attenuation, roughness, etc., in the solid surface make, at most, secondary contributions. The experimental situation is similar for metals [J. D. N. Cheeke, B. Hébral, and J. Richard, J. Low Temp. Phys. 12, 359 (1973)].

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Stability of Spin-Aligned Hydrogen at Low Temperatures and High Magnetic Fields: New Field-Dependent Scattering Resonances and Predissociations*

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Spin-aligned hydrogen (H↑) and deuterium (D↑) are generally predicted to be stable for $\mathcal{H}/T \gtrsim 10^6$ G/K. Magnetic-field-dependent resonances (inverse to field-induced predissociations of high vibrational-rotational levels of HD and D$_2$) provide exceptions to this general rule. Their existence suggests 50 kG (H↑ + D↑) and 19 kG (D↑ + D↑) should be avoided for stable H↑ and D↑. Induced predissociation observations should yield ultraprecise resonance information and dissociation limits.

Spin-aligned hydrogen (H↑) and deuterium (D↑) are extremely interesting but heretofore hypothetical substances with all electronic spin projections (M_s) parallel. Here only the lowest energy M_s is considered (e.g., $M_s = -\frac{1}{2}$ for H↑). H↑ and D↑ are especially simple, and complete understanding of all phenomena should be possible. For example, H↑ is predicted[1-3] to remain a gas down to absolute zero temperature (for pressures $\lesssim 50$ atm where it should solidify[2]) and to show strong quantum behavior[2] characteristic of a nearly ideal Bose gas (including Bose-Einstein condensation and superfluidity). D↑ is predicted[2] to be on the verge of liquidity at absolute zero temperature and low pressures (compared to a solidification pressure of ~ 8 atm), and unique liquid-gas equilibria of this highly quantal Fermi fluid should occur. T↑ is predicted[2] to be very similar to that of ^{4}He. The solid phases[4,5] and magnetic properties of these ferromagnetic substances should also be of major interest. The energy content per gram of H↑ is higher than any known substance; hence, it is possibly of interest for rocket propulsion[1,6-10] (which is the original motivation[6,7]).

It has been suggested[1,2,6,9] that H↑ and D↑ would be stable under low-temperature ($T \lesssim 1$ K), high-magnetic-field ($\mathcal{H} \gtrsim 50$ kG) conditions. Experiments under roughly these conditions on D/D$_2$ mixtures[8] and H/H$_2$ mixtures[9] suggest marginal stability for partial electronic spin alignment. The primary purpose here is to argue that long-

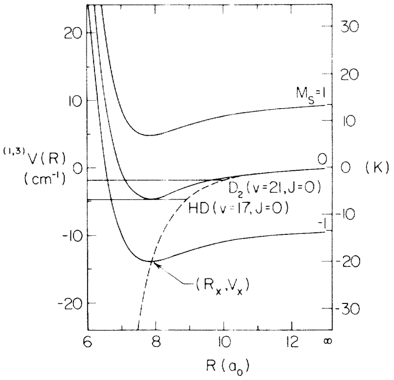

FIG. 1. Potential energy curves for $X^1\Sigma_g{}^+$ (---) and $b^3\Sigma_u{}^+$ (——) states of isotopic H_2. The three triplet components (the lowest being H↑+H↑) are shown for $\mathcal{H}=100$ kG. Note the crossing at (R_x, V_x) and the "long-range" levels of singlet HD$(v=17, J=0)$ and $D_2(v=21, J=0)$ which correspond to low-energy scattering resonances.

term stability (even at high densities) of pure H↑ and D↑ should occur for $\mathcal{H}/T > 10^6$ G/K (e.g., feasible combinations such as 100 mK and 100 kG).

In connection with these arguments, a new resonance mechanism for destruction of H↑ and D↑ at specific magnetic fields is presented. Resonance occurs when the lowest-energy asymptote of the $b\,^3\Sigma_u{}^+$ potential curve (proportional to $\mathcal{H}$) matches the ($\mathcal{H}$-independent) energy of the highest vibrational-rotational states of the $X^1\Sigma_g{}^+$ ground-state potential curve (Fig. 1). These high-lying levels ("long-range molecules") are of interest in their own right[11,12] since their properties are different and nonintuitive, but related to the long-range potential (e.g., $-C_6/R^6$). The inverse of the above resonant collisions, namely the magnetic-field-induced predissociation of long-range molecules is also discussed, with specific regard to isotopic H_2. Such predissociations should allow accurate determination of resonance parameters and dissociation limits.

Stability involves the rate of processes which destroy H↑ (and produce recombination to H_2 and destructive heating). Consider low-density gaseous H↑, in which three kinds of collisions are of concern: H↑-H↑, H↑-wall, and H↑-impurity. For higher densities, three-atom (and, ultimately, multi-atom) collisions become important.

