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Research Article

Concerning the Role of Electromagnetism in Low-energy Nuclear Reactions

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Abstract

Considerable confusion has resulted in the "debate" (and lack of "debate") about whether or not Low-Energy Reactions (LENR) can take place. A key reason for this has involved the lack of a cogent argument, based on fundamental physical ideas, involving electromagnetism. In this paper, I re-examine this question. In fact, a cogent argument does exist, based on resonant electrodynamics, and its more general formulation, involving quantum electrodynamics. Lessons learned from this and their relevance are key to understanding the most salient effects, including the Infra-Red (IR) results from the SPAWAR experiments, and Mitchell Swartz's experiments. The associated arguments suggest that magnetic effects that have only been indirectly applied may be used to trigger LENR in particular situations. A new experiment, based on this line of reasoning, is suggested.
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1. Introduction

Talbot Chubb and I suggested in 1989 that deuterons (d's), in fully loaded palladium deuteride (PdD), could behave very differently than in free space, by occupying the kinds of states (energy band states) that electrons occupy in periodically ordered solids [1,2]. Based on this conjecture, we suggested that the normal rules about fusion might not apply to the cold fusion (CF) claims by Fleischmann and Pons (FP). Because d's are bosons, on the length scales associated with conventional electromagnetism, implicit in this hypothesis, we were also suggesting that by occupying the lowest energy (band) state, the d's could form a Bose Einstein Condensate (BEC). At the time we made this suggestion, confusion about its relevance resulted [3] because it was widely believed that BEC's could form only at very low temperatures, as opposed to a situation in which they are induced (as in the case of laser-cooling of alkali vapors) dynamically through the presence of externally applied forces. In addition, our suggestion was not widely publicized for two reasons: The experiments were not widely believed to be valid; and Perceptions about the limitations of conventional energy band theory.

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Implicitly, as well, it was widely believed that in the initial experiments by FP, conventional fusion reactions were taking place. But because in conventional fusion, the dominant reactions ($d + d \rightarrow ^3 He + n$ and $d + d \rightarrow ^3 H + p$) are mediated by the strong force, the collision process inherently occurs over nuclear scale dimensions, and details about the nature of the reaction process far from the reaction are not important. Then, a static electromagnetic interaction (EMI) applies because the reacting particles have high velocity. This is relevant in these kinds of situations, but this certainly does not have to be relevant in a solid because in a solid, time-dependent changes involving many particles can become relevant. In fact, the relevant reaction in the FP results and in other experiments involving excess heat appears to involve the creation of ^{4}He. Although ^{4}He rarely occurs in conventional fusion, it is produced but through a reaction ($d + d \rightarrow ^4 He + \gamma$) that is mediated by the electromagnetic force, and in this reaction (as a consequence) details about the behavior of the reacting particles far from the location of the reaction play an important role in initiating it.

Although the initial band theory idea that Talbot Chubb and I proposed seemed to be preposterous at the time, by responding to the critics, new ideas evolved from our thinking. A key point in what we developed is associated with the potential relevance of finite size and finite time-scales, as they might apply in band theory. A natural generalization of band theory, in fact, does exist [4], which is associated with the underlying formalism that Felix Bloch used, in his formulation of transport phenomena, which involves multiple-scattering theory, as opposed to the conventional "picture" that has been used to introduce ideas related to band theory. When this alternative picture is used, finite size effects can be introduced in a manner that can explain how, through many-body effects associated with a finite solid, a form of ($d + d \rightarrow ^4 He + \gamma$) reaction can occur in which the gamma ray can be suppressed.

In fact, a cogent argument does exist, based on resonant electrodynamics, and its more general formulation, involving quantum electrodynamics (QED), that explains this last effect, as well as conventional energy band theory. The associated logic, which is quite general, is based on a generalization of multiple scattering theory. As in the case of extending band theory to finite systems, I developed [5–7] this generalization in response to the critics of our initial theory.

A particular limit, involving near-resonant electrodynamics in a solid, which is most relevant in the situation in which d's occupy energy band states, can be related to a physical effect: that when periodic order is approximately preserved in a solid, the lowest energy excitations of the solid occur through resonant forms of interaction, involving elastic recoil, in which the solid as a whole moves rigidly. These occur when all of the particles in the solid move at once, without their relative separations being altered, except at the boundaries of the solid, where translational symmetry is broken.

This last picture has been partially summarized elsewhere [8,9]. But a complete summary has not appeared previously. Specifically, details about how it relates to understanding how the gamma ray (in the ($d + d \rightarrow ^4 He + \gamma$) reaction) can be suppressed have not been discussed. This is done in Section 4 of this paper. Because confusion has existed [3] about the initial formulation of our model [1,2], it seems appropriate to provide some background about it. This is done in Section 2. In addition, in this section, some background information is presented about two other QED models (by Schwinger and Preparata), that includes comments about deficiencies in these models, which resulted from a lack of information about the relevance of (the QED of) the ($d + d \rightarrow ^4 He + \gamma$) reaction, and the fact that ^{4}He is produced at levels in the excess heat experiments that are consistent with a form of this last reaction in which the gamma ray is converted into alternative forms of energy.

