Required Conditions for Successful Lattice Confinement Fusion in D/Pd Electrolysis Experiments

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Fleischmann and Pons [1989, 1990] reported electrochemically induced excess heat in palladium–deuterium system. No new chemical product has been detected in the experiments. The observed quantity of heat could not have been produced by any known chemical reaction. It was speculated that the reaction must be nuclear. In the past three decades many hundreds of successful experiments, producing electrochemically induced excess heat in the palladium–deuterium system, have been reported [Storms, 2007; Storms & Grimshaw, 2010]. Experiments along with the excess heat, also detected ^{4}He with qualitative correlation to the measured excess heat [Bush et al. 1991; Gozzi et al., 1998; Arata & Zhang, 1999/a, b; Miles et al., 2003; 10]. The collected ^{4}He had the correct magnitude for the deuterium fusion reaction:

$$D + D \rightarrow {}^4He\ (73.7\ keV) + (23.8\ MeV). \tag{1}$$

The production of ^{4}He was confirmed by many independent experiments [Liaw et al., 1991; Chien et al., 1992; Miles et al., 1996], and the measured quantity of ^{4}He in many cases exceeded the ^{4}He content of the air. Thus, possible contamination by air can be excluded.

The many hundreds of experiments reporting excess heat, which cannot be explained by chemical reaction, the measured ^{4}He fission product commensurate with deuterium fusion, demonstrates that fusion can occur at low temperature and pressure. Despite these convincing experimental verifications, the possibility of low temperature nuclear reaction is still debated by the scientific community, because the reproducibility of the experiments is a problem. In this study the conditions, reported from successful experiments, are collected and analyzed.

The process originally was called cold fusion, but has been renamed many times. The most widely used contemporary name is Low Energy Nuclear Reaction (LENR). The author believes that the most descriptive name for the process is - lattice confinement fusion - which is used in this study.

Fusion of Deuterium

The known and detected nuclear fusion processes of deuteriums in plasma and hot fusion reactors are [Storms, 2022]

1./ $D + D \rightarrow {}_4He\ (73.7\ keV) + (23.8\ MeV)\ (10^{-7})$.
2./ $D + D \rightarrow T(1.01\ MeV) + p\ (3.02\ MeV)\ (50\%)$,
3./ $D + D \rightarrow {}_3He\ (0.82\ MeV) + n\ (2.45\ MeV)\ (50\%)$, and

In hot fusion the high energy collisions of the nuclei is sufficient to detach either a proton or a neutron. Based on probability the chances should be half and half for proton or neutron detachment. This assumption is consistent with the observed probability of reaction 2 and 3. In few cases, even in hot fusion experiments, the energies are insufficient to detach a nucleon and reaction 1 occurs. If the fusion occurs at low energies then predictably reaction 1 should become the dominant process. The reported probability for the occurrence of reaction 1 in successful Lattice Confinement Fusion experiments is 99.9%. Thus, at low temperatures and pressures the lattice Confinement Fusion reaction is $D + D \rightarrow {}^{4}He$ (73.7 keV) + (23.8 MeV).

The physics of fusion is very simple. Two nuclei, which have smaller atomic numbers than iron, have to encounter into femto meter distance and the reaction will occur. The major obstacle against low temperature nuclear reactions is that the atoms have insufficient energy to overcome the repulsion of the protons. Based on the current description of the electronic structure of the atoms (Garai, 2017; 2023) this objection does not necessarily hold, since the repulsion of the protons can be shielded by the surface charge electron shell, surrounding the nucleus. This shielding makes the reaction possible. Please note that the shielding affect of the electron shell is effective as long as the valence electron shell remains intact. Thus, Lattice Confinement Fusion can occur as long as the atoms are not ionized. Consequently, the first ionization energy sets an upper limit on the Lattice Confinement Fusion.

