lifetime state. Then, the usual nuclear technology for neutron or gamma radiation is no longer applicable to detect this low energy sub-barrier resonance. The calorimetric technology in chemistry turns out to be the better choice, because the energy released in a nuclear reaction is always there. If there is any energetic charged particle as a nuclear product, we may use the nuclear track detector; or we may detect the helium directly. If we are able to identify such kind of low-energy resonant tunneling; then, this is a fusion

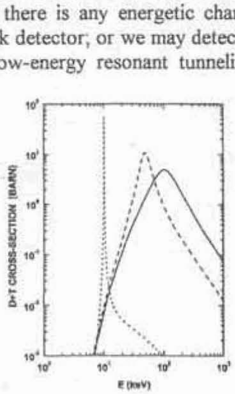


Fig.4 The shape of d+t fusion cross section predicted by the selective resonant tunneling model for the low energy resonance (if any).

reaction without strong nuclear radiation.

In conclusion, the nuclear physics for sub-barrier fusion provides a new approach towards nuclear fusion energy with no strong nuclear radiation.

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# A UNIFIED MODEL FOR ANOMALIES IN METAL DEUTERIDES

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## Introduction

There have been numerous reports of observations of anomalies in metal deuterides during the past eleven years. The anomalies that we recognize for the purposes of the present discussion include: low-level neutron emission; fast ion emission; gamma emission; the Kasagi effect (3-body ddd-fusion reaction); excess heat and correlated slow $^4$He emission; slow tritium production; and lattice-induced radioactivity. Many of these effects are under discussion in other papers that were presented at ICCF8. For many years we have sought physical mechanisms that might provide a theoretical explanation for these anomalies. During the past 2-3 years, our efforts have led to a unified picture that appears to provide mechanisms systematically for all of these anomalies. In this conference proceeding, we will provide an overview of the general approach, the basic model, and the relevant physical mechanisms.

We note that there have been a number of reports of observations of a massive transmutation effect that would involve reactions that increase the nuclear mass of the host metal. This effect is not included within the model under discussion.

## Overview of the Model

The premise of the model is that nuclear reactions in the lattice can take place, and that the lattice must be included in the physical description. There exists well-studied models for fusion reactions in free space, which we must generalize to include lattice effects. When the nuclei and lattice are described together within the basic formulation, we find that the lattice phonon degrees of freedom mix with the microscopic nuclear degrees of freedom. This coupling comes about at a very fundamental level as a consequence of the natural separation of microscopic position coordinates into center of mass coordinates, relative coordinates and internal coordinates.

While it comes as no surprise that phonons might play a role in a fusion reaction between deuterons within a lattice, our intuition suggests strongly that any such interactions can have only a small impact on the physics of the reaction. In fact the model under consideration can be used to quantify just how small the effect of the lattice is on all first order reaction processes. The exchange of a single phonon would not be expected to cause much change in the dynamics of a dd-fusion reaction involving exit channels with product nuclei separating with several MeV of relative energy. The new theory is consistent with this expectation.

However, there exists the possibility of new second order effects when the lattice is involved. For example, a reaction might occur at one site where phonon exchange takes place with a highly excited phonon mode. A second reaction might take place at a different site, again with phonon exchange with a highly excited mode. While the effect of phonon exchange for all first order processes is arguably negligible, at second order the situation can be very different. Within a second order process, it may be the case that energy conservation is apparently violated for each individual process, but rigorous energy conservation must be required for the two-step second order process. When phonon exchange with the lattice occurs, we must consider the possibility that an exothermic fusion reaction occuring at one site might be coupled with some other endothermic process at a different site.

The consequences of this are enormous, and the theory that results appears to coincide with many of the experimental observations. The most important second order site-other-site process of this sort is the "null" reaction, in which a fusion of two deuterons to a $^4$He nucleus at one site is coupled to a dissociation of a $^4$He nucleus at another site. In such a reaction, no new products are formed. The only effect of such a process is to exchange excitation between two sites. One finds that the (E2) microscopic selection rules for this can be satisfied through phonon exchange. One also finds that this process can be greatly enhanced when many sites are involved. One consequence of this process is that the probability of deuterons being found close together increases greatly (when the helium dissociates, the resulting deuterons are born close together). In the simplest case, these deuterons can react to make neutrons and other dd-fusion products. If significant phonon exchange occurs, then the two deuterons will have significant relative angular momentum, which can exclude the conventional dd-fusion reaction channels. In this case, they may remain together with significant probability. There presence can be detected then through a 3-body reaction when fast (100 keV) deuterons are incident. This appears to lead naturally to the Kasagi effect. [1]

