be mimicked by a thermal distribution with a temperature of order room temperature, once such a mechanism is specified in detail arguments similar to the above could be used to estimate its maximum efficacy. If the experimental results are confirmed, it will be urgent to try to extend these arguments beyond the lowest Born-Oppenheimer approximation.

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where $\lambda = \frac{1}{2}[E_4 + K_4 + E^{\alpha}_{zp} - 2(E_d + K_d)]/\mathrm{Ry}$, and a_0 is the usual Bohr radius. The inequality (3) is rigorous and applies to arbitrary position of the two deuterons, whether in the bulk or on the surface.

Now clearly the exponent B for penetration to $\mathbf{r} = 0$ is bounded below by its value for the potential on the right side of (3). Further, it is adequate for the present purpose to evaluate the latter by the simple WKB approximation which gives a lower limit to the barrier penetration.[4] Thus, taking into account the reduced mass of the deuteron pair, we can write

$$B \geq B_0(\lambda) \equiv 2\int_0^{a_0/\lambda} dr \left(\frac{M_d e^2}{\hbar^2}\right)^{1/2} \left(\frac{1}{r} - \frac{\lambda}{a_0}\right)^{1/2}$$
$$= \pi \left(\frac{M_d}{m_e}\right)^{1/2} \lambda^{-1/2} \simeq 189\lambda^{-1/2}, \qquad (4)$$

where m_e is the mass of the electron and M_d that of the deuteron.

The deuterium affinity, K_d, is[7] 0.17 Ry in Pd and presumably of similar size in Ti; to the best of our knowledge there is no direct measurement of the helium atom affinity, K_4, for Pd or Ti, but the fact that ^{3}He desorbs from Ti at room temperature[8] suggests that, as for other metals, K_4 is either positive or very small ($\ll 1$ eV). Similarly the zero-point energy of the α particle is not measured, but it should be bounded above by that of the deuteron; the latter can be estimated from the isotope-dependence of K for the hydrogens[7] to be $\ll 1$ eV. If we neglect K_4 and E^{α}_{zp} we find $\lambda \simeq 1.78$ and hence $B \geq 141$. This value corresponds to a fusion rate of order 10^{-50}/sec per deuteron pair, some 27 orders of magnitude below that inferred in ref. 2. To reduce B to the maximum value ($\sim$80) consistent with the fusion rates in ref. 2 would require $K_4 + E^{\alpha}_{zp}$ to be of order 100 eV, a quite incredible value, which would have other easily observable consequences. The bound given here is likely orders of magnitude above the exact barrier penetration probability, as one can see by applying the method to the free D_2 molecule, where it gives a rate $\sim 10^{-53}$/sec, some 10 orders of magnitude too fast.

Unless the potential $V(\mathbf{R}, \mathbf{r})$ is itself affected on a scale of eV by room temperature, which seems most unlikely, a simple extension of the above analysis to finite temperature with a Maxwell-Boltzmann (or Bose) distribution for the deuterons shows that the lower bound on B at room temperature is negligibly different from that quoted above.

While the present argument cannot, strictly speaking, at present exclude mechanisms which rely essentially on the presence of large numbers of "third-party" deuterons (since there is no measurement to date of helium affinities under these conditions), nor those which rely on some unspecified highly non-equilibrium energy distribution which cannot

of the electrons on sub-Angstrom scales is the bare electron mass. On the other hand, one might suspect the presence of short-range screening effects associated with the large electron densities in the metal.

The essential point of our argument is that if the effective repulsion of two deuterons at short distance is substantially weakened by solid-state effects, then these effects should lead as well to greatly increased binding of an α particle to the metal. To make the argument precise, we define, within the lowest-order Born-Oppenheimer approximation, the effective "potential energy" $V(\mathbf{R},\mathbf{r})$ of two deuterons placed in the metal at $\mathbf{R}+\mathbf{r}/2$ and $\mathbf{R}-\mathbf{r}/2$ respectively. [We assume that two additional electrons are added to the metal as well, to preserve overall charge neutrality; since these electron energies cancel out in the argument we do not consider them explicitly.] We split V into three contributions: (a) the direct Coulomb interaction, e^2/r, of the two deuterons with each other, (b) the Coulomb interaction, $V_c(\mathbf{R}+\mathbf{r}/2)+V_c(\mathbf{R}-\mathbf{r}/2)$, of the two deuterons with the "environment," *i.e.*, with all other charges, electronic and ionic, and (c) everything else, *i.e.*, the kinetic energies and mutual interactions of the environment, which we call K. Here

$$V_c(\mathbf{R}) = e\int d^3r \frac{\rho(\mathbf{r})}{|\mathbf{r}-\mathbf{R}|}, \tag{1}$$

where $\rho(\mathbf{r})$ is the charge density (expectation value) of the environment.