The structure of the atoms

It has been experimentally detected that the neutral atoms built up from oppositely charged particles. The negatively charged electrons had been discovered by J.J. Thomson in his gas tube experiments with Hydrogen in 1897. The atoms in ground state are neutral; therefore, the negatively charged electrons must be balanced out by positive charges. Thomson was well aware of Earnshaw's theorem (1842), which states that two equal but opposite charges can only be in stable stationary equilibrium if at least one of the charges is distributed one. Thomson's experiments indicated that the freed electrons from the atoms are point-like charges. Consequently, he was assuming that the positive charges should be a distributed charge. Based on this hypothesis he proposed the "plum-pudding" model for the atoms.

The scattering experiments of Hans Geiger and Ernest Marsden, supervised by Rutherford (1911), showed that there is a small, but heavy positively charged core (nucleus) inside the atom, which consist almost the entire mass of the atom. Based on these experiences it was concluded that both the electron/s and the nucleus should be considered as point charges. Please note that the point charge nature of the electron was verified experimentally outside of the atoms, which has never been confirmed for electrons captured in the atoms by the nucleus.

If both the electrons and the nucleus can be considered as a point charge, then the stability of the atoms can only be possible if the attraction of the nucleus on the negatively charged electron/s is balanced out by the centrifugal force of the orbiting electron/s. Consequently, Rutherford envisioned the atoms as a miniature solar system, in which electrons orbit around the massive nucleus. This model contradicts classical electromagnetism, since the accelerating charged particle should emit radiation, and this energy loss would spiral the electron into the nucleus. Atoms are stable in the timescale of the universe and in ground state do not emit radiation. In order to eliminate this discrepancy, Bohr (1913) postulated that parts of the laws of electromagnetism are not valid at atomic scale. Theoretical base has never been proposed for this postulate. The other postulate of Bohr is that the orbiting angular momentum of the electron (L) is quantized as:

$$L = n\hbar \quad where \quad n = 1, 2, 3... \tag{2}$$

where $\hbar$ is the reduced Planck constant. This postulation is consistent with experiments and the quantized angular momentum description of the electron successfully reproduces the main emission lines of the Hydrogen atom, and the Rydberg constant. Bohr's orbiting electron model is one dimensional with the only variable of the radius (r). His atom model; therefore, cannot describe the complete emission spectra of the Hydrogen atom. Sommerfeld realized that the precise description of the spectra requires the introduction of additional variable/s. He was suggesting elliptical orbits for the electrons instead of the circular ones. This Bohr-Sommerfeld model still had deficiencies and is incomplete.

Based on the particle-wave duality of matter, Schrödinger (1926) suggested that the orbiting electrons in the atom should be considered as waves. The proposed wave equation contains three variables, radial, (r), azimuthal (θ), and polar (ϕ). These three variables R(r); P(θ), and F(ϕ) relate to the spatial quantum numbers, principle (n), orbital angular momentum (l), and magnetic (m_l) respectively. This three dimensional wave description of the electron can reproduce all the emission lines of the Hydrogen atom. Based on Schrödinger's wave description of the electrons it is assumed that the orbiting electrons form a cloud around the nucleus, which depicts the probable location of the point charge electron/s. This description is unable to explain all the known features of the atoms, but the current consensus is that "It works, so we just have to accept it.".

Three dimensional description would not be needed for a point charge orbital. Schrödinger's wave equation, with its three variables, describes the vibration of a spherical surface. Charge is conserved; therefore, the charge of the spherical surface can only be created from the captured point charge electron. The proposed physical explanation for the Schrödinger's description of the electrons is that the point charge free electron goes through a phase transformation at capturing to a surface charge. This assumption explains the stability of the atoms in the timescale of the universe, contrarily to the orbital electron model. The assumption is further supported by the observed differences between the free* and captured electrons. These differences indicate that these electrons are not identical. Assuming "phase transformation" from point to surface charge at capturing and visa versa is consistent with and can explain the known differences between the free and captured electrons (Garai, 2023, 2024, 2026). In this atomic structure the opposite charges are in static equilibrium, which does not require to violate the laws of electromagnetism. The disturbances of this surface charge shell triggers vibration in the shell, and these generated waves propagate in the surface charge shell as described by the Schrödinger's wave equation. The timeline for the development of the atomic structure is shown on Figure 1.

