Quantum Entanglement & Quantum Tunneling

**Quantum Entanglement**

In the day-to-day world that is well described by classical physics, we often observe correlations. Imagine you are observing a bank robbery. The bank robber is pointing a gun at the terrified teller. By looking at the teller you can tell whether the gun has gone off or not. If the teller is alive and unharmed, you can be sure the gun has not fired. If the teller is lying dead of a gun-shot wound on the floor, you know that the gun has fired.

This is elementary detective work. On the other hand, by examining the gun to see whether it has fired, you can find out whether the teller is alive or dead. We could say that there is a direct correlation between the state of the gun and the state of the teller. 'Gun fired' means 'teller dead', and 'gun not-fired' means 'teller alive'. We assume that the robber only shoots to kill and he never misses.

In the world of microscopic objects described by quantum mechanics, things are not always so simple. Imagine an atom which might undergo a radioactive decay in a certain time, or it might not. We might expect that with respect to the decay, there are only two possible states here: 'decayed', and 'not decayed', just as we had two states, 'fired' and 'not fired' for the gun or 'alive' and 'dead' for the teller. However, in the quantum mechanical world, it is also possible for the atom to be in a combined state 'decayed-not decayed' in which it is neither one nor the other but somewhere in between. This is called a 'superposition' of the two states, and is not something we normally expect of classical objects like guns or tellers. Two atoms may be correlated so that if the first has decayed, the second will also have decayed, and if the first atom has not decayed, neither has the second. This is a 100% correlation. But the quantum mechanical atoms may also be correlated so that if the first is in the superposition 'decayed-not decayed', the second will be also. Quantum mechanically there are more correlations between the atoms than we would expect classically. This kind of quantum 'super-correlation' is called 'entanglement'.

Entanglement was in fact originally named in German, 'Verschrankung', by Schrodinger, who was one of the first people to realise how strange it was. Imagine it is not the robber but the atom which determines whether the gun fires. If the atom decays it sets off a hair trigger which fires the gun. If it doesn't decay, the gun doesn't fire. But what does it mean if the atom is in the superposition state 'decayed-not decayed'? Then can it be correlated to the gun in a superposition state 'fired-not fired'? And what about the poor teller, who is now dead and alive at the same time? Schrodinger was worried by a similar situation where the victim of the quantum entanglement was a cat in a box where the decaying atom could trigger the release of a lethal chemical. The problem is that in the everyday world we are not used to seeing anything like a 'dead-live' cat, or a 'dead-live' teller, but in principle, if we expect quantum mechanics to be a complete theory describing every level of our experience, such strange states should be possible. Where does the strange quantum world stop and the ordinary classical world begin? These are problems which have now been debated for decades, and a number of different 'interpretations' of the quantum theory have been suggested.

The problem was brought into focus by a famous paper in 1935 by Einstein, Podolsky and Rosen, who argued that the strange behaviour of entanglement meant that quantum mechanics was an incomplete theory, and that there must be what came to be known as 'hidden variables' not yet discovered. This produced a famous debate between Einstein and Niels Bohr, who argued that quantum mechanics was complete, and that Einstein's problems arose because he tried to interpret the theory too literally.

However in 1964, John Bell pointed out that for certain experiments classical hidden variable theories made different predictions from quantum mechanics. In fact he published a theorem which quantified just how much more strongly quantum particles were correlated than would be classically expected, even if hidden variables were taken into account. This made it possible to test whether quantum mechanics could be accounted for by hidden variables. A number of experiments were performed, and the result is almost universally accepted to be fully in favour of quantum mechanics. Therefore there can be no 'easy' explanation of the entangled correlations. The only kind of hidden variables not ruled out by the Bell tests would be 'non-local', meaning they would be able to act instantaneously across a distance.

