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Hydrogen Isotope Exchange between Fluoroform (CF_3H) and Water. 2. Catalysis by Hydroxide Ion in the Presence of Added Dimethyl Sulfoxide[1]

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Abstract: Hydroxide ion catalyzed isotope exchange between CF_3D or CF_3T and Me_2SO/water has been studied as a function of solvent composition and temperature in a stirred reactor. The solubility of CF_3H gas in the catalyst solutions has been measured over a range of temperatures to enable conversion of the experimental exchange rate constants to in-solution values. The resultant $k_{\text{obsd}}(CF_3D)$ for 0.011 $mol\cdot L^{-1}$ ^-OH at 49.1 °C increases by a factor of 10^6 on changing from water to 70 mol % Me_2SO. The heat of solution of CF_3H at 50 °C passes through a minimum in the region of 30–35 mol % Me_2SO; the "salting-out" effect on CF_3H solubility is also strongest in this region of greatest Me_2SO/H_2O association. Hydrolysis of CF_3H is a factor of ca. 600 slower than isotope exchange at 50 °C in 30 mol % Me_2SO. The slopes of linear plots of log $k_{\text{obsd}}(CF_3D)$ vs. H_- and vs. Cox and Stewart's excess basicity function are 0.80 and 0.99, respectively; their significance is discussed. The Arrhenius activation parameters (CF_3D) determined as a function of solvent composition have been broken down to enthalpy, entropy, and free energy of transfer functions for the reactants and transition state. Comparisons are made with similar data available for chloroform and molecular hydrogen. The primary kinetic isotope effect k_D/k_T, calculated from rate constant data for CF_3D and CF_3T exchange, increases smoothly from an inverse value in 20 mol % Me_2SO (ca. 0.4) to ca. 1.5 in 70 mol % Me_2SO. The above results are consistent with a product-like transition state for CF_3D isotope exchange.

It was shown in part 1[2] that, although reactivity is practically zero at ambient temperature,[3] gaseous CF_3H will undergo hydrogen isotope exchange in $NaOD/D_2O$ solution at elevated temperature. Because of our interest in developing an effective catalyst system for CF_3H/HOD isotope exchange,[2] we have studied the effect of added dimethyl sulfoxide (Me_2SO) on this hydroxide ion catalyzed reaction. It is well-known that many carbon acid reactivities are greatly enhanced under such conditions,[4] including that for the similar compound CCl_3H.[5]

It was found that this reaction with fluoroform gains the full advantage of the great increase in hydroxide ion basicity known for the alkaline aqueous Me_2SO system.[6,7] For CF_3D at 50 °C and 0.011 $mol\cdot L^{-1}$ hydroxide ion, the rate acceleration on changing from water to 70 mol % Me_2SO is a factor of 10^6. Reported below are the kinetic results of this study, including the solvent dependence of the in-solution exchange rate constant, kinetic isotope effects, and activation parameters, with the latter broken down to thermodynamic transfer functions for reactants and transition state.

Experimental Section

Reagents. CF_3H was used as received from Matheson.[2]

Initially, a batch of CF_3D was prepared by reacting CF_3I (PCR Research Chemicals, Inc.) with solid NaOD in anhydrous CH_3CH_2OD (cf. ref 8); however, the yield was less than 50%. Following discovery of the large activation energy for NaOD-catalyzed exchange of CF_3H with D_2O,[2] this reaction was adapted to the facile production of CF_3D. Half mole batches of CF_3H were contacted with 200 mL of 1 $mol\cdot L^{-1}$ $NaOD/D_2O$ in a 1-L stainless-steel tank heated to ca. 105 °C. Gentle agitation of the tank for 7 h was sufficient to produce complete equilibration of deuterium, yielding 97.6 mol % CF_3D as determined by mass spectrometry.

Similarly, tritium was introduced into fluoroform at the tracer level by using 1 $mol\cdot L^{-1}$ NaOH/HTO (23.5 $mCi\cdot L^{-1}$) as the catalyst solution. About 6000 counts per minute (cpm) were obtained for 1-mL product gas samples dissolved in 20 mL of Omnifluor in toluene (New England Nuclear, 4 $g\cdot L^{-1}$), using a Beckman LS250 scintillation counter.

Me_2SO (Fisher Scientific) was stored over activated 4A molecular sieves and then vacuum distilled, the central fraction being retained. Karl Fischer analysis on selected samples indicated an average 0.2 wt % water. Solid $Me_4NOH\cdot 5H_2O$ (Fisher Scientific) was used to make up stock aqueous Me_4NOH solutions. The $^-OH/H_2O/Me_2SO$ solvent mixtures were prepared by weight.

CF_3H Gas Solubility. Measurements were carried out by using the gas chromatographic procedure described earlier.[2] Net CF_3H pressure was maintained at 0.10 MPa; estimates of water/Me_2SO mixture vapor pressures were made from literature[9] data at 80 °C and the vapor pressures of pure Me_2SO and water between 25 and 80 °C.

