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Kinetic Isotope Effect and Tunnelling in the Reaction between 4-Nitrophenylnitromethane and Pentamethylguanidine in Acetonitrile and Toluene

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Rates and activation parameters for the proton and deuteron transfer reaction of 4-nitrophenylnitromethane with pentamethylguanidine in acetonitrile have been determined. The isotope effect and differences in activation parameters are larger than the semiclassical limits and suggest a small but significant tunnel correction. The results are well accounted for by Bell's equation for tunnelling through a parabolic barrier. Comparison of the results for acetonitrile with previously obtained values for toluene show that there is no significant effect of the solvent polarity on the tunnel correction.

Recent studies of kinetic hydrogen isotope effects in the proton transfer reaction of 4-nitrophenylnitromethane (4-NPNM) with tetramethylguanidine [TMG; $NH{=}C(NMe_2)_2$] showed large variations of k^H/k^D with the solvent.[1] Unusually high isotope effects ($k^H/k^D = 45$) were found in non-polar solvents such as toluene, while in the more polar solvents dichloromethane and acetonitrile much smaller values ($k^H/k^D = 11$) were observed. These results were interpreted in terms of tunnelling and suggested that the magnitude of the tunnel correction is strongly dependent upon the polarity of the solvent.

We have, however, presented evidence that the deuteron transfer reaction of 4-NPNM with TMG in toluene is complicated by isotopic exchange and that the isotope effect is considerably smaller than reported, probably only ≈ 11.[2] Thus there is probably no significant effect of the polarity of the solvent on the isotope effect and tunnel correction. As a further investigation of this question the isotope effect and its temperature variation have been determined for the reaction of 4-NPNM with pentamethylguanidine [PMG; $CH_3N{=}C(N\ Me_2)_2$] in acetonitrile and compared with data previously obtained in toluene.[3]

The complications due to isotopic exchange encountered in the reaction of 4-NPNM with alkylamidines [4] and TMG [2] are much less severe with PMG, which does not contain an exchangeable proton on the basic nitrogen atom. PMG is also a stronger base than TMG giving a larger equilibrium constant and a more irreversible reaction, and is thus less influenced by exchange. PMG may therefore be expected to give a more reliable measure of the effect of solvent polarity on the isotope effect and tunnel correction than can be obtained with TMG.

EXPERIMENTAL

MATERIALS

Pentamethylguanidine was prepared according to Lecher and Graf;[5] b.p. 159-160°C (lit. 155-160°C). 4-Nitrophenylnitromethane was prepared by the method of Cooke and McBeth;[6] m.p.

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90-91°C (lit. 91°C) and the deuteriated analogue was prepared from this by exchange with sodium methoxide + methan[^{2}H]ol in deuterium oxide.[7] The deuterated acid was at least 95 % deuterated as judged from the n.m.r. spectrum. Acetonitrile was stirred with calcium hydride, decanted and fractionally distilled from phosphorous pentoxide.

APPARATUS AND PROCEDURE

Absorption spectra were determined on a Cary 118C spectrophotometer. Rate constants were generally determined by following the increase with time of the absorbance at 490 nm, using a Canterbury SF-3A stopped-flow spectrophotometer (Nortech Laboratories Ltd). The signal from the stopped-flow apparatus was digitized and read out on a typewriter by an Intertechnique Didac 800 digital data-processing system. All kinetic measurements were made under first-order conditions with the base in excess. First-order rate constants were calculated by fitting 12-15 readings of approximately equally spaced absorbance to the first-order rate equation by the LSKIN1 programme of DeTar.[8] Second-order rate constants were obtained by a least-squares treatment of the observed first-order rate constant against concentration of base. Activation parameters were calculated from a least-squares treatment of $\ln(k/T)$ against T^{-1} All uncertainties quoted are standard deviations.

