Two-slit experiments

These conceptually very simple experiments show just one way how weird the quantum world can be. While we will talk about using electrons, the following experiments have been performed using photons and even large atoms, with identical results.

Macroscopic, solid particles : imagine the experiment in the figure below. We have a machine gun that fires bullets in a random direction over a fairly wide range of angles. These bullets travel in straight lines until they reach a wall which has two holes in it (1 and 2), at which point either : some of them pass right through a hole, some bounce off the sides of a hole, and others miss the holes completely becoming embedded in the wall. Beyond the wall there is a movable 'bullet detector' which can be moved up and down (defined as the *x*-direction) and we use this to measure the number of bullets that reach the backstop for a given value of *x*.

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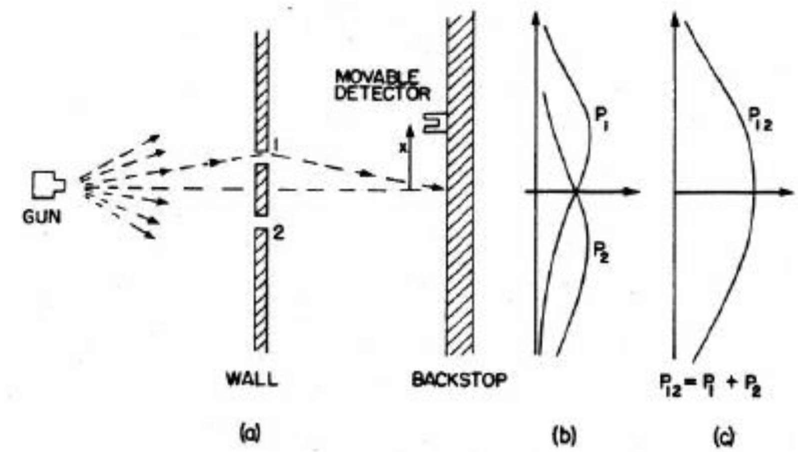
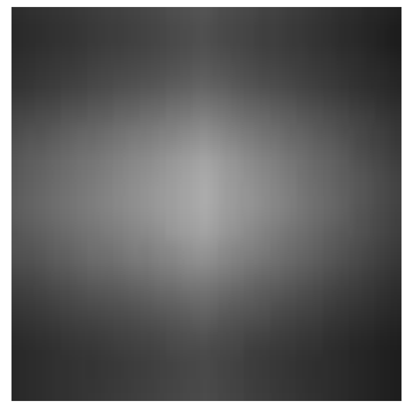
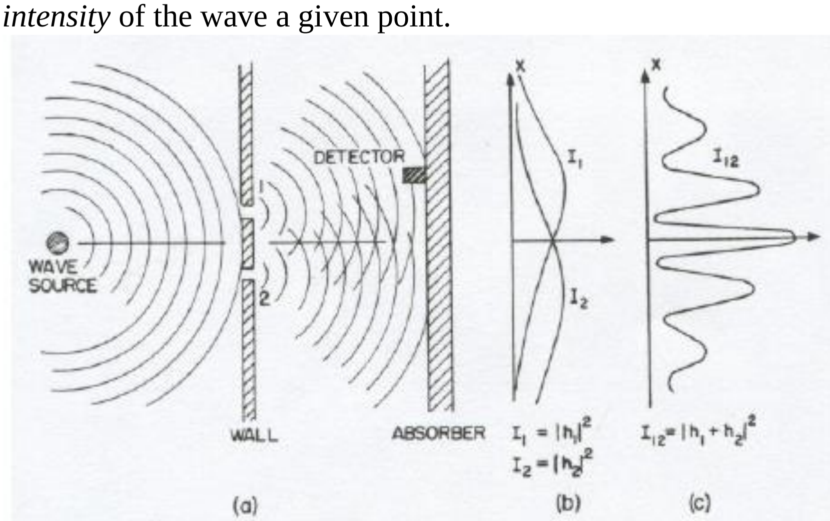
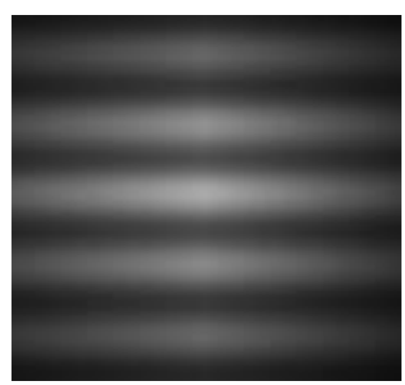




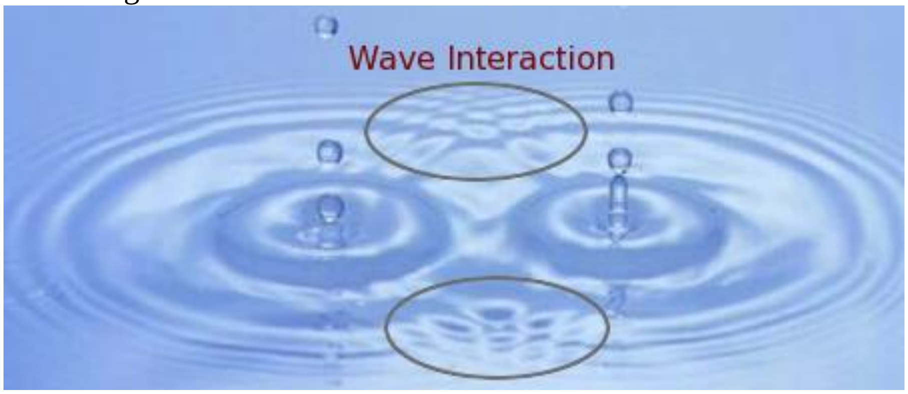
What is the probability that a bullet which passes through the holes in the wall will arrive at the backstop at a distance *x* from the center? Figure (b) shows the results P_1 (or P_2) if we cover hole 2 (or hole 1) so that bullets can only go thru hole 1 (or hole 2) – note that the peak is off-center because the maximum number of bullets will arrive at the place on the backstop which is a straight line from the gun thru the slit. When both slits are open, the result P_{12} is shown in figure (c). It may be surprising that P_{12} takes its maximum value in the middle, but the sum of P_1 and P_2 in the middle is greater than the maximum value of P_1 or P_2.

