Quantum Mechanics

and indeterminism

Quantum Mechanics – A New Theory

Bohr's quantum theory
- theory for transitions in atoms – radiating atoms
- stability of the atom

Not: complex atoms, line intensities, molecules

Quantum mechanics

- wave-particle duality
- explanation of energy states in complex atoms and molecules
- the intensities of spectral lines
- explains a wealth of other phenomena.
- accepted as being the fundamental theory underlying all physical processes
- "entanglement"

Quantum Mechanics

Dealing with the wave-particle duality:

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

Holds both for light waves and matter waves

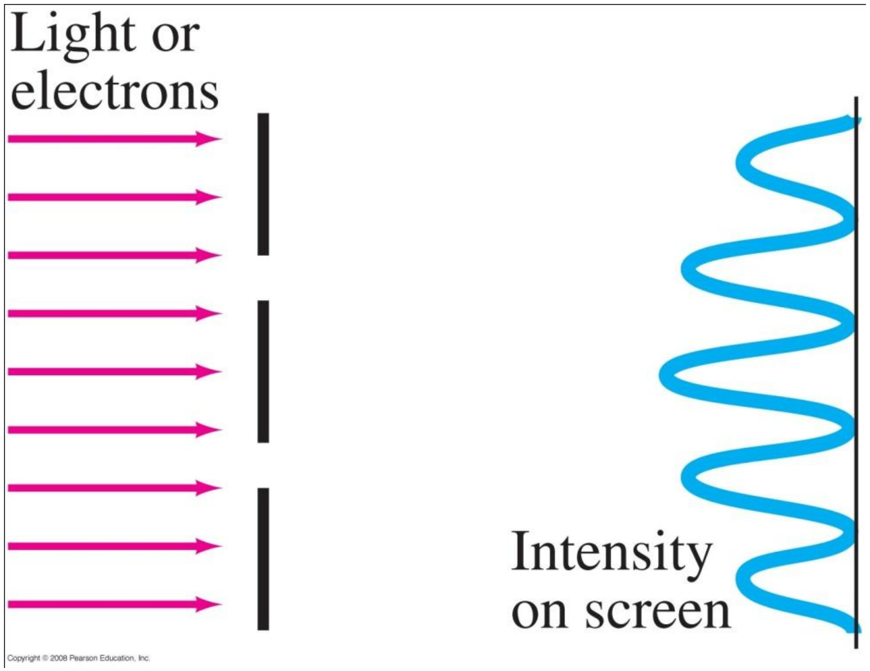
Light: $p = E/c$

For the momentum of the particle

Matter: $p = mv$

What about the wave character ?

The Wave Function and Its Interpretation; the Double-Slit Experiment



Interference for the wave amplitudes:

- **E field for electromagnetism**

– **Ψ for the amplitude of a matter wave**

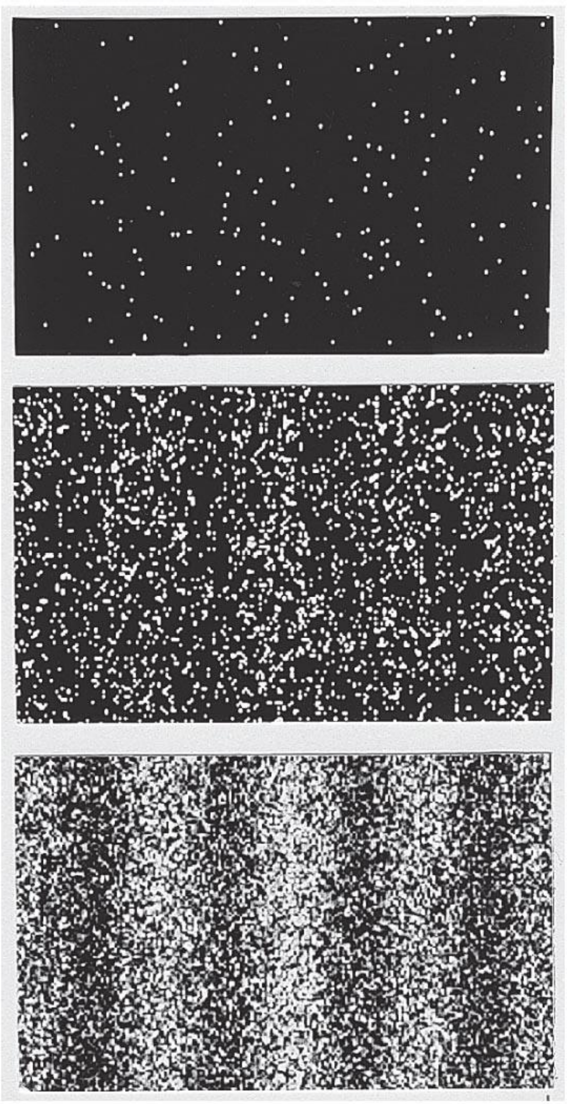
Matter behaves like a wave

Interpretation of amplitudes

Light intensity $I \propto |E|^2 \propto N$

Matter $|\Psi|^2$

Young’s Double-Slit Experiment



Can be meausured for;
Light and for electrons

Both entities can be waves and particles

Even at extremely low intensities: single-particle interference ?

Indeterminism:
You cannot predict where one particle ends up

Born interpretation of quantum mechanics; the wave function

$$\left|\Psi(\vec{r},t)\right|^2$$

Represents the probability to find a particle
At a location *r* at a time *t*

The probability density
The probability distribution

Max Born

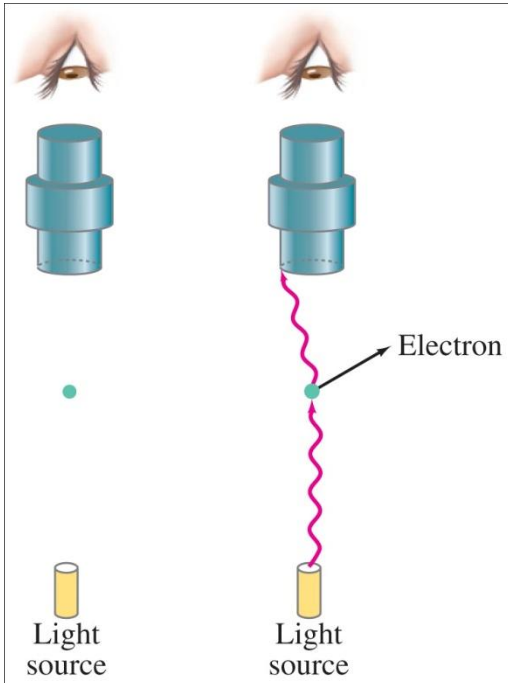
The Nobel Prize in Physics 1954
"for his fundamental research in quantum mechanics, especially for his statistical interpretation of the wavefunction"

The Heisenberg Uncertainty Principle

Fundamental limits to measurement –inherently.

- wave-particle duality

- interaction between equipment and the object being observed



Imagine trying to see an electron with a powerful microscope. At least one photon must scatter off the electron and enter the microscope, but in doing so it will transfer some of its momentum to the electron.

The Heisenberg Uncertainty Principle

A rough estimate:

If light is used to observe a particle, the uncertainty in position is

$$\Delta x \approx \lambda$$

If the object is detected by a single photon; momentum is transferred to object;

$$\Delta p_x \approx \frac{h}{\lambda}$$

This yields: $$(\Delta x)(\Delta p_x) \approx h$$

This is called the Heisenberg uncertainty principle, in a more refined calculation:

$$(\Delta x)(\Delta p_x) \gtrsim \frac{h}{2\pi}.$$

It tells us that the position and momentum cannot simultaneously be measured with precision.

The Heisenberg Uncertainty Principle

Location $\Delta x \approx \lambda$ Time $\Delta t \approx \Delta x / c \approx \lambda / c$

Energy $\Delta E \approx hc / \lambda$

Heisenberg uncertainty for time and energy (ignore the 2π):

$$(\Delta E)(\Delta t) \gtrsim \frac{h}{2\pi}.$$

This says that if an energy state only lasts for a limited time, its energy will be uncertain. It also says that conservation of energy can be violated if the time is short enough.

Consequences for the width of a short-lived quantum state

Note the relation with waves in optics and electronics (Fourier principle)

The Heisenberg Uncertainty Principle Calculations

An electron moves in a straight line with a constant speed $v = 1.10 \times 10^6$ m/s, which has been measured to a precision of 0.10%. What is the maximum precision with which its position could be simultaneously measured?

What is the uncertainty in position, imposed by the uncertainty principle, on a 150-g baseball thrown at (93 ± 2) mph = (42 ± 1) m/s?

