STATUS OF COHERENT FUSION THEORY

Peter L. Hagelstein

Massachusetts Institute of Technology
Research Laboratory of Electronics
Cambridge, Massachusetts 02139

ABSTRACT

Nuclear reactions which may exhibit coherent effects have been studied as a candidate explanation for cold fusion effects.

An analysis of a general class of two-step coherent reactions involving charged nucleons has been performed, and very small reaction rates are found. This result is due to the small tunneling factors associated with coulomb repulsion.

We are investigating two-step coherent reactions which begin through weak interaction mediated electron capture, which in hydrogen isotopes would produce off-shell (virtual) neutrons. No coulomb repulsion occurs for virtual neutrons. Virtual neutron capture by deuterons would yield tritium, and virtual neutron capture by protons would yield deuterons; the latter process is favored by a factor of 10^4 in the square of the matrix element on a per nucleon basis, and corresponds to a heat-producing reaction. The nuclear reaction energy would be coupled into the electrolysis process, with the final reaction products stationary.

We have found that the weak interaction process can in principle be superradiant in the Dicke sense. If so, then considerable acceleration of this type of coherent reaction may occur.

I. INTRODUCTION

Much controversy has surrounded the area of cold fusion research since its inception last March following the initial papers of Fleischmann and Pons at Utah[1,2] and Jones et al. at BYU[3]. During the months that followed numerous experiments were performed, most of which did not reproduce any of the various "miracles" that have become associated with cold fusion.[4–22] Especially disconcerting was the apparent inability of the principle advocates of cold fusion to reproduce their own results.

Based on these points, and based also on the complete lack of any supporting theory or basic mechanism, the scientific community views cold fusion research of any sort with extreme skepticism. The ERAB review board[23] politely summarized this position with the comment: "Based on these many negative results and the marginal statistical significance of reported positive results, the Panel concludes that the present evidence for the discovery of a new nuclear process termed cold fusion is not persuasive." *Nature* has gone further and has published a number of obituaries for cold fusion.[24–26]

The arguments that have been given for the fundamental unsoundness of cold fusion research in general are numerous. Among them is the basic physics problem associated with overcoming the coulomb barrier at room temperature, and accounting for heat with no apparent nuclear byproducts. Additionally, the positive cold fusion results appear to be in direct contradiction to very basic precepts of nuclear physics, and it seems that an extremely fundamental and totally unexpected change in our understanding of physics would be required even to begin accounting for the various "miracles" that have been claimed. Finally, it has been remarked in private countless times that the single strongest argument against cold fusion is that the experimental effects simply vanish whenever a competent physicist performs the relevant measurements with adequate instrumentation, and that anyone claiming to observe a positive result is self-deluding.

D. Morrison is studying the progress of cold fusion as an example of pathological science.[27]

In spite of the views of the majority of physicists, positive experimental results in support of anomalous effects persist (as described in a recent review by Bockris[28]). Evidence for very substantial excess heat generation in closed system calorimetry experiments has been obtained at

Stanford.[29] The isoperibolic calorimeter is simple and well-calibrated; the error bars are at the 1 % level, and the signals exceed 20 %. This evidence is compelling. Observations of heat have been reported by numerous other laboratories.[30–37]

Perhaps the strongest evidence for substantial tritium production comes from Texas A&M.[38] Additionally, tritium production has been reported numerous times.[39–44] Neutron emission in electrolysis cells has been reported by BYU,[3] and has been claimed at other laboratories.[33,45,46] Neutron emission in gas cells has been reported by Frascati[47] (who have recently seen more neutrons[48]), LANL,[40,49] and elsewhere.[50] Fast protons have been reported in Ref. 51.

Heat bursts have been reported by many workers. Pons and Fleischmann reported early on in their work that a cubic centimeter cube exploded. Bockris mentions exploding rods in his review. Extreme heat production was reported by Gozzi et al.,[52,53] in a non-reproduced experiment.

There are proponents of cold fusion and there are skeptics. The skeptics have demonstrated that no cold fusion effects occur. The proponents have answered most if not all of the skeptics criticisms with respect to experimental methodology, and have demonstrated that the effect is real. Unfortunately the skeptics and proponents rarely meet and discuss physics, and this is very unfortunate for all involved.

We have adopted the position of devil's advocate (relatively). We have looked at the problem from the point of view that the effect may both be real and be all that was originally claimed for it, and from there inquired how it could possibly come about, without breaking basic physical laws in the process. The current experimental evidence from the proponents largely supports such a view, even at this late date after the obituaries have appeared in print.

We have speculated given the assumptions that the heat is real and of nuclear origin. It seems to follow that if the heat is real and accurately measured, that it must be nuclear since the total energy production that is reported would correspond to more than 10 eV per atom of electrode. Additionally, if the tritium production is real, it most certainly involves nuclear processes since tritium cannot be made chemically. Finally, if the neutrons are real, then they too would provide evidence for the occurrence of a nuclear process.

But what nuclear process? Certainly conventional binary nuclear reactions cannot do it, for two compelling reasons: (1) there is no way known to overcome the coulomb barrier at room temperature to the degree required under electrolysis conditions, and (2) there is no experimental support for any known conventional reaction that can produce either heat or tritium as it is reportedly produced.

Furthermore, if the tritium is real at the levels reported, and if it is actually produced with a low accompanying secondary 14 MeV neutron emission rate that is smaller by many orders of magnitude as is reported, then it implies a very severe constraint on the final state tritium kinetic energy that may occur. This constraint is described in this paper, and more or less implies that no conventional binary fusion reaction is likely to be responsible, since the tritium which is produced is essentially sitting still by nuclear standards.

Another constraint must be obeyed by any nuclear reaction that is proposed to account for the "miracles." Not only do the reactions have to be consistent with the observed stability of heavy water and deuterium gas not involved in cold fusion experiments, but they must be consistent with stellar evolution models. The existence of a binary fusion reaction that occurs at room temperature would in all probability be impossible to reconcile with stellar models at higher temperatures.

Our general approach has been to explore what we have termed coherent nuclear reactions. These are proposed reactions that would proceed collectively due to some unique feature of the reaction, and occur only rarely as incoherent or binary reactions. Such reactions certainly can be postulated and are certainly physical, but most occur with an utterly negligible reaction rate. To our knowledge there is no previous work or speculation on such reactions; aside from the recent cold fusion results there would be no motivation aside from curiosity to explore collective nuclear reactions.

Our initial efforts involved the consideration the implications of coherent *dd* reactions between coupled nuclear/lattice states that were degenerate. The idea is interesting, but finding microscopic mechanisms that support such a picture has been difficult. We analyzed a rather general class of coherent fusion reactions between charged hydrogen isotopes, and we were able to show that all such reactions in general occur with reaction rates that are quite small. The basic problem is that the matrix elements between initial and final states are too small due to exponentially small tunneling factors to support reaction rates in the range of those reported.

One solution to this very general problem is to consider coherent reactions wherein the fusion occurs between a neutral nucleon (neutron) and a charged nucleon. The weak interaction can provide a mechanism to reduce the charge of a hydrogen isotope, and the resulting problem becomes one of studying virtual neutron states, since the process is by necessity off-shell. A weakness of the approach is that one very difficult problem is replaced by another very difficult problem: that off-shell neutrons almost never stray far from their point of origin.

A second perceived weakness of the approach is that a reaction that begins with a weak interaction matrix element is probably going to be vanishingly small. We have found, or so we believe, an interesting situation in which a coherence effect has the potential to enhance neutrino emission (and therefore the effective strength of the weak interaction) by a large factor. This effect can be described briefly as Dicke superradiance of neutrinos. If it occurs, a condition that must be obeyed is that the final nucleon states be stationary. This condition is consistent with the constraint imposed by the low neutron emission observations during heat generation and tritium production. In order for this to occur, the nuclear energy must be transferred elsewhere in a nondisruptive manner, a process which has no precedent in nuclear physics.

This is our general approach, and the specific scenario that we envision is one in which deuterons generate virtual neutrons through electron capture and coherent neutrino emission, and heat and tritium generation occurs through virtual neutron pickup by protons and deuterons. The nuclear energy is transferred to the macroscopic level coherently through M1 interaction of the nuclear dipoles with the current in the presence of a high order nonlinearity. Protons are substantially more reactive than deuterons in virtual neutron pickup as is discussed later in this work (section VI).

The fuel for heat production in this scenario are protons, deuterons and electrons; the palladium is in a sense a catalyst by virtue of its electrochemical and magnetic properties. The byproducts of the reaction are deuterons and soft neutrinos (which are probably unobservable), and the deuterons are born stationary. This scenario is qualitatively consistent with many of the reported observations. The process would not occur in stars due to the coherency and current requirements. It remains to be seen whether the scenario can become a predictive theory.

The remainder of this report is divided up as follows: In section II we consider the implications of the low values of observed neutron emission. We review the basic reactions that we have considered during this work in Section III. The relative strengths of M1 matrix elements for slow neutron pickup by protons and deuterons is considered in Section IV. We show that neutrino emission can occur coherently in section V; and we discuss the coupling of energy from the microscopic to the macroscopic in section VI. We provide further discussion in Section VII. Proposals for experiments that would help elucidate reaction mechanisms within the framework of our scenario are given in Section VIII.

We will not discuss other theoretical approaches in this paper. A very critical article[26] by Lindley summarizes the most popular models and their drawbacks.

II. LIMITS ON THE KINETIC ENERGY OF FINAL PRODUCTS

Consensus is appearing among some cold fusion experimentalists regarding upper bounds on neutron production when either heat or tritium is observed. It is found at numerous laboratories that the neutron production rate occurs at a rate which is less than 10^{-8} of the rate at which tritium production occurs. A stronger bound occurs in the case of heat production, under the assumption that heat producing reactions evolve MeV-level energy per reaction.

Such upper bounds imply a maximum kinetic energy possible for final state reaction products. In conventional exothermic fusion reactions, the nuclear energy released appears as kinetic energy of the products or as gamma radiation. There are no reports of the observation of gamma emission from any cold fusion experiments, and the bounds on neutron emission can be used to limit directly the final reaction product kinetic energy.