Macroscopic waves : now imagine the experiment shown in the figure below. Instead of a gun we have a wave source, which moves up and down (perpendicular to the plane of the paper) generating circular waves. Note that the absorber stops the waves completely (no reflections). The detector is a device that measures the *intensity* of the wave a given point.



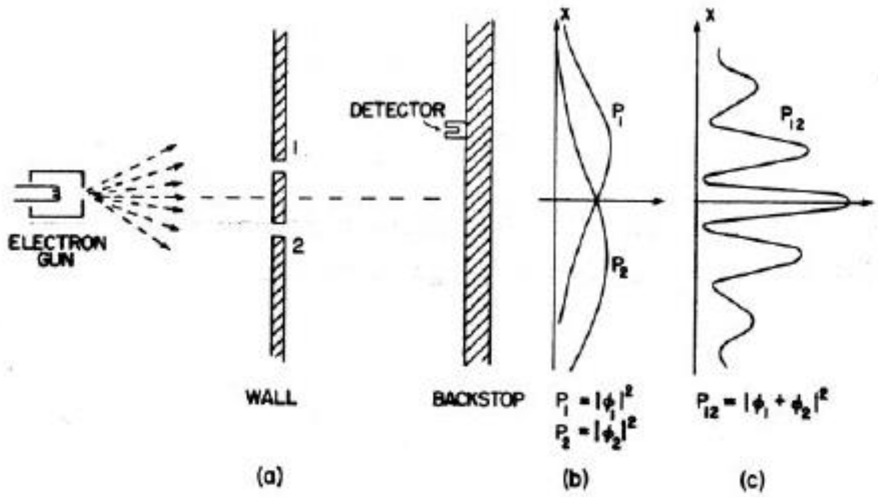


When we cover up hole 2 (hole 1), we get the intensity distribution I_1 (I_2) shown in figure (b), similar to the single-hole results from the bullets. But when both holes are open, we get the intensity distribution I_{12} in figure (c), due to the wave phenomenon known as *interference*, because holes 1 and 2 each act like sources of waves themselves, and these waves combine with each other just like the water waves shown below. What does figure (c) mean? If we placed a piece of photographic film at the absorber so the electrons exposed the film, it would show the pattern of bright (= many electrons = peaks in I_{12}) and dark (= few electrons = valleys in I_{12}) shown in the figure above at the far right.



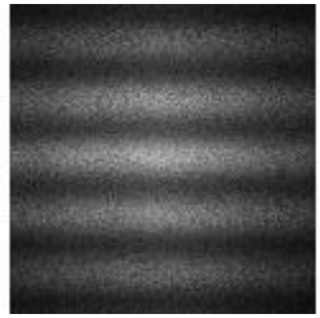
When one hole is covered, there is only one wave source after the wall, and so there is no interference since there are no other waves for it to interfere with. Clearly then, I_{12} is *not* the sum of I_1 and I_2. This is pretty much how we would expect all classical waves to behave in such experiments : they behave as non-localised wholes and their intensity distributions can't simply be added together, due to interference effects.

Many electrons : now imagine the experiment shown in the figure below. This is similar to our first experiment, but now we have a gun that fires microscopic electrons, and an electron detector, say a Geiger counter, that makes a clicking sound when an electron hits it.



When we do the experiment, we either hear a click or we don't. That is, a click corresponds to the arrival of an electron at the detector and so, like bullets, **electrons act like particles** when they reach the detector.

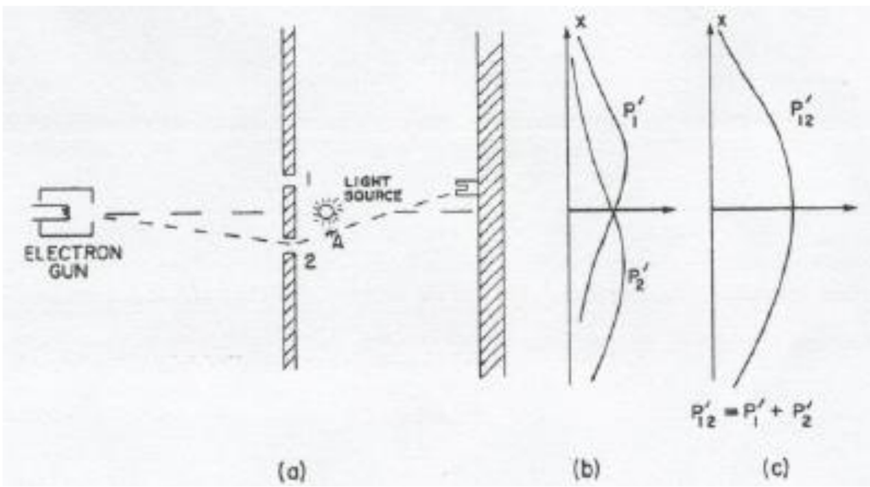
If we do the experiment with hole 2 (hole 1) covered, we get the probability distribution P_1 (P_2) sketched in figure (b). But, unlike in the bullet case, when both holes are open, we get the probability distribution given in figure (c), which is like what we found with water waves. So, electrons seem to be behaving likes waves (they exhibit interference phenomena) or particles (they are detected at a specific location), depending on what measurements we perform on them. This is the source of the *wave-particle duality* concept. By analogy with our water wave experiment, we seem forced to conclude that there is some kind of interference going on, but how? *The standard or "Copenhagen" explanation (see below) is that electrons are described by wavefunctions, and their wave-like natures are interfering with each other as they pass from the wall to the backstop.* However, this requires the electrons to "act like" a wave (described by the continuous time-dependent Schrodinger equation) while they travel, and then "collapse" to a single location (at the detector) when they reach the backstop. But this is not the only interpretation!



