each slit acts as a new point source of ordinary (curved) waves that produce an interference pattern of the kind shown.

Nothing new here (not since 1799, anyway!) This works for all kinds of physical waves — light, ocean, sound...

How about



particles? For ordinary macro particles such as baseballs, sand, or just about anything larger than a small molecule, the result is exactly what our real-world experience predicts: each slit defines its own target area.



Shrink our baseballs down to atomic size, and shoot our particles one-at-a-time at the pair of slits, and the pattern that builds up is similar to the kind that Mr. Young observed.

This works for photons (light), electrons, atoms, and small molecules.

Quantum weirdness emerges

OK, this suggests that particles have wave-like properties. *But something very strange is going on here:*

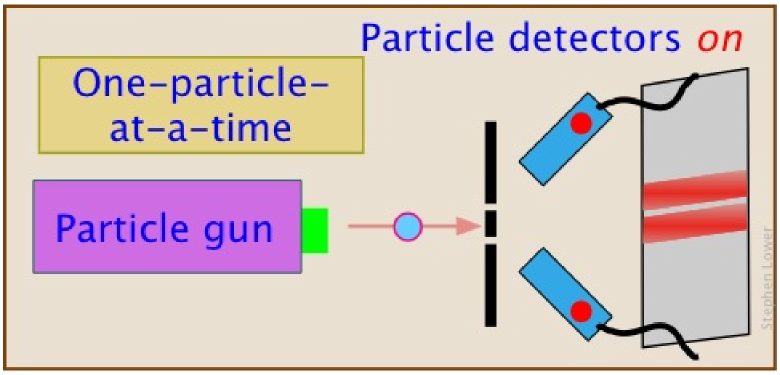
First, consider how the above experiment differ from Young's. His light source was a continuous beam of huge numbers of photons that can *only* be treated as a "wave". The process we are describing here is carried out experimentally not with a "photon gun", but by simply reducing the intensity of the light to such an unimaginably small level that only *one photon* is in transit at a time. So even if we admit that the photon "has wave-like properties", we know that it takes *two* waves (and thus presumably two photons) to form an interference pattern.

This raises the question: how can a *single* photon/"wave" (or whatever we wish to call it) emerge from the double-slit system as *two* wave-like entities that combine to form typical wave-derived interference pattern?

There is no clear answer to this question. Perhaps the simplest explanation is that the photon passes through *both* slits. *Welcome to the world of quantum weirdness!*

It gets even weirder

One way of resolving this question might be to aim two "particle detectors" at each slit, in the hope that we can determine what

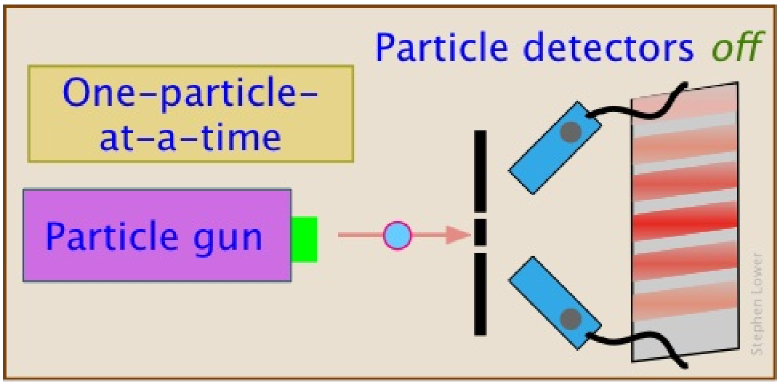


emerges from each one.

This kind of experiment has actually been done, both with photons and electrons.

The result is even more weird: the quantum-nature of the particles disappears.
They act as if they were baseballs!

Now, repeat the last



experiment, making only one change: turn the particle detectors off.

Voilà — pulling the plug on the particle detectors restores the quantum nature of the particles.

So apparently, the particle somehow "knows" that it is being watched, and reveals its wave-like nature again.

Now this is *really* weird!

There is a good Wikipedia article that explains this in more detail. See also the article on the many-worlds interpretation of these phenomena.

