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# Cold Fusion: Effects of Possible Narrow Nuclear Resonance

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# Cold Fusion: Effects of Possible Narrow Nuclear Resonance

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The influence of a possible and as yet undiscovered narrow resonance in $^4$He on the d-d fusion rate near threshold is examined. A qualitative discussion of the structure of the lowest four $0^+$ states and its impact on the partial widths of decay channels is presented.

## Introduction

The recent reports of Pons and Fleischmann[1] and Jones, et al.[2] regarding the possibility of cold fusion of deuterium nuclei within Pd and Ti electrocathodes have generated great interest and astonishment among the scientific community. Not only are such rates completely unexpected on the basis of quantum mechanical barrier penetration theory, but the reported generation of heat[1] implies fusion rates several orders of magnitude larger than the observed neutron and tritium production.

Rafelski et al.[3] explored theoretically the effects of changing some of the key parameters that sensitively control the fusion reaction rate, such as energy, maximum deuterium separation and the effective mass and/or charge of the electron. They acknowledge that it is difficult to imagine how a collective effect in a metallic hydride could lead to such unusual values for these parameters. Nevertheless, it is possible that some combination of plausible changes in these parameters would lead to extraordinary enhancement of the d-d fusion reaction rate, up to $10^{-23}$ per second per d-d pair or more. We wish here to explore the effect from another phenomenon which may also contribute to significant enhancement of the reaction rates.

## Discussion

The strong enhancement of cross sections for some fusion reactions as a result of the existence of a narrow resonance in the fused system near the reaction threshold is well known[4]. This phenomenon is of major importance in astrophysical nucleosynthesis, and has often been postulated to explain anomalies in fusion cross section data also[5]. In particular, the possible existence of $2^+$ (ref. 6) and/or $1^-$ (ref. 7)

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narrow resonances in $^4$He has been suggested to explain some d-d reaction data near threshold energy, but no conclusive evidence has been found so far[5,7].

Nevertheless, we wish here to explore the possible effect on the cold fusion reaction rates from a possible undiscovered narrow nuclear resonance near 23.8 MeV in $^4$He, corresponding to threshold energy in the d-d channel. The energy dependence of the fusion cross section about a possible narrow resonance level in $^4$He around 23.8 MeV can be written in the usual Breit-Wigner form as:

$$\sigma_f = \frac{\pi\omega}{k^2} \frac{\Gamma_d \Gamma}{(E - E_r)^2 + (\frac{\Gamma}{2})^2} \tag{1}$$

where $\Gamma$ is the total resonance width, $E_r$ is the resonance energy, and $\omega$ is a statistical factor which for an S-wave is 1.

The d-d channel width, $\Gamma_d$, is extremely small and contributes negligibly to the total width $\Gamma$. The partial width for decay to channel $i$, $\Gamma_i$, can be estimated using a very simple model:

$$\Gamma_i = \hbar S_i f_i P_i = \hbar \delta^2 P_i, \tag{2}$$

where $S_i$ is the spectroscopic factor for channel $i$, $f_i$ is the frequency and $P_i$ the penetration factor, given by

$$P_i = e^{(-2/\hbar)\int_R^{r_0} \sqrt{2\mu(V-E)}\,dx} \tag{3}$$

As an illustration, we calculate the width of a hypothetical $2^+$ resonance in $^4$He near d-d threshold. Assuming $S_i = 0.1$ for all channels, we obtain the following values for the dominant channels:

$$\Gamma_n = 50\,\text{ev}; \qquad \Gamma_p = 63\,\text{ev}$$

Using the Breit-Wigner expression for the fusion cross section, we obtain the following cross section ratios near threshold as a function of the difference in energy from the resonance:

**Table 1** Fusion Cross Section Ratios Near a $2^+$ Threshold Resonance

| $E - E_r$ (keV) | $\sigma/\sigma_{max}$ |
|---|---|
| 0 | 1 |
| 100 | $3.1 \times 10^{-7}$ |
| 1000 | $3.1 \times 10^{-9}$ |

We conclude from the above that the d-d threshold fusion reaction rate could vary by more than $10^8$ going on and off resonance. Since the maximum value for the cross section around the resonance is inversely proportional to the width, $\Gamma$, larger variations will result if the resonance width is narrower.

The problem of large heat generation relative to neutron and tritium production might be explained if the postulated narrow $0^+$ resonance had a very small spectroscopic factor for the neutron and proton decay channels and primarily decayed by internal $e^+$ $e^-$ pair formation either directly to ground or through the first excited $0^{+'}$ level at 20.2 MeV. The electrons would have at most an energy of 11.4 MeV. In water or other low-Z material such electrons will deposit most of their energy in the near surroundings as heat with but little escaping as bremsstrahlung. We now address this question and find it virtually impossible to suppress nucleon decay below pair formation.

