Announcements

- Exam 2 and HW7 are due on CAPA 8am Wednesday 3/25. Note this has been pushed back from the dates in last class!

- Today: Quantum Mechanics (Ch.13/14)

- Tuesday: More weird aspects of QM (Ch.14)
  The 4 forces of Nature, Feynman Diagrams

Sometimes light acts like a wave…

EM fields are “quantized” (photons)

EM fields are made of **discrete bundles** of energy (quanta or photons)

\[ E_{EM} = 0, 1hf, 2hf, 3hf, 4hf, \ldots \]

\[ hf = \text{energy of 1 photon} \]

\[ h = 6.625\times10^{-34} \text{ Js} \]

Planck’s Constant

1 photon deposits Energy hf

It’s tempting to think of photons as particles.
But they show interference. Indeed, the EM wave is still a wave; it’s just that it can only lose energy in units of photons.
Quantum Non-Locality

Einstein was troubled! How can a distant point in space "know" instantaneously that the spread-out EM field "knows" it has lost 1hf of energy when the photon impacts the screen at a distant point.

Example: Baseball Wavelength

What is the wavelength of a 1kg baseball moving at 1 m/s?

Data: \( h = 6.625 \times 10^{-34} \text{ J s} \)

\[
\lambda = \frac{h}{mv} = \frac{6.6 \times 10^{-34} \text{ J s}}{(1 \text{ kg}) \times (1 \text{ m/s})} = 6.6 \times 10^{-34} \text{ m}
\]

This is a TINY number! No wonder baseballs don’t seem like waves to us.

The “smallness” of h together with the “largeness” of everyday masses is why we don’t see quantum effects in day-to-day life.

Matter Waves

In 1923, de Broglie thought Nature should be symmetric. I.e., particles should display wave-like features (interference, etc.)

de Broglie’s equation tells us the wavelength of the “particle wave”

\[
\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mE}}
\]

Momentum \( p = \text{mass} \times \text{velocity} = \sqrt{2 \times \text{mass} \times \text{Energy}} \)

Example: Electron Wavelength

What is the wavelength an electron with an energy of 30 keV?

Data: \( m_e = 9.11 \times 10^{-31} \text{ kg}, h = 6.625 \times 10^{-34} \text{ Js}, 1 \text{ eV} = 1.6 \times 10^{-19} \text{ J} \)

\[
\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}} = \sqrt{\frac{6.625 \times 10^{-34} \text{ Js}}{2 \times 9.11 \times 10^{-31} \text{ kg} \times 30 \text{ keV} \times 1000 \text{ eV} \times 1.6 \times 10^{-19} \text{ J} \text{ eV}^{-1}}} = 7.084 \times 10^{-12} \text{ m}
\]

This number not so tiny. This means we can see electrons acting like waves.
Matter Waves

- At atomic scales, particles indeed interfere like waves

de Broglie was right!

Quantization of “Matter Fields”

- We see the same “lumpiness” of the fringe pattern for the electron case.

A nice duality emerges:

Light waves are waves in EM fields. They interfere. The EM fields are quantized and the “quanta” (discrete energy packets = hf) are called photons.

de Broglie’s matter waves are waves in a matter field. They interfere. The matter Fields are quantized and the “quanta” (energy packets = mc²) are the particles (electrons if an electron field, neutrons if a Neutron field, etc…).

What is “waving” (I.e., interfering) ?

- Probability – all particles described by a “wave function” \( \psi \). The square of \( \psi \) gives the probability density of finding a particle per unit volume. The \( \psi \) extends over all space, which gives weird consequences.

\[
|\psi(\mathbf{r})|^2 V = \text{prob. of finding particle in a small volume } V \text{ centered at the point } \mathbf{r}.
\]

Schroedinger (1926) found an equation that tells us how to calculate the wave function and how it evolves in time.

Observation can alter the outcome in QM

Electrons show an interference pattern in the double slit experiment.
A watched pot never boils…

… and a watched electron doesn’t show interference

[Diagram]

If you try to find out Which slit the electron Goes thru, the wave features Go away

An electron Detector

Many more weird examples…

Quantum Tunneling

Classically: A low energy particle does not Escape the box. It is always inside.

