Resonant Electromagnetic-Dynamics Explains the Fleischmann-Pons Effect

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Abstract

Science requires measurements. Interpreting measurements involves recognizing patterns. How this happens is intimately related to the instruments that are used and how the measurements are performed. One can "interpret" the process in many different ways. Historically, however, in modern physics, quantum mechanics has been used in situations involving "smaller" scale effects. In this form of interpreting science, when "measurements" take place, what is measured involves details about the measurements. A form of communication is involved: What is "seen" depends intimately on how one "looks at it." Abstractly, this can be viewed in a somewhat radical way: Nature is telling us something, but how we "interpret it" involves how we understand what Nature "is telling us". Just as in normal forms of communication, this kind of communication involves being willing to accept information that is sent to us from somewhere else. In other words, a signal is sent. If it is received, communication takes place. If it is not, it does not take place. This paper deals with a radical idea about a radical subject. The radical subject is what used to be called "cold fusion". The radical idea is that basic ideas about quantum mechanics, and the "implicit" form of communication that is present in quantum mechanics can explain this subject.

I Introduction

I argue that the real barrier for understanding how Cold Fusion reactions can take place, in the Fleischmann-Pons effect (FPE), is not overcoming the "Coulomb Barrier" but involves understanding quantum mechanics (QM). Specifically, QM does not require that the "picture" used in conventional fusion apply. A more logical "picture" includes electromagnetism in a time-dependent fashion and the idea that many particles can be involved. Then seemingly impossible "aspects of the "conventional picture" become "not so impossible," but, in fact, "quite reasonable." A key source of confusion is that as opposed to a situation in which potentially reacting deuterons (d's) are required to have such high velocity that they can be treated as if changes in their electromagnetic interaction (EMI) are important only very near the location of the reaction, where the conventional tunneling picture applies (involving a static Coulomb potential), in a situation involving many charged particles, the effects of EMI can result in time-dependent changes that can become important far from the reaction. In fact, in what appears to be the most relevant, conventional fusion reaction (in which helium-4, in the form of alpha particles is released), evidence exists that the conventional "Coulomb Barrier" actually must be modified significantly[1-3] in order to incorporate time-dependent features of the EMI that are necessary to impose the requirement that far from the reaction, the incident d's must have positive Bose Exchange symmetry and have net, vanishing spin. In this paper, I discuss a particular mechanism involving resonant electromagnetic dynamics. The associated picture is consistent with the conditions that are present in the experiments, the known laws of physics, and the underlying ideas suggested by Giuliano Preparata [13]. Predictions, based upon this alternative picture, imply that particular size crystals, involving Palladium (Pd) and particular, externally applied electromagnetic fields can be used to trigger excess heat in the FPE.

In the next section, I provide an overview of some of the commonly believed ideas about the "Coulomb Barrier" that have resulted in considerable confusion about the FPE. In addition, I explain how conventional QM deals with forms of interaction in general terms and how these can result in a counter-intuitive picture in which "collisions" can be very different than in the conventional "Coulomb Barrier" situation because they do not have to take place "at a point." Instead, collisions can take place over a finite distance through an effect that is referred to as resonance or "near resonance," in which in a particular region of space, effectively, momentum is conserved in a non-local fashion. In conventional solid-state physics, the associated effects are quite well known, but a rigorous treatment of their origin has not been adequately presented. In dealing with the cold fusion problem, I have suggested such a treatment[4, 5].

In the final section, I discuss two different pictures that involve "nearly resonant" forms of collisions in an approximately ordered solid. The first of these is based on an approximate model that was introduced to "overcome" perceived deficiencies involving how the "Coulomb Barrier" frequently has been viewed in the fusion process. But this model uses a language (time-dependent perturbation theory involving bound, ion band states) that is very different from the conventional scattering/tunneling language that is associated with the more conventional picture associated with the "Coulomb Barrier." In the second picture, a generalization of the first picture is presented, using a language that is consistent with more general aspects of QM, based on "nearly-resonant" collisions that can take place involving the lowest energy excitations of an ordered solid, which can include the possibility that all of the particles in the solid can be allowed to move all-at-once rigidly. Here, for illustrative purposes, a semi-classical limit is used to demonstrate how the associated "nearly-resonant" collisions can lead to nuclear-scale forms of overlap. More quantitative arguments that are based on the more general theory are presented elsewhere [1-5]. From these more general arguments, both the earlier picture and its generalization (in the second model) can be shown to involve forms of "nearly resonant" collisions. In the second model, external electromagnetic fields can induce adiabatic changes in the associated scattering. In the initial picture, the energy of the interaction is assumed to result from a uniform shift in the zero of energy. In the second model, these forms of motion occur as a result of a uniform shift in the zero of momentum, and the reaction involves a different final state in which changes at the boundary of the ordered region of the solid occur through a transition in which the momentum from the change in mass (from the $d+d \rightarrow {}^4He$ reaction) is transferred to the center of mass of the lattice as a whole. In this situation, the change in the final state involves coupling through "nearly resonant" collisions in which momentum is either transferred to potentially interacting helium-4 nuclei (in larger crystals) or directly to the lattice (in smaller nm-scale crystals).

