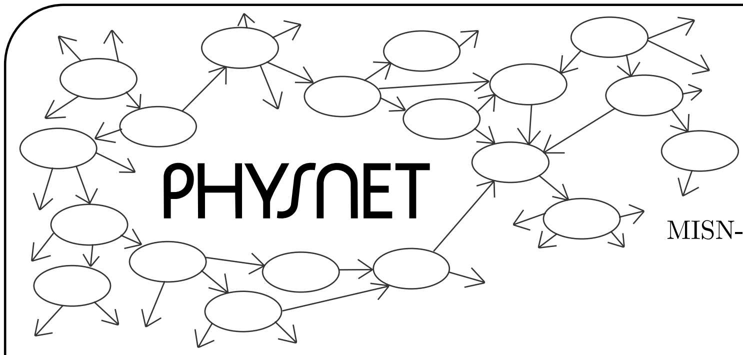

MISN-0-381

PHOTON PARTICLE - WAVE DUALITY

Quantum Physics

Project PHYSNET Physics Bldg. Michigan State University East Lansing, MI

PHOTON PARTICLE - WAVE DUALITY
by
R. Spital

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Title: **Photon Particle - Wave Duality**

Author: R. Spital, Dept. of Physics, Illinois State Univ

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Input Skills:

1. Vocabulary: thermal equilibrium (MISN-0-157), wavelength, frequency (MISN-0-201), electron volt, angstrom (Å), MeV (MISN-0-212).

Output Skills (Knowledge):

K1. Explain what is meant by the "ultraviolet catastrophe" and state the assumptions made by Planck to avoid it.

K2. Given the frequency or wavelength of a photon, write down expressions for the photon's energy and momentum.

K3. State the value of Planck's constant.

K4. Write down Einstein's equation for the photoelectric effect, explaining all symbols in the equation and giving the physical significance of each term.

K5. Explain briefly how the use of "wave-packets" to account for wave-particle duality leads to the Heisenberg uncertainty principle and what this implies about our ability to simultaneously measure certain physical quantities.

Output Skills (Problem Solving):

S1. Apply energy and momentum conservation to solve collision problems involving a photon incident on a stationary particle.

External Resources (Required):

1. E. E. Anderson, *Modern Physics and Quantum Mechanics*, W. B. Saunders Co. (1971).

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A. A. Strassenburg S. U. N. Y., Stony Brook

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by

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1. Introduction

This unit reviews one of the most important observations leading to the formulation of quantum mechanics, namely that electromagnetic radiation has both particle and wavelike properties. The wavelike properties of electromagnetic radiation are already familiar to the student from his contact with optical interference and diffraction phenomena. This unit therefore is concerned with the evidence for particle-like behavior. The three major pieces of evidence are:

1. The failure of classical physics to explain the spectrum of blackbody radiation (the "ultraviolet catastrophe"), and the successful explanation given by Planck based on a picture in which electromagnetic radiation is carried in particle-like bunches called "photons."
2. The failure of classical physics to adequately describe the photoelectric effect, and the subsequent successful treatment given by Einstein based on the photon picture.
3. The successful explanation by Compton of the increase in the wavelength of light scattered from matter, by treating the incident light as a beam of photons.

The fact that electromagnetic radiation has both particle and wavelike properties forces us to think of photons as "wave packets," i.e. localizations of energy due to the superposition of many plane waves of different wavelengths. Thus the photon is in a sense both a particle and a wave at the same time—a notion known as "particle-wave duality."

The wave-packet model of the photon has profound implications for the measurement process because of the way wave-packets are constructed. It turns out that the smaller the wave-packet (the more localized the photon), the larger the spread of wavelengths needed to construct the packet. This implies that both the wavelength and the position of a photon cannot be simultaneously measured to arbitrary accuracy, no matter how good the equipment is—which, for photons, is the essential content of the famous Heisenberg Uncertainty Principle.

2. Procedures

1. a. Read sections 2.1 and 2.2 of the text. What is the ultraviolet catastrophe of the Rayleigh-Jeans law (equation 2.5)?
   b. Read section 2.3 paying particular attention to assumption (1) and (2) on page 47. What does the Maxwell - Boltzmann distribution function (equation 2.6) tell you about the number of oscillators in high energy states? The classical theory assumes that all oscillators are excited with equal probability, regardless of the oscillator's frequency. How does the Planck theory change this picture and thereby prevent the ultraviolet catastrophe?
   c. (Optional) Do problems 2.6 and 2.7 to get a better understanding of the similarities and differences of the classical and Planck theories.
2. From assumption (1) page 47, we see that the energy carried by a quantum of electromagnetic radiation (a photon) is given by $E = h\nu$ where ν is the frequency of the radiation (and hence of the photon). From considerations of classical electromagnetic theory, the photons should also carry momentum $p = E/c = h\nu/c = h/\lambda$ (since $c = \lambda\nu$), where c is the speed of light. This turns out to be correct as shown by countless experiments (including Compton Scattering). (Exercise) Starting from $E = h\nu$, find the corresponding expression for E in terms of λ using $c = \lambda\nu$.
3. $h = 6.63 \times 10^{-27}$ erg-sec.
4. a. Read sections 2.5 and 2.6. Make sure you understand equation (2.11) fully and can write it down from memory.
   b. Solve problem 2.15.
5. a. Read section 2.7, filling in all the algebraic steps leading to equation 2.17.
   b. Solve problems 2.17 and 2.18.
6. a. Read section 2.8 slowly and carefully. This is an extremely important section. How does the width of the modulation envelope in the example given depend on $d\omega$?
   b. Read section 2.9. Derive relations 2.19 from the 2 relations immediately preceding them. What can you say about the range of wavelengths making up the wavepacket of a very localized photon? What does this imply about one's ability to simultaneous measure the position and momentum of a photon? Make similar statements about the time it took to radiate the packet (lifetime of the excited state which decayed) and the spread of frequencies in the packet.

Acknowledgments

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