Virtual State Internal Nuclear Fusion in Metal Lattices

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A model of deuterium-deuterium (D-D) fusion in metal lattices presented based on two phenomena:

(a) reactions between virtual-state pairs of deuterons "bound" by electrons of high effective mass m* and

(b) deuterium energy upscattering by fast ions from fusion or tritium reactions with virtual state nuclear structure groups in palladium nuclei.

Since m* is a decreasing function of deuterium ion bulk density n_o, the exponential barrier tunneling factor decreases rapidly with m*. As a result, the fusion rate reaches a maximum at a loading density above zero but less than saturation. This can explain observations of transient neutron output from the (^{3}He,n) branch of D-D fusion. At low energy, D-D reactions favor the (T,p) branch. Fast product tritium may be captured by palladium isotopes to form excited-state Ag*, removing tritium from the system and preventing deuterium-tritium fusion. This may decay by alpha or proton emission, yielding fast ions and excited state Rh* or Pd*. Fast ion collisional "trapping" may occur at Fermi electron speeds, enhancing in situ upscattering and yielding increased D-D reaction rates. Analysis of the dynamics of these processes suggest conditions for exponential growth.

Introduction

The normal palladium lattice configuration is face-centered cubic with a density of n_{Pd} = 6.78 x 10^{22}/cm^3, a lattice spacing of a_L = 3.89 A, and a distance to the nearest neighbor 2.75 Å. Deuterons may be loaded up to an atomic density ratio $\langle n \rangle = n_D/n_{pd}$ = 0.88. Their proximity suggests the possibility of fusion reactions. Following along lines begun by Jones *et al.*,[1] recent experiments were reported by Fleischmann and Pons,[2] who suggested that deuterium-deuterium (D-D) nuclear fusion in such lattices, or "other nuclear energy processes" stimulated by D-D fusion, were responsible for energy releases claimed to yield net power, energy, and palladium lattice meltdown. Later experimental studies of this issue[3,4] have cast serious doubt on the reported long-term power production, but related phenomena showing low-level transitory neutron generation at varying deuterium density conditions have been reported at Frascati.[5] The purpose of this technical note is to suggest a phenomenological model embodying several physical mechanisms that exhibit these effects, to analyze this model, and to consider some of its dynamic aspects.

Lattice Induced Fusion

Early work by Van Siclen and Jones[6] in muon-catalyzed D-D fusion, based on concepts introduced by Jackson,[7] showed the efficacy of synthetically reducing inter-deuterium spacing by using heavy mass negative particles for molecular binding. A simple semiclassical model for fusion reaction cross sections was used in analogy to those for normal free particle interactions. This model employed the molecular separation as the determining parameter for specification of an equivalent interaction energy between deuterium nuclei in any virtual-state molecule.

The coulomb interaction energy E_c between two D^+ ions at their point of closest approach ra is $E_c = e^2/r_a$. Mean separation is inversely proportional to the mass m^* of the binding negative electrons. In a normal molecule, $m^*/m_e = \langle m^* \rangle$ = 1, the mean separation is 0.74 Å, and r_a = 0.662 Å. The equivalent energy or deuteron pairs bound by negative particles of arbitrary mass m^* can then be written, for in situ spacing of r_a as

$$E_q = \left(\frac{e^2}{r_a}\right)\left(\frac{m^*}{m_e}\right) = E_c \left\langle m^* \right\rangle \quad (1)$$

The usual formulas for fusion interaction cross sections[8] show that the Gamow barrier penetration probability is proportional to $(a_2/E)\exp(-a_1/E^{0.5})$ at energies E < 50 keV, where a_j are constants determined by the interaction potential function shape. Taking standard values for these, for the two main branches of the D-D reaction, gives the branching ratio between (^{3}He,n) and (T,p) as

$$\frac{\sigma_{He,n}}{\sigma_{T,p}} = 1.352 \exp\left(\frac{-0.897}{\sqrt{E}}\right) = R_n \quad (2)$$

for $E = E_q$ in kilo-electron-volts, for D-D virtual pairs in the center-of-mass (c.m.) frame. From this it is readily seen that the (^{3}He,n) branch will be frozen out at normal (small) lattice energies. For example, if the lattice D-D pairs are bound (virtual state) at an equivalent energy of E_q = 10 eV, the branching ratio is only 1.81 x 10^{-4}, and the (T,p) branch is > 5500 times more likely than the (^{3}He,n) branch. Using the expression for "equivalent" energy from Equation (1) yields the favored branch cross section (σ in barns) dependence on negative particle mass as

$$\sigma_{DD}(T,p) = \frac{37.38}{E_c \langle m^* \rangle} \exp\left[-\frac{23.048}{\left(E_c \langle m^* \rangle\right)^{1/2}}\right] \quad (3)$$

where E_c (keV) is the coulomb energy of deuterons at closest approach.

