Recap I

- Evidence of Photons: Compton Effect
  \[ \lambda - \lambda' = \delta \lambda = \frac{h}{mc} (1 - \cos \phi) \]

- X-Ray Production:
  - Electrons interact with target atoms and may lose part of their kinetic energy by generating an x-ray photon.
  - Characteristic lines produced by photon emission by the target atom.
  \[ \lambda \geq \frac{hc}{K_0} = \lambda_{\text{min}} \]

- With keV-scale kinetic energy
Recap II

The quantized Atom:
Radiation emitted by independent atoms shows sharp spectral lines.
⇒ Atoms exist in states of discrete quantized internal energy!

Photon Emission

\[ E_i \rightarrow \text{photon} \rightarrow E_{ph} = hf = E_i - E_f \]

Photon Absorption

\[ E_f \rightarrow \text{photon} \rightarrow E_{ph} = hf = E_f - E_i \]

Hydrogen Atom:
Total kinetic and potential energy of proton and electron in it atom.

\[ E_n = -13.6 \text{ eV} \frac{1}{n^2} \]

\( n=1,2,3,... \)
Today:

- Lasers
- Stimulated photon emission
- Particle waves
LASER

Light Amplification by Stimulated Emission of Radiation

Example: He-Ne Laser (red):

- 99% reflective mirror
- Optical oscillator
- 100% reflective mirror
Special characteristics of laser light:

1. Highly **monochromatic** (single wavelength).

2. Highly **coherent**. Individual long waves (wave trains) for laser light can be several hundred km long. The corresponding coherence length for wave trains emitted by a light bulb is typically less than a meter.

3. Highly **directional**. Spreading of the beam is due to diffraction at the exit aperture of the laser.

4. Can be **sharply focused**. Intensity of $10^{17} \text{ W/cm}^2$ can be readily obtained. (An oxyacetylene flame only has an intensity of about $10^3 \text{ W/cm}^2$.)
Coherent vs. Incoherent Light

**Polychromatic**
- **incoherent**
  Incoherent white light contains waves of many frequencies (and wavelengths) that are out of phase with one another.

**Monochromatic**
- **incoherent**
  Light of a single frequency and wavelength is still out of phase.

**Monochromatic**
- **coherent**
  Coherent light: all the waves are identical and in phase.
Laser uses:

- Voice & data transmission over optical fibers.
- Read & write CDs, DVDs, BDs.
- Read bar codes.
- Laser printing.
- Surgery.
- Welding.
- Cutting metal.
- Cutting cloth.
- Photochemistry.

- Spectroscopy.
- Interferometry.
- Optical trapping.
- Nuclear fusion research.
- Weapons.
- Surveying.
- Range finding.
- Holography.
- Microscopy (e.g., confocal, two-photon).
Laser action depends on three processes:

1. **Absorption:**

   \[ h\nu = E_f - E_i \]

   ![Absorption Diagram]

2. **Spontaneous emission:**

   \[ h\nu = E_i - E_f \]

   ![Spontaneous Emission Diagram]

   - Emission is not triggered by an outside influence.
   - Mean lifetime of excited atoms in ‘normal’ states is \( \sim 10^{-8} \) s.
   - For **metastable** excited states this can be \( 10^5 \) times longer.
3. **Stimulated emission:**

\[ hf = E_i - E_f \]

Original & new photons are **identical**.

- Associated waves have the same: - energy, \((\lambda)\)
  - direction
  - phase
  - polarization

- The probability per atom for absorption is the same as the probability per atom for stimulated emission.
Two competing processes:

Absorption:

\[
\text{two photons} \rightarrow \text{no photons}
\]

Stimulated emission:

\[
\text{two photons} \rightarrow \text{two photons}
\]

- For lasing, need more atoms in the higher energy state than in the lower energy state. This condition is called a population inversion. It must be artificially created by some input of energy.
Example: Population Inversion Collisions

Simplified energy level diagram of a He-Ne laser:

- Inelastic collision of energetic electrons with ground state helium atoms
  - Collisions excite helium atoms from the ground state to higher energy excited states, among them a along-lived metastable state.
  - Because of a near coincidence between the energy level of the metastable He state, and an excited state of neon, collisions between these helium metastable atoms and ground state neon atoms results in a selective and efficient transfer of excitation energy from the helium to neon.
- Population inversion for Ne
Startup of a LASER

• “Pumping” produces a population inversion, i.e. more atoms in are in an excited state then in the ground state.
• Excited atoms emit photons; initially in random directions. Photons cause other exited atom to emit via stimulated emission.
• Photons parallel to axis reflect from mirrors. Reflected photons stimulate further emission by excited atoms.

-> amplification in each pass though the laser medium.

Small fraction of light "leaks" out.
**Particle (Matter) Waves**

- For photons: \( \lambda = \frac{h}{p} \)

- Louis de Broglie (1924) proposed:
  1. **All** particles have wave-like and particle-like properties, not only photons!
  2. A particle with momentum \( p \) has a "particle wave" associated with its motion with wavelength:

\[
\lambda = \frac{h}{p}
\]
for particle with mass $m > 0$:

- Kinetic energy: $K = \frac{1}{2} m v^2 = \frac{1}{2m} (m v^2) = \frac{p^2}{2m}$

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mK}}$$

According to Einstein: energy-mass relation: $E_0 = mc^2$

- can convert energy to mass and mass to energy

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mK}} = \frac{hc}{\sqrt{2E_0K}}$$

for a photon:

- Energy: $E_{ph} = hf = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E_{ph}}$

- Momentum: $p = \frac{h}{\lambda} = \frac{h}{hc} E_{ph} = \frac{E_{ph}}{c}$

$P_{photon} = \frac{E_{photon}}{c}$

$\lambda = \frac{h}{E_{photon}} = \frac{hc}{E_{photon}}$
Particle waves $\lambda = h/p$:
Order of Magnitude Estimate

Or: Why wasn’t this noticed before?

