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Deuteron Tunneling at Electron-Volt Energies

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We speculate on a new mechanism for deuteron–deuteron fusion reactions at electron-volt energies. Appealing to conservation principles, it is shown that deuteron tunneling leading to fusion is very unlikely to take place between two isolated deuterons. It is argued that in solids, however, tunneling may lead to fusion via a new reaction mechanism which populates energy levels of ^{4}He, with simultaneous energy transfer to an electron. Predictions of this theory are that d + d + e^- fusion at electron-volt energies in solids should lead to copious production of tritium, protium, energetic electrons, and small quantities of ^{4}He.

KEY WORDS: Fusion (theory); cold fusion; deuteron tunneling; nuclear reactions; electron conversion.

Recent reports of possible nuclear fusion taking place in metal electrodes at ambient temperatures,[1,2] known as "cold nuclear fusion,"[2] have been discussed in terms of the following fusion reactions:[3]

$$d + d \rightarrow t + p \qquad (Q = 4.0\ \text{MeV}) \qquad (1)$$

$$d + d \rightarrow {}^3\text{He} + n \qquad (Q = 3.3\ \text{MeV}) \qquad (2)$$

$$d + d \rightarrow {}^4\text{He} + \gamma \qquad (Q = 23.8\ \text{MeV}), \qquad (3)$$

with branching ratios of approximately 50, 50, and 0%, respectively.[4] However, observed neutron emission rates are $\sim 10^7$ times smaller than expected from the reported levels of energy generation,[1] assuming that the above branching ratios should apply.

It is the purpose of this paper to examine deuteron tunneling at electron-volt energies. We find that d-d tunneling at electron-volt energies cannot occur via any of the above two-body reactions. This conclusion is valid in the approximation that only S-wave interactions are important at these low energies.

There is already substantial evidence of sub-Coulomb tunneling processes occurring between nuclei separated by distances which are much larger than the nuclear radius. Neutron and proton tunneling was first proposed by Breit and Ebel[5] as a mechanism to explain cross sections observed by Reynolds and Zucker[6] for the reactions ^{14}N(^{14}N,^{13}N)^{15}N and ^{14}N(^{14}N,^{13}C)^{15}O. As a second example, May and Clayton[7] have suggested neutron tunneling as a mechanism in the astrophysically important reaction ^{3}He(^{3}He,2p)^{4}He, which is relevant to the ^{8}B solar neutrino flux. They emphasized that neutron tunneling can be the dominant process at energies below the Coulomb barrier when projectile and target nuclei are separated by large distances. In a separate communication,[8] we examine the possibility that neutron tunneling might take place between neighboring ^{6}Li nuclei in solids; criteria conducive to this process are a large thermal neutron capture cross section, a small neutron separation energy, and large fluctuations of the energy of the least-bound neutron which are caused by Fermi motion. The first and third criteria are not satisfied for deuterons, so that the situation is fundamentally different for d + d fusion.

Tunneling in d + d reactions can, in principle, take place via deuteron tunneling through the Coulomb barrier,[9] via neutron tunneling through the nuclear potential

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barrier, or via proton tunneling through both the Coulomb and the nuclear barriers. The Coulomb barrier for the deuteron process is ~0.4 MeV high, whereas neutron tunneling involves penetration of a barrier of 2.2 MeV (the binding energy of the deuteron). Proton tunneling would involve penetrating the Coulomb barrier as well as the 2.2-MeV barrier. Since the tunneling probability is a strong function of the product of barrier height and width, we conclude that deuteron tunneling is by far the most likely process to occur.

At low incident energies, conservation of angular momentum and parity in d-d fusion reactions leads to different final states than at higher energies. Since the deBroglie wavelength of a thermal deuteron is of the order of 0.2 Å, much larger than the size of a deuteron, only S-wave interactions between deuterons should be important. As a consequence, the conservation laws require that any combined d + d state of spin $I = 1^+$ deuterons should have total angular momentum and parity $J^\pi = 0^+$ or 2^+.

When a deuteron with bombarding energy of the order of electron-volts tunnels, it can lead either to a direct reaction with particle emission or to the formation of an excited intermediate state of a ^{4}He nucleus, with an excitation of 23.847 MeV.[10] However, neither of these is possible here, as follows: the cross sections for direct reactions leading to n or p emission approach zero at 23.847 MeV;[11] there are no positive-parity resonances close to 23.8 MeV (see Fig. 1).[11,12] Thus, it appears to be impossible for tunneling of thermal deuterons to lead to fusion.