Electron Mass Effects

This simple approach assumes that the shape of the deuteron wave function, for closely bound D-D interactions away from the palladium sites, is not changed significantly from its free-space or free-molecular form by the field structure due to palladium in the lattice. Of course, the wave function is distorted in the region of the palladium, but this is not where the deuterons will "see" each other. To a first approximation, this assumption is reasonably true, because central time averaged lattice positions of deuterons in the palladium system are within a "cage" of six or eight palladium atoms; and each deuteron is relatively free to move about within this potential well. Since the nearest neighbor spacing of deuteron centers is equal to or less than that of the palladium (depending on the fill density), and the deuterons see a rather flat central potential field over most of their trapped volume, there is ample room to approach neighboring deuteron nuclei without significant effect from fixed-point lattice palladium nuclei. The D-D interaction wave functions in this inter-palladium space must then be not markedly different from their free-molecular form, and the six- or eight-fold symmetry of the palladium lattice positions suggests that there will be very little mixing of cross terms $\langle \Phi_D | H | \Phi_{Pd} \rangle$ in the Hamiltonian for the deuterium "molecule" in its closest approach virtual-bound state, when $r_a << a_L$.

Most of the electrons are trapped in degenerate states in inaccessible energy levels in the lattice. In the regions between palladium atoms, the deuterons see and are "bound" by conduction electrons of the band structure. These electrons exhibit an "effective mass" that may be considerably higher than that of a free electron, due to their strong electric interaction with the repetitive potential structure of the lattice itself. Electron motion under externally imposed oscillating electric fields is therefore governed by the degree to which they are connected to the lattice fields. Electron density waves due to currents propagate through and interchange momentum with this structure.

If there are many free electrons at the top of unfilled energy bands (as in the case of bare palladium), the coupling will be strong and the effective mass large (m* = 27 in bare palladium). As the number density of available electrons is decreased, the coupling and the effective mass decrease. Both Seitz[9] and Kittell[10] point out that the effective mass is a real physical phenomenon, not simply a mathematical construct concerning "... density of states and energy in the band structure...," as argued recently by Garwin.[11]

The model here invokes this in-lattice effective mass as the mass of the negative binding particles in the formation of D-D virtual "molecular" states within the lattice. In effect, the D-D pairs are "bound" by the mass of a portion of the lattice, as it is coupled to its electrons through the lattice band structure. Oscillations of the trapped deuterium nuclei in their individual wells are seen by the available electrons as time varying electric fields, and they respond accordingly. Thus, large probability amplitudes for transitory D-D "bound" virtual state wave functions can be constructed at small separation distances, if the electron effective mass is sufficiently large.

As donor electrons are added to unfilled energy bands in transition metals with large effective mass, the effective mass is reduced. When the lattice-average ratio of deuterium-to palladium atoms $\langle N \rangle = N_D / N_{pd}$ reaches ~2/3 the effective mass ratio decreases to $\langle m^* \rangle = 1$, and nearly all the enhanced virtual binding effect will have vanished. The effective mass for palladium can then be written for $\langle N \rangle \leq 2/3$ as

$$\langle m^* \rangle = \left[1 + 26\left(1 - 1.5\langle N \rangle\right)\right] \quad (4)$$

From Equations (3) and (4), it is obvious that the fusion reaction probability varies with $\langle n \rangle$ and $\langle N \rangle$ as these change with time. The reaction rate density is simply $q_f = n_D \Gamma_f b_{ij}$, where b_{ij} = 0.25 for like particles and 0.5 for differing particles [e.g., deuterium-tritium (D-T)]. The reaction rate coefficient is given by

$$\Gamma_f = n_D \sigma \left(\frac{2E\langle m^* \rangle}{m_D}\right)^{1/2} \quad (4a)$$

thus

$$\Gamma_f = 7.817x10^7 \left(\frac{\langle n \rangle}{\sqrt{E_f}} \right) \exp\left[\frac{-23.048}{\sqrt{E_f - E_a}} \right] \quad (5)$$