Quantum mechanics is meant for electrons, not for baseballs

The Heisenberg Uncertainty Principle

The J/ψ meson, discovered in 1974, was measured to have an average mass of 3100 MeV/c^2 (note the use of energy units since $E = mc^2$) and an intrinsic width of 63 keV/c^2. By this we mean that the masses of different J/ψ mesons were actually measured to be slightly different from one another. This mass "width" is related to the very short lifetime of the J/ψ before it decays into other particles. Estimate its lifetime using the uncertainty principle.

Philosophic Implications; Probability versus Determinism

The world of Newtonian mechanics is a deterministic one. If you know the forces on an object and its initial velocity, you can predict where it will go.

Quantum mechanics is very different – you can predict what masses of electrons will do, but have no idea what any individual one will do.

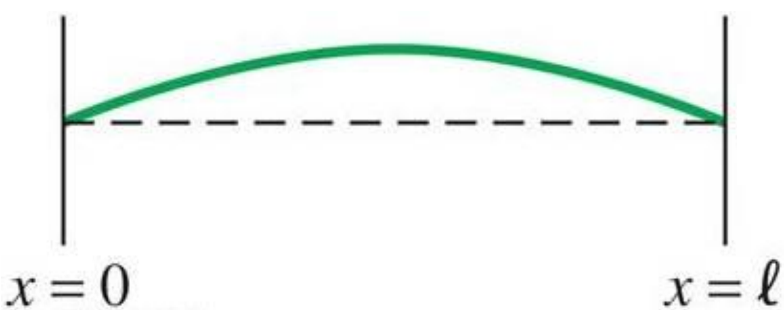
EPR-paradox
Schrödingers cat

QM measurement: collapse of the wave function

Before measurement

Probability distribution

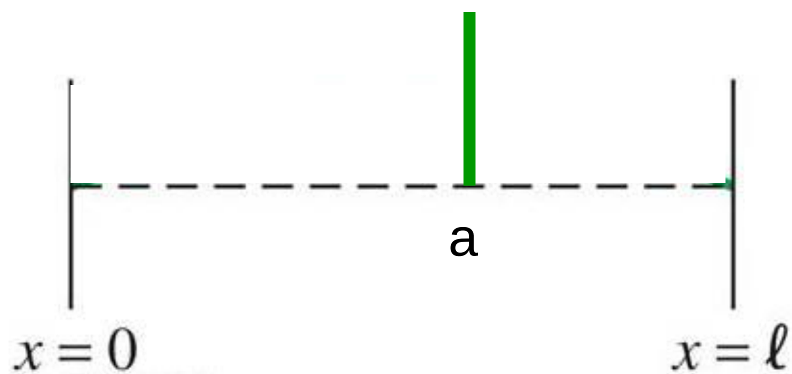
$$P(\vec{r},t)=\left|\Psi\left(\vec{r},t\right)\right|^2$$



