Characteristics of Matter

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CONCEPT 1 Characteristics of Matter

Lesson Objectives

The student will:

- describe a standing wave.
- state the Heisenberg uncertainty principle.

Vocabulary

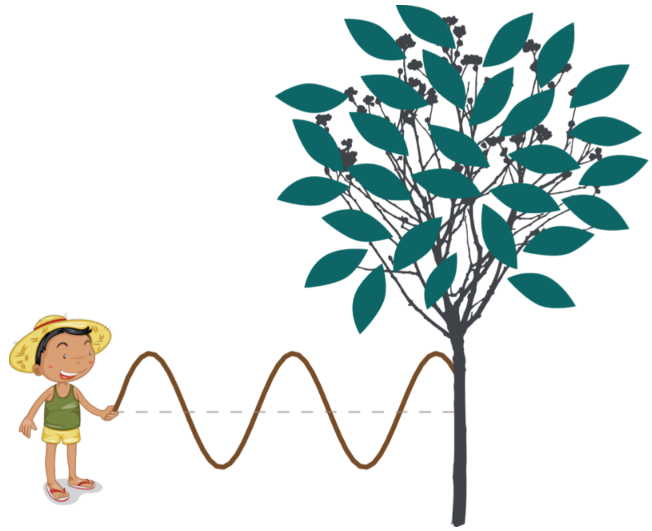
- Heisenberg uncertainty principle

Wave Character of Particles

In 1924, the Frenchman Louis de Broglie, a physics graduate student at the time, suggested that if waves can have particle-like properties as hypothesized by Planck, then perhaps particles can have some wave-like properties. This concept received some experimental support in 1937 when investigators demonstrated that electrons could produce diffraction patterns. (All objects, including baseballs and automobiles could be considered to have wave-like properties, but this concept is only measurable when dealing with extremely small particles like electrons.) De Broglie's "matter waves" would become very useful in attempts to describe the behavior of electrons inside atoms.

Standing Waves

In the chapter "The Bohr Model of the Atom," we considered a rope wave that was created by tying one end of the rope to a tree and by jerking the other end up and down. When a wave travels down a rope and encounters an immovable boundary, the wave reflects off the boundary and travels back up the rope. This causes interference between the wave traveling toward the tree and the reflected wave traveling back toward the person. If the person moving the rope up and down adjusts the rhythm just right, the crests and troughs of the wave moving toward the tree will coincide exactly with the crests and troughs of the reflected wave. When this occurs, the apparent horizontal motion of the crests and troughs along the rope will cease. This is called a standing wave. In such a case, the crests and troughs will remain in the exact same place, while the nodes between the crests and troughs do not appear to move at all.



In the standing wave shown above, the positions of the crests and troughs remain in the same positions. The crests and troughs will only appear to exchange places above and below the rope. The places where the rope does not cross the center axis line are called nodes (positions of zero displacement). These nodal positions do not change and appear to be frozen in place. By combining the concept of a standing wave along with de Broglie's matter waves, it became possible to describe an electron in an electron cloud as either a particle or a standing wave.

The Heisenberg Uncertainty Principle

In all previous attempts to describe the electron's behavior inside an atom, including in the Bohr model, scientists tried to describe the path the electron would follow around the nucleus. The theorists wanted to describe where the electron was located and how it would move from that position to its next position.

In 1927, a German physicist named Werner Heisenberg, a German physicist stated what is now known as the **Heisenberg uncertainty principle**. This principle states that it is impossible to know both the precise location and the precise velocity of an electron at the same time. The reason that we can't determine both is because the act of determining the location changes the velocity. In the process of making a measurement, we have actually changed the measurement.

This problem is present in all laboratory work, but it is usually negligible. Consider the act of measuring the temperature of hot water in a beaker. When you insert the thermometer into the water, the water transfers heat to the thermometer until the thermometer is at the same temperature as the water. You can then read the temperature of the water from the thermometer. The temperature of the water, however, is no longer the same as before you inserted the thermometer. The water has cooled by transferring some of its heat to the thermometer. In other words, the act of making the measurement changes the measurement. In this example, the difference is most likely not significant. You can imagine, however, that if the mass of water was very small and the thermometer was very large, the water would have to transfer a greater amount of heat to the thermometer, resulting in a less accurate measurement.