<u>One electron at a time</u> : now imagine an experiment where we send <u>one electron at a time</u>. If we leave only one hole open, we get the usual P_1 or P_2 patterns above, as if we were firing one bullet at a time. But the figure to the right shows the result of many <u>individual</u> electrons being fired at the detector, with both holes open. →

The interference pattern still appears; but if the electrons are fired <u>alone</u>, then what are they interfering **<u>with</u>**? *The standard interpretation is that each electron's wavefunction travels thru both slits simultaneously, becomes a superposition of "going thru 1" and "going thru 2" states, and these two states interfere with each other (the short description is that the electron "interferes with itself")!* However, note that in the next experiment we <u>never</u> see flashes at hole 1 <u>and</u> 2, indicating that the electron did not "travel thru both". Another alternative is that each electron somehow "knows" whether there's one or two holes!

<u>Observing the electrons</u> : now imagine the experiment shown in the figure below. We have added a light source just behind the wall. Since electrons scatter light, if an electron goes through hole 2 we will see a little flash of light in the vicinity of the point marked A in figure (a). Similarly, if an electron goes through hole 1, we will see a flash of light near that hole.



When we perform the experiment with both holes open, we find that *every* click of the detector is preceded by a flash of light which is *either* near hole 1 *or* near hole 2 (never both), as expected. But we find that we get the probability distribution P'_{12} shown in figure (c), which looks like what we found in the bullet experiment, and is in fact just the sum of P'_1 and P'_2! Whenever we can <u>detect which slit an electron has travelled thru</u>, the interference pattern instantly disappears. An interference pattern only appears when the electron's path is unknown.

<u>Delayed choice</u> : ok, so what if we <u>open or close one hole after the electron has passed by the wall?</u> Things get even weirder – the resulting pattern (interference or no interference) **depends on the state of the holes when the electron reaches the backstop**! So the electron could pass thru the wall while there's only one open hole, and while it's travelling to the backstop we open the other hole, at which point when the electron reaches the detector, it will exhibit interference. So the electron "knows" whether there's one or two holes <u>at the time of measurement</u>! This happens even if we wait until the electron **is so far from the holes that not even a light-speed signal** could travel from the holes (once they change) to the electron before it reaches the detector (to let it know how to act), thus violating one of Einstein's basic premises about special relativity (**non-locality**).

Terms and Definitions

In science, **positivism** rejects speculations that are inherently non-verifiable (non-measurable). **Logical positivism** also requires that any statement about reality be formally logical. This removes any discussion about the mind, existence, God, etc. from scientific discussion.

Realists assume that there is some underlying reality, independent of the observer (Einstein was a realist). A positivist would argue that this is a logical contradiction, since there is no way to observe an observer-independent reality. A realist says there is an **ontological** (objective) reality, a positivist says there is only an **epistological** (measurable) reality.

For a logical positivist, a theory or equation is an instrument which can be used to explain observations and make predictions. It describes aspects of a reality which depends on the observer and measuring device for its existence, but is the same for all observers. For a realist, the theory or equation describes an independent reality, or how the world is, which does not depend on the observer in any way.

A theory or equation is **complete** if every element of physical reality is accounted for in the theory – in other words, if all possible measureable values are present in the equations.

Determinism says that **the state of a system at a future instant is a function of the state in the present**. A physical theory is deterministic if, roughly, **given a complete state of the universe at any one time, a unique past and future follow**. For simple systems, classical mechanics is deterministic. The Schrodinger evolution of the wavefunction is deterministic, but if wavefunction collapse upon measurement is assumed, it becomes non-deterministic. While a topic of debate among philosophers of science, we will assume here that determinism is the same thing as **causality**.

Locality says that an object is directly influenced only by its immediate surroundings, and **local realism** adds that all objects have an objective, pre-existing value before any measurement is made.

Interpretations of Quantum Mechanics (QM)

QM is the only branch of physics where the equations work perfectly (match experimental results), but *what they mean* is still open to debate over 100 years after their discovery! There are many aspects to QM :

Wave-particle duality

In QM, photons and particles seem to exhibit both wave and particle properties (as demonstrated in the above experiments), so classical concepts like "particle" and "wave" cannot fully describe the behavior of quantum-scale objects. Some interpretations explain this apparent paradox as a fundamental property of the universe, while others explain the duality as a consequence of various limitations of what the observer can measure. Wave–particle duality is one aspect of the general concept of "complementarity", that a phenomenon can be viewed in one way or in another, but not both simultaneously.

Complementarity

Complementarity says there is no logically consistent picture that can simultaneously describe and be used to think about all properties of a quantum system. This is often phrased by saying that there are "complementary" propositions *A* and *B* that can *each* describe the quantum system, but not at the same time (such as "electrons are particles" and "electrons are waves").

<u>Superposition</u>
Subatomic particles often exist in a superposition of two or more states (spin up and down, polarized left and right, etc.), while the measured results only ever give us one state. We can easily prepare an electron to have a spin that is mathematically *both* up *and* down, for example, but any measurement will yield *either* up *or* down.

<u>Uncertainty</u>
QM says that some *pairs* of measurements (most famously, position and velocity) cannot both be measured very precisely. If one of these pairs is measured "sharply", the value of the other becomes "fuzzy". The more sharply one is measured, the less accurately the other can be measured. This is called the uncertainty principle.

The question regarding uncertainty is not whether it exists, but <u>whether it is an inherent part of reality or not</u>. That we cannot simultaneously **<u>measure</u>** the exact position and momentum of a particle is an experimental fact; but whether or not the particle **<u>has</u>** both an exact position and momentum at the same instant cannot be determined experimentally (because of uncertainty!). This is the difference between saying that **reality is deterministic but unable to be measured arbitrarily precisely** (an electron <u>has</u> a position and momentum, but they can't be measured accurately at the same time), and saying that **reality is itself basically non-deterministic** (the electron's momentum <u>does not exist</u> once we measure its position).

<u>Entanglement</u>
If two photons or particles are emitted in a single event, conservation laws ensure that the measured polarization or spin (or whatever) of one object must be the opposite of the other. But QM says each one is simultaneously both because of superposition. If the spin of one object is measured, the spin of the other object is now <u>instantaneously</u> known (thus their states are "entangled"). But according to Einstein's theory of special relativity, no information-bearing signal or entity can travel faster than the speed of light, which is finite. Thus entanglement seemingly violates principles of causality (it is **non-local**). Many experiments have confirmed the existence of entanglement.