In discussing the relevant physics of this last reaction, I point out that a degree of confusion exists concerning the relevance of conventional Gamow tunneling ideas in the associated dynamics. Because confusion has existed about this, it is appropriate to provide additional background material that clarifies what is known quantum mechanically about the reaction and why Gamow tunneling does not apply. This is covered in Section 3. This material, in turn, provides a useful way to introduce the material (associated with how the gamma ray can be suppressed) found in the fourth section. Here, I also explain how magnetic effects potentially can trigger CF excess heat.

2. Background

At the time we initially proposed the Ion Band State idea (in which d's would occupy energy band states), we were motivated by work that I did, based on a model developed by Fox [10] on a form of BEC that is created dynamically. The particular problem involved the possible formation of a BEC consisting of excitons [10]. In the physical situation associated with this form of BEC, the condensation evolves after excitons are created. In particular, an exciton is created when an electron is excited by light into a higher energy state in an insulator or semi-conductor in such a way that its energy is not large enough for it to "escape" from the location completely, where it was located initially. When this occurs, an idealized picture becomes appropriate in which the electron and the "electronic-hole" (associated with the location where the electron was located initially) move together, in a manner that can be thought of as resulting from the motion of a quasi-particle.

The idealized limit in which excitons possibly can form occurs when there are only a small number of them interacting with each other and a periodic structure (a crystal lattice). (The atoms in a lattice are symmetrically located in such a way that each atom is periodically displaced relative to the others.) Then, when the excited electron is not too localized, an exciton can form, in which the electron and electronic-hole effectively "see" a periodic potential, just as electrons in the valence and conduction bands in an insulator or semi-conductor see a periodic potential. As a consequence, both the electron and electronic-hole, associated with the exciton, occupy an energy band state, similar to the kinds of (valence and conduction band) states electrons occupy.

As a consequence, the process in which an isolated, excited state electron would decay occurs over a considerably longer period of time than occurs in a situation in which it has been located in an atom, and the composite electron/electronic-hole pair wanders around the lattice in a way that is similar to the way electrons wander around the lattice. The excitons can be viewed as bosons because electronic-holes are treated as being fermions (as a result of the excitation process) and (like d's), each electron/electronichole pair obeys Bose–Einstein statistics. In the unconventional idea of extending this kind of limit to d's interacting with a lattice, we argued that, if a comparable picture might apply to d's in Ion Band States (in which effectively, the electronic-hole in an exciton could be replaced by a neutron and the electron by a proton) the associated proton-neutron pair implicitly could interact with the lattice and with other, comparable proton-neutron pairs over very different time scales than when the associated interaction occurs with d's in free space.

Also implicitly, by treating each d as a boson, we assumed a form of Born–Oppenheimer separability [11] between atomic- and nuclear-scale processes (similar to the Born–Oppenheimer Separability (BOS) between electronic and nucleus degrees of freedom that occurs in molecules), in which the dominant forms of interaction that occur were mediated electromagnetically in both the nuclear- and atomic-scale dimensions. In doing this, we suggested that the Gamow factor, tunneling picture that was commonly viewed as being relevant need not apply. Implicitly, in our initial idea that an Ion Band State (IBS) model and our use of BOS might apply, we were invoking the idea the electromagnetic forces (as opposed to the strong force) were mediating the associated nuclear reaction.

As I mentioned in the Introduction, confusion about our theory developed in part because of perceived limitations of conventional band theory. In fact, the motivation for the initial model, which involved studying exciton condensation, is related to a deeper many-body problem that implicitly involves quantum electrodynamics (QED). In addressing the critics of our theory, I also demonstrated that conventional energy band theory also could be derived from QED. This fact has not been widely appreciated, possibly because energy band theory, traditionally, is presented as a semi-classical limit of a phenomenological, single-particle theory. In my reformulation of the energy band problem, I demonstrated that it can be derived as a particular limit (that preserves periodic order) of the more general QED many-body problem [4–7].

In the particular application of our IBS theory to CF[4–7], we initially identified a very particular limit where it should apply: near full-loading ($x \to 1$ in PdD_x). This limit, which preserves periodic order, is consistent with IBS formation (as a result of the anti-bonding character of the electronic states of PdD) when small variations in loading ($x = 1 \pm \delta$, $\delta \ll 1$) take place [7]. Thus, we predicted that high-loading would be required. We also predicted that the dominant product in heat-producing electrodes would be ^{4}He, and that the ^{4}He would be found, without high energy particle emission [1,2,11], primarily in the surface regions and outside heat-producing electrodes. We made these three predictions prior to experimental observations of the associated effects.

During the initial stages of the CF debate, two other theorists (Schwinger [12] and Preparata [13]) also suggested models that directly [13] and indirectly [12] invoked QED. It is potentially of merit to recognize that in addition to our theory, in these theories [12,13]), ideas were presented that could explain how the reactions could proceed without high energy particles being produced. At the time, both Preparata [13] and Schwinger [12] suggested that different reactions from the one that produces ^{4}He could be involved, although Preparata pointed out that ^{4}He could be produced in the excess heat experiments. It is also potentially noteworthy that separately we [1,2,11] and Preparata [14] suggested that the ^{4}He would be created but would be found primarily outside heat-producing electrodes.

