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Excess heat and nuclear products by D_2O/Pd electrolysis and multibody fusion

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An excess heat of 100 W/cc level, 1.7 times the input power in average, and 160 MJ in total was observed for about two months by the L-H mode pulse electrolysis of a D_2O/Pd cell with plane-symmetric configuration of D-loading into the Pd cathode. Very weak neutron emission was detected to show an inversely proportional correlation to the excess heat variation. To explain the observed anomalous results including our past results, the theoretical model of competing multibody deuteron fusions in transient PdD_x lattice has been extended. It can explain most experimental results. Cold fusion may be the multibody fusion of hydrogen isotopes in the metal lattice.

1. Introduction

Since the amazing announcements [1,2], many positive results have been obtained worldwide [3-5] these years, and the existence of cold fusion phenomena is becoming clear. Major results can be summarized as follows: (1) very weak neutron emission, (2) anomalous tritium production, and (3) excess heat generation of typically 20 MJ. However, the results are chaotic and difficult to be reproduced; some authors found excess heat without neutrons, some others found neutrons and no heat, and so on. What is the reason for this sporadicity? “Unusual fusion” has been suggested [3], but what is unusual fusion? Mechanisms of observed anomalous phenomena are yet to be solved. This paper tries to give an answer for solving the puzzle, and describes the detail of our previous work [6].

Since June 1989, we have carried out many experiments in Osaka based on pulse electrolysis with open cells [7-10]. The results are summarized as follows.

Experiment A [7]: Biased-pulse electrolysis with cast Pd rods in D_2O + 1 M Li_2SO_4 was done to observe neutrons. Weak emission of 2.45 MeV neutrons, 1-5 n/s/cc-metal, was observed. The loading condition of deuterons was low; the volume-averaged D/Pd ratio was less than 0.3.

Experiment B [8,9]: Biased-pulse electrolysis with D_2O + 0.3 M LiOD with a Pd (0.1% Ag) disk (8 mm diameter, 5 mm thick) and a cold-worked pure Pd rod (10 mm diameter, 30 mm long) was done for about one month per each Pd cathode. Peculiar neutron emission spectra having two components, 2.45 MeV and 3-7 MeV, were accidentally observed. The spectral shape changed time-dependently. The maximum neutron yield was 15 n/s/cc.

Experiment C [10]: Electrolysis of D_2O + 0.3 M LiOD was done by the low-high (L-H) pulse current mode with a long (12 h) repetition period for more than one month per each Pd cathode. Cold-worked pure Pd metals were used for cathodes. A large Pd rod (20 mm diameter, 30 mm long) gave neutron spectra with the two components of 2.45 MeV and 3-7 MeV, and a significant amount of tritium production. We obtained a yield ratio between neutron and tritium, i.e., the n/t ratio, of $10^{-5} \approx 10^{-6}$. The theoretical model of the competing process between two-body and three-body (d-d-d) fusions in PdD_x lattice could explain these experimental results consistently. A cold worked pure Pd plate (1 mm thick, 25 × 25 mm) gave similar neutron spectra. Since this experiment gave us a hint for controlling the "cold fusion reaction", we have tried to improve it in experiment D which is described in the following.

2. Experiment D

In the last Como Conference [5], it was suggested [11,12] that attaining a high D/Pd ratio (more than 0.9 in average of Pd cathode volume) was the key to meet excess heat and tritium generations. We have considered that the plane-symmetric and homogeneous D-loading into both sides of the Pd plate cathode is needed to enhance the D/Pd ratio significantly. Releasing and reloading deuterons by the L-H current mode electrolysis [13] may be effective. This idea was tried in this experiment [6].

The newly made electrolysis cell and its external cooling system are shown in fig. 1. An extended figure of the electrode unit is given in fig. 2 (upper graph). A 1 mm thick, 25 mm square Pd plate of 99.99% purity is used for the cathode which is supported by two small polyethylene bricks and surrounded with Pt anode wires (7 turns with 5 mm pitch) keeping the minimum anode-cathode distances to be 10 mm for both sides. The Pt leading wire to the cathode and the anode leading wire (Pt) are covered with Teflon tape wrapping to make electrical isolation. The electrolyte is 700 ml D_2O plus 0.3 mol/l LiOD. The electrolyte is always cooled with an external cooling system through a spiral glass tube, temperature-regulated (20°C) ordinary water flow with constant flow-rate (10 l/min nominal). The cell temperature is monitored by a thermocouple in a small glass tube filled with fresh D_2O, which was set up at the middle point between the electrode unit and the water-cooling coil of spiral glass. The cell container (120 × 75 mm, 110 mm high) is made of 5 mm thick acrylite plates.