The close coupling of the phonons and deuterons that occurs in such a process leads to a strong mixing of the phonon and nuclear degrees of freedom. Under these conditions, phonon dissipation will lead to a loss of nuclear energy from the coupled system, because the degrees of freedom are mixed. The ash from this process will be $^4$He, produced in place with no kinetic energy, as is observed. The same basic mechanism also applies to tritium production, where the associated "null" reaction is two deuterons reacting to produce a slow proton and tritium pair at one site, and the inverse process occurs at a different site. Fast charged particles can result when a fusion at one site is coupled to lattice-induced particle ejection at another site. For example,



alpha particles and other low mass ejecta can be ionized from high-Z nuclei within the lattice through "electrostatically" mediated phonon exchange, as the second part of a two-step second order process where the energy is provided by a fusion reaction as a first step. There exist reports of such an effect. [2] The lattice-induced radioactivity seen by Wolf would result from a process in which the initial fusion were mediated by a 70-phonon exchange process, with each of the phonons dissipating their energy in a roughly 350 KeV weak-interaction decay channel.

The model also predicts a proton-deuteron reaction pathway, involving $^3$He final states. While the possible existence of such a pathway has been noted by many, it has usually been assumed that any associated anomalous reactions would proceed at a rate proportional to the overlap probability, which is orders of magnitude greater for the proton deuteron system. Null reactions involving protons and deuterons would lead to a large increase in the associated probability at short range, which would be qualitatively similar to the situation for deuteron-deuteron reactions. Consequently, a heat effect involving the proton-deuteron pathway would likely be limited by phonon dissipation effects, and not by the overlap probability of the associated molecular system as has been often conjectured. If the light water heat experiments are conjectured to be the consequence of proton-deuteron reactions, then it would be sensible to assay for $^3$He as a possible ash. The present model supports this conjecture.

## Including Lattice Effects in the Basic Formulation

Most theoretical papers on the dd-fusion reaction have made use of the resonating group method or the R-matrix method. Consequently, we wish to generalize these methods to include lattice effects. The resonating group method [3] assumes a total wavefunction $\Psi_T$ of the form

$$\Psi_T = \sum_j \Phi_j F_j \tag{1}$$

where the internal nuclear states are included in $\Phi_j$, and where $F_j$ is the channel separation factor. The internal nuclear states are presumed to be fixed, and the channel factors are determined from a solution of the coupled-channel equations

$$E F_j = \langle\Phi_j|H|\Phi_j\rangle F_j + \sum_k \langle\Phi_j| (H - E) |\Phi_k F_k\rangle \tag{2}$$

In all cases, the wavefunctions must be properly antisymmetrized (a requirement not made explicit by the abstract formulation presented here).

The channel separation factor $F_j$ is a function of the relevant relative mass coordinate(s) between the center of mass coordinates of the constituent nuclei in the $j$th channel. As the center of mass coordinates of the constituent nuclei also occur in a lattice description, we can generalize the resonating group method to include lattice effects simply by replacing the separation channel factors with lattice channel factors. Consequently, we generalize the resonating group method by using an initial wavefunction of the form

$$\Psi_T = \sum_j \Phi_j \Psi_j \tag{3}$$

where $\Psi_j$ now includes the center of mass coordinates for the reacting nuclei associated with channel $j$, and also the center of mass coordinates for the other nuclei in the lattice. Assuming equivalently that the internal nuclear states $\Phi_j$ do not depend on the relative separation, the lattice channel functions can be determined from a solution of the lattice multi-channel equations

$$E\,\Psi_j = \langle\Phi_j|H|\Phi_j\rangle\,\Psi_j + \sum_k \langle\Phi_j|\,(H-E)\,|\Phi_k\Psi_k\rangle \tag{4}$$

These equations can serve as the starting point for modeling anomalies in metal deuterides. We note that a similar generalization of the R-matrix method to include lattice effects is completely straightforward. The total lattice wavefunction in this case can be developed using lattice channel factors $\Psi_T = \sum_j c_j\Phi_j\Psi_j$, and then an appropriate eigenvalue equation for the amplitudes $c_j$ can be developed.