In fact, at this early stage in the associated research, the fact that ^{4}He was being produced and at the appropriate levels to account for the heat was not known. In addition, considerable confusion existed concerning a subtlety associated with how ^{4}He might be produced, even in the conventional fusion reactions. In particular, in order for this reaction to take place, the possible wave function describing the behavior of the interacting d's must possess Bose exchange symmetry (i.e., the d's must be bosons) on length scales associated with EMI, far from the location of the reaction. A key assumption in our initial formulation of the IBS theory was that this kind of behavior be maintained on all length scales. In fact, once this assumption is made, it follows that the allowable final state must possess an even number of proton-neutron pairs when the initial state possesses an even number of proton-neutron pairs [1,2,11,15]. (This approximate selection rule was the basis of our prediction that the dominant by-product in the heat-producing reaction would be ^{4}He.) An important point is that, as discussed in the next section, it is known that not only is it required that in the ($\mathrm{d} + \mathrm{d} \to ^4 \mathrm{He} + \gamma$) reaction, the d's have to possess Bose exchange symmetry far from the reaction, but the reaction obeys other selection rules: the transition is quadrupolar (it involves a change in angular momentum $\Delta J = 2\hbar$) and also requires that the initial and final states have vanishing spin [16].

The associated physics is very different than in conventional fusion, where, by assumption, a static Coulomb barrier is used to explain how same-charged, heavy hydrogen nuclei (−d's) can have appreciable overlap. In this conventional picture, d's initially approach each other with such a high velocity that their momenta do not change appreciably, except when their separation approaches nuclear scale, where they are allowed to interact dynamically entirely through the strong force, and the EMI can be treated, entirely statically, based on the standard (WKB), Gamow tunneling formula.

These assumptions apply to the most frequently observed ($\mathrm{d} + \mathrm{d} \to ^3 \mathrm{H} + \mathrm{p}$ and $\mathrm{d} + \mathrm{d} \to ^3 \mathrm{He} + \mathrm{n}$) reactions, which occur when two proton–neutron pairs collide at a point, where the two pairs can be viewed as forming an "excited state" of a ^{4}He nucleus, in which the dynamical changes are dominated by the strong force. In this limit, the distinction between protons (p's) and neutrons (n's), at the point of nuclear contact, effectively (except through differences in kinetic energy, associated with changes in mass that do not relate to time-dependent EMI effects), is inconsequential, and the normal, intuitive picture that nuclear physicists have applies: The most frequent reactions occur when the amount of nuclear energy that is released is minimized. (This last, intuitive idea was also assumed by Schwinger and Preparata.)

When the associated picture applies, the WKB tunneling model can be used to estimate the rate of nuclear reaction. Here, the rate of reaction can be calculated from the relationship,

$$\tau = f_{\mathrm{astro}} \times G_{\mathrm{T}}, \tag{1}$$

where f_{astro} (the astrophysical factor) depends entirely on the strong force and on quantities that have nuclear scale dimension, while G_{T} (referred to as the Gamow factor), which depends on the initial velocity v and electrostatic repulsion (at the point of contact) between the d's, can be evaluated using the Gamow tunneling formula[15]:

$$G_{\mathrm{T}} = \exp\big(-\frac{2\pi\alpha}{\beta}\big), \qquad (2)$$

where $\beta = \frac{v}{c}$, c is the speed of light and $\alpha = \frac{1}{137} = \frac{e^2}{\hbar c}$ is the fine structure constant.

3. Importance of QED (as Opposed to the Coulomb Barrier) inn d + d → α + γ

Based on the intuitively appealing idea that tunneling applies and that energy release is minimized, most nuclear physicists assume that the least common reaction ($\mathrm{d}+\mathrm{d} \rightarrow \alpha+\gamma$) occurs infrequently because the energy release (23.8 MeV) is considerably (7–8 times) larger than it is in the remaining reactions. In fact, this picture is not right. Important details about time-dependent, EMI effects, which are responsible for the fact that the $\mathrm{d} + \mathrm{d} \rightarrow \alpha + \gamma$ reaction occurs rarely (a fact that was not appreciated even by Schwinger[13] and Preparata[12]), have been ignored. In particular, the fact that EMI plays a central role in this reaction is known because although $\mathrm{d} + \mathrm{d} \rightarrow \alpha + \gamma$ rarely occurs, the reverse reaction (the photo-dissociation process: $\gamma + \alpha \rightarrow \mathrm{d} + \mathrm{d}$) has been studied in detail.

As discussed elsewhere [9,16], it is known, implicitly, as a consequence, as opposed to the conventional picture, involving a static Coulomb barrier, and the common, intuitive idea that the large energy release that is involved is responsible for the reaction occurring infrequently, an alternative model applies. In particular, the selection rules, alluded to in the last section, exist and a well-defined electromagnetic transition is involved in the photo-dissociation process. The analysis shows quite conclusively [16] that the reaction can be explained as resulting from a well-characterized (quadrupolar) transition, in which the total spin of the final state d's vanishes, and that it is necessary to include the effects of EMI (and the requirement that the d's obey Bose Einstein statistics) on length- and time- scales that are far from the location of the photo-dissociation process. In QED, the rate of any transition is proportional to the absolute square of the associated transition matrix element. Thus, by construction, the theory requires that a transition rate forward in time be equal to the comparable rate for a transition backward in time, and the common intuition, that this reaction is suppressed because of the large energy release, is wrong.