The apparent"intelligence" of quantum particles

For large bodies (most atoms, baseballs, cars) there is no question: the wave properties are insignificant, and the laws of classical mechanics can adequately describe their behaviors. But for particles as tiny as electrons (***quantum particles***), the situation is quite different: instead of moving along well defined paths, a quantum particle seems to have an infinity of paths which thread their way through space, seeking out and collecting information about all possible routes, and then adjusting its behavior so that its final trajectory, when combined with that of others, produces the same overall effect that we would see from a train of waves of wavelength = h/mv.

One well-known physicist (Landé) suggested that perhaps we should coin a new word, *wavicle*, to reflect this duality.

If cars behaved as

quantum particles, this would present no problem at all!

Image source: Loyola U - "The double-slit garage experiment" from *Annals of Improbable Research*.

Will Schrödinger's cat come back?

See this Wikipedia article for a nice discussion of Schrödinger's cat paradox.

Taking this idea of quantum indeterminacy to its most extreme, the physicist Erwin Schrödinger proposed a "thought experiment" in which the radioactive decay of an atom would initiate a chain of events that would lead to the death of a cat placed in a closed box. The atom has a 50% chance of decaying in an hour, meaning that its wave representation will contain both possibilities until an observation is made.

Suppose that the decay of this atom will initiate a process in which a hammer drops onto, and breaks, a vial of liquid having a poisonous vapor.

The question, then, is will the cat be simultaneously in an alive-and-dead state until the box is opened? If so, this raises all kinds of interesting questions about the nature of reality.

[image]

The saga of Schrödinger's cat has inspired a huge amount of commentary and speculation, as well as books, poetry, songs, T-shirts, etc. This Wikipedia page is devoted entirely to "Schrödinger's cat in popular culture".

2 Understanding light and electromagnetic radiation

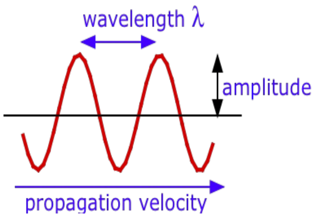
If your head is still spinning from the quantum weirdness described in the preceding section, you can now relax a bit: in this section, we are back to good old classical physics!

What you need to know about waves

We use the term "wave" to refer to a quantity which changes with time. Waves in which the changes occur in a repeating or periodic manner are of special importance and are widespread in nature; think of the motions of the ocean surface, the pressure variations in an organ pipe, or the vibrations of a plucked guitar string. What is interesting about all such repeating phenomena is that they can be described by the same mathematical equations.

Wave motion arises when a periodic disturbance of some kind is propagated through a medium; pressure variations through air, transverse motions along a guitar string, or variations in the intensities of the local electric and magnetic fields in space, which constitutes electromagnetic radiation. For each medium, there is a characteristic *velocity* at which the disturbance travels.

A rather nice **animation** of linear and transverse wave motions



There are three measurable properties of wave motion: ***amplitude***, ***wavelength***, and ***frequency***, the number of vibrations per second. The relation between the wavelength λ (Greek *lambda*) and frequency of a wave ν (Greek *nu*) is determined by the propagation velocity *v*

$$v = \nu\,\lambda$$

Problem Example 1

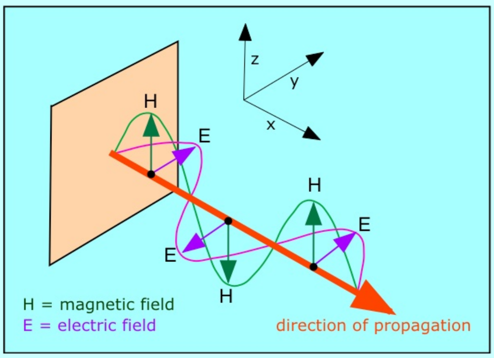
What is the wavelength of the musical note A = 440 hz when it is propagated through air in which the velocity of sound is 343 m s^{-1}?