II "The Barrier is not "the Coulomb Barrier"-- It is Quantum Mechanics

The idea that Nature is telling us something by sending us signals and requires us to receive them involves a process of interpreting what Nature is telling us. To "understand" what Nature is telling us requires us to "think" about the signal and what it represents. In conventional fusion, this process is relatively simple because an obvious model exists: conventional fusion occurs on the Sun, and it involves hot plasmas, where high velocity hydrogen nuclei (protons, or proton-neutron pairs—d's) can collide in a process that we also seem to think we understand. But our understanding of this is approximate. It is based on a theory that was created well-before details about later information involving experiments that could be explained by a more refined understanding of QM were known. For this reason, it is appropriate to re-examine some of the more common assumptions about the "Coulomb Barrier," and their relevance in our "understanding" of the FPE. With this in mind, I asked three other people who have been paying close attention to issues related to the FPE about their opinions about the importance of "Overcoming Coulomb Barrier." Their opinions and my opinion are expressed in the following:

1. Nuclear Physicists Say: You can't overcome it[6].
2. Nuclear Physicists Say: You can't overcome it. They seem to be wrong. But there is no accepted theory that can account for it[7].
3. Nuclear Physicists don't understand it. Solid State Physicists do. "Accepted theory" involving Nuclear Physics is wrong. Ground state quantum mechanics explains it[8]
4. Time dependent quantum mechanics says it can be overcome using "conventionally accepted" theory and this will eventually "be accepted"[9].

In fact, no one knows how relevant any of these statements actually is. With the exception of statement 4 (which is my opinion), what I suggested in each of these opinions is not based on an objective scientific analysis. I believe, however, there is value in including these statements because in each case, I suggest the particular opinion has resulted from biases and perceptions about the "Coulomb Barrier" that actually are not relevant to the FPE but reflect a more basic source of confusion: Interpreting and understanding what Nature is telling us through QM.

In conventional physics and chemistry, the kind of radical effect that Fleischmann and Pons observed was not at all expected, and, even after many years, statement 1 reflects the predominant opinion of most scientists. The person who made this statement actually is very concerned about and interested in the outcome of the "debate" that has taken place, and I suspect that although he made this statement, as additional facts are revealed, he may change his mind. Statement 2 reflects the opinion of an individual who has initiated a useful, scientific dialogue and debate about the subject. He also has recognized that the lack of scientific discourse about the subject has precluded realistic intellectual investment of time, much less, real investment, through significant funding. Statement 3 was made by a scientist who collaborated with me in developing the initial ideas associated with our ion band state model of the FPE. His opinion reflects a more open-minded perspective, associated with invoking ideas about quantum mechanics and solid-state physics. With time, I have sharpened the associated arguments that are the basis of his opinion. Some of these ideas are the basis of statement 4. Each view captures an important perspective. Obvious differences in opinion are implicit in these different statements that reflect biases about a seemingly transparent assumption: that opinions about the “Coulomb Barrier” have relevance in understanding the FPE (and why because of these opinions—in statements 1 and 2—it does not seem possible that the FPE can result from nuclear reactions). An important point, associated with statements 3 and 4, involves the potential role of QM and the idea that through QM it is possible to go beyond the limitations of the assumptions, associated with statements 1 and 2. In fact, statements 3 and 4 are based on a model involving QM that actually makes sense in the context of what is known[4] about palladium-deuteride (PdD). But the fact that QM might even be involved (in the PdD situation but also, even in the conventional “Coulomb Barrier” tunneling problem) does not seem to have been widely understood or appreciated. In particular, preconceived ideas about the “Coulomb Barrier”, although seemingly quite relevant and “obvious” (as expressed in statements 1 and 2), are actually quite inappropriate and quite wrong in situations in which many particles, potentially interacting electromagnetically, can be involved. In this alternative situation, the relevant dynamical situation can become (and probably is required to be) considerably more complicated. The real situation, even in conventional fusion, does involve QM, but in a very limited way, and this fact, apparently, also, has not been widely appreciated.

