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Brief Reports

Ortho- and paradeuterium effects in muon-catalyzed fusion

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We point out that in experiments on muon-catalyzed *d-d* and *d-t* fusion very sensitive tests of the theory of resonant molecular formation are provided by varying the ratio of ortho- to paradeuterium in the target. Results of calculations for the temperature dependence of the molecular formation rates for three different target conditions are presented.

Although first observed nearly three decades ago,[1] muon catalysis of hydrogen fusion has recently become a subject of intense interest.[2] One of the critical steps in the catalysis cycle is the formation of the muonic molecular ion, and for $dd\mu$ and $dt\mu$ the existence of the *resonant formation mechanism*[3] plays an essential role. In this process the initial kinetic plus binding energy goes into the vibration and rotation of the resulting compound molecule ($[(dd\mu)d2e]^*$, etc.), yielding formation rates that are significantly enhanced over the nonresonant (Auger) ones. The theory[4,5] of this process can and has been tested by measurements of the temperature dependence of the molecular formation rates.[6-10] For the $dd\mu$ case (where the temperature dependence of the molecular formation rate is not masked by *d*-to-*t* transfer as it is for $dt\mu$), the measurements[6] appear to be consistent with theory, but the experimentally determined value of the resonance energy is much more precise than the theoretical value.[2] The purpose of the present note is to point out that experiments which vary the ortho- to paradeuterium ratio in the target can provide valuable additional tests of the theory.

I. $dd\mu$ FUSION

In a pure deuterium target without paramagnetic or ferromagnetic walls, the transition between ortho- (total spin $S=2$ or 0) and para- ($S=1$) deuterium states is quite slow.[11] By passing the D_2 through an appropriate catalyst[12] at a controlled temperature, one can readily prepare targets of low-temperature (LT) *O-P* (ortho-to-para) ratio (i.e., all ortho), or high-temperature (HT) *O-P* ratio (i.e., 2:1) in addition to the equilibrium (E) *O-P* ratio. The *O-P* ratio influences the molecular formation through its effect on the population of even and odd initial molecular rotational states in the resonant reaction

$$d\mu + D_2 \rightarrow [(dd\mu)d2e]^* \; .$$

It is conventional to denote the vibrational and rotational quantum numbers of the initial deuterium molecule by v_i and K_i, the similar quantum numbers of the final electronic molecule by J and v. The collision is resonant if the rela- charge $+1$ and mass ~ 4 amu) by v_f and K_f, and the rotational and vibrational quantum numbers of the muonic molecule by v and J. The collision is resonant if the relative collision energy plus the binding energy of a weakly bound state of the muonic molecule match the change in rovibrational energy of the electronic molecule.

We use the formalism of Leon[5] and include the electron shielding correction discussed by Cohen and Martin.[13] The resonant collision energy ϵ_0 is taken to be 4.5 meV as reported by Zmeskal *et al.*[14] for the formation of (total spin) $S=\frac{1}{2}$ $dd\mu$ molecules from the collision of thermalized (total spin) $F=\frac{3}{2}$ $d\mu$ atoms with D_2 molecules. (This ϵ_0 corresponds to a binding energy of the $J=1$, $v=1$ state of the

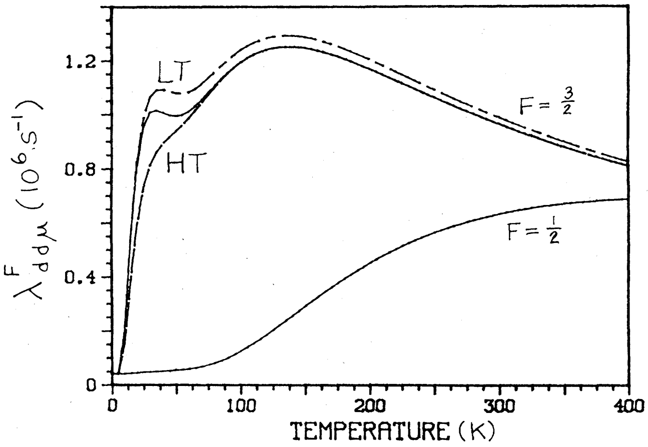

FIG. 1. Temperature dependence of the $dd\mu$ molecular formation rates for each $d\mu$ atom spin value F. Each F curve is the sum of transitions to total spin $S=\frac{3}{2}$ and $\frac{1}{2}$ of the $dd\mu$ molecule (see Ref. 14). For $F=\frac{3}{2}$, the LT and HT curves are marked, while the solid E curve lies between them. For $F=\frac{1}{2}$ the curves are identical.