If the resonance state is composed of excited proton structure and excited neutron structure, the n and p decay modes would both be suppressed. For such a light nucleus as $^4$He the shell-model notation has the disadvantage of spurious states. Let us, instead, describe configurations in terms of nucleon pair couplings that automatically take care of the Pauli principle. We denote the four basis configurations using the convention $\left\{\left\{\pi\,{}^{2S+1}L_{J_\pi};\nu\,{}^{2S+1}L_{J_\nu}\right\}_J;L\right\}_{I^\pi}$ as follows:

$$\begin{aligned} |\,0\,\rangle &= \left\{\left\{\pi\,{}^1S_0;\nu\,{}^1S_0\right\}_0;0\right\}_{0+} \;;\; |\,1\,\rangle = \left\{\left\{\pi\,{}^3P_1;\nu\,{}^1S_0\right\}_1;1\right\}_{0+} \;; \\ |\,2\,\rangle &= \left\{\left\{\pi\,{}^1S_0;\nu\,{}^3P_1\right\}_1;1\right\}_{0+} \;;\; |\,3\,\rangle = \left\{\left\{\pi\,{}^3P_1;\nu\,{}^3P_1\right\}_0;0\right\}_{0+} \end{aligned} \tag{4}$$

We believe the contribution of nucleon pair $D$ state configurations would be relatively little for such small systems. A variational calculation then, might diagonalize a $4 \times 4$ Hamiltonian matrix of the above $0^+$ configurations. We do not attempt such a $^4$He structure calculation here, since it requires extensive exploration of nucleon-nucleon force parameters. We may note qualitatively several features. Admixture of the excited configurations $|\,1\,\rangle$, $|\,2\,\rangle$, and $|\,3\,\rangle$ into $|\,0\,\rangle$ will be small, as spin recouplings are involved. The mixing of configurations $|\,1\,\rangle$ and $|\,2\,\rangle$ with one another may be large, as their diagonal energies will be very similar by isobaric spin symmetry. Thus, we might suppose the first excited $0^+$ level to be the positive linear combination

$$|\,0^{+'}\rangle \approx \frac{1}{\sqrt{2}}(|\,1\rangle + |\,2\rangle) \tag{5}$$

and the possible resonance at d-d threshold to be the negative linear combination

$$|\,0^{+''}\rangle \approx \frac{1}{\sqrt{2}}(|\,1\rangle - |\,2\rangle). \tag{6}$$

The E0 matrix element between these two states is large

$$\rho^2 = \langle 0^{+'}\,|\sum_{p=1,2}\frac{r_p^2}{R^2}\,|\,0^{+''}\rangle = \frac{1}{2}\left[\langle 1\,|\sum_{p=1,2}\frac{r_p^2}{R^2}\,|\,1\rangle - \langle 2\,|\sum_{p=1,2}\frac{r_p^2}{R^2}\,|\,2\rangle\right] \tag{7}$$

with R = $1.2\mathrm{A}^{1/3}$ by convention. For a rough estimate of mean square charge radii, we use the harmonic oscillator estimate

$$\langle N_p\,|\,r^2\,|\,N_p\,\rangle = (N+\frac{3}{2})\frac{\hbar}{m\omega_0}, \tag{8}$$

where N is the principal oscillator quantum number and the shell spacing $\hbar\omega_0 = 41A^{-1/3}$ MeV. In configuration $|\,1\rangle$, $N_p = 1$ and in configuration $|\,2\rangle$, $N_p = 0$. Thus,

$$\rho^2 = \frac{\hbar}{2R^2 m\omega_0}\left[2(\frac{5}{2}) - 2(\frac{3}{2})\right] = 0.44, \tag{9}$$

and accordingly the transition to the first excited state has a partial width $\Gamma'_{pair}$ of $2.7 \times 10^{-7}$ ev.

The mixing between resonance and ground state dominant configurations will govern the E0 matrix element direct to ground. We can only set an upper limit of $\Gamma_{pair} < 3 \times 10^{-3}$ ev from the maximal mixing value $\rho^2 < 0.44$. In fact, the mixing is expected to be quite small since the subtractive linear combination constituting the resonance wave function would exactly cancel for charge-independent nucleon-nucleon forces.

The partial decay widths (and spectroscopic factors) for decay into the two particle emission channels will be proportional to the admixture of configuration $|\,0\,\rangle$ in the proposed resonance state. Since the particle-decay channels are over-barrier, their partial widths for unity spectroscopic factors will be several MeV. It seems unlikely that the mixing could be so small as to suppress them by ten orders of magnitude necessary for internal pair emission to dominate. Hence, we have no reasonable way to explain the large ratio of fusions to neutrons implied by the Pons-Fleischmann calorimetric measurements. In addition, it is difficult to see from our framework how the nuclear structure of these $0^+$ states could lead to a significant enhancement of the $^2$H(d,p)t reaction channel over that of $^2$H(d,n)$^3$He. We do believe that suppression of the particle-channel partial widths to the order of keV or less could result quite naturally from our scheme.

Thus, a $0^{+''}$ resonance narrow enough to have eluded earlier discovery and to enhance d-d tunneling could arise.

While it would seem a fortuitous accident of nature for this resonance to occur so close to the d-d threshold, there is the precedent of the $3\alpha$ resonance in $^{12}C$ that allows nucleosynthesis in red giant stars to get past the particle instability of $^{8}Be$.

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