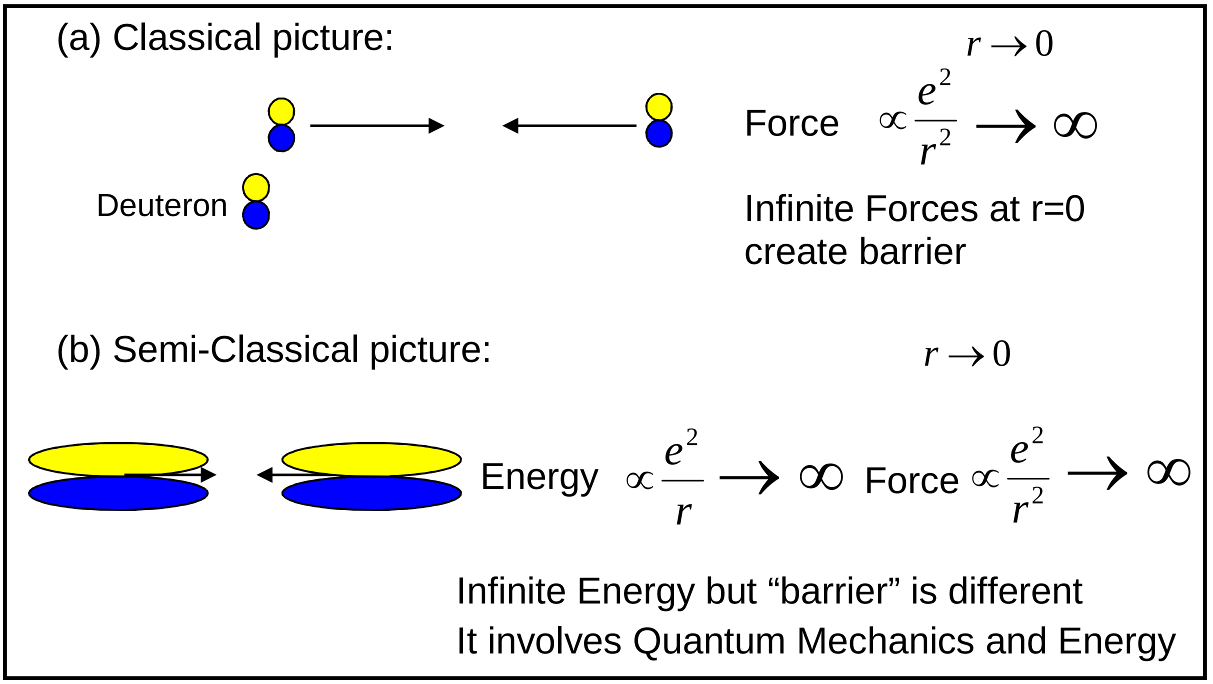


Fig.1: Schematic representations of two commonly-viewed pictures of the “Coulomb Barrier;” in (a), a “classical” point-particle picture is shown. The “perceived barrier” occurs because point particles cannot collide when infinite forces occur. This creates a “Conceptual Barrier.” But it is not the “Coulomb Barrier” that is believed to be relevant in QM. The “Coulomb Barrier,” which is believed to be relevant to most physicists is shown pictorially in (b). It is based on conventional “Gamow Theory,” where because of QM, d’s are shown as pancakes, symbolically, representing waves, not point-particles.

Fig. 1 shows a schematic representation of two "perceived" pictures of the "Coulomb Barrier." In the first of these, each d (which is shown as a proton-neutron pair, in which each proton appears as a point-particle lighter circle and each neutron appears as a point-particle darker circle) is a point-particle that cannot collide with a second d because of the infinite forces that occur classically as a result of Coulomb repulsion. Although this picture "seems to" explain why fusion cannot occur, this isn't true: *it over-simplifies the situation.* A more *"realistic*

