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CRYOGENIC IGNITION OF DEUTERON FUSION IN MICRO/NANO-SCALE METAL PARTICLES.

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Introduction: Over the last two decades, 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 'low-energy nuclear reactions' (LENR). Theoretical explanations of the LENR phenomena have been described based on the theory of Bose-Einstein condensation nuclear fusion (BECNF) in micro/nano-scale metal particles [1-7]. The BECNF theory is based on a single basic assumption capable of explaining the observed LENR phenomena; deuterons in metals undergo Bose-Einstein condensation. Proposed experimental tests of the basic assumption/theoretical predictions as well as potential application to cryogenic ignition of deuteron fusion in micro/nano-scale metal particles will be described.

Anomalous Experimental Results: The conventional deuterium fusion in free space proceeds via the following nuclear reactions:

{1} D + D → p (3.02 MeV) + T (1.01 MeV);
{2} D + D → n (2.45 MeV) + ^{3}He (0.82 MeV);
{3} D + D → ^{4}He + γ (23.8 MeV).

The cross-sections for reactions {1} – {3} are expected to be extremely small at low energies (≤ 10 eV) due to the Gamow factor arising from Coulomb barrier between two deuterons. The measured cross-sections have branching ratios: (σ{1}, σ{2}, σ{3}) ≈ (0.5, 0.5, ~10^{-6}).

From many experimental measurements by Fleischmann and Pons in 1989 [8] and many others over 20 years since then (see references in [6,7,9]), the following experimental results have emerged. At ambient temperatures or low energies (≤ 10 eV), deuterium fusion in metal proceeds dominantly via the following reactions:

{4} D(m) + D(m) → ^{4}He(m) + 23.8 MeV (m),

where m represents a host metal lattice or metal particle.

Deuteron Mobility in Metal: Experimental proof of proton (deuteron) mobility in metals was first demonstrated by Coehn in his hydrogen electromigration experiment [10]. A theoretical explanation of Coehn's results [10] is given by Isenberg [11]. The Coehn's results are not well known in review articles and textbooks.

Theory: For applying the concept of the BEC mechanism to deuteron fusion in a micro/nano-scale metal particle, we consider N identical charged Bose nuclei (deuterons) confined in an ion trap (or a metal grain or particle). Some fraction of trapped deuterons are assumed to be mobile as discussed above.

The trapping potential is 3-dimensional (nearly-sphere) for micro/nano-scale metal particles, or quasi two-dimensional (nearly hemi-sphere) for micro-scale metal grains, both having surrounding boundary barriers. The barrier heights or potential depths are expected to be an order of energy (≤ 1 eV) required for removing a deuteron from a metal grain or particle. For simplicity, we assume an isotropic harmonic potential for the ion trap to obtain order of magnitude estimates of fusion reaction rates.

N-body Schroedinger equation for the system is given by

$$H\Psi = E\Psi \tag{1}$$

with the Hamiltonian H for the system given by

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

where *m* is the rest mass of the nucleus.

The approximate ground-state solution of Eq. (1) with H given by Eq. (2) is obtained using the equivalent linear two-body method [3-5]. The use of an alternative method based on the mean-field theory for bosons yields the same result (see Appendix in [2]). Based on the optical theorem formulation of low energy nuclear reactions [12], the ground-state solution is used to derive the approximate theoretical formula for the deuteron-deuteron fusion rate in an ion trap (micro/nano-scale metal grain or particle). The detailed derivations are given elsewhere [1,2].

Our final theoretical formula for the total fusion rate R_t for large N case is given by [1,2]

$$R_t = 4\left(3/4\pi\right)^{3/2}\Omega A N_D \frac{N}{D_{trap}^3} \tag{3}$$

where N is the average number of Bose nuclei (deuterons) in a trap, D_{trap} is the average diameter of the trap, A= $2Sr_B/(\pi\hbar)$, $r_B=\hbar^2/(2\mu e^2)$, S is the S-factor for the nuclear fusion reaction between two deuterons, N_D is the total number of deuterons, and N_{trap} = N_D/N is the total number of traps. 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 {4}. A = 0.77 × 10^{-16} cm^3/s for S = 55 keV-barn. Only two unknown parameters are (i) the probability of the BEC ground state occupation, Ω, and (ii) the S-factor. Eq. (3) shows that the total fusion rates, R_t, are maximized when $\Omega \approx 1$.

