Fractionation Factors for the Aqueous Hydroxide Ion and Solvent Isotope Effects on the Ionisation of 1,8-Bis(dimethyamino)naphthalene (Proton Sponge)

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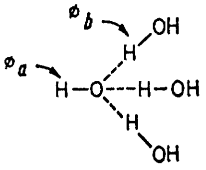
Isotopic fractionation factors ϕ_a and ϕ_b for the hydroxy hydrogen and hydrogen-bonded water hydrogens of the solvated hydroxide ion are important in controlling solvent isotope effects upon reactions involving the hydroxide ion, and were required for a vibrational analysis of the solvated ion. The product $\phi_a\phi_b^3 = 0.434$ is accurately available from e.m.f. measurements corrected for free energies of ion transfer between H_2O and D_2O, but separation of ϕ_a and ϕ_b, which requires measurements in H_2O–D_2O mixtures, is known to be subject to considerable uncertainty. Thus careful measurements with 1,8-bis(dimethylamino)naphthalene gave $K_{D_2O}/K_{H_2O} = 0.420 \pm 0.006$ for the ratio of basic ionisation constants in H_2O and D_2O and $\phi_P = 0.901 \pm 0.014$ for the fractionation factor of the protonated base, but measurements in 1 : 1 H_2O–D_2O gave an ionisation constant too small to be consistent with any reasonable fractionation factor model for the hydroxide ion. Alternative methods of dissecting ϕ_a and ϕ_b, from measurements of isotope separation factors between hydroxide solutions and water vapour and autoprotolysis constants of H_2O–D_2O mixtures, are critically reviewed and optimum values are assessed. The results are shown to be sensitive to experimental error and to medium effects but not to departures from the Rule of the Geometric Mean.

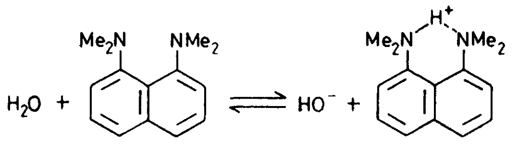
SOLVENT isotope effects offer a valuable tool for the investigation of acid- and base-catalysed reactions.[1-7] However, their interpretation requires an understanding of the isotopic fractionation of the hydronium ion and hydroxide ion, and while for the hydronium ion this understanding has been largely achieved,[7-11] for the hydroxide ion in important respects it is still lacking. In 1967 Gold and Lowe made the useful suggestion that contributions to hydroxide isotope effects should be considered as arising both from the hydrogen of hydroxide itself and from three hydrogens hydrogen-bonded in its primary solvation shell (1).[12] Writing fractionation factors for these hydrogens ϕ_a and ϕ_b, where ϕ denotes the D : H ratio at the hydrogen site relative to that of the bulk solvent in mixed isotopic solutions, the net contributions to kinetic and equilibrium isotope effects involving the hydroxide ion become $\phi_a\phi_b^3$ in D_2O and $(1 - x + x\phi_a)(1 - x + x\phi_b)^3$ in a H_2O–D_2O mixture of atom fraction x.



(1)

In principle ϕ_a and ϕ_b may be determined by combining suitable measurements in pure and mixed isotopic solvents; for example, the autoprotolysis constants of H_2O, D_2O, and H_2O–D_2O mixtures corrected for isotopic fractionation of the hydronium ion.[6,12,13] In practice separation of ϕ_a and ϕ_b is subject to certain difficulties which have been discussed by Gold and Grist [13] and by Taylor and Tomlinson.[14] On the one hand the separation is highly sensitive to errors; on the other, for a given value of $\phi_a\phi_b^3$, two solutions for ϕ_a and ϕ_b are obtained.[13-15]

The first difficulty is the subject of this paper. Existing data for evaluating ϕ_a and ϕ_b are analysed, and experimental measurements of the ionisation of 1,8-bis(dimethylamino)naphthalene [16] [equation (1)] in H_2O, D_2O, and 1 : 1 H_2O–D_2O are described. The measurements were undertaken with the object of providing new values of ϕ_a and ϕ_b, although, as will be seen, they serve to underline the problems of effecting a separation. The second difficulty is examined in the accompanying paper,[17] where an attempt is made to distinguish alternative solutions using calculations based upon vibrational analyses of a model for the solvated hydroxide ion.



