

The Quantum Tunneling Effect: From Fundamental Theory to Key Applications

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ABSTRACT: This paper provides a comprehensive overview of quantum tunneling, bridging the gap between wave-particle duality and real-world applications. We analyze how tunneling facilitates solar energy production via the proton-proton chain and enables atomic-scale imaging through Scanning Tunneling Microscopy (STM). A particular focus is placed on the evolution of STM instrumentation; we discuss how innovations in closed-cycle cryostats and feed-forward noise cancellation have overcome traditional stability limitations. By linking stellar physics with nanoscale engineering, this work highlights the enduring relevance of tunneling in both natural and synthetic systems.

KEYWORDS: Physics, Quantum Mechanics, Quantum Tunneling, Nuclear Fusion, Scanning Tunneling Microscopy.

■ Introduction

The theoretical understanding of quantum physics:

Quantum tunneling represents one of the most non-intuitive concepts in the field of quantum mechanics. To illustrate this effect, consider a classical analogy: a ball rolled up a hill. What would one expect to happen? The answer is simple enough: with a weak force, the ball will roll back, and if one rolls it with enough force, it will go over the hill. In quantum mechanics, however, particles can sometimes pass through a barrier even when they do not have enough energy to go over it. One may think that such a phenomenon cannot occur. This counterintuitive behavior is known as quantum tunneling, a fundamental consequence of the wave-like nature of matter and the probabilistic interpretation of quantum states. This effect is not only interesting but has important applications ranging from how stars produce energy through nuclear fusion to how modern electronic devices, such as transistors and diodes, function.

To explain this strange and interesting behavior, one must have a fundamental understanding of quantum mechanics. This theory enables us to analyze and explain the behavior of tiny particles, such as atoms and subatomic particles. In quantum mechanics, not all outcomes are certain, and solving equations does not always give one an exact answer.

Instead, the answers are based on probabilities. Unlike classical mechanics, where the outcomes are deterministic, quantum mechanics enables particles to maintain a finite probability of being detected in regions that are classically forbidden. As a result, this probabilistic nature allows for tunneling events where particles can penetrate barriers like a hill, which would otherwise confine them.

While quantum tunneling appears to be a minor phenomenon, it has a crucial role in processes such as nuclear fusion in stars and the development of modern technologies (e.g., semiconductors and scanning microscopes). To that end, a comprehensive understanding of this effect is essential for both

foundational physics and applied research in nanotechnology & quantum engineering.

In this literature review, the discussion will focus on the following three points:

1. The theoretical principles of quantum tunneling
2. The manifestation of quantum tunneling in natural systems
3. Practical applications of quantum tunneling in laboratory and technological settings

■ Results and Discussion

Theoretical Foundations of Quantum Tunneling:

In order to understand quantum tunneling, this section begins by explaining the interesting way particles behave in quantum mechanics. At the atomic scale, particles exhibit what is called wave-particle duality, meaning they act like both particles and waves depending on the situation.

Think of a particle, such as an electron. The electron behaves more like a water wave that spreads out, overlaps with other waves, and does not stay in one exact spot. Instead of having a fixed position, it exists as a probability cloud across multiple locations. This wave-like property is described by the Schrödinger equation, which is a mathematical equation that represents the behavior of a particle in terms of a wave function shown below.

$$-\frac{\hbar}{2m} \frac{d^2\psi(x)}{dx^2} + U(x)\psi(x) = E\psi(x) \quad (1)$$

Equation (1) represents the time-independent Schrödinger equation in one dimension.¹ The equation not only has macroscopic importance but also has meaning in each component. The first term includes $\hbar$, the reduced Planck constant ($\hbar \approx 1.054 \times 10^{-34} \text{ J}\cdot\text{s}$). m is the mass of the particle, and $\frac{d^2\psi(x)}{dx^2}$ is the second derivative of the wave function with respect to position x . These terms represent the kinetic-energy operator. The second term $U(x)\psi(x)$ represents the potential energy acting on

the wave function, and $E\psi(x)$ represents the total energy eigenvalue acting on the same state. Together, the kinetic-energy and potential-energy operators acting on $\psi(x)$ yield $E\psi(x)$. The equation tells us that $\psi(x)$ must be continuous at each boundary it encounters, and its derivative must also be continuous.² This wave function does not solve for an exact position for the particle but rather gives the probability of finding it in a particular place. As a result, particles can defy classical rules as seen in the quantum tunneling effect.