<u>Meaning of the wavefunction</u>
In QM, the "wavefunction" of a particle describes everything about it that we can measure : its position, velocity, spin, polarization, etc. However, knowing a particle's wavefunction does not let you predict exact experimental measurements, but rather gives you a set of probabilities for what measurements you might get.

Schrodinger originally viewed the wavefunction associated with the electron as corresponding to the charge density. The problem is that any object described by a wavefunction very quickly gets smeared out over an extended, possibly infinite, volume of space. So Born interpreted the wavefunction as simply corresponding to a probability distribution. This leaves open the question of whether the localized particle exists independently, or whether it is in some sense produced or at least localized in the act of observation. In some interpretations the wavefunction represents an <u>objective part of reality</u>, in others our <u>state of knowledge</u>. It is considered by some interpretations to be **complete**, but not by others.

<u>Measurement of the wavefunction</u>
The world around us seems to be in a specific state, but quantum mechanics describes it by wave functions that are often spread out over all space. How then do we **measure** a particle to be in a specific position when its wave function is spread out? How do we **measure** <u>one</u> state when the system is in a superposition of states?

The measurement problem arises from the assumptions that :

- the equation that describes how the wavefunction changes over time is **linear and continuous**
- the claim that the wavefunction is **complete** (see above)

One way to describe how specific outcomes arise from the probabilities is to claim that the time evolution of the quantum state is **not always linear** by introducing the concept of **"collapse"**. According to these interpretations, the wavefunction represents a superposition of states, and evolves in time in accordance with the laws of quantum mechanics until a measurement is performed, at which point the system "collapses" and takes on <u>one</u> of its possible values, with a probability that is governed by the wave-function. The <u>reason</u> for what causes this collapse varies by interpretation. Schrodinger's cat is the most famous example pointing out that we don't know <u>at what level</u> (quantum vs. classical) the collapse happens, either.

Other interpretations reject that the wavefunction is **complete** by postulating additional "hidden" variables (for example, the particle's exact position – see below) besides the wave function, or spontaneous collapses of the wave function by nonlinear and random modifiers to Schrodinger's equation. These interpretations are ultimately not about wavefunctions but about objects moving in space, represented by either particle trajectories, fields on space-time, or a discrete set of space-time points. <u>The role of the wavefunction then is to govern the motion of the matter</u>. Interpretations that avoid wavefunction collapse are **deterministic**.

Finally, another class of interpretations **denies the collapse**, and offer explanations as to why it *appears* that it collapses ("many worlds").

<u>Issues in QM</u>

Classical physics is essentially deterministic. But due to the multiple ways in which the above issues can be interpreted, in QM we have an extra layer of assumptions that might be called metaphysical—although in another sense these assumptions are simply the ordinary claims of any physical theory. Experiment cannot yet decide among the following interpretations, and in some cases, never will. In general, we expect any interpretation of quantum mechanics to provide answers to various questions :

- Does the wavefunction describe **what is**, or **what we know**?
- Is the wavefunction **complete**?
- What does the theory say about the nature of existence?
- Do we live in quantum "Hilbert space" or four-dimensional spacetime?
- What is the mechanism responsible for non-local quantum correlations (delayed choice, entanglement)?
- What is the interpretation of the probabilities given by $|\Psi|^2$?
- Do measurements **create** or **reveal** the measured properties?

Answers to these questions will depend on both <u>the best solution to the measurement problem</u> and <u>the best *interpretation* of that solution</u>. It is important not to confuse these two issues.

<u>The Copenhagen Interpretation</u>

There are several basic principles that are generally accepted as being part of this **logical positivist** interpretation, which is the "standard" view that is taught :

1. Our **<u>knowledge</u>** of a system is **completely described** by a wavefunction ("**complete**"), but **denies that the wavefunction is anything more than a theoretical concept**, or is at least non-committal about its being a discrete entity or a discernible component of some discrete entity. Thus this interpretation offers no physical picture of reality.
2. The **result of a measurement is probabilistic**, with the probability of an event related to the square of the amplitude of its wavefunction.
3. It is **not possible to know the value of all the properties of the system at the same time** (Heisenberg's uncertainty principle); those properties that are not known with precision must be described by probabilities. This is <u>not</u> to say that these properties are independently existent and uncertain *to us*

because of limits in our ability to obtain knowledge of them through measurements; rather it says that **no meaning** **can be given to defined particle properties** (such as position and velocity) beyond the limits specified by the uncertainty principle. Thus **uncertainty is an inherent property of reality**.

4. Light and matter exhibits a **wave–particle duality** : they are **neither** waves or particles. An experiment can show the particle-like properties, or the wave-like properties; in some experiments both of these viewpoints must be invoked to explain the results, according to the **complementarity** principle.
5. The quantum mechanical description of large systems will closely approximate the classical description. (Bohr's "correspondence principle")
6. The assumption of **superposition** and **wavefunction collapse** : a wavefunction includes in it the various probabilities that a given event will proceed to certain different outcomes. But when one or another of those more- or less-likely outcomes becomes manifest, the other probabilities cease to have any possibility in the real world. So if an electron passes through a double slit apparatus, there are various probabilities for where on the detection screen that individual electron will hit. But once it has hit, there is no longer any probability whatsoever that it will hit somewhere else. However, there is **nothing that determines the actual value measured**, and it is **assumed to arise in an undescribed way that is not subject to analysis**.
7. The collapse is caused by the transition from the microscopic (quantum) system to the macroscopic (classical) measuring device **in an undefined way**. All properties of photons and particles are inherently relative to a measuring device.
8. The existence of non-locality is accommodated by **rejecting local realism** – actual definite properties of a physical system (position, momentum, etc.) **do not exist prior to the measurement**.

Many physicists and philosophers have objected to the Copenhagen interpretation, both on the grounds that it is **non-deterministic** and that it includes an **undefined measurement process** for **collapse**. In addition, the claim that entanglement cannot be used for signaling because "another observer cannot benefit until the results of that measurement have been relayed to him, at less than or equal to the speed of light" is a somewhat spurious argument, in that speed of light limitations applies to all information (wavefunction state), not to what can or can not be subsequently *done* with the information.

Hidden Variables

Einstein, Podolsky, and Rosen (EPR) were the first to argue that the wavefunction is not a complete description of reality, and that other elements (generally called "hidden variables") must be added to quantum mechanics to explain entanglement without faster-than-light action-at-a-distance.