Here the gross equivalent energy is $E_f = \langle m^* \rangle E_c$, and the simple fit to the barrier penetration factor has been adjusted by the term $E_a = (3/2)\, E_{osc}$ (E_{osc} is deuterium ground state oscillation energy in the lattice potential well). Results from this equation agree well with those for both normal and mu-molecules, as given by more complex calculations.[8] Note that the local reaction rate depends on the local density ratio $\langle n_D \rangle$, while the equivalent energy is a function of the lattice-averaged atom ratio $\langle N \rangle$. This is because the electron wave functions are spread over the entire lattice; thus/the electron effective mass is only slightly affected by local variations of n_D.

Mass Diffusion in Lattices: Time Dependent Effects

The diffusion of deuterium into palladium is well understood.[12] During loading, higher n_D is expected locally near surfaces, while unloading results in higher interior densities. Since $\langle m^* \rangle$ is set by $\langle N \rangle$, not by $\langle n_D \rangle$, it is possible to operate with high local $\langle m^* \rangle$ and high local $\langle n_D \rangle$ during transient conditions. The reaction rate density varies as the square of $\langle n_D \rangle$; thus, rapid loading can lead to high reaction rates that fall as the deuterium spreads through the lattice. This can be seen by writing q_f to explicitly show its time dependence:

$$q_f(t) = b_1 \left[\frac{\langle n(t) \rangle^2}{F(t)} \right] \exp\left[\frac{-b_3}{F(t)} \right] \quad (6)$$

where $F(t) = [1 - b_2 \langle N(t) \rangle]^{1/2}$, the b_i are numerical factors, and the barrier kinetic energy term E_a has been suppressed. If $\langle n_D \rangle$ is changing with $\langle N \rangle$, it is evident that runaway conditions can occur as $\langle N \rangle$ varies with time. Differentiating Equation (6) for the case where $\langle n_D(t) \rangle = \langle N(t) \rangle$ yields

$$\frac{d \ln q_f}{dt} = \frac{d\langle N \rangle}{dt} \left[\frac{2}{\langle N \rangle} + \frac{b_2}{2(1 - b_2 \langle N \rangle)} - \frac{b_3 b_2}{2(1 - b_2 \langle N \rangle)^{3/2}} \right] = G(t) \frac{d\langle N \rangle}{dt} \quad (7)$$

Conditions for exponential growth are $d\langle N \rangle/dt < 0$ for negative $G(t)$ and $d\langle N \rangle/dt > 0$ for positive $G(t)$. For the units previously used, $b_2 = 13/9$ and $b_3 = 1.40$. The last term, in $G(t)$ is dominant for large $\langle N \rangle$ (and thus for large $\langle n_D \rangle$); while the first term dominates for $\langle n_D \rangle$, $\langle N \rangle \rightarrow 0$. Thus, at small $\langle N \rangle$, when q_f is also small, increasing $\langle N \rangle$ gives exponential growth, while from large $\langle N \rangle$, negative $d\langle N \rangle/dt$ yields exponentiation. If the system is being started, these transients give immediate neutron output [from the (^{3}He,n) branch], decreasing as local fill densities approach mean values. Similarly, at shutdown from uniform density, neutron output first increases, then decreases, in agreement with reported observations.[5]

Noting that $\langle N \rangle$ is limited here [by definition in Equation (4)] to 2/3, the maximum (negative) value of the coefficient $G(t)$ is approximately $G_{max} = -119.4$. If the deuterium fill is dumped in 300 s, for example, then $d\langle N \rangle/dt = -3.33 \times 10^{-3}$/s, and the reaction rate density varies with a time constant of only 2.50 s, so that $q_f(t) = q_{f0} \exp(0.4t)$.

