COMMENTS ON THE MODEL FOR COHERENT DEUTERON-DEUTERON FUSION IN CRYSTALLINE Pd-D LATTICE

COLD FUSION

TECHNICAL NOTE

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The enhancement of the deuteron-deuteron fusion rate is estimated for a coherent interaction mechanism under realistic experimental conditions. The extension of this mechanism to (n,γ) reactions is outlined.

The possibility of coherent nuclear interaction between itinerant deuterons and lattice deuterons in crystalline Pd-D was discussed in Ref. 1. In another paper,[2] we considered, as an extension of this work, the (n,γ) reactions between propagating neutrons and the nuclei on a crystalline lattice for production of intense gamma rays. The purpose of this technical note is to bring out the limitations on the enhancement of the deuteron-deuteron (*d-d*) fusion rate under realistic conditions and to discuss some additional aspects of the (n,γ) reactions. The transmission resonance condition[3] for deuterons is restated to point out the oversight made in an earlier technical note.[4]

It is generally believed that in cold fusion experiments, enhancement of the *d-d* fusion rate is due to the conduction electron screening and to certain coherence effects in the Pd-D lattice. Here, we enumerate coherence mechanisms involving the Pd-D lattice and describe the principal features of the mechanism we proposed.[1]

Schwinger[5] considered phonon-induced screening of *d-d* interactions, and Hagelstein[6] proposed a two-step mechanism involving electron capture by a deuteron followed by the capture of the resulting virtual neutron by a deuteron or lithium atom. Turner[7] and Bush[4] derived the condition for transmission resonance of deuterons through a one-dimensional lattice and suggested transmission resonance as the enhancement mechanism. However, in their work, the implications of phase coherence were not fully considered, and the wave function of interacting deuterons was not derived.

We have considered interactions between the itinerant deuterons, which fulfill the transmission resonance condition, and the lattice deuterons, i.e., the deuterons at the Pd-D lattice sites. We use a tunneling model to evaluate the overlap wave function and the fusion rate for this mechanism.[1] Chubb and Chubb,[8] pursuing a different line of development, proposed that the screened, mobile deuterons form D^+ ion bands and that the fluctuations in the system lead to the following fusion reaction:

$$D_{Bloch} + D_{Bloch} \rightleftharpoons {}^4He_{Bloch} \; .$$

In our approach, only the deuterons that meet the transmission resonance criterion are considered to be fully itinerant and to form a band state. Another difference is that while our approach is based on interactions between the itinerant deuterons and the lattice deuterons, Chubb and Chubb envisage interactions among deuterons in the D^+ ion band state. The physical picture that emerges is as follows. We are essentially considering formation of a coherent compound nucleus state due to coherence among the wave functions in a three-dimensionally periodic lattice. The arguments connected with wave-particle duality, which have been discussed at length in connection with the single-slit and double-slit diffraction experiments,[9] are applicable to this case. In a single-slit diffraction experiment with a very weak electron beam, the phosphor screen registers individual electrons at different locations, but the probability distribution of the electrons is given by quantum mechanics. In our case, the wave nature of deuterons, in accordance with the rules of quantum mechanics, does not allow us to specify the lattice deuteron site at which final absorption of the itinerant deuteron takes place. However, it is the in-phase superposition of the wave functions at coherence that leads to an increase in fusion rate.

Preparata[10] and Chubb and Chubb[8] assumed formation of de-excited ^4He as the final state of the *d-d* reaction to explain the production of excess heat and ^4He. Schwinger[5] assumed that the de-excitation of $^4He^*$ leads to excess heat and tritium. At present, it seems to us that there is little reason exclusively to choose any one of the reaction channels, because production of ^4He, tritium, and neutrons has been reported from different experiments.[11] We therefore make no assumption regarding specific reaction channel and do not consider emergence of coherence in the final state. We calculate the total transition rate for the $d + d \rightarrow {}^4He^*$ reaction compound nucleus, which implies a sum over all final states.