Eq.(3) was derived analytically (no numerial calculations were involved). Eq. (3) provides an important result that nuclear fusion rates R_t for 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 an uniform spherical charge distribution, the Coulomb field disminishes toward the center and vanishes at the center.

It is important to note that, for the case of N=2, the same theoretical derivation yields the two-body reaction rate containing the Gamow factor. For the large N case, the deuteron-deuteron reaction {4} in a BEC state proceeds via

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

where the Q-value of 23.84 MeV is shared by ^{4}He and all D's in the BEC state, thus maintaining the momentum conservation in the final state. This implies that the deuteron BEC state undergoes a micro/nano-scale explosion ("micro-explosion" or "nano-explosion"). For a micro/nano-scale metal particle of 10 nm diameter containing ~ 3.6 x 10^4 deuterons, each deuteron or ^{4}He will gain only ~ 6.5 keV kinetic energy, if the excess kinetic energy of 23.84 MeV is shared equally. For a larger metal particle, ~6.5 keV is further reduced. This mechanism can provide an explanation for constraints imposed on the secondary reactions by energetic ^{4}He, as described by Hagelstein [13].

Other exit channels, {1} and {2}, are expected to have much lower probabilities than that of the exit channel {4} (described by Eq. (4)), since both {1} and {2} involve centrifugal and Coulomb barrier transmissions of exit particles in the exit channels, while {4} (described by Eq. (4)) does not.

Proposed Experimental Tests: BECNF theory is based on one single physical hypothesis that mobile deuterons in a metal grain/particle form a Bose-Einstein condensate. Two types of experimental tests (Experiments 1 and 2) are proposed as described below. For both types of experiments, the dependences on the temperature and pressure are to be measured.

Proposed Experiment 1: As is the case for the atomic BEC experiments, experiments are proposed to measure the velocity distribution of deuterons in metal. An enhancement of low-velocity deuterons in the deuteron velocity distribution is expected when the BEC of deuterons occurs. This experimental demonstration of the BEC of deuterons in a metal may lead to a new discovery. In 1995, this type of experiments for measuring the velocity distribution was used to establish the existence of the BEC of atoms in a magnetic trap at extremely low temperatures, for which the Nobel prize was awarded in 2000.

Proposed Experiment 2: To explore the superfluidity of the BEC of deuterons in metal, experiments are proposed to measure the diffusion rates of both deuterons and protons in a metal as a function of temperature. When the BEC of deuterons in a metal occurs, it is expected that the deuteron diffusion rate will increase substantially more than that of proton. We will explore a number of other experimental methods for observing the superfluidity. Experimental demonstration of the superfluidity of deuterons in the BEC state in metal may lead to a new discovery. In 1996, the Nobel prize was awarded for the discovery of superfluidity of ^{3}He.

Application to Cryogenic Ignition: To explore possibilities of constructing a practical BECNF reactor for energy generation, both experimental and theoretical investigations are proposed to study the possibility of BECNF mini-explosion (or ignition) at extremely low temperatures. At ^{4}He liquid temperature, from estimates of reaction rates using Eq. (3), DD fusions are expected to occur nearly simultaneously from each of micro/nano-scale metal particles contained in a bulk volume. This can cause a mini-explosion (or ignition). An ignition fuel of ~1 cm^3 volume containing ~10^{18} of ~10 nm metal particles (each loaded with ~$10^{4\sim5}$ deuterons) could be used to ignite ~10^{18} DD fusions at ^{4}He liquid temperature in a very short time period. If the proposed experimental test proves this theory to be correct, the ignition fuel can be used in a reaction chamber similar to the ignition chamber containing a cryogenic-target at the National Ignition Facility, Livermore National Laboratory [14].

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