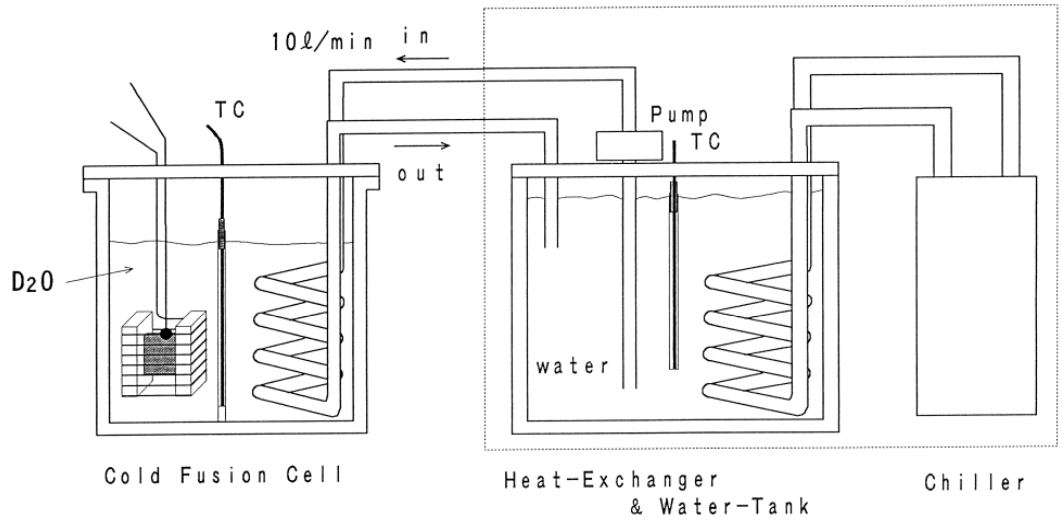


Fig. 1. Schematic view of electrolysis cell and external cooling system.

The control system of pulse electrolysis and neutron measurements is described in detail in ref. [7]. We used a constant current power supply for the electrolysis. Following the initial test operation for an hour to check the voltage-current condition (50 ≈ 100 W Joule heating by electrolysis) and cooling safety, we started the "preloading phase" with the "sawtooth current mode" (0.25 A minimum current, 5 A maximum current, linear increment from minimum to maximum, and 20 min cycling period, see fig. 2 lower) and continued it for 7 days (Exp. 114). In the 5th to 7th day, we could notice a slight (≈1 n/s) excess neutron emission and a trend of cell temperature increase. Therefore, we decided to switch to the L-H current mode operation (repeating the cycle of 0.25 A for 6 h (L) and 4.2 A for 6 h (H): see fig. 2 lower) from the 8th day to start Exp. 115. For either the L- or H-period, the electrolysis current was kept constant. The supplied voltage was almost constant for the L-periods, about 5 V, and varied from about 27 V (early cycles) to 20 V (later cycles) for the H-periods for a one "week" run. Once a "week" (4-8 days depending on the procedure; see fig. 3) we added 200-250 ml fresh D_2O, and sampled 1 ml electrolyte for the tritium measurement [10].

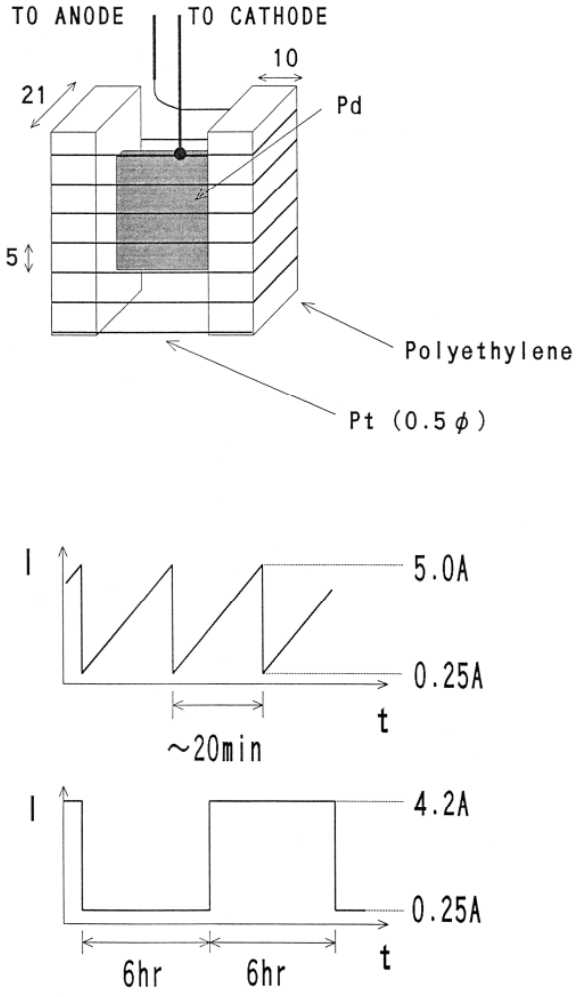


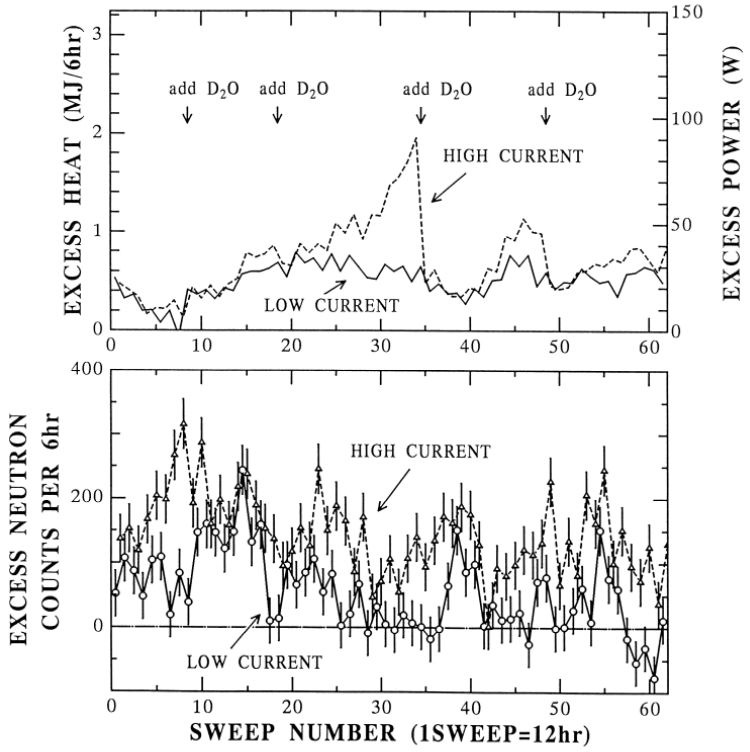
Fig. 2. Configuration of electrode unit for experiment D (upper) and current operation modes (lower).