More recently, from the beginning of the nineties, the field of quantum information theory opened up and expanded rapidly. Quantum entanglement began to be seen not only as a puzzle, but also as a resource for communication. Imagine two parties, Alice and Bob who would like to send messages to one another over a distance. In 1993, Bennett et al. showed that if Alice and Bob each hold one of two particles which are entangled together, a quantum state can be transmitted from Alice to Bob completely by sending fewer classical bits than would be required without the entanglement. This process has been called 'quantum teleportation'. It involves not only bits for sending information, but 'e-bits', or entanglement bits, which consist of a maximally entangled pair of particles. Other ways in which entanglement can be used a an information resource have also been discovered, for example, dense coding, cryptography and applications to communication complexity. Entanglement was found to be a manipulable resource. Under certain conditions, states of low entanglement could be purified into more entangled states by acting locally, and states of higher entanglement could be 'diluted' to give larger numbers of less entangled states.

Investigation of quantum entanglement is currently a very active area. Research is being done on measures for quantifying entanglement precisely, on entanglement of many-particle systems, and on manipulations of entanglement and its relation to thermodynamics.

Quantum theory predicts that a vast number of atoms can be entangled and intertwined by a very strong quantum relationship, even in a macroscopic structure. Until now, however, experimental evidence has been mostly lacking, although recent advances have shown the entanglement of 2,900 atoms. Scientists at the University of Geneva (UNIGE), Switzerland, recently reengineered their data processing, demonstrating that 16 million atoms were entangled in a one-centimetre crystal. They have published their results in Nature Communications.

The laws of quantum physics allow immediately detecting when emitted signals are intercepted by a third party. This property is crucial for data protection, especially in the encryption industry, which can now guarantee that customers will be aware of any interception of their messages. These signals also need to be able to travel long distances using special relay devices known as quantum repeaters—crystals enriched with rare earth atoms and cooled to 270 degrees below zero (barely three degrees above absolute zero), whose atoms are entangled and unified by a very strong quantum relationship. When a photon penetrates this small crystal block, entanglement is created between the billions of atoms it traverses. This is explicitly predicted by the theory, and it is exactly what happens as the crystal re-emits a single photon without reading the information it has received.

It is relatively easy to entangle two particles: Splitting a photon, for example, generates two entangled photons that have identical properties and behaviours. Florian Fröwis, a researcher in the applied physics group in UNIGE's science faculty, says, "But it's impossible to directly observe the process of entanglement between several million atoms since the mass of data you need to collect and analyse is so huge."

As a result, Fröwis and his colleagues chose a more indirect route, pondering what measurements could be undertaken and which would be the most suitable ones. They examined the characteristics of light re-emitted by the crystal, as well as analysing its statistical properties and the probabilities following two major avenues—that the light is re-emitted in a single direction rather than radiating uniformly from the crystal, and that it is made up of a single photon. In this way, the researchers succeeded in showing the entanglement of 16 million atoms when previous observations had a ceiling of a few thousand. In a parallel work, scientists at University of Calgary, Canada, demonstrated entanglement between many large groups of atoms. "We haven't altered the laws of physics," says Mikael Afzelius, a member of Professor Nicolas Gisin's applied physics group. "What has changed is how we handle the flow of data."

Particle entanglement is a prerequisite for the quantum revolution that is on the horizon, which will also affect the volumes of data circulating on future networks, together with the power and operating mode of quantum computers. Everything, in fact, depends on the relationship between two particles at the quantum level—a relationship that is much stronger than the simple correlations proposed by the laws of traditional physics.

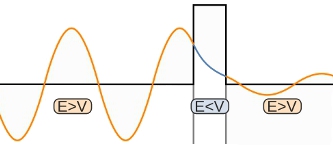
Although the concept of entanglement can be hard to grasp, it can be illustrated using a pair of socks. Imagine a physicist who always wears two socks of different colours. When you spot a red sock on his right ankle, you also immediately learn that the left sock is not red. There is a correlation, in other words, between the two socks. In quantum physics, an infinitely stronger and more mysterious correlation emerges—entanglement.

Now, imagine there are two physicists in their own laboratories, with a great distance separating the two. Each scientist has a a photon. If these two photons are in an entangled state, the physicists will see non-local quantum correlations, which conventional physics is unable to explain. They will find that the polarisation of the photons is always opposite (as with the socks in the above example), and that the photon has no intrinsic polarisation. The polarisation measured for each photon is, therefore, entirely random and fundamentally indeterminate before being measured. This is an unsystematic phenomenon that occurs simultaneously in two locations that are far apart—and this is exactly the mystery of quantum correlations.