An important point has and continues to be the role of time-dependent effects in QED phenomena. The potential relationship of these EMI effects in potential nuclear fusion reactions, and in LENR, involving $\mathrm{d}+\mathrm{d} \rightarrow {}^4\mathrm{He}$ is not widely appreciated because it is commonly believed that the charge-neutral, strong force potential provides the time-dependent dynamics associated with the reaction.

An important reason for this is that, as outlined above, the importance of the effect of QED in $\mathrm{d} + \mathrm{d} \rightarrow \alpha + \gamma$ is not widely appreciated because this reaction, superficially, appears to be dominated by strong force effects since it conserves isospin and also because it is believed, as a consequence, that it occurs infrequently because the energy from the reaction is so much larger than the comparable reaction energies associated with the other reactions. The possible importance of QED in the LENR situation, and the possibility that approximate periodic order in this situation might be important, in solids, has not been widely considered probably because the conventional theory, of periodically ordered solids, that is commonly used, involves a semi-classical limit that does not include the possibility that, effectively, many channels for de-excitation can become possible through resonant phenomena in which an approximately ordered lattice is allowed to move and accelerate rigidly. In this situation, in principle, all of the charged particles in a particular region can "move" together at once, in such a way that the separation between any two particles does not change. In fact, collisions between charged particles at the "boundaries" of such a region with "particles" outside the region introduce forms of coupling that limit the extent and lifetime of these forms of "rigid-body" motion. Because it is never possible to identify where the "boundary" of such a region occurs, implicitly, the lowest energy excitations that result from these forms of approximate symmetry occur through resonant EMI processes, in which momentum and energy are conserved globally, and the perturbations (from collisions) that result occur when the net flux of each kind of particle into and away from the "ordered" region vanishes. Possible coupling between different configurations involving different center-of-mass velocities (and momenta) necessarily can result in forms of approximate degeneracy, and (as a consequence) many alternative forms of partial excitation and de-excitation can take place.

In free space, comparable forms of coupling are not present. As summarized elsewhere [9] and below, in a finite solid, through these kinds of effects, the "single γ ray" can be converted into many (lower frequency) photons. Also, as discussed elsewhere [8,9] through the Zener/ionic breakdown model, the phenomenon can occur through a time-dependent process, involving a form of coherent tunneling, in which the necessary changes in momentum for triggering the reaction can increase in magnitude with time.

4. The QED of d + d $\rightarrow {}^4$He in Cold Fusion

As mentioned in the Introduction, in Cold Fusion (CF), a variant of the helium-4 (α particle) producing fusion reaction (which rarely occurs in conventional fusion) appears to be dominant. As I pointed out in the last two sections, most nuclear physicists assume the conventional form of this reaction occurs infrequently because it creates considerably more energy than the other fusion reactions and that the most frequent reactions minimize the amount of energy that is released. This assumption is wrong. It does not include subtleties involving EMI. It does apply when d's have high velocity, initially, and collide at a point, provided they are not "prepared" (through EMI), in a particular way. As discussed elsewhere [9] in qualitative terms, in a solid, richer forms of time-dependent EMI can take place through non-linear coupling between photons, electrons, their spins, and other charged particles. Further complicating the problem is the fact that the ã ray that one would expect to be present in the normal ^{4}He (α-particle) producing reaction can appear and disappear through adsorption and emission by electrons and other charged particles in the associated environment, that can (and must, in most situations) result in "parametric down-conversion" (PDC) processes [9], even in relatively small crystals.

In particular, PDC processes occur through non-linear forms of coupling between a single photon and matter that result in the photon being split into two or more (and possibly many, many more) entangled (lower frequency—potentially considerably lower frequency) photons. These kinds of effects are known to occur when photons propagate through insulators. In these situations, because the scattering processes occur only at a small number of points, the possibility of massive PDC processes that can create many photons from a single photon has not been observed. Also, the theoretical basis of the process, though well-understood, has been limited to two photons, primarily because the fields that are involved do not include significant coupling to the kinds of cooperative forms of electronic excitation that are possible in metals, such as the recoil effect, discussed below.

In larger metal crystals, typically, the associated forms of coupling rapidly attenuate any electromagnetic wave propagation, and because approximate boundary conditions can be used in these kinds of situations, the possibility of observing and understanding PDC processes, involving one or more (optical) photons, has not been investigated. As discussed below and elsewhere [9], when more precise boundary conditions are invoked, in finite lattices, elastic forms of resonant coupling become possible. Because it is never possible to define the boundary of a solid, precisely, in principle, it is never possible to determine if a portion of the solid moves rigidly (or actually accelerates) through a process in which the available momentum from an applied field (static or dynamic) rigidly couples to the center of mass of a collection of atomic centers and electrons. This means a potentially huge degeneracy can result, provided the applied field is sufficiently weak, and the crystal has finite extent (but has a characteristic nano-scale dimension). As discussed in the present section of the paper, this, in principle, can result in the possibility of a large number of different photons, with varying, but well-defined frequencies, being produced.

