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Solving the Puzzle of Excess Heat without Strong Nuclear Radiation

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Abstract

Five experimental evidences show that the excess heat is from a nuclear source with a life-time of 10^4 seconds. This life-time is shown to be related to the barrier penetration number, θ, in terms of the resonance penetration theory. The boson nature of the deuteron ion (D^+), and the deuteron energy band structure in lattice play the critical roles in filling the corresponding narrow resonance energy level. Prof. J. Huizenga's challenge of three miracles[1] is answered, and "excess heat" without strong nuclear radiation is a reasonable phenomenon. It predicts: (1) there must be a critical loading ratio; (2) the greater the grain size and the activation energy are, the better the reproducibility.

1. Introduction

After six years of studies on the "cold fusion" phenomenon, two facts are established: (1) Under certain conditions there is "excess heat" of several watts per cubic centimeter of palladium; (2) There are no commensurate neutrons, tritons, or γ-radiation in parallel with the "excess heat" which is of non-chemical origin. The regression is that: instead of using the neutron signal to convince people to believe there is any nuclear reaction, we attempt to explain that these two facts are due to the existence of a long life-time nuclear resonance state inside a lattice.

Early in 1928, Gamow proved that the life-time of an α-radiation nuclide, τ_α, was determined by the Coulomb barrier penetration number, θ.[2] At that time the α-particle after disintegration was a free-moving particle , and $\tau_\alpha \propto \theta^2$. Now the penetration of the Coulomb barrier happens in a reverse direction and in a different environment: the lattice confined deuteron penetrates the Coulomb barrier and enters a resonance state. The life-time of this resonance state, τ_{xh}, is determined by the θ again, but $\tau_{xh} \propto \theta$. Now τ_{xh} is linearly proportional to the θ due to the discrete nature of the energy level of the lattice confined deuteron which is different from the continuum of the free-moving deuteron.

We will start from the experimental evidences of this long life-time state (section 2); then, we calculate this life-time based on the nuclear resonance theory (section 3). In order to fill this resonance state, this theory requires a critical loading ratio which is another well-established experimental fact in the past five years (section 4). Finally, we discuss the famous challenge of three miracles (section 5), and the conclusion (section 6).

2. Evidences for Long Life-time State

The strongest evidence is from the "heat after death".[3] The boiling-to-dry electrolytic cell was kept at about 100 °C for three hours without any power input. It clearly showed that the "excess heat" source was inside the palladium deuteride. The reliable calorimetric calculation proved that the energy released in this 3 hours was 20 times greater than the heat of combustion possibly released by the deuterium stored in this system. This was a nuclear active state with a life-time of 10^4 seconds.

The second evidence is from the "heat after life".[4] The SRI electrolytic cell was a closed cell. It was not driven to boil. However, when the electrolysis was shut down, and input power was zero, the system did not cool down as a source-free system. The flow-calorimeter clearly recorded that there was an energy source inside the system. The first peak of the "excess power" was about 100 mW (the accuracy and the precision of that experiment was ±10 mW), and the width of that peak was about 3 hours again. The energy released in these three hours was also about 10 times greater than the heat of combustion possibly released by the deuterium available in the palladium electrode. This was again a nuclear active state with a life-time of 10^4 seconds.

During the ICCF-5, J.P. Biberian's "excess heat" data [5] showed that after the shut down of the input power, the "excess heat" continued for 3–4 hours. Although there was no palladium lattice, an $AlLaO_3$ single crystal provided the lattice confined deuterons. Once again the life-time of that "excess heat" source was of the order of 10^4 seconds.

In the "Critical Review of the 'Cold Fusion' Effect",[6] E.Storms talked about the replacing time of the palladium deuteride. When he put the deuteron-loaded electrode into the light water cell, he observed the "excess heat" continuing for the first several hours. He called this time the replacing time, because he considered that when the deuteride was replaced by hydride, the "excess heat" was supposed to stop. From another point of view, this showed that the life-time of the nuclear active state was again of the order of 10^4 seconds.

After my talk in ICCF-5, M.Eisner of the University of Houston was so kind as to give me his 1989 data for the "excess heat".[7] It clearly showed that the width of the first "excess power" peak after the shut down of the electrolysis was once again of the order of 10^4 seconds.

It was not realized that the answer to Prof. J.Huizenga's challenge of three miracles has been indeed implied in this long life-time of nuclear active state.

