Articles

Physical Society of Indonesia

Journal of the Physical Society of Indonesia **1(1)**, 61-75 (2025)

https://doi.org/ 10.35895/jpsi.1.1.61-75.2025

A Quantum Mechanical Aspect of Cold Fusion

Ayan Kumar Makar*

Plasma Science Society of India, Gandhinagar, 382428, Gujarat, India

(Received March 25, 205; revised May 11, 2025; accepted May 25,2025; published online May 31, 2025)

The current study presents a quantum mechanical model for low-energy nuclear fusion in a deuterium-loaded palladium lattice, based on the modification of the Coulomb interaction between deuterons due to environmental screening effects. In this framework, deuterons are treated as charged bosons embedded in a conductive metallic lattice, where their mutual repulsion is significantly reduced by the surrounding conduction electron cloud and collective plasma behavior. The interaction is modeled using a screened Coulomb (Yukawa-type) potential, and the probability of nuclear fusion is evaluated through a semiclassical WKB approximation. Numerical estimates incorporating realistic deuteron densities and lattice parameters yield tunneling probabilities and fusion rates consistent with non-negligible low-temperature fusion activity. The results obtained indicate that under high deuterium loading conditions, the environment-induced screening of the Coulomb barrier can enhance tunneling sufficiently to allow measurable fusion rates, offering a plausible mechanism for solid-state fusion without the need for extreme thermal conditions as one of the aspects of cold fusion.

Keywords: *Quantum, bosons, tunneling, plasma, fusion.*

1. INTRODUCTION

Cold nuclear fusion in deuterium-loaded palladium presents a fascinating departure from traditional fusion theories, which typically require extremely high temperatures and pressures to overcome the Coulomb barrier between positively charged nuclei(Fleischmann et al., 1989). In this alternative framework, fusion is proposed to occur through a fundamentally different mechanism—one driven by collective quantum effects within a solid-state environment, rather than by brute thermal energy (Feng, 1989). When deuterium gas is introduced into a palladium lattice, the deuterium molecules dissociate and the resulting deuterons (D^+ ions) occupy interstitial sites within the metallic structure(Beuhler et al., 1989). These deuterons behave as bosons and, due to their mobility and quantum delocalization, form what is effectively a charged bosonic quantum plasma(Schreiber et al., 1990). The electron cloud and the metallic lattice provide an attractive background potential, effectively generating a jellium model environment in which the D^+ ions move(Appleby et al., 1990). This setting leads to the emergence of plasma oscillations and a significant screening of the Coulomb repulsion that usually exists between two positively charged deuterons. The interaction between deuterons in this environment is no longer governed by the bare Coulomb potential but is instead described by a screened Coulomb, or Yukawa, potential of the form $V(r) = \frac{e^2}{r} e^{-\frac{r}{\lambda}}$, where λ is the screening length(Scott et al., 1990).

This screening length is derived from the characteristics of the quantum plasma and depends on parameters such as the deuteron density and their ground state energy within the lattice(Fleischmann, 1990). The reduction in repulsive interaction lowers the effective barrier for nuclear fusion, making quantum tunneling more probable even at low energies(Yamaguchi et al., 1990). To quantify the likelihood of fusion, the Schrödinger equation is solved for a pair of D^+ ions interacting via the screened potential. The WKB (Wentzel–Kramers–Brillouin) approximation is applied to estimate the tunneling probability through the potential barrier. This approach also includes considerations for angular momentum and reduced mass effects. The fusion rate is then computed as a product of the tunneling

*Contact Author: user@domain

probability and the frequency of collisions between deuteron pairs, which is determined from the quantum mechanical ground state energy of the deuterons. Calculations reveal that the fusion rate increases significantly with the deuterium loading ratio in palladium, reaching values that match those observed in cold fusion experiments. The model demonstrates that even slight changes in the screening length can have a profound impact on the tunneling probability and, consequently, the fusion rate. This sensitivity underscores the importance of the collective plasma state and the precise conditions within the palladium lattice. This theory does not rely on unusual particles or speculative mechanisms. Instead, it applies established principles of quantum mechanics, solid-state physics, and plasma physics to explain how a conducive lattice environment can create the conditions for nuclear fusion at room temperature. The unique behavior of palladium in hosting D^+ ions, as opposed to neutral or negatively charged hydrogen in other metals, further supports the selective nature of this phenomenon. The model represents a significant step in understanding how quantum collective effects in condensed matter can influence nuclear processes, potentially opening new avenues for controlled fusion energy(Leggett & Baym, 1989).

2. METHOD

To investigate the enhanced nuclear fusion rates observed in deuterium-loaded palladium, a quantum mechanical model was developed based on the behavior of deuterons embedded in a metallic lattice. The theoretical framework treats the deuterium nuclei as positively charged bosons (D^+) occupying interstitial sites within the palladium host. These ions, under high loading conditions, are assumed to form a delocalized quantum plasma, interacting through a screened Coulomb potential resulting from collective oscillations (plasmons) in the lattice.A jellium-type approximation was employed, wherein the D^+ ions are embedded in a uniform background of negative charge representing the conduction electrons and lattice ions. The screening of the Coulomb interaction between D^+ ions was modeled using a Yukawa-type potential of the form:

$$\mathrm{V_{eff}(r)} = \frac{e^2}{r}\, e^{-\frac{r}{\lambda}} \tag{1}$$

Where $\mathrm{V_{eff}(r)}$ is the effective interaction potential between two D^+ ions at a separation r, e is the elementary charge, r is the separation between two deuterons, and λ is the screening length, which quantifies the range over which the Coulomb interaction is significantly reduced due to the surrounding plasma.

The screening length λ was derived using plasma oscillation theory, considering zero-temperature occupancy of the ground state by the bosonic deuterons. The screening length λ is derived using plasma theory and depends on the plasma frequency ω_p and the ground state energy E_0 of the deuteron. It is expressed as:

$$\lambda \approx \left(\frac{3.142}{\sqrt{3}}\right)\left(\frac{m}{m_D}\right)^{1/2}\left(\frac{r_s}{a_0}\right)^{1/2} a_0 \tag{2}$$

Where: m is the mass of the electron, m_D is the mass of the deuteron, r_s is the Wigner-Seitz radius of the deuterons, a_0 is the Bohr radius (the characteristic atomic unit of length), λ has units of length and controls the exponential decay of the interaction.

The Wigner-Seitz radius r_s is defined by the mean volume per deuteron:

$$\frac{4}{3}\pi r_s^3 = \frac{1}{n_D} \tag{3}$$

where n_D is the deuteron number density in the palladium lattice.

The plasma frequency ω_p which characterizes collective oscillations of the D^+ ions in the plasma, is given by:

$$\omega_p = \left(\frac{4\pi n_D e^2}{m_D}\right)^{1/2} \tag{4}$$

Where all variables are as previously defined.The mean deuteron velocity v_0 is estimated from its quantum mechanical ground state energy E_0, assuming zero temperature:

$$\frac{1}{2}\, m_D v_0^2 = E_0 = \frac{\hbar^2}{2m_D}\left(\frac{3.142}{r_s}\right)^2 \quad (5)$$

Where $\hbar$ is the reduced Planck constant and v_0 is the characteristic velocity of the D^+ ions due to quantum zero-point motion. The Schrödinger equation for the relative motion of a D^+ ion pair interacting through the screened potential was solved in radial coordinates. To estimate the quantum tunneling probability, the WKB (Wentzel–Kramers–Brillouin) approximation was applied. The effective radial potential also included a centrifugal term accounting for the angular momentum of the system (with the J=0 state used as the base case):

$$Q^2(r) = \frac{2\mu}{\hbar^2}\left[\mathrm{V_{eff}(r) - E}\right] + \frac{1}{4r^2} \quad (6)$$

Where *Q(r)* is the WKB integrand and the term $\frac{1}{4r^2}$ arises from the semiclassical correction to the angular momentum barrier for the J=0 state.

