Chubb, S.R. and T.A. Chubb. *Relationship between microscopic and macroscopic interactions in low energy nuclear reactions: Lessons learned from D + D = 4He.* in *The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science*. 2002. Tsinghua Univ., Beijing, China: Tsinghua Univ. Press.

RELATIONSHIP BETWEEN MICROSCOPIC AND MACROSCOPIC INTERACTIONS IN LOW ENERGY NUCLEAR REACTIONS:
Lessons Learned from D+D$\rightarrow^4$He

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ABSTRACT

For a long time, Cold Fusion (CF) seemed to be at odds with conventional Physics both experimentally and theoretically. A key reason for this involved confusion about the possibility that processes involving characteristic length scales of nuclear- and atomic- size dimensions could couple to each other without releasing high momentum particles. As experiments have improved, this situation has changed. In the paper, we identify and contrast a number of common themes associated with the manner in which five of the more refined theories have addressed this problem.

1. INTRODUCTION

Quantum Mechanics (QM) is a language, based on mathematics, interpretation, and measurement. An unfortunate aspect of the initial Cold Fusion “debate” (or lack of it) was confusion about this. Key problems occurred because from the outset many effects associated with QM that apply in solids were ignored. As a consequence, potentially important forms of coupling through electromagnetic (EM) interaction (EMI) that occur in solids at low and moderate temperatures through coherence, wave function phase, and wave-particle duality that are explained by conventional QM were ignored.

Although in conventional nuclear fusion, these forms of coupling are inconsequential, at low temperature (T), not only can they have consequence, but QM requires that this be so. This alternative interpretation of the potential role of QM has important consequences. In particular, it can explain how EM effects, in principle, can become significantly altered through interaction with the solid in the one, known deuterium (D) fusion reaction (D+D->^{4}He+γ), in which these forms of coupling are known to be important. Thus, in agreement with experiment[1], this interpretation can explain how the necessary forms of coupling, through EMI’s, can occur between short, intermediate and longer length scales that are required for CF Excess Heat to occur from a modified form of D+D->^{4}He reaction, without high energy particles.

The associated counter-intuitive forms of coherent interaction, in condensed matter systems, can be explained, based on the loss of translation symmetry (a broken gauge symmetry[2]) that occurs at low T when a condensed matter host is subjected to outside forces. Understanding the associated process not only has provided a consistent picture that explains many important low T forms of coherence in condensed matter systems, but the associated ideas have also explained a number of anomalies associated with the coherent forms of interaction of hydrogen and deuterium with transition metals.

However, although historically, independently, in similar theories, Schwinger[3], and Chubb and Chubb (C&C) [4] emphasized that this form of broken translation symmetry might account for CF Excess Heat, confusion existed about details associated with these theories and their relationship to observed phenomena. Partly this confusion occurred because these initial theories did not explain the nuclear process, based on the conventional (Gamow) theory used in normal D+D fusion. (Instead, these theories relied on forms of coherent coupling through the EMI that appeared to be counter-intuitive.) Partly, confusion resulted because of questions that were raised, related to the origin of potential forms of coherent effects, in more general terms, in solids. Thus, an important question has existed for some time concerning the relationship of these theories to an alternative theory due to Preparata[5], and to more general questions, suggested by Preparata, concerning applications of Quantum Electrodynamis (QED) in condensed matter systems.

In fact, the initial theories by Schwinger and C&C are both consistent with a more general, widely accepted concept: spontaneously broken gauge symmetry. This refers to the idea that low-lying excitations of a many-body system can spontaneously lower the energy by disrupting approximate symmetries that are present at higher energies. Because these processes approximately conserve energy, and involve coherent low momentum particles, they lead to wave-like behavior through coupling to the EM field over many different length scales. The fact that these two theories used ideas related to this theme has provided a useful guideline for comparing and identifying common ideas associated with the early development of both theories and with Preparata's theory.