The heat of reaction was determined calorimetrically by measuring the heat evolved on breaking a 1 cm^3 ampoule containing a solution of 4-NPNM in acetonitrile in 100 cm^3 of a PMG solution in acetonitrile. Final concentrations of 4-NPNM and PMG were 1×10^{-4} and 8×10^{-3} mol dm^{-3}, respectively. The correction for the heat of dilution of the 4-NPNM solution was negligible. The calorimeter has been described elsewhere.[9]

RESULTS

The visible spectra of the reaction mixture show a single broad absorption band with a maximum at 490 nm and a molar absorptivity of 28 500 dm^3 mol^{-1} cm^{-1}. Identical spectra were obtained in the reactions of 4-NPNM with TMG and triethylamine in acetonitrile and shown by n.m.r. and equilibrium measurements to be a reversible proton-transfer giving rise to an ion pair:[1, 7]

$$NO_2C_6H_4CH_2NO_2 + B \underset{k_b}{\overset{k_f}{\rightleftharpoons}} NO_2C_6H_4CHNO_2^- \; HB^+. \qquad (1)$$

In toluene a similar spectrum to that in acetonitrile was obtained, but with a maximum at 445 nm. Both the proton- and deuteron-transfer reactions showed good first-order kinetics in runs with the base in excess. The small deviation from first-order kinetics observed in toluene for the deuteron-transfer reaction [3] was not noticeable in acetonitrile. Plots of the observed first-order rate constants against base concentration were linear, in agreement with

$$k_{obs} = k_f\,(B) + k_b \qquad (2)$$

which follows from eqn (1) when the base is in large excess. Rate constants and activation parameters are summarized in tables 1 and 2. The rate constants in table 2 for 25°C are calculated from the Arrhenius plot. The plots of k_{obs} against base concentration according to eqn (2) gave intercepts which were not significantly different from zero. Thus k_b is small and the equilibrium constant for eqn (1) large. Attempts to measure the equilibrium constant spectrophotometrically were unsuccessful and showed that the reaction went almost to completion. A few runs were performed in acetonitrile containing 0.3 % water, without any significant effect on the kinetics or the rate constants.

TABLE 1.—RATE CONSTANTS FOR THE PROTON- AND DEUTERON-TRANSFER REACTIONS OF 4-NPNM + PMG IN ACETONITRILE[a]

temp/°C	$10^{-4}\ k^{H}/dm^3\ mol^{-1}\ s^{-1}$	$10^{-3}\ k^{D}/dm^3\ mol^{-1}\ s^{-1}$	k^{H}/k^{D}
35		9.41 ± 0.05 (9.13)[b]	
25	6.96 ± 0.07 (6.95)[b]	6.51 ± 0.22 (6.74)	10.7 ± 0.4 (10.3)
15	5.62 ± 0.07 (5.61)	4.94 ± 0.22 (4.88)	11.4 ± 0.5 (11.5)
5	4.57 ± 0.07 (4.48)	3.38 ± 0.03 (3.46)	13.2 ± 0.2 (13.0)
−5	$3.55 + 0.10$ (3.55)	2.45 ± 0.05 (2.40)	14.5 ± 0.5 (14.8)

[a] Concentration of NPNM and [$^2H_2$]NPNM = 8×10^{-6}-2×10^{-5} mol dm^{-3}. Concentration of PMG, for proton transfer = 1.8×10^{-4}-3.8×10^{-3} mol dm^{-3}, for deuteron transfer = 1.2×10^{-3}-1.7×10^{-2} mol dm^{-3}. [b] Values calculated from eqn (3) with parameter values from table 3.

TABLE 2.—ISOTOPE EFFECTS AND ACTIVATION AND EQUILIBRIUM PARAMETERS FOR PROTON- AND DEUTERON-TRANSFER REACTIONS OF 4-NPNM + PMG IN ACETONITRILE AND TOLUENE AT 25°C