> *The dumping rate may also be a function of the reaction rate, if the loss of deuterium promotes release of stored lattice energy or energetic chemical reactions.*

If a filled system is producing sufficient power (from any source) to heat the lattice significantly, the deuterium outflow can be driven still more rapidly, and short time constants are generated. Since these can be much shorter than conventional means to control bulk deuterium density in the lattice, the process may run away and lead to lattice melting.

This can happen from *in situ* D-D fusion alone only if the reaction rate is large enough to generate the required heating power. Within the lattice, the equivalent binding energy in the c.m. frame is $E_q = E_c/4$, where $E_c = e^2/r_a$ as before, and r_a is the minimum internuclear spacing in the virtual state molecule. In an empty system, $\langle N \rangle = 0$, $\langle m^* \rangle = 27$, and the equivalent binding energy in the c.m. frame is $E_q = 0.147$ keV. Then, the fusion rate for D-D virtual-state pairs is given by Equations (6) and (7), and the neutron production rate density $q_n = (q_f R_n)$ is set by the branching ratio Equation (2). For the slowly varying case where $\langle n_D \rangle \approx \langle N \rangle$, both q_f and q_n teach a broad maximum in the range $0.01 < \langle N \rangle < 0.1$, as shown in Figure 1. Their initial value is zero, but it increases until a maximum of the order of 5 reaction/s cm^{-3} is reached and falls off sharply for density rising above $\langle N \rangle > 0.15$ to 0.2. Similar calculations for transient start-up show that the total initial output from a 6-cm^2 palladium element could be about $Q_f = q_f$(volume) = 5.6×10^{-2} reaction/s, and the neutron generation could be $Q_n = q_n$(volume) = 7.2×10^{-3} n/s, in crude agreement with early reports[2] of experiments.

No conditions are found at which the reaction rates can ever reach values of interest for power generation by *in situ* virtual-state D-D reactions alone; the rates are all too low by 12 to 14 orders of magnitude. Thus, some other source of energy production must be found if large power generation is sought.

Fast Ion Slowing Down, Knock-on Collisions, and Chaining Reactions

The most obvious source for additional energy is from reaction of tritium with *in situ* deuterium by the usual D + T → ^{4}He + n reaction. The D-D reaction rate may then be increased if local deuterium nuclei can be excited by collisions with fast tritons, protons, or ^{4}He to energies significantly above the effective 100 to 150 eV that characterize lattice fusion in the virtual bound state just described.

Long-range coulomb collisions with electrons constitute the major source of energy loss of fast charged particles in free ion/electron plasmas. Here, however, the electrons are frozen out of collisionality by trapping in the lattice band structure.

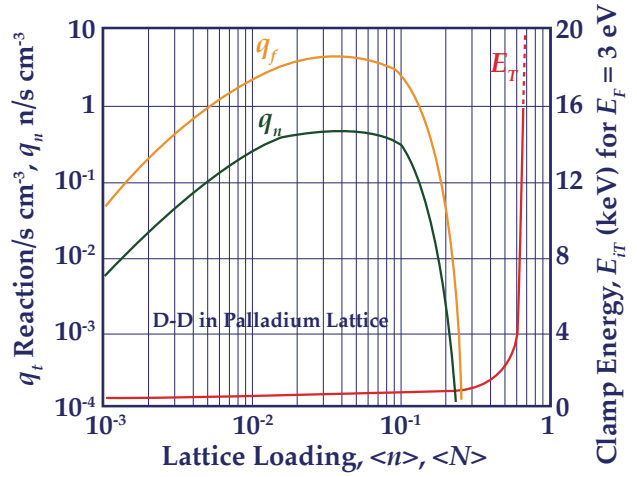

Figure 1 — In situ D-D reaction rate density qt, neutron rate density q_n, and slowing down "clamping" energy E_{iT} versus palladium lattice deuterium loading.