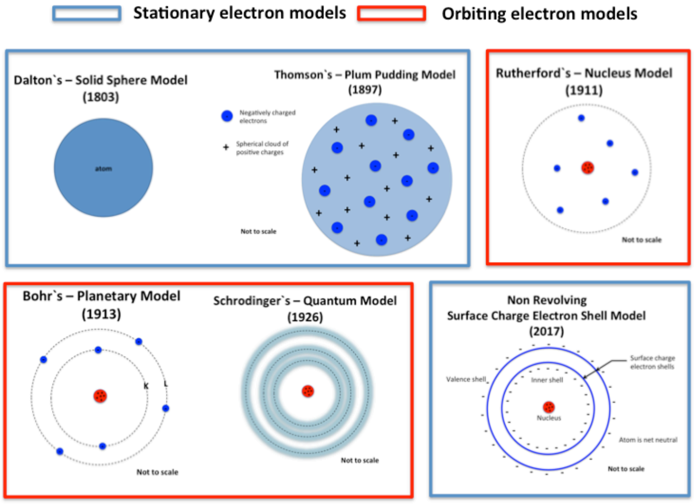

Figure 1. The timeline of atomic structures (Garai, 2025).

The surface charge electron shell atomic structure can shield the repulsion of the protons, allowing close encounters of the nuclei (Fig. 2). If the two nuclei get into femto meter distance from each other then fusion can occur. The required conditions for this reaction are discussed here.

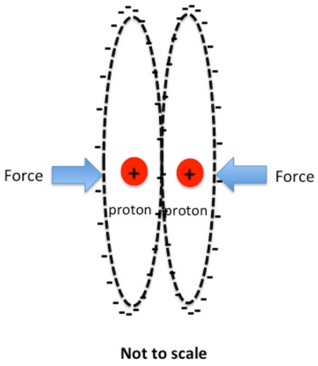

Figure 2. Schematic figure showing the shielding of the surface charge electron shell. This shielding effect allows the close encounters of the nuclei.

Conditions required for successful electrolysis experiments

In the past three decades the conditions required for successful experiments are mapped out quite well for the palladium–deuterium electrolysis. These conditions are collected from the reported successful experiments in the literature, and listed here.

- the loading of Deuterium should be very slow and the system should have a relatively low temperature [Cravens, 1993]
  (The diffusion of the deuterium into the palladium crystal structure introduces significant volume change. In order to accommodate this volume increase without damaging the crystal structures the loading must be very slow.)
- the D_2O should be pure, containing the least H_2O possible
- the loading of D/Pd should be higher than 85% [McKubre, 2009]
- mono-vacancies should be present in the crystal structure
- the current density should exceed a certain threshold
- the reaction can be enhanced by:
    - increasing the current density,
    - increasing the temperature, and
    - the application of magnetic field (Cravens, 1993; Bockris et al., 1993)
- electrical pulses can initiate and enhance the reaction
- laser excitation can initiate the reaction
- laser induced phonon vibration at 8.2, 15.1, and 20.8 THz frequencies triggers the reaction, which remains active even if the laser turned off [Letts et al., 2009]
- the fusion reaction requires special surface preparation and/or cracks or gaps on the surface of the lattice [Letts & Cravens, 2003; Storm, 2022]

(The occurrence of the reaction at the surface is supported by the detection of He. Helium does not diffuse very rapidly in Palladium. Measuring the He in the successful experiments indicates that the He must be formed at or very near to the surface of the cathode. Recipe and technical detail, how to produce nanometer size cracks on the surface of Palladium, has also been presented at ICCF-24 [Storm, 2022]. The heat production on the surface is localized, like hot spots, which are associated with mini explosions.)

Any theoretical explanation, or physical model for Lattice Confinement Fusion must be consistent with all these experimentally observed conditions. Many of the required conditions are self-explanatory, like the positive effect of current density, temperature etc. In this study the effect of magnetic field, laser excitation, and surface requirements will be discussed.

The effect of the magnetic field

Experiments of D/Pd electrolysis detected that the magnetic field has a positive effect on the reaction because it increases the produced excess heat (Bockris et al.; Cravens, 1993, ICCF-4; Liu; Romodanov; Cravens & Letts, 2003, ICCF-10). The effect of the magnetic field on the heat production had been reported only for D/Pd electrolysis experiments. How and why the magnetic field affecting the reaction is analyzed.