This possibility implies that through these PDC processes, the γ ray associated with the conventional $\mathrm{d}+\mathrm{d} \rightarrow \alpha+\gamma$ reaction can be converted into many different optical, IR, microwave, or lower frequency forms of radiation, coherently or incoherently. As a consequence, the "α" particle (henceforth referred to as ^{4}He, when it occurs in lower energy environments <1000 eV but as an "α" particle when its energy is greater than this) can be "emitted" with negligibly small energy.

In a previous paper [9], I provided an initial argument that explains how this might take place, in smaller, approximately ordered, crystals. The associated PDC effects possibly can explain how a static magnetic or electric field could lead to localized phenomena, associated with the emission of higher energy α particles that apparently have been observed in experiments [17] associated with replicating the SPAWAR protocol [18]. This possibility was explained in this earlier paper [9], based on a form of Bragg Resonant scattering, in which the "photons" are effectively "trapped" as result of the kinds of effects, suggested by Giuliano Preparato. The simplest way of explaining how this can take place involves forms of scattering that are allowed to take place in one particular region of space, but not in other regions of space.

Good reasons exist for associating these kinds of effects, with an entirely counterintuitive limit, in which the lowest forms of momentum and energy conservation, are required to obey a form of symmetry, Bloch symmetry, that is related to periodic order, that, as a consequence, can lead to forms of resonant coupling, similar to Bragg Scattering in solids that can create an imbalance in momentum that can create the kinds of effects that Giuliano Preparata intuitively identified.

Here, in general terms, resonant scattering can take place, along the lines that Giuliano Preparata intuitively recognized. Specifically, matching conditions, associated with situations in which many particles and photons approximately share a common phase, resulting from conservation of momentum and energy, can be imposed. This can occur through the requirement that many of the potentially radiation-emitting particles receive and transmit their signals in a way that can constructively interfere and cause a positive form of feed-back, very similar to the resonant laser-like effect that he suggested was involved. In the most basic form of radiation-emitting situation that appears to be relevant in PdD, how this occurs is closely related to how the deuterons can become coupled coherently. In the simplest situation, this involves forms of charge and current conservation that are non-local. This can occur as the stoichiometry of PdD_x effectively varies between $x = 1 + \delta$ and $x = 1 - \delta$ (provided δ is sufficiently small), as a result of the strongly anti-bonding nature of the electronic states near the Fermi energy of PdD, when an applied DC field (or pressure), which is required to confine the D, within the lattice, is maintained for a sufficiently long period of time, and collisions are effectively stifled. The associated coupling occurs through a highly polarized bond that, in larger crystals, involves the lowest energy acoustic phonons, which, as envisioned by Giuliano Preparata, can be viewed as a form of semi-classical oscillation of the electromagnetic zero (or "trapped photons") of the solid [21].

An important point is that in a finite crystal of PdD, discretely defined forms of momentum (P_{cm}) can be transferred rigidly to the center-of-mass of all or a portion of the solid, through resonant processes, that, in larger crystals, mimic the kind of oscillation, envisioned by Preparata. An illustrative example of how this can occur involves a 1-dimensional lattice, with real boundaries, defined by a set of unit cells, each separated from the others by an integer **(n)** multiple of the lattice constant **a**. Constructive interference can occur whenever an integer multiple **(m)** of the deBroglie wavelength (λ_{d}) equals **a**, or **na**. The allowable coupling (which is defined by $P_{\mathrm{cm}} = \hbar/\lambda d$) as a consequence, associated the lowest energy fluctuations, from rigid translations, involves size dependent forms of momentum transfer. Effectively, the associated EMI can be viewed as involving a form of antenna, defined by **na/m**. In the reference frame that is stationary with respect to the lattice, as illustrated in a previous paper [8], when there are **2N** unit cells in the lattice, the kinds of rigid translations that are consistent with these lowest energy fluctuations occur when, for $\mathbf{j} = \mathbf{m}$ or $\mathbf{j} = \mathbf{n}$, $-\mathbf{N} + \mathbf{1} \leq \mathbf{j} \leq \mathbf{N}$ or $-\mathbf{N} \leq \mathbf{j} \leq \mathbf{N} - \mathbf{1}$.

The basis for this relationship involves a form of degeneracy, associated with the potential, rigid motion of a lattice, alluded to above. Here, in the periodically ordered regions, the electromagnetic fields resonantly scatter, between many possible wave lengths, without altering the energies of particles in the lattice, within the reference frame that is stationary with respect to the lattice. (The lattice is defined by the requirement that each unit cell is electromagnetically neutral.) However, outside the lattice, in the reference frame that is stationary with respect to any externally applied (static) fields, the lattice is allowed to move. Each possible velocity or acceleration that can take place without causing a collision defines a possible energy band state (through the associated wave-vector) that is degenerate with respect to the others. The presence of any form of collision has the potential of removing these degeneracies. When interaction with the external region, outside the lattice, is sufficiently weak but persists for a sufficiently long time, the differences in energy that result from collisions, can be quite small. This means that a continuum or quasi-continuum of states exist that can potentially couple either to an external electromagnetic field or one associated with potential nuclear reactions (which technically occur in regions external to the lattice since in the immediate vicinity of reactions, net charge is allowed to accumulate).