Quantum Tunneling Explained Through the Heisenberg Uncertainty Principle:

In quantum mechanics, since particles act as waves, there is a slim probability that the particle's wavefunction can extend and pass through the energy barrier. This possibility is what we call the quantum tunneling effect. This tunneling probability is derived by solving the Schrödinger equation for a potential barrier. The Heisenberg uncertainty principle can be used as an intuitive interpretation. One form of this principle relates energy and time. Given a short amount of time to examine a particle, the uncertainty in the particle's energy increases significantly. Here, the Heisenberg uncertainty principle is used as an intuitive interpretation rather than the main mechanism. Over a very short time interval, the particle's energy can be less sharply defined, which helps explain why barrier penetration is not strictly forbidden in quantum mechanics. However, the standard description of tunneling comes from the Schrödinger equation: the wavefunction penetrates the classically forbidden region and decays exponentially, and the transmitted amplitude is determined by matching the wavefunction and its derivative at the boundaries.²

The Heisenberg uncertainty principle can be mathematically expressed as:

$$\Delta x \Delta p \geq \frac{\hbar}{2} \quad (2)$$

where Δx represents the uncertainty in a particle's position, and Δp represents the uncertainty in its momentum.² The Heisenberg uncertainty principle offers an intuitive way to think about quantum tunneling: a short-lived quantum state means the particle's energy is less sharply defined, which helps explain why barrier penetration is not strictly forbidden in quantum mechanics.

Calculating Tunneling Probability Using the Schrödinger Equation:

Beyond the conceptual understanding of how quantum tunneling works, calculations can be made to determine the probability that a wave function can tunnel through a specific finite potential barrier. This is known as transmission probability, and to understand this equation, we must look at the wave equations associated with the potential barrier.²

To begin with, we are assuming that the potential barrier is from $0 \leq x \leq L$, which can be expressed as a piecewise function. By setting the finite potential barrier, we create 3 different regions with their own unique wave function.³

$$U(x) = \{0, x < 0, U_0, 0 \leq x \leq L, 0, x > L\} \quad (3)$$

Equation (3) represents the time-independent Schrödinger equation in one dimension.^{3,4} From now on, we are calling region 1 for $x < 0$, region 2 for $0 \leq x \leq L$, and region 3 for $x > L$.

Separating into 3 regions enables setting up Schrödinger equations for each region.

$$\text{Region 1: } -\frac{\hbar}{2m} \frac{d^2\psi(x)}{dx^2} = E\psi(x)$$

$$\text{Region 2: } -\frac{\hbar}{2m} \frac{d^2\psi(x)}{dx^2} + U(x) = E\psi(x)$$

$$\text{Region 3: } -\frac{\hbar}{2m} \frac{d^2\psi(x)}{dx^2} = E\psi(x)$$

Boundary conditions require that the wave functions and their derivatives are continuous on each boundary (i.e., $x = 0$ and $x = L$). The general solution for each region,

Region 1: $\psi(x)_1 = Ae^{ikx} + Be^{-ikx}$, representing both incident and reflected waves.

Region 2: $\psi(x)_2 = Ce^{-\alpha x} + De^{\alpha x}$, where the wave decays or grows exponentially inside the barrier.

Region 3: $\psi(x)_3 = Fe^{ikx}$, representing a transmitted wave moving only to the right (we neglect the reflected component in this region), where $\alpha = \sqrt{\frac{2m}{\hbar^2}(V_0 - E)}$, $k = \sqrt{\frac{2m}{\hbar^2}(E)}$.

There are three regions in this setup, and the wave (particle) behaves differently in each of the regions. The wave functions exhibit the behavior of the particle in each region as follows: In Region 1, the particle can move in both directions, with incident and reflected waves; In Region 2, the exponentially decaying wave is in the potential barrier; In Region 3, the particle moves only in the forward direction, i.e., tunneling was successful, and there is no backward traveling wave.⁴ The tunneling probability depends on the wave function intensities, specifically, the ratio of the transmitted wave in Region 3 to the incident wave in Region 1.