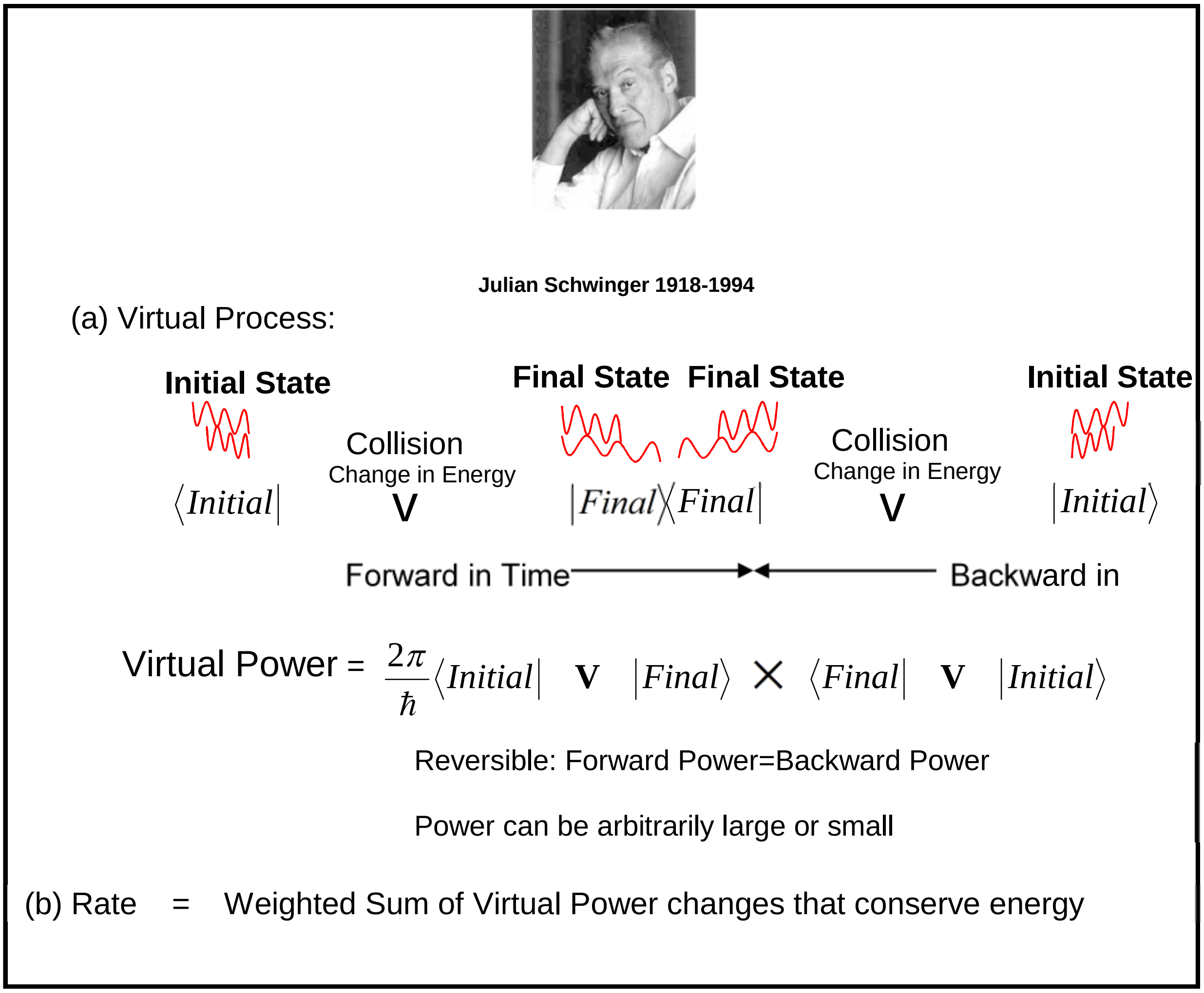
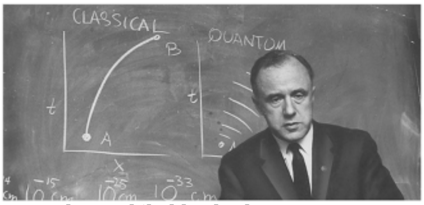


Fig.2: Shows a pictorial representation of the how collisions occur in QM, following an analysis that Julian Schwinger developed (which he presented during ICCF1[10]). The meanings of the various symbols and their significance are discussed in the text.

picture" is shown in (b). Here, "point-particle" d's are replaced by pancakes, which are used to mimic "wave-like" structures that QM requires; these structures can "collide" (their wave functions can have overlap). This can take place, despite the fact that the classical expressions for the energy and force become infinite. The picture in Fig.1b is more realistic. But the associated mathematics is approximate since it requires the d's to have high velocity.

Fig.2 shows a pictorial representation of how collisions occur in QM (and in quantum field theory), based on an analysis that Julian Schwinger developed[10]. Here, in any possible QM process, an initial state (referred to as an initial state, many-body wave function), which can be thought of as a wave, or many waves, and, which is represented schematically as a wavy line, initializes a collision process, that results in the occupation of a final state (associated with a final state many-body wave function), which is also shown as a second, wavy line. (In fact, each of these waves can involve any number of particles—many waves—conceivably.) In particular, collisions involve changes in energy. In principle, they can take place through any possible form of “Virtual Process.” Each “Virtual Process” is initiated through a change in the potential energy V, resulting from a collision and leads to a scattering event in the forward direction in time (initial state to final state) and a second scattering event involving the same change V that occurs in the reverse direction in time (final state to initial state). Forward reactions very often are balanced in this equation by backward reactions. When a balance takes place, no reaction occurs (as represented in Fig.2a) by the statement forward power=backward power (which implicitly is used in conventional thermodynamics). A net change in power (referred to as a



John Archibald Wheeler 1911-2008

In Virtual Processes:

1. Future events can affect (or resonate with) past events.
2. Particles that are far apart can interfere with each other.
3. Sum over final states means creative physics is possible.

Fig.3: Shows a picture of John Wheeler and summarizes some of the novel aspects associated with QM that he and Richard Feynman used throughout their careers that have not been appreciated in “discussions” about the role of QM in cold fusion and low energy nuclear reactions.