If tritium is created initially at high (MeV) kinetic energy, then the probability that a DT reaction which produces a 14 MeV neutron occurs can be computed from the yield formula to be in the vicinity of $10^{-5} - 10^{-4}$ per triton. In order to obtain a neutron to triton ratio which is as low as 10^{-8}, the emitted triton energy must be quite low. We have estimated the neutron yield for fast tritons in a deuterated palladium lattice from

$$Y(E) = \int_0^\infty N_D \sigma_{DT}(\epsilon) \left[\frac{d\Delta E}{dx}\right]^{-1} d\epsilon \quad (II.1)$$

following Batra et al[54] and Armstrong et al[55], where N_D is the deuterium number density, and σ_{DT} is the fusion cross section. We have adopted the range data of Janni[56] for palladium. The result is shown in Figure 1. A neutron yield of 10^{-8} would correspond to an upper limit on tritium kinetic energy of about 25 keV.

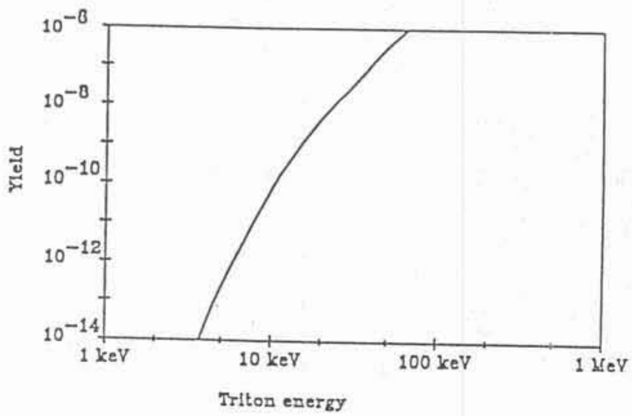

Figure 1: Yield of 14 MeV DT neutrons through fusion of fast tritons in deuterated palladium as a function of triton energy.

A point of interest here is that the neutrons which have been reported to date are not consistent with 14 MeV emission, but rather the observed neutrons are thought to be 2 MeV neutrons (consistent with dd fusion neutrons). If so, then the relevant constraint on 14 MeV neutron yield emission is more severe, and bounds the maximum triton kinetic energy to even smaller values. Kevin Wolf at Texas A&M estimates that this bound can currently be taken to be 15 keV.[57]

The relative lack of neutron emission can be used to rule out essentially all known nuclear fusion reactions which evolve tritium, even if some mechanism were found to overcome the coulomb barrier. Furthermore, any proposed theoretical explanations for Pons-Fleischmann effects (heat and tritium) should be consistent with these observations.

We have considered the possibility that heat production occurs through virtual neutron capture by protons. The end product of such a capture process would be a deuteron, and the above arguments can be repeated to obtain an upper limit on the deuteron kinetic energy. The yield formula

$$Y(E) = \int_0^\infty N_D \sigma_{DD}(\epsilon) \left[\frac{d\Delta E}{dx}\right]^{-1} d\epsilon \quad (II.2)$$

was evaluated using the dd cross section of Brown and Jarmie[58], and the result is shown in Figure 2. One is tempted to apply this yield formula to the original Pons-Fleischmann data, and take the upper bound on neutron yield from Ref. 4. This gives an upper bound on neutron yield on the order of 10^{-11}. By itself, this would give an upper bound of less than 20 keV for a deuteron kinetic energy, under the two assumptions that the Pons-Fleischmann heat is real and that deuteron production is responsible.

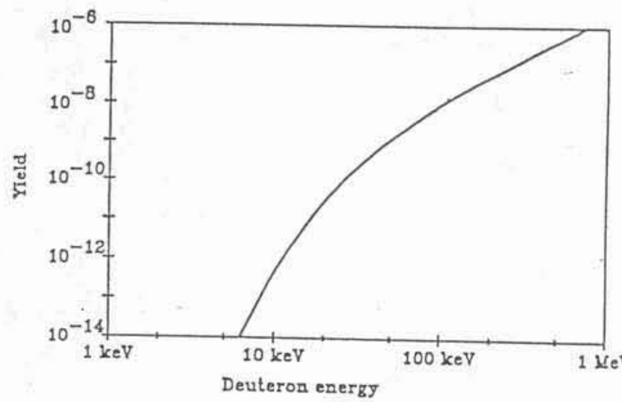

Figure 2: Yield of 2.4 MeV DD neutrons through fusion of fast deuterons in deuterated palladium as a function of triton energy.

III. SUMMARY OF REACTIONS EXAMINED

In the course of our efforts, we have focussed on the general notion that collective effects may be involved.[59] This notion will be illustrated in the examples under discussion. We have looked for effects which involve primarily deuterium and protons.

A. $d + d \longleftrightarrow {}^4He$

The initial report of Pons and Fleischmann proposed that *dd* fusion was responsible for the effects, and we considered initially what would be required for this to occur. One idea was that a lattice under stress might show multiphonon response in the MeV range due to fractures, and that in some way the electromagnetic interaction could get the energy out coherently at an enhanced rate.

The principal drawback to this approach is the exponentially damped electric quadrupole moment between initial and final states due to the Coulomb barrier between nucleons.

B. Fusion/Beta Two step reactions: $p + d \longleftrightarrow ({}^3He)_V \rightarrow t + e^+ + \nu_e$

Two step reactions in which fusion is followed by an incoherent decay process have the possibility of behaving coherently if the exchanged photon is soft. We were able to formulate a many-body theory for this class of reaction based on the analogy with laser physics models. We found that the model was mathematically tractable but that all effects due to this type of reaction were quite small due to the small electromagnetic moment between initial and final fusing states. In essence, if there were some way to enhance the tunneling, then coherent two-step reactions of this type might occur. The detailed analysis of such processes is documented in our ASME paper.

C. Beta/Fusion Two-step Reactions: $d + e + 2p \longrightarrow (\nu_e + 2n + 2p)_V \longleftrightarrow \nu_e + 2d + 2.05\ MeV$

The exponential inhibition of fusion reactions due to the coulomb barrier is responsible for the general view among physicists that no cold fusion effects are possible in spite of supporting experimental results. If weak interaction electron capture by a deuteron occurs first, then the fusion reaction is between a neutral and charged nucleus, with no accompanying coulomb barrier. The price to be paid for this is twofold: the weak interaction is not so large of an effect, and the intermediate states with neutrons present is virtual. The detailed analysis of this reaction as an incoherent process is straightforward, and one finds that the range of the virtual neutrons is measured in tens of fermis.

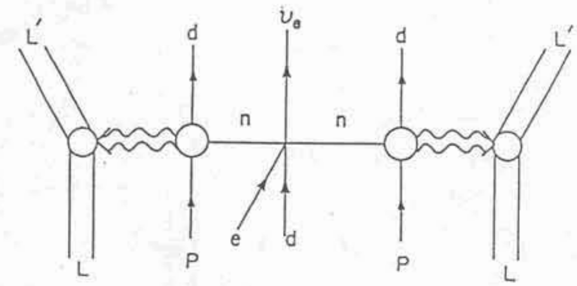

Figure 3: Feynman-like diagram for the proposed heat-producing two-step *depp* reaction.

We have been exploring a coherent version of this reaction as a many-particle process. The most interesting result which we have found is the possibility that the neutrino emission has the potential to be superradiant in the Dicke sense. In order to reach maximum superradiance, the fusion states would have to retain phase coherence, which is consistent with the requirement that the final states be stationary.

IV. MAGNETIC DIPOLE STRENGTHS

One approach towards developing an explanation for tritium production is to adopt a scenario in which tritium is formed through the capture of a neutron by deuterium. One proposed version of this reaction is

$$d + e + p + d \longrightarrow (2n + \nu_e + p + d)_V \longrightarrow \nu_e + d + t$$

We are interested in the strength of this reaction in comparison with the strength of the *depp* reaction mentioned above. An examination of the known slow neutron capture cross sections leads to the conclusion that virtual neutron capture by protons is favored over capture by deuterons by a moderately large factor. We conjecture that the magnetic dipole matrix element for neutron capture by protons is larger than for any other system by a large factor as well, and we have concluded this based on an examination of a relatively small number of capture cross sections.

Our approach will be very simple; we shall view the capture process as a radiative decay from an extended bound state. For example, in the presence of a magnetic field, neutrons of the appropriate spin polarization will see an attractive potential which is very weak. For low enough neutron energy, bound states will exist (although they will be unstable to collisions by thermal nucleons). Such states will decay radiatively according to

$$\gamma_R = \frac{4}{3}\frac{\omega^3}{\hbar c^3}\frac{1}{(2J_u+1)}\left|\langle\Gamma_u J_u\middle|\middle|\mu\middle|\middle|\Gamma_l J_l\rangle\right|^2 \quad (IV.1)$$

where $\left|\Gamma_u J_u\right\rangle$ denotes the upper state in which the neutron is relatively delocalized, and $\left|\Gamma_l J_l\right\rangle$ denotes the lower state in which neutron capture has occurred. By necessity for these arguments, these states are many-particle states.

The radiative decay rate is related to the capture cross section through

$$\gamma_R = N\sigma_c(v)v \quad (IV.2)$$

where N is the number density of target nucleons, and $\sigma_c(v)$ is the capture cross section into the ground state. For M1 capture of neutrons by protons and deuterons, the capture cross sections vary as $1/v$ at low energy.