The comparison shows that the different applications of QED in Cold Fusion that appear in these theories can be traced to comparable differences that appear in the way theories based on QED were used to study condensed matter, before and after the importance of spontaneously broken gauge symmetry was discovered. Specifically, prior to 1960, when this discovery occurred, it was not widely accepted that the elimination of degeneracy through broken gauge symmetry could profoundly alter key forms of low-energy interaction, in a many-body system. Subsequently, after spontaneously broken gauge symmetry was accepted[2], it provided the basis for significant, additional breakthroughs not only in Condensed Matter Physics, but in other fields, including High Energy and Nuclear Physics.

Although all of these theories have intrinsic merits, each is limited by particular sets of assumptions, related to the coupling between the characteristic length scales involving atomic processes and the associated EMI's, and those involving nuclear processes and the associated EM and strong force interactions. Later theories, based on this earlier work, by C&C, Kim, and Hagelstein have evolved within the context of a more general framework, in which explicit expressions are used to illustrate the coupling between both sets of scales. Hence, these later theories are better able to address particular limitations associated with length scale and environment in a quantifiable manner, based on (implicit) generalizations of the earlier work. Because a degree of consensus in the later theories, concerning the need to include ideas that were seemingly counter-intuitive initially has evolved, it is especially useful to examine both the relationships between the earlier theories and common features of the later theories. The goal of this paper is to provide an initial attempt to address this problem.

In the next section, we present background material about spontaneously broken gauge symmetry and its relationship to the early theories. An analysis of limitations of the theories , based on rate expressions associated with modern many-body physics at low/moderate temperatures, is presented in the following section. This, in turn, is used to identify common themes and limitations of the later theories.

2. THE ROLE OF SPONTANEOUSLY BROKEN GAUGE SYMMETRIES IN LONG-RANGE EMI'S

A key difference (and source of confusion) between the theoretical framework adopted by Preparata and the common starting point, used in the early theories by Schwinger and C&C is related to a subtlety involving the potential role of static, as opposed to dynamic processes in Quantum Electrodynamics (QED). This subtlety reflects an ambiguity, required by QM, in the manner that measurements can be performed of the potentials (the vector, $\vec{A}$ and scalar, ϕ fields) that are related to the energy, as opposed to the fundamental (electric $\vec{E}$ and magnetic $\vec{B}$) fields, associated with EM forces that are defined classically, through Maxwell's Equations.

The potentials $\vec{A}$ and ϕ are used, in this context, because QM is formulated in terms of the energy, as opposed to the behavior of the various forces, from which the energy is derived. The ambiguity occurs because since $\vec{A}$ and ϕ are related to the energy and momentum, they are not uniquely defined classically. Historically, Fermi recognized problems could result from the non-uniqueness of $\vec{A}$ but seemed to find a way to avoid possible ambiguities when he formally defined a quantization procedure in the 1930's that became the foundation of QED. He did this by first adopting a particular convention for defining $\vec{A}$ (referred to as "using the transverse gauge"), in which the classical normal mode amplitudes of $\vec{A}$ are chosen to be orthogonal to the direction parallel to $\vec{E} \times \vec{B}$ (so that $\vec{A}$ is perpendicular to the propagation of the EM field). Then, he showed this convention appears to be self-consistent, in the sense that provided it holds at one time, even in the presence of currents and charges, the equations associated with the convention dictate that the convention always holds, provided charge is conserved.

Subsequently, as the use of the transverse gauge became the basis for the more modern formulation of QED, a simpler argument evolved for explaining the procedure. Implicitly, when applied self-consistently, the convention seemed to be equivalent to the requirement that when Gauss's law could be used to locate all of the charge within a particular volume, at one time, then, at succeeding times, the theory appeared to predict how both light and the charge would evolve.

In fact, an important subtlety (which is the basis of the confusion alluded to above) can occur because the argument only applies to the EM fields, and it actually requires that at all times Gauss's law can be used unambiguously to determine the charge. However, this ambiguity is inconsequential provided it is possible to define the number of charges within a particular region of space. And for this reason, throughout the 50's and 60's, QED as it was applied, based on this convention, in situations involving well-defined distributions of charge, both in high energy and nuclear physics, worked well. However, in condensed matter systems, at low T, consistently problems arose when these ideas were seriously applied in a number of situations. In 1960, Goldstone and Nambu identified a particularly important effect that explains the origin of many of the associated inconsistencies.