“Virtual Power change” in Fig.2a) can occur that is defined by the product of the matrix element of the forward process, $\langle Initial|\boldsymbol{V}|Final\rangle$, with the matrix element of the backward process, $\langle Final|\boldsymbol{V}|Initial\rangle$, provided energy is conserved. During ICCF1, Schwinger explicitly cited this relationship[10], implicitly using a well-known equation (referred to as the

Lippmann-Schwinger equation) that has not been widely-appreciated in the analysis of cold fusion theory:

$$\text{Rate of reaction} = \frac{2\pi}{\hbar}\langle Initial|V\delta(H - E_{Initial})V|Initial\rangle$$
$$= \frac{2\pi}{\hbar}(\textstyle\sum_f \langle Initial|V|Final\rangle\langle Final|V|Initial\rangle\delta(E_{Initial} - E_{Final})), \quad (1)$$

where $E_{Initial}$ and E_{Final}, respectively, are the energies of the initial and final states, and the summation includes all final states.

In fact, the terminology “collision” is a generalization of the classical concept. In Eq.1, a more appropriate idea implicitly is presented. In the expression, any number of particles, over any length and time scale can be involved in each virtual process. As stated in words in the figure, collisions in QM involve a rate that is formed as a weighted sum of the possible Virtual Power changes that can be created through virtual processes. The possible power (the Virtual Power) resulting from any virtual process can be arbitrarily large or small, and each process, in principle, is reversible. When the sum over final states conserves energy (which is implied through the notation involving the delta function in Eq.1), the process can take place. Time reversibility is broken because it is never possible to determine the change in potential, the initial state and the final state precisely. The associated relationship (Eq. 1), in principle, is exact. It provides a prescription for modeling new and novel effects that is considerably richer than is possible in Gamow theory. In particular, Gamow theory, in the fusion process, assumes a single final state is involved with a collision (consisting of three nucleons, moving away from a third nucleon) at high velocity, except in regions in the immediate vicinity of the collision, and that the essential dynamical changes in the potential energy (V, in Eq. 1) involve the strong force exclusively. This picture ignores many possible final states and implicitly fails for this reason. This occurs because Gamow theory does not include many of the possible “signals” that QM allows. The more complete picture (outlined in Fig.2 and Eq.1), explains how many creative possible forms of interaction (“communication”) can occur from “signals” involving the final state (the receiver) and the transmitter (the initial state). Discussions about this involving how light interacts with electrons, between John Wheeler and Richard Feynman, helped Feynman to win a Nobel Prize. He won this prize by explaining how, through a subject that is referred to as Quantum Electrodynamics (QED), electrons must be treated using QM when they interact with light. The three ideas that I “attribute” in Fig.3 to John Wheeler (which were well-known by him and others when he worked with Feynman) are related to the fact that by construction, in QM, in isolation (i.e., without measurements involving collisions and related effects), time has no preferential direction, and implicitly, “time reversal invariance” takes place, which means it is impossible to distinguish between situations in which how electrons and light interact evolves forward in time from situations in which their interaction evolves backward in time.