One potential mechanism for triggering these effects (that appears to be consistent with many of the experiments) involves a situation (in which x varies between $1 + \gamma$ and $1 - \gamma$, in PdD_x) that occurs when ionic charge enters and leaves the solid. Then, instantaneously, charge need not be conserved locally within the solid since it is impossible to measure either the charge or current. Also when this occurs, a form of broken gauge symmetry [4] can take place (resulting from finite size effects), in which portions of the "lattice" can appear to not conserve charge, as a consequence of many charged particles moving in lock-step in a way that is contrary to the conventional situation in which charge is conserved locally, and the associated response, referred to as gauge symmetry, cannot be violated locally [4]. As a consequence, in the interior regions of a solid, charge conservation can occur non-locally, but at the boundaries and outside this region, this is not possible. The possibility that such a region can exist and be important in potential fusion reactions has been ignored in the theoretical pictures that have formed the basis for rejecting CF-related phenomena.

At the boundaries of solids, these kinds of effects can occur in situations in which the associated momentum and energy can grow with increasing time. In particularly unusual situations, associated with PdD_x (as x varies between $1 + \delta$ and $1 - \delta$), fluctuations in charge (of d's and electrons into and away from the lattice for values of x immediately above and below the value x =1) can cause this kind of effect to occur because the net electron–deuteron charge that is allowed to enter the lattice can increase (when x is above the value x =1) and decrease (when x is below the value x =1), as a consequence of the strongly anti-bonding behavior of the electrons, and the associated electron, energy band states (near the Fermi energy) in PdD. As a result, in a finite metallic PdD lattice, a form of "preparation" can take place (involving, effectively, a form of dissociation between the nucleus of each D from its electron). This can occur provided the fluctuations in charge into and away from the lattice are sufficiently small, occur over a sufficiently long period of time, and can result in possible nuclear effects.

This kind of effect can alter possible forms of nuclear fusion in PdD because the d + d → helium-4 + 23.8 MeV reactions (in a host material) are allowed to occur, provided momentum is allowed to change sufficiently rapidly (even in a quasi-discontinuous manner, for example, through wave function cusps [15]). An important point, in this context, is that even classically, when a particle has mass m, velocity v, charge q, momentum

$$mv = p - \frac{q}{c}A,$$

as opposed to the situation associated with a static, time-independent Coulomb potential situation, where $mv = p$. In particular, in the more general situation associated with the two reactions, $\mathrm{d}+\mathrm{d} \rightarrow^4 \mathrm{He}+23.8$ MeV and $\mathrm{d}+\mathrm{d} \rightarrow \alpha+\gamma$, non-local effects are required. In more general situations, it follows from basic electro-dynamic considerations that simply by stressing a metal, with a sufficient force, in particular ways, as the metal approaches nano-scale dimension, potentially new effects, through resonant EMI, can occur that potentially can induce a spectrum of X-rays, lower frequency forms of light (including the kinds of IR forms of heat, observed by Mitchell Swartz [19] and in the SPAWAR experiments [20], and microwaves), and/or phonons. Thus, in any nano-scale PdD "crystal," as opposed to a static, electrostatic, "Coulomb" barrier, being involved in $\mathrm{d} + \mathrm{d} \rightarrow^4$ He (or α-particle) reactions, for example, a more sophisticated, time-dependent QED barrier is probably involved. In general terms, involving larger crystals, Giuliano Preparata [13,21] recognized this possibility (that the barrier that prevents fusion in free space should be very different in solids). But superficially, it appears that he relied on an over-simplified model, in which interactions with charged matter are treated semiclassically through a modified form of free particle interaction.

In fact, in a more realistic theory [8,9], based on a generalization of the conventional semi-classical model of (electron and ion [15]) energy band theory (which, in the case of electrons, is known to accurately describe heat and charge transport), the simplest approximation of the most relevant picture shares many of the intuitive features of the plasma picture suggested by Giuliano Preparata. Important differences exist. Giuliano Preparata assumed well-defined boundaries exist in a solid, so that the lattice could be treated as being stationary with respect to its external environment. In a real solid, it is never possible to determine precisely where the lattice begins and ends, where its boundaries are located, and whether or not it is in motion. The generalized energy band picture that applies to finite lattices is considerably richer because it includes quantum mechanical effects that are implied by these facts.

Starting from these assumptions, in the previous paper [9], the more general theory was used to suggest a number of effects, including the possibility that in the SPAWAR co-deposition experiments, the emission of high energy particles might be related to the orientation of the applied fields. This earlier paper presented an intuitive picture of the underlying QED.