In particular, implicitly, Nambu and Goldstone pointed out that this subtle difference can have important consequences in many practical situations. They did this by showing that implicitly real ambiguities in our ability to determine the number of particles within a volume can be expected to occur in the ground state configurations of many, many-body systems. Specifically, this can occur when an idealized limit exists in which it is possible to perform a continuous series of measurements (symmetry operations O), involving small changes of a parameter r, that do not change the energy of a many-body system, when the system is close to its ground state. The idealization occurs because it is never possible to precisely define the particular extent of a many-body system, and for this reason, all symmetries are approximate.

The origin of the effect, which has since been generalized for applications in high energy and nuclear physics, is that in many-body systems, identifying uniquely when the energy E of a many-body system is minimized can be difficult when a major portion (H_o) of the exact microscopic Hamiltonian H_{exact} that defines E can remain unaltered after many successive symmetry operations O are performed that are continuously linked to each other through a single, continuously-varying parameter r (which could include the relative angle, or position, of the system, for example, relative to a fixed orientation). This is because when O is a symmetry operation, although applications of O=O(r) will not alter measurements of E, each application of O(r) , involving a particular value of r, in principle, defines a separate many-body system eigenstate that is degenerate with respect to the others. Thus, when small perturbations P are added to H_o that fail to commute with O(r), they may induce many different but similar values of E, there-by replacing a large degeneracy with a complicated form of interaction.

When additional restrictions are imposed so that O(r) also approximately preserves the inner products between the stationary states of H_o that are physically allowed through interactions associated with P, the effect of applying O(r) to any of the low-lying stationary states associated with either H_{exact} or H_o to an excellent approximation, will not alter the magnitude of the inner product of a state associated with either Hamiltonian with a second state. (But it can alter the relative phase of the inner product.) Thus, with respect to the states associated with the system H_o, or H_{exact}, O can be required to behave as if it is a unitary operator. Then, when O(r) is defined through a continuous (but not necessarily continuously differentiable) variation of the parameter r, the eigenvalue $\lambda(r)$, defined by $O(r)|\Psi\rangle = \lambda(r)|\Psi\rangle$, associated with a wave function $|\Psi\rangle$, of either H_{exact} or H_o, can be written in terms of a continuously varying phase $\Phi(r)$, according to

$$O(r)\,|\,\Psi >= \lambda(r)\,|\,\Psi(r) >= e^{i\Phi(r)}\,|\,\Psi > \qquad (1)$$

A key point is that when the ground state is stable, the wave function involves the lowest number of degenerate states that are associated with a particular symmetry. Then, except in the boundary regions, where outside perturbations potentially may induce residual interactions, all of the charges approximately will share a common phase, associated with an average, energy-minimizing value of r. However, the dependence of the phase on r will be different in different regions of space.

In more concrete terms, spontaneously broken gauge symmetry becomes important as the momentum p of individual particles becomes small (and the particles become wave-like). Then the common assumption (made by physicists who use Gamow theory) that p=mv can become very inappropriate, and the more precise expression, that incorporates the vector potential,

$$\boldsymbol{v = v(x) = \frac{1}{m}(p - \frac{e}{c}A(x))} \qquad (2)$$

is required. Here, in particular, the velocity v of the associated particle occurs when the particle has mass m, charge e, and it interacts with vector potential A at location x.

