CHINESE JOURNAL OF PHYSICS VOL. 29, NO. 4 AUGUST 1991

Cluster-Impact Fusion and Warm Atomic Plasma*

Shin Nan Yang (楊信男), Yi-Chen Cheng (鄭以禎), W-Y. P. Hwang (黃偉彥),
Shyh-Tzong Lee (李士宗) and Chi-I Wu (吳志毅)
Department of Physics, National Taiwan University,
Taipei, Taiwan 10764, Republic of China

(Received June 2, 1991)

We propose a mechanism that may allow for understanding of the cluster-impact fusion experiment of Beuhler, Friedlander, and Friedman. When the cluster of D_2O molecules collides with the metallic surface, the cluster dissociates into a collection of D and O atoms, as caused by a large number of collisions due to the interaction between the cluster and the lattice. In the process, a significant portion of the translational kinetic energy of the cluster is converted to thermal energy, so that the system thermalizes to become a "warm atomic plasma". The neutral D atoms in the warm atomic plasma then fuse with the D atoms in the lattice via direct scattering, without going through the doorway step of forming D_2 molecules. As a rough estimate for the fusion reaction rate, the velocity distribution of the thermalized D atoms is taken to be Maxwell-Boltzmann, leading to results in qualitative agreement with the experimental observations.

Recently, Beuhler, Friedlander, and Friedman (BFF)[1] claimed that the nuclear fusion reaction $d + d \to {}^3H + p$, detected via the 3-MeV protons produced, has been observed to take place as singly charged clusters of 25 to 1300 D_2O molecules, accelerated to 200 to 325 keV, impinge on TiD targets. The BFF experiment has often been cited as another evidence to support the result reported earlier by S. E. Jones et *al.*[2] who have observed deuteron-deuteron fusion at room temperature during low-voltage electrolytic infusion of deuterons into metallic titanium or palladium electrodes. Nevertheless, the situation concerning "cold fusion" (CF) remains rather confusing and is certainly far from being settled. Some claimed[3] that they have seen CF, while others[4] declared the opposite.

In this work, we wish to explore if the BFF experiment can be understood on plausible grounds. To this end, we noted that in the BFF experiment each D atom in the D_2 molecular cluster, which will dissociate upon impinging on the target, has energy around 20 to 300eV. (Here and henceforth we shall use D and d to denote a deuterium atom and a deuteron nucleus, respectively.) It seems unlikely that these energetic D atoms will give up all their kinetic energies and form D_2 molecules with D atoms on the lattice such that fusion reactions take place after the formation of D_2 molecules. Recent calculation? of the interaction potentials between two D atoms inside Pd and Ti suggest that the shortest stable equilibrium distance between two D atoms inside the metals is not shorter than that in a free D_2 molecule. This in turn suggests that, if the fusion reactions took place by going through a doorway step of forming D_2 molecules, then the fusion reaction rate inside the metals would be less than that in the free space, contradicting some people’s belief that the metals enhance the reaction rate. On the other hand, fusion reactions can occur via direct scattering between the incoming dissociated D atoms and the D atoms on the lattice. If the dissociated D atoms are neutral, the interaction potential in the scattering process is more like D + D, i.e., atom-atom interaction rather than the usually assumed d + d, i.e., bare Coulomb interaction. When the free space D + D interaction potential is used, the fusion cross section is 6 orders of magnitude larger than that of the pure Coulomb d + d interaction potential for the center-of-momentum energy of about 150eV. Although this is a significant improvement, the predicted fusion reaction rate is still lower than the observed one by more than 19 orders of magnitude. As suggested by the title of the BFF experiment, however, “cluster” and “impact” are the two ingredients which appear in the BFF experiment but not in atom-atom scattering in free space. A possible effect of “cluster-impact” is that the translational motion of the cluster will be stopped by the target and a dissociation of the cluster into D and O atoms occurs. The lost kinetic energy of the translational motion of the cluster may be redistributed to the dissociated atoms. If the cluster is large enough, a quasi-thermal equilibrium state may be reached, forcing the system to form a “warm atomic plasma” of some sort. For a crude approximation the velocity distribution of the dissociated atoms may be taken as Maxwell-Boltzmann. With the above proposed scattering process and the velocity distribution our calculated results for the fusion rate are in qualitative agreement with the observations in the BFF experiment. We call this type of nuclear fusion as “warm fusion” (WF) which is to be distinguished from the so-called cold fusion (CF) and the much studied hot fusion. Cold fusion is usually referred to fusion which could take place, if exists, at room temperature or below. Hot fusion refers to deuterons with thermal energy as high as 10^9 degrees and above. Our proposed warm fusion, which occurs via formation of a warm atomic plasma, provides another type of fusion. When the D_2O cluster impinges upon the target with energy around 300 keV, the dissociated D atoms are thermalized up to a temperature of around 10^6 to 10’ degrees and therefore a "warm" fusion.