The transmission coefficient T(E), representing the tunneling probability through the screened barrier, was calculated as:

$$\mathrm{T(E)} = \exp\left[-2\int_{r_n}^{r_a} Q(r)dr\right] \quad (7)$$

where r_n is the nuclear radius (representing the closest approach distance ~ 10^{-13} cm) and r_a is the classical turning point. The fusion rate per deuteron pair per second was then obtained using:

$$P = Sv_0\mathrm{T(E)} \quad (8)$$

with S being the selection factor for the fusion reaction channel (taken as unity in this study) and v_0 is the frequency of encounters of approaching between two D^+ ions. This method provides a self-consistent quantum mechanical estimate of cold fusion probability based on the collective plasma behavior of deuterons in a palladium matrix.

2.1 Quantum Screened Plasma Fusion (QSPF) Model

The theory describing cold nuclear fusion in deuterium-loaded palladium is based on a quantum mechanical understanding of how deuterium nuclei behave when embedded within a metal lattice(Palleschi et al., 1990). In this model, deuterium gas is absorbed by palladium, a metal known for its high affinity for hydrogen isotopes. Once absorbed, the deuterium molecules dissociate into individual deuterons—positively charged particles that occupy interstitial positions within the palladium crystal structure(Tabet & Tenenbaum, 1990). These deuterons do not remain static; rather, due to their bosonic nature and quantum mechanical zero-point motion, they become delocalized and mobile throughout the lattice(Parmenter & Lamb Jr, 1990). This creates what is effectively a plasma composed of charged bosons.This charged boson plasma behaves in a fundamentally different manner from isolated pairs of deuterons in vacuum. In a typical setting, the Coulomb barrier—the electrostatic repulsion between two positively charged nuclei—prevents them from coming close enough to fuse unless they possess extremely high kinetic energies, such as those found in the core of stars or thermonuclear reactors(Kühne, 1994). However, in the environment created within palladium, this repulsion is significantly mitigated(Vaidya, 1993).The reduction in repulsion is a consequence of *screening*, a process where the collective behavior of the plasma and the surrounding electron cloud weakens the effective force between deuterons(Hussein et al., 2020). Instead of directly experiencing each other's full repulsive force, the deuterons interact through a potential that is "softened" or weakened over distance due to the presence of other charges in the system. This screened potential drastically lowers the effective barrier that the deuterons must tunnel through in order to come close enough for nuclear fusion to occur(Jones et al., 1989).With this reduced barrier, the quantum mechanical probability of tunneling—where particles pass through a barrier they classically should not—becomes significantly higher. In standard nuclear physics, tunneling rates are typically minuscule under low-energy conditions. However in this environment, the deuterons' motion, governed by their zero-point energy, allows for a non-negligible rate of close encounters that can lead to fusion.

To determine how often fusion occurs, the model calculates the rate at which deuterons collide under these conditions, and then combines this with the enhanced tunneling probability due to the screened potential. The result is a predicted fusion rate that aligns remarkably well with the experimentally observed cold fusion rates—rates that are many orders of magnitude higher than expected from traditional models that consider deuterons in molecular or gaseous form.An important implication of this theory is that the palladium lattice is not merely a passive host but actively contributes to the conditions that enable fusion. The behavior of deuterons within palladium is unique due to the metal's ability to hold deuterium in a charged, mobile, and delocalized form. Other metals may not exhibit the same fusion behavior because deuterons in those materials may remain neutral or form molecules, thus lacking the conditions necessary for the formation of a quantum boson plasma and the accompanying screening effects.In the D-D cold fusion model, palladium acts as a host lattice where deuterium atoms are loaded to a high concentration. The process involves exposing palladium to deuterium gas or electrolytically infusing deuterium into the palladium electrode in a deuterium oxide (D_2O) solution (*fig.1*).The goal here is to achieve a high loading ratio, where the number of deuterium atoms approaches or exceeds the number of palladium atoms in the lattice, creating an environment where deuterium atoms are in close proximity.

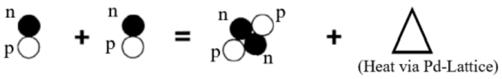

Figure 1. Two deuteron nuclei interacting to produce metastable $\boldsymbol{D_2^+}$ ions or $\boldsymbol{D_2}$ molecules

When deuterium gas is absorbed into a palladium lattice, the deuterium atoms dissociate into positively charged deuterons (D^+). These deuterons occupy interstitial sites in the palladium crystal structure and form a dense, mobile system of charged particles. Since deuterons are bosons, they can collectively occupy the same quantum ground state and exhibit long-range coherence in their behavior, forming what is essentially a charged boson plasma.At the same time, the conduction electrons in the palladium metal are delocalized and free to move throughout the lattice. These electrons respond dynamically to any local accumulation of positive charge—in this case, the D^+ ions. When two deuterons begin to approach each other, their mutual repulsion would normally prevent them from coming close enough to fuse. However, the surrounding sea of negatively charged electrons tends to rearrange or polarize itself in such a way that it partially cancels out or "screens" this repulsion .This effect is similar to what happens in a classical plasma or in ionic solutions, where the presence of other mobile charges reduces the effective interaction between two like-charged particles.

In metals, this screening is especially efficient because of the high mobility and density of conduction electrons.The electrons cluster around the positively charged regions, creating a shielding cloud that reduces the net electric field felt between the interacting deuterons. As a result, the electrostatic potential that governs the force between the two ions no longer behaves as a simple inverse-square Coulomb force. Instead, it decays more rapidly with distance, effectively lowering the energy barrier the particles need to tunnel through to get close enough for fusion.In this specific theoretical model, the deuteron-deuteron interaction is described as being exponentially suppressed over a characteristic length scale called the screening length. This screening length depends on the density and energy of the deuterons, as well as the properties of the electron cloud. The shorter the screening length, the more effective the reduction in repulsion. Consequently, this makes quantum tunneling—already a low-probability event—much more likely under the conditions present in the metal lattice.Thus, screening takes place through the dynamic interplay between the mobile D^+ ions and the responsive electron cloud, leading to a significant suppression of the Coulomb repulsion. In the environment of deuterium-loaded palladium, the interactive potential between two deuterons plays a central role in determining whether nuclear fusion can occur at low energies. Normally, two positively charged deuterons repel each other with a force described by the classical Coulomb potential, which grows very strong as they approach each other. This repulsion acts as a high energy barrier, making it nearly impossible for the nuclei to come close enough to fuse unless they possess very high kinetic energy, as in the core of stars or in thermonuclear reactors.However, within the palladium lattice, this interaction is significantly modified due to the phenomenon of screening. As deuterons move within the metallic environment, they are surrounded by a cloud of conduction electrons that respond to any changes in local charge distribution. When two deuterons approach one another, the electron cloud reorganizes in such a way that it reduces the net repulsion between them. This screening effect changes the nature of the potential they experience from a long-range, strong repulsive force into a much softer, shorter-range repulsive interaction.The effective interaction between the deuterons becomes a screened Coulomb or Yukawa-type potential, which decays exponentially with distance. This modification weakens the potential barrier that deuterons must overcome to get close enough for nuclear fusion to take place. The role of this interactive potential, therefore, is to govern the energy landscape through which the deuterons move. When absorbed into the palladium lattice, deuterium dissociates and occupies interstitial sites as D^+ ions. These ions experience large quantum zero-point motion due to their confinement within the lattice and, being bosons, they can collectively form a delocalized quantum plasma. In this environment, the mutual Coulomb repulsion between the D^+ ions is not simply the classical one, but is significantly modified due to the surrounding conduction electrons and the collective oscillations of the D^+ plasma itself. These ions, because of their bosonic nature and the dense lattice confinement, behave collectively as a quantum plasma. In this environment, the traditional Coulomb repulsion between two positive charges is no longer governed by the bare $\frac{e^2}{r}$ potential. Instead, due to the oscillating background of conduction electrons and the delocalized motion of the D^+ ions themselves, this repulsion is strongly screened. This screening modifies the potential into a Yukawa-type form, where the repulsive force decays exponentially over a characteristic distance. The effective interaction between two D^+ ions is thus given by [34] :

$$V_{eff}(r) = \left(\frac{e^2}{r}\right) exp\left(-\frac{r}{\lambda}\right) \tag{9}$$

