Proceedings of the International Conference “Fusion 03: From a Tunneling Nuclear
Microscope to Nuclear Processes in Matter”, Matsushima, Miyagi, Japan,
November 12-15, 2003 (to be published in Progress of Theoretical Physics)

Quantum Many-Body Theory and Mechanisms for Low Energy Nuclear Reaction Processes in Matter

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Recently, a theoretical model of Bose-Einstein Condensation (BEC) mechanism has been developed to describe low-energy nuclear reaction in a quantum many-body system confined in a micro/nano scale trap. The BEC mechanism is applied to explain various anomalous results observed recently in experiments involved with low–energy nuclear reaction processes in matter and in acoustic cavitation. Experimental tests of the BEC mechanism are also discussed. In addition to the BEC mechanism, plasma impact fusion (PIF) and particle cavitation fusion (PCF) mechanisms are also described.

§ 1. Introduction

In 1995, Arata and Zhang reported that after D_2O electrolysis, they had detected large amounts of ^{4}He, ~10^{16} to 10^{17} atoms/mg, in Pd-black powder sealed under vacuum in specially prepared hollow Pd cathodes, and that the results were “fully repeatable [1]. In 1996, they reported that they had confirmed the aforementioned ^{4}He observation, that they had also detected ^{3}He with ^{3}He/^{4}He ~ 0.25, and that ^{3}He and ^{4}He were not detected in comparable electrolysis experiments using H_2O instead of D_2O [2]. In subsequent papers, Arata and Zhang [3-8] reported additional data and restated their claims regarding production of excess ^{3}He and ^{4}He in Pd-black from the interior of Pd cathodes during D_2O electrolysis.

Most recently, Clarke [9] has described a recent search for ^{3}He and ^{4}He in four Pd-black samples that had been provided by Arata and Zhang. His search revealed no evidence for the very high ^{3}He and ^{4}He concentrations found by Arata and Zhang in similar specimens for Pd-black. However, recently, McKubre et al. [10] have reported observations of significant excess heat generated during D_2O electrolysis using an Arata-style hollow palladium cathode.

Most recently, Clarke et al. [11] have made measurements of ^{3}He, ^{4}He, and ^{3}H in a sample containing 2.7% of the gas from the interior of an Arata-style hollow palladium electrode charged with ~5g Pd-black that had undergone electrolysis in D_2O as a cathode for 90 days and then as an anode for a further 83 days. There is no evidence for the much larger amounts of ^{4}He observed by Arata and Zhang in similar experiments. However, a very large concentration has been found of ^{3}He, $2.3\pm0.5\times10^{12}$ atoms/cm^3, at standard temperature and pressure that apparently can all be attributed to the decay of tritium produced during electrolysis. No indirect production of ^{3}He can be specified [11]. The evidence of tritium production of ~10^{15} atoms observed by Clarke et al. [11] has a profound significance.

Recently, Taleyarkhan et al. [12] reported observation of tritium and neutron production during their acoustic cavitation experiment using deuterated acetone and a

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pulsed neutron generator. Earlier, there were acoustic cavitation experiments of another type carried out by Stringham [13]. In Stringham's experiments [13], transient cavitation bubbles (TCB) were created in heavy water without the use of a neutron generator and were driven to impact on target metal foils as a jet plasma. It has been reported [13] that these TCB jet plasma impacts produce excess heat and nuclear products (^{4}He and tritium) suggesting a plasma impact fusion.

Recently, anomalous enhancement has been also observed for the D(d,p)T cross-section at low energies with metal targets by Yuki et al. [14], Raiola et al. [15], and Miley et al. [16].

Most recently, non-thermal nuclear fusion based on a thermodynamic force was proposed by Ikegami for experiment with ion implantation into a surface of liquid Li metal [17]. In recent experiments, anomalous enhancement of reaction rates was observed with 10~24 kev deuterons implanted on metallic Li in the liquid phase [18].

In this paper, several mechanisms are proposed to provide possible explanations of anomalous nuclear phenomena observed by Arata-Zhang [1-11], Taleyarkhan et al. [12], Stringham [13], Yuki et al. [14], Raiola et al. [15], Miley et al, and Ikegami and Petersson [18].

