

How Quantum Is Life?

One of the hottest topics right now, quantum physics, is the set of rules of physics that work in the realm of the extremely tiny particles such as sub-atomic particles like protons and electrons. We might hear terms like quantum tunneling, where one thing can go through a barrier no matter how colossal of repulsion it might offer; superposition, where one thing can be at one, two or multiple positions at the same time; or the quantum entanglement, where 2 things can be at the non-adjacent ends of the universe and can exhibit instant connection between them. For a normal person living in the classical world dictated by the classical rules discovered by great scientists like Sir Isaac Newton, Galileo Galilei, and countless others, these rules seem to offer some kind of extreme-futuristic technology where we could, someday, quantum tunnel through the walls of buildings to sneak and do pranks on our friends, or apply superposition, like a superhuman, to be at the work to do the tedious task and at the same time, at home playing a contender of the 2025 Game Awards: Clair Obscur: Expedition 33, or, enable quantum entanglement with your partner and instantly feel what your partner is thinking.

Let's walk through some examples to understand some quantum concepts by simplification. This brief introduction will, later, enable the readers to be better guided going through this essay. The conventional mechanism that we, all, have heard is that the sun is a nuclear fusion reactor that burns Hydrogen gas to form the heat and light that we are sustaining our life on. This is a good explanation but there is a little nuance in this explanation if we follow the classical mechanics. Remember the Coulomb's law taught in high school that like charges repel and unlike charges attract and also, the Coulomb's formula to calculate the force between 2 charges. The 2 charges are positive charge like in proton and negative charge like in electron. There exists a neutral charge as well like in neutron. The Sun is about 74 % hydrogen by mass. But it's not Hydrogen gas (H_2) like we find in Earth. Instead, the Sun is made of plasma, a state of matter where atoms are stripped of their electrons. The Sun's core is around 15 million degrees Celsius and even the surface is about 5500 degrees Celsius. At these temperatures, hydrogen atoms (1 proton + 1 electron) collide with so much energy that their electrons are knocked away. In the absence of the 1 electron it had, the hydrogen's nucleus is just a single proton (H^+). Now, for the fusion of the Hydrogen atoms to happen, two protons (or, 2 hydrogen nuclei), they must come very close to each other. But adhering to the Classical Mechanics, 2 protons coming together will cause repulsion between them. Also, the Coulomb's formula gives extreme force of repulsion between the like charges of proton that the enormous temperature and pressure available on the sun also can't fulfill. But, still, in reality, the fusion does happen. So, what is the explanation here? What happens is that the hydrogen nucleus goes through the barrier posed by Classical laws. The sub-atomic particles like protons, electrons and neutrons have this quantum property of wave-particle duality. In the Sun, the proton just goes through the barrier as a wave. Think of it as how sound waves can pass through walls so that you can hear what your brother is watching on T.V. from another room. The sound waves pass around the object. Of course, the air carrying the wave doesn't actually pass through the wall itself: the vibration in the common wall, due to the vibration of the sound waves of the T.V., vibrates the air in your room. But if you could behave like an atomic nucleus, you could go through the wall like ghosts.

Secondly, let's talk about the universe as an artist. The diversification in the universe is huge. The universe is, or creates, such a diversified environment, like can you believe no 2 things in the universe are exactly the same. But when the Big Bang happened, the universe was just awash with hydrogen nuclei. Deuterium, an isotope (elements having same proton number but different neutron number) of Hydrogen atom, has one neutron while the protium, which the universe was formerly awash with, has zero neutron. So, after the hydrogen gas clusters coalesced to form stars like our sun in which nuclear fusion happened due to quantum tunneling, as explained before, to provide heat and light, heavier atoms than Protium also formed. Quantum mechanics says when there are too many of one type or the other, the balance has to be redressed and those excess particles will change into the other form: protons will become neutrons, or neutrons protons, via a process called beta-decay. So, when 2 protons get bound together during the nuclear fusion process in the sun, one thing is that one proton will get converted to neutron giving us the Deuterium containing one proton and one neutron and the second thing is that if we follow classical mechanics, there will be not enough force to bind the protons in the first place. What causes the binding is the property of quantum superposition. Let's focus to learn quantum spins for a moment. Every proton, neutron and electron has spin. They all have the spin value: $1/2$. Also, if I say that the spin value of proton is $1/2$, it means that the proton

