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Theoretical Analysis and Reaction Mechanisms for Experimental Results of Hydrogen-Oxygen-Metal Systems

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***Abstract*—Theoretical analysis of recently observed excess heat and anomalous vacuum effects for hydrogen-oxygen-metal systems is described based on theory of Bose-Einstein condensation nuclear fusion (BECNF). The anomalous excess heat effect is explained by oxygen fusion via BECNF process producing sulfur. The observed vacuum effect is explained by BEC process.**

***Index Terms*—Oxygen fusion in metals, Bose-Einstein condensation nuclear fusion, excess heat generation, anomalous vacuum effect**

1. Introduction

Recently, the experimental results of excess heat generation and anomalous vacuum effect with hydrogen-oxygen-metal (HOM) systems have been reported [1]. Over the past twenty five years, there have been many publications reporting experimental observations of excess heat generation and anomalous nuclear reactions occurring in metals at ultra-low energies, now known as the Fleischmann-Pons effect [2,3] which include both electrolysis and gas loading experiments [3-5] and also include experiments involving deuterium-metal systems [2-5] and hydrogen-metal systems [6-9]. Theoretical explanations of the Fleischmann-Pons effect [2,3] and the low energy nuclear phenomena [2-5] have been described based on the theory of Bose-Einstein condensation nuclear fusion (BECNF), occurring in micro/nano-scale traps/metal particles [10-23].

In this paper, we describe the results of the recent experimental work [1] with hydrogen-oxygen-metal systems, including the observation of excess heat generation and anomalous vacuum effect. After reporting the experimental results, we describe theoretical analysis and reaction mechanisms for the observed experimental results of hydrogen-oxygen-metal systems based on the BECNF theory [10-23].

2. Recent Experimental Works with HOM Systems

Recently, it has been shown by Justin Church and Neal Ward that anomalous excess heat appears to be generated when HHO gas (mixture of hydrogen gas and oxygen gas with a 2:1 molar ratio of H_2 and O_2 gases) is injected into a commercial automobile catalytic converter [1]. This type of experiments is now known as a "H-cat" or "HHO-cat" experiment which has been made as "open-source" experiment by Church and Ward [1].

More recently, a HHO-cat experiment carried out by Sterling Alan and Darrell Jacobson showed an effect of anomalous vacuum created in the HHO-cat associated with flashback occurring with their HHO outlet [1]. Since the HHO-cat experiment is open-source, we expect that HHO-cat experiments are being carried out all over the world.

In the catalytic converter, an essential part is the catalytic matrix where catalytic reactions occur. The catalytic matrix is located in the center of the catalytic converter. It has many channels in honeycomb-like monolithic structure made of either from metallic (stainless steel) or ceramic (cordierite) material. Each channel in honeycomb-like structure has an inner diameter of ~1 mm with the channel density of ~300 to ~ 600 channels per square inch. The inner surface of each channel is coated with catalytic metal particles (Pt, Rh, and Pd) of nano-scale size (~10 nm).

3. Conventional Theory of Low-Energy Nuclear Reactions

The BECNF theory [10-23] was originally developed to explain the Fleischmann-Pons effect [2-5]. It is based on a single basic assumption capable of explaining the observed phenomena; Bose nuclei with integer spin trapped in a trapping potential generated by a metal particle undergo Bose-Einstein condensation (BEC). In this section, some details and review of the BECNF theory are described.

3.1. Optical theorem formulation of reaction rates

In this sub-section, we describe theoretical derivation of the reaction rates for the BECNF theory based on the optical theorem formulation of the low-energy nuclear reactions [10]. In nuclear physics, theoretical analyses of low energy nuclear reactions are carried out using quantum scattering theory. The optical theorem formulation is based on the quantum scattering theory.

Based on the optical theorem, the following optical theorem formula was derived in reference [10]

$$\mathrm{Im}\, f_\ell^{n(el)} \approx \frac{k}{4\pi}\sigma_\ell^r \tag{1}$$

where $f_\ell^{n(el)}$ and σ_ℓ^r are the l-th partial wave nuclear elastic scattering amplitude and reaction cross-section, respectively. The above formula is rigorous at low energies.