The liquid heavy water (D_2O) in the electrolyte dissociates to deuteroxide (OD^-), and to the deuteron (D^+), which immediately protonated by another heavy water molecule and forms a deuteronium cation (D_3O^+). The deuteronium cation has a dipole moment. The extra positive charge of the deuteronium is equally distributed on the three deuterium atoms, while the oxygen atom has excess negative charge. In the electrolyte the deuteronium cations move toward the negatively charged cathode. The charge of the cathode is stored on the surface of the metal, which produces an electric field perpendicular to the surface of the metal. The electric field forces the charged particle in the electrolyte to move along the field lines. Consequently, the most likely direction of an impact of the charged particles on the surface of the cathode or anode is perpendicular to the surface of the metals. Under the effect of the electric field the three deuterium atoms will orient themself towards the negative cathode and most likely will hit the surface of the cathode as shown in Figure 3.

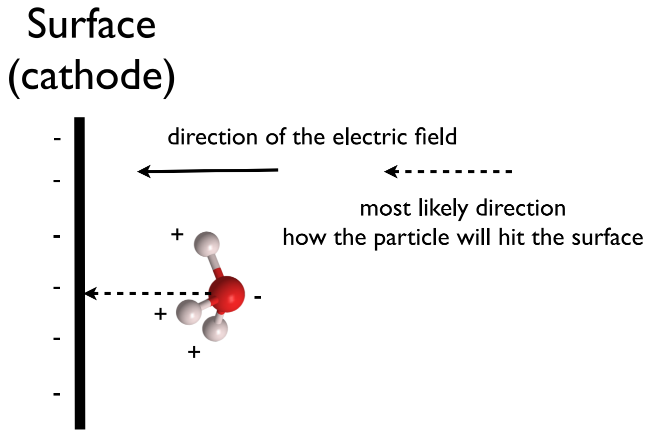

Figure 3. The most likely direction of the impact of the deuteronium cation (D_3O^+) on the surface of Palladium.

This impact position of the cation would not utilize the entire momentum of the deuteronium. The most effective direction of the impact would be, when the deuterium and the oxygen atoms (more precisely with the center of the mass of the cation) are lining up with the direction of the impact. This way the momentum of the oxygen/entire cation will be fully transferred to the deuterium, when the deuterium hits the surface. The increased energy of the impact, predictably, should enhance the possibility of fusion.

The application of magnetic field can modify the direction of the impacting deuteronium cation. The combined effect of the electro and magnetic fields could force the deuteronium cation to hit the surface of the cathode when the direction of the impact is aligned with the direction of the deuterium-oxygen (Fig. 4).

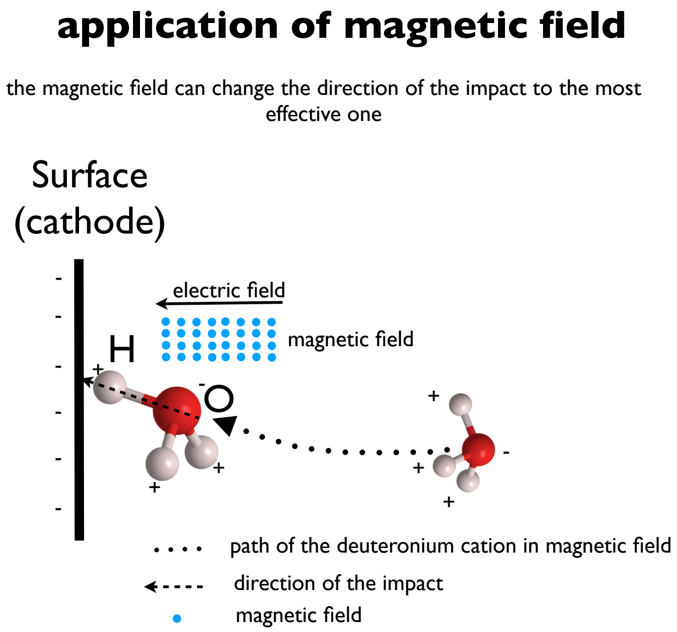

Figure 4. The most effective utilization of the momentum of the deuteronium cation projectile if the deuterium and oxygen atoms are in line up with the direction of the impact. In this case the entire momentum of the oxygen atom is fully utilized by the deuterium, hitting the surface of the metal.