## Interaction between Two Sites

We can extend the analysis to include coupling between reactions at different sites. For simplicity, we consider the case of two sites here. The "null" reaction of interest can be written as

$$(d+d)_a + ({}^4He)_b \longleftrightarrow ({}^4He)_a + (d+d)_b \tag{5}$$

To model this, we assume a total wavefunction of the general form

$$\Psi_T = \sum_j \sum_n \Phi_j^a\,\Phi_j^b\,\phi_n\,\Psi_{j,n} \tag{6}$$

The internal nuclear states at site $a$ are included in $\Phi_j^a$, and the internal states at site $b$ are included in $\Phi_j^b$. We assume a highly excited delocalized phonon mode with $n$ phonons present, modeled by $\phi_n$. The rest of the lattice wavefunction is modeled by the lattice channel function $\Psi_{j,n}$. The relevant two-site coupled lattice channel equations are of the form

$$E\,\Psi_{i,n} = \langle\Phi_i^a\Phi_i^b\phi_n|H|\Phi_i^a\Phi_i^b\phi_n\rangle\,\Psi_{i,n} + \sum_{j,n'\neq i,n} \langle\Phi_i^a\Phi_i^b\phi_n|\,(H-E)\,|\Phi_j^a\Phi_j^b\phi_{n'}\Psi_{j,n'}\rangle \tag{7}$$

No interesting new effects are present at first order. We can eliminate intermediate states to obtain a second order model

$$\begin{aligned} E\,\Psi_{i,n} = {} & \langle\Phi_i^a\Phi_i^b\phi_n|H|\Phi_i^a\Phi_i^b\phi_n\rangle\,\Psi_{i,n} \\ & + \sum_{j,n'\neq i,n}\ \sum_{k,n''\neq j,n'} \frac{\langle\Phi_i^a\Phi_i^b\phi_n|\,(H-E)\,|\Phi_j^a\Phi_j^b\phi_{n'}\,\langle\Phi_j^a\Phi_j^b\phi_{n'}|\,(H-E)\,|\Phi_k^a\Phi_k^b\phi_{n''}\Psi_{k,n''}\rangle\rangle}{E-E_{j,n'}} \end{aligned} \tag{8}$$



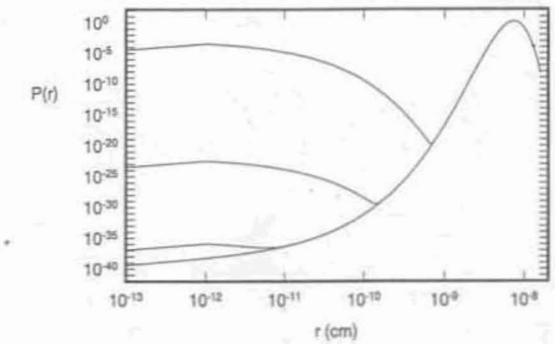


Figure 1: Model computation of the probability amplitude for the ${}^5S$ channel assuming 2-phonon exchange. One observes the effect of a source term near the origin for different coupling strengths.

This equation can then be used to understand the coupling of a reaction at site $a$ with its inverse at site $b$. If we focus on the local probability amplitudes for relative separation at each of the two sites, we obtain coupled equations, one of which is given by

$$\begin{aligned} E\,\psi_{a,n}(\overline{\mathbf{R}}_1,\overline{\mathbf{R}}_2) = {} & \left[-\frac{\overline{\nabla}_1^2}{2M_1}-\frac{\overline{\nabla}_2^2}{2M_2} + V_{lat}(\overline{\mathbf{R}}_1) + V_{lat}(\overline{\mathbf{R}}_2) + V_{nn}(\overline{\mathbf{R}}_1,\overline{\mathbf{R}}_2)\right]\psi_{a,n}(\overline{\mathbf{R}}_1,\overline{\mathbf{R}}_2) \\ & + \sum_{n'\neq n} \frac{\langle\Phi_{dd}^a|\,V_{nn'}\,|\Phi_{He}^a\,\langle\Phi_{He}^b|\,V_{n'n}\,|\Phi_{dd}^b\,\psi_{b,n}(\overline{\mathbf{S}}_1,\overline{\mathbf{S}}_2)\rangle\rangle}{\Delta E - (n'-n)\hbar\omega_0} \\ & - \sum_{n'\neq n} \frac{\langle\Phi_{He}^b|\,V_{nn'}\,|\Phi_{dd}^b\,\langle\Phi_{dd}^a|\,V_{n'n}\,|\Phi_{He}^a\,\psi_{b,n}(\overline{\mathbf{S}}_1,\overline{\mathbf{S}}_2)\rangle\rangle}{\Delta E + (n'-n)\hbar\omega_0} \end{aligned} \tag{9}$$