The elastic scattering amplitude can be written in terms of t-matrix as

$$f_l^{n(el)} = -\frac{2\mu}{\hbar^2 k^2} < \psi_l^c | t_l | \psi_l^c > \tag{2}$$

where ψ_l^c is the Coulomb wave function for scattering between two charged particles. From Eqs. (1) and (2), we obtain the optical theorem formula for the dominant s-wave state as:

$$\frac{k}{4\pi}\sigma^r = -\frac{2\mu}{\hbar^2 k^2} < \psi_0^c | \mathrm{Im}\, t_0 | \psi_0^c > \tag{3}$$

with

$$\sigma^r = \frac{S}{E} e^{-2\pi\eta} \qquad and \qquad \mathrm{Im}\, t = -\frac{S r_B}{4\pi^2}\delta(\vec{r}) \tag{4}$$

where

$$r_B = \frac{\hbar}{2\mu e^2} \qquad with \qquad \mu = \frac{m_i m_j}{m_i + m_j}$$

The reaction rate is given by

$$R \; = v\sigma^r = - < \psi^c | \mathrm{Im} V | \psi^c > \tag{5}$$

with Fermi potential

$$\mathrm{Im} V = -A\delta(\vec{r}_{ij}), \qquad A = \left(\frac{2}{\hbar}\right)\frac{S r_B}{\pi}$$

where S is called "astrophysical S-factor" and related to the nuclear force strength. The delta-function represents the short-range nature of the nuclear force.

3.2. Generalization to low-energy nuclear phenomena in metals

The above result given by Eq. (5) can be generalized to D+D (or O+O) fusion reactions in metal systems to obtain [11,12]

$$R_t = -\frac{2}{\hbar}\frac{\Sigma_{i<j} < \Psi | \mathrm{Im} V_{ij}^F | \Psi >}{< \Psi | \Psi >} \tag{6}$$

with Fermi potential

$$\mathrm{Im} V_{ij}^F = -\frac{A\hbar}{2}\delta(\vec{r}_{ij}), \qquad A = \left(\frac{2}{\hbar}\right)\frac{S r_B}{\pi}.$$

Ψ is the bound-state solution of the many-body Schroedinger equation

$$H\Psi = E\Psi \tag{7}$$

with

$$H = T + V^{confine} + V^{Coulomb} \tag{8}$$

The above general formulation can be applied to (a) D+D nuclear fusion reaction, (b) O+O nuclear fusion reaction, etc. For each case of (a), (b), etc., an appropriate Hamiltonian is to be chosen for Eqs. (7) and (8). To be realistic to a chosen physical system, the Hamiltonian H could include many degrees of freedom for electrons, metal lattice structures, etc. However, we may have to choose a simpler model Hamiltonian (Eq. (8)) for which Eq. (7) can be solved approximately.

3.3. Importance and significance of the optical theorem formulation of reaction rates

It is important to note differences between Eq. (5) and Eq. (6). Eq. (5) is for nuclear reactions at positive energies (such as for nuclear scattering experiments using beam of nuclei), while Eq. (6) is for nuclear reactions between two nuclei in a bound state (such as deuterons bound in a metal). In the past, Eq. (5) is inappropriately used to argue that low-energy nuclear reactions in metals are impossible. It should be emphasized that the use of Eq. (6) is more appropriate for low-energy nuclear reactions in metals than the use of Eq. (5).

4. BECNF Theory – Deuteron, Oxygen, and Light Bose Nuclei

In this section, we describe theoretical analysis of the experimental results [2-5] involving deuterons as applications of the theory of Bose-Einstein nuclear fusion (BECNF) (Eqs. (6), (7), and (8)). This case is applicable for the theoretical explanation of the Fleischmann-Pons effect [2,3] and the deuterium-metals experiments [3-5].

The same theoretical formulation described in this section for the reaction, D + D $\rightarrow$ ^{4}He + 23.48 Mev, can also be applied to the reaction, ^{16}O + ^{16}O $\rightarrow$ ^{32}S + 16.54 MeV, and other cases with light Bose nuclei with integer spins:
2 ^{6}Li $\rightarrow$ ^{12}C + 28.17 MeV, 2 ^{10}B $\rightarrow$ ^{20}Ne + 31.14 MeV, 2^{12}C $\rightarrow$ ^{24}Mg + 13.93 MeV, 2^{14}N $\rightarrow$ ^{28}Si + 27.22 MeV, 2^{18}O $\rightarrow$ ^{36}S + 29.10 MeV, 2^{20}Ne $\rightarrow$ ^{40}Ca + 20.76 MeV, 2^{22}Ne $\rightarrow$ ^{44}Ca + 25.42 MeV, etc.

