Chapter One: Introduction

(1) A brief history of optics and photonics
(2) Wave-particle duality
(3) A brief comparison between photons and electrons
(4) Electromagnetic spectrum
(1) A Brief History of Optics and Photonics

Isaac Newton

Newton described light as a stream of particles, which was used to explain rectilinear propagation, and developed theories of reflection and refraction. The particles in rays of different colors were supposed to have different qualities, possibly of mass, size, or velocity.

Published in 1704
He thought of light as a pressure wave in an elastic medium.

Huygens, a Dutch contemporary of Newton, developed the wave theory of light. His explanation of rectilinear propagation is now known as "Huygens' construction".

A spherical wavefront $W$ has an origin at $P$ and a radius of $r = ct$ after a time of $t$. Each point at the wavefront $W$ generates a Huygens' secondary wavelet. These secondary wavelets combine to form a new wavefront $W'$ at time $t'$, with the radii of the secondary wavelets being $c(t'-t)$. 
Thomas Young’s double slit experiment can only be explained in terms of waves.
Augustin Fresnel, in 1821, showed that light is a transverse wave.
James Clerk Maxwell gave a final vindication of the wave theory by integrating electricity and magnetism into the four Maxwell equations.

The wave theory of light was firmly established 100 years after Newton’s *Opticks*.

- Thomas Young’s double slit experiment can only be explained in terms of waves.
- Augustin Fresnel, in 1821, showed that light is a transverse wave.
- James Clerk Maxwell gave a final vindication of the wave theory by integrating electricity and magnetism into the four Maxwell equations.
Creation of a needle of longitudinally polarized light in vacuum using binary optics

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The conceptual origins of Maxwell’s equations and gauge theory

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In 1900, Max Planck used the particle theory to explain the “blackbody spectrum”.

\[ E = h \nu \]

In 1905, Albert Einstein postulated that electromagnetic radiation is itself quantized in order to explain the photoelectric effect.
Louis de Broglie (born in 1892) proposed in 1924 that particles also have wave-like properties, which was confirmed experimentally three years later.

A legend: Some scientists did not comprehend de Broglie's thesis (81 pages). One faculty passed it onto Einstein for his interpretation. Einstein replied that de Broglie did not just deserve doctorate but a Nobel Prize. de Broglie was awarded the Nobel Prize in 1929.

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

Although particles have very similar wave-like characteristics, there are fundamental differences in their behaviors.

Schrödinger developed the general wave theory of the behavior of matter, *wave mechanics*, in 1926. Wave mechanics revolutionized our understanding of the description of microscopic particles and placed limitations on the extent of information we could have about such systems, that is, the famous Heisenberg uncertainty relationship.

Photons: Bose-Einstein statistics
Electrons: Fermi-Dirac statistics
(2) Wave-Particle Duality

Example: transmission electron microscopy (TEM) uses electrons to image atomic structures of solid materials. A typical acceleration voltage for electrons is 200 kV. If the relativity effect is ignored, what is the wavelength of electrons?

Solution:

\[ \lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2m\left(\frac{1}{2}mv^2\right)}} = \frac{h}{\sqrt{2mE}} \]

\[ \lambda = \frac{6.626 \times 10^{-34} \text{ Js}}{\sqrt{2 \times (9.109 \times 10^{-31} \text{ kg}) \times (200 \times 10^3 \times 1.602 \times 10^{-19} \text{ J})}} = 2.743 \text{ pm} \]

\[ E: \text{ keV} \]

\[ = 38.8E^{-1/2} \text{ pm} \]
Wave-Particle Duality of \( C_{60} \) Molecules

**Buckyballs:**

- 60 tightly bound carbon atoms
- Mass: 720 amu \((1.197 \times 10^{-21} \text{ g})\)
- Diameter: \(~1 \text{ nm}\)
- Total vibrational energy: 7 eV (900 K)
- 174 vibrational modes
- Coupling to the environment (decoherence)
Alignment of the collimation slits, grating, and detector is crucial for this experiment.