In 1964, John Bell theoretically proved that no physical theory of **local** hidden variables can reproduce all of the predictions of quantum mechanics. If Bell's reasoning is correct, then some quantum effects travel faster than light, and the class of tenable ***hidden variable*** **theories are limited to the non-local variety**. It is also worth stressing that **Bell's analysis shows that any account of quantum phenomena must be non-local, not just any hidden variables account**. Bell showed that non-locality is implied by quantum theory, that reality itself is non-local.

Many experiments have been done to test Bell's theorem, and while the tests seem to indicate that it is true, objections arise for each test that claim some QM aspect or another was not accounted for. Thus while Bell's theorem has probably been experimentally confirmed, there are those who say it has not.

If true, these tests prove the intrinsic non-locality of quantum mechanics, demonstrating that **nature arranges the correlations between entangled objects by some faster-than-light mechanism** that violates Einstein's intuition about the intrinsic locality of all natural processes.

The Pilot Wave/Quantum Potential Interpretation

The Pilot Wave (original theory by de Broglie) or Quantum Potential (later re-discovered by Bohm) uses the same mathematics as Copenhagen QM; consequently, it is also supported by the current experimental evidence to the same extent as the other interpretations. It attempts to interpret quantum mechanics as a **deterministic** theory, avoiding problems such as instantaneous **wavefunction collapse** and the paradox of Schrödinger's cat. It is also sometimes called "causal" QM, "Bohmian mechanics", or the "Bohmian interpretation".

The quantum potential interpretation is a **hidden variable theory**, consequently it is **realist** and **deterministic**. <u>The positions and momentums of the particles are the hidden variables, and both exist exactly and simultaneously</u>. But the **observer doesn't <u>know</u> the precise value of these variables**, which introduces uncertainty into the theory. It is **ontological**, which means that there is a <u>well-defined process actually occurring</u>, regardless of our <u>knowledge of</u> the details of this process. The price which has to be paid for determinism is **non-locality**, which makes it compatible with **Bell's theorem**.

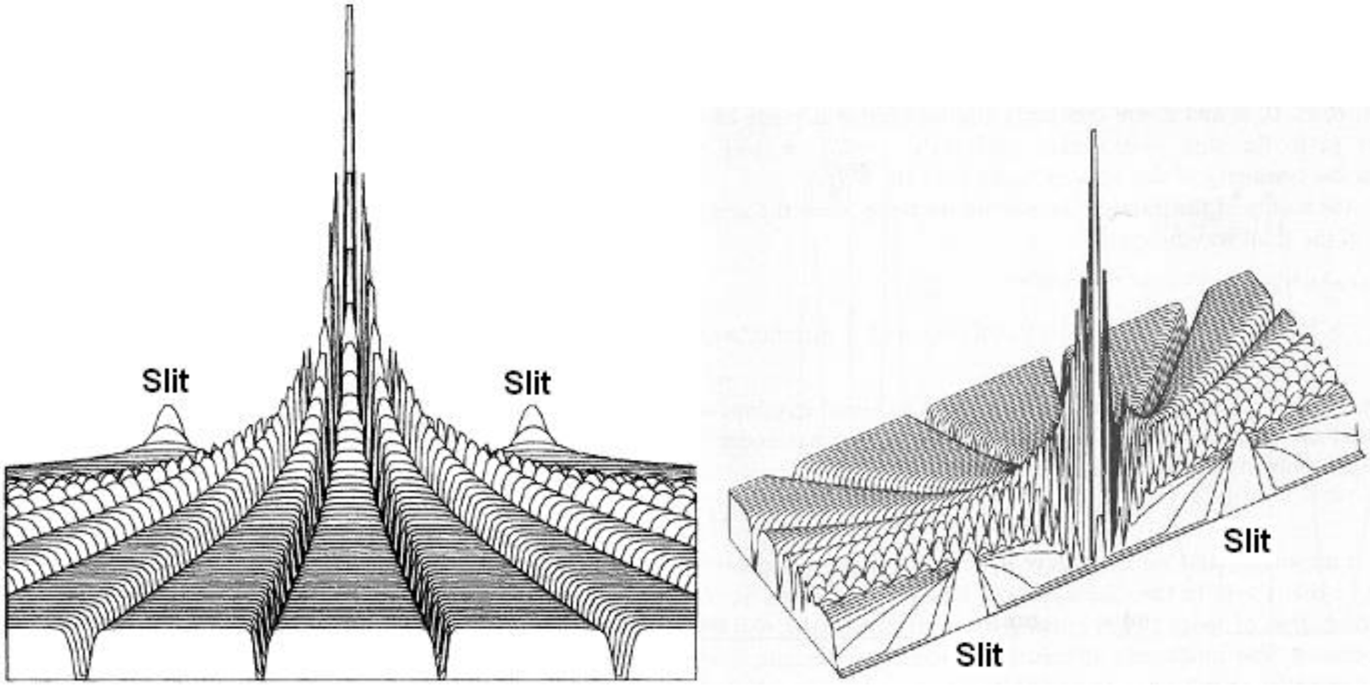
Essentially, Bohm separated Schrodinger's equation and extracted a part which he called the *quantum potential*. The quantum potential is non-local (the shape of the entire potential changes instantly as the environment changes), and is responsible for all the non-local effects predicted by the theory. The quantum potential does not impart energy to the particle (like gravitational potential energy), but <u>determines its path of motion</u>. Using a standard equation-of-motion with an added term for the quantum potential, the quantum potential guides the path of an electron in a way similar to how a radio beacon guides an airplane coming in for a landing at the airport. However, the wavefunction always evolves according to Schrodinger's equation.

According to this interpretation, the **particle and the quantum potential are both real <u>and distinct</u> physical entities** (unlike Copenhagen QM, where particles and waves are considered to be the same entities). Thus it has **no need for wave-particle duality or complementarity**. The <u>wavefunction (and hence the quantum potential) is not influenced by the particle</u>.