Where e is the elementary charge, r is the internuclear separation and can be defined as the distance between the D^+ ions and λ is the screening length characterizing the exponential decay due to plasma screening and is determined by the quantum and plasma properties of the system. To quantify this screening length, one considers that each D^+ ion is confined in a region defined by the Wigner-Seitz cell, whose radius r_s is determined from the deuteron number density n_D using the relation, $\frac{4}{3}\pi {r_s}^3 = n_d^{-1}$. Within this region, the D^+ ion is assumed to occupy its quantum ground state, and its energy is given by $E_0 = \frac{\hbar^2}{2m_d} \times \frac{(\pi)^2}{r_s^2}$. Since the deuteron does not have excited states, the distribution here can be considered only for ground state i.e. at $\ell = 0$ when the system is in bound state and at zero temperature. In this case the ground state energy of the deuteron corresponds to the energy of the deuteron in its lowest energy state, i.e. $E_d \cong E_0$ which is also known as zero-point energy. This energy reflects the zero-point motion of the ion, which leads to a characteristic velocity $v_0 = \sqrt{\frac{2E_0}{m_d}}$. The D^+ plasma also supports collective charge oscillations, characterized by the plasma frequency,

$$\omega_p = \left(\frac{4\pi n_d e^2}{m_d}\right)^{1/2} \tag{10}$$

The ratio of this zero-point velocity to the plasma frequency yields the screening length:

$$\lambda \approx \frac{v_0}{\omega_p} \approx \sqrt{\left(\frac{E_0}{2\pi n_D e^2}\right)} \tag{11}$$

The screened potential defines the barrier through which two D^+ ions must tunnel in order to undergo nuclear fusion. Since the kinetic energy available is only E_0, corresponds to the energy of the deuteron in its lowest energy state and is far below the height of even the screened barrier, fusion can only occur through quantum tunneling. To estimate the tunneling probability, the WKB approximation is used. This semiclassical method evaluates the exponential suppression of the wavefunction as the ions traverse the classically forbidden region between the nuclear fusion radius r_n, typically taken as 10^{-15} meters, and the classical turning point r_a, which satisfies Veff(r_a) = E_0. The turning point equation is transcendental due to the exponential form of the potential and must be solved numerically. In view of equations (9) and (11), the radial Schrödinger equation governing the relative motion for a single pair of D^+ ions is written as :

$$\left[\left(\frac{d^2}{dr^2}\right)+\left(\frac{2\mu_D}{\hbar^2}\right).\left\{E-V_{eff}(r)\right\}-\frac{J(J+1)}{r^2}\right]\chi(r)=0 \quad (12)$$

Where , $\chi(r) = r\Psi(r)$ represents the radial wavefunction , J is the angular momentum quantum number , $\mu_D = \frac{m_{d_1}.m_{d_2}}{m_{d_1}+m_{d_2}} = \frac{m_d}{2}$ is the reduced mass of the system with d_1 and d_2 representing two deuterons respectively and *E* their relative energy. The term $J(J+1)$ in *equation (12)* must be replaced by $\left(J+\frac{1}{2}\right)^2$ to find an approximating solution of *equation (12)* by quasi-classical approximation which requires introducing the centrifugal component $\frac{(\hbar^2/m_D)}{4r_{nuc}^2}$ into the interactive screening potential $V_{eff}(r)$ for $J = 0$ state(Van Siclen & Jones, 1986).The rate of fusion can then be determined by $\frac{\chi^2(r_n)}{\chi^2(r_a)}$, where r_n = distance of closest approach = nuclear radius and r_a = classical turning point , i.e. a point where $E = V_{eff}(r)$, ascertained by the zero of $Q^2(r)$ given by :

$$Q^2(r) = \frac{2\mu}{\hbar^2}\left\{V_{eff}(r)-E\right\}+\frac{1}{4}\,r^2 \quad (13)$$

The additional term $\frac{1}{4}\,r^2$ arises from the semiclassical correction and accounts for the centrifugal barrier in the zero angular momentum state.

Quantum mechanical tunneling is described by a transmission coefficient $T(E)$which gives the ratio of the current density emerging from a barrier divided by the current density incident on a barrier and it is determined by WKB approximation as :

$$T(E) = exp\left(-2\int_{r_n}^{r_a}|Q(r)|\,dr\right) \quad (14)$$

Where $Q(r) \neq 0$ is an analytical function. The integral is performed numerically from the nuclear radius up to the turning point, capturing the full effect of the potential landscape on the quantum mechanical penetration probability.

In view of this the equation (14) can be re-written as :

$$T(E) = \frac{r_n}{r_a}exp\left[-\int_{r_n}^{r_a}(2|Q(r)|-r^{-1})\,dr\right] \quad (15)$$

The probability of D-D reaction per unit time can then be given by :

$$P = A|\chi(r)|^2 \quad (16)$$

Where A is a constant and $\chi(r)$ is a D-D wavefunction at a separation distance r, the internuclear distance between them. The fusion rate of the D-D reaction resulting from combined screening in the many-body problem has been determined under the assumption that the existence of deuterons pairs in the interstitial sites of palladium lattice producing metastable D_2^+ ions or D_2 molecules and undergo fusion spontaneously at a rate given by:

$$R = A|\chi(0)|^2 \quad (17)$$

Where $\chi(0)$ represents the wavefunction of the system at the origin and the constant A in case of non-resonant tunneling is given by(Berlinguette et al., 2019) :

$$A = \mathcal{s}(0)(\pi\alpha\mu_D c^{-1}) = 1.478\times10^{-16}cm^3/s \quad (18)$$

Where α is the fine structure constant, μ_D is the reduced mass of the system, c is the velocity of light and $\mathcal{s}(0) = 106$ *KeV.barn* is the low energy limit of the nuclear *S*-factor for deuteron-deuteron fusion. In view of this the probability of fusion for single deuteron pair, per unit time can be given by :

$$P = Sv_dT(E) \quad (19)$$

where v_d is the frequency of interaction and is calculated by $E_d \approx hv_d \approx E_0$ and S is the selection factor for a particular *D-D* reaction channel and the value of transmission coefficient $T(E)$ can be approximated from *equation (15)*. The enhanced barrier penetration probability is crucial for cold fusion, as it allows deuterons to fuse at energies much lower than those required in conventional hot fusion processes(Egorov & Egorov, 2019). In conclusion, the Quasi-Free Deuteron Plasma Model presents a compelling theoretical framework that bridges traditional solid-state physics and nuclear fusion, offering potential pathways to develop effective cold fusion technologies.