**Quantum Tunneling**

The quantum tunnelling effect is, as the name suggests, a quantum phenomenon which occurs when particles move through a barrier that should be impossible to move through according to classical physics. The barrier can be a physically impassable medium, like an insulator or a vacuum, or it can be a region of high potential energy.

In classical mechanics, if a particle has insufficient energy to overcome a potential barrier, it simply won't. In the quantum world, however, particles can often behave like waves. On encountering a barrier, a quantum wave will not end abruptly - its amplitude will decrease exponentially. This drop in amplitude corresponds to a drop in probability of finding a particle as you look further into the barrier. If the barrier is thin enough, the amplitude may be non-zero on the other side, so there is a finite probability that some of the particles will tunnel through the barrier.



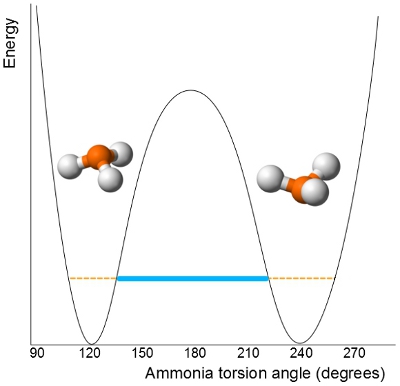
In regions where the potential energy is higher than the wave's energy, the amplitude of the wave decays exponentially. If the region is narrow enough, the wave can have a non-zero amplitude on the other side. Image Credit: Wikipedia

The tunneling current is defined as the ratio of the current density emerging from the barrier divided by the current density incident on the barrier. If this transmission coefficient across the barrier is a non-zero value, there is a finite likelihood of a particle tunneling through the barrier.

**Discovery of Quantum Tunneling**

The possibility of tunneling was first noticed by F. Hund in 1927, whilst calculating the ground state energy in a "double-well" potential - a system where two separate states of similar energies are separated by a potential barrier. Many molecules, such as ammonia, are examples of this type of system. "Inversion" transitions between two geometric states are forbidden by classical mechanics, but are made possible by quantum tunneling.

In the same year, L. Nordheim noticed another incidence of the tunneling phenomenon whilst studying the reflection of electrons from a variety of surfaces. In the following few years, tunneling was successfully used to calculate the ionization rate of hydrogen by Oppenheimer, and to explain the range of alpha decay rates of radioactive nuclei by George Garnow, and, independently, R. W. Gurney and E. U. Condon.



The two energetically equivalent states of ammonia, NH3, can exchange more readily than is classically predicted - this is because the molecule can tunnel through the potential barrier at lower energies than are required to pass through the transition state.

**Quantum Tunneling in Nature**

Although, like much of quantum physics, tunneling may appear to have little relevance to everyday life, it is a fundamental process of nature which is responsible for many things on which life itself is dependant.

It has even been hypothesized that the very beginning of the universe was caused by a tunneling event, allowing the universe to pass from a "state of no geometry" (no space or time) to a state in which space, time, matter, and life could exist.

**Tunneling in Stellar Fusion**

Fusion is the process by which small nuclei can join together to form larger nuclei, releasing huge amounts of energy. Fusion inside stars produces all the elements of the periodic table, except hydrogen, and fusion of hydrogen into helium is the process which gives stars their power.

However, fusion happens much more often than we originally thought it should. As all nuclei are positively charged, they repel each other very strongly, and their kinetic energy is very rarely sufficient to overcome this repulsion and allow fusion to occur. If tunneling effects are taken into account, however, the proportion of hydrogen nuclei which are able to undergo fusion increases dramatically.

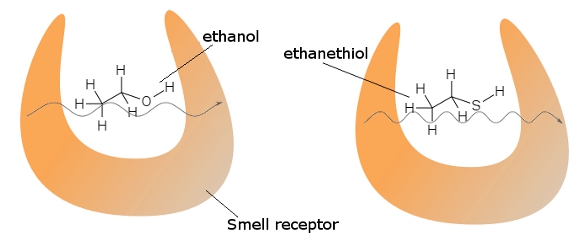
This helps to explain how stars are able to remain stable for millions of years. The process is still not very likely though - an average hydrogen nucleus will undergo over 1000 head-on collisions before it fuses with another.