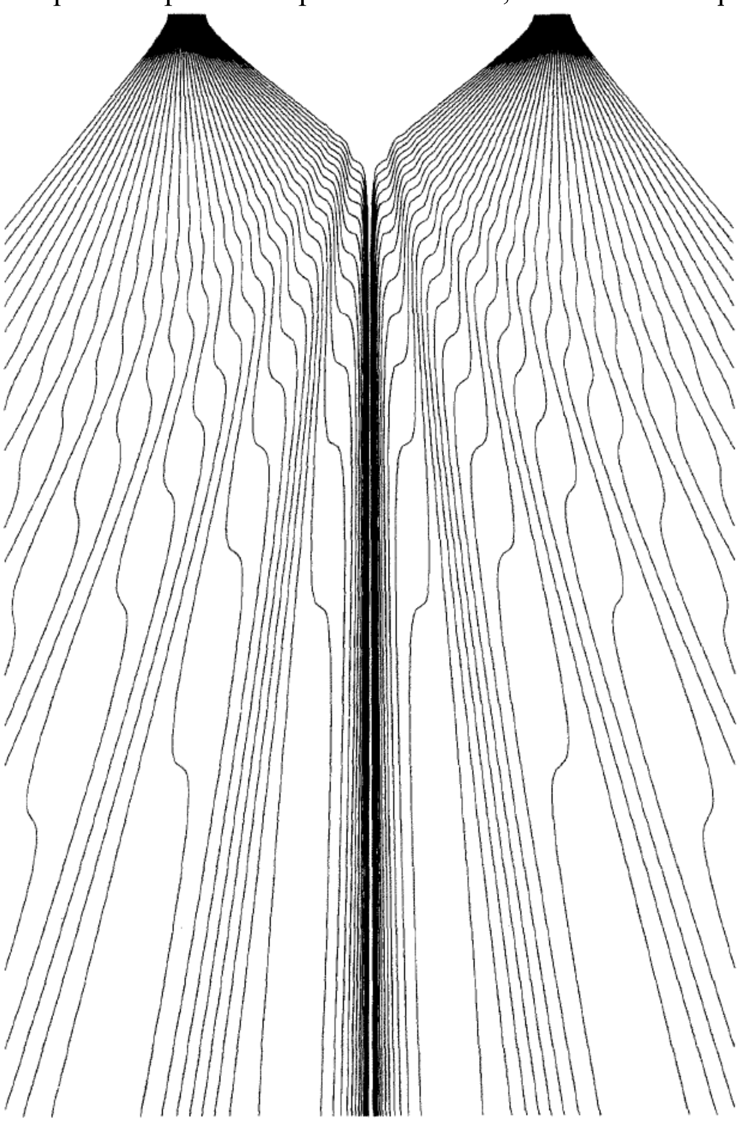
For the case of the double slit experiment for electrons, <u>each electron goes through either the upper slit or the lower slit, and it has a definite path independent of its observation</u> (see figures on the next page). However, the quantum potential is different depending on whether the other slit is open or closed; since this potential is non-local it can instantaneously change if the other slit is opened or closed. Thus the electron paths are different depending on whether or not the other slit is open, explaining delayed-choice results simply (if non-locally).

Uncertainties in measurement arise from rapid fluctuations (over space) in the quantum potential caused by overlapping wavefunctions (see figures on next page), whose effects are sensitive to initial conditions, and so appear unpredictable and uncontrollable. This makes the electron's future motion unknowable to us, even though strictly speaking it is deterministic. Thus the **uncertainty principle** is not an inherent property of reality, but **a practical limitation on the precision with which pairs of variables (position & velocity) can be measured**. **However, in many-particle or repeated experiments, the measured particle density matches that predicted by the wavefunction.**

In this interpretation, **measurement is not a passive process; it is an active process changing the system under investigation in a fundamental and irreducible way, arising from the quantum potential created by the measuring apparatus.**



Above : quantum potential for a pair of slits; dark bands in the interference pictures at the top of the document coincide with the valleys. Below : particle trajectories from the quantum potential; particles travel straight in the quantum potential "plateaus" above, and accelerate quickly (the "jogs") thru the valleys.



Bohm's Implicate Order

Later in life, Bohm went beyond the Pilot Wave/Quantum Potential interpretation to something he called "implicate order", where the non-local quantum potential creates an implicate (**hidden variable**) order, and may itself be the result of yet a further implicate order (superimplicate order).

Bohm called our everyday world of space, time and causality the *explicate order*. He proposed that underlying this everyday world is an interconnected one which he calls the *implicate order*. He used a number of analogies and images to discuss these two orders.

In one analogy (which actually inspired this line of thinking when he first saw it demonstrated), he imagined a large cylindrical glass container of glycerine mounted on a turntable. We place a spot of black ink in the glycerine. We slowly rotate the container, and the ink gradually disperses throughout the glycerine. If we slowly rotate the cylinder in the opposite direction the spot of ink gradually re-forms. When the ink is dispersed it is in an implicate state: it exists throughout the glycerine. When the ink is a spot it is explicate: it exists in one part of the glycerine but not in the other parts.

We extend the image as follows. We place the spot of ink as before. We slowly rotate the cylinder one revolution, and the ink has begun to disperse. We place a second spot of ink just beside where the first spot was, and rotate for one more revolution. A third spot is placed beside where the second was, one more revolution, and we continue this for a few spots. Then we continue slowly rotating the cylinder until all the ink is fully dispersed. When we reverse the direction of rotation we see the last spot coalesce, then the next to last one right beside the last one, and so on. We could interpret what we are seeing as a single spot of ink that is moving. So in the implicate, fully dispersed state we have enfolded the motion in space and time of an object throughout the glycerine. Reversing the rotation unfolds the reality back into space and time.

Another analogy is a hologram. To make a hologram we split a laser beam into two pieces with a half-silvered mirror. One piece goes straight to a photographic plate, the other bounces off the object and then goes to the plate. In order to reconstruct the image of the object we shine a laser beam through the developed plate: the three-dimensional image appears. Note that in some sense the hologram on the plate is an interference pattern between the beam that has experienced the thing and the beam that experienced no-thing. One characteristic of a hologram is that down to at least a few grains of the silver in the plate, each piece of the plate contains the entire image. If we cut the plate in half we do not lose half the image; instead we lose resolution and the image becomes more fuzzy. Thus each piece of the plate contains the entire space of the object in an enfolded way; this is an analogy to the implicate order. When we reconstruct the image, we have unfolded the implicate order into an explicate one. There even are "multiplexed" holograms that contain time information too : if the object is moving, we rotate the photographic plate. When we reconstruct the image if we look from different angles we see the object's motion. Hence the object's time behavior is also enfolded into the totality.