It follows that the reduced matrix element can be related to the capture cross section through

$$\frac{1}{N}\frac{1}{(2J_u+1)}\left|\langle\Gamma_u J_u\middle|\middle|\mu\middle|\middle|\Gamma_l J_l\rangle\right|^2 = \frac{3}{4}\frac{\hbar c^3}{\omega^3}\sigma_c(v)v \quad (IV.3)$$

We may define a single particle reduced matrix element in terms of the left hand side

$$\frac{|\langle u\,||\,\mu\,||\,l\rangle|^2}{(j_u+1)} = \frac{1}{N}\frac{1}{(2J_u+1)}\,|\,\langle\Gamma_u J_u\,||\,\mu\,||\,\Gamma_l J_l\rangle\,|^2 \quad (IV.4)$$

which can be used to obtain a ratio of the reduced matrix elements for neutron capture by protons and deuterons.

$$\frac{(2j_{np}+1)^{-1}\,|\,(np\,||\,\mu\,||\,d)\,|^2}{(2j_{nd}+1)^{-1}\,|\,(nd\,||\,\mu\,||\,t)\,|^2} = \left(\frac{\omega_t}{\omega_d}\right)^3\frac{(\sigma_c v)_d}{(\sigma_c v)_t} \quad (IV.5)$$

Experimental measurements on slow neutron capture by protons have yielded a value of the capture cross sections for room temperature neutrons (2200 m/sec) which we may use

$$(\sigma_c v)_d = (3.342\times 10^{-25}cm^2)(2.200\times 10^5\frac{cm}{sec})$$

$$= 7.35\times 10^{-20}cm^3/sec \quad (IV.6)$$

from Cox et al[60] (for a theoretical examination of this, see Mathiot[61]). For neutron capture by deuterons, and similar estimate gives

$$(\sigma_c v)_t = (5.7\times 10^{-28}cm^2)(2.200\times 10^5\frac{cm}{sec})$$

$$= 1.25\times 10^{-22}cm^2/sec \quad (IV.7)$$

where we have used the somewhat dated value from Kaplan et al[62], which is in rough agreement with the CRC value of $5.1\times 10^{-28}cm^2$.

The ratio of (IV.5) actually requires channel specific cross sections to be valid. Neutron pickup by a proton requires a singlet initial state, and so we may require this unique channel in our ratio. Neutron capture by a deuteron involves two channels, and we do not have data for the two channels individually. In order to get a general estimate, we shall take the deuteron capture quantities to imply an averaged sum, and we then obtain for the ratio of (IV.5)

$$\frac{(2j_{np}+1)^{-1}\,|\,(np\,||\,\mu\,||\,d)\,|^2}{(2j_{nd}+1)^{-1}\,|\,(nd\,||\,\mu\,||\,t)\,|^2} = \left[\frac{6.25MeV}{2.22MeV}\right]^3\left[\frac{7.35\times 10^{-20}}{1.25\times 10^{-22}}\right] = 1.3\times 10^4 \quad (IV.8)$$

This ratio is relatively independent of photon energy, and would be valid in the limit that the emitted photons are soft. The key result here is that protons would be substantially more reactive in terms of accepting a virtual neutron in a coherent fusion model than deuterons. It is this point which has focused our attention on the importance of protons in our coherent fusion work.

The two step beta/fusion reaction under discussion is essentially a generalized neutron transfer reaction, which is proposed to deposit S-wave neutrons in the ground state of an isotope through an M1 transition. Reactions in which a neutron is transferred into an s-orbital of an acceptor isotope are of most interest. Candidate 1s orbital isotopes are presented in Table I. It is observed that out of the three possible candidates, two are implicated in the present scenario. We have not yet obtained an estimate of the gamma channel of the low energy neutron-^{3}He reaction, so we are not in a position to predict how strongly ^{3}He would react relative to protons or deuterons.

Isotope	Abundance	$(J_i)^{\pi_i}$	$(J_f)^{\pi_f}$	τ_f	Q(MeV)
^1H	99.985 %	$(\frac{1}{2})^+$	$(1)^+$	∞	2.32
^2H	0.015 %	$(1)^+$	$(\frac{1}{2})^+$	12.26 y	6.16
^3He	0.00014 %	$(\frac{1}{2})^-$	$(0)^+$	∞	20.58

Table I: Parameters for slow neutron pickup mediated by M1 electromagnetic transitions to nuclear 1s orbitals.

Candidate 2s orbital isotopes are given in Table II. Of interest in the list is silicon, which was used in Claytor's tritium experiments and which is the subject of a number of undocumented reports concerning Wada's neutron experiments. Also of interest is ^{31}P, which would be activated to ^{32}P upon capture of a neutron; the product is radioactive with a half-life of 14 days (the decay mode is β^- with a 1.7 MeV energy), which would make a useful marker for autoradiography experiments. If we assume that the branching ratio is 0.7 % from Lycklama and Kennet,[63] and adopt the CRC value of 0.233 b for the total thermal neutron cross section, then we obtain a partial cross section of 1.6 mb. The ratio of equation (IV.8) evaluates to about 9.4×10^3 for ^{31}P, which is similar to that for deuterium. Hence, if the scenario is right, then we might hope to activate phosphorous as a second order effect (on par with tritium production) if P is present in quantity.

Isotope	Abundance	$(J_i)^{\pi_i}$	$(J_f)^{\pi_f}$	τ_f	Q(MeV)
^{26}Mg	11.01%	$(0)^+$	$(\frac{1}{2})^+$	9.45m	6.44
^{28}Si	92.23	$(0)^+$	$(\frac{1}{2})^+$	∞	8.47
^{29}Si	4.67	$(\frac{1}{2})^+$	$(0)^+$	∞	10.61
^{31}P	100.	$(\frac{1}{2})^+$	$(1)^+$	14.28d	7.94

Table II: Parameters for slow neutron pickup mediated by M1 electromagnetic transitions to nuclear 2s orbitals.

The branching ratios for slow neutron capture in ^{29}Si have been given by Beard and Thomas.[65] The partial cross sections for capture of thermal neutrons to the ground state of ^{30}Si can be estimated to be 0.26 mb.

Although we have assembled a table of candidate transitions for slow neutron capture into 3s neutron orbitals,[66] the resulting table is moderately long due to the mixing of the 3s orbital with other neutron shells. The list includes isotopes between Cd and Ba. Of most interest may be the cadmium and tin isotopes, which include a small number which are unstable following neutron activation (for example, ^{112}Sn lead to ^{113}Sn with a half-life of 115 days).

We note that tritium cannot be an acceptor in this scenario.

The spin flip transitions under discussion here can proceed in principle coherently, in which case there can arise an N^2 factor associated with the coherence. It is this effect which is proposed to account for the observation that deuterons are favored over protons as sources of virtual neutrons. We expect that such processes would be enhanced by net nuclear spin polarization locally, which would follow from electronic spin polarization.[67–69] Unfortunately the case is not strong for this since the magnetic susceptibility is known to be very low in PdD_x at high loading.[70–71] A reduction in hopping at high loading would improve coherence and may provide a rationalization of the observed loading requirements.

V. COLLECTIVE EFFECTS IN NEUTRINO EMISSION

In this section we shall explore a semi-classical model of neutrino emission. This analysis is motivated by analogous models for photon emission in quantum electronics. Starting from QED, an evolution equation for the expectation value of the electric and magnetic fields can be developed readily. The equations obeyed by the averages are Maxwell's equations, and the source terms are found explicitly in terms of averages of the quantum equivalents of the classical sources.[72–75]

Neutrino emission can in principle be viewed analogously. The expectation value of the neutrino field obeys the Weyl equation with a source term, and this model is in essence a semiclassical model for neutrino emission in the quantum electronics sense. This semi-classical model can be used to explore conditions under which neutrino emission occurs as a collective process. The motivation for this analysis is that the phenomenon of Dicke superradiance is accounted for within the framework of the semiclassical model for electromagnetics, and it follows that neutrino emission may show an equivalent effect.

It is known that neutrinos can participate in coherent phenomenon. Based on the analogy with photons, Weber suggested that neutrinos would scatter coherently proportional to N^2 the number of scatters in a crystal.[76–77] A detector based on this principle has been constructed and there is evidence for the detection of neutrinos.[78] The extension to coherent emission of neutrinos is straightforward conceptually.

Our starting point is the Dirac equation for the classical neutrino field, which is the expectation value of the field-theoretic neutrino field operator. This equation is

$$\left[i\hbar\frac{\partial}{\partial t} - \alpha\cdot c\mathbf{p}\right]\psi_\nu = \frac{1}{\sqrt{2}}s_\nu \qquad (V.1)$$

where s_ν is the semiclassical neutrino source function, analogous to electromagnetic polarization. The semiclassical source function s_ν is

$$s_\nu(\mathbf{r},t) = \langle gC_V\sum_i \tau_i^{(-)}\delta^3(\mathbf{r}-\mathbf{r}_i)(1+\gamma_5)\gamma_4\hat{\psi}_e\rangle + \langle gC_A\sum_i \sigma_i\tau_i^{(-)}\delta^3(\mathbf{r}-\mathbf{r}_i)(1+\gamma_5)\sigma\gamma_4\hat{\psi}_e\rangle \quad (V.2)$$

where the expectation value is over a macroscopic lattice.

If we adopt a Furry picture for the electron field operator, where the potential is taken to be due to many nucleii in a lattice, then the individual electron orbitals which are converted are Bloch waves. If we define the expectation value to be between a state with an electron present in a Bloch state Γ_j and a state with no electron present, then we may write

$$s_j(\mathbf{r},t) = gC_V\langle\sum_i \tau_i^{(-)}\delta^3(\mathbf{r}-\mathbf{r}_i)\rangle(1+\gamma_5)\gamma_4\psi_j(\mathbf{r},t) + gC_A\langle\sum_i \tau_i^{(-)}\sigma_i\delta^3(\mathbf{r}-\mathbf{r}_i)\rangle\cdot(1+\gamma_5)\sigma\gamma_4\psi_j(\mathbf{r},t) \quad (V.3)$$

The electron orbitals which have strong overlap with the deuterons will be well described in a non-relativistic approximation. In this case we may take the 4-vector $\psi_j(\mathbf{r},t)$ and break it down into two components

$$\psi_j(\mathbf{r},t) \approx \begin{bmatrix} \phi_j(\mathbf{r},t) \\ \frac{\sigma\cdot c\mathbf{p}}{2mc^2}\phi_j(\mathbf{r},t) \end{bmatrix} \qquad (V.4)$$

It follows that

$$(1+\gamma_5)\gamma_4\phi_j(\mathbf{r},t) \approx \begin{bmatrix} (I+\frac{\sigma\cdot c\mathbf{p}}{2mc^2})\phi_j(\mathbf{r},t) \\ -(I+\frac{\sigma\cdot c\mathbf{p}}{2mc^2})\phi_j(\mathbf{r},t) \end{bmatrix} \qquad (V.5)$$

and

$$(1+\gamma_5)\sigma\gamma_4\phi_j(\mathbf{r},t) \approx \begin{bmatrix} \sigma(I+\frac{\sigma\cdot c\mathbf{p}}{2mc^2})\phi_j(\mathbf{r},t) \\ -\sigma(I+\frac{\sigma\cdot c\mathbf{p}}{2mc^2})\phi_j(\mathbf{r},t) \end{bmatrix} \qquad (V.6)$$

