Photon

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An entity that can be loosely described as a quantum of energy of electromagnetic radiation. According to classical electromagnetic theory, an electromagnetic wave can transfer arbitrarily small amounts of energy to matter. According to the quantum theory of radiation, however, the energy is transferred in discrete amounts. The energy of a photon is the product of Planck's constant and the frequency of the electromagnetic field. In addition to energy, the photon possesses momentum and also possesses angular momentum corresponding to a spin of unity. The interaction of radiation with matter involves the absorption, scattering, and emission of photons. Consequently, the energy interchange is inherently quantized. *See See also:* ANGULAR MOMENTUM; ENERGY; MOMENTUM; SPIN (QUANTUM MECHANICS).

Particlelike behavior

For many purposes, the photon behaves like a particle of zero rest mass moving at the speed of light. Unlike spin-1 particles of finite mass, the photon has only two, rather than three, polarization states. This corresponds to the transverse nature of a classical electromagnetic wave in free space. The particlelike nature of the photon is vividly exhibited by the photoelectric effect, predicted by A. Einstein, in which light is absorbed in a metal, causing electrons to be ejected. An electron absorbs a photon, gaining its energy. In leaving the metal, it loses energy because of interactions with the surface; the energy loss equals the product of the so-called work function of the surface and the charge of the electron. The final kinetic energy of the electron therefore equals the energy of the incident photon minus this energy loss. *See See also:* PHOTOEMISSION.

A second demonstration of the particlelike behavior of photons is provided by the scattering of an x-ray photon from an electron bound in an atom. The electron recoils because of the momentum of the photon, thereby gaining energy. As a result, the frequency, and hence the wavelength of the scattered x-ray, is altered. If the x-ray is scattered through a certain angle, the wavelength is shifted by an amount determined by this scattering angle and the mass of an electron, according to the laws of conservation of energy and momentum. *See See also:* COMPTON EFFECT.

Quantum theory

From a more fundamental view, the photon is the quantum of excitation of a single mode of a radiation field. The dynamical equations for the electric and magnetic energy in such a field are identical to those of a harmonic oscillator. According to quantum theory, the allowed energies of a harmonic oscillator are given by $E = (j + {}^1/_2)h$

f, where h is Planck's constant, f is the frequency of the oscillator, and the quantum number $j = 0, 1, 2, \ldots$, describes the state of excitation of the oscillator. This quantum relation was first postulated by M. Planck for the material oscillators in the walls of a thermal enclosure in order to obtain the correct form for the density of radiation in a thermal field, but it was quickly applied by Einstein to describe the state of the radiation field itself. In this picture, j describes the number of photons in the field. *See See also:* HARMONIC OSCILLATOR.

Photon distributions

Different sources of light are characterized by photon distributions with fundamentally different statistical properties. If light from a monochromatic source at high intensity, for instance a laser source, impinges on a photomultiplier, then each signal count corresponds to the absorption of a single photon. If repeated measurements are made, then the fractional root-mean-square (rms) scatter of the readings is exactly as would be expected for independent particles. In the limit of large numbers of absorbed photons, the fluctuations are unimportant, and the photon distribution describes a field with well-defined amplitude and phase, a classical field.

In contrast, for thermal radiation the fractional fluctuation is much larger than for independent particles. The larger fluctuation expresses the fact that photons, having integral spin, obey Bose-Einstein statistics. Such particles tend to clump together, producing large fluctuations. Finally, a radiation field can be considered in which the photon number is precisely determined, called a Fock state. In such a case, the phase of the corresponding electromagnetic field is completely random. Such a state has no classical analog. *See See also:* BOSE-EINSTEIN STATISTICS; SQUEEZED QUANTUM STATES.

Need for quantized fields

Many of the processes by which radiation interacts with matter can actually be described without employing a quantized description of the radiation field or the concept of photons, that is, by treating the radiation field classically. However, the fundamental process of spontaneous emission, in which an excited atom or molecule emits a photon and makes a transition to its ground state, can be described only on the basis of a quantized field. Also, many statistical properties of the radiation field, for instance correlations between photons that are emitted simultaneously in a nonlinear process, are inexplicable in terms of classical fields but have a natural explanation in the quantum theory of radiation and the concept of photons. *See See also:* NONRELATIVISTIC QUANTUM THEORY; QUANTUM ELECTRODYNAMICS; QUANTUM FIELD THEORY; QUANTUM MECHANICS.

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