In particular, the concept of "trapped photons," as envisioned by Preparata, was introduced, and a more general feature of their behavior, that explains how momentum can be conserved non-locally, coherently, through lattice recoil, was identified, through a generalized form of resonant Bragg scattering. Implicitly, the relevant physics of this involves a many photon, coherent state. For this reason, a more complete description of the microscopic physics involves assumptions about the representation of the manyphoton wave function. In order to incorporate Bragg resonance into the multi-photon state, it is sufficient to require that when a photon possesses wave-vector $\vec{k}$, it also possesses the wave-vector $\vec{k}+\vec{G}$, where

$$|\vec{k}| = |\vec{k}+\vec{G}|, \tag{3}$$

$\vec{G}$ is a reciprocal lattice vector, and the angular frequency of the photon, ω_0, is given by $\omega_0 = c|\vec{k}|$. In a sufficiently large lattice, Eq. (3) can be required to be valid provided

$$2|\vec{K}| \geq |\vec{G}|. \tag{4}$$

If there are M values of $\vec{G}(\equiv \vec{G}_i, i = 0, M-1)$ that satisfy Eq. (4), the requirement that the multi-photon state $\Psi_k(x_1, ..., x_M)$ possess photons with wave-vectors $\vec{k}$ and $\vec{k}+\vec{G}_i$ (for each value of i, with $\vec{G}_0 \equiv 0$) can be imposed through the relationship,

$$\Psi_{\vec{k}}(x_1, ..., x_M) \equiv \int \mathrm{d}^3k_1 ... \mathrm{d}^3k_M \left\langle \vec{k}_1, ..., \vec{M} | \vec{k}, \vec{k}+\vec{G}_1, ..., \vec{k}+\vec{G}_{M-1} \right\rangle \\ \times \Phi_{\vec{k}_1}(x_1)\Phi_{\vec{k}_2}(x_2)|...\Phi_{\vec{k}_M}(x_M), \tag{5}$$

where

$$\left| \vec{k}, \vec{k}+\vec{G}_1, \ldots, \vec{k}+\vec{G}_{M-1} \right\rangle = \frac{1}{\sqrt{M!}} a^{+}_{\vec{k}} a^{+}_{\vec{k}+\vec{G}_1} \cdots a^{+}_{\vec{k}+\vec{G}_{M-1}} |0\rangle, \tag{6}$$

is the multi-photon eigenstate associated with the occupation of (single) photons with wave-vectors $\vec{k}$ and $\vec{k}+\vec{G}_i$, for all values of i, and

$$\left\langle \vec{k}_1, \ldots, \vec{k}_M \right| = \langle 0 | a_{\vec{k}_1} a_{\vec{k}_2} \ldots a_{\vec{k}_M} \frac{1}{\sqrt{M!}} \tag{7}$$

is an eigenstate of an arbitrary M-photon state (in which each frequency is singly occupied). In Eqs. (6) and (7), respectively, the symbols $a^{+}_{\vec{q}}$ and $a_{\vec{q}}$ are used to denote creation and annihilation operators, and in Eq. (5), each function $\Phi_{\vec{k}_j}(x_j)$ can be constructed (as shown below) according to the condition that it possess Bloch symmetry using multiple scattering theory.

Equations (5)–(7) apply when at most each photon frequency is occupied by a single photon. With minor modifications (involving changes in the prefactor $\frac{1}{\sqrt{M!}}$), a more general relationship can be constructed that includes the possibility for multiple photon occupation of each photon frequency. An important point is that the overlap between wave functions of the form given by Eq. (5) with the interaction (electromagnetic) potential $V_{Int} = -\frac{e}{c}\vec{J} \bullet \vec{A}$, defined by the currents $\vec{J}$ and vector potential $\vec{A}$, potentially involves all photons that have wave-vectors $\vec{k}$ and wave-vectors $\vec{G}$ that satisfy Eq. (4). For this reason, as opposed to the situation associated with the conventional $\mathrm{d} + \mathrm{d} \to \alpha + \delta$, in which the transition involves a single 23.8 MeV gamma ray, in the situation involving Bragg resonant, trapped photons, the transition is required to involve many photons.

Furthermore, using multiple scattering theory, it is possible to show that the associated wave function has appreciable overlap with many different nuclei, at many different locations in space. For these reasons (that many photons are involved and because overlap occurs involving many nuclei), it is not necessary for appreciable energy and/or momentum to become localized anywhere inside the lattice. As a consequence, implicit in the microscopic physics is the result that high energy particle emission not only is unnecessary, but it is unlikely.

The explicit application of multiple scattering theory (to derive each wave function $\Phi_{\vec{k}_j}(x_j)$) involves requiring that $\Phi_{\vec{k}_j}(x_j)$ satisfy the Helmholtz equation,

$$(\nabla^2 + k_j^2)\Phi_{\vec{k}_j}(x_j) = 0, \tag{8}$$

in a particular region (the interstitial region) of space (which can have infinitesimal extent) and the inhomogeneous wave equation,

$$(\nabla^2 + k_j^2)\Phi_{\vec{k}_j}(x_j) = -\frac{4\pi}{c} J, \tag{9}$$

in the remaining region (the Muffin Tin region). Then, by introducing the Green's function G(r-r') for the Helmholtz equation, it is possible to relate values of Φ in the Interstitial (IS) region to the integral of the product $(J \times G)$ of the current density (J) in the Muffin Tin (MT) region with G, and the values Φ and its normal derivative along the boundaries of the MT region using the identity,

$$\Phi_{\vec{k}_j}(r)|_{r\varepsilon IS} = \int_{\text{MT boundary}} \mathrm{d}A\hat{n} \bullet \{-\nabla_{r'}G(r-r')\Phi_{\vec{k}_j}(r') + G(r-r')\nabla_{r'}\Phi_{\vec{k}_j}(r')\} + \frac{4\pi}{c}\int_{\text{MT Region}} \mathrm{d}^3r' G(r-r')J(r'). \tag{10}$$