While calculating the exact values requires applying boundary conditions at the interfaces ($x = 0$ and $x = L$) to match wave functions and their derivatives, the essential idea is that tunneling probability emerges from how these wave components match across the three regions.⁴

Figure 1 illustrates this three-region tunneling setup and the transmitted wave after the barrier.



Figure 1: The visualization of quantum tunneling. Adapted from Physics LibreTexts.⁴ This figure shows that even when the particle's energy is below the barrier height, part of the wavefunction can extend through the barrier and produce a transmitted wave.

A potential energy barrier of height U_0 creates three physical regions with three different wave behaviors. In region 1, where $x < 0$, an incident particle moves in a potential-free zone and coexists with a reflected particle. In region 2, a part of the incident wave that has not been reflected at $x = 0$ moves as a transmitted wave in a constant potential $U(x) = U_0$ and tunnels through to region 3 at $x = L$. In region 3 for $x > L$, a

transmitted particle that has tunneled through the potential barrier moves as a free particle in a potential-free zone. The energy E of the incident particle is indicated by the horizontal line.⁴

After the long algebraic calculations, we get the following equation for tunneling probability:

$\therefore T \approx 16 \frac{E}{U_0} (1 - \frac{E}{U_0}) e^{-2kL}$, where $k = \frac{\sqrt{2m(U_0-E)}}{\hbar}$, U_0 is the barrier height, L is the width of the barrier, and E is the particle's total (incident) energy.

Table 1 summarizes the tunneling probabilities predicted by this equation for several particle energies and barrier widths. The values show a trend of how sensitive tunneling is to even small changes in barrier thickness; as the barrier becomes wider, the tunneling probability drops rapidly.

Table 1: Quantum tunneling probability for different combinations of particle energy (eV) and barrier width (nm). The table shows that the tunneling probability decreases sharply as the barrier width increases, while higher particle energy slightly increases the probability.

Barrier width (nm)	0.1 eV	0.3 eV	0.5 eV	0.7 eV	0.9 eV
0.2	6.23E-03	6.77E-03	7.37E-03	8.03E-03	8.77E-03
0.4	3.88E-05	4.58E-05	5.43E-05	6.45E-05	7.69E-05
0.6	2.42E-07	3.1E-07	4E-07	5.19E-07	6.75E-07
0.8	1.51E-09	2.1E-09	2.95E-09	4.17E-09	5.92E-09
1.0	9.38E-12	1.42E-11	2.17E-11	3.35E-11	5.19E-11

The barrier energies of 0.1–0.9 eV are common for electrons; the barrier widths of 0.2–1.0 nm are about the size of a few atoms, which is the scale where tunneling usually happens.⁴ For the most part, quantum tunneling emerged as a calculable process with measurable probabilities. A small difference in any of these parameters can drastically cause a particle to pass or not pass through the energy barrier.

Quantum Tunneling in Stellar Fusion:

Quantum tunneling has particular significance in nuclear fusion. Since protons are positively charged particles, they have an inherent tendency to repel one another through electrostatic interaction. Quantum tunneling helps them to overcome this repulsive force so that when protons come sufficiently close, fusion can take place. The fusion process, when it occurs, releases a huge amount of energy, which energizes the Sun. This is also the cause of the light and heat received on Earth. In the absence of quantum tunneling, pressures and temperatures used in nuclear fusion would be much greater, and therefore it is most unlikely to occur in stars like the Sun.⁶

To see how quantum tunneling allows fusion to occur in the Sun, it is useful to examine the particular reactions being performed in the solar core. In stars at temperatures less than fifteen million Kelvin, like the Sun, the proton-proton chain is the prevailing fusion reaction. In this reaction, four protons eventually fuse to create a helium-4 nucleus, and energy is released in the form of photons and neutrinos.¹¹ The initial reaction in this sequence is likewise the most important reaction for tunneling: two protons need to get near enough to each other to fuse into a deuteron, which contains one proton and one neutron. Because of the positive charge of the protons, though, there will be a strong Coulombic barrier, a repulsive force creating a potential energy hill between them.

