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SHORT NOTE

Opening Possibility of Deuteron-Catalyzed Cascade Fusion Channel in PdD under D_2O Electrolysis

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In the latest paper of D_2O electrolysis fusion by Fleischmann & Pons[1] (F-P experiment, in the following), they reported that the observed enthalpy generation showed $10^{6\sim7}$ times more frequent fusion-reaction rates than those of the known fusion channels, *i.e.*, $D(d, n)^3He$ and $D(d, p)T$ for which they observed consistent results between the neutron and the tritium generation, and concluded surprisingly that an "unknown fusion process" took place. What did really happen in their experiment?

The author has studied the problem from a theoretical point of view in the last few weeks, and has reached the conclusion that the D-cat. cascade fusion channel, *i.e.*, the following (i)→(ii) reaction cascade would open to be the predominant reaction channel in a highly deuterium-condensed Pd electrode. We may call this D-cat. type since deuteron exists at both the initial and the final state,

(i) $D+D \longrightarrow {}^4He^*$

(ii) ${}^4He^*+D \longrightarrow {}^6Li^* \longrightarrow {}^4He+D+23.8$ MeV.

Calculated results of fusion rates and neutron yield are consistent with the F-P experiment, and can explain the key results of the F-P experiment.

In the present note, key results of theoretical estimations are described. A detailed report will be submitted to a journal (a preliminary report describing the detail is available[2]).

1. Theoretical Results

The free particle fusion reaction cross section σ_{free} is given as follows[3]:

$$\sigma_{free}=\frac{S}{E_d}\exp(-2\pi z_1 z_2 e^2/\hbar v), \qquad (1)$$

where S is the astrophysical S-function, relating to internuclear wave functions, to be determined by experiment, E_d the incident deuteron energy and other notations are the usual ones ($z_1=z_2=1$ for the D-D reaction). For $E_d<1$ keV, S values are almost constant; for the $T(d, n)^4He$, the $D(d, n)^3He$ and the $D(d, p)T$ reactions, the values are given by Jarmie[4] as $S_{DT}=12$ MeV·b, $S_{DD}(n)=53$ keV·b and $S_{DD}(p)=60$ keV·b, respectively. We can therefore calculate cross sections for low energy using Eq. (1). For $E_d=1$ eV, calculated cross section values (b) are 9×10^{-602}, 1.7×10^{-606} and 1.9×10^{-606}, respectively for $T(d, n)^4He$, $D(d, n)^3He$ and $D(d, p)T$: It is quite evident that we have to abandon "cold nuclear fusion" by the free particle reaction.

However in a condensed matter like PdD, the barrier factor $e^{-G}=\exp(-2\pi z_1 z_2 e^2/\hbar v)$ showing the quantum-mechanical tunnel effect through the Coulomb barrier increases drastically[2] because of the charge screening effect on D^+ by surrounding electron-clouds. The fusion cross section σ_{DD} for a bound D-D pair (bound with Pd atom, for example) is given as[2]

$$\sigma_{DD}=\frac{S_{DD}}{0.5E_d}\exp(-44.4\eta/E_d^{1/2}) \text{ (barn)}, \quad E_d \text{ in keV} \qquad (2)$$

where $S_{DD}=S_{DD}(n)+S_{DD}(p)$ and $\eta=(z_1 z_2 e^2)_{eff}/e^2$ $(=e^2_{eff}/e^2)$. Here the parameter η has been introduced which equivalently represents the charge screening effect on the barrier factor. The fusion rate for a D-D pair is $\lambda_{DD}=\sigma_{DD}v_d\cdot(1/cm^3)$ (f/s per D-atom), where v_d is the velocity of deuteron. Calculated results of λ_{DD} for $E_d=1$ eV are shown in **Fig. 1**.

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Jones *et al.*[5] has shown that λ-value for D_2 gas is $\sim 10^{-70}$ (f/s per D). The distance between two D^+ is $r_d = 0.74$ Å. Since $r_d \lesssim 0.5$ Å for two neighboring D-atoms bound with Pd-atoms, we expect that the charge screening effect is much stronger ($\eta^{-1/2} > 10$; see Fig. 1); the fusion rate λ_{DD} will exceed the 10^{-13} (f/s per D) level for $\eta^{-1/2} \gtrsim 35$.