Accepting recent claims that nuclear fusion does take place in condensed matter at ambient temperatures, however, we are led to consider novel reaction mechanisms. Specifically, we propose a mechanism by which states of ^{4}He below 23.847 MeV might become populated even though there may be negligible overlap between the 23.8-MeV excitation energy and states of ^{4}He. Examination of Fig. 1 shows that there are no low-lying 1^+ or 2^+ states of ^{4}He, from which we conclude that only the combined d + d $J^\pi = 0^+$ state can lead to fusion.[13] Considering first γ-ray processes, excited states of ^{4}He should only be populated directly by simultaneous creation of a photon, as in p(n,γ)d. However, selection rules forbid photon creation when the initial and final nuclear states both have spin zero, as is the case for the ground and first two excited nuclear states of ^{4}He. Direct population of the only other accessible nuclear level, the $I = 2^-$ state at 22.1 MeV, would require an M2 transition with energy 1.7 MeV. We consider this process to be improbable owing to the high multipolarity; however, observation of 1.7 MeV γ-rays would be of great significance. With the exception of this improbable M2 transition, and ignoring P-wave interactions, we conclude that two-body d + d fusion reactions cannot occur at electron-volt energies. It therefore is not clear how cold fusion of deuterons might occur.

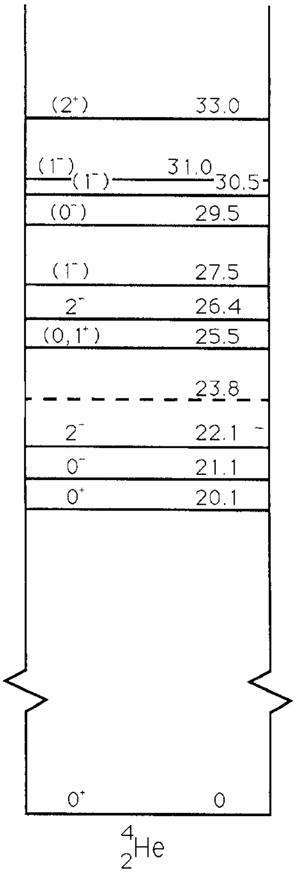

Fig. 1. Level diagram of ^{4}He, with angular momenta and parities at left and energies, in MeV, at right. The dashed line indicates the 23.8-MeV excitation energy of the reaction d + d → ^{4}He and does not represent a state of ^{4}He.

In our opinion, resolution of this mystery lies in the condensed-matter environment of the deuterons and, specifically, in the presence of a high density of atomic or conduction electrons at the deuterons' locations. In contrast, in accelerator experiments all nearby electrons are likely to be ionized or excited to high-energy atomic or molecular states by impulsive Coulomb forces produced during approach of the projectile nucleus, so that electron densities at the nuclear sites can be expected to be very small compared with 1s electron densities.

We propose the following electron-conversion reactions:

$$\mathrm{d} + \mathrm{d} + \mathrm{e}^- \rightarrow {}^4\mathrm{He}\ (\text{ground state}) + \mathrm{e}^-\ (K = 23.84\ \mathrm{MeV}) \tag{4}$$

$$\mathrm{d} + \mathrm{d} + \mathrm{e}^- \rightarrow {}^4\mathrm{He}\ (20.1\ \mathrm{MeV\ state}) + \mathrm{e}^-\ (K = 3.7\ \mathrm{MeV}) \tag{5}$$

with the second reaction followed only by[11]

$$ {}^4\mathrm{He}\ (20.1\ \mathrm{MeV\ state}) \rightarrow \mathrm{t}\ (K = 0.08\ \mathrm{MeV}) + \mathrm{p}(K = 0.23\ \mathrm{MeV}) \tag{6}$$

because the 20.1-MeV excitation is below the threshold for neutron emission. There is obvious similarity between reactions (4) and (5) and internal conversion processes between $I = 0$ states (see, e.g., Ref. 4), although here the initial, combined d + d state is not a nuclear eigenstate. Conceptually, the tunneling and electron-conversion processes may be thought of as taking place simultaneously. Assuming that the electron conversion probabilities vary here as $\Delta E^{-5/2}$, in the same way as for internal conversion of $L = 0$ multipolar transitions,[14] branching probabilities of reactions (4) and (5) should be 0.97 and 99.03%, respectively. Thus reactions (5) and (6) may dominate, leading to copious production of tritium, protium, energetic electrons, and via reaction (4), lesser amounts of ^{4}He may be produced.[15]

At present there are only limited experimental data in the literature with which to compare predictions from these d + d + e$^-$ reactions. Observation of very small numbers of neutrons in Ref. 1, when compared with energy production, is consistent with our reactions. The neutrons could be produced by secondary reactions between energetic particles in the electrodes, leading to conventional nuclear fusion. Neutrons would also be produced via the weak M2 transition to the 22.1-MeV level, since the 22.1-MeV level decays via neutron or proton emission.[11] The most direct test of our reactions would come from measurements of emissions of electrons with energies of 3.7 or 23.8 MeV. Such measurements will be complicated by energy losses in materials.

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13. Thinking heuristically of tunneling as a scattering process, this means that the reaction can take place only when the deuterons' spins are opposed. Tunneling with $J^\pi = 2$ would lead to no reaction.
14. To *compare* the transition probabilities for electron conversion to different $I = 0$ states, we use the energy dependence on the internal conversion coefficient $\alpha(E0)$ from Ref. 4, Eq. 10.26.
15. If these d + d + e$^-$ tunneling reactions produce the energy production reported in Ref. 1, then there will be significant radiation hazards from energetic electrons and radioactive tritium.