Since electron Fermi energy is 2.92 eV in bare palladium and lattice temperature is typically <0.03 eV, only a fraction $f_e \approx 0.01$ of the electrons are accessible for energy exchange collisions with fast triton or proton ions. In effect, long-range forces have been turned off beyond the lattice spacing distance, and coulomb collisions with lattice palladium and deuterium ions are also important. Analysis of slowing down collisions shows approximate energy exchange cross sections to be σ_e = 0.6 to 1.2 x $10^{-12}/E_k^2$ cm^2 for (T,p) on deuterium, a_e = 2.2 to 6.6 x $10^{-12}/E_k^2$ on palladium, and σ_e = 1.5 x $10^{-11}/E_k^2$ for the accessible electrons. With these, the triton energy loss rate is found to be

$$-\left(\frac{dE_T}{dt}\right)=\frac{\left(3.8x10^{-7}n_D+5.0x10^{-7}f_e n_e+1.0x10^{-7}n_{Pd}\right)}{\sqrt{E_T}} \quad (8a)$$

Rewriting this in terms of n_{Pd} gives

$$-\left(\frac{dE_T}{dt}\right)=\frac{\left(3.8x10^{-7}\langle N\rangle+2.3x10^{-5}f_e+1.0x10^{-7}\right)n_{Pd}}{E_T} \quad (8b)$$

For f_e = 0.01 and <N> in the midrange for maximum reaction rate density ($\langle N\rangle \approx 0.067$) the loss rate becomes

$$-\sqrt{E_T}\frac{dE_T}{dt}=3.52x10^{-7}n_{Pd}=S\left(n_{Pd}\right) \quad (8c)$$

Here only 0.071 of the triton energy is given to lattice deuterons, 0.276 to palladium, and 0.653 to the electrons. Other assumptions (for f_e and $\langle N\rangle$) would give different results, but it is clear that electrons would dominate the process if not for their largely degenerate state. The slowing down time to to "zero" energy from E_{T0} initial energy is found by integration of Equation (8c) to be

$$t_0 \approx \left(\frac{2}{3}\right)\frac{E_{T0}^{3/2}}{Sn_{Pd}}=2.8x10^{-8}\,s \quad (9)$$

in approximate agreement with standard models[13,14] for accessible electrons in the Debye sphere in the lattice.

This simple model fails for losses to electrons as the particle speed approaches the speed of lattice electrons. So long as ions are faster, "electron drag" slows them down. However, the speed of accessible electrons is that of the kinetic energy component of the lattice Fermi energy for the effective electron mass. At comparable ion speed, the ion energy is $E_i = E_{F0}(m_i/m_e\langle m^*\rangle)$, where E_{F0} = 3.69 x 10^{-15} $(N_e)^{2/3}$ / $\langle m_0^*\rangle$, N_e is total electron density, and $\langle m_0^*\rangle$ = 27 for unfilled palladium. This gives E_{F0} = 2.92 eV, and the triton energy becomes E_i = 16.03/<m*> keV. As the triton slows down below this energy by collisions with other lattice ions (deuterium and palladium), it is trapped by collective electron density waves[14] driven by faster slowing down tritons, and energy is added to the colder tritons trying to drop below E_i. Thus, the density of tritium tends to build up at this energy, which is seen to depend strongly on the degree of deuterium-filling <N> of the lattice, through Equation (4). As shown in Figure 1, at small loading the effective mass <m*> is large and E_i is at its minimum value; at maximum <N>, <m*> = 1 and E_i = 16.03 keV. Such particle trapping in energy space has been called "velocity clamping" and was recently suggested by Ponomarev[11] for application to the instant problem.

The effect that these processes might have on fusion reaction density in the lattice can be examined by analysis of their time dependence. Triton density n_T is controlled by D-D reaction production and D-T reaction removal rate, and knock-on deuteron density n_{Dko} is driven by fast ^{4}He, ^{3}He, tritium, and proton products of

D-D fusion. These processes can be crudely approximated by

$$\frac{dn_T}{dt} = \frac{n_{DL}^2 (\sigma v)_L}{4} + n_{DL} (\sigma v)_{k0} n_{Dk0} - n_{DL} (\sigma v)_T n_T \quad (10a)$$

and

$$dn_{Dk0} = \frac{K n_{DL}^2 (\sigma v)_L}{4} + (K-1) n_{DL} (\sigma v)_{k0} n_{Dk0} + \left(\frac{K n_{DL} (\sigma v)_T n_T}{2} \right) \quad (10b)$$

where subscripts L denote lattice reaction conditions, k_0 denote knock-on conditions, and K is the average number of knock-on deuterons upscattered to average energy E_{k0} that characterizes the reaction parameter $(\sigma v)_{k0}$, per (T,p) produced by $(D\text{-}D)_L$ reactions. For systems of interest, it is found that $2 < K < 10$. Approximate solutions of these equations (ignoring terms linear in n_T) have the form