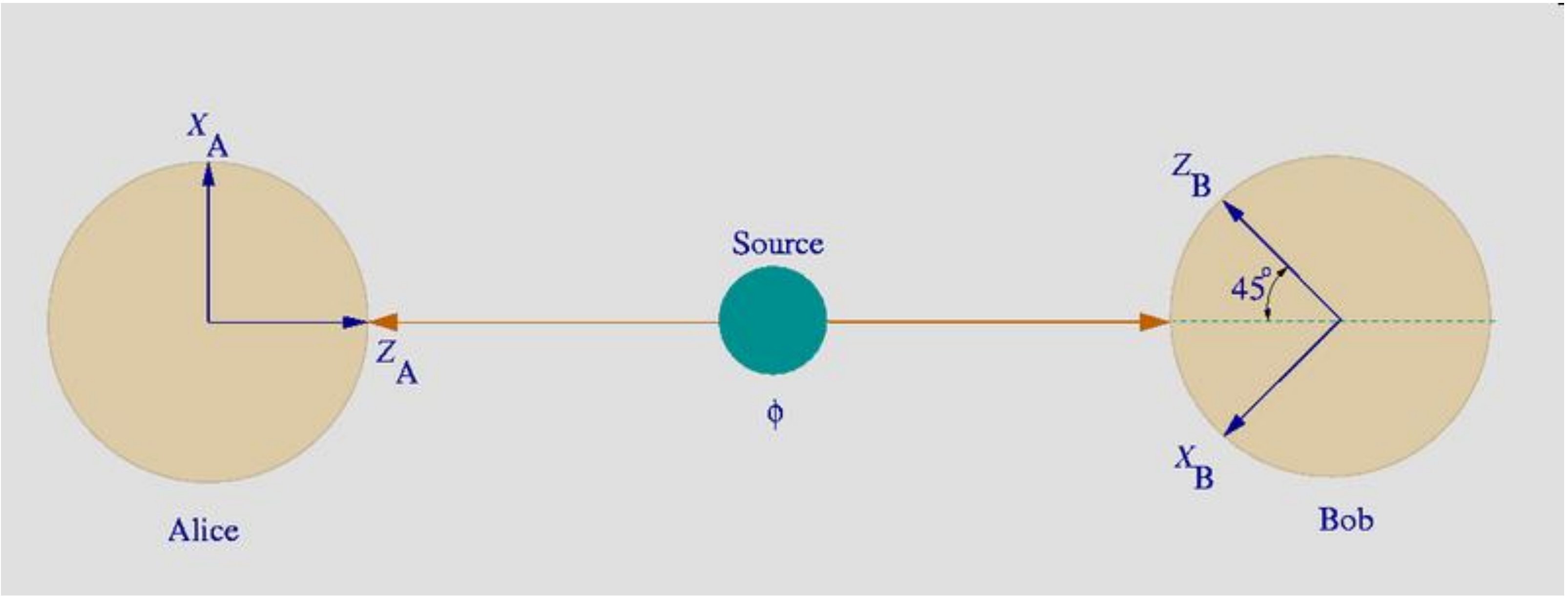
After measurement

Position determination

$$P(\vec{r}=a)=1 \qquad P(\vec{r}\neq a)=0$$



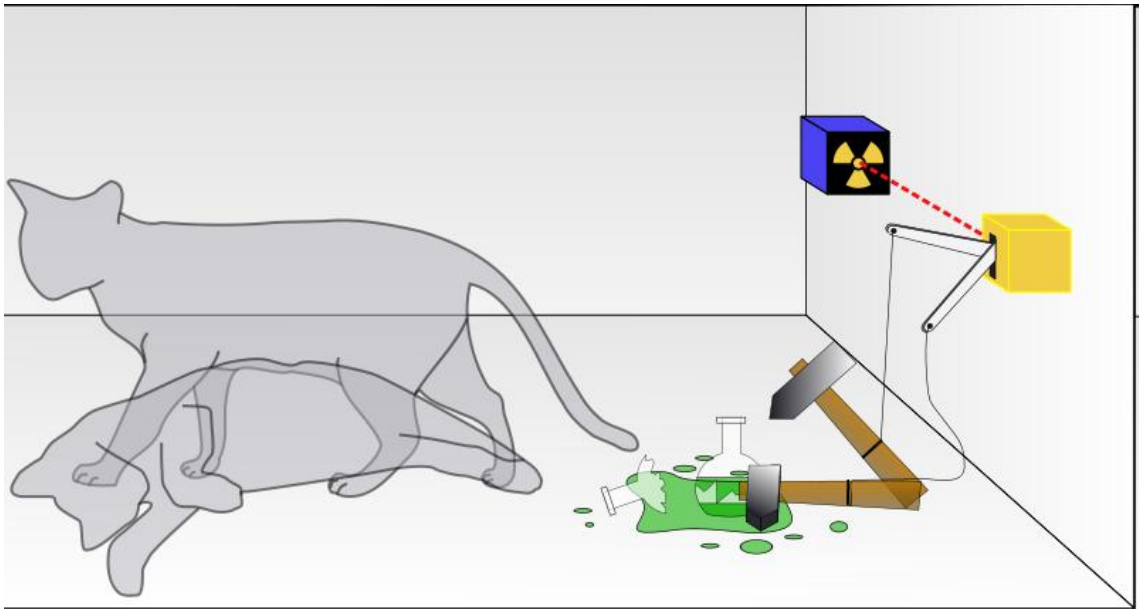
Einstein Podolsky Rosen – Paradox



Entangled states $\Psi = \psi_1 + \psi_2$

How about information transport ?

Schrödingers cat (1935)



The Copenhagen interpretation of quantum mechanics implies that after a while, the cat is *simultaneously* alive *and* dead. Yet, when we look in the box, we see the cat *either* alive *or* dead, not both alive *and* dead.