We find that thermalization of the D atoms in the cluster could enhances the fusion rate by more than 15 orders of magnitude, in comparison with the deltafunction velocity distribution, in the energy range we considered. Therefore the establishment of quasi-thermal equilibrium state is essential for this type of nuclear fusion to be observed.

In the cluster-impact experiment of Beuhler, Friedlander, and Friedman,[1] the observed reaction rate is related to the fusion cross section a(E) as follows:

$$R = n\sigma(E)\Phi t A \qquad (1a)$$

$$= 2N_i n\sigma(E) t I_d, \tag{1b}$$

where n is the density of the deuterium atoms in the target material, t and A are respectively the thickness (or the penetration depth) and the cross section area of the target, Φ is the incoming flux of the deuterium atoms, I_d is the incoming $N_i$lc current heavy-d water molecules contained in the singly charged cluster. The fusion cross section a(E) is given by the standard formula

$$a(E) = \frac{S(E)}{E} e^{-G}, \tag{2a}$$

$$G = 2\int_a^{r_0} k(r)dr, \tag{2b}$$

$$k(r) = \{2\mu(V(r) - E)\}^{1/2}, \tag{2c}$$

where E and μ are respectively the kinetic energy in the center-of-momentum (CM) frame and the reduced mass of the deuteron pair, and S(E) is the astrophysical S factor for the specific process. (S(E $\approx$ 0) $\approx$ 55 keV-barn for d + d $\rightarrow {}^3$ H + p and d + d $\rightarrow {}^3$ He + n.) V(r) is the repulsive interaction potential between the reacting particles, d + d, d + D, or D + D. When the reacting particles are d + d, the e^{-G} term is the standard Gamow Coulomb barrier penetration factor in the WKB approximation. When the reacting particles are d + D or D + D, the e^{-G} term still represents the penetration factor but its value is many orders of magnitude larger than the standard Gamow factor for E in the energy range we considered. Note that r_0 in Eq. (2b) is the classical turning point as the two deuterons approach each other, while the inner distance a $(< r_0)$ is such that V(a) = $V(r_0)$. In practice, we may set a $\approx$ 0.

We begin our investigations by comparing the results corresponding to three different choices of the potential V(r), viz.: (1) the pure d + d Coulomb repulsive potential shown as the long dashed curve in Fig. 1, (2) the screened D + D potential V(r), as obtained in the calculation on D_2 molecule by Kolos and Wolniewicz (KW)[6], shown as the solid curve in Fig. 1, and (3) the partially screened d + D potential in D_2^- shown as the short dashed curve in Fig. 1. A glance at Fig. 1 already suggests that the difference between the D + D and d + D cases is much less dramatic than that between the D + D and d + d cases.

In Fig. 2, the calculated fusion cross section is shown as a function of the atom-atom CM kinetic energy E_d. In the long dashed curve is the prediction for the d + d Coulomb repulsive potential, in the solid curve for the D + D potential[6] in D_2, and in the short dashed curve for the partially screened d + D potential in D_2^-. It is clear that the predicted cross section is the largest in the case of the fully screened D + D potential.