$$n_T(t) = \left(\frac{c_1 n_{DL}}{2k} \right) \left[\exp(c_2 k t) - \exp(c_3 t) \right] \quad (11)$$

where

$$k = (K-1)$$

$$c_1 = \frac{\sigma v_L}{\sigma v_{k0}}$$

$$c_2 = n_{DL} (\sigma v)_{k0}$$

$$c_3 = n_{DL} (\sigma v)_T$$

Ignoring the second term (for D-T reactions) Equation (11) becomes

$$n_T(t) = \frac{n_{Dk0}(t)}{k} = \left(\frac{c_1 n_{DL}}{2k} \right) \left[\exp(c_2 k t) - 1 \right] \quad (12)$$

Taking $n_{DL} = n_{pd} \langle N \rangle$, the initial time constant t_c for tritium multiplication (and thus for all other reaction rates and energy production) is simply

$$\frac{1}{t_c} = c_2 k = n_{DL} (\sigma v)_{k0} \left[\left(\frac{1}{\mu} \right) \left[\ln \left(\frac{E_f f_{h0}}{E_{k0}} \right) - 1 \right] \right] \quad (13)$$

The total energy available for knock-on $D_L \rightarrow D_{k0}$ is 4.03 MeV = $2E_f$ from the two particles (T,p). Let f_{k0} of this go to D_{k0} and 1 - ff_{k0} to electron and palladium collisions. Then

$$K = \left(\frac{1}{\mu} \right) \ln \left(\frac{E_f f_{k0}}{E_{k0}} \right)$$

where μ is the average log energy ratio per energy exchange (90-degree) scattering collision. For coulomb scattering of fast tritons and protons on deuterium in the lattice spacing of palladium, $\mu \approx 0.9$. For particle multiplication to occur, K must be > 1; thus E_{k0} must be $< E_f f_{k0} \exp(-\mu)$. Taking $f_{k0} = 0.071$ [see Equation (8c)] and $E_f = 2$ MeV, for example, then $E_{k0} < 57.7$ keV = E_{Dk0}.

The reaction cross-section parameter for D_L-D_{k0} slowing down reactions is

$$(\sigma v)_{k0} = \frac{5.3 \times 10^{-15}}{\sqrt{E_{k0}}} \exp \left(\frac{-46.1}{\sqrt{E_{k0}}} \right) fusion / s \ per \ D_{k0} \quad (14)$$

With these, the time constant varies as shown in Figure 2 for $\langle n \rangle = \langle N \rangle = 2/3$ and 0.07. Note the very rapid change of t_c with E_{k0}. If $E_{k0} \leq 1$ keV no chaining can occur over any reasonable time span; if $E_{k0} > 3$ keV and $\langle N \rangle > 0.5$, chain- ing is very rapid, barring other loss mechanisms. However, as shown earlier, the base *in situ* D-D reaction rate becomes extremely small at high $\langle N \rangle$, and maximum rates are found in the range $0.01 < \langle N \rangle < 0.1$. Thus, very short time constants occur for conditions of very small reaction rate and vice versa. Furthermore, velocity clamping tends to freeze knock-on and slowing down ions at energy $E_i = 16.03/\langle m^* \rangle$, given previously. The situation is further complicated because the knock-on energy fraction f_{k0} is itself a function of $\langle N \rangle$, varying approximately as $0.07\langle N \rangle$ for conditions as sufficient for Equations (8). All of these competing effects lend themselves to an optimization study, not undertaken here. If chaining does occur, copious numbers of neutrons will be produced at 14.1 MeV from D-T reactions. That no such neutrons have been reported suggests that either the mean knock-on energy is < 1 keV or the fast tritons are removed by other means while still at high energy.

Virtual State Internal Nuclear Structure Group Reactions

A possibility for this latter alternative is found in the capture of fast tritons by lattice palladium nuclei, at a rate sufficient to remove the tritium before it can make D-T fusions.