(2) (1)

EXPERIMENTAL

Materials.—1,8-Bis(dimethylamino)naphthalene (Aldrich Chemical Co.) was purified by sublimation. Deionized water was purified further by distillation from alkaline permanganate; D_2O (Merck; 99.7 atom % D) was used as received. Both H_2O and D_2O were made CO_2-free just prior to use by boiling for a few minutes followed by cooling under protection by Ascarite. Sodium hydroxide stock solutions (*ca.* 0.1M) were prepared from NaOH and either H_2O, D_2O, or 1 : 1 H_2O–D_2O; the latter was made by mixing equal volumes of H_2O and D_2O. Exact hydroxide ion concentrations of these stock solutions were determined by acidimetric titration. More dilute sodium hydroxide solutions were prepared by diluting stock solutions by weight.

pK_a *Determinations*.—These were carried out spectrophotometrically by making measurements at 335 nm where the free base, 1,8-bis(dimethylamino)naphthalene, absorbs strongly and its conjugate acid does not absorb at all. A Cary model 118C spectrometer was used, and its cell block was thermostatted at 25.0 ± 0.1° despite the fact that changes in temperature of as much as 1° were found to have no perceptible effect on absorbance. Measurements were made in 1 cm cuvettes; the very limited solubility of 1,8-bis(dimethylamino)naphthalene in water required use of the 0—0.1 spectrometer absorbance scale, but readings could nevertheless easily be made to 0.001 absorbance unit or better.

In a typical experiment, 3 ml of sodium hydroxide solution of the appropriate concentration was pipetted into the cell. After this had come to temperature equilibrum with the spectrometer cell compartment, the base line was adjusted and a fixed amount, usually 100 λ, of stock 1,8-bis(dimethylamino)naphthalene solution (H_2O, D_2O, or H_2O–D_2O) was added. The resulting mixture was shaken and an absorbance reading was taken. This procedure was repeated three times for each sodium hydroxide concentration.

The ratio of unprotonated to protonated 1,8-bis(dimethylamino)naphthalene was calculated using the relationship $[\mathrm{B}]/[\mathrm{BH}^+] = (A - A_{\mathrm{BH}^+})/(A_{\mathrm{B}} - A)$; A_{B} was measured in concentrated (1.3M) sodium hydroxide solution and A_{BH^+} was taken to be zero.

RESULTS

The determinations were made at ionic strengths fixed by the sodium hydroxide concentrations, which were both appreciable and variable (see Table 1). The data were therefore extrapolated to infinite dilution; this was done as follows.

The thermodynamic or infinite dilution ionization constant for reaction (2) under investigation is given by

$$\mathrm{B} + \mathrm{L_2O} \rightleftharpoons \mathrm{BL}^+ + \mathrm{LO}^- \qquad (2)$$

equation (3) in which parentheses denote molar activities,

$$K_{\mathrm{b}} = \frac{(\mathrm{BL}^+)(\mathrm{LO}^-)}{(\mathrm{B})} = \frac{[\mathrm{BL}^+][\mathrm{LO}^-]_{y^+y^-}}{[\mathrm{B}]} \qquad (3)$$

square brackets denote molar concentrations, and y^+ and y^- are the molar activity coefficients of the BH^+ and LO^- ions respectively. (The symbol L is used to signify either H or D.) The activity coefficient of the neutral base was taken to be unity, while those of the ions were assumed to depend on ionic strength, μ, in the manner shown by equation (4) where $B_\pm$ are specific ion interaction constants.

$$\log y_\pm = \frac{-0.5\sqrt{I}}{1 + \sqrt{I}} + B_\pm I \qquad (4)$$

Combination of equations (3) and (4) gives an expression, which upon taking logarithms and making the substitutions $\mathrm{p}K_{\mathrm{c}} = -\log[\mathrm{BL}^+][\mathrm{OL}^-]/[\mathrm{B}]$ and $\mathrm{p}K_{\mathrm{b}} = -\log K_{\mathrm{b}}$ leads to equation (5). This expression shows that pK_{b} may be

$$\mathrm{p}K_{\mathrm{c}} + \frac{\sqrt{I}}{1 + \sqrt{I}} = \mathrm{p}K_{\mathrm{b}} + (B_+ + B_-)I \qquad (5)$$

obtained as the intercept of a linear plot of $[\mathrm{p}K_{\mathrm{c}} + \sqrt{I}/(1 + \sqrt{I})]$ *versus* $\sqrt{I}$.