can be in some combination of 2 spin orientations: spin-up (+1/2) or spin-down (-1/2). When 2 protons with their each spin orientations bind together, they do so in the way that the atom they form will be in “superposition” or combination of the 4 spin orientations formed by their binding. Those 4 spin orientations are: $1/2 + 1/2$, $1/2 - 1/2$, $-1/2 + 1/2$, and $-1/2 - 1/2$. If the binding had to formed through only one of the spins orientations, then the short-ranged nuclear force won’t be strong enough to bind them. So, here, likewise, all the other heavier elements are formed contributing to the diversification of the universe we live in. Next, let’s try to understand why even the great Albert Einstein couldn’t believe that this thing could exist: quantum entanglement. Einstein called it ‘spooky action at a distance’. What quantum entanglement means that 2 things, no matter, how far they are, they will always have instant connection of some sort between them. This bothered Einstein because it could pose that the fastest thing in the universe mightn’t be the speed of the light, but rather some connection between quantum particles (very small particles). One famous example is that when atoms are formed, then the electrons at the valence shell combine so that they are in singlet state. The single state arises when two spin 1/2 particles combine such that their total spin is zero - in other words, $1/2 - 1/2 = 0$. When the electrons are then separated and, let’s say, kept at the opposite ends of the universe and we measure the spin state of one electron to be, let’s say, spin-up (+1/2) then the wave property of the other electron collapses, and its spin state becomes spin-down (-1/2) in an instant. Quite crazy, eh. We can imagine this as you are going on a trip to the Arctic and your father is going on a trip to Antarctica, and by some chance, you have one shoe of a pair in your bag and other shoe in your father’s bag. Now, when you open the bag on Arctic to see what shoe you have, you will instantly know what the other shoe is for which leg. There’s something wrong here which is not consistent with the Quantum world: you can’t predetermine the state of shoe, or the quantum particles, the quantum particles actually remain in the combination of the spins until you measure it.

These quantum phenomena are as real as the grandma’s pudding you eat or the football you play with. The reason why we macroscopic objects cannot see these effects is that we have extremely great mass than what is required for them to occur. De-Broglie says that more mass a body has, the less wave nature it will have. Since we have great mass, we can’t exhibit the wave nature. Also, it is thought that molecular vibrations are the ones causing ‘quantum decoherence’. Quantum coherence is the state when quantum particles can exhibit the various quantum phenomena and quantum decoherence is the loss of quantum coherence. One thing scientist regard why quantum phenomenon mustn’t occur in plants was that to maintain quantum coherence, there should be absolute zero temperature, isolation from the environment, and no measurement.

Let’s start from this: our body is filled with enzymes whose job is to catalyze all sorts of biochemical reactions which help to sustain life tremendously. We know the Transition State Theory, or if you don’t know, just look it up on the internet. Activation energy is the amount of energy that the reactants must attain so that they can be converted into products. Enzymes lower the activation energy of biochemical reactions by binding substrates (the substances on which enzyme acts), holding in right orientation, and stabilizing the transition state so that reaction happens extremely fast - the efficiency of using enzyme can speed up the reactions millions or trillion times than without using them. But here, the problem comes. Classical mechanics predicts that enzymes speed up the reactions fast but extremely slower than what real reactions using enzymes show. Now, quantum tunneling comes into play. We know, that classical physics say that the reactants must climb over the activation energy, but instead the reacting protons or electrons in the reaction quantum tunnels through it and achieves that extreme speeding capacity. Now, we can look at how quantum mechanics helps in one of the fascinating topics in human physiology: Respiration. Breathing, which we all assume to be respiration, is but a small part in the process. Respiration encompasses many steps and is fundamentally an electron transfer process inside mitochondria. Classically, it is how food like glucose are converted into usable energy (ATP). ATP is like the currency of energy in biological systems. The steps of Respiration are: Glycolysis, Krebs Cycle and Electron Transport Chain. Glycolysis involves the splitting of glucose from 6-carbon compound to two 3-carbon compounds and some ATP is released. In Krebs cycle, the 3-carbon compounds are burned to release energy-rich electrons. Most of the high-energy electrons are now stored in NADH and FADH₂. The electrons are passed through the electron transport chain where they are transferred through a series of respiratory enzymes and with each transfer, the electrons release some energy, and that released energy pumps protons out of mitochondria. Now, there are more protons outside mitochondria than inside, so there is creation of proton gradient, which flows back through ATP synthase enzyme to produce ATP. The crucial thing is that classical physics says that the distance between