The deuteronium cation has a dipole moment; therefore, the magnetic field can create a torque on the dipole of the cation and by that change the orientation of the deuteriums. In this case the impact remains close to perpendicular to the surface with optimum momentum transfer. The application of the magnetic field can increase the transferred energy of the projectile in two ways, changing the direction of the impact, and turning the projectile into the optimum impact position. The perpendicular magnetic field to the electric field allows to change the direction of the impact, while the close to parallel magnetic field with the electric field can aline the cation into the most effective impact position. Thus, the application of a close parallel magnetic field with the electric field should be more effective than the perpendicular magnetic field. This theoretical prediction is consistent with experimental results. The highest effect of the magnetic field on the excess heat was observed when the field was perpendicular to the surface of the cathode (Chubb and Letts, 2011).

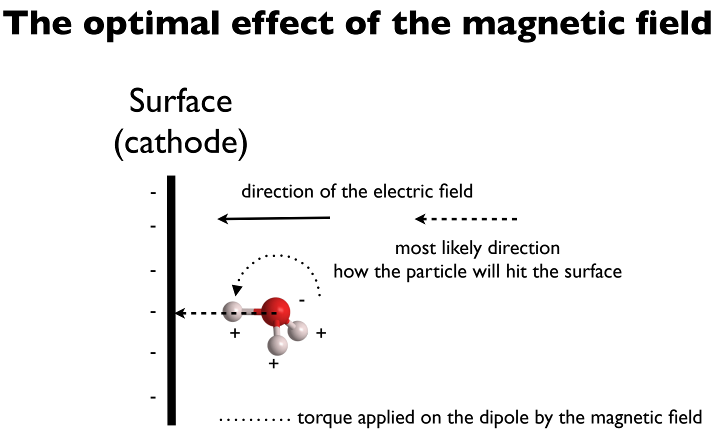

Figure 5. The magnetic field has its optimal effect if the projectile hits the surface perpendicularly and the deuterium atom lines up with the oxygen atom and the direction of the impact.

Applying a magnetic field with the right strength and direction should force the deuteronium cation to hit the surface of the cathode in the most effective way, which maximizes the momentum of the impact (Fig. 5). The optimum direction and the strength of the magnetic field, which is most likely also affected by the temperature and current, should be experimentally defined.

Laser excitation

Optical phonon vibrations induced by laser/s can trigger the reaction under conditions where the cathode was below threshold for the excess power production. In the PdD system the so-called "sweet spots", where excess heat production were initiated, are 8.2, 15.1, and 20.8 THz [Cravens & Letts, 2003; Letts et al., 2009]. The observed 8.2 and 15.1 THz frequencies correlates well with the Γ and L point vibration of PdD respectively. Thus these vibrations can be associated with optical phonon frequencies of PdD with zero group velocities. There are no optical phonon modes in PdD, which would associate with the peak in the excess power spectrum at 20.8 THz. It was suggested that this frequency relates to the resonant frequency of the deuterium molecule in a cavity (Garai, 2019). In order to activate this triggering frequency either vacancies or cavities are needed. The resonance frequency of the Deuterium molecule, which is bouncing back and forth from the wall of the cavity is different from the zero point energy of the diatomic deuterium. The calculated fundamental frequency of the vibrating Deuterium molecule in a cavity is 2.165×10^{13} Hz (21.65 THz), which is almost identical with the observed "sweet spot" at 20.8 THz (Fig. 6).

Using the same model, the self frequencies of HD and H2 in the cavity had also been calculated. The calculated frequencies of HD and H2 are 2.500×10^{13} Hz (25.0 THz), and 3.062×10^{13} Hz (30.62 THz) respectively. The temperatures relating to the fundamental vibrational frequencies of D2, HD, and H2 in the cavity had also been calculated. These temperatures should be the optimum values for stimulating the reactions. The calculated frequencies in the cavity, the experimental vibrational ZPE energies, and the equivalent temperatures for D2, DH, and H2 are listed in Table 1.