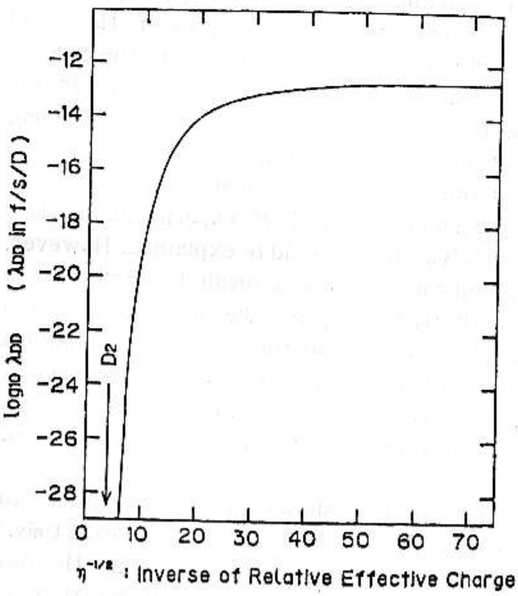

Fig. 1 D-D fusion rate for D-D pair screened with electron clouds in condensed matter, ignoring cascade fusion process; $E_d = 1$ eV

If we suppose that the deuteron density N_d in Pd is $\sim 10^{22}$ atoms/cm^3, the number of fusion events is $Y_{DD} \sim 10^9$ (f/s/cc) at this level. Therefore, we would expect to observe a lot of neutrons from the $^4He^* \to n + {}^3He$ channel. However, the situation changes drastically when the D-cat. cascade fusion channel, (i)$\to$(ii) opens in condensed PdD, as explained in the following. Fleischmann & Pons[1] suggested that D^+ bound with Pd-atom behaves as a harmonic oscillator having energy $\hbar\omega$ up to ~ 1 eV. So, we set $E_d = 1$ eV in the following calculations.

Let us define σ_{D*} as the cross section for the reaction channel (ii). We can write, assuming the charge screening effect for $^4He^*$ is almost the same as that for D^+, since there remain electron clouds ($\Delta t = r_d / v_{el} \sim 10^{-16}$ s) until $^4He^*$ decays.

$$\sigma_{D*} = \frac{S_{D*}}{E_d} \exp(-4\pi e_{\text{eff}}^2 / \hbar v). \tag{3}$$

We compare S-factors between the $T(d, n)^4He$ and the D-D reaction, and obtain $S_{DT}/S_{DD} \simeq 100$. If we could guess $S_{D*}/S_{DD} \geq S_{DT}/S_{DD}$, $S_{D*} = 100\varepsilon_S S_{DD}$, $\varepsilon_S \geq 1$. In the following calculations we set $\varepsilon_S = 1$. The cross section σ_{cas} of the (i)$\to$(ii) cascade channel can be defined as[2];

$$\sigma_{cas} = \lambda_{DD} \cdot \sigma_{D*} \cdot \tau^* \cdot M, \tag{4}$$

we guess[2] life time $\tau^* \sim 10^{-20}$ s for $^4He^*$, and M is the multiplicity of deuteron flux for harmonic oscillator D^+ which is bound with Pd-atom and oscillating with high frequency ω. We roughly estimate here $M \simeq 2.7 \times 10^{14}$ ($= v_d / r_d \cdot s$). Consequently we obtain;

$$\sigma_{cas} \doteqdot 2.7 \times 10^{-4} \cdot \varepsilon_S \cdot \lambda_{DD} \cdot \sigma_{DD} \exp(-1{,}404\eta). \tag{5}$$

The fusion rate λ_{D*} of the D-cat. cascade channel (i)$\to$(ii) is; $\lambda_{D*} = \sigma_{cas} v_d N_d$ (f/s per D), and can be estimated (roughly) using Eq. (5) (λ_{D*}: relative to λ_{DD}). The neutron+proton (triton) emission rate is $\lambda_{n,p} = \lambda_{DD} - \lambda_{D*} \geq 0$. Calculated results are shown in **Fig. 2**, where λ/λ_{DD} values are shown.