1 cal ≡ 4.184 J

	acetonitrile	toluene[a]
$10^{-4}k^{H}/dm^3\ mol^{-1}\ s^{-1}$	6.94 ± 0.03	4.69 ± 0.09
$\Delta H^{\ddagger H}$/kcal mol^{-1}	3.01 ± 0.04	2.4 ± 0.3
$\Delta S^{\ddagger}$/cal K^{-1} mol^{-1}	-26.3 ± 0.1	-29 ± 1
$\log A^{H}$	7.46 ± 0.03	6.88 ± 0.20
$10^{-3}k^{D}/dm^3\ mol^{-1}\ s^{-1}$	6.75 ± 0.13	3.39 ± 0.06
$\Delta H^{\ddagger D}$/kcal mol^{-1}	4.9 ± 0.2	4.6 ± 0.3
$\Delta S^{\ddagger D}$/cal K^{-1} mol^{-1}	-24.5 ± 0.6	-27 ± 1
$\log A^{D}$	7.85 ± 0.14	7.29 ± 0.18
k^{H}/k^{D}	10.3 ± 0.2	13.8 ± 0.4
$\Delta H^{\ddagger D} - \Delta H^{\ddagger H}$/kcal mol^{-1}	1.9 ± 0.2	2.2 ± 0.4
$\log (A^{D}/A^{H})$	0.39 ± 0.14	0.4 ± 0.3
$10^{-4}K^{H}/dm^3\ mol^{-1}$		1.1 ± 0.1
ΔH°/kcal mol^{-1}	-14.3 ± 0.5[b]	-12.9 ± 0.5
ΔS°/cal K^{-1} mol^{-1}		-25 ± 2

[a] Values from ref. (3). [b] Determined calorimetrically.

DISCUSSION

The reaction of 4-NPNM with PMG in acetonitrile and toluene is in general similar to that with TMG. The visible absorption spectra of the reaction product, identified as the coloured anion $NO_2C_6H_4CHNO_2^-$, is identical for the two bases and show the same shift in absorption maximum from 445 to 490 nm on going from toluene to acetonitrile. Such a bathochromic shift (up to 100 nm) in the absorption maximum for the 4-NPNM anion is general for a non-polar to polar aprotic solvent change.[1] The magnitude of the shift suggests that different absorbing species are involved [10] rather than merely an increased solvation of the excited state in the more polar solvent.[1] Possible species may be different types of ion pairs, a differently solvated anion or higher polymeric complexes. This has not been investigated, but does not affect the interpretation of the isotope effect, since any further rearrangement or reaction of the anion will occur after the rate-determining proton-transfer.

The molar absorptivity of the reaction product, 28 500 dm^3 mol^{-1} cm^{-1}, is identical within experimental error to that observed with TMG and other nitrogen bases. The only exception is triethylamine in acetonitrile where, although the absorption spectrum is the same as for other bases, the molar absorptivity is 10 000 $dm^3\ mol^{-1}\ cm^{-1}$.[7]

The effect of changing the solvent from toluene to acetonitrile on the rate and activation parameters (table 2) is in the same direction as that observed in reactions with TMG, triethyl- and tributyl-amine.[7, 11] The magnitude of the solvent effect is small for the present reaction but increases with a decrease in the equilibrium constant along the series PMG, TMG, Et_3N and Bu_3N. A parallel increase in activation energy is observed. This is consistent with a transition state occurring progressively further along the reaction coordinate with decreasing basicity of the base, giving rise to increased bond formation, charge development and interaction with the solvent.

In contrast to the general similar behaviour of PMG and TMG referred to above is the effect of solvent on the kinetic isotope effect. For PMG a change from toluene to acetonitrile has a very small and barely significant effect on k^H/k^D (table 2), whereas for TMG such a solvent change apparently reduced k^H/k^D from 45 to ≈ 12. This discrepancy is removed if it is accepted that the value for TMG in toluene is in error due to isotopic exchange and that the true value is ≈ 11.[2]

The rate and activation parameters in table 2 show qualitative evidence for tunnelling. Thus the isotope effect and the difference in observed activation parameters, $E_a^D - E_a^H$ and A^D/A^H, are all greater than the " semi-classical " limits of 7, 1.1 kcal mol^{-1} and 2, respectively, based on the loss of vibrational zero-point energy in the transition state. The difference in the parameters between toluene and acetonitrile is small and probably not significant. Thus there is no experimentally detectable difference in the magnitude of the tunnel correction between the two solvents. The idea [1] that the transfer of the proton should be coupled to motions of solvent molecules for polar solvents such as acetonitrile, but not for those that are non-polar, like toluene, resulting in an increased effective mass and reduced tunnelling, is not supported by the present results. To assess the magnitude of the tunnel correction the experimental rate constants were fitted to Bell's equation [12] using the program GENLSS by DeTar.[13] GENLSS is a general program for obtaining a least-squares fit of parameters of virtually any function. The user supplies two short subroutines ($\approx$ 100 lines in the present case) to identify the expression being treated, the variables and the parameters. For tunnelling through an unsymmetrical truncated parabola, the equations are:[1, 12]