As two deuterium atoms scatter from each other, there is of course some chance that both atoms become ionized. In the case that both deuterium atoms are ionized, d + d fusion is dictated by the need to penetrate the pure Coulomb potential. The penetration factor e^{-G} is found

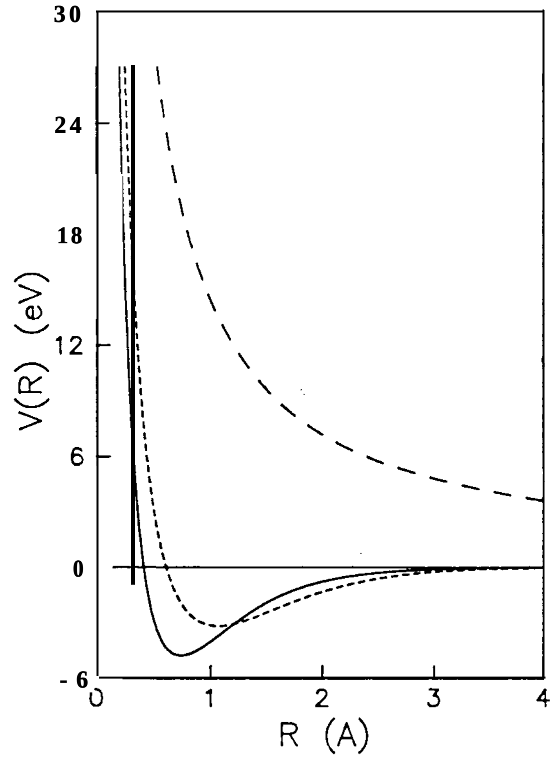

FIG. 1. The potentials which we choose to consider in this work. The long dashed curve refers to the pure d + d Coulomb repulsive potential, the solid curve is the D + D potential V(r) in D_2 molecule as obtained by Kolos and Wolniewicz,[6] and the short dashed curve is the partially screened d + D potential in D_2.

to be 10^{-35} at E = 150eV (the energy relevant for the BFF experiment). On the other hand, if both deuterium atoms remain electrically neutral, the penetration factor becomes 10^{-29} which is an enhancement of about 6 orders of magnitude. It is thus an experimental question to decide the level of complete ionization as two deuterium atoms collide. A similar question for He + He and H + He collisions has been studied,[7] indicating that elastic atomic scattering dominates in the laboratory energy range of 200 to 500eV. So long as there is a significant fraction of time that complete ionization is irrelevant, the approximation to consider only the atom-atom collisions through the KW potential should yield a reasonable estimate for the fusion cross section, at least in terms of the order of magnitude.

Koonin and Nauenberg[8] investigated the scenario in which a D_2 molecule is formed prior to nuclear fusion by tunneling through the KW potential. They obtain the rate for d + d fusion which is some 10 orders of magnitude faster than previous estimates, but still far below the value that might be needed to account for those experiments which claim to have seen CF. In such scenario, the Coulomb barrier remains very high although trapping of the two deuterium atoms

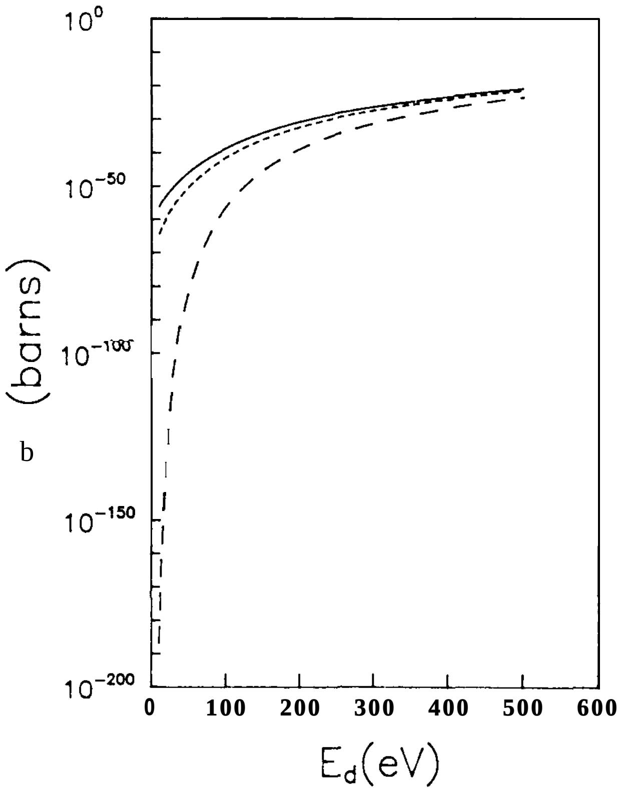

FIG. 2. The deuteron-deuteron calculated fusion cross section as a function of the CM kinetic energy E_d. In the long dashed curve is the prediction for the d + d Coulomb repulsive potential, in the solid curve for the (D + D) potential in D_2 molecule,[6] and in the short dashed curve for the partially screened d + D potential in D_2. .