4.1. Solution of Hartree-Fock mean-field theory with correlation effects

For applying the concept of the BEC mechanism to deuteron fusion, we consider N identical charged Bose nuclei (deuterons) confined in a trap (a magnetic trap generated by nano-scale metal particle). For simplicity, we assume an isotropic harmonic potential for the trap to obtain order of magnitude estimates of fusion reaction rates. N-body Schroedinger equation Eq. (7) is solved with the Hamiltonian H for the system given by

$$H = \frac{\hbar^2}{2m}\sum_{i=1}^{N}\Delta_i + \frac{1}{2}m\omega^2\sum_{i=1}^{N}r_i^2 + \sum_{i<j}\frac{e^2}{\left|\mathrm{r}_i - \mathrm{r}_j\right|} \tag{9}$$

where m is the rest mass of the Bose nucleus.

Approximate solutions of Eq. (7) with H given by Eq. (9) were obtained using two methods: (i) the equivalent linear two-body method [11-15] and (ii) Hatree-Fock mean field approximation with correlation effects.

Both were used in Eq. (6) to derive the approximate theoretical formula Eq. (11) for the deuteron-deuteron fusion rate in a magnetic trapping potential generated by micro/nano-scale metal particle. The detailed derivations are given elsewhere in references [10 -23].

The use of an alternative method (ii) [12] based on the Hartree-Fock mean field theory for bosons [24] yields the same result which is a factor of 2 larger than the result obtained using the method (i) (see Appendix in [12]). This method (ii) [12] involves reducing the original many-body Schroedinger equation Eq. (7) with the Hamiltonian given by Eq. (9) to the mean field equation Eq. (10), using the Hatree-Fock approximation with correlation effects [24]:

$$\left[-\frac{\hbar^2}{2m}\Delta+\frac{1}{2}m\omega^2r^2+(N-1)e^2\int\frac{d\vec{r}'}{|\vec{r}-\vec{r}'|}|\psi(\vec{r}')|^2\right]\psi(\vec{r})=\mu\psi(\vec{r}) \tag{10}$$

$$\mu=\frac{3}{2}\hbar\omega\left(\gamma_c N\right)^{2/3}\ and \qquad \gamma_c=2\sqrt{mc^2/\hbar\omega}$$

Eq. (10) is a non-linear Schroedinger equation. In atomic, molecular, and optical physics, non-linear Schroedinger equation similar to Eq. (10) is known as the Ginzburg-Pitaevskii-Gross equation ("GPG" equation) [24]. GPG equation is used as the basic equation for Bose-Einstein condensation of atoms and provides fairly accurate theoretical descriptions of the observed properties of Bose-Einstein condensation of atoms.

For the case of N » 1, the first two terms of Eq. (10) are small compared with the third term., hence Eq. (10) can be solved analytically to obtain Ψ, which can be used in Eq. (6) to calculate the appropriate reaction rate shown below in Eq. (11). For this case of large N, Eq. (10) is solved analytically (see the Appendix of [12]). Eq. (11) was also derived analytically (no numerical calculations were involved) [12].

Recent theoretical analysis [23], which includes two-particle correlations, indicates that these additional two-particle correlations cannot alter the results of [12] (Eqs. (10) and (11)) significantly. Hence Eq. (11) is quite rigorous.

4.2. Reaction rates for the primary reaction channel

Our final theoretical formula for the total fusion rate R_t for large N case is given by [11,12]

$$\mathrm{R}_t^{\mathrm{D}}=\frac{1}{2\pi}\left(\frac{3}{\pi}\right)^{1/2}\mathrm{S}\Omega\mathrm{V}n_{\mathrm{D}}^2\frac{1}{\mathrm{Z}_{\mathrm{D}}^2}\left(\frac{\hbar}{\mathrm{e}^2\mu_{\mathrm{D}}}\right) \tag{11}$$

where μ_D is the reduced mass of deuteron, S is the S-factor for the nuclear fusion reaction between two deuterons, n_D is the deuteron number density, and V is the total volume. For D(d,p)T and D(d,n)^{3}He reactions, we have S ≈ 55 keV-barn. We expect also S ≈ 55 keV-barn or larger for reaction {1} described below in sub-section 4.3. Only two unknown parameters are (i) the probability of the BEC state occupation, Ω, and (ii) the S-factor. Eq. (11) shows that the total fusion rates, R_t, are maximized when Ω ≈ 1.