$$k_{obs} = Q\,A_s \exp(-E/\boldsymbol{R}T) \tag{3}$$

where

$$Q = \tfrac{1}{2}u/\sin\tfrac{1}{2}u - u\exp(E/\boldsymbol{k}T)\left(\frac{y}{2\pi-u} - \frac{y^2}{4\pi-u} + \dots\right) \tag{4}$$

and

$$u = \boldsymbol{h}\nu/\boldsymbol{k}T,\ y = \exp(-2\pi E/\boldsymbol{h}\nu),$$
$$\nu = [E^{\frac{1}{2}} + (E-\Delta H^\circ)^{\frac{1}{2}}]/2\sqrt{2}\,\pi b m^{\frac{1}{2}};^*$$

E is the height of the barrier, A_s the pre-exponential factor that would be found in the absence of tunnelling, $2b$ the width at the base of the unsymmetrical barrier and ΔH° the standard enthalpy change. The mass m was taken as 1 and 2 a.m.u. for the proton

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* This expression for ν in ref. (1), [eqn (7)] contains an error.

and deuteron, respectively. The usual assumptions [1, 14] were made that $A_s^H = A_s^D$ and that the curvature of the barrier for both proton and deuteron is the same. Three terms were always used in eqn (4). An automatic test for the necessity of using additional terms, based on the criterion of a relative contribution of 1 p.p.m., was included in the program.

The results for acetonitrile are given in table 3 and confirm the conclusion that there is a small but significant tunnel correction which makes an appreciable contribution to the isotope effect. The calculated values for the barrier characteristics are reasonable in terms of molecular dimensions and similar to those calculated for other proton-transfer reactions with moderate tunnel corrections.[14] As can be seen from table 1 the calculated parameters are able to reproduce the observed rate constant to better than ±4 % over the temperature range studied.

TABLE 3.—TUNNEL CORRECTION AND BARRIER PARAMETERS FOR THE REACTION BETWEEN 4-NPNM AND PMG IN ACETONITRILE

1 cal ≡ 4.184 J

E^H/kcal mol^{-1}	4.9 ± 0.4^a
E^D/kcal mol^{-1}	6.0 ± 0.3
A_s^H/dm^3 mol^{-1} s^{-1}	$(1.21 \pm 0.46) \times 10^8$
$2b^H$/Å	1.16 ± 0.13
$2b^D$/Å	1.22
Q^H(25°C)	2.40
Q^D(25°C)	1.45
ν^H/cm^{-1}	870
ν^D/cm^{-1}	618
$(k^H/k^D)_s^b$	6.4

[a] Standard deviation. [b] Semiclassical isotope effect or zero point energy contribution.

The method of fitting experimental data to Bell's equation used in this study is different and more statistically sound than that employed by Caldin and Mateo [1] and others.[15-17] Although not initially realised, it is now clear that the original method cannot give unique values for the barrier parameters, but only for combinations of E^H, E^D and b.[17] This arises from the use of differences in Arrhenius parameters, A_a^H/A_a^D and $E_a^D - E_a^H$, as experimentally determined quantities rather than the individual rate constants, k^H and k^D. With the latter, as used in the present method, enough independent experimentally determined quantities are available, together with the assumptions of constant curvature and A_s^H/A_s^D = constant, to fix the four parameters A_s^D, E^H, E^D and b. The use of the least-squares technique is an advantage in that it provides each calculated parameter with a standard deviation, not obtainable with the other methods used.[1, 17] This is highly desirable since poor experimental data may also give values for the various parameters, although they may not have any statistical significance. Thus the data for toluene,[3] which is slightly affected by exchange and shows more scatter, gave parameter values similar to those in acetonitrile but with poor precision. The previously used [1] restriction of $E^D - E^H \leqslant 1.2$ kcal mol^{-1} is unnecessary with the present method and its removal does not lead to physically impossible solutions.

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