in the potential well improve the the chance for penetration for nuclear fusion (as there is more time to do so). It turns out that the gain really cannot outweigh the loss in the penetration factor.

While the consideration of the nuclear fusion via un-ionized atom-atom scattering can improve the calculated results many orders of magnitude, this picture alone is not enough for understanding the BFF experiment since our calculated rate is still lower than the observed one by about 19 orders of magnitude. Nevertheless, the cluster-impact experiment such as BFF has an additional feature that, upon impact, the cluster may dissociate into D and 0 atoms and a large portion of the translational kinetic energy of the cluster may convert to thermal energy. The thermalization process causes redistribution of the velocities among the D atoms. This will enhance the reaction rate by more than 15 orders of magnitude. We call this thermalization induced fusion “Warm fusion” and will discuss it in what follows.

The experimental situation of the BFF experiment has an important feature that the cluster is large. It is not difficult to imagine that, within a limited numbers of layers in the lattice, the impinging flow of D_2 cluster already suffer from a large number of collisions (electromagnetic in origin) between particles in the beam and those in the target such that the cluster dissociates into D and 0 atoms and redistribution of the kinetic energy occurs. Accordingly, it is possible that the system will reach a quasi-equilibrium state, i.e., a warm plasma of neutral atoms (“Warm atomic plasma”), when the cluster is almost stopped at a time to. When the deuterium atoms in the warm atomic plasma (WAP) fuse with the D atoms in the target, the resulting portion of high-energy deuterium atoms is found to enhance the fusion cross section in a significant way. For example, the Gamow Coulomb barrier penetration factor, the e^{-G} term, is 10^{-29}, 10^{-21}, or 10^{-18} for E = 150eV, 300eV, or 450eV, respectively. As long as the redistribution yields a non-negligible fraction of deuterium atoms of energies several times of the initial value, say a couple of per cent, the enhancement of the fusion cross section can easily be in the range of more than 10 orders of magnitude.’

In the process of forming the warm atomic plasma, the thermal energy, as converted from a portion of the translational kinetic energy $E_{cluster}$ of the cluster, is $\alpha E_{cluster}$.

$$E_{thermal} = \alpha E_{cluster}. \tag{3}$$

Assuming that, by equipartition theorem, the thermal energy is shared equally among $3N_i$ dissociated D and 0 atoms, the temperature of the plasma is given as

$$\frac{E_{thermal}}{3N_i} = \frac{3}{2} k_B T. \tag{4}$$

a will be treated as a parameter characterizing the fraction of the kinetic energy retained by the projectile flow of deuterium atoms after the flow has been stopped. Most of collision processes yield $a < 1$. In a molecular-dynamics simulation of 1-keV/atom Al32 and Al_{63} cluster-impact on Al and Au targets, Shapiro and Tombrello[10] found that up to 12% of the cluster incident energy is ultimately transferred to target atoms that are ejected from the surface. Moreover, it has been established” that during the impact the most important interaction between the projectile and the target is nuclear rather than electronic in nature. Therefore only a limited number of atoms in the target adjacent to the point where the projectile hits the target will be heated up by the impact. It hence appears reasonable to assume that $1/2 \leq a \leq 1$.