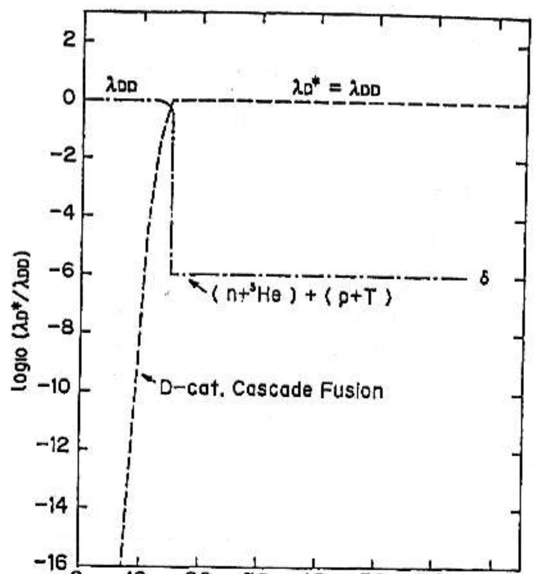

Fig. 2 Fusion rates diagram for competing process between $D(d, n)^3He + D(d, p)T$ channel and D-cat. cascade fusion channel; $E_d = 1$ eV

At $\eta^{-1/2}=5.0$, the D-D fusion rate is as high as 6.7×10^{-37} (f/s per D) and the cascade fusion rate is very small, namely $\sim10^{-81}$ (f/s per D). Above the point $\eta^{-1/2}=10.0$, the cascade fusion starts to catch up with the D+D→ $^4He^*$ fusion rates, and $\lambda_{D*}/\lambda_{DD}$ becomes 1.0 for $\eta^{-1/2}\gtrsim15.0$. At $\eta^{-1/2}=40$, $\lambda_{DD}=\lambda_{D*}=1.3\times10^{-13}$ (f/s/D) and ⟨Fusions/cc/s⟩=$\sim10^9$(f/cc/s): ⟨Energy deposit⟩$\simeq10^{-2}$ (W/cc), without any neutron emission ($\lambda_{n,p}=0$), from the usual channels.

2. Discussions

In the F-P experiment, they observed an enthalpy excess of about 10 W/cc, although they could only detect a small number of emitted neutrons. Therefore, one might predict that deuteron number density would be higher than 10^{22}; if we guess $N_d\sim10^{24\sim25}$, it could correspond to their 10 W/cc run, (r_d would be 0.1∼0.2 Å). An emitted D^+ (E_d=15.9 MeV) by the channel (ii) cannot fuse with $^4He^*$, any more, and it slows down in a volume of $V_{range}=4\pi R_E^3/3$ where R_E is the range of 15.9 MeV D^+ ($R_E\sim0.1$ cm), generating the D(d, n)^{3}He+D(d, p)T reaction (with an averaged reaction energy $E_R\sim1$ MeV, where σ_{DD} has a broad peak). The neutron yield Y_n (n/s/cc) of this process is;

$$Y_n=N_d\cdot\sigma_{free}(\bar{E}_R)\cdot\lambda_{D*}\cdot N_d\cdot R_E(\bar{E}_R). \quad (6)$$

The ratio δ between the D-cat. cascade fusion event number ($Y_{cas}=\lambda_{D*}N_d$) and the number of D(d, n)^{3}He neutrons is;

$$\delta=Y_n/Y_{cas}\doteqdot N_d\cdot\sigma_{free}(\bar{E}_R)\cdot R_E(\bar{E}_R). \quad (7)$$

The ratio δ becomes constant, once we know the energy distribution of a deuteron harmonic oscillator in PdD. For $\hbar\omega=1$ eV, we obtain $\delta\doteqdot2\times10^{-6}$, using $R_E(\bar{E}_R)=2\times10^{-3}$ cm, which gives good agreement with the F-P observation ($10^{-6\sim7}$).

3. Conclusion

When the deuteron effective charge under the screening of electron clouds in PdD (or possibly TiD *etc.*) can become $e/35$, the "cold nuclear fusion" rate exceeds 10^{-13} (f/s per D-atom) and a net power output can be expected. However, the present theoretical analysis has shown that the D-cat. cascade fusion channel can open and most (almost 100%) energy deposit is attributed to kinetic energies of $^4He^{++}$ and D^+ which are the final products of the cascade process. Neutrons can be emitted after the cascade event (by the free particle D-D reaction), with a very small portion $\sim10^{-6}$.

Using the present theoretical model, the key results of the F-P experiment on D_2O electrolysis fusion could be explained. However, to confirm the present result by further more quantitative analysis, we need complicated quantam-mechanical theories and calculations supported by many data bases of experiments, *e.g.*, for the charge screening and the nuclear reaction process of the D-cat. cascade fusion.

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