Classically, the current density of a point particle, located at x' is defined by $\vec{J}(x) = ev(x)\delta^3(x - x')$. In a many-body system, in a solid, the quantum mechanical generalization of this expression is

$$\vec{J}(x) \equiv \sum_{.j} \frac{e_j\hbar}{2m_j i}\{\vec{\nabla}_r\delta(x_j - x) - \delta(x_j - x)\overleftarrow{\nabla}_{xr_j}\} - \frac{e_j{}^2 A(x_j)\delta(x_j - x)}{m_j c} \qquad (3)$$

where, the label j within the summation, in principle, refers to each of the charged particles , located anywhere in the solid, and e_j is its charge. Also, to determine the expectation value of $\vec{J}(x)$ (as well as any matrix element involving $\vec{J}(x)$), it is assumed that the associated quantities are constructed using initial and final state wave functions, of the form $<x_1,....., x_n \mid \Psi >" \equiv " \Psi(x_1,....., x_n)$, and the integration that is used to construct the associated inner products involves all of the coordinates of all of the charged particles in the solid.

$$< f \mid \vec{J}(x) \mid i > \equiv \iint d^3x_1....d^3x_n \Psi_f^{\;*}(x_1,....., x_n)\vec{J}(x)\Psi_i(x_1,....., x_n), \tag{4}$$

where the integration variables, $x_1 \ldots x_n$ coincide with the variables that are included within the summation in Eq. 3. An important point is that in most situations it is virtually impossible to use either Eq. 4, or related expressions that include all of the charges within a condensed matter system, either precisely or approximately. However, especially at low T, it is possible to use Eq. 4 to identify important trends about the low-lying excitations and ground state, using ideas about broken gauge symmetry. An important practical reason for this is approximate symmetries involve simple, global coordinate transformations, in which small changes of particular parameters are uniformly applied, to many coordinates, at once.

An especially important symmetry, near T=0, is the requirement that in the absence of outside forces, because total momentum is conserved, up to a uniform constant, defined by the kinetic energy of the Center-of-Mass (CM), the change in the energy must remain invariant with respect to rigid translations, in which the coordinate of each particle in a solid is shifted uniformly, by the same constant amount. This symmetry is equivalent to performing a uniform Galilean transformation in which the CM of the solid moves with a constant velocity, V_{cm} , relative to an initial coordinate system, in which the solid is at rest. Since this form of transformation enters only through the dependence of the many-body wave function on the CM position, it does not affect any of the internal interactions. Thus, in the idealized limit in which the external forces that are present are negligible, the net effect of this transformation on the wave function is to introduce a modified CM wave function, defined by plane-waves:

$$e^{i\Phi(r)} \equiv e^{i\Phi(x_{cm})} = e^{ik\bullet(x_{cm})} \equiv \prod_j e^{ik_j x_j}, \tag{5}$$

where $x_{cm} = \sum \frac{m_j}{M} x_j$ is the CM, defined by the total mass $M = \sum_j m_j$, $\hbar \boldsymbol{k} = \boldsymbol{M V_{cm}}$ is the total momentum of the solid (which corresponds to the parameter r associated with the symmetry operation), and $\hbar \boldsymbol{k_j} = \frac{\boldsymbol{m_j}}{\boldsymbol{M}} \hbar \boldsymbol{k} = \boldsymbol{m_j V_{cm}}$ is the net (fractional) amount of momentum that is required to transform the particle of mass m_j associated with coordinate r_j from the frame in which the solid is stationary to the frame where it moves with velocity V_{cm} . In the parlance of many-body physics, each factor of $e^{ik_j x_j}$ is referred to as a Goldstone boson, and in the absence of outside forces, because the energy-minimizing value of k is completely undetermined, the gradient of the many-body wave function is completely unknown.

At the lowest values of T, the Galilean invariance symmetry is broken through interactions that introduce outside forces that effectively interact approximately uniformly (so that they fix the value of V_{cm}) and, then (at higher T), non-uniformly. In practice, although these forces drive the system towards a lowest energy state, how this occurs involves a complicated mixing of quasi-degenerate states, in which each value of k, within Eq. 5 can be thought of as being constrained by effects associated with changes in the boundary regions that introduce external forces.

The problem associated with applying the quantization procedure used by Preparata occurs because in the presence of these perturbations, the resulting (continuously-varying) changes in the boundaries introduce a preferential gauge that must be chosen in a manner that is consistent with the manner in which charges (and particles) are quantized within the solid. This can not be done, using the transverse gauge unless no net change in momentum of any of the particles is allowed to occur anywhere as a result of broken translation symmetry.