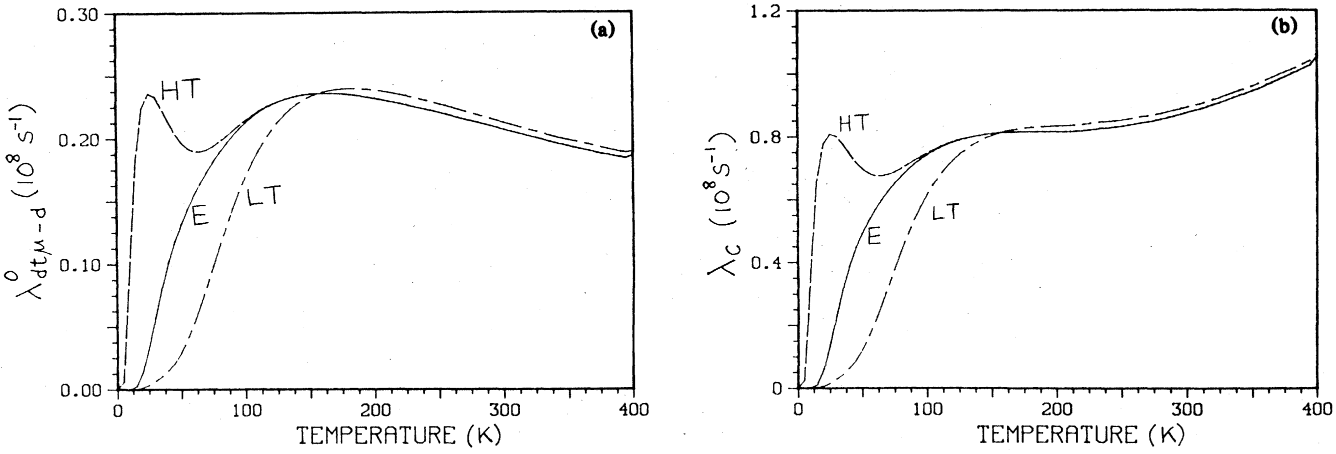

FIG. 2. (a) $dt\mu$ molecular formation rates for singlet $t\mu$ atoms colliding with D_2 molecules, with differing *O-P* ratios as marked. (b) Muon cycling rates corresponding to (a), for concentrations $C_{D_2}:C_{DT}:C_{T_2}=1:2:1$. The various parameters (see Ref. 5) have been chosen to give a reasonable fit (HT curve) to the data of Ref. 9.

$dd\mu$ molecule of 1.967 eV.) The resulting molecular formation rates for thermalized $d\mu$ atoms in the two initial states are shown in Fig. 1. The variation occurs because the $F=\frac{3}{2}$ molecular formation is completely dominated by the $(K_i=0)\rightarrow(K_f=1)$ transition at low temperature, and the K_i even population goes from $\frac{2}{3}$ to 1 upon changing from HT to LT. We see that a careful comparison of the shapes of the HT and the LT (or *E*) curves for $F=\frac{3}{2}$ in the temperature range below 50 K will provide a further test of the theory.

II. $dt\mu$ FUSION

Much larger differences are predicted for $dt\mu$ formation from singlet $(F=0)$ $t\mu$ atoms colliding with D_2 molecules, i.e., the reaction

$$(t\mu)^{F=0}+D_2\rightarrow[(dt\mu)d2e]^* \ .$$

Using the "canonical"[2] binding energy value of 0.64 eV, we find the molecular formation rates for thermalized $t\mu$ atoms shown in Fig. 2(a); the curves for the different targets are strikingly different for $T<100$ K. This is because the strong LT contribution is from the $(K_i=1)\rightarrow(K_f=3)$ resonance at 25 K, which is removed for LT and enhanced for HT. Since for high-density targets, like those used in the Jones *et al.*[9] experiment, the molecular formation rates are not directly observable, we exhibit the corresponding cycling rates in Fig. 2(b). (See Ref. 5 for the relation of the cycling rate to the molecular formation and other rates of the problem.) The various parameters used in the cycling rate calculation were chosen to give a reasonable fit to data of Jones *et al.*[9] and include an overall scaling of the molecular formation rates of a factor of 17. Most of this factor is needed to compensate for the reduction (by a factor of about 8) brought about by the inclusion of electron shielding.[13] We make the assumption that while the present Born-approximation calculation is not accurate for the very low collision velocities involved, the *relative* strengths of the contributions of various resonances, being determined by the energy balance equation and various rotational and vibrational matrix elements, *are* correctly given and the relative values of the molecular formation rates are therefore reliable. The fit to the data was made with the HT curve. Note that singlet collisions with DT, rather than D_2, molecules do *not* contribute at low temperature.[5,9]

In summary, it is clear that experiments which manipulate the *O-P* deuterium ratio in the target can provide some welcome additional tests of our understanding of the resonant formation mechanism.

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