Quantum Mechanics

Electromagnetism presents a major problem for understanding the structure of matter:
- matter has + and - charges
- negative can move around, not in atom center

Maxwell's Eq.?
- light behaves like a wave: interference
- light behaves like a particle: photoelectric effect
- electromagnetic wave extends thru space, has a

\[ \left\{ \text{a particle is localized, has position } x \right\} \]

\[ \text{for light } \rightarrow p = h/\lambda \text{ (Einstein)} \]

Wave-particles (de Broglie):
- if EM waves are particles (y), what about other particles?

Consider electron:

- superposition (sum of many diff. waves can produce)
- waves can produce localization, "wave packet" localized

\[ \Delta x \text{ = particle is most probable location within } \Delta x \]
Double Slit for Electrons

If electrons inherently waves, we should see interference

\( e^- \)  
\( \text{electron} \rightarrow \text{double slit} \)  
\( \text{screen} \) (detector)

- An interference pattern is observed when \( \Delta x \) small

I inject electrons individually, what see is:

\( e^- \)  
\( \text{screen} \)

- Pattern builds up one 'hit' at a time

- Single particle interferes with self; it's a wave!

Uncertainty

- To produce a localized particle
  - \( \Delta x \) is small
  - Need to sum more waves
    \[ \sum_{\lambda} \rightarrow \frac{\lambda}{\Delta x} \]

- Multiple \( \lambda \) associated with particle; its \( \lambda \) is not well-defined (exact)

- If more wave-like (\( \Delta x \) large)
  - Momentum \& \( \lambda \) well-defined

Since \( \lambda = h/\Delta x \rightarrow \Delta x \) related to \( \Delta p \)

So \( \Delta p \times \Delta x \) inversely related

\( \rightarrow \) when localized, \( \Delta p \) large
\( \rightarrow \) when \( \Delta p \) known well, \( \Delta x \) large

\[ \Delta p \Delta x \geq \frac{\hbar}{2} \]

Heisenberg Uncertainty Principle

\( \Delta p \) or \( \Delta x \) to zero

Not an experimental limitation
Implications

Classical physics is deterministic
- can know $\hat{x}$, $\hat{p}$, perfectly
- if know initial $\hat{x}$, $\hat{p}$, perfectly
- state of universe is completely determined

Quantum Mechanics
- determinism is gone
- we can’t know perfectly
- inherent randomness
  - e.g. radioactivity
- chemistry, semiconductor physics
- rely on uncertainty + wave-like properties of matter
  - FPsA, CPUs, PROMs...