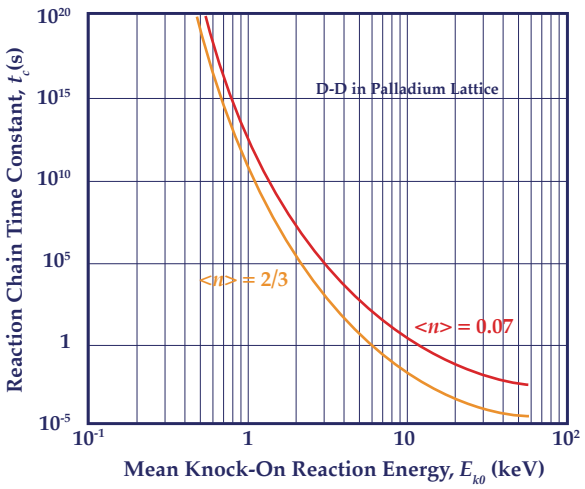

Figure 2 — Slowing down reaction chain time constant t_c versus mean collisional knock-on energy of deuterons, for two values of deuterium loading in a palladium lattice.

Excited-state Ag* resulting from such a capture may decay by emission of an alpha particle or a proton. Either of these will convert the tritium into a nonreactive fast ion, which can then markedly enhance the knock-on energy transfer in stowing down collisions. It is necessary that the final-state net energy of the reaction (the Q value) be positive. All reactions of interest here give final states with 3 < Q < 12 MeV.

The nuclear core wave function can be considered to be composed of the sum of individual particle wave functions combined statistically more often into interactive coherent virtual states of favored nucleon groups than in random ensembles. Favored groups are those classified as "magic" or "doubly magic" in nuclear shell theory.[15] Magic numbers of N or Z nucleons of interest here are 2, 8, 14, 20, 28, and 50. The lower numbers arise from nucleon oscillator potentials, while the higher values are dominated by spin-orbit coupling effects. Typical magic clusters are $^{4}He_{2}$, $^{16}O_{8}$, $^{28}Si_{14}$, $^{40}Ca^{20}$, $^{48}Ca^{28}$, etc.

A nucleus can be decomposed into a small number of such groups or closed shells. Nucleons that do not fit within these shells are statistically less tightly bound to the rest of the nucleus but able to interact with each other, in crude analogy to the separation of nuclear and electronic motions in atoms.[16] If these excess nucleons can form a bound group, even though not magic, their wave functions will combine to yield a higher probability virtual state for such a group. The formation of such structure groups as deuterons, tritons, or ^{3}He constitutes a fusion reactive fuel bound within the potential well of its larger nucleus. The wave function of an external fusion fuel approaching the nucleus can overlap that of the internal virtual cluster, and a fusion reaction may be stimulated within the core, provided the degree of wave functioning overlap is large enough over a sufficient time span. Thus, fusion reactions of energetic external tritium may take place with internal deuteron, triton, or ^{3}He groups, if these are found in virtual states within the target nucleus.

The products of such externally stimulated in-core fusion reactions may escape the parent nucleus if the energy supplied by the in-falling nucleons and from rearrangement into the escaping particles (e.g., an alpha) is concentrated into them long enough for them to climb out of the nuclear potential well. The probability of an alpha particle appearing at the nuclear surfaces after being formed from a virtual-state fusion event, with the remaining particles already arranged into the proper wave function for the daughter nucleus, depends on the dynamics of core nucleons in the ground state of the compound system. If this motion is simple as for internal magic group/shells, the emission probability is high; if complex (no internal order), it is low.[17] In the former case alphas may be emitted; in the latter, protons. Normal free D- T, tritium-tritium (T-T), and T-^{3}He reactions yield both alphas and fast neutrons; however, the neutrons will be preferentially bound to the nuclear force structure of the core, and their centrally directed momentum recoil will aid escape of the emitted particle. An example of such a structure reaction is that of D + T $\rightarrow$ ^{4}He + n on the virtual tritium cluster group found in in $^{19}F_{10}$ (doubly magic $^{16}O_{8}$ + $^{3}T_{2}$ in core), observed by Luce[18] in experiments using deuterium ions at ~1 MeV on CF_4 targets.)