The form of these formulas shows explicitly the choice of helicity of the neutrino source. A unitary transformation can be used to simplify the computation

$$\begin{bmatrix} \phi_\nu \\ \chi_\nu \end{bmatrix}' = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} \phi_\nu \\ \chi_\nu \end{bmatrix} \qquad (V.7)$$

We find that

$$i\hbar\frac{\partial}{\partial t}\begin{bmatrix} \phi_\nu \\ \chi_\nu \end{bmatrix} = \begin{bmatrix} 0 & \sigma\cdot c\mathbf{p} \\ \sigma\cdot c\mathbf{p} & 0 \end{bmatrix}\begin{bmatrix} \phi_\nu \\ \chi_\nu \end{bmatrix} + \frac{1}{\sqrt{2}}\begin{bmatrix} s_\phi \\ s_\chi \end{bmatrix} \qquad (V.8)$$

transforms into

$$i\hbar\frac{\partial}{\partial t}\begin{bmatrix} \phi_\nu \\ \chi_\nu \end{bmatrix}' = \begin{bmatrix} -\sigma\cdot c\mathbf{p} & 0 \\ 0 & \sigma\cdot c\mathbf{p} \end{bmatrix}\begin{bmatrix} \phi_\nu \\ \chi_\nu \end{bmatrix}' + \begin{bmatrix} s_\phi \\ 0 \end{bmatrix} \qquad (V.9)$$

using $s_\chi = -s_\phi$. We may therefore simplify our analysis, and use the Weyl equation with a source

$$\left[i\hbar\frac{\partial}{\partial t} + \sigma\cdot c\mathbf{p}\right]\phi'_\nu = s'_\nu \qquad (V.10)$$

where $s'_\nu = s_\phi$.

We shall henceforth omit the primes and work with unprimed variables. The source term will in general have a distribution of frequencies. If we assume that the frequencies are discrete, then

$$s_j(\mathbf{r},t) = \sum_l s_{jl}(\mathbf{r})e^{i\omega_l t} \qquad (V.11)$$

and (V.10) becomes

$$[\hbar\omega_l + \sigma \cdot c\mathbf{p}]\,\phi_{jl}(\mathbf{r}) = s_{jl}(\mathbf{r}) \qquad (V.12)$$

for a component of ϕ_j at ω_l. If we operate on both sides of V.12 with $[\hbar\omega_l - \sigma \cdot c\mathbf{p}]$, we obtain

$$[\hbar\omega_l - \sigma \cdot c\mathbf{p}]\,[\hbar\omega_l + \sigma \cdot c\mathbf{p}]\,\phi_{jl}(\mathbf{r}) = [\hbar\omega_l - \sigma \cdot c\mathbf{p}]s_{jl}(\mathbf{r}) \qquad (V.13)$$

which can be recast as

$$\left[\nabla^2 + \left(\frac{\omega_l}{c}\right)^2\right]\phi_{jl}(\mathbf{r}) = \frac{1}{\hbar^2 c^2}\left[\hbar\omega_l - \sigma \cdot c\mathbf{p}\right]s_{jl}(\mathbf{r}) \qquad (V.14)$$

It follows that

$$\phi_{jl}(\mathbf{r}) = -\frac{1}{4\pi}\int d^3\mathbf{r}'\frac{e^{i\omega_l|\mathbf{r}-\mathbf{r}'|/c}}{|\,\mathbf{r}-\mathbf{r}'\,|}\frac{1}{\hbar^2 c^2} \left[\hbar\omega_l - \sigma \cdot c\mathbf{p}\right]s_{jl}(\mathbf{r}') \qquad (V.15)$$

In the far-field we may approximate (V.15) by

$$\phi_{jl}(\mathbf{r}) \longrightarrow -\frac{\omega_l}{4\pi\hbar c^2}\frac{e^{i\omega_l|\mathbf{r}|/c}}{|\,\mathbf{r}\,|}\int d^3\mathbf{r}'e^{-i\kappa_l\cdot\mathbf{r}'} [I + i\frac{\sigma\cdot\nabla'}{|\,\kappa_l\,|}]s_{jl}(\mathbf{r}') \qquad (V.16)$$

where

$$\kappa_l = \frac{\omega_l}{c}\frac{\mathbf{r}}{|\,\mathbf{r}\,|} \qquad (V.17)$$

and where the radiator is assumed centered at $\mathbf{r} = 0$.

The total emission rate of neutrinos is

$$\Gamma_\nu = \sum_j\sum_l c\int d\Omega\;|\,\phi_{jl}(\mathbf{r})\,|^2|\,\mathbf{r}\,|^2 \qquad (V.18)$$

which is expanded out to be

$$\Gamma_\nu = \sum_j\sum_l\frac{\omega_l^2}{16\pi^2\hbar^2c^3}\int d\Omega\left|\int d^3\mathbf{r}'e^{-i\kappa_l\cdot\mathbf{r}'} \left[I + \frac{\sigma\cdot\nabla'}{|\,\kappa_l\,|}\right]s_{jl}(\mathbf{r}')\right|^2 \qquad (V.19)$$

We shall define the function

$$\zeta_{jl} = \int d^3\mathbf{r}'e^{-i\kappa_l\cdot\mathbf{r}'}\left[I + i\frac{\sigma\cdot\nabla'}{|\,\kappa_l\,|}\right]s_{jl}(\mathbf{r}') \quad (V.20)$$

and split it into Fermi and Gamow-Teller terms

$$\zeta_{jl} = \zeta_{jl}^V + \zeta_{jl}^A \qquad (V.21)$$

Explicitly, we have

$$\zeta_{jl}^V = \int d^3\mathbf{r}'e^{-i\kappa_l\cdot\mathbf{r}'}\left[I + i\frac{\sigma\cdot\nabla'}{|\,\kappa_l\,|}\right] gC_V\langle\sum_i\tau_i^{(-)}d^3(\mathbf{r}'-\mathbf{r}_i)\rangle_{jl}\left[I + \frac{\sigma\cdot c\mathbf{p}}{2mc^2}\right]\phi_j(\mathbf{r}') \qquad (V.22)$$

and

$$\zeta_j^A = \int d^3\mathbf{r}'e^{i\kappa_l\cdot\mathbf{r}'}\left[I + i\frac{\sigma\cdot\nabla'}{|\,\kappa_l\,|}\right] gC_A\langle\sum_i\tau_i^{(-)}\sigma_i\delta^3(\mathbf{r}'-\mathbf{r}_i)\rangle_{jl}\sigma(I + \frac{\sigma\cdot c\mathbf{p}}{2mc^2})\phi_j(\mathbf{r}') \qquad (V.23)$$

The electron orbitals are Bloch orbitals, and are composed of the product of an oscilltory and periodic term.

$$\phi_j(\mathbf{r}) = e^{i\mathbf{k}_j\cdot\mathbf{r}}u_j(\mathbf{r}) \qquad (V.24)$$

We are in a position to integrate (V.22) and (V.23) with respect to $\mathbf{r}'$. We note that

$$\int d^3\mathbf{r}'e^{-i\kappa_l\cdot\mathbf{r}'}\left[I + i\frac{\sigma\cdot\nabla'}{|\,\kappa_l\,|}\right]f(\mathbf{r}') = \int d^3\mathbf{r}'\left[[I - i\frac{\sigma\cdot\nabla'}{|\,\kappa_l\,|}]e^{i\kappa_l\cdot\mathbf{r}'}\right]f(\mathbf{r}') \qquad (V.25)$$

from which it follows that

$$\zeta_{jl}^V = gC_V\langle\sum_i\tau_i^{(-)}e^{i(\mathbf{k}_j-\kappa_l)\cdot\mathbf{r}_i}\rangle_{jl}[I + \sigma\cdot\hat{\kappa}_l]u_j(0) \qquad (V.26)$$

where $u_j(0)$ is the value of the periodic part of the Bloch wave at the deuteron nucleus. In this formula we have dropped the electron spin-orbit term. Similarly we have

$$\zeta_{jl}^A = gC_A \langle \sum_i \tau_i^{(-)} \sigma_i e^{i(\mathbf{k}_j - \kappa_l)\cdot \mathbf{r}_i} \rangle_{jl} [I + \sigma \cdot \hat{\kappa}_l] \sigma u_j(0) \quad (V.27)$$

We define the generalized Fermi and Gamov-Teller expectation values

$$M_{jl}^F(\mathbf{k}_j - \kappa_l) = \langle \sum_i \tau_i^{(-)} e^{i(\mathbf{k}_j - \kappa_l)\cdot \mathbf{r}_i} \rangle \quad (V.28)$$

and

$$M_{jl}^{GT}(\mathbf{k}_j - \kappa_l) = \langle \sum_i \tau_i^{(-)} \sigma_i e^{i(\mathbf{k}_j - \kappa_l)\cdot \mathbf{r}_i} \rangle \quad (V.29)$$

which allows us to write

$$\zeta_{jl}^V = gC_V M_{jl}^F(\mathbf{k}_j - \kappa_l)[I + \sigma \cdot \hat{\kappa}_l] u_j(0) \quad (V.30)$$

and

$$\zeta_{jl}^A = gC_A \mathbf{M}_{jl}^{GT}(\mathbf{k}_j - \kappa_l) \cdot [I + \sigma \cdot \hat{\kappa}_l] \sigma u_j(0) \quad (V.31)$$

At this point we are in a position to explore coherent neutrino emission. If the electron momentum and the neutrino momentum coincide, then the Fermi average becomes

$$M_{jl}^F(0) = \langle \sum_i \tau_i^{(-)} \rangle$$

$$= 2\langle T^{(-)} \rangle \quad (V.32)$$

where $T^{(-)}$ is the many-particle isospin operator. The emission of neutrinos with momentum equal to the converted electron momentum can be coherent. We may show this explicitly by considering the Fermi emission rate

$$\Gamma_j^{VV} \mid_{(\mathbf{k}_j - \mathbf{K}_l = 0)} = \frac{\omega_l^2}{4\pi^2 \hbar^2 c^3} g^2$$

$$C_V^2 \mid (I + \sigma \cdot \mathbf{K}_l) u_j(0) \mid^2 \mid \langle T^{(-)} \rangle \mid^2 \quad (V.33)$$

If the many-particle nuclear states are Dicke states, then

$$\mid \langle T^{(-)} \rangle \mid^2 \propto [T(T+1) - M_T(M_T+1)] \quad (V.34)$$

If $\mid M_T \mid$ is much less than $\mid T \mid$, then the neutrino emission will be coherent and proportional to the square of the number of emitters. The physical content of this result is that in the Dicke limit all of the nucleons participate on an equal basis in the neutrino emission process, in phase with one another throughout the lattice. The resulting emission rate can be much larger than N times the single particle incoherent neutrino emission rate.