At $T = 900$ K, velocity distribution is
\[
f(v) = v^3 \exp\left[-\left(v - v_0\right)^2 / v_m^2\right]
\]
\[
v_0 = 166 \text{ m s}^{-1}
\]
\[
v_m = 92 \text{ m s}^{-1}
\]
Most probable velocity is
\[
v = 220 \text{ m s}^{-1}
\]
Corresponding de Broglie wavelength is
\[
\lambda = 2.5 \text{ pm}
\]
Wave Nature of Biomolecules and Fluorofullerenes

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(Received 7 April 2003; published 28 August 2003)

We demonstrate quantum interference for tetraphenylporphyrin, the first biomolecule exhibiting wave nature, and for the fluorofullerene $C_{60}F_{48}$ using a near-field Talbot-Lau interferometer. For the porphyrins, which are distinguished by their low symmetry and their abundant occurrence in organic systems, we find the theoretically expected maximal interference contrast and its expected dependence on the de Broglie wavelength. For $C_{60}F_{48}$, the observed fringe visibility is below the expected value, but the high contrast still provides good evidence for the quantum character of the observed fringe pattern. The fluorofullerenes therefore set the new mark in complexity and mass (1632 amu) for de Broglie wave experiments, exceeding the previous mass record by a factor of 2.
Quantum interference of large organic molecules

Stefan Gerlich¹, Sandra Eibenberger¹, Mathias Tomandl¹, Stefan Nimmrichter¹, Klaus Hornberger², Paul J. Fagan³, Jens Tüxen⁴, Marcel Mayor⁴,⁵ & Markus Arndt¹

The wave nature of matter is a key ingredient of quantum physics and yet it defies our classical intuition. First proposed by Louis de Broglie a century ago, it has since been confirmed with a variety of particles from electrons up to molecules. Here we demonstrate new high-contrast quantum experiments with large and massive tailor-made organic molecules in a near-field interferometer. Our experiments prove the quantum wave nature and delocalization of compounds composed of up to 430 atoms, with a maximal size of up to 60 Å, masses up to $m = 6,910$ AMU and de Broglie wavelengths down to $\lambda_{db} = \frac{h}{mv} \approx 1$ pm. We show that even complex systems, with more than 1,000 internal degrees of freedom, can be prepared in quantum states that are sufficiently well isolated from their environment to avoid decoherence and to show almost perfect coherence.
(3) A Brief Comparison between Photons and Electrons


<table>
<thead>
<tr>
<th>Photons</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td></td>
</tr>
<tr>
<td>[ \lambda = \frac{h}{p} = \frac{c}{v} ]</td>
<td>[ \lambda = \frac{h}{p} = \frac{h}{mv} ]</td>
</tr>
<tr>
<td><strong>Eigenvalue (Wave) Equation</strong></td>
<td></td>
</tr>
<tr>
<td>[ \left{ \nabla \times \frac{1}{e(r)} \right} \nabla \times A(r) = \left( \frac{\omega}{c} \right)^2 B(r) ]</td>
<td>[ \hat{H} \psi(r) = -\frac{\hbar^2}{2m} \left( \nabla \cdot \nabla + V(r) \right) \psi(r) = E \psi ]</td>
</tr>
<tr>
<td><strong>Free-Space Propagation</strong></td>
<td></td>
</tr>
<tr>
<td>Plane wave</td>
<td>Plane wave:</td>
</tr>
<tr>
<td>[ E = (\frac{1}{2})E_0(e^{ik \cdot r - \omega t} + e^{-ik \cdot r + \omega t}) ]</td>
<td>[ \psi = c(e^{ik \cdot r - \omega t} + e^{-ik \cdot r + \omega t}) ]</td>
</tr>
<tr>
<td>( k = ) wavevector, a real quantity</td>
<td>( k = ) wavevector, a real quantity</td>
</tr>
<tr>
<td><strong>Interaction Potential in a Medium</strong></td>
<td></td>
</tr>
<tr>
<td>Dielectric constant (refractive index)</td>
<td>Coulomb interactions</td>
</tr>
<tr>
<td><strong>Propagation Through a Classically Forbidden Zone</strong></td>
<td></td>
</tr>
<tr>
<td>Photon tunneling (evanescent wave) with wavevector, ( k ), imaginary and hence amplitude decaying exponentially in the forbidden zone</td>
<td>Electron-tunneling with the amplitude (probability) decaying exponentially in the forbidden zone</td>
</tr>
<tr>
<td><strong>Localization</strong></td>
<td></td>
</tr>
<tr>
<td>Strong scattering derived from large variations in dielectric constant (e.g., in photonic crystals)</td>
<td>Strong scattering derived from a large variation in Coulomb interactions (e.g., in electronic semiconductor crystals)</td>
</tr>
<tr>
<td><strong>Cooperative Effects</strong></td>
<td></td>
</tr>
<tr>
<td>Nonlinear optical interactions</td>
<td>Many-body correlation</td>
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<tr>
<td></td>
<td>Superconducting Cooper pairs</td>
</tr>
<tr>
<td></td>
<td>Biexciton formation</td>
</tr>
</tbody>
</table>
(4) Electromagnetic Spectrum

\[
c = \lambda \nu \quad E = h \nu
\]

\[
\lambda = 0.1 \text{ nm} - 1000 \text{ m}
\]

\[
E = 12.4 \text{ keV} - 1.24 \times 10^{-9} \text{ eV}
\]

