Quantum Phenomena and the Theory of Quantum Mechanics

The Mechanics of the Very Small

Waseda University, SILS,
Introduction to History and Philosophy of Science

Two Dark Clouds

In 1900 at a Friday Evening lecture at the Royal Institution in London, W. Thompson, then Lord Kelvin, discussed two dark “clouds” that hung over 19th century physics.

One was the failure of Michelson and Morley to detect ether drift.

- This was the experiment that attempted to measure the speed of two beams of light traveling at right angles to one another.

The other was a technical assumption of the Maxwell-Boltzmann theory of heat radiation, which would be involved in the development of quantum dynamics.

- This was a simplifying assumption which set particles vibrating at *discrete intervals*.

Planck and Blackbody Radiation

Max Plank (1858-1947) was a theoretical physicist working on thermodynamics. He founded, almost inadvertently, a new branch of physics, which came to be called *quantum physics*, and went on to become one of the leaders of German science.

Blackbody Radiation

A blackbody (concavity) absorbs light of every wavelength and grows warmer as function of this radiation. When a blackbody is heated it should emit light at all wavelengths.

Plank studied the spectrum of radiant heat at the Physikalisch-Technische Reichsanstalt for its application in the lighting and heating industries. There were significant discrepancies between the *prediction* based on continuous radiation and the *experimental values*.

Energy Quanta

Planck introduced *energy quanta* — discrete packets of energy — as a purely theoretical device, to explain the experimental values of blackbody radiation.

Using a statistical model, he imagined the energy of the body as a statistical characteristic of a set of unknown "resonators." The important equation is

$$\epsilon = nh\nu.$$

That is, energy, ϵ, is equal to frequency of vibration, ν (a real number), times Plank's constant $h = 6.6 \times 10^{-34}$ J/s (a small contant), times some whole number $n \in \{0, 1, 2, 3\ldots\}$.

The quantum discontinuity of these whole numbers was at first not considered physically important. It was a just a *simplifying assumption* that produced an accurate radiation law.

Einstein’s Contribution

“The Photoelectric Effect,” 1905.

When light shines on a metal plate, the plate emits a negative charge, or electrons. The rate of emission is *a function of the wavelength* of the light. The function has a series of maxima around wavelengths that are whole number ratios of each other.

Einstein’s paper was a simple argument that this experimental fact could be explained on the basis of Planck’s quanta of energy radiation. It implied, however, that the quanta must no longer be considered a simplifying assumption, but must be a *physical characteristic of the light*.

The only way to understand the effect seemed to be to assume that the light acted as quanta — that is, that light it made up of particles. This was contrary to a long tradition of viewing light as a type of wave in an assumed ether.

Bohr's Atomic Theory

Niels Bohr (1885–1962) came from a Danish academic family and became one of the founders of the study of quantum dynamics and nuclear physics.

Bohr began working on atomic theory when he was in Manchester with Rutherford.

- According to Bohr, the lab was "full of characters from all parts of the world working with joy under the energetic and inspiring influence of the 'great man.'"

Bohr was interested in the theoretical conditions for the stability of the atom. Since negatively charged electrons were orbiting the positively charged protons (and neutrons), it was a question of what arrangements and velocities would keep the whole structure from collapsing.

Rutherford's Atom

Rutherford's atom was a mechanical system — like planets in orbit around a central star.

As the electrons radiated electromagnetic energy (light) they should lose speed and eventually collapse into the nucleus. That is, they should emit energy of slowly varying wavelengths into the surrounding systems, atoms, and so on. This would also mean atoms would run down over time and collapse, but neither of these effects appeared to happen.

Bohr realized he could use Planck's quanta to make a model with stable orbits. During modeling this process, a colleague pointed out that his model should also account for spectral lines of chemical elements.