Reproducibility of solubilities was generally ±1–2% for the 4–7 liquid samples taken from each solution over a period of 1 h or more after the CF_3H pressure had stabilized.

CF_3H Hydrolysis. As for the aqueous solution studies,[2] the formation of F^- ion was monitored by specific ion electrode. It was necessary to prepare NaF calibration solutions in the Me_2SO/water mixture of interest, since the absolute millivolt readings were quite dependent on solvent composition; however, the concentration–millivolt slope remained constant within experimental error.

Deuterium-Exchange Runs. The experimental procedure and data workup were as before.[2] CF_2H^+ and CF_2D^+ ion response factors were identical within 1%.

The vapor/solution conversion factor[2] decreased with increasing Me_2SO content in the solvent, as a result of the rise in fluoroform solubility. For example, at 49 °C the factor changed from 25 in water (0.94 $mol\cdot L^{-1}$ ^-OH) to 4.9 in 40 and 2.0 in 70 mol % Me_2SO (0.011 $mol\cdot L^{-1}$ ^-OH).

Tritium-Exchange Runs. The same reaction vessel was used as for the deuterium-exchange runs, with one modification. An Ace Glass threaded septum holder was glass blown horizontally to the side of the vessel top. One milliliter fluoroform gas samples could then be removed during a kinetic run by syringe. Each sample was immediately transferred to a "20-mL" scintillation vial (hole drilled in cap, fitted with a Teflon/silicone rubber septum) containing 20 mL of the fluid described above.

Plots of ln (net cpm) vs. time were linear for the period measured, up to several half-lives, with some scatter due partly, presumably, to nonuniformity of vial volumes. The solubility of CF_3H in toluene at 0.10 MPa was determined at 25 °C (see Results); calculations indicated that under the above sampling conditions more than 90% of the fluoroform in each vial would be in solution.

Results

CF_3H Gas Solubility. Shown in Figure 1 is the dependence of CF_3H solubility on mol % Me_2SO at 50.0 °C and 0.10 MPa

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(1) AECL Report No. 7293.

(2) Symons, E. A.; Clermont, M. J. *J. Am. Chem. Soc.*, preceding paper in this issue.

(3) Slaugh, L. H.; Bergman, E. *J. Org. Chem.* **1961**, *26*, 3158-2162.

(4) Buncel, E.; Wilson, H. *Adv. Phys. Org. Chem.* **1977**, *14*, 133-202.

(5) Margolin, Z.; Long, F. A. *J. Am. Chem. Soc.* **1973**, *95*, 2757-2762.

(6) Dolman, D.; Stewart, R. *Can. J. Chem.* **1967**, *45*, 911-924.

(7) Cox, R. A.; Stewart, R. *J. Am. Chem. Soc.* **1976**, *98*, 488-494.

(8) Banus, J.; Emeléus, H. J.; Haszeldine, R. N. *J. Chem. Soc.* **1951**, 60-64.

(9) Kenttämaa, J.; Lindberg, J. J. *Suom. Kemistil. B* **1960**, *33*, 98-100.

0002-7863/81/1503-3131$01.25/0

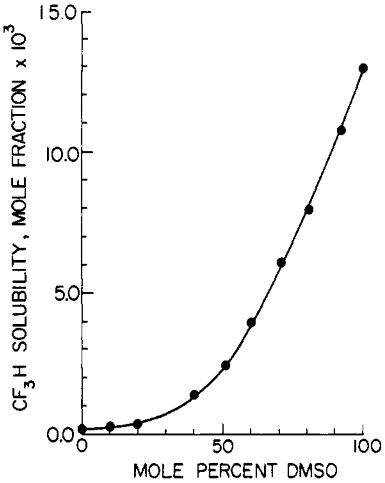

Figure 1. Solubility of fluoroform in Me_2SO/water mixtures at 50 °C and 0.10 MPa of CF_3H. Data points from smooth plots of solubility vs. temperature for each solvent composition (raw data in supplementary material).

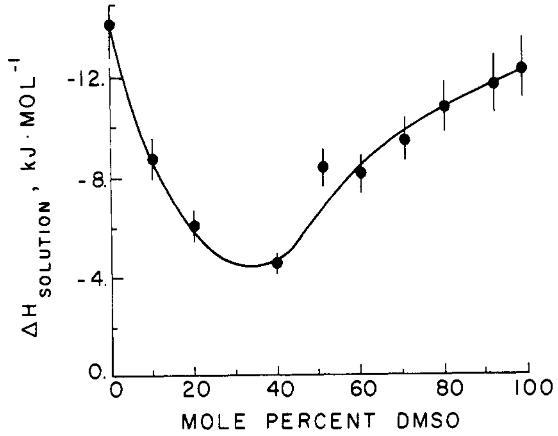

Figure 2. Dependence of heat of solution of fluoroform at 50 °C on solvent composition. Vertical bars represent ±10%.