**Tunneling in Smell Receptors**

Until quite recently, it was believed that chemical receptors in the nose (400 different kinds in humans) detected the presence of various chemicals by a lock-and-key process, which identified the molecule's physical shape.

There are some issues with this theory, however. For example, ethanol and ethanethiol, which have very similar shapes, smell completely different (ethanol is the alcohol we drink - ethanethiol smells of rotten eggs). This suggests that some other identifying mechanism is at work.

A theory which has been growing in popularity over the last decade or so is that smell receptors rely in part on quantum tunneling to identify chemicals. The receptors pump a small current across the odourant molecule, causing it to vibrate in a characteristic way. In order for the current to flow, however, the electrons must tunnel through the non-conducting gap between the cells of the receptor and the molecule.



Smell receptors can detect the differences between similarly-shaped molecules by tunneling a small current across them, causing a characteristic vibration.

**Applications of Quantum Tunneling**

**Josephson Junctions**

Josephson junctions consist of two superconductors separated by a very thin layer of non-superconducting material, which can be an insulator, a non-superconducting metal, or a physical defect. The superconducting current can tunnel across the barrier, and the electrical properties of this system are very precisely defined.

This leads to several unique applications, primarily for highly precise measurements. Josephson junctions are common components in superconducting electronics, quantum computers, and are also used extensively in superconducting quantum interference devices (SQUIDs), which are capable of measuring extremely weak magnetic fields.

**Tunnel Diodes**

A tunnel diode is a semiconductor capable of high speed operation, comprising of a thin insulator sandwiched between two semiconductors. Also known as the Esaki diode after L. Esaki for his work on the topic, this diode is capable of frequencies well into the microwave range.

Tunnel diodes are a two terminal device with a heavily doped p-n junction whereby the electric current through the diode is caused by quantum tunneling. Significantly, the current across the tunnel diode will decrease as the voltage increases meaning it will exhibit a negative resistance.

The concentration of impurities in a tunnel diode is 1000 times greater than a normal p-n junction diode, and as a result the p-n junction has an extremely narrow depletion region in the order of nanometres. In ordinary diodes, current is produced when an applied voltage is greater than the built in voltage of the depletion region.

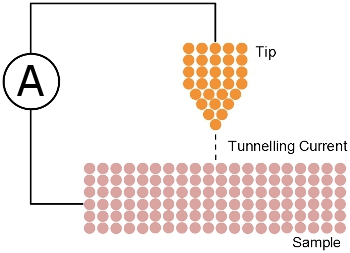
However, in tunnel diodes, a small voltage which is less than the built-in voltage of the depletion region produces an electric current due to quantum tunnelling between the n and p region. The narrow depletion region is required so that the barrier thickness is low enough for tunnelling, as mentioned in the introductory section.

Tunnel diodes are used in logic memory storage devices, relaxation oscillator circuits and as ultra-high-speed switches. Owing to the high resistance to radiation, they are commonly used in the nuclear industry.

**Scanning Tunneling Microscopes**

A Scanning Tunneling Microscope (STM) works by scanning a very sharp conducting probe across the surface of a material. An electrical current is passed down the tip of the probe, and tunnels across the gap into the material.

As the gap gets wider or narrower, the tunneling current gets smaller or larger, respectively. Using this data, we can build an incredibly detailed picture of the surface, even to the point of resolving humps in the surface due to individual atoms. This technique has allowed leaps forward in our understanding of the physics and chemistry of surfaces.



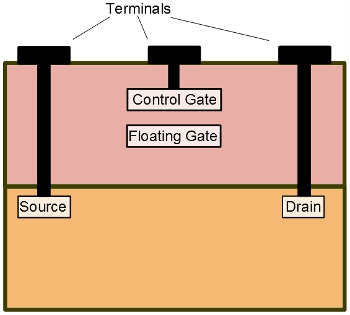
Schematic of an STM - the tunneling current varies with the distance between the tip and the atoms on the surface, allowing defects and even individual atoms to be mapped.