§ 2. Bose-Einstein Condensation Mechanism

In an attempt to understand and explain anomalous nuclear phenoma such as the results of Arata and Zhang [1-11], Bose-Einstein condensation of integer-spin nuclei was suggested as a possible mechanism for ultra low-energy nuclear reaction in 1998 [19]. Recently, theoretical studies of the Bose-Einstein condensation mechanism have been carried out by solving approximately many-body Schroedinger equation for a system of N identical charged integer-spin nuclei ("Bose" nuclei) confined in ion traps [20-22]. The solution is used to obtain theoretical formulae for estimating the probabilities and rates of nuclear fusion for N identical Bose nuclei confined in an ion trap or an atomic cluster.

These theoretical formulae yield two main predictions. The first prediction is that the Coulomb interaction between two charged bosons is suppressed for the large N case and hence the conventional Gamow factor is absent. This is consistent with the conjecture made by Dirac [23] that each interacting neutral boson behaves as an independent particle in a common average background for the large N case. The second prediction is that the fusion rate depends on the probability of the Bose-Einstein condensate (BEC) ground state instead of the conventional Gamow factor. This implies that the fusion rate will increase as the temperature of the system is lowered since the probability of the BEC state is larger at lower temperatures.

To test these theoretical predictions, a series of experiments have been devised and performed with the intention of detecting low energy nuclear reactions at both room temperature and liquid nitrogen temperature under similar conditions used by Arata and Zhang [1-11]. After we describe the BEC mechanism, experimental procedure and preliminary results of the experiment will be presented.

2.1 Ground-State Solution

We consider N identical charged Bose nuclei confined in an ion trap (an atomic cluster or cavitation bubble). For simplicity, we assume an isotropic harmonic potential for the ion trap to obtain order of magnitude estimates of fusion reaction rates. The hamilton for the system is then

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

where *m* is the rest mass of the nucleus. In order to obtain the ground-state solution, we will use the recently developed method of equivalent linear two-body (ELTB) equations for many-body systems [22, 24, 25].

For the ground-state wave function Ψ, we use the following approximation [24]

$$\Psi(\vec{r}_{1,\ldots}\vec{r}_N) \approx \tilde{\Psi}(\rho) = \frac{\Phi(\rho)}{\rho^{(3N-1)/2}}, \tag{2}$$

where

$$\rho = \left[\sum_{i=1}^{N} r_i^2\right]^{1/2} \tag{3}$$

In reference [24] it has been shown that approximation (2) yields good results for the case of large *N*.

By requiring that $\tilde{\Psi}$ must satisfy a variational principle $\delta\int\tilde{\Psi}^* H\tilde{\Psi}d\tau = 0$ with a subsidiary condition $\int\tilde{\Psi}^*\tilde{\Psi}d\tau = 1$, we obtain the following Schrödinger equation for the ground state wave function $\Phi(\rho)$

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{d\rho^2} + \frac{m}{2}\omega^2\rho^2 + \frac{\hbar^2}{2m}\frac{(3N-1)(3N-3)}{4\rho^2} + V(\rho)\right]\Phi = E\Phi, \tag{4}$$

where [24]

$$V(\rho) = \frac{N(N-1)}{\sqrt{2\pi}}\frac{\Gamma(3N/2)}{\Gamma(3N/2-3/2)}\frac{1}{\rho^3}\int_0^{\sqrt{2}\rho} V_{\text{int}}(r)\left(1 - \frac{r^2}{2\rho^2}\right)^{(3N/2-5/2)} r^2 dr. \tag{5}$$

For $V_{\text{int}}(r) = e^2/r, V(\rho)$ reduces to [22]

$$V(\rho) = \frac{2N\Gamma(3N/2)}{3\sqrt{2\pi}\Gamma(3N/2-3/2)}\frac{e^2}{\rho}. \tag{6}$$