As discussed in the previous subsection 4.1, Eq. (11) was derived analytically. Eq. (11) provides an important result that nuclear fusion rates R_t for the large N case do not depend on the Gamow factor in contrast to the conventional theory for two-body nuclear fusion in free space. There is a simple classical analogy of the Coulomb field suppression. For a uniform spherical charge distribution, the Coulomb field diminishes toward the center and vanishes at the center.

4.3. Reaction mechanism for BECNF - "Bosenova"

For a single trap containing a large number N of deuterons in a BEC state, the deuteron-deuteron fusion can proceed with the BECNF via the following reaction {1}:

{1} $$\Psi_{BEC}\{(D+D)+(N-2)D's\} \rightarrow \Psi^{*}_{BEC}\{^{4}He+(N-2)D's\}(Q=23.84MeV)$$

where the Q-value of 23.84 MeV is shared by ^{4}He and all D's in a BEC state, thus maintaining the total momentum conservation in the final state. This implies that the deuteron BEC undergoes a nano-scale explosion due to the total momentum conservation.

This phenomenon/mechanism of nano-explosion of a BEC state was proposed in 2009 [17]. It is related to a BEC explosion phenomenon occurring with the atomic BEC now known as "Bosenova" [25-27].

For a micro/nano-scale trap of 10 nm diameter containing ~ 3.6 x 10^{4} deuterons, each deuteron or ^{4}He will gain only ~ 0.7 keV kinetic energy, if the excess kinetic energy of 23.84 MeV is shared equally. This mechanism of "Bosenova" can provide an explanation for constraints imposed on the secondary reactions by energetic ^{4}He, as described by Hagelstein [28].

Furthermore, as these deuterons slow down in the host reactor metal materials, they can release electrons from the host metal atoms, thus providing extra conduction electrons which may reduce the resistivity of the host metal.

4.4. Reaction rates for the secondary reaction channels

Other exit channels, D(d,p)T and D(d,n)^{3}He, are expected to have much lower probabilities than that of the exit channel {1}, since both D(d,p)T and D(d,n)^{3}He involve centrifugal and Coulomb barrier transmissions of exit particles in the exit channels, while {1} does not. Thus this mechanism can provide a theoretical explanation for the experimental observation of dominance of the reaction {1} over D(d,p)T and D(d,n)^{3}He in the exit channels.

4.5 Application to oxygen-oxygen fusion

For the oxygen-oxygen fusion, $^{16}O + {}^{16}O \rightarrow {}^{32}S$ + 16.54 MeV, Eq. (11) is modified as

$$R_t^O = \frac{1}{2\pi}\left(\frac{3}{\pi}\right)^{1/2} S\Omega V n_O^2 \frac{1}{Z_O^2}\left(\frac{\hbar}{e^2\mu_O}\right) \tag{12}$$

where μ_O is the reduced mass of oxygen, S is the S-factor for the nuclear fusion reaction between two oxygen nuclei, n_O is the oxygen number density, Ω is the probability of the BEC state occupation, and V is the total volume.

The above reaction rate formula can be applied to the HHO-cat experiments [1] and also to the hydrogen-metal systems [6-9] as discussed later in the sub-section 5.6.

4.6. Anomalous vacuum effect

Recently observed effects of flashback and vacuum in the HHO-cat experiment by Sterling Alan and Darrell Jacobson can be explained using BECNF theory.

BECNF process consists of two-stages: (1) formation of BEC on nano-scale (~10 nm) magnetic metal particles (which act as magnetic traps for BEC) which are coated on inner surfaces of channels in honeycomb-like monolithic structure made of either from metallic (stainless steel) or ceramic (cordierite) material, and (2) BEC of nuclei (hydrogen pair, deuterium, and/or oxygen: the ratio of D/H is ~ 0.015%) undergoing BECNF.

For the stage (1), a magnetic trap of ~10 nm diameter can accommodate ~ 10^4 atoms/molecules as a BEC assuming a solid density. For the stage (2), when a BECNF takes place, a BEC explodes ("Bosenova" phenomena is described in sub-section 4.3 above), releasing ~ 10^4 energetic particles contributing to high-density and high pressure. This in turn contributes to the flashback.

The vacuum effect is associated with stage (1) while the flashback effect is associated with stage (2). The pressure or gas density decreases during the stage (1) while it increases during the stage (2). For more detailed dynamics, we will need to measure time correlation data of both the flashback and the vacuum phenomena as a function of time.