Solution:

$$\lambda = v / \nu = (343 \text{ m s}^{-1})/(440 \text{ s}^{-1}) = 0.80 \text{ m}$$

The nature of electromagnetic waves

Michael Faraday's discovery that electric currents could give rise to magnetic fields and *vice versa* raised the question of how these effects are transmitted through space. Around 1870, the Scottish physicist James Clerk Maxwell (1831-1879) showed that this electromagnetic radiation can be described as a train of perpendicular oscillating electric and magnetic fields.



What is "waving" in electromagnetic radiation?

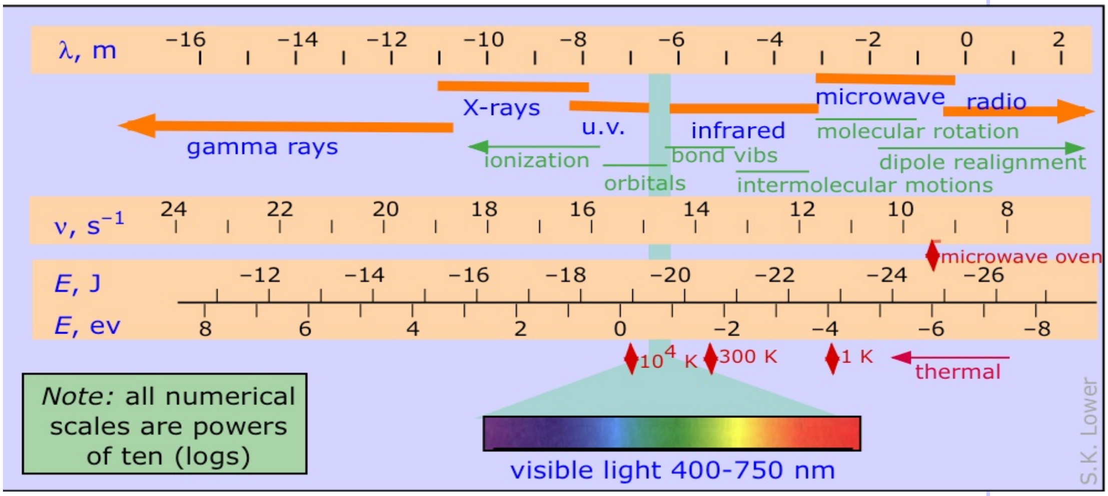
According to Maxwell, it is the strengths of the electric and magnetic fields as they travel through space. The two fields are oriented at right angles to each other and to the direction of travel.

As the electric field changes, it induces a magnetic field, which then induces a new electric field, etc., allowing the wave to propagate itself through space.

Maxwell was able to calculate the speed at which electromagnetic disturbances are propagated, and found that this speed is the same as that of light. He therefore proposed that light is itself a form of electromagnetic radiation whose wavelength range forms only a very small part of the entire electromagnetic spectrum. Maxwell's work served to unify what were once thought to be entirely separate realms of wave motion.

The electromagnetic spectrum

The electromagnetic spectrum is conventionally divided into various parts as depicted in the diagram below, in which the four logarithmic scales correlate the wavelength of electromagnetic radiation with its frequency in herz (units of s^{-1}) and the energy per photon, expressed both in joules and electron-volts.



The other items shown on the diagram, from the top down, are:

- the names used to denote the various wavelength ranges of radiation (you should know their names and the order in which they appear)
- the principal effects of the radiation on atoms and molecules
- the peaks of thermal radiation emitted by black bodies at three different temperatures

See here for a more detailed look at the electromagnetic spectrum

Electromagnetic radiation and chemistry

It's worth noting that radiation in the ultraviolet range can have direct chemical effects by ionizing atoms and disrupting chemical bonds. Longer-wavelength radiation can interact with atoms and molecules in ways that provide a valuable means of indentifying them and revealing particular structural features.