the enzymes is too large for electron hopping (if the enzymes are near, then electrons can simply hop to get transferred from one enzyme to another). Quantum mechanics comes into play here. The electrons behave like quantum waves, utilizing quantum tunneling to just go through the enzymes efficiently despite large gaps. Moreover, electrons often exist in a quantum superposition, exploring multiple possible pathways simultaneously before settling into the most efficient route.

Next, our human body is just made up of oxygen, carbon, hydrogen, nitrogen, calcium and other elements that are found everywhere whether living or non-living. So, what is it that helps us sustain life, as we call it, and demarcate a line between the living and the non-living? We know from the famous statement of Richard Feynman which is paraphrased here that the inanimate matter like air, water and light around us gets converted into nearly all of the biomass of plants, microbes and, indirectly, all the rest of us on our planet. Let's start with the basic structure of the cell; cell is the fundamental and smallest self-sustaining (self-maintaining) unit of life. Let's see what's leaf like. When we zoom in on a leaf using a microscope, then we can see that the apparent smooth surface of the leaf becomes an irregular surface composed of green epidermis cells and round stomata. The stomata allow air and water (necessary for photosynthesis) inside the leaf. Also, zooming inside the leaf are vein-like structures: xylem which carries water from the roots of the plant to the leaf and phloem which carries the newly made sugar from the leaf to the rest of the plant. These are mesophyll cells in the plants which are also called plant cells. They have tough cell wall that provides shape and protection, water-impermeable cell membrane that selectively allows materials in and out, porin proteins, or channels, that allow nutrients to enter and waste products to leave, and thick gel-like cytoplasm that contains organelles, enzymes, and macromolecules. Floating on the cytoplasm is the chloroplast: green organelles within which the central action of photosynthesis takes place. Inside the chloroplasts are the thylakoids which are full of molecules of chlorophyll. First step of photosynthesis happens in the chromophores: a light-harvesting region inside the leaf, of which chlorophyll is the most known example. Chlorophyll is a two-dimensional structure composed of pentagonal arrays of Carbon(C) and Nitrogen(N) atoms enclosing a central magnesium (Mg) atom connected to a string of carbon, oxygen(O) and hydrogen(H) atoms. The outer-most electron on the Mg atom is loosely bound so, when photon from the sun is absorbed by the chlorophyll, the electron gets knocked out leaving a gap, or electron hole. The electron hole is positively charged hole. This creates an exciton which is like a tiny battery with positive and negative poles capable of storing energy for later use. The exciton is unstable so, the positive electron hole and the knocked-out electron have attractive electrostatic force. But, if they combine, the energy of the photon will be wasted. So, the electron is transferred to the reaction center; the reaction center, the process of charge separation (stripping an energetic electron completely from its atom and transferring it to a neighboring molecule) happens creating a more stable chemical battery called NADPH than exciton which drives the photosynthetic chemical reactions. But here is the problem: since the reaction center is quite far from the chlorophyll molecules, the molecules transfer the energy through the molecules to the reaction center. Here, quantum mechanics comes in play to find the most efficient route to take to reach the reaction center. There are many routes to take to reach the reaction center. If it takes all routes alternatively to find the shortest route, then it will hamper the reputation of the efficiency of photosynthesis. Rather, what happens is that the excitation takes multiple routes simultaneously. It's called the 'quantum walk'. In the reaction center, ATP and NADPH are produced. The lost electrons are replaced by splitting water, releasing oxygen as byproduct.