In particular, in quantizing the matter field, when the single particle field operators, $\Psi(x)$ and $\Psi^+(x)$, are re-written in terms of a relative phase operator $\phi(x)$ (which is assumed to behave as an uncharged boson), and amplitudes a(x) and a^+ (x), according to $\Psi(x) \equiv e^{i\Phi(x)} a(x)$, and $\Psi^{+}(x) \equiv a^{+}(x)e^{-i\Phi(x)}$, it follows that provided a(x) and $a^{+}(x')$ commute (anti-commute) when $\Psi(x)$ is a boson (fermion), the density $\rho(x) \equiv \Psi^{+}(x)\Psi(x)$ and phase $\phi(x)$ are required to obey a conjugate variable commutation relationship:

$$[\Phi(x'),\rho(x)] \equiv \Phi(x')\rho(x) - \rho(x)\Phi(x') = \pm i\delta^{3}(x - x'), \tag{6}$$

where the positive sign is used for fermions, and the negative sign is used for bosons. The problem with imposing the transverse gauge occurs because, by construction, to apply Gauss's law, $\vec{A}$ and $\nabla \bullet \boldsymbol{E}$ must commute, and for $\nabla \bullet \vec{A}$ to vanish and be constant, it must simultaneously commute with ***E***:

$$[\vec{A}(x), \nabla_{x'} \bullet E(x')] \equiv \vec{A}(x), \nabla_{x'} \bullet E(x') - \nabla_{x'} \bullet E(x')\vec{A}(x) = -[\nabla_{x} \bullet \vec{A}(x), E(x')] = 0 \tag{7}$$

But when the system energy is approximately unaffected through a Galilean transformation associated with Eq. 5, since for charge to be conserved within the solid, the current density flux at all points within the solid must also remain unaffected by the transformation. However, when Eq. 5 is substituted into Eq. 3, each Goldstone boson of the form $e^{ik_j x_j}$ contributes a constant uniform amount of current $\frac{e_j \hbar k_j \rho(x_j)}{m_j} = \frac{e_j \hbar k \rho(x_j)}{M} = e_j V_{cm} \rho(x_j)$ that was not included initially. In order for the current flux to remain constant, as a consequence, at each location x, the vector potential A is required to be shifted by an amount $\frac{\hbar c k_j}{e_j m_j} = \frac{\hbar c}{e_j} \nabla\Phi(x_j)$, where $\nabla\Phi(x_j)$ identically equals the gradient of the relative phase, associated with Eq. 6, that is introduced as a result of the Goldstone boson, associated with the Galilean transformation. But this means that as a consequence of Eq. 6, when this transformation is applied, the appropriate vector potential

$$\vec{A}' = \vec{A} + \frac{\hbar c k_j}{e_j m_j} = \vec{A} + \frac{\hbar c}{e_j} \nabla \Phi(x_j) \tag{8}$$

that is supposed to be used (in order for the current density to be not affected by the transformation) will not commute with. $\nabla \bullet E(x') = e4\pi\rho(x')$. In fact, since this failure occurs for all finite values of k, all of the transformations that preserve Galilean translation symmetry, except the one associated with k=0, violate Eq. 7. And for this reason, it is virtually impossible to require that during any subsequent forms of interaction that the transverse gauge will be preserved.

As a consequence, Preparata's application of QED must be restricted to cases that do not involve significant coupling to ground state configurations in which the gauge symmetries associated with the Galilean transformations involving Eq. 5 are present, or to situations in which the kinds of quantum fluctuations that are implicit in Eq. 6 are forbidden from occurring. In fact, possibly for this reason, Preparata used a semi-classical approximation to describe the coupling between matter and EM, as well as a formalism (Gamow theory) for evaluating reaction rate, in which it is assumed that clearly defined particles collide at particular locations. Thus, his theory is consistent with the requirement that the fluctuations associated with Eq. 6 can be expected to be inconsequential. On the other hand, he made a number of assumptions about the form of the interaction, as a consequence, that conceivably may become appropriate in dynamical processes at elevated T, but can become very inappropriate for describing coupling to the ground state.