We proposed[1] that nuclear interactions can be coherent when the difference in the phases of the wave functions of the compound nucleus states formed by overlap between the itinerant deuteron (neutron) and the lattice deuterons (nuclei) is an integral multiple of 2π. In a perfect crystal, for incident deuterons of unlimited coherence length, the enhancement in the *d-d* fusion rate was shown to be $(R_{coh}/R_{inc}) = N$, where

R is the reaction rate and N is the number of deuterons in the crystal. In practice, the coherence length of deuterons may not be large, and for $l_c = 100a$, where a is the lattice constant, the enhancement factor is the number of deuterons in volume l_c^3, or $\sim 10^6$. Moreover, for a crystal of mosaic length l_m, which can range from 10^3 to $10^5 a$, the enhancement factor is $(l_m/a)^3$, or 10^9 to 10^{15}. Hence, the enhancement due to coherence N_c is of the order of $(l_c/a)^3$ or $(l_m/a)^3$, whichever is smaller, and will not be as high as the value of $\sim 10^{22}$ obtained earlier.[1]

The condition for coherent interaction between itinerant deuterons having de Broglie wavelength λ and the deuterons in a face-centered-cubic (fcc) lattice is $\lambda = (a/2n)$ for propagation along direction [100], $\lambda = (a/2\sqrt{2}n)$ along [110], and $\lambda = (a/\sqrt{3}n)$ along [111], where a is the lattice constant and n is an integer. Similarly, for a body-centered-cubic lattice, the coherence conditions are $\lambda = (a/2n)$ along [100] and $\lambda = (a/\sqrt{2}n)$ along [110], and for a hexagonal close-packed lattice, $\lambda = (c/2n)$ along [001]. In the Pd-D lattice, in particular, there are rows of deuterons[4] along direction [110] and $\lambda = (a/2\sqrt{2}n)$ for coherence.

Coherent interactions can occur when the deuterons also fulfill the transmission resonance condition and propagate freely through the lattice. The transmission coefficient of a potential well of width L is unity[3] when the length of the classically accessible region is an integral multiple of $\lambda/4$; that is,

$$(L - 2r_t) = (2m + 1)\lambda/4 \ , \tag{1}$$

where m is an integer (Fig. 1). Turner[7] and Bush[4] suggested that this condition is also applicable to a periodic lattice. The turning distance r_t is defined as the distance between the nucleus and a point P along the line joining it to the next nucleus, at which the energy of the itinerant deuteron E equals the potential energy at P, $V(r_t)$. Since $V(r)$ depends on the strength of screening, the value of r_t depends on the screening model employed. For d-d interactions in Pd-D, r_t is estimated to be ~0.7 Å for screening by conduction electrons[12] and ~0.1 Å for screening by heavy electrons or by deuterons.[12,13] Since r_t has a finite value for deuterons in Pd-D, the length of the classically accessible region $(L - 2r_t) \neq L$. The transmission resonance condition, Eq. (6a) of Ref. 4, for deuterons in Ti-D at 243 K should therefore be modified to

$$(L - 2r_t) = (2m + 1)(0.349 \text{ Å}) \ ,$$

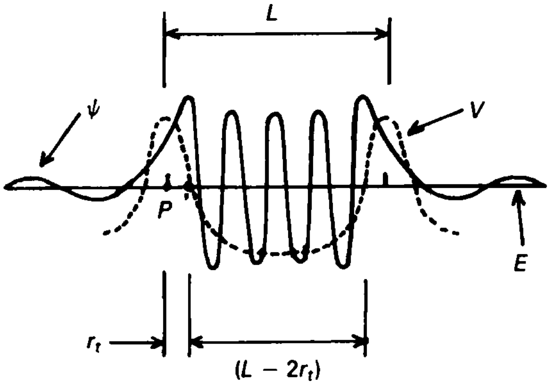

Fig. 1. Schematic variation of the wave function ψ for transmission of deuterons of energy E.

and Eq. (7a) of Ref. 4 for Pd-D at 293.2 K should be modified to

$$(L - 2r_t) = (2m + 1)(0.318 \text{ Å}) \ .$$

It follows from Eq. (1) that transmission resonance would require smaller λ values or higher temperatures than those estimated with $r_t = 0$. We emphasize that the coherence condition and the transmission resonance condition must be fulfilled simultaneously for enhancement of the fusion rate in crystalline Pd-D.