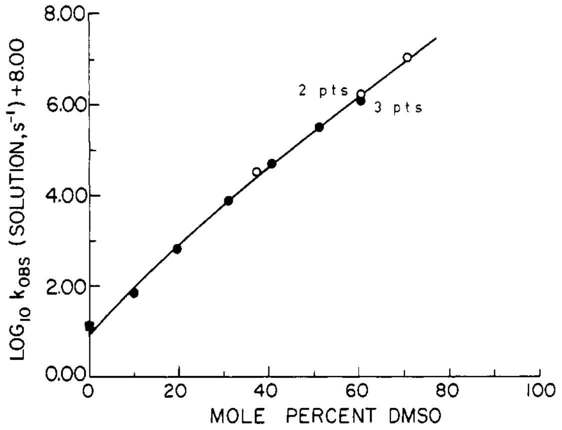

Figure 3. Dependence of in-solution rate constant for CF_3D exchange at 49.1 °C on solvent composition, with 0.011 mol·L^{-1} hydroxide ion: closed symbols, NaOH; open symbols, Me_4NOH. Value for water is from extrapolation of higher temperature and [$NaOD/D_2O$] data and the 70.7 % Me_2SO value from data at lower temperature.

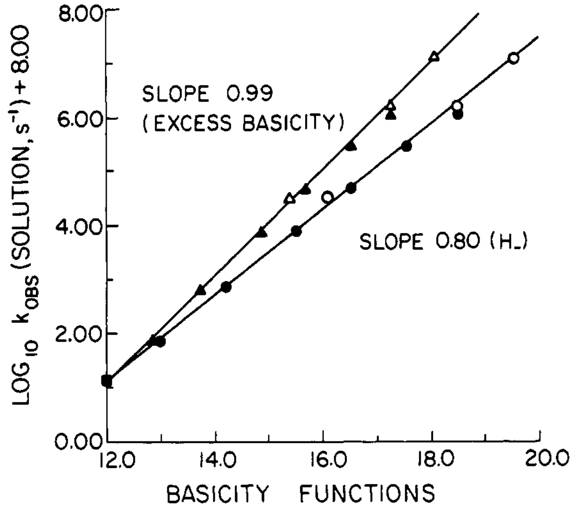

Figure 4. Dependence of in-solution rate constant for CF_3D exchange at 49.1 °C on basicity functions for the Me_2SO/water system. Symbols are defined in the Figure 3 caption; excess basicity + 12.0.

partial pressure of CF_3H. The solubility increase with added Me_2SO becomes quite marked above 40 mol % Me_2SO. The points for this plot were obtained from smooth curves through arrays of data measured as a function of temperature for each solvent (see Supplementary Material). Although the solvent mixtures contained low (for most, 0.01 mol·L^{-1}) concentrations of hydroxide ion, the effect on CF_3H solubility would be minimal at this level.[2] The solubility data are believed to be accurate within ±2%.

These data were calculated on a mole fraction basis. Where mol·L^{-1} values were required, the mole fraction data were converted by using the appropriate solvent mixture densities; the latter were interpolated from literature data at several temperatures.[10]

The effect of CF_3H partial pressure on its solubility was examined for 79.4 mol % Me_2SO at 30.0 °C. Henry's law was clearly obeyed over the range 0–120 kPa.

In Figure 2 is shown the change in heat of solution of CF_3H with solvent composition. The ΔH values were calculated from the slopes of tangents at 50 °C to plots of ln (mole fraction solubility) vs. reciprocal absolute temperature;[11] these plots were prepared from smooth curves drawn through solubility data at the various temperatures.

The solubility of CF_3H in toluene at 24.9 °C was found to be 1.06×10^{-2} mole fraction.

CF_3H Hydrolysis. The hydrolysis reaction was studied for only one Me_2SO/water mixture, 30.2 mol % Me_2SO containing 0.011 mol·L^{-1} NaOH at 50 °C. Hydrolysis is still quite slow, but the initial rate,[2] 3×10^{-9} mol·L^{-1}·s^{-1}, is about 3000× faster than that expected for pure water (based on the value measured with 1.0 mol·L^{-1} NaOH[2]). For this system, isotope exchange is still a factor of almost 600× faster than hydrolysis.

CF_3D Isotope Exchange. The effect of added Me_2SO on catalytic reactivity of the $^-OH/H_2O$ solution for CF_3D isotope exchange is shown in Figure 3 for 0.011 mol·L^{-1} hydroxide ion at 49.1 °C. The k_{obsd}(soln)[2] increases by a factor of 10^6 on changing from pure water to 70 mol % Me_2SO. The point at the latter composition was obtained by extrapolation of data at lower temperatures (1–30 °C), while the point for water was estimated from data at higher deuteroxide ion concentration and temperature (runs with CF_3H). Because reaction in solution is so rapid above about 70 mol % Me_2SO, no measurements were made beyond this point; suitably lower temperatures were not possible because of the relatively high freezing points of such solutions.