The H↑-H↑ collisions are governed by precisely known[13,14] potential curves (Fig. 1). (Accurate close-coupled calculations[15] of these collisions are planned.) Recall that H has four hyperfine states (using Brown's notation[16]):

$$|1\rangle = \alpha a \;\leftarrow \mathrm{H}\!\downarrow \rightarrow\; |2\rangle = (1-\theta)^{1/2}\alpha b + \theta^{1/2}\beta a,$$

$$|3\rangle = \beta b \;\leftarrow \mathrm{H}\!\uparrow \rightarrow\; |2\rangle = (1-\theta)^{1/2}\beta a - \theta^{1/2}\alpha b.$$

Hence the collision of two H atoms involves 16 hyperfine "molecular" states.[16,17] For H↑-H↑, the possibilities are listed in Table I. Only relative angular momentum $J=0$ and $J=1$ collisions should be important at these low energies. Because $M = M_s + M_I$, J, and P_{AB} (the *atomic* permutation eigenvalue) are good quantum number, during collision (spin-rotation coupling is negligible), for energies below threshold only nondestructive scattering and $|3\rangle/|4\rangle$ exchange occur. For energies above threshold, destructive processes begin, but are dramatically suppressed by the small collision fraction with sufficient energy, i.e., by a factor $\exp[-E_T(K)/T(K)]$. [Bose statistics for H↑ do not modify this as $\exp(-E_T/T) \ll 1$.] Even

TABLE I. Low-energy H↑+H↑ collisions in hyperfine states $|3\rangle$ or $|4\rangle$ conserve $M = M_s + M_I$, P_{AB} (the *atomic* permutation eigenvalue), and J (relative angular momentum). Threshold energies E_T for channel openings at 100 kG, as well as approximate probabilities P [from Ref. 16, with $\gamma \equiv \exp(-E_T/T)$], are given.

M	P_{AB}	J	Initial		Final	E_T (K)	P
−2	1	0	$\|3,3\rangle$	→	$\|3,3\rangle$	0	1
−1	1 −1	0 1	$\left\{\begin{matrix}\|3,4\rangle\\ \|4,3\rangle\end{matrix}\right\}$	→	$\left\{\begin{matrix}\|3,4\rangle\\ \|4,3\rangle\end{matrix}\right\}$	0	$1-2\theta\Delta\gamma$
				→	$\|3,2\rangle, \|2,3\rangle$	13.4	$2\theta\Delta\gamma$
0	1	0	$\|4,4\rangle$	→	$\|4,4\rangle$	0	$1-4\theta\Delta\gamma-4\theta^2\Delta\gamma^2$
				→	$\left\{\begin{matrix}\|3,1\rangle, \|1,3\rangle\\ \|2,4\rangle, \|4,2\rangle\end{matrix}\right\}$	13.4	$4\theta\Delta\gamma$
				→	$\|2,2\rangle$	26.9	$4\theta^2\Delta\gamma^2$

for a very high density such as 10^{22} H↑/cm^3 (~solid H↑), one estimates a rough upper bound to the H↑-H↑ destruction rate (Ref. 16 with $\Delta = \frac{1}{2}$) at $E_T = 10$ K ($\mathcal{H} = 74.4$ kG) to be ~10^{24} atoms/cm^3 sec at 1 K (explosive!?), ~10^{-14} at 100 mK (geologically stable), and ~10^{-404} at 10 mK (infinitely stable). Indeed, this exponential energy factor is the key to stable H↑. Even if the selection rules ($\Delta M = 0$, $\Delta P_{AB} = 0$, $\Delta J = 0$, and $\Delta M_J = 0$) broke down slightly, the *destructive* collisions ($\Delta M_s = 1$) would still be negligible for small $\exp(-E_T/T)$ ($\mathcal{H}/T \gtrsim 10^3$ kG/K). Jones *et al.*[6] made much of the singlet-triplet crossing at (R_x, V_x) in Fig. 1. However, there are no energetically accessible states of the singlet curve below the $M_s = 0$ asymptote. For impractically high $\mathcal{H} > 520$ kG, this crossing point becomes energetically inaccessible.[18] Tri- (or poly-) atomic collisions should similarly be limited by the $\exp(-E_T/T)$ factor. Collisions with diamagnetic impurities (e.g., ^{4}He) and (e.g., Ne-coated, though perhaps H↑-covered) walls should be unimportant because no spins are present as well.

The only destruction mechanism found thus far involves D↑ impurities. As shown in Fig. 1 and Table II, the "long-range" $v = 17$, $J = 0$ level of $X^1\Sigma_g^+$ HD (symbolized HD$^\infty$) lies only 4.71 (±~0.5) cm^{-1} below dissociation. At 50.4 (±~5) kG, HD$^\infty$ becomes degenerate with the $M_s = -1$ asymptote, and hence mixing via the hyperfine interaction of previously bound HD$^\infty$ and the H↑-D↑ continuum occurs. [For H_2, the highest levels ($v = 14$, $J = 0$ and 1) do not become degenerate except for impractical fields of 1525 and 1365 kG.] This mixing has negligible effects on the potentials except near the crossing point (R_x, V_x), where most hyperfine states show avoided crossings ($M = -\frac{5}{2}$ does not). Landau-Zener-type treatments[19] indicate triplet-singlet transition probabilities of ~10^{-6}, predissociative lifetimes for HD$^\infty$ of ~10^{-6} sec, and field-dependent scattering resonance widths of ~10^{-5} K. The precise determination of such widths (and also energy shifts of ~10^{-5} K) particularly in the zero-energy limit (where modified effective-range theory[20] is appropriate) is a major motivation for the above-mentioned close-coupled calculations.

