SPH4U UNIVERSITY PHYSICS

REVOLUTIONS IN MODERN PHYSICS: ...

- Matter Waves
  (P.632-639)

Matter Waves

By the 1920s, physicists had accepted the quantum theory of light and continued to refine the concepts. Once again, however, the scientific community was startled by the revolutionary theory proposed by a young French graduate student. As part of his doctoral dissertation, Louis de Broglie proposed that not only do light waves behave as particles, but also that particulate matter has wave properties.

Matter Waves

This quantity – the wavelength associated with the motion of a particle with momentum p – is the ***de Broglie wavelength****.*

$$\because \quad p_{photon} = \frac{h}{\lambda}$$

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

Matter Waves

NOTE!

De Broglie's professors thought that his hypothesis was rather bizarre, so they sent the manuscript to Einstein and asked for his response. Einstein read the dissertation with excitement and strongly supported de Broglie's proposal. De Broglie was promptly granted his Ph.D., and six years later, he was honoured with the Nobel Award in Physics for his theory of matter waves.

Matter Waves

DE BROGLIE WAVELENGTH

- the wavelength associated with the motion of a particle possessing momentum of magnitude p

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

where λ is the wavelength associated with a moving particle (m)
h is Planck's constant (6.63×10^{-34} J·s)
p is the momentum of the particle (kg·m/s)

Matter Waves

NOTE!

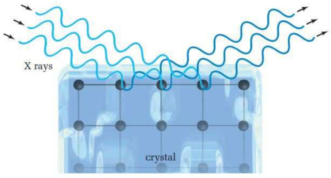
*If a particle has a wavelength, the particle should exhibit interference just as waves do. The test of de Broglie's hypothesis was to look for interference involving classical particles. The first observation of **matter waves**, the wave-like behaviour of massive particles, came from an experiment done with electrons.*

MATTER WAVES

- the wave-like behaviour of particles with mass

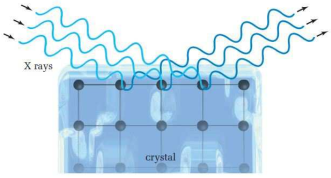
The Electron Double-Slit Experiment

During the 10 years prior to de Broglie's proposal, physicists Laue and Bragg were developing the theory and technique for the diffraction of X-rays by crystals. When X-rays scatter from the atoms in a crystal, they form diffraction patterns in much the same way that light forms diffraction patterns when it passes through a double slit or a diffraction grating.



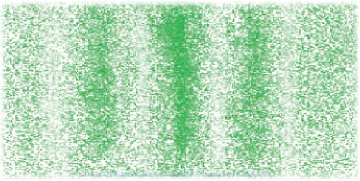
The Electron Double-Slit Experiment

NOTE!
The spacing between the atoms is in the same magnitude as both the wavelength of X-rays and electrons (~ 10^{-10} m). If electrons have wave properties, then the same crystals that diffract X-rays should diffract electrons and create a pattern.



The Electron Double-Slit Experiment

In 1927, physicists Clinton Davisson and Lester Germer performed an experiment in which they aimed a beam of electrons at a crystal target. The atoms in the target were spaced at regular intervals, acting as a series of slits for the electrons. Just as with the diffraction of light, the Davisson-Germer experiment exhibits interference when the wavelength of the electrons is similar to the spacing between the atoms in the crystal.



The Electron Double-Slit Experiment

NOTE!

The diffraction technique used in the Davisson-Germer experiment is still used today as a way to measure molecule spacing within a crystal.

MATTER WAVES (continued ...)

- experiments by Davisson and Germer confirmed that electrons exhibit the wave-like property of interference with a wavelength given by de Broglie's wavelength

de Broglie Wavelength

PRACTICE

1. In their studies of interference with electrons, Davisson and Germer used electrons with kinetic energy of ~ 50 eV or 8.0×10^{-18} J. The mass of an electron is 9.11×10^{-31} kg.
   (a) How fast are these electrons moving?

   (a) $v = 4.2 \times 10^{6}$ m/s

de Broglie Wavelength

PRACTICE

1. In their studies of interference with electrons, Davisson and Germer used electrons with kinetic energy of ~ 50 eV or 8.0×10^{-18} J. The mass of an electron is 9.11×10^{-31} kg.
   (b) Calculate the de Broglie wavelength of these electrons (m and nm).