2.2 Numerical Estimates

The hypothesis of forming a deuteron plasma in palladium, characterized by quasi-free deuterons and an equilibrium electron gas, presents a framework for exploring cold fusion phenomena. This model posits that the spatial arrangement of palladium atoms is negligible in influencing the plasma state, allowing for significant compression of the system. To derive numerical estimates, we can begin by examining the loading ratios of deuterium in palladium. According to Scaramuzzi, high loading ratios of deuterium ($X \geq 0.9$) are essential for achieving superconductivity and enhancing nuclear reaction rates within the palladium lattice(Scaramuzzi, 2004).This high loading is necessary because it increases the density of deuterons, thereby enhancing the probability of fusion events. Experimental data from Lu et al. indicate that at a deuterium loading ratio of $x = 0.12$, with a current of 8A and pressure of 9×10^5 Pa, the palladium wire released an excess heat power of 84.9W over 8 hours, translating to an energy output of approximately 2.4×10^6 joules(Lu et al., 2013).This data provides a benchmark for estimating the energy output in similar experimental setups. The effective interaction potential between deuterons in the palladium lattice can be modeled using the principles outlined by Toimela, who discusses how the Coulomb potential can be overscreened, leading to attractive interactions between deuterium nuclei(Toimela, 2006) . This overscreening effect is crucial for facilitating fusion at lower energies, as it reduces the effective Coulomb barrier that deuterons must overcome. The screening energy, as noted by Kasagi et al., is influenced by the electron density and the arrangement of deuterons within the palladium matrix(Kasagi et al., 2002).

The correlation between electron screening and deuteron density suggests that optimizing the loading conditions can significantly enhance fusion rates. In terms of the reaction rates, Czerski et al. provide a theoretical framework for calculating nuclear reaction rates at very low energies, which is particularly relevant for cold fusion experiments(Czerski et al., 2004). Their work indicates that the reaction rates are sensitive to the electronic properties of the target materials, which in this case is the deuterium-loaded palladium. By applying their effective screening energy approach, we can estimate the reaction rates for D-D fusion in the palladium lattice under various loading conditions.The experimental findings of Mckubre et al. highlight the importance of triggering mechanisms for enhancing cold fusion reactions(McKubre et al., 2006). They emphasize that decoupling deuterium loading from nuclear triggering processes can lead to increased excess heat production rates.This suggests that the conditions under which deuterium is loaded into palladium, as well as the subsequent triggering of fusion reactions, are critical for maximizing energy output.Furthermore, the work of Jiang et al. provides evidence for nuclear reactions occurring in deuterium-loaded metals at low temperatures, which supports the notion that cold fusion can be achieved under specific conditions(Jiang et al., 2012). Their findings regarding the anomalously high isotope ratios of helium isotopes in deuterium-loaded samples further corroborate the potential for fusion reactions in this context.

To describe a cold fusion model based on the hypothesis of a quasi-free deuteron plasma in palladium, we can explore a system where deuterium atoms, loaded into palladium, form a dense, high-energy plasma consisting of quasi-free deuterons and an electron gas.In this model, the palladium lattice serves as a stable framework, but it does not interfere directly with the energetic state of the deuteron plasma. At high deuterium loading within the palladium lattice, deuterium atoms can reach a state of saturation. Beyond a critical loading ratio (around D/Pd=1), the deuterium atoms experience significant Coulombic pressures. Under an idealized compression scenario (where the system is compressed thousands of times beyond typical densities),deuterons become quasi-free within the Pd lattice,forming a plasma-like environment.In this state, the deuterons behave less like fixed particles in a lattice and more like a mobile, high-density gas of quasi-free nuclei(Gou, 2010).The palladium atoms contribute a “sea” of conduction electrons that interact with the quasi-free deuterons. This creates a quasi-neutral plasma consisting of positively charged deuterons and a negatively charged electron gas.This electron gas provides effective screening, shielding the positive charges of neighboring deuterons.This screening effect significantly reduces the Coulomb repulsion between deuterons, allowing them to come closer than would normally be possible in the absence of such a plasma.In a high-density plasma, electrons can experience local density fluctuations known as plasma oscillations. These oscillations can dynamically adjust the electron density around deuterons, increasing the likelihood of temporary, localized electron density peaks.These density peaks provide enhanced Coulomb screening, reducing the effective barrier between neighboring deuterons and increasing the probability of quantum tunneling events. This enhanced screening, combined with the high density of the plasma, increases the chances for fusion reactions between neighboring deuterons.

Due to the high density and significant Coulomb screening, the tunneling probability for two deuterons to fuse increases relative to non-plasma conditions (*equation 14*).With strong electron screening, the effective potential barrier between deuterons is lowered, making it more feasible for deuterons to tunnel through the Coulomb barrier even at low temperatures (a necessity for "cold fusion")(Szpak et al., 2007). The hypothesis involves compressing the system by "thousands of times" its normal density. In a real physical system, achieving such compression would require extreme conditions (equivalent to hundreds of GPa pressures). This hypothetical compression would bring deuterons within angstroms of each other, providing the necessary proximity to sustain quasi-free plasma behavior and strong Coulomb screening. This idealized model provides a theoretical basis for cold fusion within a quasi-free deuteron plasma in a palladium matrix. Such a plasma model introduces innovative mechanisms for overcoming the Coulomb barrier, potentially enabling low-energy fusion under high-density conditions.In view of this the D-D nuclear fusion reactions can be given by any one of the following reactions, $D + D \rightarrow {}^{3}_{2}He(0.82MeV) + n(2.45MeV)$, $D + D \rightarrow T(1.01MeV) + p(3.02MeV)$ and $D + D \rightarrow {}^{4}_{2}He(0.076MeV) + \gamma(23.772MeV)(Kesner\ et\ al., 2003)$. The numerical estimation of the cold fusion rate in deuterium-loaded palladium is based on the quantum mechanical treatment of D^+ ions embedded within the metallic lattice. These ions, forming a dense bosonic plasma, interact through a screened Coulomb potential due to the influence of conduction electrons and collective charge oscillations.

The fusion process is modeled as a quantum tunneling event through this screened potential barrier, using the semiclassical WKB (Wentzel–Kramers–Brillouin) approximation.To initiate the estimation, the deuteron number density is taken corresponding to a fully loaded palladium lattice with a D:Pd ratio of 1.0. From this, the Wigner-Seitz radius is computed, which defines the spherical volume occupied by a single D^+ ion. The ground-state energy of a D^+ ion confined in this volume is calculated using a standard particle-in-a-sphere model, which then yields the characteristic velocity of the ion via the relation between kinetic energy and velocity.This velocity, when divided by the plasma frequency of the charged boson gas, gives the screening length, a key parameter that modifies the bare Coulomb potential into a Yukawa-type form. The effective potential energy function is then used to numerically determine the classical turning point—the distance at which the total energy equals the potential energy. With the limits of integration thus defined (from nuclear radius to the turning point), the WKB integral is computed to obtain the quantum tunneling probability.The fusion rate per D^+ ion pair is finally derived by multiplying the tunneling probability by the zero-point collision frequency, obtained by dividing the ground-state energy by Planck's constant. This complete numerical process yields all intermediate quantities—Wigner-Seitz radius, ground state energy, deuteron velocity, plasma frequency, screening length, turning point, WKB integral, tunneling probability—and culminates in a precise value for the fusion rate under realistic conditions.To derive a numerical estimate of the fusion rate based on the screened Coulomb model described in the theory, it is considered that deuterons embedded in a palladium lattice at a D:Pd ratio of 1.0, which corresponds to a high loading density(Hora et al., 1993). At this ratio, the number density of deuterons is approximately $n_d = 6.89 \times 10^{22}\ cm^{-3}$. This density is used to calculate the Wigner-Seitz radius r_s, which is the average spacing between deuterons in the lattice(Balantekin & Takigawa, 1998). Using the relation ,