Bohr's Atomic Model

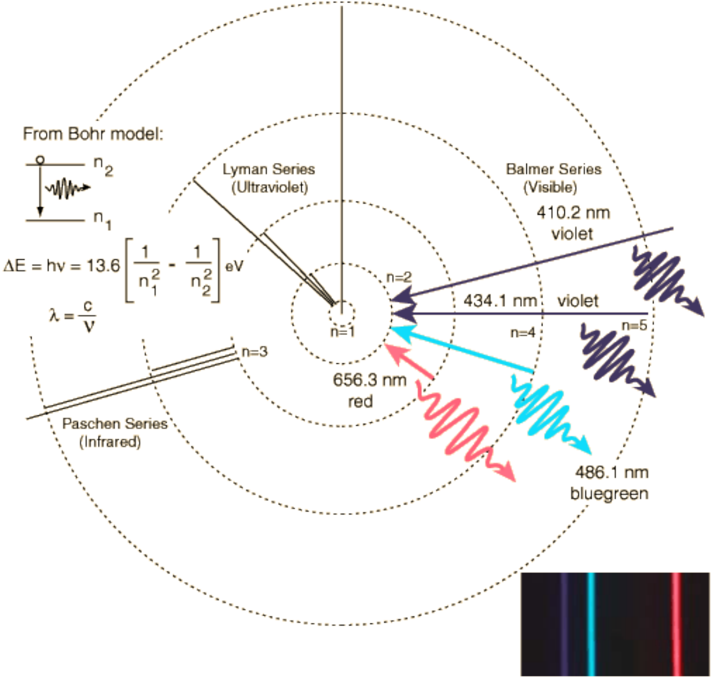
"On the Constitution of Atoms and Molecules," 1913–1915.

Bohr set the electrons orbiting around the nucleus only at certain determined intervals. When they were in those prescribed positions, he thought they obeyed the laws of classical mechanics but when they absorbed or emitted electromagnetic radiation they did so in *quantum jumps*.

Bohr, 1913

"The dynamical equilibrium of the systems in the stationary states is governed by the ordinary laws of mechanics, while those laws do not hold for the transition from one state to another."

We no longer hold that the "stationary" state is governed by ordinary mechanics, but this quote shows a realization that stable and transitionary states are different, and that the laws of mechanics *would have to be rewritten* for subatomic particles.


From Bohr model:
n_2
n_1
$\Delta E = h\nu = 13.6 \left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right] eV$
$\lambda = \frac{c}{\nu}$
Lyman Series
(Ultraviolet)
Balmer Series
(Visible)
410.2 nm
violet
n=2
434.1 nm
violet
n=1
n=4
n=5
n=3
656.3 nm
red
Paschen Series
(Infrared)
486.1 nm
bluegreen

The Implications of the Model

Bohr was able to use his model to give an explanation of the visible spectral lines of hydrogen. He predicted further lines in the ultraviolet and infrared ranges. These were found the next year. That is, the model made *novel* predictions, which were later confirmed. (The confirmation required integration with Einstien's theory of relativity.)

The model, however, indicated that atoms have fundamental behaviors that are unlike anything we encounter with ordinary objects.

Both light radiation and electrons seem to exhibit some wave characteristics and some particle characteristics. But the mathematics and mechanics of ordinary waves and particles is very different.

Furthermore, there seems to be no way to visualize these atoms.

The Limits of Visualization

Letter from Bohr to Heisenberg

"There can be no descriptive account of the structure of the atom; all such accounts must necessarily be based on classical concepts which no longer apply. You see that anyone trying to develop such a theory is really trying the impossible. For we intend to say something about the structure of the atom but lack a language in which to make ourselves understood… In this sort of situation, a theory cannot 'explain' anything in the strict scientific sense of the word. All it can hope to do is reveal connections and, for the rest, leave us to grope as best we can."

Quantum Objects

Quantum objects, like *electrons*, *photons* and all *subatomic particles*, have a strange behavior that we never could have imagined by studying the macroscopic world around us.

At the end of the 19th century it was a long established *fact* that light was a wave.

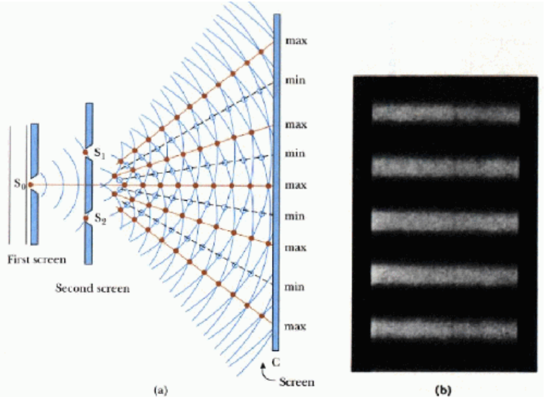
Now, Einstein and Bohr were proposing that light is a kind of particle. But the behaviors and effects of ordinary particles and waves are very different.