Particle bouncing around in a box

Quantum Tunneling

Classically: A low energy particle does not Escape the box. It is always inside.

Quantum Theory: The $\psi$ function extends over all space, even outside the box. There is a finite probability the particle will “tunnel” thru the box and found outside.

This is why some nuclei can radioactively decay.

The old picture of Atoms

Pre-Quantum Picture of Atoms

- Negatively charged electrons orbit the positively charged nucleus
- “Planetary model” of atoms
- The electron can have any value of energy (e.g., you can have any value of Kinetic energy on a merry-go-round by Going faster or slower)
Electron Wave functions in atoms

The shaded areas indicate regions of high probability to find the electron. Each figure is a different “quantum state” the electron can exist in.

Quantization of Energy Levels in Atoms

Electrons in atoms can only assume discrete, quantized values of Energy.

Quantization of Energy Levels in Atoms

Electrons in atoms can only assume discrete, quantized values of Energy.

Photon Emission: When an electron in an excited state “de-excites” back into it’s ground state, atom emits a photon with energy $hf = E_2 - E_1$
Quantization of Energy Levels in Atoms

Photon Emission: When an electron in an excited state “de-exites” back into its ground state, atom emits a photon with energy $h\nu = E_3 - E_1$

Emission from different quantum States give different photon frequencies $h\nu = E_3 - E_1$

How do we know? Atomic Spectra

All of chemistry is a consequence of QM energy levels

Lasers

Photon of energy $h\nu = E_2 - E_1$ emitted
When electron de-exites from 2 to 1

This happens naturally even if you don’t “do anything” to the atom (“spontaneous emission”)

But it happens even faster if you bombard The excited atom with photons having $h\nu = E_2 - E_1$. (“Stimulated emission”)

Lasers

• Say you have many identical atoms that are all in the excited state.

• You can set off a “chain reaction” where many of them de-excite together, and the emitted photons stimulate the de-excitation in the other atoms that releases still more photons.

Light Amplified Stimulated Emission
Bosons and Fermions

- Particles come in two types
- Bosons have the property that they can overlap. Examples are photons and certain atoms (helium). They are social.
- Fermions can not exist in the same state. They are anti-social. Examples – electrons, protons.
- The fermion nature of electrons explains atomic structure (periodic table and all that).

Heisenberg’s Uncertainty Principle

- Uncertainty Principle: It is not possible to know exactly the position and momentum of a particle at the same time.

\[ \Delta p \Delta x > \frac{\hbar}{4\pi} \Rightarrow \Delta v \Delta x > \frac{\hbar}{4\pi m} \]

- There is no absolute knowledge. The Newtonian view of the world (if everything were known, everything could be predicted) in not attainable.

Uncertainty depends on mass

There are two versions

\[ \Delta x \Delta p \geq \frac{\hbar}{4\pi} \quad \Delta E \Delta t \geq \frac{\hbar}{4\pi} \]

If the position of a proton, mass 1.67E-27 kg, is known to 1E-9 m the momentum and velocity could have a range of

\[ \Delta p \geq \frac{\hbar}{4\pi \Delta x} = \frac{6.625 \cdot 10^{-34} \text{Js}}{4\pi 1.00 \cdot 10^{-9} \text{m}} = 5.27 \cdot 10^{-26} \text{kg} \cdot \text{m/s} \]

\[ \Delta v = \frac{m \Delta p}{m} = 5.27 \cdot 10^{-26} \text{kg} \cdot \text{m/s} \]

\[ \Delta v = \frac{5.27 \cdot 10^{-26} \text{kg} \cdot \text{m/s}}{1.67 \cdot 10^{-27} \text{kg}} = 31.6 \text{m/s} \]
Some Ramifications

• Nature is governed by the rules of probability. No one can predict the exact outcome of a single measurement. Only probabilities and trends can be predicted.

• **All knowledge is imperfect.** There is no absolute knowledge of the position and velocity of objects.