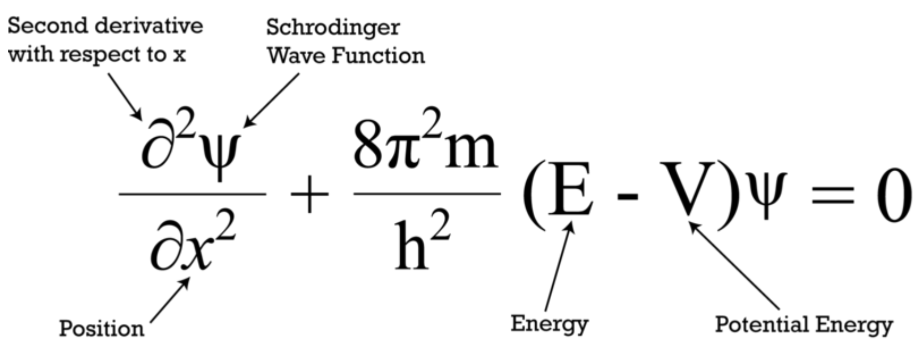
Consider the method that humans use to see objects. We see an object when photons bounce off the object and into our eye or other light-measuring instrument. Recall that photons can have various wavelengths, which correspond to different colors. If only red photons bounce back, we say the object is red. If no photons bounce back, we don't see the object. Suppose for a moment that humans were gigantic stone creatures that use golf balls, instead of photons, to see. In other words, we see objects when the golf balls bounce off them and enter our eyes. We would be able to see large objects like buildings and mountains successfully, because the golf balls would bounce off and reach our eyes. Could we see something small like a butterfly with this technique? The answer is no. A golf ball has a greater mass than a butterfly, so when the golf ball bounces off the butterfly, the motion of the butterfly will be very different after the collision. We will know the position of the butterfly, but we won't know the motion of the butterfly.

In the case of electrons, the photons we use to see them with are of significant energy compared to electrons and will change the motion of the electrons upon collision. We may be able to detect the position of the electron, but its motion is no longer the same as before the observation. The Heisenberg uncertainty principle tells us we cannot be sure of both the location and the motion of an electron at the same time. As a result, we must give up on the idea of determining the path an electron follows inside an atom.

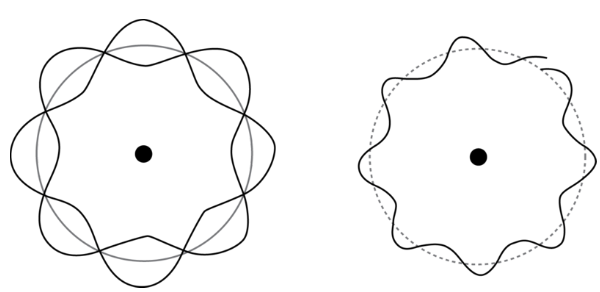
Schrödinger's Equation

The Heisenberg uncertainty principle treated the electron as a particle. In effect, the uncertainty principle stated that the exact motion of an electron in an atom could never be determined, which also meant that the exact structure of the atom could not be determined. Consequently, Erwin Schrödinger, an Austrian physicist, decided to treat the electron as a wave in accordance with de Broglie's matter waves.

Schrödinger, in considering the electron as a wave, developed an equation to describe the electron wave behavior in three dimensions (shown below). Unfortunately, the equation is so complex that it is actually *impossible* to solve exactly for atoms and ions that contain more than one electron. High-speed computers, however, can produce very, very close approximations, and these "solutions" have provided a great deal of information about the possible organization of electrons within an electron cloud.



When we represent electrons inside an atom, quantum mechanics requires that the wave must "fit" inside the atom so that the wave meets itself with no overlap. In other words, the "electron wave" inside the atom must be a standing wave. If the wave is to be arranged in the form of a circle so that it attaches to itself, the waves can only occur if there is a whole number of waves in the circle. Consider the image below.



On the left is an example of a standing wave. For the wave on the right, the two ends of the wave do not quite meet each other, so the wave fails to be a standing wave. There are only certain energies (frequencies) for which the wavelength of the wave will fit exactly to form a standing wave. These energies turn out to be the same as the energy levels predicted by the Bohr model, but now there is a reason why electrons may only occupy these energy levels. (Recall that one of the problems with the Bohr model was that Bohr had no explanation for why the electrons could only occupy certain energy levels in the electron cloud.) The equations of quantum mechanics tell us about the existence of principal energy levels, the number of energy levels in any atom, and more detailed information about the various energy levels.

Lesson Summary

- The Heisenberg uncertainty principle states that it is impossible to know both the precise location and the precise motion of an electron at the same time.
- Electrons in an electron cloud can be viewed as a standing wave.
- The reason that an electron in an atom may have only certain energy levels is because only certain energies of electrons will form standing waves in the enclosed volume.
- The solutions to Schröedinger's equation provide a great deal of information about the organization of the electrons in the electron cloud.

Further Reading / Supplemental Links

A question and answer session on electrons behaving as waves.

- http://www.colorado.edu/physics/2000/quantumzone/debroglie.html

Review Questions

1. Which of the following statements are true?
    a. According to the Heisenberg uncertainty principle, we will eventually be able to measure both an electron's exact position and its exact momentum at the same time.
    b. The problem that we have when we try to measure an electron's exact position and its exact momentum at the same time is that our measuring equipment is not good enough.
    c. According to the Heisenberg uncertainty principle, we cannot know both the exact location and the exact momentum of an automobile at the same time.
    d. The Heisenberg uncertainty principle applies only to very small objects like protons and electrons.
    e. The Heisenberg uncertainty principle applies only to large objects like cars and airplanes.
    f. The Heisenberg Heisenberg uncertainty principle applies to very small objects like protons and electrons and to large objects like cars and airplanes.