For transitions between orthogonal channels, the nuclear and Coulomb interaction appears through

$$V_{n,n'} = \langle\phi_n|(H-E)|\phi_{n'}\rangle \tag{10}$$

We see in the first line of equation (9) a two-body problem for the two deuterons at site $a$, which is essentially the molecular $D_2$ problem in an external potential. This problem is written in terms of the residual local position variables $\overline{\mathbf{R}}_1$ and $\overline{\mathbf{R}}_2$, which are the true position variables minus the contribution of the excited phonon mode (see Ref [4]). The second and third lines include source terms due to the dissociation of the ${}^4He$ nucleus at site $a$. This dissociation comes about as part of a the second order null reaction, in which a fusion at one site is coupled to a dissociation at another site. There exist some technical issues regarding the denominator of the second summation which are important but suppressed in this discussion. Two deuterons that are produced close together can either tunnel or interact, thereby destroying the relative symmetry of the two channels. This effect reduces significantly the destructive interference between the two possible intermediate pathways, and increases the effects under discussion.

In Figure 1, we illustrate the essential physics contained in this model in a computation of the probability amplitude for the separation between the two deuterons assuming a molecular $D_2$ potential, and injection of probability amplitude at 10 fermis. The source term is linear in the number of sites that participate in phase. We have illustrated results for different coupling strengths (ie. different number of sites and different phonon interaction strengths).

## Discussion

The discussion above indicates that second order coupling between reactions at two sites is expected when the lattice is included in the initial formulation of the nuclear problem. For the S-wave example illustrated in the last section, we require two-phonon exchange to satisfy the microscopic selection rules. This kind of effect would lead to neutron emission, since the deuterons at close range would run into each other occasionally and react. If more than 25 phonons are exchanged, then a strong inhibition of the normal dd-fusion channels occurs. In this case, a very large amount of probability amplitude could accumulate at short range, which would be observable in a Kasagi-type of experiment. The approach outlined here can be applied uniformly to neutron emission as well as to the Kasagi effect. Inclusion of phonon dissipation in the model leads to heat and helium production.

It remains to be proven experimentally that the Kasagi effect is due to a 3-body reaction (this will probably require a coincidence measurement of the proton and alpha particle). If it proves to be due to ddd-fusion, then the model outlined here may provide the only possible explanation. The experimental result could then be interpreted in proving that energy could be exchanged through the lattice between reactions at different sites. In our view, this is ultimately the basis for understanding all of the anomalies.

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# ELECTRON SCREENING IN METAL DEUTERIDES


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## Introduction

Experimental evidence in support of anomalies in metal deuterides has accumulated during the past decade. These anomalies include neutron emission, fast (MeV) charged particle emission, excess power generation and correlated $^4He$ production, tritium production and induced radioactivity. As yet, there is no consensus on a theoretical explanation for these effects. Prior to the introduction of any new physics that pertain specifically to the anomalies, one would like to have a basic understanding of the deuteron-deuteron interaction at close range due to conventional solid state effects. In this work we examine the general issue of electron screening between deuterons in a metal deuteride.

## Screening and Recent Accelerator Experiments

In the case of molecular $D_2$, the screening between the deuterons is a consequence of the change of the electronic energy due to modifications in the electronic orbitals as a function of the deuteron separation. Within the framework of the Born-Oppenheimer approximation, this effect can be included as an effective potential in addition to the Coulomb repulsion between the deuterons. For example, when a fast deuteron collides with a stationary deuteron, electron screening should occur in much the same way as in the $D_2$ molecule. This should produce an increase in the fusion probability over the theoretical ion-ion calculation (with an unscreened Coulomb barrier) that will be most noticeable at low incident energy. Experiments involving keV deuterons incident on molecular deuterium gas targets give an increase in the fusion rate at low energy over