As a zeroth-order approximation, we will take the energy distribution in WAP to be of the Boltzmann-Maxwell form

$$f(\mathrm{v}) = \left(\frac{M}{2\pi k_B T}\right)^{3/2} exp\left\{-\frac{M}{2k_B T}\mathrm{v}^2\right\}, \tag{5}$$

with M the deuteron mass and v the deuterium velocity seen in the rest frame of the target material (the laboratory frame). Assuming that fusion takes place between the deuterium atom in the cluster projectile and that in the target material, we obtain the CM kinetic energy:

$$E = \frac{1}{2} E_d^L \equiv \frac{1}{2} \mu v^2. \tag{6}$$

On the first sight, the cross section to be used in connection with Eq. (1) would be given by

$$< \sigma >= \int_0^{N_0 k_B T} \sigma(E) f(\mathrm{v}) d^3 v, \tag{7}$$

where a(E) is obtained from Eqs. (2). However, a close look at Eq. (1) indicates that $\sigma(\mathrm{E})\mathrm{v}$ is the quantity to be replaced by

$$< \sigma v >= \int_0^{N_0 k_B T} \sigma(E) |\mathrm{v}| f(\mathrm{v}) d^3 v, \tag{8}$$

since the flux Φ, contains the relative velocity between the two fusion particles. A temperature-dependente cut-off $N_0 k_B T$, with No = 6 - 10, has been introduced in Eqs. (7) and (8) to avoid the “high energy” region where the WKB approximation is no longer justified while the contribution to warm fusion cross section is likely to be of less importance.

In Figs. 3(a) and 3(b), we show our predictions, for the case N_i = 150, together with the results from the BFF experiment, for the quantity $<\sigma v>$ as a function of the energy respectively for a = 1 and a = 0.5. The long dashed and solid curves are results obtained with No = 10 and 6, respectively. The experimental results are extracted with the use of Eq. (1) and the following estimates,

$$\begin{aligned} & n \approx 6 \times 10^{22}/cm^3, && \Phi \approx 1.25 \times 10^{12} cm^{-2}\,\mathrm{sec}^{-1} \\ & t \approx 10^{-5} cm, && A \approx 1 cm^2. \end{aligned} \tag{9}$$

It is seen that the shape of the energy dependence seen in the BFF experiment is reproduced very well. In addition, our predictions are surprisingly close to the points extracted qualitatively from the BFF experiment. Considering the fact that our estimates can easily be off by a couple of orders of magnitude and that there are many effects which can give rise to modification in the range of a couple of orders of magnitude, we have come a long way to resolve the mystery of 10’s orders of magnitude in understanding the BFF experiment.

Figure 4, shows our predictions, together with the results from the BFF experiment, on the quantity $<\sigma v>$ as a function of the number of D_2O molecules in the cluster projectile for fixed cluster incident energy $E_{cluster}$ = 300keV and a = 1. Here it is seen that additional cluster effects set in as the size of the cluster increases. This can be taken as another evidence for our conjecture that the projectile flow can in fact be described as a Boltzmann transport phenomenon of some sort. As the cluster size increases, the approach in which only the deuterium atoms in the cluster projectile are assumed to be “thermalized” becomes too limited