**Flash Drives**

Data on flash drives is stored in a network of memory cells made up of "floating-gate" transistors. These consist of two metal gates, a control gate and a floating gate. The floating gate is trapped in an insulating layer of metal oxide.

A floating-gate transistor in its normal state registers a "1" in binary code. When an electron is attached to the floating gate, it becomes trapped in the oxide layer, affecting a change in the voltage of the control gate - a transistor in this state registers a "0" in binary.

When data is erased from flash memory, a strong positive charge applied to the control gate causes the trapped electron to tunnel through the insulating layer, returning the memory cell to a "1" state.



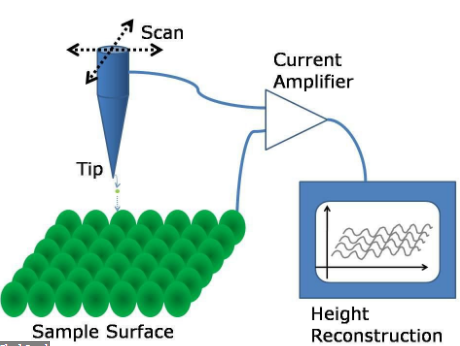
Schematic of a floating-gate transistor. Trapping an electron in the floating gate causes a change in the voltage across the control gate. Each transitor stores a bit of information.

**The Speed Of Quantum Tunneling**

Tunneling is, at its heart, a wave phenomenon. Because quantum particles like electrons have wave nature, they can't come to a stop in an infinitely short time, but need to tail off a little more slowly, for basically the same reasons described in this animated explanation of the Uncertainty Principle: If you want a wave-like probability distribution to stop suddenly, you need to add a huge number of wavelengths to get that sharp edge, which means you would lose all information about its momentum. An electron with a reasonably well-known momentum, then, must have some uncertainty in position, which means the wavefunction will extend into regions the particle doesn't have enough energy to reach according to classical physics.

If you have a really large excluded area, the consequences of this are pretty negligible, since there's not much way to measure the presence of an electron inside a material that's designed to exclude it. Things get interesting, though, if you exclude the electron from only a narrow region of space, forming a thin barrier between two regions where it's perfectly happy to exist.

For a classical particle, the thickness of the barrier makes no difference-- if it can't enter, it can't enter and the probability of finding it in the forbidden region drops immediately to zero. The quantum particle, though, has a wavefunction that extends into the forbidden region. This drops off very fast as you move into the region where it shouldn't be-- it's generally an exponential decay-- but if the barrier is thin, the value of the wavefunction can be non-zero when you get to the other side. And that means there's some probability to find the particle on the far side of the barrier, even though it should be impossible for it to get there.



Schematic of a scanning tunneling microscope: a sharp tip is scanned over a surface, and the current from electrons tunneling to the surface lets you reconstruct the height.

This is an odd phenomenon, but it has enormous practical applications. For one thing, it makes it possible for the Sun to shine. It's also the basis of the Scanning Tunneling Microscope, which uses the exponential decay in the probability of electrons tunneling across a tiny air gap as an incredibly sensitive probe of the distance between a probe and the surface of some sample. This is the technology that allows scientists to make images of matter that resolve individual atoms and molecules sitting on some surface.

So, tunneling is unquestionably a real process, which then raises the question of exactly how this business works. That is, what happens to the particle as it's crossing the barrier, and how does the crossing affect its properties? Specifically, is there a measurable effect of time spent in the crossing process?

These are really difficult questions to answer, because the time scales are so short. Whenever you start talking about time and distance in physics, you can define a sort of natural time scale, namely the time needed for light to cross the relevant distance. With tunneling, you're dealing with really small distances. The time required for light to cross the thickness of an atom (which is the relevant scale for an STM) is less than an attosecond (0.0000000000000000001s, if you like to see lots of decimal places). If you're going to look for a time delay associated with tunneling, you need a way of timing your experiment at that kind of level, which is really hard.

In recent years, people have been investigating this process using a "streaking" technique with ultrafast lasers. They don't directly measure the start and end of the tunneling process, but they use a clever analysis trick to set up a situation where they can measure a change in trajectory for electrons tunneling through a barrier.