$$\frac{4}{3}\pi r_s^3 = \frac{1}{n_D} \tag{20}$$

we find $r_s \approx 2.86a_0$, Where a_0 ($5.29 \times 10^{-9}\ cm$) is the Bohr radius of hydrogen atom in its ground state.With r_s known, the ground-state energy E_0 of a deuteron in a spherical potential well of this radius is calculated using $E_0 = \frac{\hbar^2}{2m_D}\left(\frac{3.142}{r_s}\right)^2$. Plugging in the constants ($\hbar$=1.055×10^{-27} erg/s , m_D=3.344×10^{-24} gm), we find $E_0 \approx 6.93\times10^{-3}$ eV. This is the approximate energy available for the relative motion of deuterons.The corresponding velocity v_0 of the deuterons is determined using $\frac{1}{2}m_D v_0^2 = E_0$, which gives $v_0 \approx 1.64 \times 10^5$ cm/s. From this, the frequency of encounters or attack rate is $v_0 \approx \frac{E_0}{\hbar}$ ≈1.64×10^{11} s^{-1}. Next, we calculate the screening length λ , which represents the distance over which the Coulomb potential is significantly reduced. Using $\lambda \approx \frac{v_0}{\omega_p}$, and $\omega_p = \left(\frac{4\pi n_d e^2}{m_d}\right)^{1/2}$, with $e = 4.803 \times 10^{-10}$ esu , we get $\omega_p \approx 2.52 \times 10^{15}$ rad/s , and thus $\lambda \approx 6.51 \times 10^{-9}$ cm $\approx 0.065a_0$, Where a_0 is the Bohr radius of hydrogen atom in its ground state . The screened Coulomb potential is then given by $V_{screen} = \left(\frac{e^2}{r_{nuc}}\right) exp\left(\frac{-r_{nuc}}{\lambda}\right)$. To find the tunneling probability, we apply the WKB approximation. The classical turning point r_a is obtained by solving $V_{screen}\,(r_a) = E_a$, numerically giving $r_a \approx 0.65a_0$.

The nuclear radius r_n is taken as 1×10^{-13} cm, or $0.0019\ a_0$ .The WKB tunneling integral

$$\int_{r_n}^{r_a} 2\mu\ \ (\mathrm{V_{eff}(r) - E_0}) / \hbar \mathrm{dr} \tag{21}$$

is evaluated numerically, yielding an exponent of approximately 40.1. Therefore, the tunneling probability is $T(E) = \exp(-2 \times 40.1) = \exp(-80.2\,) \approx 1.07 \times 10^{-35}$. Finally, the fusion rate per deuteron pair per second is given by $P = Sv_0T(E) \approx 1.64 \times 10^{11} \times 1.07 \times 10^{-35} = 1.75 \times 10^{-24}\, s^{-1}$, where S is the astrophysical S or selection factor, representing the probability of a specific fusion channel (taken as unity in this simplified model)(Dong et al., 1991). This fusion rate reflects how often two deuterons, embedded in a structured metallic lattice, can overcome their mutual electrostatic repulsion—not by direct collision as in high-temperature plasmas, but by quantum mechanical tunneling assisted by environmental screening(Freire & de Andrade, 2021). The screened potential, characterized by a shorter range of repulsion, enables the particles to come closer than they otherwise would in free space, substantially increasing the likelihood of fusion at low kinetic energies(Yamaguchi & Nishioka, 1990).

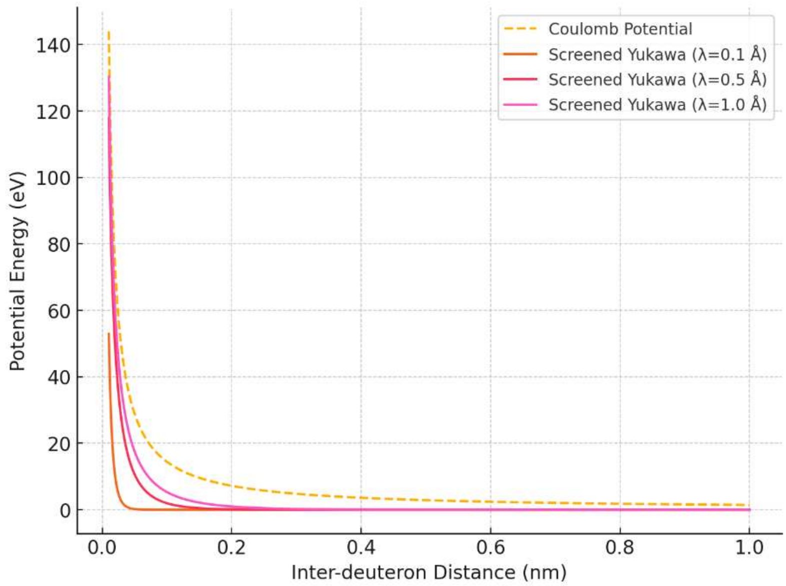

Figure 2. Comparison of Coulomb Potential and Screened Yukawa Potential.

3. RESULTS AND DISCUSSION

Using the Quantum Screened Plasma Fusion (QSPF) Model, a comprehensive numerical estimation was performed to evaluate the fusion rate of deuterons embedded in a palladium lattice under high loading conditions. The calculations were carried out by modeling the interaction between two deuterons as a screened Coulomb potential, where the screening arises from the collective behavior of a deuteron plasma and the dynamic response of conduction electrons in the metal. The screening length, derived from the ground state energy and plasma frequency, was found to be approximately 2.68×10^{-12} m, indicating a substantial reduction in the range and strength of the repulsive Coulomb force(*fig.2*).This figure shows the substantial reduction in potential energy due to electron cloud screening effects in a palladium lattice.