In order for this process to occur, phase coherence must be maintained between the initial and final states, which implies that the final states must be stationary. This requirement seems to be consistent with the experimental observations of low neutron yield. In order for this to occur the nuclear energy must be transferred elsewhere coherently, and we discuss this problem in the following sections.

VI. COUPLING OF ENERGY FROM THE MICROSCOPIC TO THE MACROSCOPIC

In order to achieve superradiance in the neutrino emission in the coherent scenario, the neutrino energy must be very low (on the order of 1 eV or less), and the final state nucleons must be stationary. The overall reactions of interest are exothermic by multiple MeV, hence the nuclear energy must be deposited elsewhere in a nondisruptive manner in order for coherence to be maintained. Coupling nuclear energy from the microscopic to the macroscopic coherently is unprecedented, and we require a fundamentally new mechanism to do this.

In our earlier efforts, we have proposed coupling of the nuclear energy into phonons in the palladium lattice. The phenomenon of deexcitation of electronic transitions into phonons is known in molecules and solids,[79–83] and the fundamental quantum mechanics seems to be qualitatively similar between these well-known systems and our earlier coherent fusion model. However, in essentially all systems in which a relatively high quantum energy transition is coupled with phonons, the non-radiative processes proceed through at most a relatively small number of phonons at a time. The rate of phonon emission decreases exponentially with increasing number of phonons generated, which is characteristic of a high order emission process.[80] As a result, unless some new and compelling physical mechanism is found, it seems improbable that nuclear energy can be coupled directly to lattice phonons in bunches of 10^7 or more at a nonvanishing rate.

The arguments above apply to radiation of large numbers of quanta in a system which is fundamentally linear or near linear. Phonons within a macroscopic lattice or large molecule are well-described by linear or weakly nonlinear models, which is ultimately why the emission rate is exponentially damped for large numbers of emitted phonons. Radiation of photons into a vacuum is exponentially weak for large number of photons for the same reason. As a result, if we hope to make any progress at all, we must search for a mechanism which is fundamentally nonlinear to very high order in order to avoid exponential extinction of emission rate at high quantum energy.

There are examples of systems which appear to behave in this fashion. One such mechanism is the electrochemical process, as can easily be seen. Consider an electrochemical cell which is driven by a low frequency LC-circuit (an example which we shall focus on in this section), and assume that when in operation gas molecules are generated from chemical species within the electrolyte. The generation of each gas molecule requires a relatively high chemical energy quanta, which must be supplied by relatively low energy electrical quanta from the LC circuit. In order for this to occur, a mechanism must exist which is capable of exchanging a very large number (10^6 to 10^{12}) of electrical quanta for a single chemical quanta. Such a mechanism would have to be nonlinear to extreme order, and in what follows in this section we explore the possible application of this type of nonlinearity to the coherent fusion problem.

We begin by considering the quantization of a simple LC circuit. The Hamiltonian is derived from the classical electric and magnetic field energies

$$H = \frac{1}{2}Cv^2 + \frac{1}{2}Li^2 \qquad (VI.1)$$

which leads to the Schrödinger equation for the probability amplitude

$$i\hbar\frac{\partial}{\partial t}\psi(v,t) = -\frac{\hbar^2}{2LC^2}\frac{\partial^2}{\partial v^2}\psi(v,t) + \frac{1}{2}Cv^2\psi(v,t) \qquad (VI.2)$$

where we have used the current operator

$$i_{op} = -i\frac{\hbar}{LC}\frac{\partial}{\partial v} \qquad (VI.3)$$

The quantization of the LC circuit is of course well known,[84,85] and is usually written in terms of creation and destruction operators as we shall shortly do also. In this form, it is emphasized that the current operator is to within a constant simply a derivative of the voltage. This will be of use later.

In terms of raising and lowering operators, the current and voltage operators are

$$\hat{v} = \sqrt{\frac{\hbar\omega}{2c}}(a^\dagger + a) \qquad (VI.4)$$

$$\hat{i} = -\sqrt{\frac{\hbar\omega}{2L}}\frac{(a^\dagger - a)}{i} \qquad (VI.5)$$

The Hamiltonian for this system is

$$\hat{H}_{LC} = \hbar\omega a^\dagger a \qquad (VI.6)$$

where $\omega = 1/\sqrt{LC}$, and where we have suppressed the zero-point contribution which is not important for our discussion. The eigenfunction solutions for this problem are completely standard, and the energy levels are quantized with a constant spacing of $\hbar\omega$. That the inductance or capacitance might be somewhat nonlinear in the corresponding physical system has no impact on the present arguments. The presence of resistive losses can be included directly using standard techniques of coupling to a heat bath,[84–86] however, such processes play no role in the nuclear coupling process of interest here. We may add such resistive terms to our Hamiltonian at our pleasure; they will show up additively at the end of the computation – hence there is no reason to carry them along here.

We may consider the coupling of the LC circuit to a two-level nuclear system, which is in essence a toy model for virtual neutron capture in our scenario. A full model including superradiant neutrino emission cannot be described as a two-level system, however, if we focus on a two-level system we will have a better chance of elucidating the basic mechanism. A more complete model will have to follow in a future work. The Hamiltonian for the coupled system is

$$\hat{H} = \hat{H}_{LC} + \hat{H}_N + \hat{H}_I \qquad (VI.7)$$

where

$$\hat{H}_N = \frac{\hbar\omega_N}{2}\sum_j (b_j^\dagger b_j - b_j b_j^\dagger) = \frac{1}{2}\hbar\omega_N \hat{\Sigma}_z \quad (VI.8)$$

$$\hat{H}_I = \frac{\partial^2 H}{\partial a \partial b}\frac{(a^\dagger - a)}{i}\sum_j (b_j^\dagger + b_j)$$
$$= \frac{\partial^2 H}{\partial a \partial b}\frac{(a^\dagger - a)}{i}\hat{\Sigma}_x \qquad (VI.9)$$

The Σ_x and Σ_z operators are many-particle "spin" operators, which are used commonly in this type of model. The b and $b^\dagger$ operators are fermionic creation and annihilation operators. The interaction term is appropriate for $-\mu\cdot\mathbf{B}$ coupling where the magnetic field is uniform throughout and where the magnetic field is in the near-field (which couples the nuclear energy directly to current increments). The microscopic coupling links a single energetic spin flip with the creation or destruction of a single current quantum.

This model is simple and can be diagonalized approximately through a unitary transformation:

$$\Psi' = e^{i\hat{R}}\Psi \qquad (VI.10)$$

$$\hat{H}' = e^{i\hat{R}}\hat{H}e^{-i\hat{R}} \qquad (VI.11)$$

The rotation operator which accomplishes this is

$$\hat{R} = \frac{1}{2}\tan^{-1}\left[\frac{2}{\hbar\omega_N}\frac{\partial^2 H}{\partial a \partial b}\frac{(a^\dagger - a)}{i}\right]\hat{\Sigma}_y \quad (VI.12)$$

The resulting Hamiltonian is

$$\hat{H}' = \hat{H}_{LC} + \hat{H}_N' + \hat{H}_I' \qquad (VI.13)$$

where

$$\hat{H}_N' = \frac{1}{2}\hbar\hat{\omega}_n'\hat{\Sigma}_z \qquad (VI.14)$$

$$\begin{aligned}\hat{H}_I &= e^{i\hat{R}}\hat{H}_{LC}e^{-i\hat{R}} - \hat{H}_{LC} \\ &\approx i\left[\hat{R}, \hat{H}_{LC}\right]\end{aligned} \qquad (VI.15)$$

The diagonalization of this Hamiltonian is similar to rotations discussed elsewhere.[87–89]

The coupling term in the rotated picture is very small, and we have achieved a relatively accurate diagonalization through this transformation. One result of this diagonalization is that it becomes apparent that the interaction term, which is of low order, does not help the transfer of net nuclear excitation to a linear circuit. The nuclear quanta can only be transferred in units of 10^n quanta at a time in order to conserve energy, and such processes are exponentially inhibited as remarked upon above. There is some small degree of mixing between the nuclear levels and the oscillator levels which will be of use shortly.

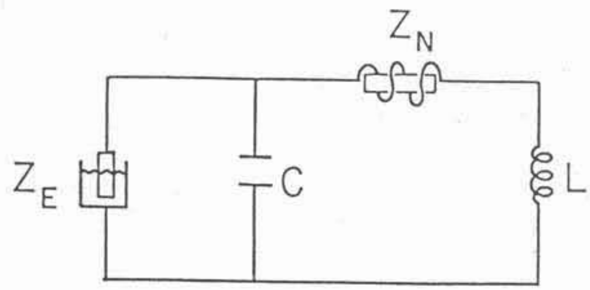

Figure 4: LC circuit couple to a nuclear spin system at high energy and a nonlinear element.