- The highest energy cosmic gamma rays so far detected is $10^{35}$ Hz ($4 \times 10^{20}$ eV).
- Wave behaviors dominate in the long wavelength microwaves and radios, and photon behaviors dominate in the short wavelength X-rays and gamma rays.
- We most deal with the “wave-particle duality” in the optical range.
- The propagation of light is determined by its wave nature, and its interaction with matter is determined by quantum physics.
## Chart of the Electromagnetic Spectrum

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>1 pm</th>
<th>1 Å</th>
<th>1 nm</th>
<th>1 μ</th>
<th>1 mil</th>
<th>1 mm</th>
<th>1 cm</th>
<th>1 ft</th>
<th>Size Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavenumber (cm⁻¹)</td>
<td>10⁻¹²</td>
<td>10⁻¹¹</td>
<td>10⁻¹⁰</td>
<td>10⁻⁹</td>
<td>10⁻⁸</td>
<td>10⁻⁷</td>
<td>10⁻⁶</td>
<td>10⁻⁵</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>λ (m)</td>
<td>10⁻¹²</td>
<td>10⁻¹¹</td>
<td>10⁻¹⁰</td>
<td>10⁻⁹</td>
<td>10⁻⁸</td>
<td>10⁻⁷</td>
<td>10⁻⁶</td>
<td>10⁻⁵</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>1 ZHz</td>
<td>1 EHz</td>
<td>1 PHz</td>
<td>1 THz</td>
<td>1 GHz</td>
<td>1 MHz</td>
<td>10⁵</td>
<td>10⁶</td>
<td>10⁷</td>
</tr>
<tr>
<td>Electrons (eV)</td>
<td>10⁻¹⁰</td>
<td>10⁻⁹</td>
<td>10⁻⁸</td>
<td>10⁻⁷</td>
<td>10⁻⁶</td>
<td>10⁻⁵</td>
<td>10⁻⁴</td>
<td>10⁻³</td>
<td>10⁻²</td>
</tr>
</tbody>
</table>

### Bands

<table>
<thead>
<tr>
<th>Radio Spectrum</th>
<th>Terahertz</th>
<th>Infrared</th>
<th>Ultraviolet</th>
<th>X-ray</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast and Wireless</td>
<td>Far IR</td>
<td>Mid IR</td>
<td>Near IR</td>
<td>Extreme UV</td>
<td>Soft X-ray</td>
</tr>
<tr>
<td>Microwave</td>
<td>Near UV</td>
<td>Visible Light</td>
<td>Dental Curing</td>
<td>Medical X-rays</td>
<td>Cosmic ray observations</td>
</tr>
</tbody>
</table>

### Sources and Uses of Frequency Bands

- **AM radio**: 600kHz-1.6MHz
- **FM radio**: 88-108 MHz
- **Mobile Phones**: 900MHz-2.4GHz
- **Radar**: 1-100 GHz
- **TV Broadcast**: 54-700 MHz
- **Wireless Data**: ~2.4 GHz
- **Microwave Oven**: 2.4 GHz
- **Ultrasound**: 1-20 MHz
- **Sound Waves**: 20Hz-10kHz
- **PET imaging**: 0.1-0.01 Å
- **Crystalllography**: 2.2-0.7 Å
- **Baggage screen**: 10-1.0 Å
- **Remotes**: 850 nm
- **Visible wavelengths (nm)**: 440-700
- **Visible Light**: 425-750THz
- **Night Vision**: 10-0.7 μ
- **Suntan**: 400-290nm
- **Screening**: 0.2-4.0 THz
- **“mm wave” “sub-mm”**: 180 GHz
- **Remote**: 850 nm

### Electromagnetic Spectrum Scale

\[ \lambda = 3 \times 10^9 \text{ ifreq} = 1/(\text{wn}^*100) = 1.24 \times 10^{-9} \text{ eV} \]