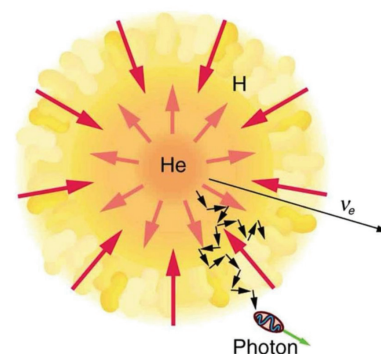


Figure 2: Fusion in the Sun's Core Diagram (fusion with $H \rightarrow He + \text{photons} + \text{neutrinos}$). Adapted from Texas Gateway.⁷ This figure shows that hydrogen fusion in the solar core produces helium, photons, and neutrinos, and that quantum tunneling makes this process possible at solar temperatures.

Figure 2 shows how nuclei of hydrogen are fused to create helium in the Sun's core, and release energy in the form of photons (light) and neutrinos (particles that travel through space). The process of fusion occurs at the center of the Sun, where it is hottest and densest. Importantly, quantum tunneling is what makes this entire fusion process possible at the temperatures in the Sun.⁷

Tunneling Probability and the Gamow Peak:

Fusion in the Sun depends on the Coulomb repulsion between protons and the probability of penetrating that barrier. The next figure illustrates the Coulomb barrier that protons must overcome to fuse.

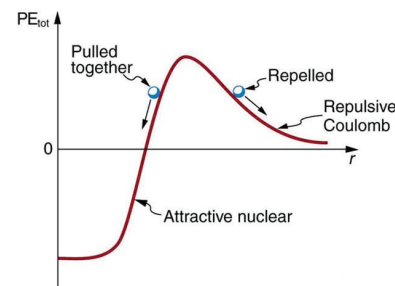


Figure 3: Potential energy between two protons as a function of distance. Adapted from Texas Gateway.⁷ This figure highlights the Coulomb barrier that resists proton fusion and the attractive nuclear region that protons can reach only when they get close enough.

Figure 3 illustrates the potential energy between two protons as they approach each other. The steep hill represents the Coulomb repulsion, which resists the protons getting close enough to fuse. In the Sun, because their kinetic energy alone is not sufficient, quantum tunneling is the process that allows them to penetrate this barrier and reach the attractive region where nuclear fusion can occur.⁸

$$V(r) = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 r} \quad (4)$$

Equation (4) shown above represents the Coulomb potential energy of two interacting nuclei as a function of the distance r of their interaction. Z_1 and Z_2 are the charges of the interacting nuclei (both 1 for protons), e is the elementary charge, ϵ_0 is the permittivity of vacuum, and r is the distance between the protons. As the protons approach one another, their electrostatic repulsion of like positive charges causes this potential

energy to rise quickly, creating what is known as the Coulomb barrier. This is an effective barrier to fusion: its effective height is much greater than the kinetic energies of the protons in the core of the Sun.

In classical physics, this would inhibit fusion completely, since the protons would not have sufficient energy to cross over the barrier. Quantum mechanics, on the other hand, yields a different result. The wave function of the proton penetrates in and beyond the barrier, leading to a finite probability of the proton on the other side of the barrier through a process known as quantum tunneling.

Mathematically, this probability is described by a transmission coefficient for a potential barrier, derived from solving the Schrödinger equation for this situation. Equation (5) is similar in form to the tunneling probability described for a square potential barrier:

$$T \approx e^{-2G} \quad (5)$$

where G is known as the Gamow factor, given by:

$$G = \frac{2\pi Z_1 Z_2 e^2}{\hbar v}$$

The Gamow factor quantifies how difficult it is for two positively charged nuclei to tunnel through their Coulomb barrier and fuse. In this formula, Z_1 and Z_2 are the charge numbers of the nuclei (both 1 for protons), e is the elementary charge, $\hbar$ is the reduced Planck's constant, and v is the relative velocity of the nuclei. Higher charges or lower velocities make G larger, so e^{-2G} it becomes very small, meaning tunneling, and therefore fusion, is much less likely. However, the Sun's core contains an enormous number of protons with a spread of velocities given by the Maxwell-Boltzmann distribution, so enough protons still tunnel to sustain fusion.