Schwinger[3] and C&C[4] both developed theories, which implicitly use limiting forms of coherent interaction associated with perfect Galilean translation symmetry that is implied in Eq. 5. Schwinger[3] invoked this form explicitly in his model calculation of fusion rate, based on coherent phonon generation. He also alluded to this point in his comment concerning the possibility that momentum could be shared by many locations, simultaneously in the Mossbauer effect[3]. Unfortunately, a degree of confusion about the source of the associated coherent behavior occurred[6] , possibly because the details of his theory were related to an inappropriate model that was discussed in a reputable journal[7] during a preliminary stage of the associated debate. Similarly, C&C used ideas associated with a particular form of Eq. 5 that could be used, as a starting point to understand how CF Heat could occur. But, unfortunately, as in the case of Schwinger's analysis, C&C did not emphasize the general nature of the reaction (which involves a spontaneously broken gauge symmetry). For this reason, confusion occurred because the relationship to the non-local effects associated with the underlying breakdown in translation symmetry and the possibility that coherent effects could be at work was viewed as being impossible seemed to be so counter-intuitive that it was not viewed as credible[8].

An important point is that initially all three theories were based on counter-intuitive ideas, and they also made implicit assumptions about the nature of the governing forms of interaction. Fortunately, as our knowledge of the experimental situation has improved, it has become possible to assess the importance and limitations of these initial theories. This has led to the evolution and refinement of a number of theories that are based on a standard many-body framework. This framework, which is described in the next section, not only can be used to incorporate, generalize, and explain the relationship between these earlier theories, but it provides a useful context for understanding potential, more general, forms of LENR's.

3. IMPLICATIONS OF REACTION RATE IN CF EXCESS HEAT, LENR'S AND BY-PRODUCTS

With time, it has become obvious that the lack of high momentum and energy particles that are produced in CF is a necessary phenomenon that must be explained by a viable CF theory. However, it is also apparent that high momentum particles do occasionally occur and that at intermediate, and lower energies, anomalies in conventional DD nuclear reactions do occur. Because the earlier theories were not capable of addressing this problem, self-consistently, they must be viewed as being incomplete.

However, within the context of QM, in general, and many-body physics, in particular, a formal structure does exist, based on expressions associated with reaction rate, that can be used to account, in principle, for all of these effects. Although, at a fundamental level, because this expression involves coupling between all length scales, and all charges in a condensed matter host, universally, in initial theories of CF, limiting approximations associated with dominant length and time scales, and relevant processes were introduced. As the experimental situation has become more transparent, three theories (by Kim, Hagelstein, and C&C) have evolved in which, the full reaction, and reaction rate expression has been adopted to understand potentially relevant processes.

During ICCF8, C&C observed[9], formally, that the reaction rate, defined by the time rate of change of the absolute square of the overlap $<E'^{-}(t)|E^{+}(t)>$ between two states that asymptotically approach eigenstates of arbitrarily different many-body Hamiltonians could be written in terms of the total (implicitly, multi-dimensional) divergence of the flux of particles, across boundaries where collisions between particles occur

$$\frac{\partial |<E'^{-}(t)|E^{+}(t)>|^2}{\partial t} = \frac{2\pi}{\hbar}\delta(E-E')|<E'^{-}(0)|\int d^3r\nabla\bullet\{\vec{v}(r)\}|\Psi_E(0)>|^2 \quad (9)$$

where $\vec{v}(r) \equiv \sum_{.j}\frac{\hbar}{2m_j i}\{\vec{\nabla}_r\delta(r_j-r)-\delta(r_j-r)\overleftarrow{\nabla}_{r_j}\}$.

In this expression, all length and time scales in principle are coupled, and the equations are impossible to solve. However, implicitly, because these forms of coupling are expressed in terms of the total fluxes of momentum across boundaries where effective collisions can occur, the representation can be used to identify distinctly different situations in which particular forms of reaction can occur. At low T, for example, where small numbers of collisions occur, and reaction rates are low, states are long-lived, and asymptotic limits can be defined where locally energy is conserved, while forms of coherent interaction can enter that are consistent with the initial picture presented by Schwinger and C&C. At higher T, alternative theories can apply.