Consider now the "chemical energy" $U(\mathbf{R}+\mathbf{r}/2)$ of an α particle placed at $\mathbf{R}+\mathbf{r}/2$, *i.e.*, its potential energy relative to that of an α particle placed at infinite distance from the metal. If we use the exact environment wavefunction for the ground state of the two deuteron problem as a variational wavefunction for the α-particle problem, noting that the α has charge $2e$, we see that $U(\mathbf{R}+\mathbf{r}/2) \le K + 2V_c(\mathbf{R}+\mathbf{r}/2)$, with a similar inequality at $\mathbf{R}-\mathbf{r}/2$. Adding the two inequalities we find, for all $\mathbf{R}$ and $\mathbf{r}$, that

$$V(\mathbf{R},\mathbf{r}) \ge \frac{1}{2}[U(\mathbf{R}+\frac{\mathbf{r}}{2})+U(\mathbf{R}-\frac{\mathbf{r}}{2})]+\frac{e^2}{r}. \tag{2}$$

In the limit of zero temperature, which we consider initially, the actual energy eigenvalue E_{2d} of the deuteron pair is bounded above by the energy of two deuterons at infinite separation in the metal, which is $-2(E_d+K_d)$, where $E_d = 1\mathrm{Ry}$ is the binding energy of the deuteron in free space (Ry is the Rydberg), and K_d is its affinity to the metal. Similarly, $U(\mathbf{R}\pm\mathbf{r}/2)$ is bounded below, for all $\mathbf{R}$, $\mathbf{r}$, by $-(E_4+K_4+E_{zp}^{\alpha})$, where $E_4 = 5.802\mathrm{Ry}$ and K_4 are, respectively, the free-space binding energy and affinity of the ^{4}He atom, and E_{zp}^{α} is the zero-point energy of the α-particle in the metal, *i.e.*, its energy relative to the minimum value of the potential $U(\mathbf{R})$. Inserting these inequalities into (2) we find

$$V(\mathbf{R},\mathbf{r}) - E_{2d} \ge \frac{e^2}{r} - \lambda\frac{e^2}{a_0}, \tag{3}$$

CAN "SOLID-STATE" EFFECTS ENHANCE THE COLD FUSION RATE?

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Recently two groups[1,2] have reported finding experimental evidence for an unexpectedly high rate of nuclear fusion at room temperature during the process of electrolytic deposition of deuterium on palladium[1,2] and titanium.[2] To achieve the rate of neutron production ($\sim 10^{-23}$/sec/pair) cited in ref. 2 (and *a fortiori* that inferred in ref. 1) requires the solid-state environment to produce either an unusual enhancement of the fusion reaction rate, or a large suppression of the Coulomb barrier between deuterons – the latter presumably arising from some kind of sophisticated many-body screening effect in Pd and Ti, perhaps associated with quasiparticles of large effective mass.[2] In this note we point out that within the framework of the lowest-order Born-Oppenheimer approximation a very severe constraint is imposed on *all* such enhanced screening mechanisms in solids in equilibrium by observable behavior of a ^{4}He atom in the metal in question; and that unless the latter is quite anomalous, no enhancement of the Coulomb barrier penetration anywhere near the magnitude required to explain the fusion rates inferred from the experiments is possible in a solid in equilibrium.

The theoretical rate, Γ, of neutron production by fusion per second per deuteron pair is of the form $\Gamma = Aa^{-3}e^{-B}$, where A is the rate of the fusion reaction, d+d $\rightarrow$ ^{3}He+n, per unit probability density at $\mathbf{r} = 0$, $\mathbf{r}$ is the relative separation of the two deuterons, a^3 is approximately the volume of classically accessible motion for the pair, and e^{-B} is a Coulomb barrier penetration factor.[3–5] The fusion rate is $\simeq 1.5 \times 10^{-16}\mathrm{cm}^3$/sec; a generous lower order-of-magnitude limit on a in any solid-state environment is 0.1Å, and thus the experiments would require $B < 80$. While for the D_2 molecule in free space[5] $B \simeq 175$, both theory[4] and experiment[6] suggest that much smaller values can be obtained when the deuterons are bound together by a muon or other heavy particle, which effectively screens the nuclear Coulomb charges from one another down to very small distances. A heavy electron quasiparticle is unlikely to produce the required screening on sub-Angstrom scales, since such quasiparticles have an extended structure in space; the effective mass