5. BECNF Theory - Hydrogen

In this section, we present a generalization of the theoretical results for one species of Bose nuclei (deuterons) described in the previous section to the case of two species of Bose nuclei, such as hydrogen-Ni systems investigated by Piantelli et al. [6,7], Hadjichristos, et al. [8], and Rossi [9].

Since hydrogen nucleus (or atom) is fermion, we need formation of hydrogen pairs (molecular ground state or excited "Rydberg" states) [29] which have the magnetic moments. They can be trapped by magnetic trapping potentials of the nano-scale metal particles, thus forming Boson cluster states (BCS) and proceed to nuclear fusion (BCSNF).

5.1. Theory for mixed species

Generalization of The BECNF theory to the case of two species of Bosons was carried out in 2006 [30].

The reaction rates for two species (i and ii) is given by

$$R_t = \frac{1}{2\pi}\left(\frac{3}{\pi}\right)^{1/2} S_{ij}\sqrt{\Omega_i\Omega_j}\,V\frac{n_i n_j}{Z_i Z_j}\left(\frac{\hbar}{e^2\mu}\right) \tag{13}$$

where μ is the reduced mass, $\mu = m_i m_j/(m_i + m_j)$.

5.2. One-particle exit reaction channel

As in the case of BECNF theory for the single specie (deuterium) case of the Fleischmann-Pons effect, the primary reaction channel for this case of hydrogen-metal systems involves one-particle exit reaction channel, which can be written as

$$p + {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z+1}L + Q \tag{14}$$

This one-particle primary reaction channel involves nano-explosion ("Bosenova").

5.3. Two-particles exit reaction channel

For the two-particles exit reactions, examples are,

$$p + {}^{A}_{Z}X \rightarrow {}^{4}He + {}^{A-3}_{Z-1}M + Q \tag{15}$$

Two-particle exit reaction channel producing two nuclei is expected to have the reaction rates which are much slower than that of the one-particle exit reaction channel, as described in the sub-section 4.4.

5.4. Multi-particles exit reaction channels

Multi-particles exit reaction channels involving three or more nuclei are expected to have the reaction rates which are much slower than that of the two-particle secondary reaction channel.

5.5. Roles of proton-deuteron reaction

Since hydrogen may not involved as primary fusion reactions as described, there are possibilities that other light nuclei present as impurities may be participating in the BCSNF processes. One example is the primary reaction described by Eqs. (13) and (14) involving deuteron impurity (0.015%) with hydrogen:

$$p + d \rightarrow {}^{3}He + 5.494\,MeV \tag{16}$$

It is interesting to note that Vollmer et al. [31] observed decrease in deuterium concentration in exhaust down-stream in their experiment with the automobile catalytic converter, suggesting that hydrogen-deuteron fusion reaction, Eq. (16), and/or deuteron-deuteron fusion reaction might have occurred. Future HHO-cat experiments could provide scientific test of this proposed explanation.

5.6. Possible role of the oxygen fusion in the hydrogen-metal experiments [6-9]

The oxygen is known to exist as contaminants in many materials. This ubiquitous presence of the oxygen, in particular in metals, suggests that the oxygen fusion may have occurred in enclosed reactors of the hydrogen-metal experiments [6-9] when the internal temperatures of the reactors are raised. This possibility can be tested by measuring the presence of sulfur in the reactor both before and after each experiment.

6. Summary and Future Prospects

Theoretical analysis and the reaction mechanisms are presented for the experimental data generated by the recent open-source experiments using the HHO-cat reactor consisting of HHO gas and catalytic converter. The theory of the Bose-Einstein condensation nuclear fusion (BECNF) is applied to show that oxygen fusion ${}^{16}O + {}^{16}O \rightarrow {}^{32}S + 16.54$ MeV may be a dominant reaction mechanism. The BECNF could occur in reactors containing Boson nuclei and nano-scale metal particles, such as a HHO-cat reactor.

It is shown that the BECNF theory is capable of explaining qualitatively the experimental results and observations reported from HHO-cat experiments. In particular, the observed effects of excess heat, the flashback, and the anomalous vacuum can be explained by the BECNF theory involving the formation of BEC of Bose nuclei and nano-explosions ("Bosenova") of the BEC.

More importantly, the BECNF theory can be tested by observing the fusion products, such as sulfur in particular, from HHO-cat experiments.

There may be an intriguing possibility that the oxygen fusion may have occurred in the previous experiments with the hydrogen-metal systems [6-9]. This possibility can be checked by measuring sulfur contents before and after hydrogen-metal experiments [6-9] in future.

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