3. Theory of Resonance Penetration for Lattice Confined Ions

The life-time of a quantum mechanical state, τ, is related to the width of its energy level, Γ, by the uncertainty principle:

$$\tau \approx \frac{\hbar}{\Gamma} \tag{1}$$

The width of the energy level can be expressed by the imaginary part of the wave number, k^i, through the identity:

$$\Gamma = \mathrm{Im}U \equiv \frac{\hbar^2}{m} k^r k^i \tag{2}$$

Here $\mathrm{Im}U$ is the imaginary part of the potential well U, k^r and k^i are the real and imaginary part of the wave number k, respectively. $k^2 \equiv \frac{2m}{\hbar^2}(E-U)$. E is the total energy of the relative motion of the two deuterons. When the energy E coincides with the energy level inside the nuclear well, $(k^r a) \approx O(1)$. Here a is the size of the nuclear well. However

$$\left|k^i a\right| \approx O(\theta^{-1}) \tag{3}$$

for this resonance. Here θ is defined as

$$\theta \equiv \exp[\int_a^b \sqrt{\frac{2m}{\hbar^2}(U-E)dr}] \tag{4}$$

and θ^{-2} is just the famous Gamow barrier penetration factor. Equation (3) has been rigorously proved for the square well case, [8] and for the arbitrary potential configuration.[9] Here we just explain why the imaginary part of the wave number, k^i , should be such a small number in order to have a resonance penetration. As we know, when $k^i < 0$, k^i determines the damping of the wave function. The wave e^{-ikr} will be damped by a factor of $\exp[-\left|k^i a\right|]$ when the wave propagates through a length of a. On the other hand the Coulomb barrier suppresses the amplitude of the penetrating wave function by a factor of θ^{-1}. In order to use the resonance effect to build-up the wave amplitude to its initial value in terms of the constructive interference between the reverberating wave and the penetrating wave, we need at least θ-times reverberation before the wave is damped. So we need $\left|k^i(\theta a)\right| \le O(1)$, or $\left|k^i a\right| \le O(\theta^{-1})$.

Consequently, sustituting k^r and k^i in eq.(1) and (2), we have the life-time for "excess heat"

$$\tau_{xh} \approx \frac{ma^2}{\hbar}\theta \qquad (5)$$

For the d+d interaction, $m \approx 10^{-24}$g., $a \approx 10^{-13}$ cm, $\theta \approx 10^{27}$, [10,11] we have $\tau_{xh} \approx 10^4$ sec. The theory just gives the correct order of magnitude of the life-time of the nuclear active state.

4. Bose Condensation and the Critical Loading Ratio

Such a long life-time state corresponds to a very narrow energy level in the order of 10^{-19} eV. This is the reason why we could not observe this resonance level in any low energy beam-target experiment.[12] Because the beam energy distribution is much wider than the width of the resonance energy level, it is an analogy to using a screw driver to detect a tiny crack in a brick wall. The crystal lattice assists in observing this narrow resonance in two ways: (1) the trapped deuteron ion in the lattice well is sitting on a discrete energy level with very narrow width also; (2) the periodical structure of the lattice well creates an energy band for the trapped deuteron ions. Then, we have a bunch of needles to detect the single tiny crack on the brick wall. The number of the energy levels (needles) in this band is determined by the grain size, L (i.e. the size of the periodical structure, or the coherent length), and the size of the primitive cell in the palladium lattice, δ (i.e. the size of the PdD molecule). When $\delta \approx 3\mathring{A}$, $L \approx 60\mu$, we have roughly $(L/\delta)^3 \approx 10^{16}$ energy levels inside a deuteron energy band. On the other hand the deuteron energy band width, Γ_B, is determined by the size of the primitive cell as:

$$\Gamma_B \le \frac{\hbar^2}{2m}\left(\frac{1}{\delta}\right)^2 \approx 10^{-3}\text{eV} \qquad (6)$$

Thus, the energy difference between each neighboring energy level inside the band is about 10^{-19} eV. Hence, if the whole band is occupied by the deuterons; then, the whole population has the chance to be in resonance penetration of Coulomb barrier, as long as the energy band is adjusted to a level in resonance with the nuclear energy level. When $(L/\delta)^3 \ll 10^{16}$, we have much less chance to have resonance penetration of the Coulomb barrier due to the difficulty in matching the narrow nuclear energy level with the lattice energy level.