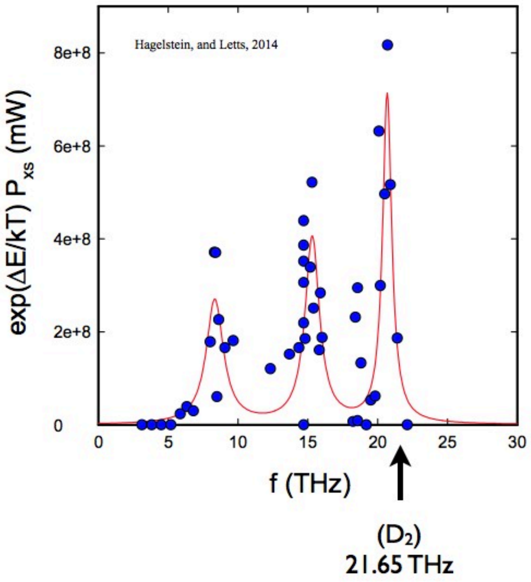

Figure 6. Frequencies relating to excess heat production. The two lower frequencies relate to lattice vibration, while the higher one is almost the same as the calculated fundamental frequency in the cavity for deuterium molecules.

Table 1 The fundamental vibrational frequencies in cavity, the zero point energy of the diatomic vibration [Irikura, 2007], and the equivalent temperatures of these vibrations for D2, HD, and H2 are shown.

vibration in cavity	**D_2**	**HD**	**H_2**
fundamental frequency (THz)	21.65	25.00	30.62
wave number (cm^{-1})	722	834	1,021
activating temperature (K)	1,039	1,200	1,470
diatomic vibration	**D_2**	**HD**	**H_2**
ZPE frequency (Hz) [52]	46.36	56.67	65.33
ZPE wave number (cm^{-1})	1546.50(8)	1890.3(2)	2179.3(1)
activating temperature (K)	2,225	2,720	3,135

Surface requirements

In the plasma phase the deuterium atoms are ionized, and the close encounter of the nucleus, resulting in nuclear reaction, requires very high energies. However, if the deuterium atoms are not ionized, then the surface charge electron shell can shield the repulsion of the protons allowing them to get close to each other. Low temperature nuclear reactions are not reported from vapor or liquid phase phase but rather in solids. The role of the solid phase in the reaction is investigated.

In solid phase the deuteriums are bonded to the metal, like Palladium or Nickel. Thus their position is fixed in space. Upon encountering another atom these bonded atoms would not bounce away but rather absorb the energy of the impact. The bonding is the strongest against the impact if the atoms are trapped in the bottom of a cavity. In this case the support of the neighboring atoms makes the “bonding” stronger and fixes the position of the atom.

Assuming equal probability for the impacting projectile in space, the probability of two nuclei getting close enough can be estimated by the ratio of the cross section of the nucleus, and the cross section of the atoms. The ratio of the two cross sections, or estimated probability for encountering deuterium nuclei is 3.6×10^{-10}.

$$P(encounter) = \frac{A_{nucleus}}{A_{Deuterium}} = 3.6 \times 10^{-10} \tag{3}$$

The cavity on the surface of the metal not just fixes the position of the Deuterium, but also guides the impacting atom to the right position to encounter with the other deuterium.