In about two weeks for the L-H operation, we started to notice anomalous increases in the cell temperature. Typical wave forms of the cell temperature are shown in fig. 4, together with the

supplied voltages and currents. Looking at the temperature variation curves right after the current switching from L to H, the thermal equilibrium time of the present system consisting of a heat source and cooling (heat sink) is about 15 min. Comparing Sweep 1 (input power 113 W) and Sweep 34 (input power 92 W), a significant temperature increase in the H-period is seen for Sweep 34, though the input power has decreased. Similar temperature increases and decreases were found in comparison with the H-period temperatures in “week”-cycles with the same electrolyte level heights. From these, we were convinced of excess heats in H-periods. Since the cell is cooled strongly by the external water flow of 20°C, the cell temperature for the L-period (1.5 W input power) should be very close to 20°C unless there is a large heat excess. In contrast, we have observed significant temperature increases even for L-periods as shown, for example, in Sweep 34 and Sweep 42 of fig. 4. We decided to make a calibration for calorimetry, though the present temperature monitoring system was “primitive”.

In the present cell (see fig. 1), circulation of the convection current of the electrolyte, which is going up from the electrode unit due to the bubbling flow by electrolysis and going down in the cooling coil zone, works much for the thermal equilibrium to make a “steady” temperature gradient between the heat source (electrode unit) and the heat sink (cooling coil). Therefore, the usual method of calibration with a resistor heater setting up at the electrode unit position cannot be applied. Instead, we employed the calibration by Joule heating of the electrolysis itself. By the initial test operation, we observed a temperature increase (ΔT) of 7°C by 100 W Joule heating of electrolysis, which can be a measure of calorimetry calibration assuming there was no excess heat. At Sweep 1, the temperature increase from L to H current switching was almost the same (7°C) for 106 W (subtracting 7 W for D_2O dissociation). In our previous experiment (Exp. 102), in which we used a side-by-side electrode setup in the same position of the cell, we had 8 data points that showed a linearly increasing relation for ΔT versus the power curve up to 230 W, and that gave almost 7°C increase for 100 W. With the support of this experiment, we regarded that ΔT versus the input-power curve for Exp. 115 was linear up to about 250 W, and used 100 W per 7°C for calibration.

(a)



(b)

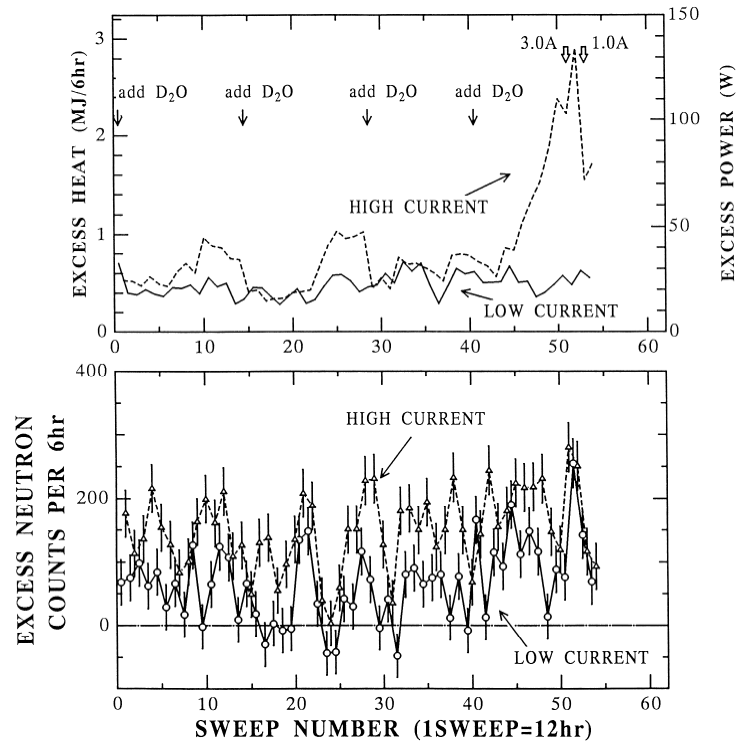


Fig. 3. Evolutions of excess heat and neutron yield as a function of cycles (sweep number) of the L-H current mode electrolysis: (a) for the 1st month of Exp. 115, (b) for the 2nd month of Exp. 115.