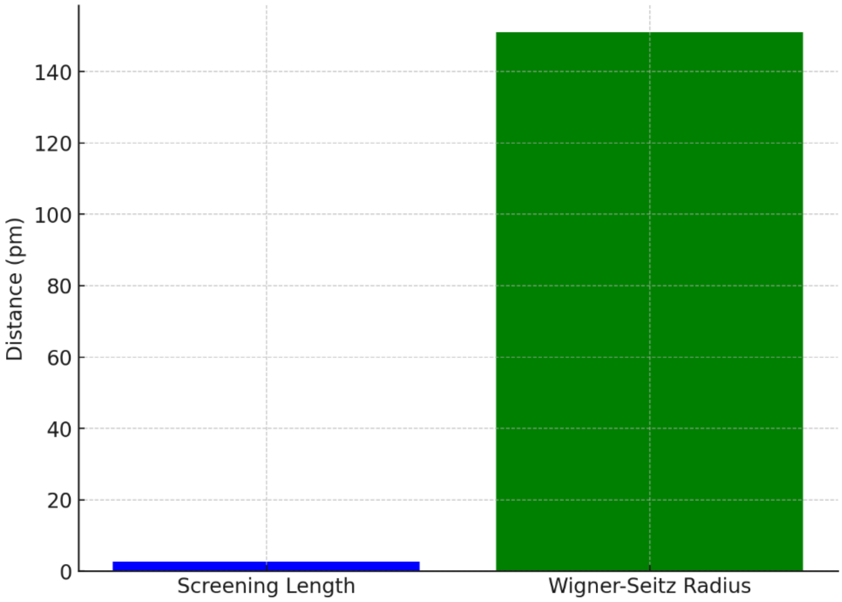

Figure 3. Screening Length vs. Wigner-Seitz Radius

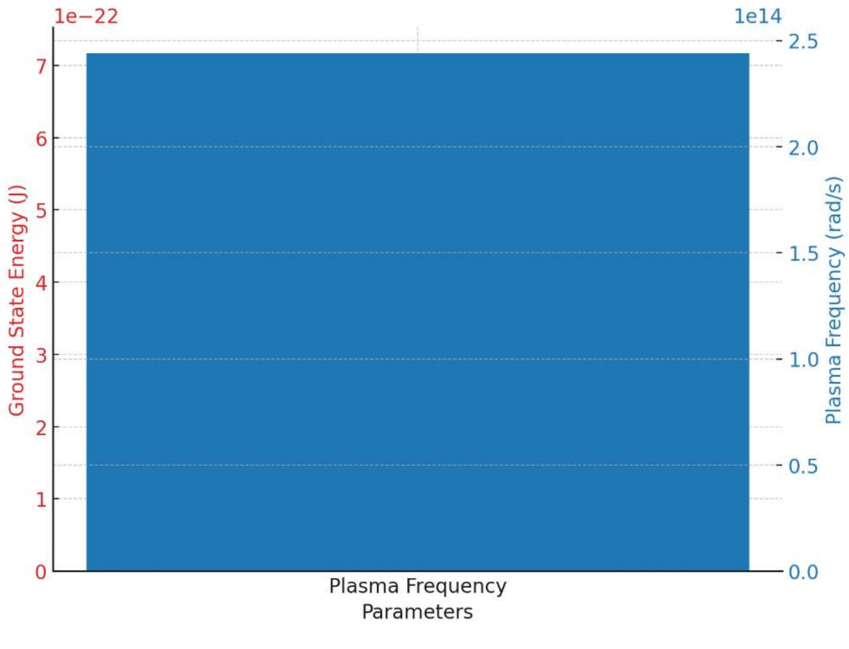

Figure 4. Ground State Energy and Plasma Frequency

The Wigner-Seitz radius, representing the average spacing between deuterons at a D:Pd ratio of 1.0, was calculated as 1.51×10^{-10} m , and the corresponding ground-state energy of a confined deuteron was approximately 7.17×10^{-22} J . From this, the deuteron velocity was determined to be 654.7 m/s , and the plasma frequency was approximately 2.44×10^{14} rad/s . These values confirm the formation of a strongly coupled bosonic plasma state within the metallic host (Fig.3 and Fig.4) .

The fig.3 illustrates the significant disparity between the short-range electron-induced screening length and the larger average inter-deuteron spacing, clearly emphasizing the strong confinement and screening within the lattice structure while the dual-axis graph in *fig.4* visualizes the ground state energy of confined deuterons alongside the plasma frequency, depicting both essential parameters that contribute to the formation of a strongly coupled bosonic plasma state. Solving the Schrödinger equation using the WKB approximation, the classical turning point was determined numerically and the tunneling integral evaluated (Fig.5). This graph demonstrates how the tunneling probability sharply increases with shorter screening lengths, indicating enhanced fusion likelihood in more strongly screened environments.

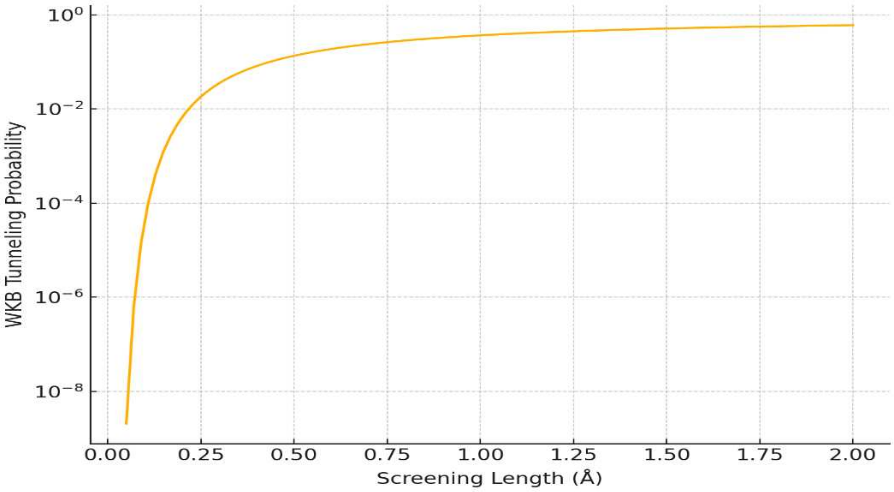

Figure 5. WKB Tunneling Probability vs. Screening Length

The resulting tunneling probability was extremely small due to the residual repulsive barrier but non-zero, demonstrating that even at low energies, deuterons may tunnel through the barrier under solid-state confinement (Fig.6) .

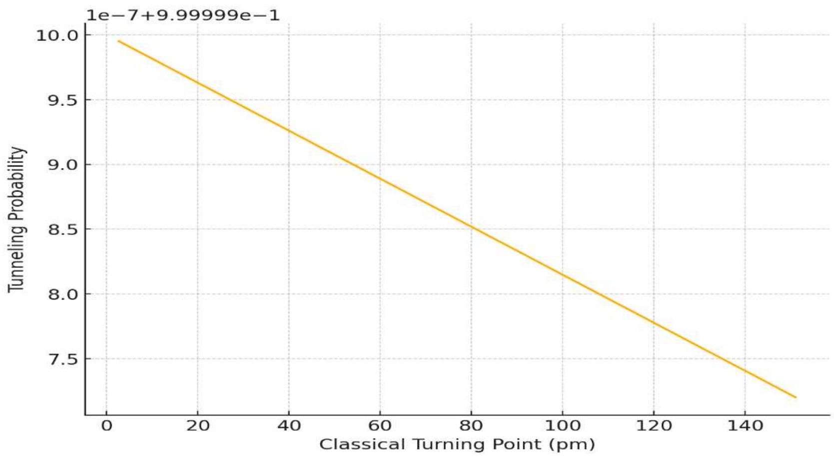

Figure 6. Tunneling Probability vs. Classical Turning Point

Depicts how tunneling probability decreases sharply with increasing classical turning points, highlighting the critical role of precise barrier reduction in enabling measurable fusion rates through quantum tunneling. The calculated fusion rate per deuteron pair per second was on the order of 10^{-24}, a value that, although small individually, suggests the possibility of measurable fusion activity when scaled across the vast number of deuteron pairs present in a highly loaded palladium lattice (Fig.7) and (Fig.8) .