The coupling of the LC circuit to the electrolysis process is to be considered next, and for this we adopt a model Hamiltonian of the form

$$\hat{H} = \hat{H}_{LC} + \hat{H}_N + \hat{H}_I + \hat{H}_E + \hat{H}_C \quad (VI.16)$$

where we include the "bath" for the chemical system through

$$\hat{H}_E = \sum_j \frac{1}{2}\hbar\omega_j(c_j^\dagger c_j - c_j c_j^\dagger) \qquad (VI.17)$$

where c and $c^\dagger$ are fermionic creation and destruction operators relevant to chemical species. The coupling with the chemical bath is accounted for through $\hat{H}_C$, which we conjecture has the form

$$\hat{H}_C = \sum_j \Theta(\hat{v} - v_j)\Delta H_j \qquad (VI.18)$$

The important feature of the coupling Hamiltonian is that is must have an explicit nonlinearity of high order in order for the electrolysis process to be able to convert low energy electrical quanta to chemical quanta. The use of a step function to describe this coupling is conjecture (we expect it to be sharp, be we do not know whether it is sharp to the degree to which we will shortly require). The summation over j in this equation is a summation over available quantum mechanical microscopic channels. A summation over channels weighted by a thermal occupation average of this Hamiltonian would give a nonlinear current-voltage characteristic which is more gentle and locally linear.

If we apply a unitary transformation to diagonalize the coupling between the nucleii and the current to first order in the presence of the electrochemical terms, we obtain a new and very interesting term due to the resulting commutation. If we rotate:

$$\hat{H}' = e^{i\hat{R}} \hat{H} e^{-i\hat{R}} \qquad (VI.19)$$

using the transformation described above, then we obtain

$$\hat{H}' = \hat{H}'_{LC} + \hat{H}'_N + \hat{H}'_I + \hat{H}'_E + \hat{H}'_C \qquad (VI.20)$$

where

$$\begin{aligned} \hat{H}'_C &= e^{i\hat{R}} \hat{H}_C e^{-i\hat{R}} \\ &\approx \hat{H}_C + i\left[\hat{R}, \hat{H}_C\right] \\ &= \hat{H}_C + \sum_j A_j \left[\hat{i}, \Theta(\hat{v} - v_j)\right] \hat{\Sigma}_y \\ &= \hat{H}_C + \sum_j A_j \delta(\hat{v} - v_j) \hat{\Sigma}_y \end{aligned} \qquad (VI.21)$$

In the dressed state picture, a new term appears which couples nuclear energy into the LC circuit, assisted by the electrochemical process. This term is extremely nonlinear, and is approximated by a delta-function in voltage in this simple model. Depending on how strong the nonlinearity is, it has the potential to exchange a nuclear quantum into a very large number of LC circuit quanta in a nondisruptive manner required for the coherence in neutrino emission.

The scenario described in this paper rests on the conjecture that the electrochemical process is nonlinear to a somewhat higher degree than is required in order for electrochemisty to occur. Some consideration of the microscopic physics suggests that this conjecture is not entirely unreasonable. The voltage operator is approximately proportional to the number operator of electrons within an electrode, and the nonlinearity comes about because the electrode orbitals are filling (or emptying) as the voltage increases. Each newly entering electron sits on the shoulders of previous electrons in energy; at some point a newly entering electron will fill an orbital through which electrochemical current flow is energetically allowed. This microscopic picture leads to a coupling Hamiltonian of the general form given above, except that the step function will be replaced by something softer depending on the details of the tunneling between metal orbitals and surface orbitals.

We note that the nonlinearity, if it worked as conjectured here, might provide under certain conditions, a source of $1/f$ electrical noise.

The extension to the full model would require analysis of superradiance in a multi-level system, and some work has been done on this type of system.[90–92]

VII. DISCUSSION

The binary fusion of two charged nucleons at room temperature as an explanation for cold fusion effects seems to us to be hopeless due to the presence of the coulomb barrier, in spite of the proposals which have been suggested for ways to circumvent coulomb repulsion. Even if a way were found, there remains the problem of developing a reaction which produces cold reaction products. The *dd* binary fusion reaction which has been discussed so much in the last year simply does not begin to fit the reaction profile of the observations.

The fusion of a virtual neutron with a charged nucleon can provide a way to circumvent the coulomb barrier, and our current effort is based on the exploration of this possibility. In place of the problem of coulomb repulsion, an issue of nearly equal severity arises, specifically one of transport. The range of virtual neutrons is quite small (fermi scale) unless the energy deficit can be somehow reduced. Additionally, the weak interaction is a numerically small effect; it is difficult to understand how any reaction, whether coherent or not, could have a substantial reaction rate if the weak interaction is a part of it.

We have proposed that the neutrino emission can be superradiant if the neutrino momentum is equal to the Bloch wave momentum of the electron and if the reaction final products are stationary. This provides a possible mechanism to boost the weak interaction by a considerable factor.

The neutron transport problem may in principle be solved if the coupling of the nuclear energy to the current occurs collectively, which preferentially favors long wavelength virtual neutron states. In conventional incoherent nuclear reactions where off-shell neutrons occur, the time-duration of the excursion of the neutrons can be obtained from the uncertainty principle if the energy deficit is known. In a coherent reaction, which is ultimately a resonance process, the transition width can be very small (less than 1 eV) even though the energy deficit is large. This translates directly into a potentially large spatial excursion for the off-shell neutrons.

There is considerable interest in defining what factors are required to produce cold fusion effects, under the assumption that they are real. This has been of concern, especially to the experimentalists, and there have been some attempts at assembling a list of requirements. No such list has been produced by theorists at this point, and that fact is a consequence that no theory currently exists. Our work is speculative, and although we have not produced a theory as recognized by physicists, we have developed a scenario which may lead to a predictive theory. It is of some interest to address the problem of what requirements would follow under the assumption that the scenario is at least partially correct.

With the above proviso in mind, we offer a list of factors which would be required in our scenario for heat production:

1. A source of virtual neutrons: specifically deuterium or tritium are possible sources. Within the scenario, deuterons would be favored by an N^2 coherent factor over protons.

2. A regular potential which supports electron Bloch waves to enable coherent neutrino emission. This is probably not a requirement that the lattice be perfect, but clearly water will have less order of this sort than a palladium rod.

3. An exothermic sink for virtual neutrons: protons are proposed to be the recipients of virtual neutrons in current heat-producing experiments. As discussed earlier, protons are favored over deuterons in this respect due to the larger M1 matrix element.

4. A magnetic field which is due to a current which sees a highly nonlinear impedance. Although the magnetic field must be present where virtual neutrons are converted, the nonlinearity may be separate. This mode of coupling is specific to M1 interactions.

5. Net (local) nuclear spin polarization.

For tritium production, the requirements would be very similar as the above list applicable to M1 neutron pickup, except that protons would no longer be required. It is likely that they will be helpful, in that the conversion of two virtual neutrons (from electron capture on deuterium) may be enhanced if one is captured onto a proton.

The outstanding issues in the field are: (1) the unequivocable proof that there is indeed a new effect, (2) reproducibility, and (3) mechanism. Engineering and applications must ultimately wait for some very basic level of demonstrable physical understanding. It seems unlikely that the theoretical situation will improve much without more experimental input.

If neutrino emission can occur superradiantly, and if the nonlinearity in current-voltage characteristic actually can take up the nuclear energy, then it may be possible that the various "miracles" can be explained rationally. Future theoretical efforts towards the development of our scenario must involve further quantification of the scenario.

Consideration of these issues has its motivation in the controversial cold fusion experiments. If the experiments are right, then there ought to be some sensible explanation. It is important to establish firmly whether there are indeed cold fusion effects, and if so, a second generation of experiments focusing on mechanism need to be started. We have developed what amounts to a wish list for experiments which would help clarify whether our scenario is indeed a correct approach. This list is given in the following section.

Theory and experiment need to go hand in hand. If proton depletion in heat experiments can be demonstrated quantitatively, then this would be regarded as strong motivation for pursuing our scenario. But it remains to be settled as to whether there is an effect at all, and this must still be regarded as a top priority.

VIII. PROPOSALS FOR EXPERIMENTS

At this point, it is still not accepted that cold fusion effects are real rather than experimental artifacts. If we take the position that the heat and tritium are real effects that can be reproduced by one or more groups, then the question arises as to what new or related experiments can be done which might help clarify mechanisms.

A. Reproducibility

Ever since the initial announcement of the effect, the issue of apparent nonreproducibility has plagued the field. It almost seems as if some researchers have the "magic touch," while most do not, and this has been used as a primary argument that the effect is not real. Currently, numerous researchers are apparently able to obtain one or more of the miracles with much improved probability of success for a given experiment.

Probably the highest priority project which is faced by workers in the field is to define one or more experiments which produce either heat, tritium, neutrons or isotope shifts at some probability level. This accomplishment would go far to make the effect accessible to the scientific community in general. From the large variety of positive experimental results which are being reported now, I think that the definition of an "industry standard" set of cells could be done.

B. Proton Loss

Within the framework of the coherent fusion scenario discussed in this work, protons play a key role in constituting the primary fuel for heat production. A demonstration of this would represent a fundamental step in the elucidation of a mechanism for the Pons-Fleischmann effect. A null result in this area would serve to eliminate the proposed scenario. The key experiment which we recommend is a proton loss experiment, in which the proton concentration is monitored (which presents severe experimental difficulties) over the course of an extended experiment in which multiple megajoules of heat is produced.

C. Proton Concentration

Pons-Fleischmann cells are often run at low levels of light water (on the order of 1%). The initial pre-march work of Pons and Fleischmann suggested that there is an optimum mix of proton and deuterons which gave the best results. The question of interest is: what is the sensitivity of the effect to relative proton concentration within the palladium? Associated with this is whether a rod loaded with less than 0.01% protons can show heat. Within the scenario, such a rod should not exhibit heat, although it could in principle evolve tritium.

C. Tritium loss

Tritium production has been reported in a number of laboratories. A small number of reports of tritium loss exists. The question which arises, is simply whether there is such an effect and whether it is reproducible. An experiment could be done in which a heat producing closed cell is injected with a known amount of tritium, after which tritium content is monitored. Noise levels in the $\frac{\mu\text{Curie}}{ml}$ range have been reported, and an added signal of 100 times this level would be of interest. Within the present scenario, tritium may serve as the source for virtual neutrons, although the primary *teppp* reaction is not allowed energetically.

D. Production of slow neutrinos

Electron capture through the weak interaction involves the emission of a neutrino. If the neutrinos were energetic (which is not consistent with the present scenario), then they could be observed by conventional solar neutrino detectors.[93,94] A point source of $10^{13} - 10^{14}$ neutrinos in the MeV range would be detected by the Kamiokande detector, for example.