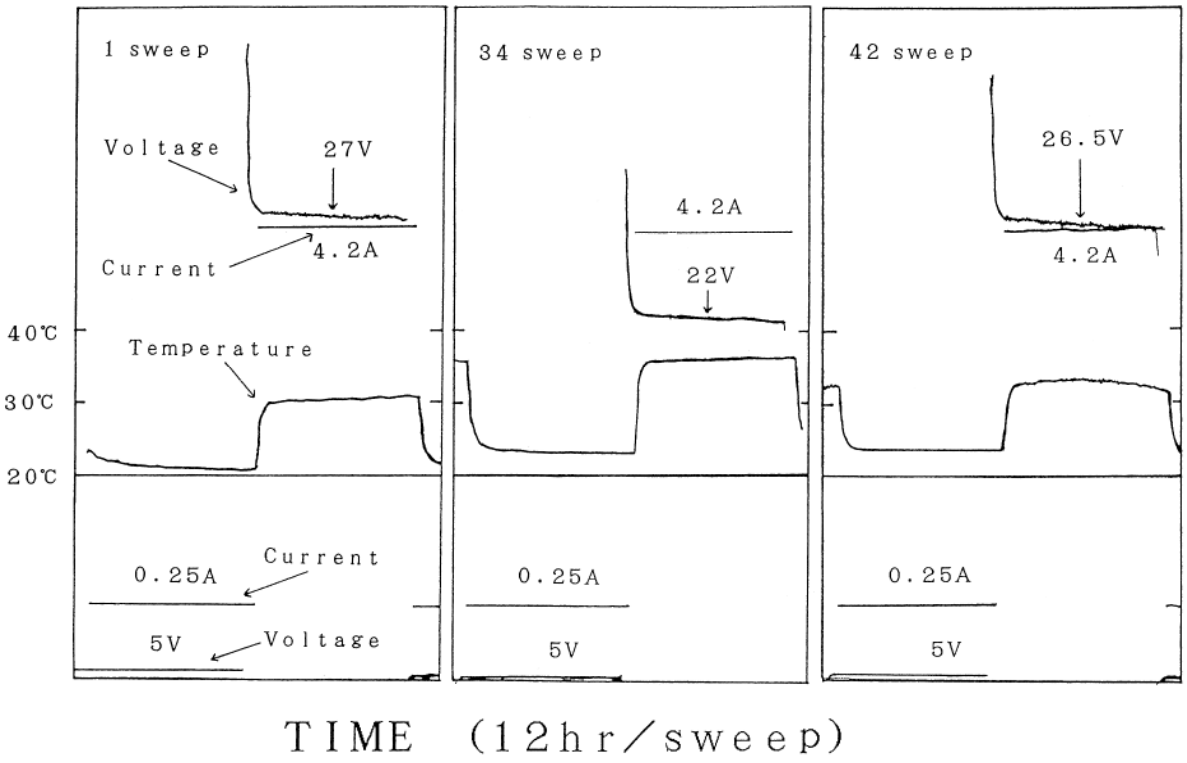


Fig. 4. Typical data of cell temperature, voltage, and current in Exp. 115.

To calibrate the "zero power" line (equivalent to the 20°C line) rigorously for the two months long run of experiments, we had to make corrections for compensating the effect of room temperature variations on the cell temperature measurements due to the very slowly varying drift of the used thermocouple output. The correlation of this drift and room temperature change was observed for about two weeks to obtain correction factors to zero power levels on all days of the two months for Exp. 115. Because of this drift effect on the zero-power level, we decided to deduce only integrated heat or averaged power within the L- or H-mode. Corrections by this effect varied from -20 W to +5 W around the ideal constant zero-power line and drew cycle (day) dependent zero-power curve. The step difference of temperatures by switching from the L- to H-mode is independent of this drift effect, because of only 15 min thermal equilibrium time.

Monitoring the excess neutron emission and its energy spectrum was done with an NE213 liquid scintillator system, which is a well established technique [7]. The NE213 detector was set up as close to the electrode unit as possible, at 3 cm from the cell surface. Except for the detector head and the high voltage supply, the electronics modules were located in a separate air-conditioned room for monitoring the total neutron counts every 4 min, the recoil-proton energy spectra for L and H periods, and the n-γ pulse shape distribution. For crosschecking variations in the total neutron counts, the count integral within the ^{3}He(n, p) sum peak of a ^{3}He detector, which was located at about 20 cm distance from the cell surface, was monitored every 6 h, and showed reasonable correlation with neutron counts by the NE213 system [7]. There was no correlation found between the excess neutron counts and the room temperature change for 60 days of Exp. 115. Backgrounds were measured by removing the Pd cathode.

Evolutions of the excess power (heat) and excess neutron counts thus obtained in Exp. 115 are shown in figs. 3a and 3b, which show the relation between the excess heat and neutron emission. An overall trend shows that the excess neutron yield decreases as the excess power level increases, as we see relatively clear in the earlier one month run ignoring fluctuations by statistics. However, excess neutron counts in H-periods are slightly larger than those in L-periods where the excess powers are small. If the observed excess heat was attributed to the usual d-d fusions, we should have observed "detector-killingly intense" neutrons, i.e., $10^{13} \approx 10^{14}$ n/s/source. In contradiction, the observed neutron yields were in the order of $1 \approx 2$ n/s/source (taking 1% detector absolute-efficiency into account), surprisingly small. The neutron energy spectrum integrated over two months was expected to give the two (2.45 MeV and 3-7 MeV) components, as in the cases of experiments B and C. However, counting the statistics of Exp. 115 was not enough to deduce the clear neutron spectra. Additionally, no detectable increase in the tritium level in the electrolyte was observed in the two months of Exp. 115 in contrast to experiment C [10] which showed a weak trend (≈1 W/cc) of excess heat and a significant tritium generation.

Mysterious depressions of the excess heat curve were mostly found when we added fresh D_2O, and lasted 1-2 days. This may suggest the phenomenon occurring near the surface of the Pd cathode. A similar effect is suggested in the tritium generation [14]. Another mysterious but amazing happening was the "surface film boiling" of the electrolyte at the near end of two months run (see fig. 3b). From the 55th day, the excess heat level started to increase (run away) in H-periods and on the 56th day "film boiling" on the Pd plate was noticed by a sudden and frequent fluctuation in the voltage curve (a large (≈350 cc) decrease e of electrolyte in 6 days was found later on the 59th day). We decreased the H-current from 4.2 A to 3 A, but the excess heat continued to increase for a day and the electrolyte still boiled. We had to decide to decrease the H-current drastically to 1 A, and we could stop the boiling. However, an excess power of about 90 W was recorded by 15 W (1 A × 15 V) input. By adding fresh D_2O after this event, the excess power level decreased to about 10 W.