The correlation of rate constant with effective basicity of the solvent system is better shown in Figure 4, where log k_{obsd} is plotted against both the normal H_- function for the Me_2SO/water system with 0.011 mol·L^{-1} hydroxide ion[6] and the refined "excess basicity" function suggested by Cox and Stewart.[7]

The Arrhenius activation parameter functions given in Figure 5 were calculated[12] from rate constant data (CF_3D) obtained at

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(10) Cowie, J. M. G.; Toporowski, P. M. *Can. J. Chem.* **1961**, *39*, 2240–2243.

(11) Battino, R.; Clever, H. L. *Chem. Rev.* **1966**, *66*, 395–463.

(12) Bunnett, J. F. In "Technique of Organic Chemistry", 2nd ed.; Interscience: New York, 1961, Vol. VIII, Part I, p 177.

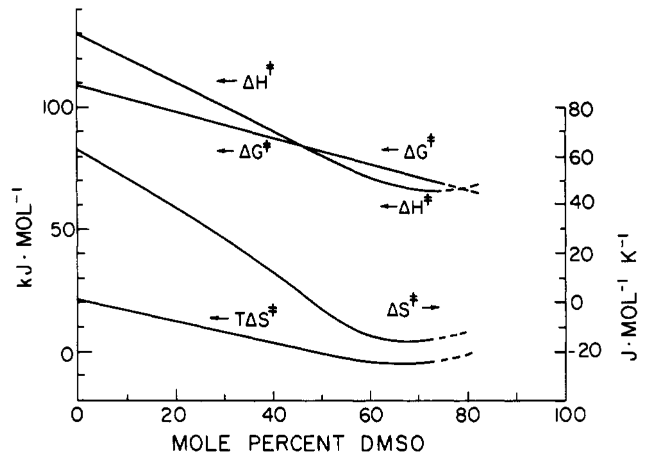

Figure 5. Dependence of activation parameters for CF_3D exchange at 49.1 °C on solvent composition.

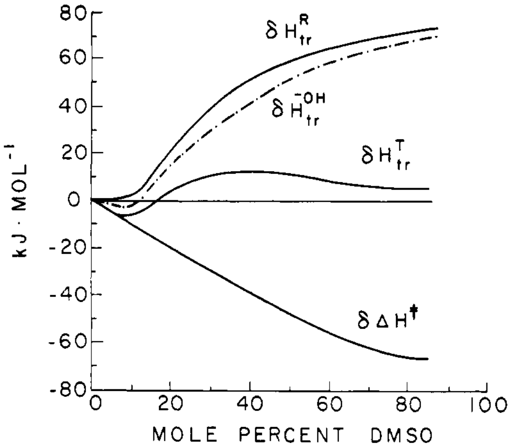

Figure 6. Enthalpy of transfer functions for ^-OH-catalyzed exchange of CF_3D in the Me_2SO/water system at 50 °C.

two or three temperatures over a range of at least 19 °C at each of the seven solvent compositions. These plots were derived from smooth curves drawn through the E_a and log k_{obsd} vs. mol % Me_2SO data. The E_a points fell within ±5 kJ of their curve. The value for water was measured with CF_3H at 0.94 mol·L^{-1} NaOD.

Where sufficient data are available, it is possible to determine for a given reaction the effect of solvent change on the enthalpy, entropy, and free energy of the transition state.[13] For the present reaction (eq 1), literature data for the enthalpy of transfer function

$$CF_3D + {}^-OH \rightarrow [CF_3{}^{\delta-}\cdots D^{\delta+}\cdot\cdot{}^{\delta-}OH]^{-\ddagger} \rightarrow \text{exchange} \quad (1)$$

for hydroxide ion in Me_2SO/water,[14] $\delta H_{tr}{}^{-OH}$, were combined with $\delta H_{tr}{}^{CF_3D}$ values derived from the change in heat of solution of CF_3H with solvent composition to obtain $\delta H_{tr}{}^{R}$ for reactants.[13] Differences between the CF_3H and CF_3D functions were assumed to be negligible. The function $\delta H_{tr}{}^{T}$, for the transition state, was then calculated via eq 2.[13] These enthalpy functions are plotted

$$\delta H_{tr}{}^{T} = \delta H_{tr}{}^{R} + \delta \Delta H^{\ddagger} \quad (2)$$

in Figure 6. The corresponding free energy function $\delta G_{tr}{}^{T}$ was obtained in a similar manner, by using $\delta G_{tr}{}^{-OH}$ literature data[15] (interpolation/extrapolation) and $\delta G_{tr}{}^{CF_3D}$ values derived from the CF_3H solubility data according to ref 16. Finally the entropy function $\delta TS_{tr}{}^{T}$ was determined via eq 3.[13] The δG, δH, and δTS transition-state functions representing CF_3D isotope exchange are

$$\delta G_{tr}{}^{T} = \delta H_{tr}{}^{T} - \delta TS_{tr}{}^{T} \quad (3)$$

given in Figure 7.