Key Point

Quantum objects are neither waves nor particles. They are a new class of objects, unknown in the macro-world that we inhabit, which have some wave-like properties and some particle-like properties.

The Wave Theory of Light

One of the simplest *confirmation arguments* of the wave theory of light was that light which is passed through a double slit displays patterns of wave interference.



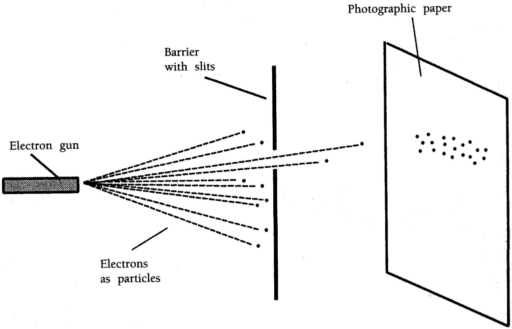
Wave interference in a bay

One-Slit Experiment

When quantum objects are passed through a single-slit apparatus, they behave as we would expect particles to behave.

The quantum objects go through the slit and are received on the screen like particles.

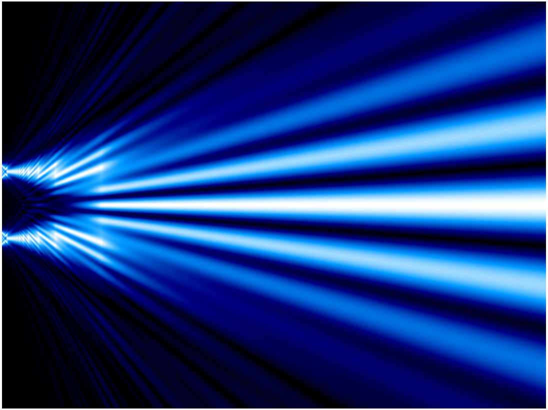
Actually, there is some wave-like interference, but it is very hard to detect.



Double-Slit Experiment

When quantum objects are passed rapidly through a double-slit apparatus, they behave as we would expect waves to behave.

We can clearly see the wave-interference patterns. There are a number of bright bands and the brightest are not directly in front of the two slits.

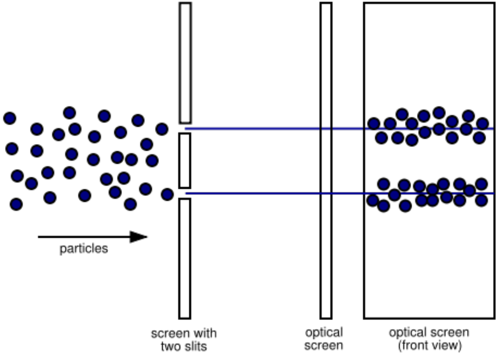


Double-Slit Experiment, with Detectors

The strange thing is that when we put *detectors* near the slits of the two-slit set up, the pattern changes.

We get two single-slit results with no wave interference.

The overall pattern has been changed, merely by detecting the particles.

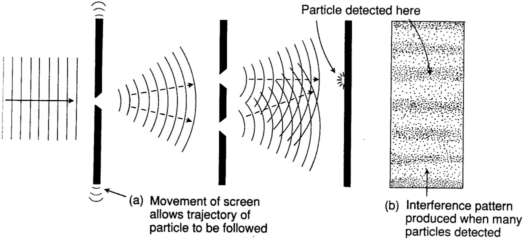


Double-Slit Experiment, in Slow Motion

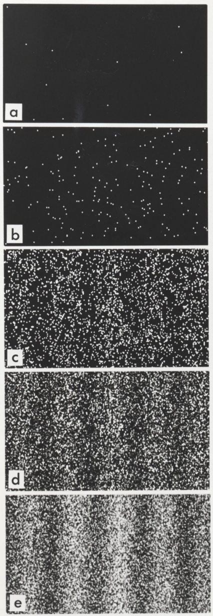
We can even set up the apparatus to fire particles slowly. Say, once every few (micro) seconds.

Then there can be no doubt that the particles go through individually.

Nevertheless, after a while, we see the wave pattern. What is causing the interference?



Photographic images of the particles collected over time on an optical screen, using the two-slit apparatus with no detectors.



Randomness

Quantum objects have a certain indeterminacy, but this is not total randomness.