Wigner's Friend

Wigner basically said that **consciousness causes the wavefunction collapse**, or that **measurement requires consciousness**.

The Wigner's Friend thought experiment posits a friend of Wigner who performs the Schrödinger's cat experiment after Wigner leaves the laboratory. Only when Wigner returns does he learn the result of the experiment from his friend, that is, whether the cat is alive or dead.

If a material device is substituted for the conscious friend, the linearity of the wave function implies that the state of the system is in a linear sum of possible states. It is simply a larger indeterminate system that still evolves linearly according to Schrodinger's equation. Given that QM applies to all purely physical systems (whether micro or macro), the collapse cannot occur due to an interaction with a purely physical system. Thus, the collapse must occur *via* an interaction with a non-physical system, i.e. the *mind* of a conscious observer.

Objective Collapse

Objective collapse theories are **realist**, **non-deterministic** and **reject hidden variables**. The approach is similar to Copenhagen QM, but more firmly objective in order to solve the measurement problem.

All collapse theories stand in opposition to many-world theories, in that they hold that a process of **wavefunction collapse** curtails the branching of the wavefunction and removes unobserved behavior. They differ from the Copenhagen QM in **regarding both the wavefunction and the process of collapse as objectively real**. Copenhagen QM is non-committal about the objective reality of the wave function, and because of that it is possible to regard Copenhagen-style collapse as a subjective or informational phenomenon. In objective theories, there is a real wave of some sort corresponding to the mathematical wave function, and collapse occurs randomly ("spontaneous localization"), or when some physical threshold (such as mass density or particle number) is reached, but with observers having no special role.

The Ghirardi–Rimini–Weber theory, or GRW, is a collapse theory. GRW differs from other collapse theories by proposing that wavefunction **collapse happens spontaneously** by a nonlinear and stochastic modification of Schrodinger's equation.

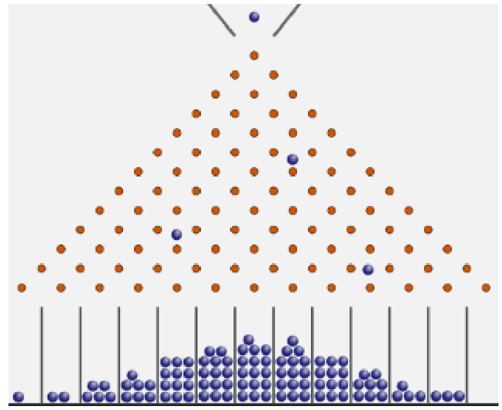
GRW says that particles can undergo spontaneous wave-function collapses. For individual particles, these collapses happen probabilistically and will occur at a given rate with high probability but not with certainty; groups of particles behave in a statistically regular way, however. Since experimental physics has not already detected an unexpected spontaneous collapse, it can be argued that GRW collapses happen extremely rarely. Ghirardi, Rimini, and Weber suggest that the rate of spontaneous collapse for an individual particle is on the order of once every hundred million years.

By suggesting that particles spontaneously collapse into stable states, GRW **denies the idea that measurement is a special act** or that **some specific part of measuring** a subatomic particle causes the particle's wavefunction to collapse. At the same time, GRW theory is compatible with single-particle experiments that do not observe spontaneous wave-function collapses; this is because spontaneous collapse is posited to be extremely rare.

However, since measurement entails **quantum entanglement**, GRW still describes the observed phenomenon of quantum collapses whenever we measure subatomic particles. This is because the measured particle becomes entangled with the very large number of particles that make up the measuring device. (For any macroscopic measuring device, there are sure to be very many orders of magnitude more than 10^8 entangled particles, so the likelihood of at least one particle in the entangled system collapsing at any given moment is extremely high.)

GRW collapse theories have unique problems. In order to keep these theories from **violating the principle of the conservation of energy, the mathematics requires that any collapse be incomplete**. *Almost* all of the wave function is contained at the one measurable (and measured) value, but there are one or more small "tails" where the function should intuitively equal zero but mathematically does not. It is not clear how to interpret these "tails." They might mean that a small bit of matter has collapsed elsewhere than the measurement indicates, that with very low probability an object might "jump" from one collapsed state to another, or something else entirely. All of these options seem counterintuitive.

Popper's Propensities



Popper's **realist** interpretation is that the particle **and** the experiment that it is in creates a "propensity" that determines the probability of a certain outcome.

The most often used example is dropping a ball on a slanted board with a bunch of pins in it. → The probability that a ball falls in a given bin is determined by the propensity of the system-as-a-whole to produce a specific result. Even if a single ball only hits some pins, all the pins determine the "propensity" of the entire system to produce its statiscial results. Propensity is a function of the ball **and** pins – remove a pin, and the propensity changes instantaneously (**non-local**).

For Popper, **reality is only composed of particles**; the wavefunction provides the statistics, describing the propensity of the system to produce given results. Thus **a measurement does not change reality, only our knowledge of it**.

Popper says that confusion arises when we take the wavefunction (which describes probabilities) and treat it like a physical property of the particle it describes. He also avoids the measurement collapse problem by saying we're mixing apples and oranges : there's a probability **before** measurement (given by the wavefunction) and a probability **after** measurement (which must be 0 or 1). To quote Popper,

> *Assume that we have tossed a penny – the probability of each of its possible states is 1/2. As long as we don't look at the result of our toss, we can still say that the probability will be 1/2. If we bend down and look, it suddenly "changes": one probability becomes 1, the other 0. Was there a quantum jump, owing to our looking? Was the penny influenced by our observation? Obviously not. Not even the propensity (probability) was changed. There is no more involved here, or in any reduction of the wave packet, than this trivial principle : if our information contains the result of an experiment, then the probability of this result, given this information will always be 1 (100%).*

While objects (experimental setups) have the propensity to cause events, it may not always be possible to trace the causality in any given interaction**.** Nevertheless, events do happen. Probabilistic descriptions, by their very nature, miss the underlying causality, and hence individual predictions. We can only change the configurations of macroscopic objects, as in deciding to close or open both slits. These different experimental choices lead to different probabilities for observable outcomes. The notion of propensities helps us to understand how the probabilities concerning outcomes that we observe can objectively change when we simply make changes in the macroscopic configurations with which the quantum particle interacts, without the need for propensities themselves being the underlying reality. Thus, there is no sudden change from potential to actual. There are only changes in experimental setups and corresponding outcomes.