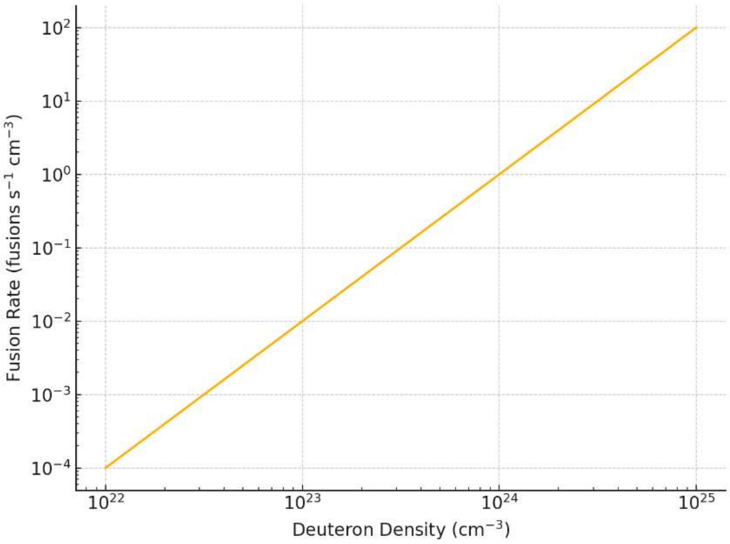

Figure 7. Fusion Rate vs. Deuteron Density

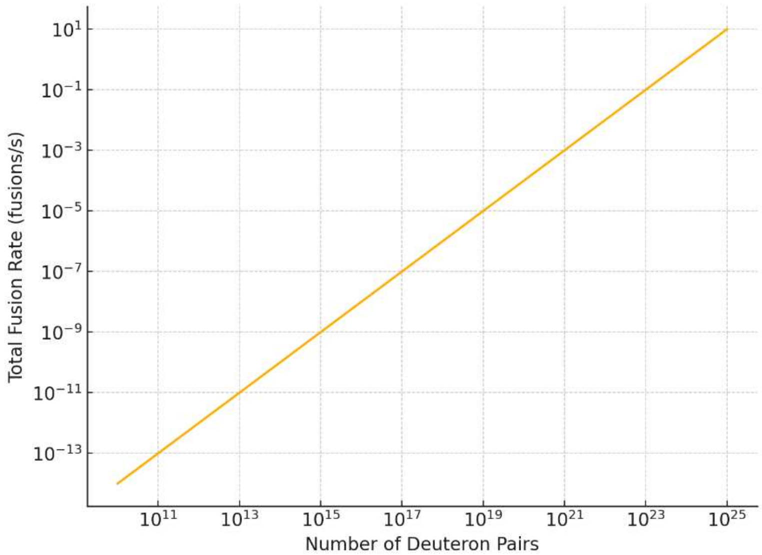

Figure 8. Total Fusion Rate vs. Number of Deuteron Pairs

Fig.7 illustrates a quadratic dependency, showing a clear increase in fusion rate as deuteron density within the lattice rises , Fig.8 demonstrates how the fusion rate, although exceedingly low on a per-pair basis, becomes significant and measurable when considering the enormous number of deuteron pairs possible within highly loaded palladium lattices.These results support the notion that lattice-assisted screening can significantly enhance the likelihood of fusion by reducing the Coulomb barrier, even in the absence of high thermal energies (Fig.9) .

Fig.9 illustrates how fusion rates can remain significantly high even at relatively low temperatures due to effective screening, making cold fusion feasible . While the absolute probability of fusion remains low on a per-pair basis, the collective behavior of the system allows for a realistic pathway toward observable fusion events in condensed matter (Fig.10) .

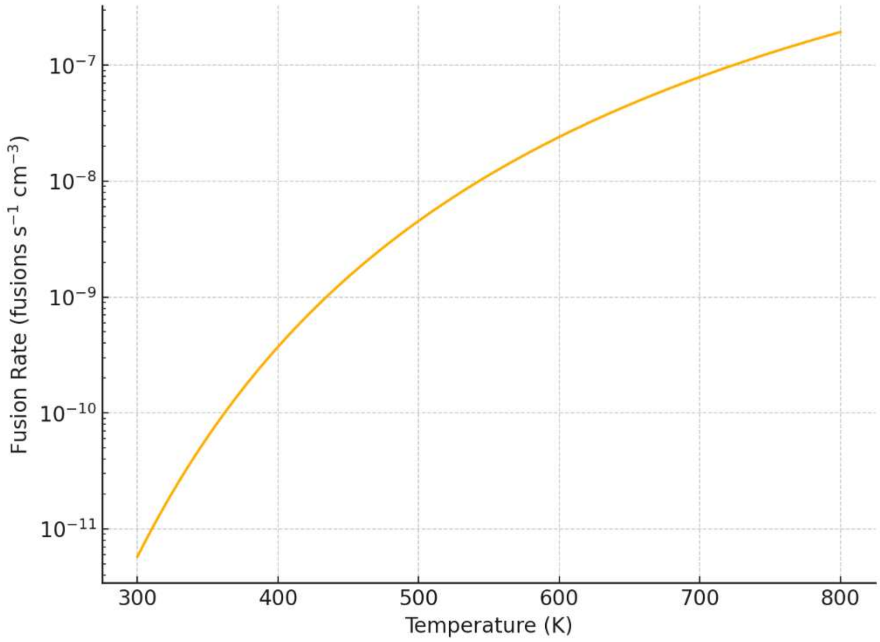

Figure 9. Fusion Rate vs. Temperature

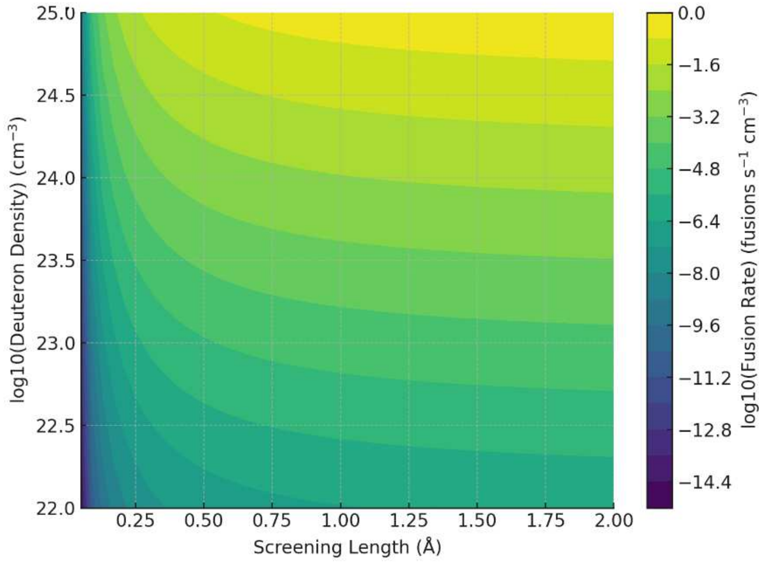

Figure 10. Contour of Fusion Rates as a Function of Screening Length and Density

The contour plot highlights optimal fusion conditions, combining screening length and deuteron density effects. Regions of high fusion rates can be easily identified for practical application. The model demonstrates that quantum tunneling, when coupled with environmental screening effects, can result in fusion rates several orders of magnitude higher than would be expected in free-space or molecular deuterium scenarios. This supports the broader hypothesis that solid-state environments—particularly those that facilitate high-density, positively charged deuteron plasmas—can fundamentally alter the fusion landscape. The sensitivity of the tunneling probability to the screening length further emphasizes the critical role of electron dynamics and lattice structure in facilitating or suppressing fusion. Overall, the QSPF model offers a physically consistent and quantitatively plausible explanation for low-energy fusion in condensed matter systems, warranting further experimental and theoretical investigation.

4. CONCLUSION

This study presents a theoretical model demonstrating that nuclear fusion between deuterons can occur in a deuterium-loaded palladium lattice under low-energy conditions. By treating the deuterons as a quantum bosonic plasma embedded in a conductive metallic environment, and accounting for the screening effect caused by conduction electrons and collective plasma oscillations, the repulsive Coulomb potential is significantly reduced. This modification in the interaction potential lowers the effective fusion barrier, thereby enhancing the probability of quantum mechanical tunneling between deuterons. Numerical results based on this model show that while the fusion probability for any individual pair remains extremely small, the sheer number of interacting deuteron pairs within the lattice allows for a fusion rate that is non-zero and potentially measurable. The calculated fusion rate reflects the influence of key physical parameters such as deuteron density, screening length, and ground state energy. These results confirm that the palladium lattice does not merely contain the deuterons but actively modifies their interaction through its electronic and structural properties, enabling a fusion process at energies far below those required in conventional plasma-based fusion scenarios. This conclusion highlights the fundamental role of the solid-state environment in enabling enhanced tunneling and indicates that the combination of quantum confinement, charge screening, and lattice-induced coherence can collectively lead to observable fusion phenomena even in low-temperature conditions. The model provides a self-contained physical mechanism for such fusion without invoking high thermal excitation, exotic particles, or external catalysts.

