By the end of the 19th century, most problems with what has come to be known as classical physics had been solved. There were only a few questions that remained unanswered so physicists of the time thought that they were ready to say they knew all about the field of physics. However, as they tried to answer these questions, they came to realize that they were not generating answers but more questions that required different kinds of answers. It was then that physicists came to see that these unanswered questions would not mark the end of physics, but rather the beginning of a new field: quantum theory.

Introduction

While classical physics is more than enough to explain what occurs at a macroscopic level (for example, throwing a ball or pushing a car), a new set of rules and ideas is required to deal with things that occur at the subatomic level. That is where quantum theory comes in. Quantum theory is a field of physics that requires us to understand phenomena at the molecular and atomic levels. Quantum theory is simply a new way of looking at the world. The rules as they apply to us don’t apply to the tiny particles that quantum theory deals with. However, it was a breakthrough that led physicists to discover more about the world of physics and to understand our own world better, starting from the tiny particles of matter that are its building blocks.

Blackbody Radiation and Planck's Equation

One of the first ideas proposed to set quantum mechanics apart from classical physics was Max Planck’s idea that energy, like matter, was discontinuous. This revolutionary idea stemmed from blackbody radiation. A blackbody is an object that absorbs all the radiation falling on it. An object that absorbs all the radiation can also perfectly emit all radiation. Therefore, a blackbody will radiate maximum energy when heated to a given temperature. Under classical physics, this energy emitted was predicted to be infinite. However, when it didn’t radiate energy indefinitely, scientists were faced with the problem of explaining the phenomenon. This led to Planck’s proposed idea that unlike classical physics, quantum theory limits energy to a set of specific values. Each of these values isn’t continuous but rather increases from one allowed value to another by a small, or quantum, jump. More specifically, a quantum is the difference between two allowed values in a set.

Based on the assumption that all atoms on the surface of the heated solid vibrate at the frequency, Planck developed a model that came to be known as Planck’s equation. Through experiments of frequencies and temperature, Planck was able to generate a constant, Planck’s constant:

$$h = 6.62607 \times 10^{-34} \text{ J} \cdot \text{s}$$

Using this constant he was able to restate his theory: energy was directly proportional to frequency. He wrote his equation as

$$E = h \nu$$

where $E$ is energy, $h$ is Planck’s constant, and $\nu$ is frequency.

However, due to lack of solid proof, scientists, including Planck, were skeptical about the new field of quantum theory.
Since Planck’s hypothesis couldn’t be applied to anything other than blackbody radiation, it was unaccepted until much later when it was successfully applied to other phenomena.

**The Photoelectric Effect**

The basic idea behind the photoelectric effect is that under certain conditions when light is shined on a sample, electrons are ejected from that sample. Experimentation showed that the frequency of the light has to be above a certain threshold value for electrons to be emitted. After studying the photoelectric effect under several conditions, scientists made three observations.

1. A certain minimum frequency is required for electrons to be emitted.
2. Kinetic energy is directly proportional to frequency.
3. The number of electrons emitted from the surface was not dependent on intensity.

Scientists realized that frequency, not intensity, controlled whether or not electrons were emitted. Under classical wave theory electrons would be ejected at any frequency as long as it was intense enough, but this doesn’t happen. Since this dependency on frequency couldn’t be classical physics, scientists had to turn to quantum theory.

In order to explain this effect, Albert Einstein proposed that electromagnetic radiation also had particle-like qualities. Each of these particles of light was called a **photon**. Einstein suggested that each photon has an energy equal to $h\nu$, which is called a quantum of energy. This quantum of energy is the energy that is required of each electron in order to leave the metal surface.

The above mentioned threshold value for the frequency comes from the work function

$$h\nu = \frac{1}{2}mu^2 + w$$

where $w$ is the potential energy that is required to remove the electron from the surface and $\frac{1}{2}mu^2$ is the kinetic energy of the electron once it has left the surface of the solid. The **threshold frequency**, $\nu_0$, is the energy that is just sufficient to remove one electron and is denoted by

$$\nu_0 = \frac{w}{h}$$

A light of smaller frequency cannot eject an electron no matter how long it falls on the metal surface.

The reason the photoelectric effect was so significant was that the relationship between radiation and a particle of matter caused scientists to understand that the wave theory of radiation wasn’t going to be enough to explain a lot of phenomena. This led to the development of a new way of thinking: **wave-particle duality**.