Least-squares analysis of the data listed in Table 1 gave the following results, pK_{b} 1.973 ± 0.003 in H_2O, 2.395 ± 0.005 in D_2O, and 2.181 ± 0.006 in 1 : 1 H_2O–D_2O. These translate into the following thermodynamic basicity constants, $K_{\mathrm{H_2O}}$ (1.064 ± 0.007) × 10^{-2}, $K_{\mathrm{D_2O}}$ (0.403 ± 0.005) × 10^{-2}, and K_{HDO} (0.659 ± 0.009) × 10^{-2} mol l^{-1}, and give the following isotope effects, $K_{\mathrm{H_2O}}/K_{\mathrm{D_2O}}$ 2.64 ± 0.04 and $K_{\mathrm{H_2O}}/K_{\mathrm{HDO}}$ 1.61 ± 0.03.

TABLE 1

Ionization constant measurements for 1,8-bis(dimethylamino)naphthalene in aqueous solution at 25°

10^3 [NaOL] [a]/M	$\mathrm{p}K_{\mathrm{c}} + \sqrt{I}\,(1 + \sqrt{I})$
H_2O	
74.1	2.043, 2.054
48.4	2.084. 2.055, 2.098
18.3	2.027, 2.033, 2.059
16.5	2.012, 2.002, 1.992
13.2	1.997, 1.977, 2.007
11.8	1.987, 2.016, 1.978, 1.978
10.2	1.993, 1.976, 1.993, 1.993
9.92	1.989, 1.979
9.65	1.981, 2.007
8.25	1.977, 1.977, 1.970
7.71	1.977, 1.994, 1.977
7.26	1.98, 1.99, 1.966
6.63	1.977, 1.984
5.09	1.976, 1.986, 1.976, 1.966
4.42	1.977
4.27	1.988, 1.974
3.30	1.965, 1.983, 1.965, 1.974
2.52	1.989, 1.967
$\mathrm{p}K_{\mathrm{c}} + \sqrt{I}/(1 + \sqrt{I}) = (1.973 \pm 0.003) + (1.547 \pm 0.142)[\mathrm{NaOL}]$	
D_2O	
14.8	2.382, 2.398
10.4	2.405, 2.385, 2.385, .2411
9.8	2.410
7.81	2.411, 2.411
5.94	2.383, 2.392, 2.383, 2.392
3.94	2.406, 2.388, 2.379, 2.397
2.70	2.391
1.97	2.406, 2.396, 2.396
0.91	2.415, 2.378
$\mathrm{p}K_{\mathrm{c}} + \sqrt{I}/(1 + \sqrt{I}) = (2.395 \pm 0.005) + (0.041 \pm 0.617)[\mathrm{NaOL}]$	
HDO	
13.36	2.206, 2.182
10.72	2.192, 2.17
7.96	2.192, 2.181, 2.192, 2.181
5.40	2.190, 2.165
4.61	2.181, 2.181, 2.168
2.63	2.194, 2.204, 2.183
1.65	2.173
$\mathrm{p}K_{\mathrm{c}} + \sqrt{I}/(1 + \sqrt{I}) = (2.181 \pm 0.006) + (0.557 \pm 0.802)[\mathrm{NaOL}]$	

[a] The symbol L is used to indicate either H or D.