Energy units and magnitudes

It is useful to develop some feeling for the various magnitudes of energy that we must deal with. The basic SI unit of energy is the *Joule*; the appearance of this unit in ***Planck's constant h*** allows us to express the energy equivalent of light in joules. For example, light of wavelength 500 nm, which appears blue-green to the human eye, would have a frequency of

$$\nu = \frac{c}{\lambda} = \frac{(3 \times 10^{8}\ \mathrm{m\,s^{-1}})}{(5 \times 10^{-7}\ \mathrm{m})} = (6 \times 10^{14}\ \mathrm{s^{-1}})$$

The quantum of energy carried by a single photon of this frequency is

$$e = h\nu = (6.63 \times 10^{-34}\ \mathrm{J\,s}) \times (6 \times 10^{14}\ \mathrm{s^{-1}}) = 4.0 \times 10^{19}\ \mathrm{J}$$

Another energy unit that is commonly employed in atomic physics is the *electron volt*; this is the kinetic energy that an electron acquires upon being accelerated across a 1-volt potential difference. The relationship 1 eV = 1.6022E–19 J gives an energy of 2.5 eV for the photons of blue-green light.

Worth knowing! Two small flashlight batteries will produce about 2.5 volts, and thus could, in principle, give an electron about the same amount of kinetic energy that blue-green light can supply. Because the energy produced by a battery derives from a chemical reaction, this quantity of energy is representative of the magnitude of the energy changes that accompany chemical reactions.

In more familiar terms, one mole of 500-nm photons would have an energy equivalent of Avogadro's number times 4E–19 J, or 240 kJ per mole. This is comparable to the amount of energy required to break some chemical bonds. Many substances are able to undergo chemical reactions following light-induced disruption of their internal bonding; such molecules are said to be *photochemically active*.

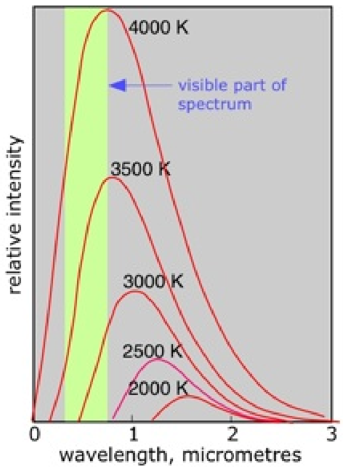
3 Spectra: how light reveals matter

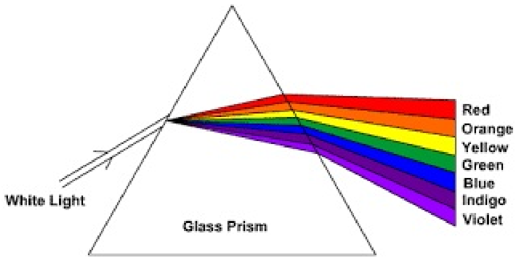
Atoms are far too small to observe directly, even with the most powerful optical microscopes. But atoms do interact with and under some circumstances emit light in ways that reveal their internal structures in amazingly fine detail. It is through the "language of light" that we communicate with the world of the atom. This section will introduce you to the rudiments of this language.

Continuous spectra

Any body whose temperature is above absolute zero emits radiation covering a broad range of wavelengths. At very low temperatures the predominant wavelengths are in the radio microwave region. As the temperature increases, the wavelengths decrease; at room temperature, most of the emission is in the infrared.

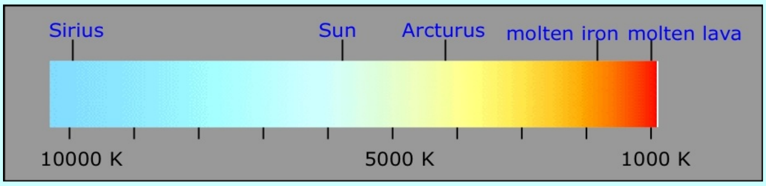
At still higher temperatures, objects begin to emit in the visible region, at first in the red, and then moving toward the blue as the temperature is raised. These *thermal emission spectra* are described as ***continuous spectra***, since all wavelengths within the broad emission range are present.





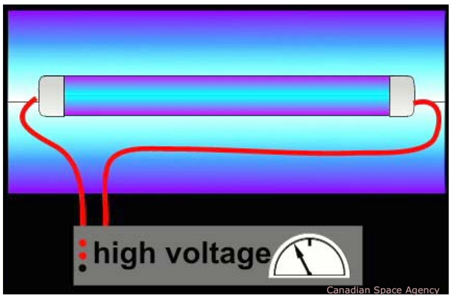
The source of thermal emission most familiar to us is the Sun. When sunlight is refracted by rain droplets into a rainbow or by a prism onto a viewing screen, we see the visible part of the spectrum.