The streaking technique starts with a sample of atoms, which they blast with a super-intense laser pulse that lasts only a few femtoseconds. This pulse is sufficiently intense that it doesn't make sense to talk about in terms of unimaginably huge numbers of photons; instead, it acts like a huge electric field, which lowers the energy for an electron on one side of the atom and raises it on the other. The shift is almost but not quite enough to rip an electron out, but leaves a small barrier holding it in.

Of course, any time you have a small barrier and a quantum particle, you get tunneling, so even though the pulse technically isn't strong enough to ionize the atoms, they nevertheless see some free electrons produced. These escape via tunneling, and because tunneling decreases exponentially with the size of the barrier, the vast majority of the tunneling should occur in a really short window around the time when the pulse is at its most intense. This gives a reasonably well-defined "start" time for the process.

Once the electrons are out, they get pushed around by the same giant electric field that extracted them, and this is where the "streaking" part comes in. The exact direction of the push on the escaping electron depends on the orientation of the field. The clever trick they use to get timing information is to use a circularly polarized laser pulse, where the direction of the electric field rotates at the speed of oscillation of the laser. The direction of the initial push, then, depends on exactly when the electron comes out-- if it emerges instantaneously, it starts off pushed in one direction, but if the tunneling requires some time, then the light field has rotated, and it gets pushed in a slightly different direction. They use a position-sensitive detector to measure exactly where the electrons end up, which will depend on that initial push.

This is, of course, a ferociously complicated process, with lots of fiddly details that could confound the measurement. Which is where the argument comes in: different groups use different methods to try to sort this out, and come to different conclusions about the tunneling time.

In the Physical Review Letters paper linked above, they opt for a differential technique: rather than trying to take on the nearly impossible task of locking all those factors down, they look at a difference between two very similar atoms: argon and krypton, which are mixed together in their target. Argon and krypton sit next to each other in the noble gas column of the periodic table, which means that they're extremely similar chemically. The only difference between them that really comes into the current experiment is the ionization potential: it takes slightly more energy to pull an electron off argon than krypton.

This difference in ionization potential shows up as a slight difference in the height and thickness of the barrier the electrons have to tunnel through. Electrons leaving argon need to go a little farther than electrons leaving krypton, which means that if tunneling takes time, it should take them a little longer to make their way out. This manifests as a small difference between the position distribution for electrons from argon atoms and electrons from krypton atoms, and that's the thing they measure.

This is a clever trick, because everything else is the same-- the same detector, the same laser pulse, etc. So they take out most of the possible confounding factors, and get a difference that they can compare to theoretical predictions. When they do that, they find that their results are consistent with the picture where electrons need some time to tunnel through the barrier, and not easy to explain in the picture where they just instantaneously appear on the far side.

So, what's the problem? Well, the "compare to theoretical predictions" step is a bear, because argon and krypton are fairly complicated atoms. So, another experiment, posted to the arxiv a few days after the paper linked above was published tries a different attack: They work with hydrogen, which is the only atom simple enough to allow exact calculations.

The core technique is the same: ultrafast intense laser pulse, circular polarization, streaking detection. The difference is that the simplicity of hydrogen makes it easier to calculate the expected trajectories for the comparison. When they do that, they claim that there's nothing in the data to indicate a finite tunneling time. They see a variation in the angle depending on the laser intensity (which varies the height of the barrier through which the electrons must tunnel), but they claim this is due not to the timing of the tunneling, but the electrostatic tug of the proton left behind. They try to verify this by re-doing the calculation in a way that shuts off the force from the proton, and find no change in the trajectory with laser intensity. This, they say, indicates that the "tunneling time" can't be any longer than a couple of attoseconds.

On the one hand, the differential measurement comparing argon and krypton should remove most of the complications that make the theory hard to do for multi-electron atoms. On the other, though, they're still very much not hydrogen, and I believe theory calculations involve hydrogen a lot more than those involving argon and krypton... There will inevitably need to be further experiments refining and expanding the technique before anything is completely settled, and if you read the papers closely, there's a bit of sniping in there indicating that this is likely to be a lengthy and contentious process.