Now the question is: how can we populate the deuterons into this energy band ? We need the Bose-Einstein condensation. Experiment has shown that hydrogen solved in palladium acts like an ion,[13] so deuteron should act like a boson. If the deuterons are totally free-moving particles like a gas inside the palladium; then, the critical density for Bose-Einstein condensation is about[14]

$$n_c = 2.612\left(\frac{mk_B T}{2\pi\hbar^2}\right)^{3/2} \approx 8.5\times10^{24}\ \text{cm}^{-3} \tag{7}$$

It is much higher than the maximum possible deuteron density inside the palladium ($\approx 6.8\times10^{22}$ cm^{-3}). However, the experiment has also shown that the hydrogen solved in palladium is not a free-moving gas. In order to explain the anomalous diffusion behavior of the hydrogen in the palladium, we must assume that there is a component of trapped hydrogen ions (localized).[15] If we assume an energy spectrum as that in Fig. 1,

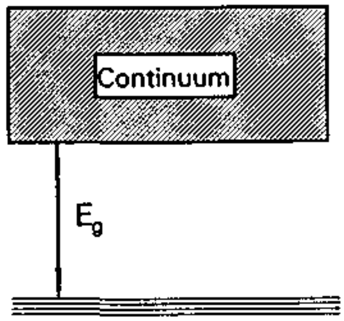

Fig.1 Energy Band Structure in Palladium Deuteride lattice

then the critical density for Bose-Einstein condensation would be

$$n_{cg} = n_c \exp(-\frac{E_g}{k_B T}) \tag{8}$$

Using $n_{cg}\approx 6.8\times10^{22}$ cm^{-3} (corresponding to critical loading ratio$\approx$1), T=300 K, we have

$$E_g = -k_B T \log(\frac{n_{cg}}{n_c}) \approx 125\ \text{meV} \tag{9}$$

this number is very close to the activation energy for hydrogen in palladium.[15]

In fact this condensation model gives a good reason for the critical loading ratio. If the deuteron density is lower than this critical density n_{cg}; then, there will be no enough population in the low lying energy band, and less chance for resonance penetration.

5. Nuclear Surface Absorption and $0^+ \rightarrow 0^+$ Forbidden Transition

The low energy beam-target experiments have established a fact that the strong interaction will annihilate the penetrating deuteron wave after several reverberations. When one assumes the reaction rate

$$\Lambda = A|\Psi(0)|^2 \tag{10}$$

low energy experimental data show that $A = 1.5\times10^{-16}\text{cm}^3\,\text{sec}^{-1}$.[16] Considering that the volume of the deuteron-deuteron nuclear interaction is the order of 10^{-39} cm^3, we know that the life-time of the deuteron-deuteron strong interacting system is the order of 10^{-23} sec, i.e. the order of the reverberation time. Then, one may ask the reason why the built-up wave function in the resonance case is not annihilated by this strong interaction .

In fact, the strong absorption in the nuclear well is concentrated on the surface region as suggested by the nuclear optical model.[17] The reaction "constant", λ, is not a constant inside the nuclear well; hence, the reaction rate, Λ, should be

$$\Lambda = \int \lambda(r)|\Psi(r)|^2 d^3\vec{r} = \int \lambda_V(r)|\Psi_V(r)|^2 d^3\vec{r} + \int \lambda_S(r)|\Psi_S(r)|^2 d^3\vec{r} \tag{11}$$

Here, the subscripts, V and S, denote the volume and surface, respectively. $\lambda_V(r)$ is much smaller than $\lambda_S(r)$ by a factor of θ^{-1}. When there is no resonance, $|\Psi_V(r)| \approx |\Psi_S(r)|$; then, the reaction happens mainly in the surface region of the nuclear well, and the life-time is the order of the reverberation time. When the energy reaches the resonance level, the wave function, $\Psi_V(r)$, builds up due to the constructive interference between the penetrating wave and the reverberating wave. $|\Psi_V(r)| \approx \theta|\Psi_S(r)| >> |\Psi_S(r)|$ .Hence,

$$\int \lambda_V(r)|\Psi_V(r)|^2 d^3\vec{r} \approx \int \frac{1}{\theta}\lambda_S(r)|\theta\Psi_S(r)|^2 d^3\vec{r} >> \int \lambda_S(r)|\Psi_S(r)|^2 d^3\vec{r} \tag{12}$$

The life-time of the state is determined by the core part of the wave function, and is greater than the reverberation time by a factor of θ.