However, in order to explain interference, propensities must be physically real things that can interefere with each other, which begins to sound like quantum potentials.

Many-worlds

The fundamental idea of many-worlds, first suggested by Everett, is that there are myriads of universes in addition to the one we are aware of. In particular, every time a quantum experiment with different outcomes with non-zero probability is performed, all outcomes are obtained, each in a different "world" or "universe", even if we are aware only of the one with the outcome we have seen. Thus quantum measurements literally split the world into two or more new worlds—one corresponding to each possible measurement outcome. Many-worlds implies that all possible alternative histories and futures are real, each representing an actual world. In this context, “quantum experiments” take place everywhere and very often, not just in physics laboratories – even in the irregular blinking of an old fluorescent bulb.

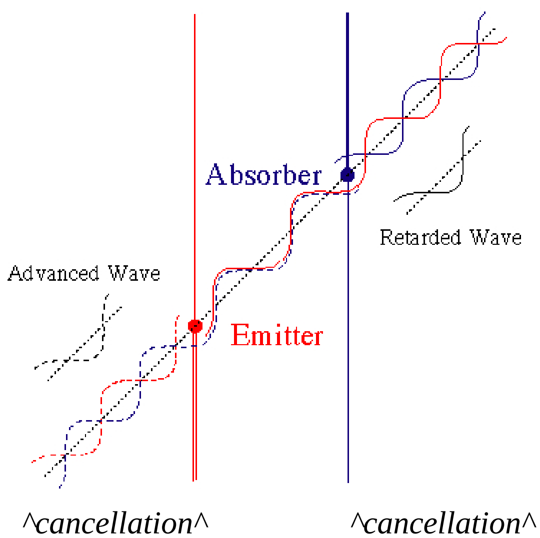
This interpretation treats the wavefunction as real, and while the formal theory is objectively continuous and causal, it is subjectively discontinuous and probabilistic. Variations on Everett’s original idea have been suggested by Albert (“bare theory”), Zeh (“many minds”), and DeWitt (who coined the phrase “many-worlds”).

While most quantum “splits” are irrelevant (blinking of a fluorescent bulb, what flavor ice cream you picked yesterday, etc.), some may have a dramatic effect on a person’s life (which job to take, who to marry, etc.), or even world history (what if the British won the Revolutionary war, or the Germans won WWII?). The metaphysical implications of this view for our conception of ourselves, the external world and probabilities—to name just three topics—are quite dramatic.

It seems that the majority of the opponents of many-worlds reject it because, for them, introducing a very large number of worlds that we do not see is an extreme violation of Ockham's principle: "Entities are not to be multiplied beyond necessity". However, in judging physical theories one could reasonably argue that one should not multiply <u>physical laws</u> beyond necessity either, and in this respect many-worlds is the most economical theory : it has all the laws of the standard quantum theory, but without the collapse postulate, the most problematic of physical laws. Many-worlds is also more economic than Bohm’s quantum potential which adds the objectively real particle position and momentum.

<u>Cramer’s Transactional Interpretation</u>

The transactional interpretation uses an explicitly non-local transaction model to account for quantum events. This model describes any quantum event as a space-time "handshake" executed through an exchange of “retarded” wavefunctions and “advanced” wavefunctions. It is generalized from the time symmetric Lorentz-Dirac electrodynamics introduced by Dirac and on "absorber theory" as originated by Wheeler and Feynman. Absorber theory leads to exactly the same predictions as conventional electrodynamics, but it differs from the latter in that it employs a two-way exchange, a "handshake" between advanced and retarded waves across space-time leading to the expected transport of energy and momentum.



This advanced-retarded handshake, illustrated schematically above, is the basis for the transactional interpretation of quantum mechanics. It is a two-way contract between the future and the past for the purpose of transferring energy, momentum, etc, while observing all of the conservation laws and quantization conditions imposed at the emitter/absorber terminating "boundaries" of the transaction. The transaction is explicitly non-local because the future is, in a limited way, affecting the past (at the level of enforcing correlations).

To accept the transactional interpretation it is necessary to accept the use of advanced solutions of wave equations for retroactive confirmation of quantum event transactions, which smacks of backwards causality. No interpretation of quantum mechanics comes without conceptual baggage that some people find unacceptable. This is a **non-positivistic** interpretation in which the **observer plays no special role**.

From one perspective the advanced-retarded wave combinations used in the transactional description of quantum behavior are quite apparent in the Schrodinger-Dirac formalism itself, so much so as to be almost painfully obvious. Wigner's time reversal operator is just complex conjugation, and the complex conjugate of a retarded wave is an advanced wave. What else, one might legitimately ask, could the complex conjugate of the wavefunction possibly mean except that the <u>time reversed (or advanced</u>) counterparts of <u>normal (or retarded)</u> wave functions are playing an important role in a quantum event?

In this interpretation, the wavefunction is a **real physical wave** with spatial extent and is identical with the initial "offer wave" of the transaction. The particle (photon, electron, etc.) and the collapsed wavefunction are identical with the completed transaction. The **complementarity** concept still exists, but like the **uncertainty principle** is just a <u>consequence</u> of the requirement that a given transaction going to completion can result in only one of a pair of solutions.

<u>Summary</u>

The many interpretations of quantum mechanics illustrate why the line between metaphysics and physics is sometimes blurry. Given current technology, there is no way to experimentally decide between Bohm’s quantum potential, a Wignerian interpretation (“human consciousness causes collapse”), GRW (“reaching a particle number threshold in the system makes collapse likely”) and the many-worlds interpretation.

So here's the real ultimate quantum weirdness : **only in the quantum world do the equations perfectly predict the experimental results, but <u>the equations themselves are open to different interpretations</u>!**