The fascinating interplay between this velocity distribution and the tunneling probability results in what is called the Gamow peak. The Gamow peak identifies the most probable energy range for fusion to occur, balancing two competing factors: Higher-energy protons are rarer (because of the Maxwell-Boltzmann distribution), but as proton energy increases, the tunneling probability also increases due to the decreasing Gamow factor. So simply put, this combined effect determines where fusion is most likely to occur in the Sun's core.

Figure 4 shows this balance as the Gamow peak.

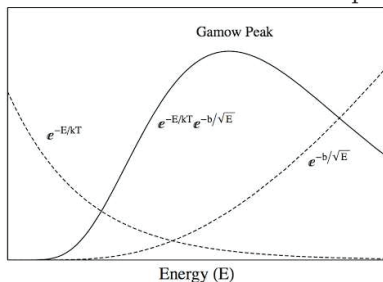


Figure 4: This diagram shows the Gamow peak, which shows the most likely energy range where fusion happens in the Sun. The Gamow peak results from multiplying the Maxwell-Boltzmann distribution of proton energies, the number of protons at a given energy, $e^{-E/kT}$ and the probability of tunneling through the Coulomb barrier $e^{-b/\sqrt{E}}$.⁹ This figure shows that fusion is most likely at an intermediate energy where enough protons exist and tunneling is still probable.

Reaction Probability in the Solar Core

Using quantum tunneling, protons in the Sun's core can overcome the Coulomb barrier at energies where fusion is most likely to occur.⁸ The typical proton energy in the solar core is only about 1 keV, while the Coulomb barrier energy is roughly 500 keV, which makes fusion impossible according to classical physics since the protons do not have sufficient kinetic energy to overcome the barrier.⁴ However, using quantum mechanics, the proton's wave function extends into and across the barrier, creating a finite probability that the proton will be found on the other side. As a result, protons with energies near the Gamow peak (~10-20 keV effective energy) can successfully tunnel through the barrier and fuse, despite having total energies below the barrier height.⁸

Figure 5 compares the classical repulsion case with the quantum tunneling case.

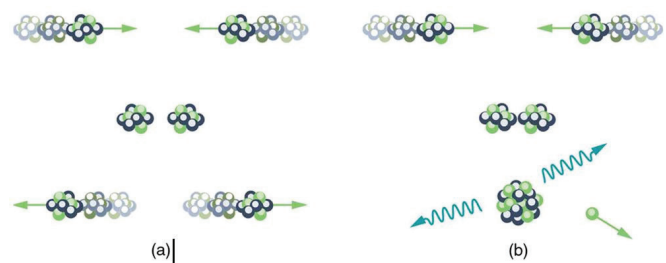


Figure 5: This diagram compares two scenarios when protons approach each other. In part (a), without enough energy or tunneling, the protons repel and bounce away. In part (b), quantum tunneling allows the protons to bypass the repulsive barrier, allowing protons to fuse and release energy, shown as emitted light and particles.⁴ This comparison shows why tunneling is necessary for solar fusion at the Sun's core temperature.

This effect fundamentally determines the rate of fusion in the Sun. The fusion cross-section is essentially the “reaction probability” or an effective area that represents the likelihood of a reaction taking place during a collision. For two protons, fusion is heavily influenced by the tunneling probability and the proton energy:

$$\sigma(E) \propto \frac{1}{E} e^{-2G} \quad (6)$$

Equation (6) represents the fusion cross-section for two protons in the Sun.¹⁰ The $1/E$ term factor is a slowly varying prefactor in this expression. The dominant reason fusion is suppressed at low energies is that the tunneling term e^{-2G} , which decreases exponentially as proton energy decreases. This term contains the quantum tunneling probability through the Coulomb barrier, with G being the Gamow factor. Exponential suppression e^{-2G} takes over at low energies, which indicates that without tunneling, fusion is extremely improbable in the core of the Sun. In the absence of tunneling, the fusion cross-section would be essentially zero since protons would not surmount their electrostatic repulsion at the core temperature. Computing precise fusion rates in the Sun, therefore, entails integrating this tunneling-modulated cross-section over all proton energies in the core, as characterized by the Maxwell-Boltzmann energy distribution.¹¹