- We can never know exactly both the *position* and *momentum* of a quantum object, but we can know their product with *great accuracy*. (The Uncertainty Principle.)
- We can never know exactly when a quantum object will decay, but we can model the probability of it. (This leads to the concept of the *half-life* of radioactive elements.)
- We can never know the *path* that a quantum object took to get to the detector, but we can predict the probability that it will arrive at a detector.

We can know the probabilities of all these events with great accuracy.

Beam splitter with two detectors

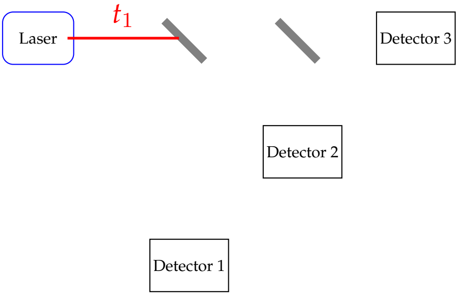
If we set up a beam splitter that passes half the particles (photons, electrons, etc.) and reflects the other half, then we get half the particles going one way, half the other.

We can set up multiple splitters, such that we have detectors at 50%, 25% and 25%.

But what about for any individual particle? We can use the theory of quantum mechanics to predict the probability that it will arrive at any detector.

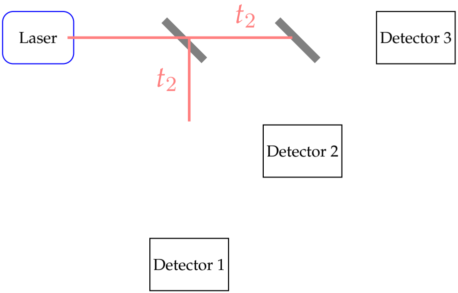
But where is the particle before it arrives at a detector? The theory doesn't say — in fact, in the fully developed theory of quantum electrodynamics, one assumes that the particle could have traveled by any possible path.

Beam Splitter Experiment



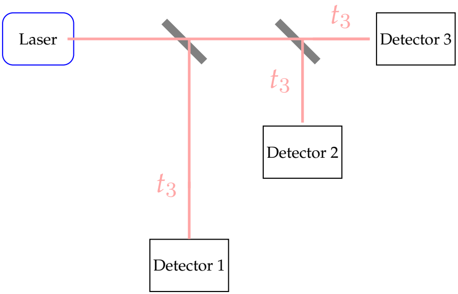
In t_1, the photon leaves the laser and travels to the first semi-mirror.

Beam Splitter Experiment



In t_2, the photon travels to the second mirror 50% of the time and towards **Detector 1** the other 50% of the time.

Beam Splitter Experiment



In t_3, the photon travels to **Detector 1** 50% of the time, to **Detector 2** 25% of the time, and to **Detector 3** the final 25% of the time.

It is possible to know where the photon is before it has been detected? How can we say where the photon is at time = 2.5?

Quantum Mechanics

- Quantum mechanics was developed over a number of years in the 1920s by many physicists — such as Bohr, Max Born (1882–1970), Louis de Broglie (1892–1987), Paul Dirac (1902–1984), Pascual Jordan (1902–1980), Wolfgang Pauli (1900–1958), Robert Oppenheimer (1904–1967), etc., but the theories of Heisenberg and Schrödinger were the most important.
- There are a number of different mathematical theories that formulate the quantum behavior of sub-atomic processes through mathematical models that can be used to predict the probabilities of various outcomes.
- Heisenberg, and others, argued that these mathematical rules are the only understanding we will ever have — that the underlying structure, if there is such a thing, can never be discovered.

Heisenberg' Matrix Mechanics

- In 1925, Heisenberg published his theory of quantum mechanics that used matrixes.
- He abandoned any attempt to formulate a picture or description of the internal structure of the atom, and worked directly with mathematical objects that could calculate measurements that could be made with an instrument — like charge, spin, and so on.
- Each position in the matrix represents some state of the quantum entity. The probability of certain events can be calculated on the basis of these matrixes.

Schrödinger's Wave Theory

Erwin Schrödinger (1887-1961) developed a wave mechanics that was meant to be a *unified field theory* in the tradition of Einstein.

In 1926, he published a quantum theory based on his *wave equation*.