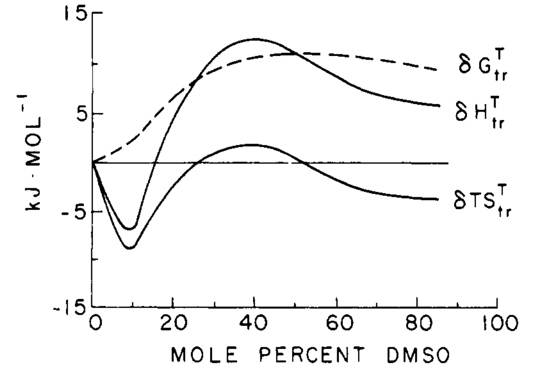

Figure 7. Enthalpy, entropy, and free energy of transfer functions for ^-OH-catalyzed exchange of CF_3D in the Me_2SO/water system at 50 °C.

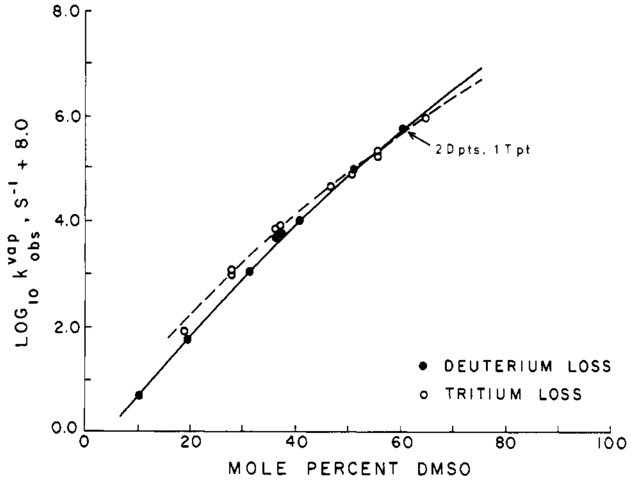

Figure 8. Dependence of the vapor-phase[2] rate constants for deuterium and tritium loss from fluoroform on solvent composition at 49.1 °C and 0.011 mol·L^{-1} hydroxide ion.

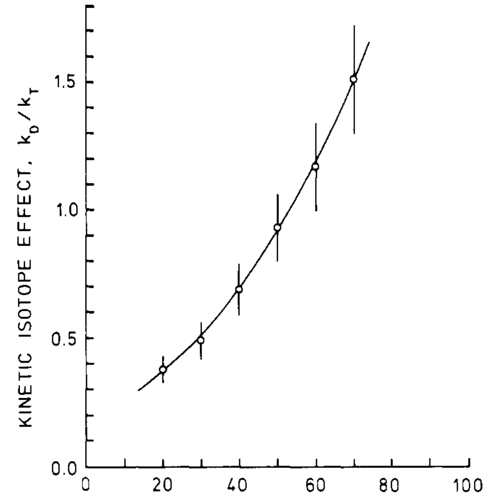

Figure 9. Dependence of the primary kinetic isotope effect for ^-OH-catalyzed CF_3D/CF_3T exchange at 49.1 °C on solvent composition.

The primary kinetic isotope effect k_D/k_T was determined by using data taken at 10 mol % Me_2SO intervals from smoothed plots of log k_D(vap) and log k_T(vap) (k_{obsd}(vap) defined in ref 2) for fluoroform exchange vs. solvent composition (Figure 8). Although k_H/k_D could be calculated via the equation[17] $k_H/k_D = (k_D/k_T)^{2.344}$, the k_D/k_T values are plotted as a function of solvent composition in Figure 9.

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[13] Buncel, E.; Wilson, H. *Acc. Chem. Res.* **1979**, *12*, 42–48.

[14] Fuchs, R.; Hagan, C. P.; Rodewald, R. F. *J. Phys. Chem.* **1974**, *78*, 1509–1511.

[15] Villermaux, S.; Delpuech, J. J. *Bull. Soc. Chim. Fr.* **1974**, 2534–2540.

[16] Abraham, M. H. *Prog. Phys. Org. Chem.* **1974**, *11*, 25.

[17] Streitwieser, A., Jr.; Hollyhead, W. B.; Pedjaatmaka, A. H.; Owens, P. H.; Kruger, T. L.; Rubenstein, P. A.; MacQuarrie, R. A.; Brokaw, M. L.; Chu, W. K. C.; Niemeyer, H. M. *J. Am. Chem. Soc.* **1971**, *93*, 5088–5096.

Discussion

CF_3H Gas Solubility. The shapes of the solubility and heat of solution curves in Figures 1 and 2, respectively, are consistent with other physical property data (e.g., ref 18 and references therein) that demonstrate the strong interaction between Me_2SO and water molecules in these mixtures. The 1:2 Me_2SO/H_2O complex formation manifests itself in the minimum observed for the CF_3H heat of solution in the region 30–35 mol % Me_2SO.