What color is the Sun?
Wikipedia article on Solar radiation



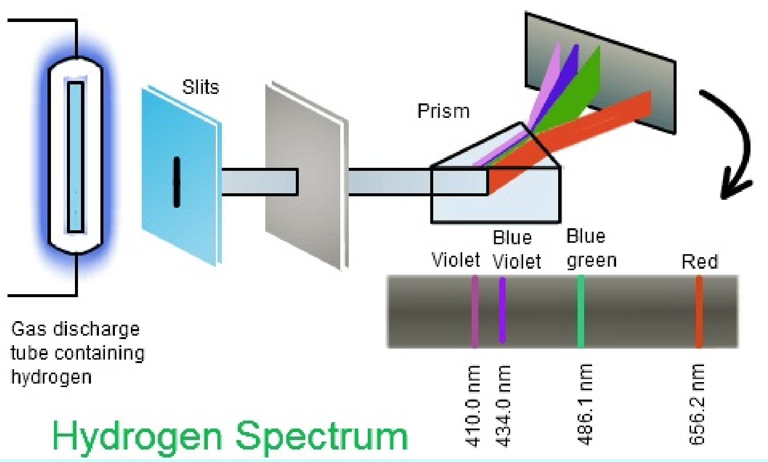
Red hot, white hot, blue hot... your rough guide to temperatures of hot objects.

Line spectra and their uses



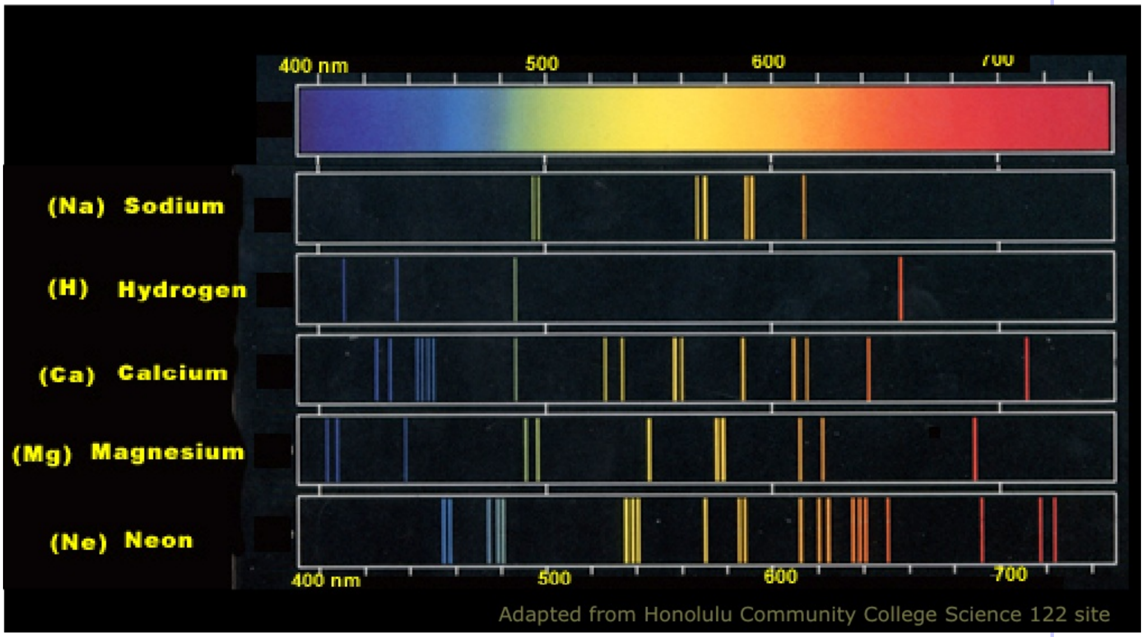
Heat a piece of iron up to near its melting point and it will emit a broad continuous spectrum that the eye perceives as orange-yellow. But if you zap the iron with an electric spark, some of the iron atoms will vaporize and have one or more of their electrons temporarily knocked out of them. As they cool down the electrons will re-combine with the iron ions, losing energy as the move in toward the nucleus and giving up this excess energy as light. The spectrum of this light is anything but continuous; it consists of a series of discrete wavelengths which we call *lines*.