In other words, the strong interaction annihilates only the deuteron wave near the nuclear surface. The deuteron wave function can still be built up inside the core of the nuclear well where the absorption due to strong interaction is weak. Physically, the absorption (i.e. deuteron loses its identity) only happens in the region where the nuclear force (the derivative of the nuclear potential) is large. Inside the nuclear core, although the nuclear well is deep, the nuclear force is weak there. So the deuteron wave can survive inside the core of the nuclear well.

In contrast to the short range of the nuclear force, the electromagnetic interaction is a kind of long range force. One may ask the reason why the electromagnetic force does not annihilate the long life-time state . This is due to the symmetry of the system. The symmetry of the wave function of the d+d system is determined by their orbital motion and their spin motion. At the low incident energy, only the S-wave (orbital angular momentum l = 0) is dominant inside the core of the nuclear well. So the symmetry for the orbital motion is symmetric about the exchange of the two deuterons. Then, the spin motion part of the wave function should be symmetric also in order to keep the symmetry of the total wave function which is necessary for a boson-boson indistinguishable particle system. The spin for each deuteron is 1, the resultant angular momentum may be 0,1, or 2. Since the state of resultant spin 1 is anti-symmetric about the exchange of the two deuterons, it is not an allowable state. The resultant spin should be 0 or 2.[18] Consequently, the possible total angular momentum and parity for the d+d system is 0^+, or 2^+. If the resonance state takes the 0^+; then, it should be stable against the electromagnetic interaction. Because the ground state for d+d system is 0^+ (helium-4), and the spin for photon (the electromagnetic quantum) is 1, it is forbidden to have a $0^+ \to 0^+$ electromagnetic transition due to the conservation of the angular momentum.

What we have to figure out is the mechanism through which the excited d+d system transfers the energy to the lattice system in a slow time scale.

6. Conclusion: Thunder without Lightning is OK

Based on above-mentioned discussion, we have seen that the long life-time nuclear active state may be created after the resonance penetration of Coulomb barrier in the d+d system in terms of the lattice confined deuterons. This is a resonance state which cannot be observed in a low energy beam-target experiment. This resonance state will not emit strong nuclear radiation (neutron, triton, or γ radiation). This is just the answer to Professor J.Huizenga's challenge of three miracles. Only the chemists have a better chance to discover this nuclear active state in terms of calorimeter, because there is no strong nuclear radiation.

Although it is a long life-time slow reaction, it is still a practically useful energy source. Even if only one thousandth of the deuterons inside the palladium are involved in this state, the "excess power" is of the order of 1 kW per cubic centimeter of the palladium. This is about the same as that in a fuel rod of a fast fission breeder reactor.

In these two meanings, we say that thunder without lightning is O.K. This theory predicts that if we could produce the palladium with greater grain size and greater activation energy, it should be easier to reproduce the "excess heat" experiment.

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List of Symbols

a=size of the nuclear well, cm

A=experimental bulk reaction constant, $cm^3 sec^{-1}$

b=classical turning point of Coulomb barrier, cm

d=deuteron

E=total energy of relative motion, erg.

$\hbar$=Planck constant divided by 2π, erg·sec

k, k^i and k^r=wave number, its imaginary and real part, cm^{-1}

k_B=Boltzmann constant, erg·K

L=grain size in crystal, cm

m=mass of deuteron, g

n_c=critical density for Bose condensation of free-moving particles, cm^{-3}

n_{cg}= critical density for Bose condensation of particles with energy gap in spectrum, cm^{-3}

r =radial coordiante, cm

T=temperature, K

U=potential energy, erg

ImU=imaginary part of the potential energy, erg

Γ= width of energy level, erg

Γ_B=width of energy band, erg

δ=size of the primitive cell of a crystal, cm

λ=reaction constant, sec^{-1}

λ_V=reaction constant in core region of the nuclear well, sec^{-1}

λ_S=reaction constant in surface region of the nuclear well, sec^{-1}

Λ=reaction rate, sec^{-1}

θ=square root of the reciprocal of Gamow factor

τ=life-time of an energy level, sec

τ_{xh}=life-time of the resonance state releasing "excess heat"

Ψ=wave function, $cm^{-3/2}$

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