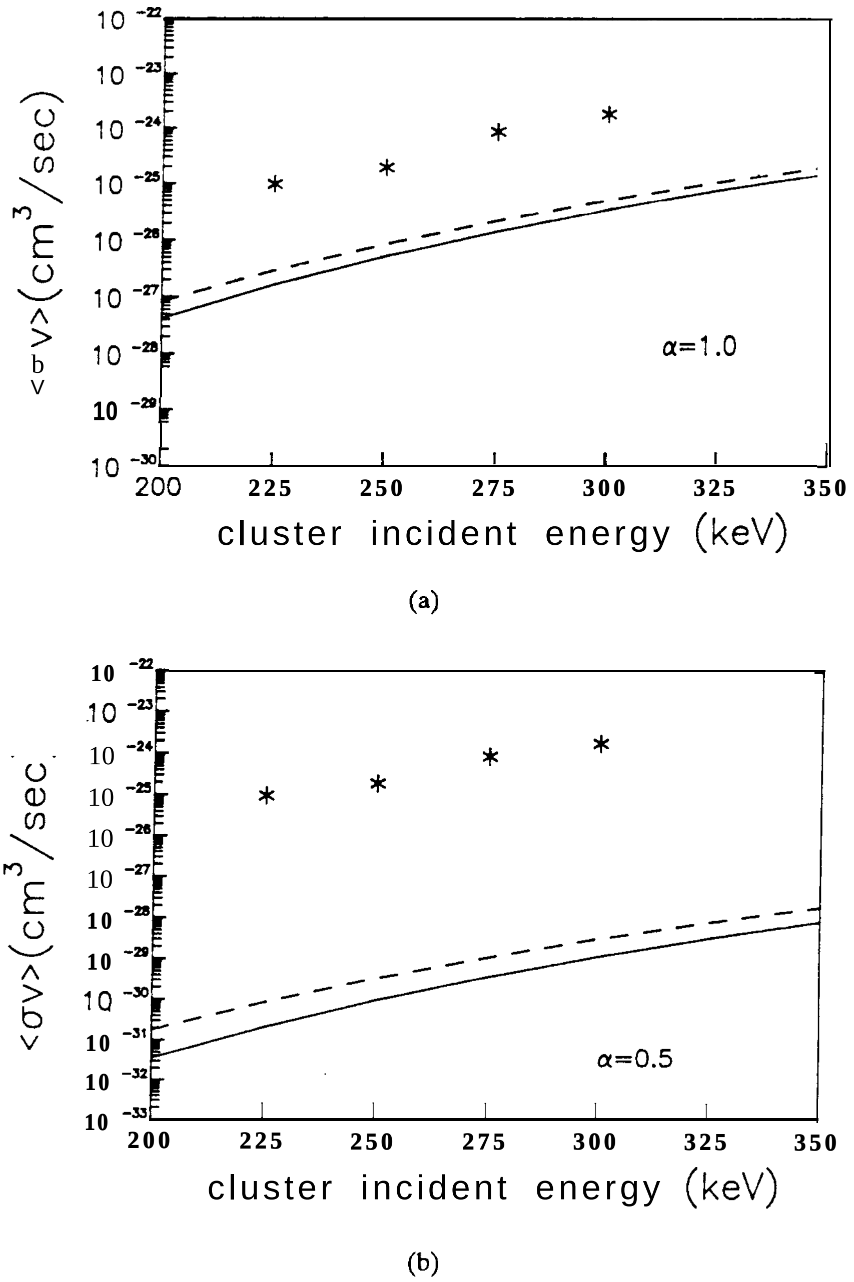

FIG. 3. Our predictions, together with the results from the BFF experiment, on the quantity $<\sigma v>$ shown as a function of cluster incident energy, respectively, with a = 1 (a) and with a = 0.5 (b), for the case that cluster projectile contains 150 D_2O molecules. The long dashed and the solid curves are results obtained with different choices of energy cut-off, i.e., N_0 = 10 and 6, respectively.

since compression forced on the target material by the large cluster should become of great importance.

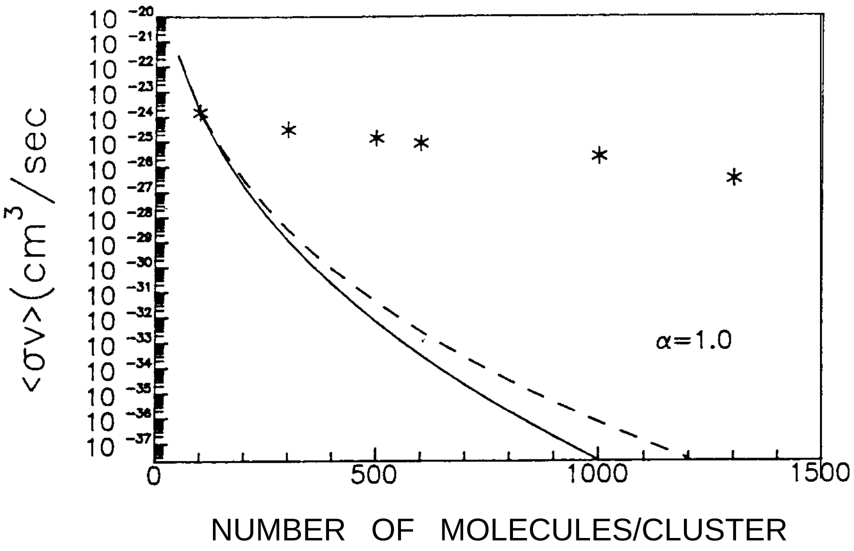

FIG. 4. **Our predictions, together with the results from the BFF experiment, on the quantity $<\sigma v>$ shown as a function of number of D_2O in the cluster at fixed cluster incident energy of 300keV with a = 1. The long dashed and the solid curves are results obtained with different choices of energy cut-off, i.e., N_0 = 10 and 6, respectively.**

It is **possible that some kind of redistribution of velocity** of the D atoms (or d ions), which will enhance the fusion rate, also occur in the low-voltage electrolysis experiments performed by Jones et *al.*[2] and Fleischmann et *al.*[3] and others.