The total energy balance for the one week and two months run was as follows: total input energy = 250 MJ, total output energy = 410 MJ, and net excess heat = 160 MJ. After one week of the sawtooth run, we gave up trying to do calorimetry [1] As the average power of the two months for the L-H operation we obtained: average input power = 50 W, average output power = 85 W, and average excess power = 35 W. The average gain (output/input) = 1.7. We should, therefore, have a "hidden" excess heat source in the cell.

Dissociated D_2 and O_2 might have recombined in the cell to release heat. In the calibration of heat, we have already subtracted this energy (1.5 V × current). However, we estimate it again. By electrolysis (average current = 2.23 A), 8.4×10^{24} D_2O molecules are dissociated every week, and 2 MJ can be, at maximum, be produced by the "complete recombination". The observed excess heat is about 25 MJ per week, and cannot be explained by recombination. Truly, recombination never happened since adding 250 ml of fresh D_2O corresponds to 8.4×10^{24} D_2O molecules dissociated, which should have been consumed to go out of the cell. Other possible heat sources by chemical reactions can be estimated to be too small to explain the observed excess heat. For example, any exothermic chemical reaction by deuterons in the Pd lattice (1 ml assumed volume) can produce a heat level of the order of 15 kJ. The order of excess heat observed is about 1000 times greater than the chemical heat sources.

[1] Note added in 2009: it was difficult to calibrate the calorimetry for this dynamic operation.

Since we have observed in Exp. 115 that there is a relation between excess heat and neutron yield, unknown nuclear reactions as the "hidden" excess heat source would have happened.

We have no in-situ data of the D/Pd ratio in Exp. 115 that may be a key factor. However, we may speculate that D/Pd = 1.0 to 1.5 was attained in Exp. 115 by referring to Mizuno's work [13].

3. Multibody fusion

To explain the series of experiments (A, B, C, and D), a hypothetical model is extended in the following based on the idea in ref. [7].

When all octahedral sites in Pd fcc lattice are filled with deuterons, the D/Pd atomic ratio becomes 1.0, which may correspond to the reported value of 0.85 as the minimum volume averaged D/Pd ratio to produce an anomalous amount of tritium [12]. The reported minimum value 0.9 of the volume averaged D/Pd ratio needed to meet the excess heat generation [11] is considered to be over this condition and some of the tetrahedral sites may be locally filled with deuterons. We consider the excitation screening model [7] for D/Pd > 1.0. When all the o- and t-sites are filled with deuterons, D/Pd becomes 3.0 which will be the limit. Cluster formation is possible up to 5D, because of the three-dimensional periodic condition around a fusion domain (see fig. 5; one o-site at the center is missing in fig. 4 of ref. [7]) with four o-sites and one t-site which together form a tetrahedron with a centered t-site. There are experimental evidences of t-site occupation for high D/Pd ratios, i.e., greater than 1.0. It is considered that trapped deuterons at t-sites attribute to the very slowly diffusing out component, while o-site deuterons rapidly diffuse out. The D/Pd > 1.0 condition is considered as unstable in the transient mode due to dynamical (probably coherent) motions of deuterons and electrons. In this dynamical condition, the potential well of t-site may be deeper than that of o-site, so that by the vibrational excitation three deuterons may "fall" into the t-site well where another deuteron trapped more rigidly is waiting to make a 4D cluster and 4D fusion, in competition with 2D and 3D fusions. The competing process is imagined in the atomic level, looking at the tetrahedron of 4 o-sites and 1 t-site; D-D pair formation is possible in the transient when one o-site D "falls" into the centered t-site (we have 4 combinations for a tetrahedron). 3D cluster formation is possible when two Ds fall into the t-site (6 combinations), 4D cluster (4 combinations) and at last 5D cluster (1 combination). We neglect the 5D process in the following because of its low combination.

It is assumed in this hypothetical model that a strong electron screening effect is induced transiently when deuterons "fall" into the t-site since attracted "many" electrons can move toward the t-site. This "coherent" screening effect is not solved yet but is estimated with an arbitrary scaling factor q to define the effective deuteron charge [7]. This scenario is approximately simulated in the following. The reactions are:

(i) $2D \rightarrow n + {}^3He + 3.27$ MeV,
$p + t + 4.03$ MeV: $S_{2D} = 1.1 \times 10^2$ keV b
(ii) $3D \rightarrow d + \alpha + 23.8$ MeV,
$t + {}^3He + 9.5$ MeV: $S_{3D} \approx 10^8$ keV b
(iii) $4D \rightarrow \alpha + \alpha + 47.6$ MeV: $S_{4D} \approx 10^{11}$ keV b

Fusion rates are given by:

$\lambda_{ND} = F_{ND} S_{ND} (V_d/E_d) \exp(-G_N)$,

$N = 2, 3, 4,$ (1)

where F_{ND} is the cluster or pair formation probability, S_{ND} the astrophysical S-value for two-body or multibody fusion, E_d the deuteron energy, V_d the deuteron velocity, and exp(-G_N) the barrier penetration probability with the Gamow integral G_N *[7]*. Pair and cluster formation probabilities are given by using wave function integrals around a t-site [7]:

$$F_{2D} = \left\langle \Psi_0^2 \right\rangle_t \cdot \left\langle \Psi_t^2 \right\rangle_t \cdot \left(1 - \left\langle \Psi_0^2 \right\rangle_t\right) \times \left(1 - \left\langle \Psi_0^2 \right\rangle_t\right) \cdot P_{t-site}, \quad (2)$$

$$F_{3D} = \left\langle \Psi_0^2 \right\rangle_t \cdot \left\langle \Psi_0^2 \right\rangle_t \cdot \left\langle \Psi_t^2 \right\rangle_t \cdot \left(1 - \left\langle \Psi_0^2 \right\rangle_t\right) \times P_{t-site}, \quad (3)$$

$$F_{4D} = \left\langle \Psi_0^2 \right\rangle_t \cdot \left\langle \Psi_0^2 \right\rangle_t \cdot \left\langle \Psi_0^2 \right\rangle_t \cdot \left\langle \Psi_t^2 \right\rangle_t \cdot P_{t-site}, \quad (4)$$

where $P_{t\text{-site}}$ is the deuteron filling probability for a t-site.

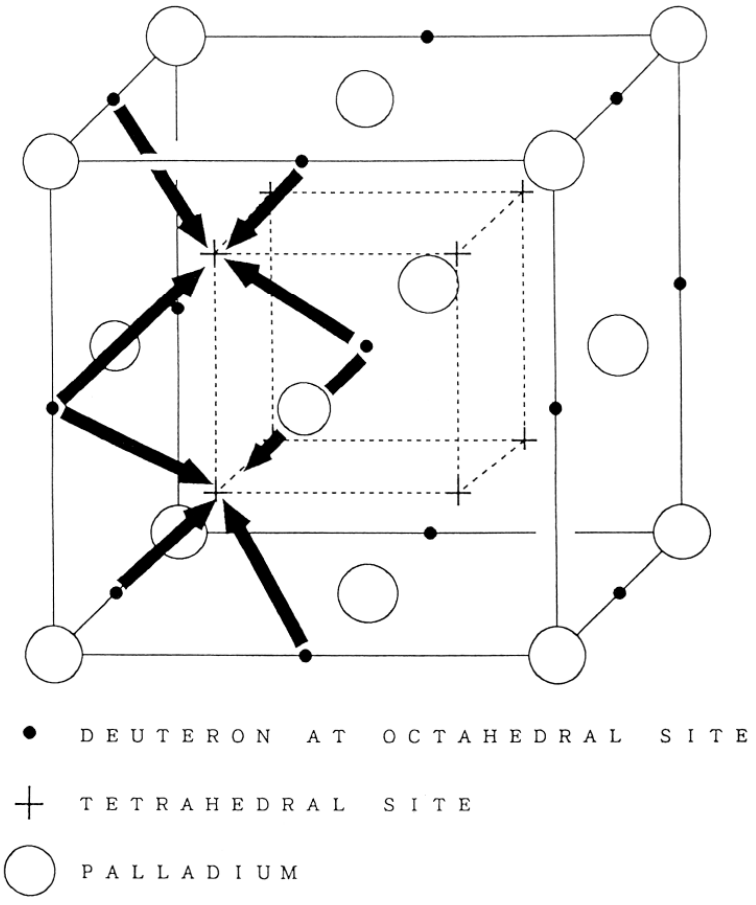


Fig. 5. Face-centered cubic PdD lattice (the deuteron wave function at a highly excited state has eight wings spreading toward the eight nearest tetrahedral sites of the four surrounding fcc cubes, hence four deuterons at most meet at a tetrahedral site as indicated by the arrows).

We do not have data for S_{3D} and S_{4D} values. However, we can make rough estimations by extrapolating S-values of p-d, d-d, and d-t reactions as a function of the pion exchange force (PEF). Within the nuclear well potential, neutron and proton exchange pions (π^+, π^-, π^0) and

strong p-n coupling holds. However, p-p and n-n are decoupling as we know that ^{2}He and dineutron never exist. We set the relative PEF for p-n to be 1.0, and zero for p-p and n-n interactions. Then, we obtain PEF of 1, 2, 3, 6, and 12, respectively, for p-d, d-d, d-t, d-d-d, and d-d-d-d simultaneous interactions. We can draw fig. 6 for estimating *S*-values of multibody fusions by hydrogen isotopes. The validity of this bold extrapolation has to be further studied since p-t and t-t reactions provide much smaller *S*-values [15] (2.6×10^{-3} and 1.6×10^{2} keV b), because of Pauli's exclusion principle to fermion-fermion interactions. Deuteron fusions (d-d, d-t, d-d-d, 4d, d-p-d, d-p-d-d) as boson interactions may have breakup channels to charged particles with big *S*-values, which systematics on PEF is independent of that for the fermion-fermion fusions. Estimated S_{3D} and S_{4D} values are three and six orders of magnitude greater than the previously used ones [7]. The hatched area in fig. 6 shows ambiguity of the extrapolation. These very large *S*-values are essential to meet the observable excess heat level [7]. We may call this the "multibody fusion resonance at room temperature".

Details of numerical estimations of formation probabilities and excitation screening by electrons are given in ref. [7]. A much milder screening condition (q = 1.6) is given in the present calculation.