- It could solve many problems and explain the known phenomena but it had no intuitive *physical interpretation*. It could predict future states of the quantum system, but the equation gave only probabilistic predictions.
- Moreover, it implied that a particle had to have more than one possible path at the same time.

And Others

- De Broglie had set out in his dissertation, 1924, to make a wave theory of matter. He joined Einstein and Planck's equations and generated wave equations for the fundamental particles of matter. He interpreted electrons as wave packets and showed how they would have all the properties of particles.
- After Heisenberg and Schrödinger published, P. Dirac, and P. Jordan, showed that both Heisenberg's matrix theory and Schrödinger's wave theory give equivalent results.
- M. Born and W. Pauli concluded that the wave equation simply gave a *probability of finding a particle* at or near a given place. For them, quantum mechanics was a form of statistical mechanics.

The Uncertainty Principle

In 1927, Werner Heisenberg (1901–1976) approached *subatomic uncertainty* from a philosophical perspective.

He used a thought experiment involving a microscope which measures the position of electrons in atoms by firing photons at them and measuring the reaction. We want to know the position and the momentum of the electron.

When the photon collides with the electron, however, it disturbs it in such a way that we no longer know its momentum precisely. What we know is $\Delta x \cdot \Delta p \geqslant h/4\pi$, where Δx is change in position and Δp is change in momentum, and h is Plank's constant. (Remember, h is very small.)

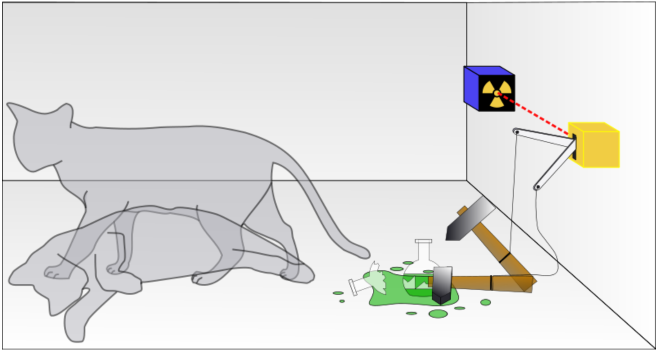
This means, again, we can only develop a statistical idea of the electron's path. In fact, the more precisely we know the position the less precisely we know the momentum and the converse.

Schrödinger's Cat

Schrödinger, however, believed that there was something missing in this statistical account. He tried to exemplify this with his famous thought experiment about a cat.

Schrödinger, 1935

"One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device…: in a Geiger counter, there is a tiny bit of radioactive substance, so small that perhaps in the course of the hour, one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges, and through a relay releases a hammer that shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts."



Schrödinger's Cat

Fundamental Indeterminacy

The statistical path, or *orbital*, of a quantum object can be exhibited with x-ray diffraction, but at the time they were technically difficult to produce.

Heisenberg's matrixes or Schrödinger's wave equations, however, could be used to calculate the probability distributions.

The fundamental particles exhibit either the properties of waves or particles, depending on how they are observed.

Bohr

"Quantum mechanics is about one thing: What can we do with our instruments?"

Resistance

The paradoxical features of the quantum theory were unacceptable to many physicists of the older generation.

Einstein to Max Born, personal communication

"Quantum mechanics is very worthy of regard, but an *inner voice* tells me that it is not the true Jacob. The theory yields much, but it hardly brings us closer to the secrets of the Ancient One. In any case, I am convinced that he does not play dice."

Pauli called QM young *boy's physics*. In 1925, Heisenberg was 23yo, Pauli 25yo, Jordan 22yo, Dirac 22yo. More than half were under 30 years old and they wrote 65% of the papers in the field.

Nevertheless, QM went on to become the most important physical theory of the 20th century and lead to all of the advances in physical chemistry, solid state physics, molecular biology, etc., that have produced our modern world.

What kind of world?

Our natural inclination is to believe that the world is something that will make intuitive sense to us. But why do we believe this? How are our intuitions formed?

In the 20th century, we had to question our intuitions of space and time; we learned that some attributes of objects appear to be developed by an interaction between observer and observed.

Our tools for understanding the world are our ideas — our conceptual metaphors and models, our mathematics.

But, at the most fundamental level, the world may be something unlike anything we have ever thought of and as we build more developed models and new mathematical theories we may find new areas of application for them, and we will have to develop new models to conceptualize new experimental discoveries.