In summary, we have proposed a mechanism that may allow for understanding of the cluster-impact fusion experiment of Beuhler, Friedlander, and Friedman. ’ As caused by a large number of collisions due to the interaction between the cluster and the lattice, the cluster dissociates into a collection of D and 0 atoms when the cluster of D_2O molecules collides with the metallic surface. In the process, a significant portion of the translational kinetic energy of the cluster is converted to thermal energy, so that the system thermalizes to become a “ Warm atomic **plasman.** The neutral D atoms in the warm atomic plasma then fuse with the D atoms in the lattice via direct scattering, without going through the doorway step of forming D_2 molecules. As a rough estimate for the fusion reaction rate, the velocity distribution of the thermalized D atoms is taken to be Maxwell-Boltzmann. When the cluster is of the size that it contains about 100-300 molecules, our results are in qualitative agreement with the experimental observations. As the cluster size increases, our results could be as far as 10 orders of magnitude smaller than the experiemental observations. This indicates that the approach in which only the deuterium atoms in the cluster projectile are assumed to be **"thermalized"** becomes too limited since compression forced on both the target material and the cluster may also become important.

ACKNOWLEDGMENT

We wish to acknowledge the support toward this work by the Atomic Energy Council of the Republic of China.

* This work is based on a talk presented in the First Annual Conference on Cold Fusion, March 28-31, 1990, Salt Lake City, Utah, USA.

REFERENCES

1. R. J. Beuhler, G. Friedlander and L. Friedman, Phys. Rev. Lett. **63, 1292** (1989).
2. S. E. Jones, E. P. Palmer, J. B. Czirr, D. L. Decker, G. L. Jensen, J. M. Thorne, S. F. Tayler and J. Rafelski, Nature 338,737 (1989).
3. M. Fleischmann and S. Pons, J. Electroanal. Chem. 261, 301 (1989); N. Wada and K. Nishizawa, Japanese J. Applied Phys. 28, L2017 (1989); R. Taniguchi, T. Yamamoto and S. kie, ibid., 28, L2021 (1989).
4. R. B. Campbell and L. J. Perkins, Fusion Technology, 16, 383 (1989); M. A. Butler, D. S. Ginley, J. E. Schirber and R. I. Ewing, *ibid.,* 16,388 (1989); J. E. Schirber, M. A. Butler, D. S. Ginley and R. I. Ewing, *ibid.,* 16, 397 (1989); H. Werle, G. Fieg, J. Lebkiicher and M. Möschke, *ibid.,* 16, 391 (1989); V. C. Rogers, G. M. Sandquist and K. K. Nielson, *ibid.,* 16, 523 (1989); D. J. Gillespie, G. N. Kamm, A. C. Ehrlich and P. L. Mart, *ibid.,* 16,526 (1989); A. G. Gu, R. K. F. Teng, M. S. Miller and W. J. Sprouse, *ibid.* 248 (1989).
5. X. W. Wang, S. G. Louie and M. L. Cohen, Phys. Rev. **B40, 5822** (1989); K. Sohlberg and K. Szalewicz, Phys. Lett. **A144, 365** (1990).
6. W. Kolos and L. Wolniewicz, J. Chem. Phys. **41, 3663** (1964); 49,404 (1968); W. Byers-Brown and J. D. Power, Proc. Roy. Soc. Lond. **A** 317,545 (1970).

Barat and Lorents, Molec. Phys. L330 ,

C. Benoit and J. P. Gauyacq,

8.

Nucl.een known for sometime. See, for example, D. Keefe, Ann. Rev.

Mansondifferent form from ours by P. M. Echenique, J. R.

64, 1413tt.

Lett. **65**, 92