2.2 Fusion Probability and Rates

For N identical Bose nuclei (deuterons) confined in a trap (an atomic cluster or a cavitation bubble), the nucleus-nucleus (deuteron-deuteron) fusion rate is determined from the ground state wave function Ψ for trapped deuterons as [20]

$$R_b = -\frac{2\Omega}{\hbar}\frac{\Sigma_{i<j} < \Psi\left|\text{Im}V_{ij}^F\right|\Psi >}{< \Psi\left|\Psi\right. >}, \tag{7}$$

where $\mathrm{Im}V_{ij}^F$ is the imaginary part of the Fermi potential, which is related to nuclear interaction and D-D fusion cross-section, and Ω is the probability of the ground state occupation.

The reaction rate R_b can be written as

$$R_b = \frac{\Omega A N(N-1)\Gamma(3N/2)}{2(2\pi)^{3/2}\Gamma(3N/2-3/2)} \frac{\int_0^\infty \Phi^2(\rho)\rho^{-3}d\rho}{\int_0^\infty \Phi^2(\rho)d\rho} \tag{8}$$

where Φ is the solution of Eq. (4).

2.3 Total Fusion Rate and Theoretical Predictions

Using Eq. (8) and an approximate solution for $\Phi(\rho)$ from Eq. (4), we obtain the total nuclear fusion rate *R* per unit volume per unit time ($R = n_b R_b$)

$$R = n_b \sqrt{\frac{3}{4\pi}}\Omega B\alpha\left(\frac{\hbar c}{m}\right)N n_B, \tag{9}$$

where B is given by $B = 3Am/4\pi\alpha\hbar c$, n_b is a cluster number density n_b (number of clusters per unit volume) as defined as $n_b=N_b/N$, N_b is the total number of Bose nuclei in clusters per unit volume and *N* is the average number of Bose nuclei in a cluster. A is given by $A = 2Sr_B/\pi\hbar$ where $r_B = \hbar^2/2\mu e^2, \mu = m/2$, and S is the S-factor for the nuclear fusion reaction between two deuterons. For D(d,p)T and D(d,n)^{3}He reactions, S≈55kev-barn for each case.

We note a very important fact that *R* does not depend on the Gamow factor in contrast to the conventional theory for nuclei fusion in free space. This is consistent with the conjecture noted by Dirac [23] and used by Bogolubov [26] that boson creation and annihilation operators can be treated simply as numbers when the ground state occupation number is large. This implies that for large N each charged boson behaves as an independent particle in a common average background potential and the Coulomb interaction between two charged bosons is suppressed. Furthermore, the reaction rate *R* is proportional to Ω which is expected to increase as the operating temperature decreases. Only unknown parameter in Eq. (9) is the probability of the BEC ground-state occupation, Ω.

Our theoretical formula for the total nuclear fusion rate *R* per unit time per unit volume given by Eq. (9) gives the following three predictions.

Prediction 1: *R* does not depend on the Gamow factor in contrast to the conventional theory for nuclear fusion in free space. This is consistent with Dirac's conjecture [23].

Prediction 2: *R* increases as the temperature decreases since Ω increases as the temperature decreases.

Prediction 3: R is proportional to $n_b N n_B = n_b N^2 < r >^{-3}$ where N is the average number of Bose nuclei in a single atomic cluster (or bubble) and $\langle r \rangle$ is the average size of atomic clusters (or bubbles).

The above predictions 1 and 2 imply that the acoustic cavitation nuclear fusion may be achievable at lower temperatures. These theoretical predictions can be tested experimentally.

2.4 Experimental Test with Nanoparticles

Experimental tests of predictions 1 and 2 for Arata Zhang type experiments [1-11] have thus far been performed in two different temperature regimes: room temperature and liquid nitrogen temperature [27]. For both types of experiment, the active cell was prepared following the same procedure, but measurements were performed using different types of temperature transducers to maximize sensitivity and reduce experimental error at the different ranges of absolute temperature that were measured. The housings for the active cells were different in the two types of experiment as well. While for room temperature experiments, we attempted only to minimize fluctuations in ambient temperature with simple insulation, the low temperature experiments prompted the construction of a more sophisticated calorimeter using vacuum insulation.