Here, $\hat{n}$ is a unit vector pointing in the direction normal to the boundary of the MT region, and

$$G(r-r') \equiv G_{k_j}(r-r') = \frac{c}{4\pi}\frac{\cos(k_j|r-r'|)}{|r-r'|} = \frac{c}{4\pi}k_j \Sigma_L n_l(k_j r^>) j_l(k_j r^<) Y^* L(\hat{r}) Y_L(\hat{r}), \tag{11}$$

where $r^>(r^<)$ is $|r'|(|r|)$ when $|r'| > |r|$ and $r^>(r^<)$ is $|r|(|r'|)$ when $|r| > |r'|$, $k_j \equiv |\vec{k}_j|$, respectively, n_j and j_l are l^{th} order spherical Neumann and Bessel functions, $Y_L(\hat{r}) = Y_{l,m}(\hat{r})$ denotes a spherical harmonic, evaluated in the direction of the unit vector $\hat{r}$ (where the index $L = (l, m)$ is used to signify the two values l and m associated with each spherical harmonic).

To make further progress, we introduce the physics associated with lattice recoil. In particular, in the idealized limit associated with a situation in which the lattice moves elastically and rigidly (and the particle–particle separations do not change within the lattice), effectively, regions where charge can accumulate can occur at locations where d's occupy IBS's (and are not part of the lattice); while elsewhere, charge does not accumulate. The recoil effect can be introduced by allowing the locations where charge can accumulate to move relative to locations where it does not accumulate.

Within this approximation, a second interstitial region (where the possible electromagnetic fields also satisfy a Helmholtz equation) is required. It begins at the boundary of each nuclear region, which surrounds a location where d's can have appreciable overlap and extends to the boundary of each MT, where the frequency of each potential photon is Doppler shifted by an amount equal to a suitable frequency associated with the conditions that are responsible for the recoil. This last condition is satisfied (in the non-relativistic limit) when the angular frequency ù in this second IS region satisfies the equation,

$$\omega_0(1-\beta_{\mathrm{CM}}) = \omega = cG_i, \tag{12}$$

where G_i is one of the reciprocal lattice vectors that satisfies Eq. (4), $\beta_{\mathrm{CM}} = \frac{\upsilon_{\mathrm{CM}}}{c}$ is the velocity of the center-of-mass of the lattice (υ_{CM}) that results from the recoil process, divided by the speed of light (c), and, as in Eq. (3), $\omega_0 = ck_j$. Again, within the context of this last approximation, a slightly modified version of Eq. (11) (in which k_j is replaced by $\frac{\omega}{c} = G_i$) can be used to determine $\Phi_{k_j}(x)$, and the values $\Phi_{k_j}(x)$ at the boundary of each MT in the MT region can be computed, using this second equation.

Because the MT region in Eq. (10) extends throughout the lattice (specifically, there is at least one MT in each unit cell), implicitly, appreciable overlap can occur between values of $\Phi_{k_j}(x)$ inside the IS region that are located in different unit cells. This result becomes more transparent if we apply multiple scattering theory, as it is used in conventional energy band theory [22]. In particular, to do this, we impose the boundary condition that each wave function $\Phi_{k_j}(x)$ possesses Bloch symmetry, $\Phi_{k_j}(x + R_n) = \mathrm{e}^{i\vec{k}_j \bullet R_n)}\Phi_{k_j}(x)$ (R_n = Bravais lattice vector). As a consequence, it is possible to re-express both integrals on the right-hand side of Eq. (10) (using conventional expansions that are used in energy band theory [22]) in terms of quantities that have comparable magnitude throughout the lattice.

Besides explaining how non-local, reduced energy and momentum processes can result when "trapped photon" states are involved, because these states possess Bloch symmetry, they can couple coherently to the electronic and ionic band states coherently in the kinds of situations associated with PdD. As a result, small changes, associated with coupling between photons that occupy these kinds of states with the solid and (as a consequence) with externally applied fields can take place. A particularly interesting case involves a situation involving an applied magnetic field. In particular, even small, external magnetic fields might play an important role in triggering excess heat, provided they have a suitable orientation.

A particular situation that might apply in this context involves applying a constant magnetic field $\vec{B}$ parallel to the surface. When this occurs, the spins of d's in IBS's , in principle, can couple coherently to $\vec{B}$ (through the Zeeman effect) in such a way that preferentially their precession can induce states that have vanishing spin normal to the surface. This in turn can result in a preferential orientation for possible nuclear reactions in directions that are also normal to the surface. Furthermore, through a form of NMRlike coupling in which a second, external (RF) field is applied normal to the surface, a resonant condition can be established (associated with flipping the spins of the d's that occupy IBS's). Essentially, the optimal way of performing this kind of experiment involves introducing an RF field, that has an angular frequency Ω_L that matches the Larmor frequency of the applied magnetic field ($\Omega_L = \frac{e|\vec{B}|}{m_d c}$, where m_d = deuteron mass) associated with flipping each deuteron spin. This could help to trigger excess heat because to preserve periodic order ^{4}He has to be removed from the solid [1,2,11].

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