In recent decades, precise modeling of the Sun's energy output, neutrino production, and fusion rates has relied heavily on improved calculations of tunneling probabilities. The

modern Standard Solar Model (a theoretical/computational model) incorporates these effects in detail and enables accurate predictions of phenomena such as the solar neutrino flux. These predictions have been confirmed by experiments like Super-Kamiokande and the Sudbury Neutrino Observatory (SNO).¹²

The Astrophysical Impact of Quantum Tunneling:

The consequences of this quantum effect are profound. First, it allows the Sun to fuse hydrogen at relatively “modest” temperatures compared to what would be required in a purely classical system. Without tunneling, the necessary core temperature for fusion would need to be hundreds of millions of Kelvin, not the observed ~15 million Kelvin.¹¹ Second, it provides a delicate balance that regulates the Sun's energy output. Tunneling probability's temperature dependence enables infinitesimal core temperature changes to produce vast differences in fusion rates, and this is a natural feedback process that stabilizes the structure of the Sun over billions of years.⁶

Moreover, the detailed understanding of quantum tunneling in the Sun has broader implications for astrophysics. The same principles apply to fusion in other stars, including those much larger or smaller than the Sun. In massive stars, tunneling allows fusion of heavier elements like carbon and oxygen. In cooler, smaller stars, tunneling determines whether they can sustain stable fusion at all. Even the synthesis of elements in the early universe, Big Bang nucleosynthesis, relied on quantum tunneling to enable fusion reactions under extremely low-density, rapidly cooling conditions.⁸

In summary, the theory behind the Sun's energy production is quantum tunneling, allowing protons to overcome their mutual repulsion and initiate fusion at solar core temperatures. The tunneling probability, by the Gamow factor and the Maxwell-Boltzmann distribution of protons, defines the fusion rates that power the Sun and sustain life on Earth. In practical terms, every photon of sunlight that reaches Earth owes its existence to quantum tunneling. As Patchali concludes: “The fact that our sun is a star might seem magical, but it's really just quantum mechanics.”⁷⁹

Applications of Quantum Tunneling Technology:

By applying the tunneling mechanics that allow fusion in the Sun, scientists and engineers have managed to develop tools named the Scanning Tunneling Microscope (STM). It can be utilized to observe individual atoms and manipulate electronic behaviors at the nanoscale.¹³

Principles of STM operation:

The STM was invented by Gerd Binnig and Heinrich Rohrer in 1981.¹³ It visualizes surfaces at the atomic level by measuring tunneling currents between a sharp metal tip and a conducting surface; electrons can tunnel through a vacuum between the tip and the sample surface when voltage is applied, and the tip is brought extremely close (< 1 nanometer). Recently, STM has been used to explore and study materials like superconductors, which have the potential for advancing quantum computing technology. The tunneling current de-

pends exponentially on the distance between the tip and the surface.¹⁶ Because of this high sensitivity, STM can achieve sub-ångström resolution, and topographic maps of surface atoms can be created by scanning the tip with a piezoelectric scanner and a positioning stage that moves the tip in x - y - z with tiny steps. The scanner uses piezoelectric ceramic actuators (electrically responsive crystals) that expand or contract when a voltage is applied to produce those precise motions. The microscope is typically operated in constant-current mode in most applications, where the feedback system translates the tip in a manner that maintains a constant current. This correction translates to an image of the electronic density of the surface.¹⁵ The process is shown in Figure 6, which demonstrates the mechanism of the piezoelectric scanner and feedback loop working together to maintain the tip's height and produce a high-resolution image.

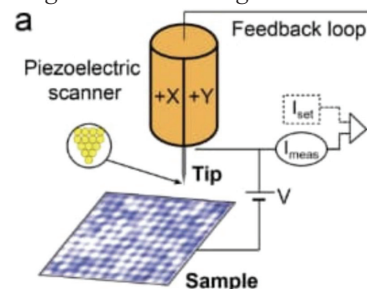


Figure 6: Basic principles of STM. Schematic representation of STM, where V , a voltage, is applied between the tip and the sample. The tip is scanned across the surface in the x - y plane, and its z coordinate is adjusted using the three-dimensional piezoelectric scanner controlled by a feedback loop, which automatically adjusts the tip's height to maintain a constant tunneling current as the surface contour changes. Adapted from Boston College.¹⁵ This figure shows how maintaining a constant tunneling current allows STM to produce atomic-scale surface images.