- thermal neutrons (300K) $\Rightarrow \lambda = 1.5 \text{Å}$
- electrons at 100 eV $\Rightarrow \lambda = 1.2 \text{Å}$
- neutrons at 10 MeV $\Rightarrow \lambda = 5 \times 10^{-15} \text{m}$
- compare to visible light
- recall 2-slit exp.: maxima for $\sin \theta = \frac{m \lambda}{d} < 1$
- need $\lambda > d$

$\Rightarrow$ for particle: need "slit" spacing / diffraction grid on Å scale (or less)

$\Rightarrow$ use crystals!
An electron’s kinetic energy $K$ is the same as the energy $E_{ph}$ of a photon with 10 nm associated wavelength. How does the electron’s de Broglie wavelength compare with the wavelength associated with the photon ($hc = 1240 \text{ eV nm}; E_{0,e^-} = 511 \text{ keV}$)?

A. $\lambda_{\text{electron}} > \lambda_{\text{photon}}$

B. $\lambda_{\text{electron}} < \lambda_{\text{photon}}$

C. $\lambda_{\text{electron}} \equiv \lambda_{\text{photon}}$

D. Not enough information.

\[
\lambda_{ph} = 10 \text{ nm} = \frac{hc}{E_{ph}}
\]

\[
\Rightarrow E_{ph} = \frac{hc}{\lambda_{ph}} = \frac{1240 \text{ eV nm}}{10 \text{ nm}} = 124 \text{ eV}
\]

\[
\lambda_{e^-} = \frac{h}{p} = \frac{hc}{\sqrt{2E_{0,e^-}c^2}}
\]

\[
= \frac{1240 \text{ eV nm}}{\sqrt{2 \cdot 511 \text{ keV} \cdot 124 \text{ eV}}} = 0.1 \text{ nm}
\]
Evidence for de Broglie’s Particle Waves:

Davisson-Germer Experiment (1925): Scattering of low energy electrons by a crystal surface

\[ \lambda \approx 1 \text{ Å} \]

Evidence for de Broglie’s Particle Waves:

Davisson-Germer Experiment (1925): Scattering of low energy electrons by a crystal surface

\[ \lambda \approx 1 \text{ Å} \]
G. P. Thompson’s Experiment: Diffraction of 10 – 40 keV electrons by a thin polycrystalline foil

\[ \lambda \approx 0.1 \, \text{Å} = 10^{-11} \, \text{m} \]

polycrystalline film \( \Rightarrow \) Bragg condition satisfied for any given reflecting plane \( \Rightarrow \) concentric circles
Diffraction pattern of X-ray beam passing through Al foil

Diffraction pattern of electron beam passing through Al foil
Electron diffraction by polycrystalline aluminum

Laue pattern of electron diffraction by a single crystal

(Courtesy of Prof. Y. Soejima, Dept. of Physics, Kyushu Univ.)
2-slit Interference of Electrons

(a) Moving electrons

(b) After 100 electrons

(c) After 3000 electrons

(d) After 70,000 electrons
**Diffraction of Neutrons**

\[ \lambda = \text{several Å down to } <10^{-14} \text{ m} \]

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**Diffraction of fast neutrons from Al, Cu, and Pb nuclei.**

[from French, after A Bratenahl, Phys Rev 77, 597 (1950)]

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The Spallation Neutron Source (SNS) in Oak Ridge, TN
Why Neutrons?

Neutrons are **NEUTRAL** particles. They
- are highly penetrating,
- can be used as nondestructive probes, and
- can be used to study samples in severe environments.

Neutrons have a **MAGNETIC** moment. They can be used to
- study microscopic magnetic structure,
- study magnetic fluctuations, and
- develop magnetic materials.

Neutrons have **SPIN**. They can be
- formed into polarized neutron beams,
- used to study nuclear (atomic) orientation, and
- used for coherent and incoherent scattering.

The **ENERGIES** of thermal neutrons are similar to the energies of elementary excitations in solids. Both have similar
- molecular vibrations,
- lattice modes, and
- dynamics of atomic motion.

The **WAVELENGTHS** of neutrons are similar to atomic spacings. They can determine
- structural sensitivity,
- structural information from $10^{-13}$ to $10^{-4}$ cm, and
- crystal structures and atomic spacings.

Neutrons “see” **NUCLEI**. They
- are sensitive to light atoms,
- can exploit isotopic substitution, and
- can use contrast variation to differentiate complex molecular structures.
Angular distribution of 40 MeV alpha particles scattered from niobium nuclei.
[from French after G. Igo et al., Phys Rev 101, 1508 (1956)]
Crystal Diffraction of Neutral Helium (1930)

\[ \lambda \approx 1 \text{ Å} \]

Fig. 2-16  (a) Experimental arrangement used by Stern et al. to investigate crystal diffraction of neutral helium atoms.  (b) Experimental results showing central reflection peak \( (\phi = 0^\circ) \), plus first-order diffraction peaks \( (\phi = 11^\circ) \). In the experiment, \( \theta = 18.5^\circ \).

from French after Estermann and Stern, Z Phys 61, 95 (1930)
Interference of Molecules

Fullerene molecule C60, consisting of 60 carbon atoms.