If the neutrinos are low energy neutrinos (< 1 eV) as might be produced superradiantly, then they would be detectable only through use of a Weber neutrino detector specifically designed and optimized for a large flux of soft neutrinos.

E. Activation of Phosphorous

Natural phosphorous occurs as ^{31}P. Neutron activation to the ground state of ^{32}P involves an M1 virtual neutron pickup reaction analogous to proton and deuteron reactions discussed above. The activated phosphorous isotope is unstable with a 14 day half-life, and produces a 1.7 MeV electron. If this process can be demonstrated, it would be important mechanistically in that it would be much more difficult to imagine how ^{32}P could be produced through the types of mechanisms which have been discussed elsewhere. A clean demonstration of a new neutron activation reaction would be of great value.

F. Separation of Reactants and Nonlinearity

The mechanism proposed to convert the nuclear energy works through a near field magnetic field generated by a current which sees a high order nonlinearity. This nonlinearity need not necessarily be in the same location as the reactants, and an extremely interesting experiment would be to demonstrate this effect. If the current running through the palladium electrolysis cell were run through another element exhibiting a high order nonlinearity (for example, another electrolysis cell, a battery, a diode or other systems), then it is possible that anomolous energy deposition into the series nonlinear element might occur. A demonstration of this effect would strongly support the present scenario. More interesting still would be the replacement of the original palladium cell with a crystal containing deuterium and hydrogen as constituents (partially deuterated LiH, etc.).

G. Net Nucleon Spin Polarization

Spin-spin coupling between electrons and nuclear spins can be a relatively rapid process. Protons and deuterons undergoing electrolysis in palladium or titanium will see some degree of net nuclear spin alignment. Any coherent mechanism for fusion effects of the class which we have been considering may be sensitive to the state of net nuclear spin polarization. Questions which are of interest involve the relation of nuclear spin polarization to the Pons-Fleischmann effect.

1. Is net nuclear spin polarization present in a heat producing cell? What is the direction, spatial dependence, and strength of proton and deuteron polarization.

2. Can a Pons-Fleischmann cell produce heat if the nuclear spins are randomized?

3. What does the NMR spectrum of a working Pons-Fleischmann cell look like?

IX. SUMMARY AND CONCLUSIONS

We have proposed a new coherent fusion scenario involving exotic two-step beta/fusion reactions to account for the still highly controversial Pons-Fleischmann effect. The previous discussions of *dd* reactions as candidates for explaining the observations suffered from the fact that the reported observations simply do not fit the *dd* reaction profile, and that reactions at room temperature involving fusion of charged nucleii have exceedingly small reaction rates.

The present scenario offers a number of advantages relative to the claimed observations, including

1. Heat production without fast reaction products, neutrons or gammas.

2. Tritium production as a second order process, unaccompanied to first order by secondary neutron production.

3. No explicit exponential damping factors occur at room temperature.

4. The scenario is consistent with the known stability of heavy water and can be consistent with stellar evolution models.

5. The time-dependence of a superradiant system is qualitatively consistent with the dynamics of the observations of the heat and tritium observations.

6. The dependence of the strength of the effect on current density is in qualitative agreement (maximum di/dv is favored, rather than maximum i).

7. The scenario is consistent with contamination-dependent production of low levels of residual radioactivity.

Real neutron production can occur as an incoherent process parasitic with the coherent processes described in the paper. It is at best a third order process in comparison to heat and tritium production in the model.

The principle weakness of the scenario at this point is the lack of quantitative predictions. This weakness is not inherent in the model; the effects discussed here are amenable to precise quantification. Further effort is required to obtain predictions.

Acknowledgements

The author would like to thank his friends for their encouragement and technical support. This work was supported under DOE contract DEFG02/89CR14012.

REFERENCES

1. M. Fleischmann, S. Pons and M. Hawkins, *J. Electroan. Chem.* **261** 301 (1989), **263** 187 (1989).

2. M. Fleischmann, S. Pons and R. J. Hoffman, *Nature* **339** 667 (1989).

3. S. E. Jones, E. P. Palmer, J. B. Czirr, D. L. Decker, G. L. Jensen, J. M. Thorne, S. F. Taylor and J. Rafelski, *Nature* **338** 737 (1989).

4. R. D. Petrasso, X. Chen, K. W. Wenzel, R. R. Parker, C. K. Li, C. Fiore, *Nature* **339** 183 (1989); *Nature* **339** 667 (1989).

5. J. F. Ziegler, T. H. Zabel, J. J. Cuomo, V. A. Brusic, G. S. Cargill, E. J. O'Sullivan and A. D. Marwick, *Phys. Rev. Lett.* **62** 2929 (1989).

6. M. Gai, S. L. Rugari, R. H. France, B. J. Lund, Z. Zhao, A. J. Davenport, H. S. Isaacs and K. G. Lynn, *Nature* **340** 29 (1989).

7. N. S. Lewis, C. A. Barnes, M. J. Heben, A. Kumar, S. R. Lunt, G. E. McManis, G. M. Miskelly, R. M. Penner, M. J. Sailor, P. G. Santangelo, G. A. Shreve, B. J. Tufts, M. G. Youngquist, R. W. Kavanagh, S. E. Kellogg, R. B. Vogelaar, T. R. Wang, R. Kondrat and R. New, *Nature* **340** 525 (1989).

8. D. Albagli, R. Ballinger, V. Cammarata, X. Chen, R. M. Crooks, C. Fiore, M. J. P. Gaudreau, I. Hwang, C. K. Li, P. Linsay, S. Luckhardt, R. R. Parker, R. D. Petrasso, M. O. Schloh, K. W. Wentzel, M. S. Wrighton, submitted to *J. of Fusion Energy* (1989).

9. H. Hsuan, D. M. Manos, S. Cohen, S. Cowley, R. Motley, A. L. Roquemore, T. Saito, J. Timberlake, W. Ayers, T. Bennet, M. Bitter, F. E. Cecil, J. Cuthbertson, J. Dong, H. F. Dylla, J. Evans, H. Furth, L. Grisham, H. Hendel, K. Hill, R. Kulsrud, D. Meade, S. S. Medley, D. Mueller, E. Nieshmidt, R. Shoemaker and J. Thomas, "Lack of neutron and gamma radiation from PPPL's cold fusion experiments," presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989.

10. M. H. Salamon, M. E. Wrenn, H. E. Bergeson, K. C. Crawford, W. H. Delaney, C. L. Henerson, Y. Q. Li, J. A. Rusho, G. M. Sandquist, and S. M. Seltzer, *Nature* **344** 390 (1990).

11. G. Schrieder, H. Wipf and A. Richter, *Z. Phys. B: Condensed Matter* **76** 141 (1989).

12. E. Kashy, W. Bauer, Y. Chen, A. Galonsky, J. Gaudiello, M. Maier, D. J. Morrissey, R. A. Pelak, M. B. Tsang and J. Yurkon, *Phys. Rev C* **40** R1 (1989).

13. S. H. Faller, R. W. Holloway and S. C. Lee, *J. Radioanal. Nucl. Chem. Letters* **137** 9 (1989).

14. J. J. G. Durocher, D. M. Gallop, C. B. Kwok, M. S. Mathur, J. K. Mayer, J. S. C. McKee, A. Mirzai, G. R. Smith, Y. H. Yeo, K. S. Sharma and G. Williams, *Can. J. Phys.* **67** 624 (1989).

15. R. Behrisch, W. Moller, J. Roth, B. M. U. Scherzer, *Nuclear Fusion* **29** 1187 (1989).

16. A. Baurichter, W. Eyrich, M. Frank, H. Gohr, W. Kreische, H. Ortner, B. Roseler, C. A. Schiller, G. Weeske and W. Witthun, *Z. Phys. B: Condensed Matter* **76** 1 (1989).

17. D. Alber, O. Boebel, C. Schwartz, H. Duwe, D. Hilsher, H. Homeyer, U. Jahnke and B. Spellmeyer, *Z. Phys A: Atomic Nuclei* **333** 319 (1989).

18. D. Abriola, E. Achterberg, M. Davidson, M. Debray, M. C. Etchegoyen, N. Fazzini, J. Fernandez Niello, A. M. J. Ferrero, A. Filevich, M. C. Galia, R. Garavaglia, G. Garcia Bermudez, R. T. Gettar, S. Gil, H. Grahmann, H. Huck, A. Jeck, A. J. Kreiner, A. O. Macchiavelli, J. F. Magallanes, E. Maqueda, G. Marti, A. J. Pacheco, M. L. Perez, C. Pomar, M. Rameriz and M. Scasserra, *J. Electroanal. Chem* **265** 355 (1989).

19. R. D. Armstrong, E. A. Charles, I. Fells, L. Molyneux and M. Todd, *J. Electroanal. Chem* **272** 293 (1989).

20. J. Balej and J. Divisek, *J. Electroanal. Chem.* **278** 85 (1989).

21. J. Divisek, L Furst, and J. Balej, *J. Electroanal. Chem.* **278** 99 (1989).

22. M. Chemla, J. Chevalet, R. Bury and M. Perie, *J. Electroanal. Chem.* **277** 93 (1990).

23. "Cold Fusion Research," a report of the Energy Research Advisory Board to the U. S. Department of Energy, November 1989.

24. *Nature* **343** 6 (1990).

25. "Farewell (not fond) to cold fusion," *Nature* **344** 365 (1990).

26. D. Lindley, *Nature* **344** 375 (1990).

27. D. R. O. Morrison, "The Rise and Decline of Cold Fusion," to appear in *Physics World* (1990).

28. J. O'M. Bockris, G. H. Lin and N. J. C. Packham, "A Review of the Investigations of the Fleischmann-Pons Phenomena," (unpublished) Dept. of Chemistry, Texas A&M University, March, 1990.

29. R. Huggins et al., presented at the Technology and Society Division of the *ASME Winter Meeting* in San Francisco, December 12, 1989. Huggins described recent experiments that employ closed cell calorimetry, and reported the production of 1.15 MJ in 260 hours in one experiment. He mentioned that in another cell he was able to sustain 8.5 Watts for 275 hours. Extensions of this work were presented at the First Anuual Cold Fusion Conference, Utah, 1990.