A *spectrum* is most accurately expressed as a plot of intensity as a function of wavelength. Historically, the first spectra were obtained by passing the radiation from a source through a series or narrow slits to obtain a thin beam which was dispersed by a prism so that the different wavelengths are spread out onto a photographic film or viewing screen. The "lines" in ***line spectra*** are really images of the slit nearest the prism. Modern spectrophotometers more often employ diffraction gratings rather then prisms, and use electronic sensors connected to a computer.



[image: Purdue U.]

Each chemical element has its own characteristic *emission line spectrum* which serves as a "fingerprint" capable of identifying a particular element in a complex mixture. Shown below is what you would see if you could look at several different atomic line spectra directly.



What do these spectra tell us about the nature of chemical atoms? We will explore this question in some detail in the next lesson.

Worth knowing! Atomic line spectra are extremely useful for identifying small quantities of different elements in a mixture.

- Companies that own large fleets of trucks and buses regularly submit their crankcase engine oil samples to spectrographic analysis. If they find high levels of certain elements (such as vanadium) that occur only in certain alloys, this can signal that certain parts of the engine are undergoing severe wear. This allows the mechanical staff to take corrective action before engine failure occurs.
- Several elements (Rb, Cs, Tl) were discovered by observing spectral lines that did not correspond to any of the then-known elements. Helium, which is present only in traces on Earth, was first discovered by observing the spectrum of the Sun.
- A more prosaic application of atomic spectra is determination of the elements present in stars.

Line spectra of discharge lamps and neon signs

If you live in a city, you probably see atomic line light sources every night! "Neon" signs are the most colorful and spectacular, but high-intensity street lighting is the most widespread source. A look at the emission spectrum (above) of sodium explains the intense yellow color of these lamps. The spectrum of mercury (not shown) similarly has its strongest lines in the blue-green region.

About high-intensity discharge lamps
Neon signs: their history and how they work

4 Particles as waves

The wavelength of a particle

de Broglie's name is widely mis-pronounced. The "g" is silent; "de-broy" is reasonably close.

There is one more fundamental concept you need to know before we can get into the details of atoms and their spectra. If light has a particle nature, why should particles not possess wavelike characteristics? In 1923 a young French physicist, Louis de Broglie, published an argument showing that matter should indeed have a wavelike nature. The *de Broglie wavelength* of a body, denoted by λ (*lambda*) is inversely proportional to its momentum *mv*:

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

If you explore the magnitude of the quantities in this equation (recall that *h* is around 10^{-33} J s), it will be apparent that the wavelengths of all but the lightest bodies are insignificantly small fractions of their dimensions, so that the objects of our everyday world all have definite boundaries. Even individual atoms are sufficiently massive that their wave character is not observable in most kinds of experiments.

Electrons, however, are another matter; the electron was in fact the first particle whose wavelike character was seen experimentally, following de Broglie's prediction. Its small mass (9.1E–31 kg) made it an obvious candidate, and velocities of around 100 km/s are easily obtained, yielding a value of λ in the above equation that well exceeds what we think of as the "radius" of the electron. At such velocities the electron behaves as if it is "spread out" to atomic dimensions; a beam of these electrons can be diffracted by the ordered rows of atoms in a crystal in much the same way as visible light is diffracted by the closely-spaced groves of a CD recording.

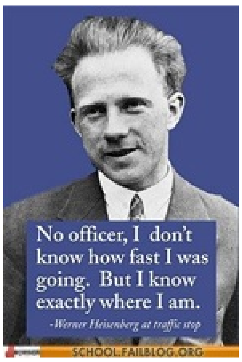
Some examples of de Broglie wavelength calculations

Electron diffraction has become an important tool for investigating the structures of molecules and of solid surfaces.