   (b) $\lambda = 1.7 \times 10^{-10}$ m or 0.17 nm

de Broglie Wavelength

PRACTICE

1. In their studies of interference with electrons, Davisson and Germer used electrons with kinetic energy of ~ 50 eV or 8.0×10^{-18} J. The mass of an electron is 9.11×10^{-31} kg.
   (c) The spacing between atoms in a typical crystal is ~ 0.3 nm. How does this spacing compare with the wavelength of the electrons used by Davisson and Germer?

   (c) the wavelength of the electrons is less than, but similar to, the spacing between the atoms in a crystal solid

January 6, 2013 4U5 - Matter Waves 12

de Broglie Wavelength

NOTE!

It is possible to determine the de Broglie wavelength of larger objects, such as baseballs. However, the momentum of large objects tend to be so large that it implies an incredibly small wavelength. That is why we are unable to see the interference of these objects.

January 6, 2013 4U5 - Matter Waves 13

Interpreting the Double-Slit Experiment

The results of double-slit experiments using photons, electrons, or any other small particles are surprising and difficult to understand. The picture of nature at very small scales differs greatly from the classical picture at large scales. Electrons arrive at a screen in single, particle-like amounts, but the spot on the screen where they arrive is determined by wave-like interference behaviour.

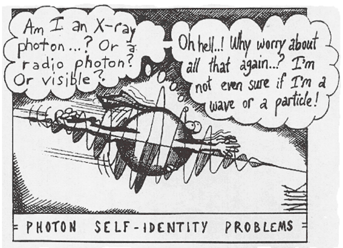
NOTE!

The equations of quantum mechanics make precise predictions about the results of a double-slit experiment. However, they do not give a clear description of what happens to photons, electrons, or other particles as they pass through the slits and travel to the screen.

January 6, 2013 4U5 - Matter Waves 14

Interpreting the Double-Slit Experiment

As a result of this uncertainty, researchers have proposed different interpretations of what happens in the quantum world. The debate still continues over which interpretation gives the best description.



Interpreting the Double-Slit Experiment

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COLLAPSE INTERPRETATION

- *the electron leaves its source behaving as a particle, but then it spreads out and travels and interferes as a wave*
- *however, if the location of the electron is measured, it collapses back into a particle and arrives at one location on the screen just as a particle would*

Interpreting the Double-Slit Experiment

As a result of this uncertainty, researchers have proposed different interpretations of what happens in the quantum world. The debate still continues over which interpretation gives the best description.

PILOT WAVE INTERPRETATION

- *the electron is just a simple particle whose motion depends on a mysterious pilot wave (whose behaviour depends on everything everywhere in the universe including future events)*
- *the pilot wave "knows" whether one or two slits are open, and whether or not a detector is turned on at the screen*

Interpreting the Double-Slit Experiment

As a result of this uncertainty, researchers have proposed different interpretations of what happens in the quantum world. The debate still continues over which interpretation gives the best description.

MANY WORLDS INTERPRETATION

- *a parallel universe exists for each of an electron's possible states*
- *when an electron reaches the slits, the entire universe splits into two – in one version the electron passes through the left slit, and in the other version it passes through the right slit*

Interpreting the Double-Slit Experiment

As a result of this uncertainty, researchers have proposed different interpretations of what happens in the quantum world. The debate still continues over which interpretation gives the best description.

COPENHAGEN INTERPRETATION

- *only deals with the results of measurements made on physical objects*
- *certain questions do not have answers, such as what electrons are "doing" as they travel to the detection screen – you can only ask what the results will be if you do a certain experiment*
- *this view was dominant for most of the 20th century*

Applications of the Quantum World

NOTE!

The double-slit interpretations may leave you feeling that science cannot adequately explain quantum physics. But you need to remember that scientific understanding is always evolving and partly uncertain. Quantum mechanics does, however, make quite accurate predictions about the statistics of observed results, such as the interference patterns made by many particles in a double-slit experiment. It simply says that the world is unpredictable for single events, such as a single electron passing through a double-slit setup.

✔ Check Your Learning

TEXTBOOK

P.634 Q.1-3

P.642 Q.3 (PJ: Quantum Information Technology) ☞ *you need to read!*