It is speculated that the closest approach of the two nuclei can be achieved if the electron shells of the D/H atoms “completely flatten out”. The complete flattening of a spherical surface can be achieved when the width of the cavity is half of the great circle of the Deuterium atom (Fig. 7). Assuming the Bohr`s radius for the atomic size of the Deuterium/Hydrogen, the optimum width of the cavity for nuclear reaction is then:

$$\frac{d_{cavity}}{d_{Deuterium}} \approx \frac{\pi}{2} \qquad \Rightarrow \qquad d_{cavity} \approx \frac{\pi}{2} d_{Deuterium} \approx 1.7\mathring{A} \tag{4}$$

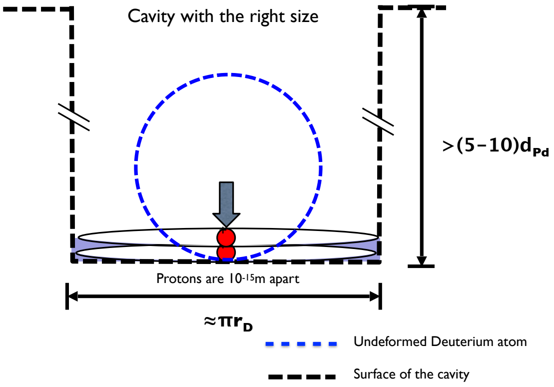

Figure 7. The optimum size of the cavity on the surface of the cathode results in the closest encounter of the nucleus and fusion. The Deuterium atoms are flattened out completely, and the side of the cavity guides the two nuclei to be in contact with each other.

This optimum size is about one order smaller than the proposed 2 nm by Storm (2022). Experiments with 2 nm, nano-size particles still report excess heat [Itoh et al. 2017; Iwamura et al, 2020], which sets an upper limit on the size of the opening. Thus, the opening size should be smaller than 2 nm. Consequently, the calculated 1.7Å optimum size seems to be more reasonable than the proposed 2 nm by Storm. Bigger size of the cavity than the optimum one would reduce the probability of the fusion (Fig. 8).

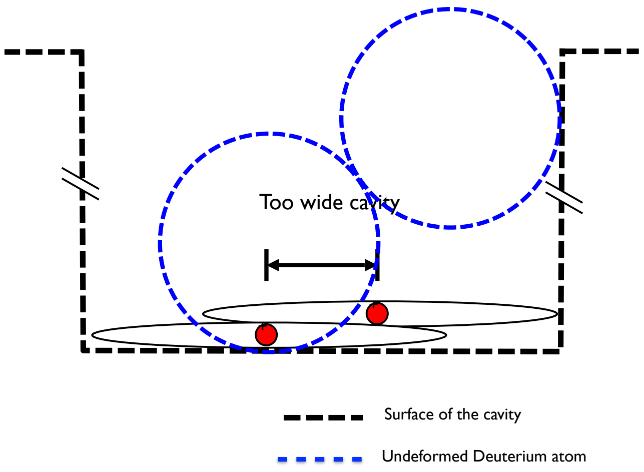

Figure 8. If the cavity is too small then the electron shells of the atoms cannot be flattened out completely; therefore, the two nuclei could not encounter closely enough for fusion. If the cavity is too wide then there is a high chance the two nuclei would miss each other, and fusion would not occur.

The energy released by each reaction is 23.8 MeV/fusion. In order to absorb the released energy, the energy absorption per lattice must remain below the lattice bond energy, which is estimated to be 20-25 eV for the host metals. Based on this assumption the estimated minimum depth of the cavity/cracks or NAE should be at least 5-10 atomic layers, or about 1-2 nm (Fig. 6). If the NAE sites are too close to each other, then the lattice cannot absorb the released heat, and the reaction site will be melted. Melting spots on the surface of the metal have been reported by many experiments. In order to avoid this melting, the minimum distance between the nuclear active sites should be 10-20 nm. The suggested the crack or gap size, and distribution from theory should be verified experimentally. The cavities on the surface dominantly originate from lattice vacancies. Correlation between excess power and the number of vacancies on the surface had been reported by Letts (2013). He was suggesting that the positive effect of temperature on the excess power resulting from the created higher number of vacancies at higher temperatures.

Hydrogen diffusion in nano-size composite material can also generate heat, or presumably a nuclear reaction [Itoh et al. 2017; Iwamura et al, 2020]. In this case the reaction is activated by inside out flow, or outgoing flux of D/H. In this “inside out flow” the reaction presumably occurs in vacancy, the physical process should be the same as described here, and only the direction of the flux is reversed.

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* Based on the standard definition, the electron is free, when the potential field is zero. In this text the expression of free electrons refers to non-bonded electrons.

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