Theoretical studies on an externally driven bistable system[14] have shown that remarkable changes in the tunneling rate occur even when the ratio of the driver frequency to the unperturbed tunneling frequency is of the order of 0.01 to 0.1. This suggests that the d-d fusion rate in Pd-D can be increased further by application of longitudinal ultrasonic waves.

The experiment can be on the following lines. We take a single crystal of palladium grown along direction [110] and plate its cylindrical surface with a thin layer of gold (Fig. 2). Since the diffusion coefficient of deuterium in gold is very small,[15] the gold coating will help to create a flow of deuterons preferentially along the cylinder axis. The crystal is now charged with deuterium to a high D/Pd ratio by gas loading or electrolysis, and longitudinal ultrasonic waves of high frequency ($>10^9$ Hz) are applied by means of a transducer attached to one of the cylindrical ends. The ultrasonic energy is absorbed by the electrons and deuterons in the crystal. If the mobile deuterons acquire, at a certain frequency and amplitude of the ultrasonic waves, energy appropriate for cooperative tunneling of n deuterons along direction [110], then the d-d fusion rate will increase to nN_cR_{inc}. The occasional bursts of heat and neutrons reported in some experiments[11] may be due to the cooperative tunneling of deuterons.

(n,γ) Reactions: We consider, as an example of the (n,γ) reaction, the reaction between the propagating thermal neutrons and the nuclei of ^{103}Rh in an fcc crystal of rhodium. For thermal neutrons, the cross section of the $^{103}\text{Rh}(n,\gamma)^{104}\text{Rh}$ reaction is $\sigma_\gamma = 145$ b (Ref. 16). For neutrons, $r_t = 0$ (Fig. 1), and hence, the condition for coherent interaction, Eq. (1), becomes

$$L = m\lambda/2 \ . \tag{2}$$

According to our model, the rate of the reaction leading to the formation of $^{104}\text{Rh}^*$ increases by N_c. There is a corresponding increase in the intensity of the gamma rays of various energies produced by the decay of $^{104}\text{Rh}^*$. As in the case of the d-d fusion reaction, we estimate the total reaction

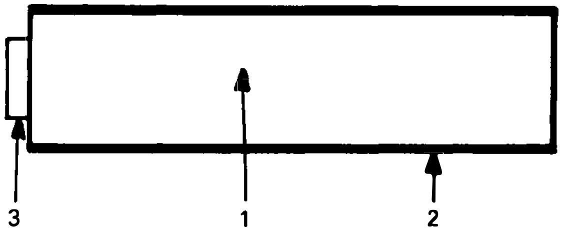

Fig. 2. (1) Single crystal of palladium charged with deuterium, (2) gold coating, and (3) transducer.

rate. We do not consider specific decay channels of ^{104}Rh*, nor do we analyze the conditions for emergence of coherence in the final state. We note, however, that Eq. (2) is also the Bragg condition for normal incidence. Hence, a small fraction of the neutron beam is scattered back ($b_{coh} = 5.9$ fm). Furthermore, Eq. (2) is also the condition for cooperative transmission of neutrons through the crystal—the Bormann effect.[17]

Turhune and Baldwin[18] considered the possibility of superradiant gamma emission by radiative neutron capture in a crystalline solid. The feasibility of developing a graser[19] by pulsed pumping of Mossbauer levels by radiative neutron capture has been analyzed for several isomers, and many schemes for grasers have been proposed. All the methods require the production of active isomers, by neutron capture, at a very high rate. The coherence method suggested here can be used to attain high conversion rates by using a very large flux of monoenergetic thermal neutrons of appropriate energy.

We suggest two methods for studying coherence enhancement in the (n,γ) reaction rate by using thermal neutrons from a research reactor. A single crystal of ^{103}Rh can be mounted on the sample turntable of a neutron diffractometer so that the monochromatic neutron beam is incident along, say, direction [110]. The intensity of the emitted gamma rays measured as a function of the wavelength of the neutrons will show a maximum at coherence. This effect can also be studied by comparing the activities of neutron-irradiated specimens of a single crystal and a polycrystalline rhodium of the same size and mass irradiated under identical conditions, choosing an irradiation wavelength and setting appropriate for coherence in the single crystal. The single-crystal specimen will show a higher activity due to coherence.

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