Study of palladium isotopes shows that some of these may exhibit virtual internal deuteron, triton, or ^{3}He states. Two of the natural stable isotopes of palladium (104 and 108) show none; the others do (102, 105, 106, 110). Estimation of these weighted for isotopic abundance, gives an average for available virtual-state fuels as f_{He} = 0.55, ^{3}He, f_T = 0.58 triton, and f_D = 0.22 deuteron per natural palladium nucleus. Reaction rates of these with external fast tritons can be estimated by use of normal free-particle fusion cross sections taken at an energy equivalent to that required in the lab frame to reach the same internuclear approach distance as in the lattice. The virtual-state rate coefficient Γ_f(T - T) = $(n_{Pd}\sigma_{TT})\,v_T$ per second per triton incident on palladium is

$$\Gamma_f(T-T) = \frac{4.6x10^{9}\, f_T}{\sqrt{E_T}} \exp\left(\frac{-38.39}{\sqrt{E_T}}\right) \quad (15)$$

where f_T is the fractional virtual triton state in the natural palladium mixture, and E_T is the equivalent lab frame energy at closest approach. This is found to be to a distance slightly outside the 1s electron shell in palladium; thus the effective charge seen by the triton is Z' = Z - 2 = 44, and $E_T = 2(E_k/44)$ = 45.9 keV for the lab frame triton at E_k = 1.01 MeV. With this, the rate coefficient is found

to be Γ_f = 2.0 x 10^5/s per triton, and the time constant is $t_f = 1/\Gamma_f$ = 5.0 x 10^{-6} s. Carrying out the same calculation for the virtual deuteron found in ^{105}Pd gives

$$\Gamma_f(D-T) = \frac{2.27x10^{12} f_D}{\sqrt{E_T}} \exp\left(\frac{-45.95}{\sqrt{E_T}}\right) \quad (16)$$
$$= 1.25x10^7 / s \ per \ triton$$

and t_f = 8.0 x 10^{-8} s. Calculation of reaction rates with virtual ^{3}He states shows these to be very much less than either of the above.

The T-T reaction is thus improbable for the conditions chosen in the slowing down analysis. If a larger fraction of the lattice electrons were frozen out than is assumed, the slowing down time could be increased by an order of magnitude or more. In contrast, the D- T reaction seems probable with only slight reduction of lattice electron collisionality:

Slowing down equations for other fast particles (p,^{4}He) can be written in analogy with Equation (8c). For fast ^{4}He and p ions, electron collision loss rates will be somewhat greater than for tritons, but these can have energies > 3 MeV, yielding significantly longer slowing down times and greater upscattering than for tritium.

General Conclusions

Other lattice metals may offer more favorable virtual state nuclear reaction prospects; these remain to be explored. Other metals (e.g., titanium, nickel, manganese) may also yield more favorable *in situ* D-D reaction characteristics. And, finally, the entire range of parametric optimization for both time-dependent and steady-state conditions is yet to be analyzed; it is clear that the simple models and examples used here do not approach such an understanding, but some general effects and consequences have been illustrated.

If *in situ* D-D reactions can be initiated, conditions may be found for growth of these, producing fast (T,p). The triton may react with palladium nuclei to produce energetic ^{4}He (or another fast p) and a radioisotope of Rh* (or Pd*). Slowing down of these fast ions can upscatter in situ deuterium, and result in enhanced reaction rates, thus leading to more tritium, fast ions, knock-on upscattering, etc. Conditions might be found from careful analysis and parametric study under which such an energy "chain" may be able to yield net power generation in an appropriate metal lattice material. The work reported here does not rule out this possibility.

However, even if these conditions could be determined (and they have not been found) for the case of palladium, this material is forever useless for economic power generation because of its excessive cost. If significant energy were to be generated by fast particles from nuclear reactions, the palladium lattice would be destroyed by lattice displacements. If these reactions included the virtual-state nuclear transitions above, the palladium would be transmuted into some other element. Taking all of these into account, and allowing standard radiation damage levels of 15 dpa in the lattice, the effective cost for use of palladium alone (not including other elements of a hypothetical power plant) for energy generation was found to be ~600 mill/kW(electric) hour, equivalent to burning oil at roughly $400/bbl. Other metals may offer practical applications if they can yield net power in a similar process at costs less than $100/lb. However, until further research defines the physics processes and prospects much more clearly than has been done to date, such possibilities must be viewed as highly speculative and relatively remote.

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