30. A. J. Appleby, S. Srinivasan, Y. J. Kim, O. J. Murphy and C. R. Martin, "Evidence for excess heat generation rates during electrolysis of D_2O in LiOD using a palladium cathode - a microcalorimetric study," presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989.

31. O. J. Murphy, A. J. Appleby and S. Srinivasan, presented at the First Annual Conference on Cold Fusion, Utah, (1990).

32. R. C. Kainthla, O. Velev, N. J. C. Packham, L. Kaba and J. O'M. Bockris, *Electrochim. Acta* **34** 1315 (1989).

33. C. D. Scott, J. E. Mrochek, E. Newman, T. C. Scott, G. E. Michaels and M. Petek, "A preliminary investigation of cold fusion by electrolysis of heavy water," ORNL report TM-11322, Nov. 1989. G. Michaels et al, presented at the Technology and Society Division of the *ASME Winter Meeting* in San Francisco, December 12, 1989. Presented at the First Annual Conference on Cold Fusion, 1990.

34. D. Hutchinson, C. A. Bennett, R. K. Richards, J. Bullock and G. L. Powell, Oak Ridge National Lab Report ORNL/TM-11356 (1989).

35. M. C. H. McKubre, R. C. Rocha-Filho, S. Smedley, F. Tanzella, B. Chexal, T. Passell and J. Santucci, "Calorimetric and Electrochemical Studies of the Deuterium-Palladium System," First Annual Cold Fusion Conference, Utah (1990).

36. L. L. Zahm, A. C. Klein, S. E. Binney, J. N. Reyes, J. F. Higginbotham, A. H. Robinson and M. Daniels, Oregon State University Report OSU-NE-8914 Dec. 1989.

37. S. Pons and M. Fleischmann, to appear *J. Fusion Tech.*.

38. K. L. Wolf, N. Packham, J. Shoemaker, F. Chung and D. Lawson, "Neutron emission and the tritium content associated with deuterium loaded palladium and tritium metals," presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989.

39. N. J. C. Packham, K. L. Wolf, J. C. Wass, R. C. Kainthla and J. O'M. Bockris, *J. Electroanal. Chem.* **270** 451 (1989). Also K. Wolf, private communication (1990).

40. T. N. Claytor, P. A. Seeger, R. K. Rohwer, D. G. Tuggle and W. R. Doty, "Tritium and neutron measurements of a solid state cell," LANL report LA-UR-89-39-46, October 1989. There is a LANL memorandum of Jan. 23, 1989 from T. N. Claytor, D. G. Tuggle, P. Seeger, H. O. Menlove, R. K. Rohwer and W. Doty which contains an update of this work. Claytor reported the production of tritium in gas cell experiments. A number of his cells produced tritium between 8 and 245 μCuries.

41. E. Storms and C. Talcott, "Electrolytic Tritium Production," LANL report LAUR: 89-4138. This work was presented at the First Annual Cold Fusion Conference, Utah, 1990.

42. "BARC Studies in cold fusion," edited by P. K. Iyengar and M. Srinivasan, Bhaba Atomic Research Centre, Trombay, Bombay, India, December (1989). This work was presented at the First Annual Cold Fusion Conference, Utah, 1990.

43. C. Sanchez, J. Sevilla, B. Escarpizo, F. Fernandez and J. Canizares, "Cold Fusion during Electrolysis of Heavy Water with Ti and Pt Electrodes," Societa Italiana di Fisica Conference Proceedings Vol. 24 - Understanding Cold Fusion Phenomena- Edited by R. A. Ricci, E. Sindoni, and F. DeMarco, (1989).

44. J. Chene and A. M. Brass, *J. Electroanal. Chem.* **280** 199 (1990).

45. A. Bertin, M. Bruschi, M. Capponi, S. DeCastro, U. Marconi, C. Moroni, M. Piccunini, N. Semprini-Cesari, A. Trombini, A. Vitale, A. Zoccoli, J. B. Czirr, G. L. Jensen, S. E. Jones and E. P. Palmer, "Experimental evidence for cold fusion in a measurement in the Gran Sasso Massif," *Il Nuovo Cimento* **101** 997 (1989).

46. P. Perfetti, F. Cilloco, R. Felici, M. Capozi and A. Ippoliti, *Il Nuovo Cimento* **11D** 921 (1989).

47. A. De Ninno, A. Frattolillo, G. Lollobattista, L. Martinis, M. Martone, L. Mori, S. Podda, and F. Scaramuzzi, *Europhysics Letters* **9** 221 (1989).

48. F. Scaramuzzi, presented at the First Annual Cold Fusion Conference, Utah, 1990.

49. H. O. Menlove, M. M. Fowler, E. Garcia, A. Mayer, M. C. Miller, M. C. Miller, R. R. Ryan and S. E. Jones, "The measurement of neutron emission from Ti plus D_2 gas," presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989. This work was presented at the First Annual Cold Fusion Conference, Utah, 1990.

50. N. Wada and K. Nishizawa, *Jap. J. Appl. Phys.* **28** L2017 (1989).

51. R. Taniguchi, T. Yamamoto and S. Irie, *Jap. J. Appl. Phys.* **28** L2021 (1989).

52. D. Gozzi, P. L. Cignini, L. Petrucci, M. Tomellinin, G. De Maria, S. Frullani, F. Garibaldi, F. Ghio, M. Jodice and E. Tabet, "Nuclear and thermal effects during electrolytic reduction of deuterium at a palladium cathode," presented at the Workshop on Cold Fusion Phenomena at Santa Fe, May 1989.

53. D. Gozzi, P. L. Cignini, L. Petrucci, M. Tomellini and G. De Maria, *Il Nuovo Cimento* **103A** 143 (1990).

54. G. J. Batra, D. K. Bewley and M. A. Chaudhri, *Nucl Inst Meth* **100** 135 (1972).

55. D. D. Armstrong, C. R. Emigh, K. L. Meier, E. A. Meyer, and J. D. Schneider, *Nucl Inst Meth* **145** 127 (1977).

56. J. F. Janni, *Atomic Data Nucl Data Tables* **27** 341 (1982).

57. K. Wolf, private communication. This conclusion was discussed by Wolf at the NSF/EPRI meeting October 16-18, 1989.

58. R. E. Brown and N. Jarmie, submitted to *Phys Rev C* (1989). LANL Preprint LA-UR-89-953 (1989).

59. P. L. Hagelstein, "Coherent Fusion Theory," Presented at the ASME Winter Meeting, San Francisco, Dec. 1989, paper TS-4.

60. A. E. Cox, J. A. R. Wynchank and C. H. Collix, *Nucl. Phys.* **74** 497 (1965).

61. J. F. Mathiot, *Nucl. Phys.* **A412** 201 (1984).

62. L. Kaplan, G. R. Ringo and K. E. Wilzbach, *Phys. Rev.* **87** 785 (1952).

63. H. Lycklama and T. J. Kennett, *Can. J. Phys.* **45** 3039 (1967).

64. K. Kaminishi, *Jap. J. Appl. Phys.* **19** 1399 (1980).

65. G. B. Beard and G. E. Thomas, *Nucl. Phys.* bf A157, 520 (1970).

66. P. L. Hagelstein, "Status of Coherent Fusion Theory," DOE annual report, Jan. 1990.

67. J. Korringa, *Physica* **XVI** 601 (1950).

68. B. Hohler and H. Kronmuller, *Phil. Mag. A* **45** 607 (1982).

69. W. Gotz and W. Ketterle, *Z. Phys. B - Condensed Matter* **54** 49 (1983).

70. T. R. P. Gibbs, *Prog. Inorg. Chem.* **3** 315 (1962).

71. R. E. Norberg, *Phys. Rev.* **86** 745 (1952).

72. R. H. Dicke, *Phys. Rev.* **93** 99 (1954).

73. N. E. Rehler and J. H. Eberly, *Phys. Rev. A* **3** 1735 (1971).

74. J. H. Eberly, *Am. J. Phys.* **40** 1374 (1972).

75. R. Bonifacio and G. Preparata, *Lettre al Nuovo Cimento* **1** 887 (1969).

76. J. Weber, *Foundations of Physics* **14** 1185 (1984).

77. J. Weber, *Phys. Rev. C* **31** 1468 (1985).

78. J. Weber, *Phys. Rev. D* **38** 32 (1988).

79. M. Bixon and J. Jortner, *J. Chem. Phys.* **48** 715 (1968).

80. R. Englman and J. Jortner, *Mol. Phys.* **18** 145 (1970).

81. A. Nitzan and J. Jortner, *J. Chem. Phys.* **56** 3360 (1972).

82. A. Nitzan and J. Jortner, *Mol. Phys.* **25** 713 (1973).

83. R. Englman, *Non-radiative decay of ions and molecules in solids*, North-Holland, NY (1979).

84. J. Weber, *Phys. Rev.* **90** 977 (1953).

85. J. Weber, *Phys. Rev.* **94** 211 (1954).

86. R. Silbey and R. A. Harris, *J. Chem. Phys.* **80** 2615 (1984).

87. M. Wagner, *Z. Phys.* **256** 291 (1972).

88. E. Sigmund and M. Wagner, *Z. Phys.* **268** 245 (1974).

89. V. Denner and M. Wagner, *Z. Phys. B - Condensed Matter* **58** 255 (1985).

90. D. F. Walls and R. Barakat, *Phys. Rev. A* **1** 446 (1970).

91. M. Takatsuji, *Phys. Rev. A* **4** 808 (1971).

92. Z. C. Wang and H. Haken, *Z. Phys. B - Condensed Matter* **55** 361 (1984).

93. J. N. Bahcall, *Rev. Mod. Phys.* **50** 881 (1978).

94. K. S. Hirata, T. Kajita, M. Koshiba, M. Nakahata, Y. Oyama, N. Sato, A. Suzuki, M. Takita, Y. Totsuka, T. Kifune, T. Suda, K. Takahashi, T. Tanimori, K. Miyano, M. Yamada, E. W. Beier, L. R. Feldscher, W. Frati, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, W. Zhang, and B. G. Cortez, *Phys. Rev. D* **38** 448 (1988).