TABLE II. Binding energies $\epsilon_{v,J}$ of vibration-rotation levels near dissociation in HD [from I. Dabrowski and G. Herzberg, Can. J. Phys. 54, 525 (1976)] and D_2 (from Ref. 12b) and corresponding threshold magnetic fields $\mathcal{H}_T$ for field-induced predissociation.

Species	v	J	$\epsilon_{v,J}$ (cm^{-1})	$\mathcal{H}_T$ (kG)
HD$^\infty$	17	0	4.7_1	$50._4$
	17	1	0.0	0.0
D_2^∞	21	0	1.80_3	19.3_1
	21	1	-0.08_7	···

A direct study of the field-induced predissociation would be valuable, although the predissociation linewidth itself is too sharp. Several schemes for producing long-range levels are now contemplated in this laboratory. Since available magnetic fields are homogeneous and stable to $\lesssim 10^{-3}$ G (corresponding to ~10^{-7} cm^{-1}), the magnetic-field onset of predissociation should provide exceedingly accurate binding energies of long-range levels (e.g., determined as frequencies relative to proton NMR).

These Feschbach scattering resonances are harmless themselves (i.e., at very low densities) since they dissociate to H↑ + D↑. However, they involve long time delays[12a] (~10^{-6} sec) with appreciable singlet character, as opposed to ordinary nonresonant collisions with ~10^{-13}-sec time delays and negligible singlet character. Thus, at higher densities destructive processes such as HD$^\infty$ + H↑ → [HD($v < 17$) + H↑ + heat] or (H_2 + D↑ + heat), etc. will occur with small but significant rates *without input energy*. However, for $\mathcal{H} \gg \mathcal{H}_T$, the formation of HD$^\infty$ can be suppressed by $\exp(-E_R/T)$, where $E_R(K)$ is the resonance energy with respect to the field-dependent $M_s = -1$ asymptote.

In principle, paramagnetic impurities such as O_2 (in its lowest M_s state) also yield resonant destruction processes similar to (but more complex than) those outlined above. An additional complication for these species is the formation of clusters such as (H↑)$_n$(O_2↑) [species such as (H↑)$_n$ or (H↑)$_n$(D↑) should not be bound[1-3]]. Fortunately, the vapor pressure of O_2 is negligible (e.g., at 1 K $P_{O_2} \approx 10^{-78}$ Torr), but air leaks should be avoided!

While it might be possible to prepare H↑ only in the hyperfine state $|3\rangle$, and thereby seemingly avoid worrying about $\Delta M_s = 1, 2$ processes (Table I), in practice $\Delta M_I = 1$ processes should occur unless the nuclear Zeeman energy is much greater than kT (i.e., $\mathcal{H}/T > 10^9$ G/K). Thus no advantage is expected, except possibly at low density.

Spontaneous emission was considered and rejected by Jones *et al.*[6] (giving an estimated lower bound to lifetime of 3.4×10^{22} sec). Magnetic inhomogeneities (and instabilities) at boundaries could cause electronic Majorana transitions but should be avoidable.[21]

High-density and, ultimately, solid H↑ should not involve new destruction mechanisms. Moreover, local fields from adjacent atoms are still small [for a high density interatomic distance of $\sim 10a_0$, $\mathcal{H}_{\mathrm{local}} \sim \mu_B/(10a_0)^3 \sim 1$ G]. Destructive spin waves (magnons) should be unimportant for large $\mathcal{H}/T$.

Stability conditions for D↑ are like those for H↑. There are six hyperfine states for D (three for D↑) and 36 hyperfine molecular states.[17b] Again, only $J=0$ and $J=1$ collisions are important (except perhaps $J=2$ at ~ 1 K); and similar selection rules should be valid; in any case, the $\exp(-E_T/T)$ factor insures negligible spin-flip rate for $\mathcal{H}/T \gtrsim 10^3$ kG/K. In addition to HD^∞ (50.4 kG), there is a D_2^{∞} resonant level only $1.80_3 \pm 0.20$ cm^{-1} below singlet dissociation,[12b] corresponding to a 19.3 ± 2.0 kG threshold field to be avoided.

Stability predictions for other spin-aligned systems [e.g., N↑ or (Li↑)(H↑)] are hampered by lack of information on potentials and long-range levels and by anticipated clustering. Nevertheless, it is expected that additional stable spin-aligned systems can be prepared for large $\mathcal{H}/T$.

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