

The Quantum Nature of Light

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Key concepts, historical milestones, experimental evidence, and theoretical framework

1. Overview

- Light exhibits both **wave-like** and **particle-like** properties.
 - The **quantum description** unifies these dual aspects through the concept of the **photon**—a discrete quantum of the electromagnetic field.
 - Understanding light's quantum nature is essential for modern optics, quantum information, and particle physics.
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2. Historical Development

Year	Event	Significance
1801	Thomas Young's double-slit experiment	Demonstrated interference ? wave nature of light.
1900	Max Planck – Black-body radiation	Introduced energy quantization ($E = h\nu$).
1905	Albert Einstein – Photoelectric effect	Proposed light quanta (photons) with ($E = h\nu$).
1913	Niels Bohr – Atomic model	Used quantized photon emission/absorption to explain spectra.
1925–1927	Development of quantum mechanics (Heisenberg, Schrödinger, Dirac)	Formalized photon as a field quantum.
1932	Arthur Compton – X-ray scattering	Confirmed photon momentum ($p = h/\lambda$).
1947	First laser (Maiman)	Practical source of coherent photons.
1960s–70s	Quantum optics experiments (Han? Han, Bell tests)	Showed non-classical photon statistics and entanglement.
1990s–present	Single-photon sources, quantum cryptography, quantum computing	Direct applications of photon quantum properties.

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3. Fundamental Concepts

3.1 Photon

- **Definition:** Quantum of the electromagnetic (EM) field; the smallest indivisible packet of light energy.
- **Energy:** ($E = h\nu = \frac{hc}{\lambda}$)
 - ($h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$) (Planck constant)
 - (ν) – frequency, (λ) – wavelength, (c) – speed of light.
- **Momentum:** ($\mathbf{p} = \frac{h}{\lambda} \hat{\mathbf{k}}$) (direction ($\hat{\mathbf{k}}$) of propagation).
- **Spin:** Intrinsic angular momentum ($s = 1$) (two helicity states: left? and right? circular polarization).

3.2 Wave-Particle Duality

Phenomenon	Wave Description	Particle Description
Interference & Diffraction	Superposition of EM fields; intensity ($\propto E^2$)	
Photoelectric Effect	Not explained by classical wave theory.	Photon transfers its entire quantum ($h\nu$) to an electron; kinetic energy ($K = h\nu - \phi$).
Compton Scattering	Classical Thomson scattering predicts wrong wavelength shift.	Photon collides with an electron, conserving energy & momentum ? wavelength shift ($\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$).

3.3 Quantization of the Electromagnetic Field

- **Field Operators:**
$$\hat{\mathbf{E}}(\mathbf{r}, t) = i \sum_{\mathbf{k}, \lambda} \sqrt{\frac{\hbar \omega_{\mathbf{k}}}{2\epsilon_0 V}} \hat{\mathbf{e}}_{\mathbf{k}, \lambda} \left(\hat{a}_{\mathbf{k}} e^{i(\mathbf{k} \cdot \mathbf{r} - \omega_{\mathbf{k}} t)} + \hat{a}_{\mathbf{k}}^\dagger e^{-i(\mathbf{k} \cdot \mathbf{r} - \omega_{\mathbf{k}} t)} \right)$$