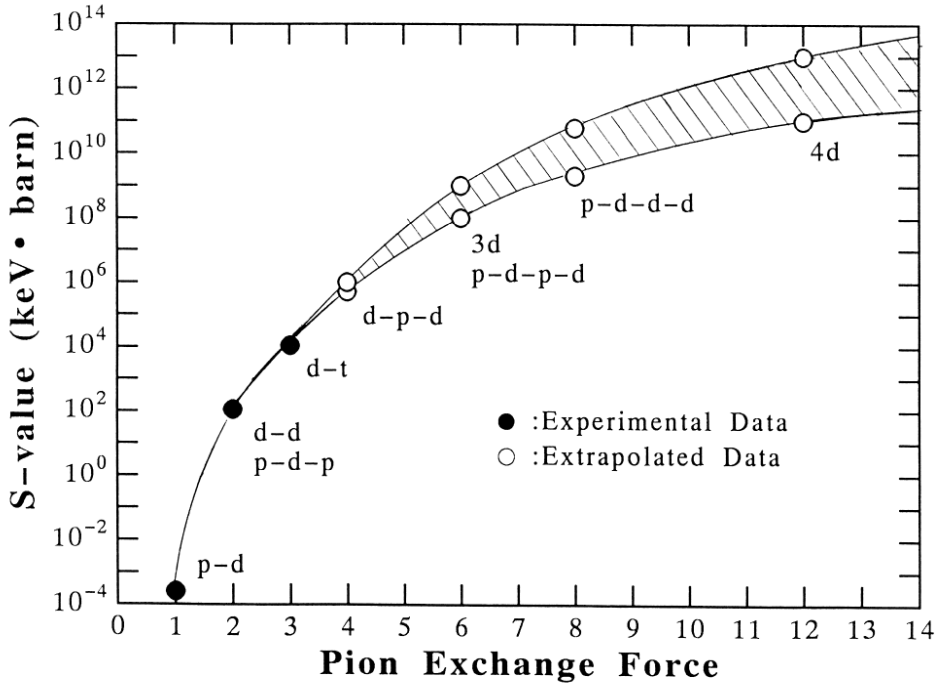


Fig. 6. Extrapolated *S*-values for multibody fusions of deuteron and deuteron-proton systems.

Results for $PdD_{1.25}$ ($P_{t\text{-}site}$ = ⅛) are shown in fig. 7. If P_{t_site}=0.5 (D/Pd = 2.0) the contribution of 3D fusion becomes much higher. For 4D fusion, 10^{11} f/s/cc corresponds to 1 W/cc. We pick up three typical conditions (a), (b), and (c) as indicated in fig. 7:

Condition (*a*)*:* Heat level is 1 kW/cc. Neutron yield is about 10 n/s/cc with 3-7 MeV energy (byproduct of 3D fusion [7-10]). The neutron yield per fusion reaction, i.e., the n/f ratio is 10^{-13}. The n/t ratio is 10^{-8} to 10^{-5} depending on the assumed branching ratio of t + ^{3}He and d + ^{4}He channels of 3D fusion. This condition can correspond to the results of experiments D,

considering that the difference in power level is due to excitation efficiency by pulse electrolysis. When the power level increases, the neutron yield decreases; this explains the overall relation between the neutron yield and heat in fig. 3. The reason why the H-current mode gave a larger excess neutron yield than the L-current in experiment D is not explained with this model. We have to further study the electrochemical triggering mechanism of cold fusion. However, the present model can explain the overall trend of Exp. 115, as for excess heat and neutron yield. If the 4D fusion was really the major source of excess heat, we should have a significant amount of ^{4}He production ($\approx 10^{14}$ ^{4}He atoms/s), which should be further investigated by mass spectroscopy of the used Pd plate.

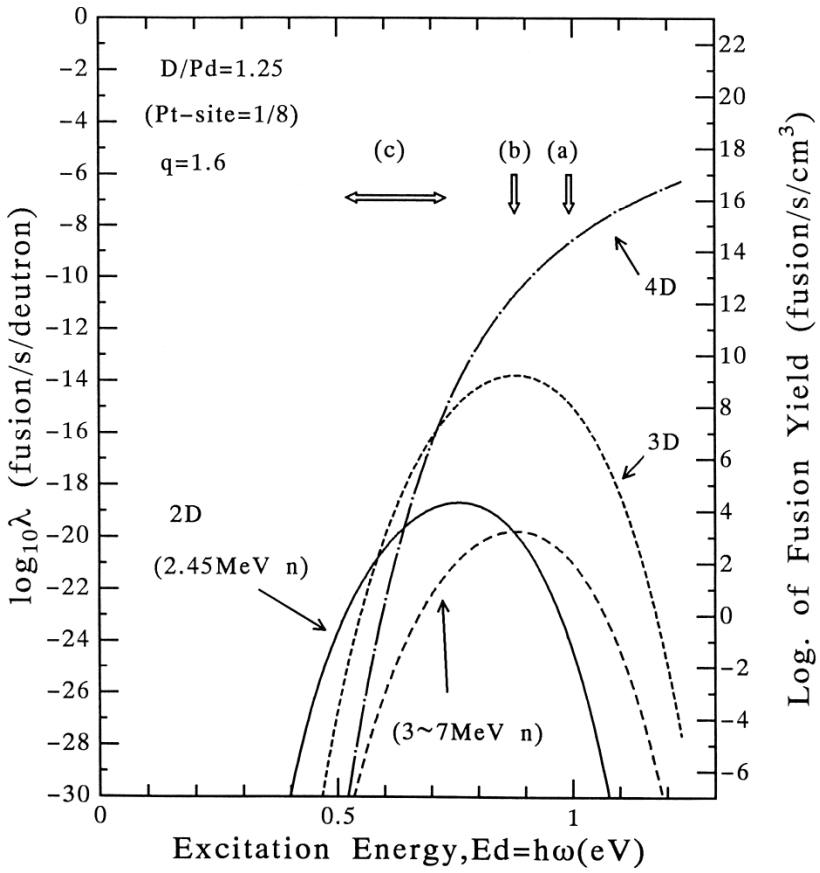


Fig. 7. Competing cold fusion rates for 2D, 3D, and 4D reactions as a function of phonon excitation energy for D-in-lattice, calculated by hypothetical excitation screening model for PdD_x (x = 1.25).