Although C&C alluded to the fact that as a consequence of symmetry, the right-side (RS) could become significantly reduced in magnitude, they did not elaborate about this. In particular, periodic symmetry, need not ever hold, rigorously, provided a collection of particles can move freely, in a rigid fashion (as in Eq. 5). However, both experimentally, and for reasons associated with stability, this potentially is required for reaction rate to be minimized at low T. Although Eq. 9 is sufficiently general that it includes coupling to the EM field, it is not gauge invariant. An important reason exists for this. QM does not require gauge invariance. In particular, when the initial state is the ground state, when the vector potential $\vec{A}$ can be measured (using a well-defined gauge), in either the initial or final state, the expression can be modified by the requirement that globally, the ground state wave function preserve gauge. Then, it is possible to further constrain the form of the allowable perturbations by adding a diamagnetic term of the form, -$\sum_{.j}\frac{e\vec{A}(r)\delta(r_j-r)}{m_j c}$, to $\vec{v}(r)$. Then, although in the general problem $\vec{v}(r)$ is never required to be gauge invariant, provided the vector potential only changes through variations in gauge, the resulting expression for $\vec{v}(r)$, on the right-side (RS) of Eq. 9 remains gauge invariant. As a consequence, it follows that processes that exclusively result from spontaneously broken gauge symmetry do not alter $\vec{v}(r)$, its divergence, or the net particle flux across all boundaries on the RS of Eq. 9. However, because the gradient of the wave function, and $\vec{A}$ separately asymptotically can become discontinuous, non-local coupling can occur that results in the divergence in either the local momentum or $\vec{A}$ asymptotically becoming singular. This explains why considerable overlap can occur, without high momentum particles being produced, at low T, in situations in which broken gauge symmetry is allowed to occur.

As the number of Goldstone bosons in Eq. 5 increases, spontaneously broken gauge symmetry can become increasingly important. Implicit degeneracies associated with particle exchange can enhance this effect. In fact, even in the conventional D+D->4He+γ reaction, it is known from important selection rules, and detailed calculations, that the reaction occurs infrequently because the interaction is non-magnetic and involves long-range (quadrupolar interaction) EM coupling, and the two D's are required to preserve Bose symmetry over large lengthscales (where EMI becomes dominant) with respect to exchange. For this reason, even in the conventional case, the standard tunneling model fails because it does not include important, known correlation between the initial and final states. It is also known that to describe transport and a number of phenomena, the nuclei of individual D's can occupy ion band states in a number transition metals[10], in which each D can be treated as a boson. These facts lend credibility to the idea that in ordered systems, spontaneously broken gauge symmetry can play a pivotal role in explaining Excess Heat without high momentum particles.

Because periodic order is not required for Eq. 5 to apply, similar effects can also become important in disordered systems, and in clusters of atoms and/or ions. Kim and Zubarev[11] have developed a formalism, based on the assumption that when these forms of coupling can become important, overlap can occur, and momentum can be rigidly absorbed without releasing high energy particles. They also have quantified this relationship, using a rigorous representation of reaction rate, effectively, in a limit, involving large numbers of D nuclei, in which the dominant modes of interaction can be characterized using a single variable, defined by the root-mean-square deviation between all of the charged D's. They have demonstrated that their model reproduces important experimental results associated with atomic Bose Einstein Condensates.

. Hagelstein's theory [12]applies to situations where the effects of spontaneously broken symmetry are not directly assumed to be important although he also assumes, implicitly, that a degree of periodic order (as in the C&C theory) is present. Because he explicitly includes coupling to all length scales, like C&C, he incorporates important D-D coupling at short separation and longer-range coupling to the EM field (in his case, through coherent phonons).

All of these theories make use of a common framework, defined by Eq. 9. But the various models are most applicable in different situations. Additional detail about this can be found elsewhere[13].

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