Using STM as a Research tool Today, this capability to produce high-resolution images positions STM as an important tool in various fields such as materials science, nanotechnology, and semiconductor studies. This atomic-level imaging and control are needed to define material properties, build electronics, and create nanoscale devices. For instance, researchers at the University of Oxford recently created the Andreev STM technique, which has been used to study electronic behavior in superconducting materials that are relevant to quantum materials research. This allows for imaging and observing topological superconductors' unusual quantum behaviors.¹⁹ Similarly, researchers at the University of Illinois have employed STM to "wire up" individual graphene nanoribbons.²⁰ This creates the atomically precise metal contacts, essential for future nanoelectronics devices. STM serves as a leading research tool that stimulates the creation of new technologies across quantum information science and nanoengineering.^{19,20}

Challenges: Environmental Disturbances:

On the other hand, the STM has a drawback in that the majority of quantum mechanical machines struggle with external disturbances. The STM's performance can be drastically degraded by surrounding equipment, temperature fluctuations, and air currents. Since distorting the tunneling current a bit or placing the tip by mere picometers can severely affect the

result, the STM must be meticulously cautious with slight changes in environment, including surrounding equipment, temperature fluctuations, and air currents.

Advances in Vibration and Thermal Control:

Considering this issue, placing an STM in an isolated, thermally stabilized environment can also improve the measurement accuracy of the STM. For instance, cryogenic environments that can suppress both mechanical noise - any tiny vibrations or noise from the environment - and thermal drift, which refers to position shifts caused by temperature fluctuations, can preserve STM performance and enable researchers to have more opportunities to achieve consistently accurate results. According to Hackley *et al.*, a closed-cycle cryostat STM is one of the solutions. They managed tip vibrations of less than 1.5 picometers, which is over 10 times smaller than typical temperature STM systems that produce vibrational noise in the range of 20 picometers or above. They also implemented a minuscule lateral drift of 0.18Å per hour at about 16 K temperatures with the mechanical isolation and low-vibration cryogenic cooling.¹⁷ Moreover, in the past decades, the severe shortage of helium has made it increasingly difficult to conduct low-temperature scanning probe microscopy (SPM) experiments. This motivates cryogen-free STM designs that can reach low temperatures without liquid helium.

Building on this, researchers led by Kasai developed a cryogen-free pulse-tube STM, which achieved operating STM near 5K and atomic-resolution imaging on gold surfaces and superconducting materials. Using the helium exchange gas and mechanical decoupling layers, they achieved lattice resolution on Au(111) surfaces and superconducting gap spectroscopy Pb(lead) with high stability. Specifically, their system incorporates a home-made interface between the PTR (pulse-tube refrigerator) cold head and the SPM head to minimize vibrational coupling and an automatic gas-handling system to regulate helium exchange pressure. This innovation performs at the same level as the conventional systems requiring liquid helium, but also alleviates the environmental concerns.¹⁸ Altogether, by using integrated cryogen-free designs under appropriate mechanical and thermal control, STM can overcome its vulnerability to external disturbances and can operate at atomic resolution consistently.

Feed-Forward Cancellation (Correction Technique):

Beyond these advancements, considering the current challenges STM faces, implementing a PTR-synched feed-forward cancellation can greatly reduce the effects of external interference on STM measurement. The main idea is to accept that it is almost impossible to create such an environment where the STM does not receive any external disturbance from the pulse-tube refrigerator (PTR), a vital device for operating the STM at low temperatures. However, if we could correct the mistakes the STM made rapidly, we could create a disturbance-free environment as close as possible. Specifically, this technique is called feed-forward cancellation, and by applying it to the small vibration sensor and automating the adjustment of the STM scanning tip in advance to predict the disturbance, we

can greatly reduce the image noise of the atomic surface and improve the accuracy in spectroscopic measurement, which gives us a better understanding of how electrons occupy energy levels in specific surface regions.