Condition (*b*): Heat level is 1 W/cc. Neutron yield is about 100 n/s/cc with two energy components (2.45 MeV and 3-7 MeV), additionally assuming that the D(α, n) cross section is less than 1 μb (previously it was assumed 1 mb [10]). The n/f ratio is 10^{-9}. The n/t ratio is 10^{-5} to 10^{-6}. This condition can explain the results of experiment C.

Condition (*c*): Heat level is less than 1 mW/cc and not detectable. The neutron yield is in the order of 1 to 10^3 n/s/cc with 2.45 MeV energy. The n/f ratio is 0.5 to 10^{-3}. The n/t ratio is 1.0 to 10^{-2}. Transition between condition (b) and condition (c) explains the results of experiment B.

Chaotic results for heat, tritium, charged particles, and neutrons from other authors can be explained in the same way. Detection of a large amount of ^{4}He comparable to fusion nuclear

heating [16] can also be explained by the present model. Thus, it seems that we have obtained many clear evidences to believe in multibody deuteron fusions in a PdD_x lattice with selective excitations for deuterons. The above conclusion leads us to the following crazy speculation of multibody fusions for H-D systems. Considerable fusion reactions are:

(iv) $H + D \rightarrow {}^3He + \gamma + 5.5$ MeV:
$S_{pd} \approx 10^{-4}$ keV b
(v) $H + D + H \rightarrow {}^3He + p + 5.5$ MeV:
$S_{pdp} \approx 10^2$keVb
(vi) $D + H + D \rightarrow \alpha + p + 23.8$MeV:
$S_{dpd} \approx 4 \times 10^5$ keV b
(vii) $H + D + H + D \rightarrow {}^3He + {}^3He + 11$ MeV:
$S_{pdpd} \approx 10^8$keVb
(viii) $H + D + D + D \rightarrow \alpha + {}^3He + 29.3$ MeV:
$S_{pddd} \approx 10^9$ keV b

Reactions (v) and (vii) will have to be eliminated due to Pauli's exclusion to fermion-fermion interactions. Fusion rates can be estimated for PdD_rH_y in the same way for D-systems. We speculate that cold fusion with 1-100 W/cc power level without neutron and triton productions may occur in an electrolysis cell with a mixture of light- and heavy-water. Cold fusion may also occur in a cell with ordinary water after a very long run, since 1/6700 of hydrogen atoms are deuterium and D in metal-lattice might be enriched by repeating absorption and desorption. The Barrier penetration probability is much enhanced for a proton, compared with a deuteron, so that the "trigger" point of cold fusion can be much milder for the H-D mixed system. However, considering the S_{pddd} value of about 2-3 orders of magnitude smaller than S_{4d}, the maximum power level will be 1 kW/cc for H-D multibody fusion, while 4D fusion may reach the 1 MW/cc level which is well beyond the explosion condition. The electrolysis experiment with mixed H_2O/D_2O electrolyte is really expected, since the cold fusion with H-D systems would give us the ultimately rich and clean nuclear energy source. Some recent reports about heat generations from ordinary water wells might be due to these phenomena. In experiment D, we employed an open cell for a long (two months) run. There is a reason that several percent of light-water might have been contained in the electrolyte during the run of Exp. 115. Therefore, another plausible excess heat source in experiment D might be the p-d-d and p-d-d-d fusions which produce no neutrons and no tritium but ${}^4He$ and ${}^3He$.

4. Concluding remarks

Cold fusion is very likely the multibody fusion of hydrogen isotopes in metal lattice. The present reported experiments have confirmed that clean power generation, already useful in level and gain, with extremely low generations of neutron and tritium would really have happened.

The deuteron loading method into Pd was regarded as the key to meet the excess heat and other nuclear products. The L-H current operation of electrolysis and homogeneous loading from both sides of the Pd plate showed remarkable effect. Improvement of this method is expected to control the power level and time-variation of cold fusion. However, further confirmation experiments are of course needed to establish reproducibility (*See 2009 note added at the end of paper).*

Many things are yet left to be solved by further experimental studies, e.g., in-situ determination of the D/Pd ratio, in-situ and off-line helium analysis, charged-particle

spectroscopy for direct confirmation of multibody fusion, condition of metal fabrication, effect of impurity, other metals and alloys than Pd, triggering mechanisms by electrochemical effect on cathode surface and by other methods, and so forth.

The hypothetical model of multibody fusion may give us a great hint to solve the puzzle of cold fusion. However, the validities of key assumptions, namely, (1) D-cluster formation, (2) strong screening by coherent dynamics of electrons under excitation of D-in-lattice and (3) resonant *S*-values of multibody fusions, have to be further studied.

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Note added by A. Takahashi, July 2009

The results reported in this paper were not reproduced well in later runs tried in 1993-1996, except for one reported at ICCF3 (experiment D2, p. 85). However, I remain convinced that the excess heat we observed in 1992 was real, and not an instrument artifact. The power level was too high to be an artifact, and the film boiling was visually observed.

In retrospect, it seems likely that the effect could not be reproduced because nano-structures did not form on near surface of Pd cathode. The importance of nano-structures and surface conditions were not clear at that time.