For a given solvent composition the "ideal"[18] CF_3H solubility at any temperature can be estimated from the amount of CF_3H that would dissolve independently in the two solvent components at that temperature. The calculated *difference* between a curve based on such values and the measured solubility as a function of solvent composition goes through a maximum, at e.g., 30 °C, near 35–40 mol % Me_2SO. The same behavior was seen for another inert gas, hydrogen.[18] In effect the CF_3H is "salted out" of the mixed solvents, with the effect being maximized in the region of strongest Me_2SO/water association.

CF_3D, $CF_3H(T)$ Isotope Exchange. (A) Acidity Function Correlations. The big increase in k_{obsd} for hydroxide ion catalyzed CF_3D exchange with water when Me_2SO is added as cosolvent is demonstrated in Figure 3. A more quantitative indication of the effect is given by the slope of 0.80 for the log k_{obsd} vs. H_- plot in Figure 4. This value compares with the range of smaller slopes, 0.23–0.36, seen for exchange of D_2 in the same solvent system.[19] The detritiation of Me_2SO itself produced a slope of 0.94.[20] For detritiation of another haloform, chloroform, log k was plotted against $H_- + \log([H_2O]/[^-OH])$[5]; the slope of the resultant straight line was 0.98. Cox and Stewart have suggested[7] that the "excess basicity" function $H_- - pK_w - \log[OH^-] + \log a_{H_2O}$ better represents the real change in solution basicity. This function is roughly parallel to, but offset from, that employed for the chloroform plot, so that the slopes of plots against either will be quite similar. For CF_3D exchange the plot against "excess basicity" (Figure 4) yields a slope of 0.99, in close agreement with the value above for the similar acid $CCl_3H(T)$. Note that the H_- data were determined at 25 °C, while the kinetic data were obtained at various temperatures (e.g., 50 °C for CF_3D).

If one makes the standard assumption that the slope of such basicity function plots can be equated with Brønsted β values for degree of proton transfer (e.g., ref 21–23), then the transition state for both fluoroform and chloroform exchange should be quite product-like, $[CF_3{}^{\delta-}\cdots\cdots D^{\delta+}\cdot{}^{\delta-}OH]^{-\ddagger}$.

The slope of 0.8 for the H_- plot for CF_3D changes to 1.0 when the excess basicity function is used. For cases such as Me_2SO detritiation where the H_- slope is already close to 1.0, the slope of the excess basicity plot becomes greater than one.[24] The significance of β greater than unity for the Me_2SO exchange case has not been explained,[24] although it has been suggested[21] that such values are possible for situations where the rate of the reverse reaction, i.e., reprotonation of the carbanion, is strongly dependent on change in the medium.

(B) Activation Parameters/Transfer Functions. The behavior of the activation parameters with change in solvent composition, shown in Figure 5, is similar to that seen for D_2 exchange in the same system.[25] However, the decline in $\Delta G^\ddagger$ is much greater for CF_3D exchange. In both cases the decreases in $\Delta H^\ddagger$ and $T\Delta S^\ddagger$ are complementary.

The results for chloroform detritiation are also similar to those for CF_3D over the solvent composition range available for comparison (0–24 mol % Me_2SO);[5] however, E_a for chloroform is always about 25 kJ·mol^{-1} lower than E_a for fluoroform. The deactivating effect of the fluorine atom relative to the chlorine atom on hydrocarbon acidity[26] is clearly demonstrated in this case. Chloroform is estimated[2] to be a factor of ~3 × 10^6 more reactive than fluoroform for ^-OH-catalyzed proton exchange in water at 0 °C. In 23.6 mol % Me_2SO at 25 °C the factor is almost the same, ~2 × 10^6, on the basis of data in Table III of ref 5 and on the E_a and 49 °C rate constant interpolated for CF_3D at this solvent composition.

A better indication of the general structure of the CF_3D-exchange transition state can be obtained from interpretation of the transfer functions shown in Figures 6 and 7. The distinct minimum seen near 10 mol % Me_2SO for the $\delta H_{tr}{}^{T}$ and $\delta TS_{tr}{}^{T}$ functions is a direct result of the dip measured for the $\delta H_{tr}{}^{-OH}$ function in this region;[14] the hydroxide ion undergoes a maximum in solvation at this point.[14] The magnitude of the $\delta H_{tr}{}^{T}$ function is close to that for $\delta H_{tr}{}^{CF_3D}$ (difference between two top curves in Figure 6), which suggests that solvation of the transition state is very similar to that of CF_3D, on an enthalpy basis. Thus the proton must be very close to the hydroxide ion, and the negative charge on the CF_3^- carbanion is dispersed onto the strongly electronegative fluorine atoms.[27] In fact, a comparison of $\delta H_{tr}{}^{T}$ with enthalpy of transfer data for halide ions[28] indicates solvation comparable to that for Cl^- up to 40 mol % Me_2SO but closer to that for Br^- above 50 mol %, again on an enthalpy basis.

