

Quantum Tunneling

Scientific Essay

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(September 6, 2025)

What if I told you that there is a tiny chance I could slam my hand through this table and it would pass right through? It sounds absurd, yet in quantum physics it is not strictly impossible. The reason lies in one of the strangest and most counterintuitive features of the microscopic world, a phenomenon called quantum tunneling. This effect allows particles to slip through barriers that should, according to classical physics, block them entirely. For large everyday objects like a human hand the probability of such an event is so unimaginably small that it will almost certainly never occur. Still, the fact that the chance is not zero marks a profound departure from the classical worldview. Even more striking is that this improbable quantum process is not an idle curiosity but the very reason stars shine and life exists at all.

To see why tunneling is so extraordinary, we must recall the contrast between classical and quantum pictures of nature. In classical physics, if a ball lacks the energy to climb over a hill, it simply rolls back down. The barrier is absolute. Quantum mechanics tells a different story. Particles are not rigid points tracing definite trajectories, they are described by wave functions that spread through space like ripples. When such a wave meets a barrier, part of it reflects, but part penetrates into the forbidden region. The amplitude decays exponentially, yet crucially it does not vanish at once. If the barrier is thin enough or the particle light enough, there remains a small but finite probability that the particle will emerge on the far side, as if it had passed through a wall without ever having the energy to climb over it.

Mathematically, this is seen in solutions to the Schrödinger equation. When the particle energy is less than the barrier height, the wave function inside the barrier decays rather than oscillates. The transmission probability falls exponentially with the barrier width and with the square root of the barrier

height and particle mass. For electrons, protons, and other light particles facing barriers only nanometers wide, tunneling is an everyday occurrence. For something as massive and complex as a human hand meeting the densely packed atoms of a wooden table, the probability becomes so fantastically small that it is effectively zero for all practical purposes. Calculations show that the odds of every atom in a hand tunneling through a centimeter of solid wood are so small that not even the entire age of the universe, multiplied by every atom in the cosmos trying each instant, would ever yield a single success. Yet the mathematics insists that the probability, however absurdly tiny, is not precisely zero. The impossible becomes only the unfathomably improbable.

This redefinition of impossibility has consequences far beyond thought experiments with hands and tables. Quantum tunneling is the key that unlocks nuclear fusion in stars. Consider the Sun, whose core burns at around fifteen million degrees. At such temperatures protons carry only about one thousandth the energy they would need to overcome their mutual electrostatic repulsion. Classical physics would predict that the Sun could never ignite, and indeed that most stars could never shine at all. The Coulomb barrier between two protons is simply too high. And yet the Sun has burned for billions of years, steadily converting hydrogen into helium and flooding space with light. The resolution to this paradox is tunneling. Protons do not need to surmount the barrier in the classical sense, they can tunnel through it with a probability so small it defies ordinary intuition. Most collisions fail, but given the enormous number of protons in the stellar core, even the tiniest probability becomes enough. Out of countless encounters, some succeed, and those rare successes release the energy that powers the star.

The physics of tunneling in stars has been worked out in detail. Protons in the hot plasma of the Sun follow a distribution of energies, with some lying in the high-energy tail. These have a greater chance of approaching close enough for tunneling to occur. The narrow overlap between the energy distribution and the tunneling probability defines what is called the Gamow peak, the sweet spot where fusion is most likely. It is this subtle interplay, rather than brute force, that sustains the chain reactions at the heart of stars. Step by step, hydrogen fuses into helium, helium into carbon, and in massive stars the sequence continues through oxygen, silicon, and eventually to iron. Each stage depends on tunneling to overcome ever greater Coulomb barriers. Without tunneling, none of the heavier elements essential for planets, chemistry, and biology would ever have formed. The very atoms that make up our bodies are products of a quantum process

that allows nature to bypass what classical barriers forbid.

Experimental physics has confirmed tunneling in many contexts. In laboratories, beams of particles striking thin barriers show measurable probabilities of transmission, matching the exponential laws predicted by theory. More recently, ultrafast techniques have allowed researchers to probe the timing of tunneling itself with attosecond precision, finding that the process occurs in intervals so brief as to be indistinguishable from instantaneous. Such experiments highlight just how deeply tunneling belongs to the structure of quantum mechanics, not as an approximation but as a fundamental aspect of the way matter behaves.

Reflecting on all this, one realizes that the solidity of the world around us is not as absolute as it appears. Tables, walls, and stones seem impenetrable only because the probabilities are so vanishingly small, not because the laws of physics make them strictly impossible. At the same time, the Sun shines above us precisely because, at the nuclear scale, tunneling is not rare but essential. What appears to us as a bizarre loophole in the laws of nature turns out to be the mechanism by which the universe generates energy and builds the elements of life. It is a reminder that the classical world we trust in daily is itself a special case, an emergent approximation of the deeper quantum reality.

Perhaps the most humbling thought is that our very existence rests on the same principle that makes the fanciful idea of a hand through a table conceivable, however unlikely. When we place our hand firmly on the wood and feel its unyielding surface, we may think of the countless protons in distant stars that once tunneled against astronomical odds to forge the carbon in our cells. The table resists us, but the universe itself owes its light and its complexity to the fact that matter, under the strange logic of quantum mechanics, sometimes passes through barriers it has no right to cross.