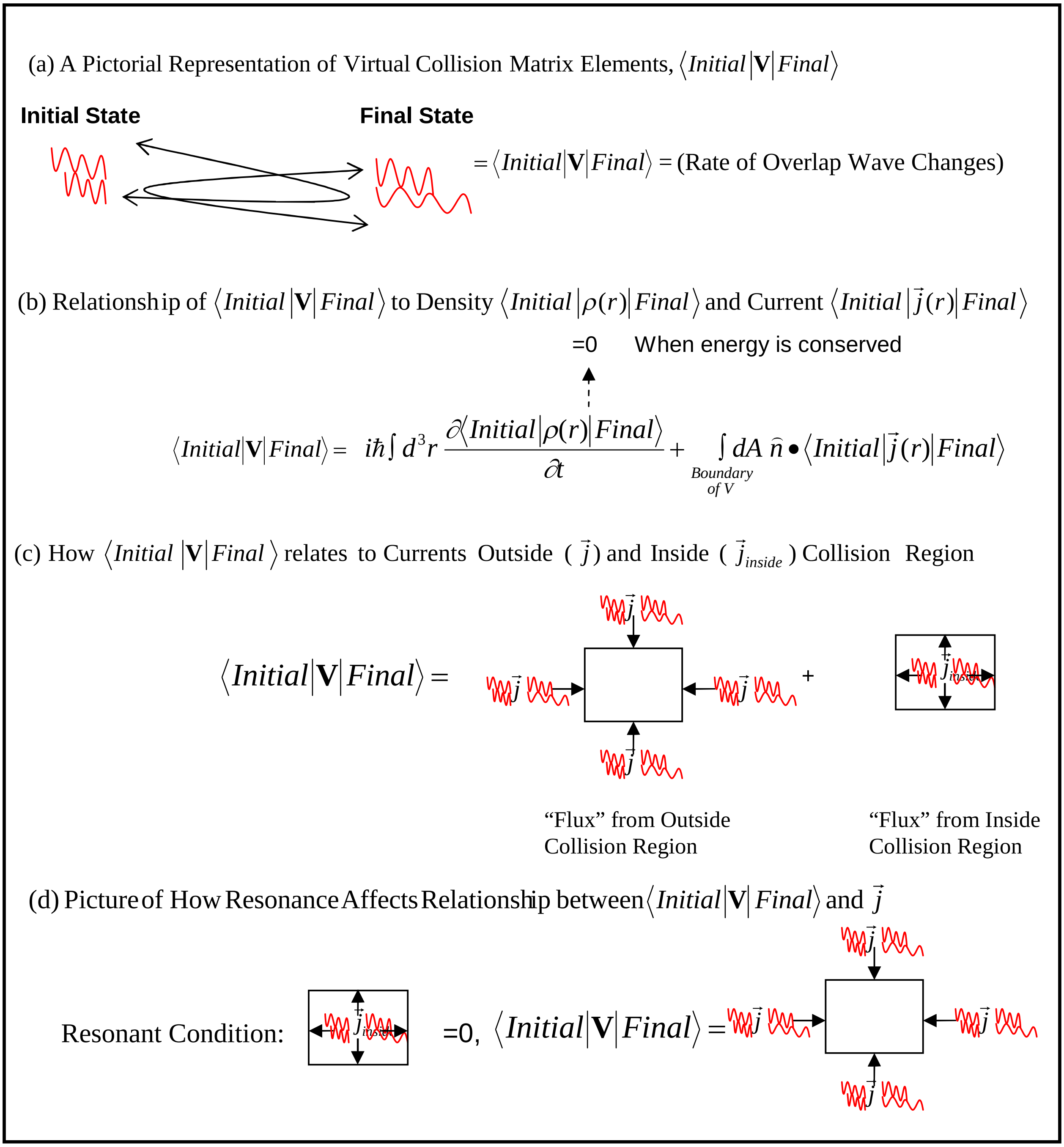


Fig.4: Shows a pictorial representation of each virtual collision matrix element $\langle Initial|\mathbf{V}|Final\rangle$ (in (a)), how (in (b)) $\langle Initial|\mathbf{V}|Final\rangle$ is related to the current and density matrix elements, $\langle Initial|\vec{j}|Final\rangle$ and $\langle Initial|\rho|Final\rangle$ through a surface region integration representation (when energy is conserved) involving flux contributions at the boundaries of the collision region from currents located outside ($\langle Initial|\vec{j}|Final\rangle$) and inside ($\langle Initial|\vec{j}_{inside}|Final\rangle$) and a pictorial representation (in (c)) of this fact. Resonance occurs (in (d)) when the flux contribution from inside the region vanishes.

At a very early stage in the evolution of QED, John Wheeler suggested rather extraordinary ideas (associated with the words in Fig. 3), including this concept of "time reversal invariance" and other "counter-intuitive" features of QM, in which: 1. "Particles" that are located far apart can "interfere" with each other (i.e., the wave-like characteristics of different particles that are far apart can affect each other in measurements); 2. Since it is never possible to identify a particular final state with certainty, assumptions about the behavior of the final state can be used to postulate new and novel physical effects; and (possibly the most novel idea) 3. How light propagates in the future can "affect" (or resonate with) how it has propagated in the past. This kind of logic is a starting point for believing the "real barrier" to our understanding of cold fusion probably is not only understanding "the Coulomb Barrier," but it involves using a more complete picture of what is possible in QM.

III Resonant and Near-Resonant Interactions

A problem, involving the possibility that light being transmitted and received in the future, in the absence of collisions, could alter how it was transmitted and received in the past was suggested by Wheeler to his (at the time) young, graduate student, Richard Feynman. This idea required that Feynman think in basic terms about how light might interact with matter at its most fundamental level. Intuitively, one might view this problem in a paradoxical way: That what happens in the future could affect the past. In fact, as opposed to viewing this problem in this particular way, an alternative way of looking at it involves an important assumption, associated with how quantum mechanics works: In the absence of collisions, it is impossible to "know" anything at a fundamental level, and (possibly more significantly) that how natural forms of harmony (or resonance) might exist in which it is simply impossible to distinguish between the past and future, or even in situations in which "seemingly natural" boundaries are present that can prevent unexpected collisions from taking place. In suggesting this seemingly odd and bizarre idea, Wheeler asked Feynman to address a fascinating question that might be impossible to answer: If a tree falls in a forest and there quite literally is no one around to hear it, does the tree make a sound. Possibly equally remarkable is the conclusion, based on what is known about the existing theory of electromagnetism, that he suggested, is that a sound actually might not be created. In doing this, John Wheeler and Richard Feynman "re-invented" the kinds of ideas associated with how QM works, and the forms of harmony and resonance that I just mentioned, which are not widely appreciated, associated with "time reversal invariance" and causality that (I think) have direct bearing on questions related to cold fusion.