As in the case of chloroform exchange,[29] over the region 0–10 mol % Me_2SO it appears to be increased solvation of the transition state that is responsible for the rate acceleration with added Me_2SO. Above 10 mol %, however, progressive desolvation of the hydroxide ion is the major contributor. For the D_2-exchange system, a localized charge was largely retained near oxygen in the transition state; there the $\delta H_{tr}{}^{T}$ function was only somewhat below the $\delta H_{tr}{}^{-OH}$ function.[25]

In Figure 7 the complementary behavior of the $\delta H_{tr}{}^{T}$ and $\delta TS_{tr}{}^{T}$ functions is reflected in the almost constant value of 10 ± 1 kJ·mol^{-1} seen for $\delta G_{tr}{}^{T}$ above ca. 30 mol % Me_2SO. By comparison, $\delta G_{tr}{}^{-OH}$ at 50 mol % is ca. 45 kJ·mol^{-1} and rising.

(C) Primary Kinetic Isotope Effect (KIE). The rather unusual dependence of the KIE on solvent composition (sharp rise from inverse to normal with added Me_2SO, Figure 9) raises an obvious question—is the effect real or does it arise from some error(s) in the data? Consistent k_D(vap) and k_T(vap) rate constant data (Figure 8) were obtained with different batches of reagents over a period of more than eight months. Therefore it is felt that the KIE results are valid. The indicated experimental error in the plotted points was derived from an assigned error of ±10% in the k values taken from the smooth curves in Figure 8.

What then is a reasonable explanation for the KIE results? When proton transfer to base is rate limiting, a "normal" kinetic isotope effect would be expected, with its magnitude dependent on the position of the proton in the transition state. The range of possible values, on changing from reactant-like to product-like transition state, is $1.0 \rightarrow (k_H/k_D)_{sym} \rightarrow K_H/K_D$,[30,31] the latter being the equilibrium isotope effect. In the present system the slopes of the basicity function plots and the behavior of the enthalpy of transfer functions (see above) strongly suggest that the proton is almost fully transferred over most of the solvent composition range. Thus it seems plausible that in water-rich solutions, where the hydroxide ion basicity is weakest (relative to in Me_2SO-rich solutions), the observed KIE is equal to K_D/K_T and that therefore the latter must be inverse. This is possible; for example, the corresponding equilibria involving D and T distribution between

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(18) Symons, E. A. *Can. J. Chem.* **1971**, *49*, 3940–3947.

(19) Symons, E. A.; Buncel, E. *Can. J. Chem.* **1973**, *51*, 1673–1681.

(20) Stewart, R.; Jones, J. R. *J. Am. Chem. Soc.* **1967**, *89*, 5069–5071.

(21) Albagli, A.; Stewart, R.; Jones, J. R. *J. Chem. Soc. B* **1970**, 1509–1512.

(22) Jones, J. R. *Prog. Phys. Org. Chem.* **1972**, *9*, 241–274. More O'Ferrall, R. A. *J. Chem. Soc., Perkin Trans. 2* **1972**, 976–982.

(23) Bowden, K.; Cook, R. S. *J. Chem. Soc., Perkin Trans. 2* **1972**, 1407–1411.

(24) Cox, R. A.; Stewart, R., private communication.

(25) Buncel, E.; Symons, E. A. *J. Am. Chem. Soc.* **1976**, *98*, 656–660.

(26) Hine, J.; Burske, N. W.; Hine, M.; Langford, P. B. *J. Am. Chem. Soc.* **1957**, *79*, 1406–1412.

(27) Cram, D. J. "Fundamentals of Carbanion Chemistry"; Academic Press: New York, 1965; p 11.

(28) Fuchs, R.; Hagan, C. P. *J. Phys. Chem.* **1973**, *77*, 1797–1800.

(29) Jones, J. R.; Fuchs, R. *Can. J. Chem.* **1977**, *55*, 99–101.

(30) Buncel, E.; Symons, E. A.; More O'Ferrall, R. A. *J. Am. Chem. Soc.* **1978**, *100*, 1084–1092.

(31) Melander, L.; Saunders, W. H., Jr. "Reaction Rates of Isotopic Molecules"; Wiley-Interscience: New York, 1979; pp 42–43.

Scheme I

Exchange

$$CF_3\text{-}D + {}^{-}OH \underset{}{\overset{\text{slow}}{\rightleftharpoons}} CF_3^{-} + DOH \qquad (4)$$

$$CF_3^{-} + HOH \overset{\text{fast}}{\rightleftharpoons} CF_3\text{-}H + {}^{-}OH \qquad (5)$$

Hydrolysis

$$CF_3^{-} \xrightarrow{\text{very slow}} :CF_2 + F^{-} \xrightarrow[o]{{}^{-}OH,\ H_2O} CO, HCO_2^{-}, F^{-} \qquad (6)$$

molecular hydrogen and water are inverse, with $K_D/K_T = 0.54$ at 25 °C.[32]

As the Me_2SO content of the solvent is increased, the hydroxide ion basicity also increases (cf. the H_- and excess basicity functions[6,7]), and the proton should move progressively away from ^{-}OH in the transition state.[33] This change would produce the observed smooth increase in KIE from the inverse value seen for water-rich solutions (Figure 9).