Taken together, STM visualizes surfaces at the atomic level by measuring tunneling currents between a sharp metal tip and a conducting surface. However, external disturbance is a long-lasting issue because it destabilizes the tip and reduces imaging accuracy. To countermeasure this issue, a closed-cycle cryostat STM, a cryogen-free pulse-tube, and a PTR-synched feed-forward cancellation are promising approaches that bring STM closer to a disturbance-free environment, allowing researchers to capture more accurate and reliable data.

■ Conclusion

From the theory of quantum tunneling to its role in solar fusion in the Sun and its application in scanning tunneling microscopes, quantum tunneling is a foundational concept necessary for explaining concepts in astrophysics and modern technology. In stars, the protons tunnel through the electrostatic repulsion to generate the light and heat that reaches the Earth as sunlight. In the lab setting, STM uses the same principle to visualize atoms and electronic structures at sub-angstrom resolution. Its performance, however, can be strongly affected by external disturbances. Methods such as closed-cycle cryostats, pulse-tube cryogen-free refrigerators, and feed-forward cancellation can prevent performance deterioration of STM, reducing image noise and improving spectroscopic precision. The broad applicability of quantum tunneling is in the fundamental process driving the evolution of stars and its contribution to progress in quantum computing, nanoelectronics, and materials science. Future work could test the proposed PTR-synched feed-forward approach by comparing STM images and spectra before and after correction under the same PTR operating conditions. In particular, quantifying changes in low-frequency vibration peaks and reductions in line striping would help evaluate effectiveness. This would clarify how much improvement can be achieved beyond established cryogen-free and closed-cycle stabilization methods.

■ Appendix

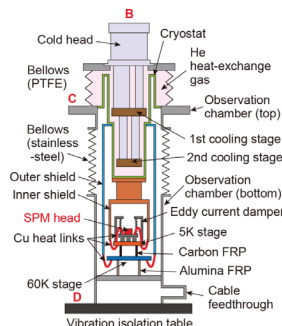


Figure A1: Schematic diagram of the cryogen-free pulse-tube STM system developed by Kasai *et al.*¹⁸ The system integrates a PTR cold head, mechanical decoupling layer, and helium gas exchange interface to minimize vibrational coupling while achieving low base temperatures suitable for measuring atomic-level resolution. Adapted from Kasai *et al.* This figure shows how mechanical decoupling and thermal control are used to reduce vibration in a cryogen-free STM system.

Supplemental information:

Technical methodology for PTR-synced feed-forward cancellation

This type of strategy has been applied in robotics, where predicting and compensating for disturbances in advance helps prevent repeated errors and maintain system stability.²⁴ For instance, this feed-forward control has been utilized to control expected counteracting forces to increase precision in robot manipulation. Translating the same idea to STM, the feed-forward correction is timed to the known PTR cycle and applied just before the disturbance reaches the junction.

Proposed Experimental Setup and Procedure (PTR-Synced Feed-Forward):

Mount a small accelerometer on the pulse-tube cold head (or read the valve-timing output), park the tip over a flat region, and record the accelerometer signal and tunneling current simultaneously for ~60 seconds to identify the ~2–3 Hz component and any harmonics.¹⁸ Using those frequencies and phases, time the most sensitive parts of each scan to the quiet portion of the cycle, and apply tiny, phase-matched nudges to the z piezo (extend to x-y if needed) right before each disturbance. Start at picometer amplitudes and use a simple adaptive model, such as a lightweight machine-learning regressor or autoregressive filter that retunes amplitude and phase every few seconds, to stay locked as conditions drift. Monitor the current spectrum for a drop in the ~2–3 Hz peak and inspect the images for reduced striping, a sharper lattice, and cleaner spectroscopy. For spectroscopy, check for clearer traces (i.e., differential conductance vs. voltage), a standard proxy for the local density of states. Enforce hard limits on the nudge size for safety, and pause or reduce the correction if any signs of junction instability have appeared. Save the sensor traces, correction signals, and before/after plots for repeatability, and, if needed, add the first harmonic or extend the same approach to x-y to address slow drift.¹⁸

This setup is illustrated in Figure A1.¹⁸

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