In particular, Wheeler and Feynman made use of ideas related to what we know and can never know about electrodynamics, and the fact that precise solutions of the associated equations are allowed to become non-local both in time and space. By invoking this, they postulated the somewhat "spooky" idea that for radiation to ever be transmitted, it is necessary to have both a "well-defined" receiver and transmitter. Wheeler suggested that if this does not take place, no signal is ever transmitted. Implicitly, in order to account for how the associated signal is transmitted, Feynman invoked a form of the effect that I have referred to as resonance or harmony. When this kind of effect is approximate, a condition that I will refer to as "near resonance" can take place, in which "collisions" can take place, but their magnitude and duration can be vanishing-ly small. In both situations, as opposed to a "conventional effect" (in which how light and electrons interact only involves how light is emitted in the future), Feynman and Wheeler thought about a very different effect, involving conditions in which how light is emitted involves a situation in which how it interacts with electrons in the future can affect how it has interacted with electrons in the past. They suggested how this occurs "appears" to involve a situation in which what happens in the future "in anticipation" of what will take place can affect what has taken place in the past. This idea is entirely non-classical, in the "real universe," and it also "appears" to violate causality. (But, as stated above, because in QM, by construction, in the absence of collisions, time has no preferential direction, such a violation does not take place.)

In Fig. 4(a), I show a pictorial representation of the overlap between initial and final states using wavy lines, and its rate of change with respect to time (in the interaction picture[11]), using a wavy line that begins and ends with arrows. Each virtual collision matrix element, $\langle Initial|\mathbf{V}|Final\rangle$ (in Fig.4a) that is used to define the virtual power (Eq. 1), can be related (as shown in Fig.4b) to the (Schroedinger picture[11]) "off-diagonal" many-particle current (associated with all, neutral or charged particles) and density (associated with the same particles) matrix elements[11], $\langle Initial|\vec{j}|Final\rangle$ and $\langle Initial|\rho|Final\rangle$, through an integral representation that reduces to a simpler (surface region integration) representation, when energy is conserved, involving flux contributions at the boundaries of the collision region from currents located outside ($\langle Initial|\vec{j}|Final\rangle$) and inside ($\langle Initial|\vec{j}_{inside}|Final\rangle$). The condition associated with future and past forms of scattering being in harmony with each other (as in Fig.3) occurs when particle number and energy are conserved, throughout space. This implicit assumption is illustrated through the arrow, from the first term in the integral equation, shown in Fig.4b, to the symbols and words, associated with the wording, "=0 When energy is conserved." In Fig.4c, a pictorial representation is presented that shows how this can take place.

The resonant condition (shown in Fig.4d) occurs when the contribution from inside the region vanishes. Then, $\langle Initial|\mathbf{V}|Final\rangle$ depends only on contributions $\langle Initial|\vec{j}|Final\rangle$ that occur at the boundaries of the region. Effectively, when this occurs, the "collision" process can become non-local, and through near resonant conditions that "almost mimic" resonance, non-local forms of collisions can occur that can result in gradual increases in momentum. In particular, as opposed to a situation in which particles "collide" in the interior of the collision region, in perfectly resonant situations all of the particles that are external to it pass through it, as if the region is transparent. In near resonant situations, all of the particles either pass through it, or some of them may remain near the boundary or be reflected, in such a way that momentum is transferred non-locally. In both situations, the changes in potential only occur either at the boundaries of the region or in regions external to it.

IV How Resonant Electromagnetic-Dynamics Explains the Fleischmann-Pons Effect

Implicitly, in an approximately ordered solid, a form of "Galilean relativity" exists, associated with the fact that in the limit in which there are no collisions, it is impossible to tell whether or not the "ordered regions" in the solid are in motion or at rest. This can have especially interesting consequences when collisions are weak because their contributions in Eq. 1 can be stifled as a result of periodic order. The associated effect is a specific example of the more general phenomenon, discussed in the last section: near-resonance and nearly resonant collisions. This occurs when contributions from many virtual collision matrix elements (many values of $\langle Initial|\mathbf{V}|Final\rangle$ in Eq. 1) become very small in a particular region of space. In particular, perfect resonance occurs when energy is conserved and the contribution to the "flux" (as in Fig. 4b) from the many-particle current matrix elements, $\langle Initial|\vec{j}(r)|Final\rangle$, over the boundary of the region, from the interior portion of the integral (as in Fig.4d) vanishes. Since energy is conserved in Eq. 1, in this kind of situation, the total contribution from collisions in the interior vanish (so in this region $\langle Initial|\mathbf{V}|Final\rangle = 0$), and with respect to $\langle Initial|$ and $|Final\rangle$, the total Hamiltonian (*H* in Eq. 1) can be viewed as being a self-adjoint (Hermitean) operator in this region.