A problem with the above argument is that there is, for example, no corresponding decrease in the slopes of the basicity function plots as Me_2SO is added to the solvent (Figure 4). The reason may be that there is a difference in sensitivity of the two probes to changes in transition-state structure.[34] A similar situation arose for ionization of ethyl nitroacetate with a series of bases; while the log k vs. pK_a plot was essentially linear, the k_H/k_D ratio passed through a distinct maximum.[36] In the present case it would be valuable to have KIE and basicity function dependence data to beyond 90 mol % Me_2SO. An alternate means of sample recovery or gas/solution contact would be necessary because the in-solution reaction becomes so fast.

Margolin and Long reported[5] a value of $k_H/k_D = 1.42$ for hydroxide-catalyzed exchange of chloroform with water at 25 °C. However, the experimental method involved relative rates of tritium *uptake* from the solvent by CCl_3H and CCl_3D; there is some concern about the validity of such an approach,[37] and values nearer to 1.0 might always be expected under such conditions.[37]

(D) Fluoroform Exchange/Hydrolysis Mechanism. Both hydrolysis and hydrogen isotope exchange of fluoroform, catalyzed by hydroxide ion, should proceed via the same initial stage, i.e., proton transfer, as indicated in Scheme I. For *hydrolysis* of most trihalomethanes, the faster step is considered to be *reversible* formation of the trihalomethyl anion, with halide ion loss from the latter being rate limiting.[38] While the fluorine atom is the best (relative to the other halogens) for stabilizing $:CX_2$, it is the least effective in stabilizing the CX_3^- ion.[38] The latter observation is counter to that predicted from a simple inductive effect argument[26] (i.e., CF_3H is much less, not more, reactive than CCl_3H for hydrolysis and exchange). Hine et al.[26] considered qualitatively several possible reasons for this reversal in ability of halogen atoms to activate haloforms for carbanion formation; factors included were d orbital resonance, steric strain among the three halogen atoms in the tetrahedral haloform, and polarizability. They favored a combination of polarizability and the inductive effect. In addition, destabilization of the CF_3^- ion arising from repulsion between the free-electron pair on carbon and the electron pairs in the p orbitals of the fluorine atoms may be involved[39] (the "α effect").

The structure of the transition state for the slow proton-exchange step, eq 4, is quite product-like, i.e., $[CF_3^{\delta-}\cdots\cdots D^{\delta+}\cdot{}^{\delta-}OH]^{-\ddagger}$, on the basis of our results as discussed earlier. The final products suggested for the hydrolysis step, eq 6, are analogous with those observed for the more rapid chloroform hydrolysis reaction.[40]

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Supplementary Material Available: A table of CF_3H solubilities as a function of solvent composition and temperature and the figure showing CF_3H solubility dependence on CF_3H pressure at 30 °C, 79.4 mol % Me_2SO (2 pages). Ordering information is given on any current masthead page.

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(32) From $K_D = 3.806$: Rolston, J. H.; den Hartog, J.; Butler, J. P. *J. Phys. Chem.* **1976**, *80*, 1064–1067. $K_T = 6.996$: Butler, J. P., private communication.

(33) Bordwell, F. G.; Boyle, W. J., Jr. *J. Am. Chem. Soc.* **1972**, *94*, 3907–3911.

(34) It has been suggested that (a) from studies involving deprotonation of several types of carbon acids by a series of bases, "... the *absolute* size of β for carbon acids can provide, therefore, little or no information concerning the nature of the transition state of the deprotonation",[33] (b) from studies of several base-catalyzed proton-transfer reactions in different types of solvent mixtures, "... the use of solvent variation to alter the total free-energy change occurring during proton-transfer reactions does not lead to normal Brønsted β values..."[35].

(35) Cox, B. G.; Gibson, A. *J. Chem. Soc., Chem. Commun.* **1974**, 638–639.

(36) More O'Ferrall, R. A. In "Proton Transfer Reactions"; Caldin, E., Gold, V., Ed.; Chapman and Hall: London 1976; Chapter 8, pp 230–231.

(37) Powell, M. F.; Kresge, A. J., Chemistry Department, University of Toronto, private communication.

(38) Hine, J. "Physical Organic Chemistry", 2nd ed.; McGraw-Hill, New York, 1962; pp 484–488.

(39) Edwards, J. O.; Pearson, R. G. *J. Am. Chem. Soc.* **1962**, *84*, 16–24. Faird, R.; McMahon, T. B. *Can. J. Chem.* **1980**, *58*, 2307–2311.

(40) Hine, J. *J. Am. Chem. Soc.* **1950**, *72*, 2438–2445.