**Ideas That Led to Quantum Theory**

One important idea that is the basis of quantum theory is **wave-particle duality**, first shown through the photoelectric effect. In order to prove that the electron was a wave G.P. Thomson designed an experiment—the double-slit experiment. When a stream of electrons was directed at metal foil through one slit, a thin band was formed on the foil as expected. Likewise, when the electrons were directed through two slits, two bands would be expected to form. However,
the experiment showed that an interference pattern, like would be expected of a wave, was formed instead. This experiment was one of several that gave rise to Quantum Mechanics.

This is an example of another separate rule for quantum mechanics. In the macroscopic world of classical theory, a wave is a wave and a particle is a particle. One cannot and will not ever be the other. However, in the microscopic quantum world, this isn’t true. Electrons of atoms and photons of light aren’t necessarily particles or waves. In fact, physicists are having a hard time determining just what they even are since they have the properties of both waves and particles.

Another important idea in the field of quantum mechanics is the Heisenberg uncertainty principle. From a broad perspective, the uncertainty principle states that the position and momentum of a particle can never be precisely measured simultaneously. If one is known, the other cannot be determined accurately. This principle is a consequence of wave-particle duality and therefore leads physicists to embrace a modern description of atoms.

References


Outside Links

- Dr. Quantum Double Slit Experiment: www.youtube.com/watch?v=O55Xi...eature=related (this video explains the double slit experiment and wave-particle duality)
- The Photoelectric Effect: www.jce.divched.org/JCEDLib/W...peeffect5.html (this website has great visual representations of the photoelectric effect)

Problems

1. What is a quantum of energy?
2. Explain the significance of the photoelectric effect.
3. If an atom has a frequency of $5.357 \times 10^{14}$ s$^{-1}$, using Planck’s equation, what is the energy of a single photon?
4. Using the answer from number 3, calculate the energy of a mole of photons.
5. Assume you have light at a wavelength of 640nm. Using the equation below as well as Planck’s equation, calculate the energy of one photon of light at that wavelength. Remember that $c= 3.00 \times 10^8$ m s$^{-1}$ and $\lambda$ (\(\lambda\)) is wavelength in meters.

\[
\text{Energy} = \frac{hc}{\lambda}
\]
Answers

1. A quantum of energy is the energy difference between the two allowed values in a set. It is a tiny jump that moves from one value to another without ever reaching intermediate values.

2. The photoelectric effect was especially significant in the field of quantum theory because it essentially proved the necessity of this new field. Since it showed the frequency, not intensity, causes electrons to be expelled, it disproved some of the theories of classical physics that physicists of the time thought to be true, causing the need for a new field: quantum theory.

3. Since we know the frequency of the photon, we simply plug it into the formula.

\[
E = (6.626 \times 10^{-34} \text{ J s})(5.357 \times 10^{14} \text{ s}^{-1})
\]

The resulting energy is \(3.550 \times 10^{-19} \text{ J}\).

4. In order to find the energy of a mole of atoms, we use the energy we found in question 3. We then use dimensional analysis to calculate the energy. Since there is \(3.550 \times 10^{-19} \text{ J}\) of energy in 1 photon, and \(6.022 \times 10^{23}\) photons in a mole, the energy per mole would be \(213,781 \text{ J/mol}\).

5. We know that the wavelength is in nanometers and speed of light is in meters. So we first convert wavelength to meters so they're in the same units. 1nm = \(1.0 \times 10^{-9} \text{ m}\). So in meters, the wavelength would be \(6.40 \times 10^{-7} \text{ m}\). Next, we calculate frequency by dividing \(c\) by \(\lambda\).

\[
\nu = \frac{c}{\lambda}
\]

\[
\nu = 3.00 \times 10^8 \text{ m s}^{-1} / 6.40 \times 10^{-7} \text{ m}
\]

The resulting frequency is \(4.688 \times 10^{14} \text{ s}^{-1}\). Now we can use Planck's equation to find the energy of a photon.

\[
E = (6.626 \times 10^{-34} \text{ J s})(4.688 \times 10^{14} \text{ s}^{-1})
\]

The energy of a photon at 640nm is \(3.106 \times 10^{-19} \text{ J}\).

Contributors and Attributions

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