A more familiar exploitation of the wavelike properties of electrons is seen in the *electron microscope*, whose utility depends on the fact that the wavelength of the electrons is much less than that of visible light, thus allowing the electron beam to reveal detail on a correspondingly smaller scale.

The uncertainty principle

In 1927, the German physicist Werner Heisenberg pointed out that the wave nature of matter leads to a profound and far-reaching conclusion: no method of observation, however perfectly it is carried out, can reveal both the exact *location* and *momentum* (and thus the *velocity*) of a particle.



Suppose that you wish to measure the exact location of a particle that is at rest (zero momentum). To accomplish this, you must "see" the molecule by illuminating it with light or other radiation. But the light acts like a beam of photons, each of which possesses the momentum h/λ in which λ is the wavelength of the light. When a photon collides with the particle, it transfers some of its momentum to the particle, thus altering both its position and momentum.

This is the origin of the widely known concept that the very process of observation will change the value of the quantity being observed. The Heisenberg principle can be expressed mathematically by the inequality

$$\delta x \times \delta y \geq \frac{h}{2\pi}$$

in which the δ's (deltas) represent the uncertainties with which the location and momentum are known. Notice how the form of this expression predicts that if the location of an object is known exactly ($\delta x = 0$), then the uncertainty in the momentum must be infinite, meaning that nothing at all about the velocity can be known. Similarly, if the velocity were specified exactly, then the location would be entirely uncertain and the particle could be anywhere.

> One interesting consequence of this principle is that even at a temperature of absolute zero, the molecules in a crystal must still possess a small amount of *zero point vibrational motion*, sufficient to limit the precision to which we can measure their locations in the crystal lattice. An equivalent formulation of the uncertainty principle relates the uncertainties associated with a measurement of the energy of a system to the time δt taken to make the measurement:

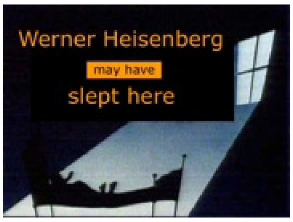
$$\delta e \times \delta t \geq \frac{h}{2\pi}$$

The "uncertainty" referred to here goes much deeper than merely limiting our ability to *observe* the quantity $\delta x \delta p$ to a greater precision than $h/2\pi$. It means, rather, that this product has no exact value, nor, by extension, do *position* and *momentum* on a microscopic scale. A more appropriate term would be *indeterminacy*, which is closer to Heisenberg's original word *Ungenauigkeit*.

Two well-done non-technical discussions of the uncertainty prinicple:

The American Institute of Physics "exhibit" of the HUP

Some practical and philosophical implications of the HUP



The uncertainty principle in popular culture

The revolutionary nature Heisenberg's uncertainty principle now extends far beyond the arcane world of physics; the term has entered the realm of ideas and has inspired numerous creative works in the arts. But few of these really have much to do with Heisenberg's concept. [Zazzle T-shirt] →

Perhaps the best known of these is Michael Frayn's widely acclaimed 1998 play *Copenhagen* that is based on a secret meeting between Heisenberg and Niels Bohr in German-occupied Denmark during the second world war.

About the play *Copenhagen* - commentary on the play - DVD of the 2002 film

What you should be able to do

Make sure you thoroughly understand the following essential ideas which have been presented above. It is especially imortant that you know the precise meanings of all the highlighted terms in the context of this topic.

- Cite two pieces of experimental evidence that demonstrate, respectively, the wave- and particle-like nature of light.
- Define the terms ***amplitude***, ***wavelength***, and ***frequency*** as they apply to wave phenomena.
- Give a qualitative description of ***electromagnetic radiation*** in terms of electrostatic and magnetic fields.
- Be able to name the principal regions of the ***electromagnetic spectrum*** (X-rays, infrared region, etc.) and specify their sequence in terms of either wavelength or energy per photon.
- Describe the difference between ***line spectra*** and ***continuous spectra*** in terms of both their appearance and their origins.
- What is meant by the ***de Broglie wavelength*** of a particle? How will the particle's mass and velocity affect the wavelength?
- State the consequences of the ***Heisenberg uncertainty principle*** in your own words.

Quantum Concept Map