REFERENCE

Appleby, A. J., Kim, Y. J., Murphy, O. J., & Srinivasan, S. (1990). Anomalous calorimetric results during long-term evolution of deuterium on palladium from alkaline deuteroxide electrolyte. *The First Annual Conference on Cold Fusion*.

Balantekin, A. B., & Takigawa, N. (1998). Quantum tunneling in nuclear fusion. *Reviews of Modern Physics*, *70*(1), 77.

Berlinguette, C. P., Chiang, Y.-M., Munday, J. N., Schenkel, T., Fork, D. K., Koningstein, R., & Trevithick, M. D. (2019). Revisiting the cold case of cold fusion. *Nature*, *570*(7759), 45–51.

Beuhler, R. J., Friedlander, G., & Friedman, L. (1989). Cluster-impact fusion. *Physical Review Letters*, *63*(12), 1292.

Czerski, K., Huke, A., Heide, P., & Ruprecht, G. (2004). The 2H (d, p) 3H reaction in metallic media at very low energies. *Europhysics Letters*, *68*(3), 363.

Dong, S. Y., Wang, K. L., Feng, Y. Y., Chang, L., Luo, C. M., Hu, R. Y., Zhou, P. L., Mo, D. W., Zhu, Y. F., & Song, C. L. (1991). Precursors to “Cold Fusion” Phenomenon and the Detection of Energetic Charged Particles in Deuterium/Solid Systems. *Fusion Technology*, *20*(3), 330–333.

Egorov, V. K., & Egorov, E. V. (2019). About cold fusion possibilities in frame of the waveguide-resonance propagation of radiation fluxes. *Journal of Physics: Conference Series*, *1370*(1), 012021.

Feng, S. (1989). Enhancement of cold fusion rate by electron polarization in palladium deuterium solid. *Solid State Communications*, *72*(2), 205–209.

Fleischmann, M. (1990). *OVERVIEW OF COLD FUSION PHENOMENA*.

Fleischmann, M., Pons, S., & Hawkins, M. (1989). Electrochemically induced nuclear fusion of deuterium. In *J. Electroanal. Chem* (Vol. 261).

Freire, L. O., & de Andrade, D. A. (2021). Preliminary survey on cold fusion: It’s not pathological science and may require revision of nuclear theory. *Journal of Electroanalytical Chemistry*, *903*, 115871.

Gou, Q.-Q. (2010). *Full atomic theory of cold fusion*.

Hora, H., Kelly, J. C., Patel, J. U., Prelas, M. A., Miley, G. H., & Tompkins, J. W. (1993). Screening in cold fusion derived from DD reactions. *Physics Letters A*, *175*(2), 138–143.

Hussein, A. A., Al-agealy, H. J. M., & Majeed, R. H. (2020). Theoretical Study and calculation The cold Reaction Rate of Deuteron Fusion In Nickel Metal Using Bose–Einstein Condensate Theory. *IOP Conference Series: Materials Science and Engineering*, *871*(1), 012085.

Jiang, S.-S., He, M., Wu, S.-Y., & Qi, B.-J. (2012). Anomalously high isotope ratio 3He/4He and tritium in deuterium-loaded metal: evidence for nuclear reaction in metal hydrides at low temperature. *Chinese Physics Letters*, *29*(1), 012503.

Jones, S. E., Palmer, E. P., Czirr, J. B., Decker, D. L., Jensen, G. L., Thorne, J. M., Taylor, S. F., & Rafelski, J. (1989). Observation of cold nuclear fusion in condensed matter. *Nature*, *338*(6218), 737–740.

Kasagi, J., Yuki, H., Baba, T., Noda, T., Ohtsuki, T., & G. Lipson, A. (2002). Strongly enhanced DD fusion reaction in metals observed for keV D+ bombardment. *Journal of the Physical Society of Japan*, *71*(12), 2881–2885.

Kesner, J., Garnier, D. T., Hansen, A., Mauel, M., & Bromberg, L. (2003). Helium catalysed D–D fusion in a levitated dipole. *Nuclear Fusion*, *44*(1), 193.

Kühne, R. W. (1994). The possible hot nature of cold fusion. *Fusion Technology*, *25*(2), 198–202.

Leggett, A. ~J., & Baym, G. (1989). *Can solid-state effects enhance the cold-fusion rate? 340*(6228), 45–46. https://doi.org/10.1038/340045a0

Lu, X., Wang, H. Y., Tian, J., Jin, L. H., Shen, B. J., & Zhao, X. Le. (2013). Abnormal Heat by Thermal Changing in a D-Pd Gas-Loading System. *Advanced Materials Research*, *614*, 253–258.

McKubre, M., Tanzella, F., Hagelstein, P. L., Mullican, K., & Trevithick, M. (2006). The need for triggering in cold fusion reactions. In *Condensed Matter Nuclear Science* (pp. 199–212). World Scientific.

Palleschi, V., Harith, M. A., Salvetti, G., Singh, D. P., & Vaselli, M. (1990). A plasma model of the process of cold nuclear fusion in metals. *Physics Letters A*, *148*(6–7), 345–350.

Parmenter, R. H., & Lamb Jr, W. E. (1990). Cold fusion in palladium: a more realistic calculation. *Proceedings of the National Academy of Sciences*, *87*(21), 8652–8654.

Scaramuzzi, F. (2004). Gas loading of deuterium in palladium at low temperature. *Journal of Alloys and Compounds*, *385*(1–2), 19–27.

Schreiber, M., Gur, T. M., Lucier, G., Ferrante, J. A., Chao, J., & Huggins, R. A. (1990). Recent measurements of excess energy production in electrochemical cells containing heavy water and palladium. *Proc. 1st Annual Conf. Cold Fusion, Salt Lake City, UT*, 44.

Scott, C. D., Mrochek, J. E., Scott, T. C., Michaels, G. E., Newman, E., & Petek, M. (1990). *The initiation of excess power and possible products of nuclear interactions during the electrolysis of heavy water*. Oak Ridge National Lab., TN (USA).

Szpak, S., Mosier-Boss, P. A., & Gordon, F. E. (2007). Further evidence of nuclear reactions in the Pd/D lattice: emission of charged particles. *Naturwissenschaften*, *94*, 511–514.

Tabet, E., & Tenenbaum, A. (1990). Nuclear reactions from lattice collapse in a cold fusion model. *Physics Letters A*, *144*(6–7), 301–305.

Toimela, T. (2006). Effective interaction potential in the deuterium plasma and multiple resonance scattering. In *Condensed Matter Nuclear Science* (pp. 622–634). World Scientific.

Vaidya, S. N. (1993). Comments on the model for coherent deuteron-deuteron fusion in crystalline Pd-D lattice. *Fusion Technology*, *24*(1), 112–114.

Van Siclen, C. D., & Jones, S. E. (1986). Piezonuclear fusion in isotopic hydrogen molecules. *Journal of Physics G: Nuclear Physics*, *12*(3), 213.

Yamaguchi, E., & Nishioka, T. (1990). Cold nuclear fusion induced by controlled out-diffusion of deuterons in palladium. *Japanese Journal of Applied Physics, Letters*, *29*(4), 666–669.

Yamaguchi, E., Nishioka, T., Rafelski, J., Gajda, M., Harley, D., & Jones, S. E. (1990). *Cold Nuclear Fusion Induced by Controlled Out-Diffusion of Deuterons in Palladium*.