In all experiments, palladium and deuterium loading were performed under the same procedure. Stainless steel cells were loaded with palladium nanoparticles in the range of 80 nm to 180 nm in diameter [28]. Loading was performed in a clean box under a nitrogen atmosphere. Once loaded, the cells were placed under vacuum on the order of 0.1 – 1.0 mTorr and baked out to reduce nanoparticle clumping caused by the presence of water vapor.

The cells were then attached to a Haskel AGT-62/152 dual stage gas booster and pressurized with research grade deuterium gas at pressures ranging from 1,000 p.s.i. to 20,000 p.s.i. After the loading was complete, the cells were removed from the gas booster and equipped with temperature measuring sensors. The heat of deuterium absorption into the palladium nanoparticles was observed in each experiment.

Two experiments have been completed at room temperature, and one experiment has been completed at liquid nitrogen temperature. In the second room temperature experiment, the setup was moved to an interior room so as to minimize weather-based temperature fluctuations, and the foam enclosure was remodeled to eliminate line of sight cracks that could potentially cause data error. Preliminary results of the experimental measurements at both room and liquid nitrogen temperatures are within experimental sensitivity of ~200 μW/gram. The experimental values for deuterium pressure, grams of palladium used, duration of the experiment, and calculated experimental limits are given in reference [27].

For future experimentation, we are considering the effect that deuterium pressure has on the absorption of deuterium into palladium. Examination of the phase diagram for hydrogen has indicated that at the high pressures that were used, it was probable that the deuterium was forced into the liquid phase upon pumping in the first room temperature experiment and the solid phase in the latter two experiments. In the future, we intend to perform further experiments using smaller palladium nanoparticals (<50*nm*) at lower deuterium pressure, so as to keep the deuterium in the gaseous phase.

2.5 Proposed Experimental Test with Cavitation Bubbles

One of the major criticisms of recent experiments [12,29] has been the use of a pulsed neutron generator to induce the production of large radius cavitation bubbles. When using a neutron generator in this mode, 10^4 neutrons are produced at the same time. Because the fusion signal is also based on the observation of neutrons, questions have been raised about the die away time of the generator neutrons within the experimental area due to neutron reflections off materials within the room. Typical neutron die away times range between 100 and 200 microseconds which is significantly longer than the expected arrival time, of 27 microsecond for the neutron fusion signal using time zero as the start of the neutron pulse from the neutron generator to the observation of a fusion neutron from bubble implosion. We propose to replace the pulsed neutron generator system with an associated particle neutron generator to induce the cavitation bubbles. Further details are described in reference [30].

Another interesting consequence (or prediction) of the BEC mechanism is that reaction $D + D \to {}^4He$ is possible without emitting γ-ray, since the BEC state can absorb the recoil momentum in order to conserve the total momentum. This is a new phenomenon involving the BEC state. The fusion rate for the reaction $D + D \to {}^4He$ should be much greater than that of the reaction $D(d,\gamma)^4He$ since the former is a strong-interaction process while the later is an electromagnetic interaction process. The rate for the reaction $D + D \to {}^4He$ cannot be determined in free space and could be comparable to that of the reaction $D(d,\gamma)^4He$ as implied by the results of Arata and Zhang [1-11].

§ 3. Plasma Impact Fusion Mechanism

Plasma impact fusion (PIF) mechanism is proposed here as a possible explanation of anomalous results of Stringham [13], Yuki et al. [14], Raiola et al. [15], Miley et al. [16], and Iklegami and Petersson [18]. In their experiments, ablation electrons knocked out from the inner surface of the crater created by beam ions tend to drift along the inner surface and produce the current which creates and maintains the magnetic field. Because of the field, the ions in the plasma are squeezed and constrained to move along the original direction of motion of the ion beam, and impact on the target, as shown on Fig. 1.