Formally, as a consequence, perfect resonance can be used to justify the approximate boundary conditions associated with the single-particle, energy band theory, developed by Bloch, which is the basis of heat and charge transport in solids, with the understanding that the theory actually can be applied even in situations in which the crystal lattice that is used has finite extent, provided the energies of the various states that are used are all very close to each other in value. As I have pointed out elsewhere[1-5] the associated conditions are guaranteed to apply to the full many-body Hamiltonian when the initial and final states involve many particles, provided the energies of the states involve the ground state, and the lowest-lying excitations, which, by construction, are all required to be related to each other through rigid Galilean transformations, in which all of the "particles" are allowed to move at once, rigidly, without the separation between any particle and the remaining particles being altered. As a consequence, as opposed to justifying conventional band theory, using stationary, bound, eigenstates of an approximate single-particle Hamiltonian, the theory can be viewed as a near-resonance limit, involving the full Hamiltonian, as it applies to a periodically ordered, finite lattice that is allowed to move rigidly within the interior of a solid, and the associated eigenstates are wave function "resonant states" that preserve periodic order. Because, in fact, it is never possible to determine the boundary of a solid[4,5], formally, the associated picture can be viewed as a definition. This alternative perspective justifies, formally, the implications of the initial ion band state model model[12], in which an approximate "Fermi Golden" rule fusion rate calculation and the possibility of overcoming the "Coulomb Barrier" was inferred from approximate eigenstates, derived from a two-body d-d wave function, that possesses Bloch symmetry (similar to the comparable symmetry that occurs when non-interacting d's occupy ion band states[12] in both its dependence on its center-of-mass and relative d-d separation variables). In this model, the Fermi Golden rule is used to evaluate the fusion reaction rate, using initial and final states, that only change in regions (which are located at the interior boundaries of the ordered lattice) where nuclear overlap takes place, based on the assumption that in both the initial and final states, the same wave function applies in regions where overlap does not take place but as the separation variable either vanishes or its magnitude approaches the magnitude of a Bravais Lattice vector, overlap becomes possible by allowing the change in momentum to become infinite. When the d-concentration is sufficiently small, this assumed, asymptotic, energy-minimizing solution satisfies a resonant condition, while the Fermi Golden Rule rate expression occurs through nearly-resonant forms of collisions, associated with small (infinitesimal) perturbations, in the zero of energy of the electromagnetic potential, defined by Eq. 1, in regions where nuclear overlap can occur, both in interior and external regions of the lattice. This initial calculation of fusion rate is justified only when the energy per unit cell is on the order of the smallest (optical) phonon energies (~20 meV) which means the lattice must have 23.8 MeV/0.02 eV~10^9 unit cells. However, a considerably smaller lattice size is possible in the presence of very weak externally applied forces. In this case an alternative model, associated with near resonance can take place, in which the zero of momentum adiabatically changes, without exciting the system. This can occur provided the effective change in virtual power associated with the process is sufficiently small. In particular, as a function of time, when an external field $\vec{E}$ is applied, nearly resonant fluctuations in the center of mass momentum can take place that can increase in magnitude, with time. When the complete many-body expression is included (through Eq. 1, based on a generalization of multiple scattering theory[1-4]), as the available momentum builds up, virtual collisions can couple resonantly between the lowest lying excitations of the solid when the product of the force ($e\vec{E}$) on each d, associated with "a collision," with the time *t* that is involved (which, in one dimension, for example defines a particular momentum $p(t)=e\vec{E}t$) obeys a matching condition (in which, for example, again, in one-dimension, the associated deBroglie wavelength $\lambda_{deBroglie}=\frac{h}{p(t)}=\frac{N}{n}a$; *h*=Planck's constant, n = integer $\leq$ N, 2N=number of lattice sites). In the many-body generalization[4,5], whenever this condition occurs once, it can occur 2N times. In the simplest (one-dimensional) limit, N=n, $2N\lambda_{deBroglie}=a$, and as p(t) increases in time, $\lambda_{deBroglie}$ can approach nuclear dimension. The apparent "simplicity" of this picture involves relating the microscopic physics to the semi-classical limit involving how light interacts with matter. Here, the underlying idea that coherent oscillations of charge that Giuliano Preparata [13] suggested could be important, in the long-wave limit, in the associated interaction is absolutely correct. His observation about this is truly important.

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[11] $\langle Initial|\mathbf{V}|Final\rangle = i\hbar \frac{\partial\langle Initial(t)\,|\,Final(t)\rangle}{\partial t}$ when $\langle Initial(t)|$ and $|Final(t)\rangle$ evolve in time, in the interaction picture representation, when they (as well as the density operator $\rho(r) \equiv \sum_{r_i} \delta(r - r_i)$ and total current operator $j(r)$) evolve in time, in the Schroedinger picture representation, $\langle Initial|\mathbf{V}|Final\rangle$ (which is the same when all quantities are expressed in a common representation) can be expressed using the expression that is shown in Fig.4b.
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