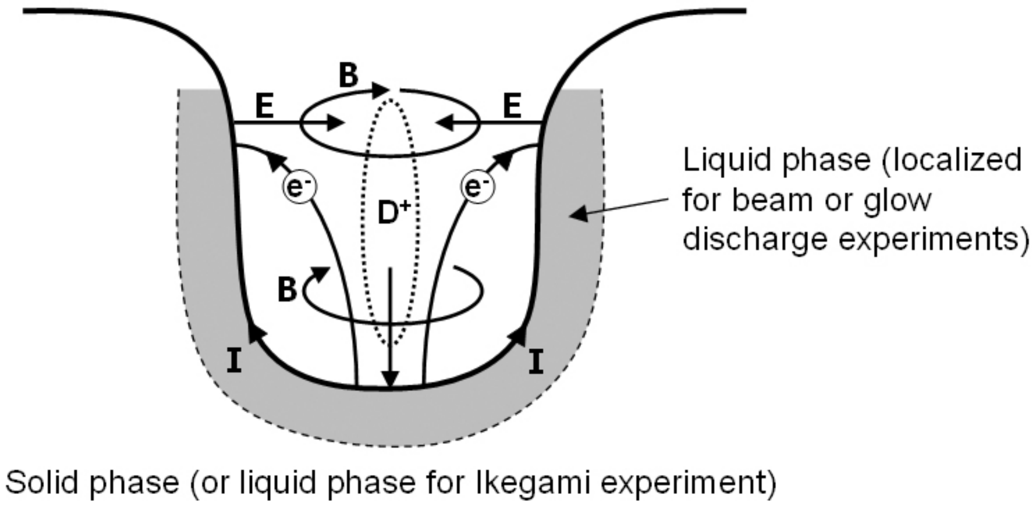

Fig. 1 Plasma Impact Fusion (PIF): Schematic process of magnetic field generation in a crater created by ion beam impact.

The temperature of this quasi-one dimensional ion plasma (QODIP) can be extracted [31] by measuring the energy spectrum of proton from *D(d,p)T* for the cases of experiments by Yuki et al. [14], Raiola et al. [15], and Miley et al. [16]. If the QODIP has achieved a higher temperature than the incident energy by back-scattering of deuterons upon impact, the fusion rate for the reaction *D(d,p)T* can be enhanced over the conventional rate predicted by the Gamow factor. Another possibility is that the QODIP may contain the BEC state with a smaller probability, which can lead to the anomalous enhancement observed by experiments [13-16,18]. For the case of Ikegami-Petersson experiment [18], the QODIP will contain also ^{6}Li and ^{7}Li ions in addition to deuterons.

§ 4. Particle Cavitation Fusion Mechanism

When incident deuterons (10-24 kev) are implanted on metallic Li in the liquid phase in Ikegami-Petersson experiment [18], deuterons going through the *Li* liquid will create cavitation bubbles in the *Li* liquid [32]. If a cavitation bubble contains ^{6}Li and *D*, there may be small finite probabilities of the BEC states of *D* and ^{6}Li in the bubble. Then $D+{}^{6}Li \rightarrow {}^{8}Be$ is possible. ^{8}Be will move out of the BEC state in the bubble with the full Q-value (22.28MeV) and will be observed as two ^{4}He particles moving in the same direction with the kinetic energy of 11.186 MeV for each ^{4}He, since ^{8}Be will decay into two ^{4}He particles with a very short life time. This particle cavitation fusion (PCF) process would be a new phenomenon.

The above scenario could be one possible explanation of the results of Ikegami-Petersson experiment [18].

§ 5. Summary and Conclusions

Anomalous enhancements of the nuclear fusion reactions at low energies have been recently reported from several recent experiments [1-16,18]. These results are different from the same reactions occurring in the free space. Several mechanisms based on quantum many-body theory is presented as possible explanations. Further experimental improvements and theoretical understanding are needed to obtain full quantitative understandings of these new phenomena, which will have profound significances and may lead to a new emerging field in nuclear physics.

Acknowledgements

The author wishes to thank Yoshiaki Arata, Hidetsugu Ikegami, Jirohta Kasagi, David Koltick and Alexander Zubarev for helpful discussions.

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