The value pK_{b} 1.97 for H_2O solution may be converted into pK_{a} 12.03 by subtraction from pK_{w} (=14.00). The result obtained is in good agreement with pK_{a}' 12.1 ± 0.1 measured at an ionic strength of 0.1M,[18] and is consistent with pK_{a} 12.34 reported for an unspecified ionic strength.[16]

Fractionation Factor Determination.—The D : H fractionation factor for the acidic hydrogen of monoprotonated 1,8-bis(dimethylamino)naphthalene was determined by dissolving the unprotonated substrate in an acidic (0.2M-hydrochloric acid) H_2O–D_2O solution of known deuterium content and then measuring the area of the n.m.r. signal from the acidic proton located at δ 19.5. (Under these conditions, exchange of this hydrogen with the solvent is slow on the n.m.r. time scale.) This signal area was translated into protium content by comparison with the area of the nearest other n.m.r. signal of the protonated substrate, that from the six non-exchanging aromatic hydrogens located at about δ 8. Since these two signals were still more than 10 p.p.m. apart, the comparison was done stepwise using glacial acetic acid as an external reference, *i.e.* the area of the substrate acidic hydrogen signal was compared with that of the hydroxy-group signal from acetic acid and the area of the substrate aromatic hydrogens signal was compared with that from the methyl group of acetic acid; the presence of some water in the glacial acetic acid reference, which added to the hydroxy-group signal, was taken into account by determining the ratio of hydroxy to methyl group signal areas separately. The results, summarized in Table 2, give ϕ_P 0.901 ± 0.014.

TABLE 2

Measurements of the fractionation factor ϕ_P for the $N-H^+$ hydrogen of protonated 1,8-bis(dimethylamino)naphthalene

	D : H atom ratio		
[Substrate]/M	Solvent	Substrate	ϕ_P
0.73	0.908	0.779	0.858
0.53	0.933	0.894	0.959
0.43	0.944	0.845	0.896
0.28	0.963	0.852	0.885
0.20	0.973	0.869	0.893
0.20	0.973	0.890	0.915
		Average	0.901 ± 0.014

DISCUSSION

Measurements in D_2O.—In evaluating fractionation factors for the hydroxide ion it is convenient to consider measurements in D_2O and H_2O–D_2O mixtures in turn. In pure isotopic solvents the ratios K_{D_2O}/K_{H_2O} for equilibria involving hydroxide ion yield products of fractionation factors: in terms of model (1), $\phi_a\phi_b^3$, or, more generally, $\prod_i \phi_i$. The general expression makes no assumption about the number of fractionating hydrogens and includes a term for medium effects, denoted Φ_s by Albery,[6] representing fractionation effects too small to distinguish individually and commonly associated with ionic solvation; this term may also be considered as the activity coefficient counterpart of free energies of transfer between H_2O and D_2O.[15,19] In this paper the results are discussed in terms of model (1) with alternative possibilities noted as appropriate.

(a) *Autoprotolysis and electrochemical measurements.* Before considering the measurements for 1,8-bis(dimethylamino)naphthalene it is pertinent to consider previous determinations of $\phi_a\phi_b^3$, and most importantly those from measurements of the ratio of autoprotolysis constants of H_2O and D_2O, $K_W^{H_2O}/K_W^{D_2O}$.[12,20-23] The ratio of autoprotolysis constants may be considered as an effective equilibrium constant for the isotope exchange (6), and $\phi_a\phi_b^3$ may be obtained from $(K_W^{D_2O}/K_W^{H_2O})/l^3$, where l is the fractionation factor for the hydronium ion, that is $L^{-1/6}$ where in turn L is the equilibrium constant for the exchange reaction (7). Determination of $\phi_a\phi_b^3$ thus requires a knowledge of L.

$$H_3O^+ + HO^-(H_2O)_3 + 5D_2O \rightleftharpoons D_3O^+ + DO^-(D_2O)_3 + 5H_2O \qquad (6)$$

$$2D_3O^+ + 3H_2O \rightleftharpoons 2H_3O^+ + 3D_2O \qquad (7)$$

What is probably the best method of evaluating L has been summarised by Salomaa and Aalto.[7] E.m.f. data for the electrochemical cells comprising hydrogen and silver–silver chloride electrodes in H_2O and D_2O are combined to give $\Delta\bar{G}^0$ for reaction (8). Further combination with measurements of the equilibrium constant

$$\tfrac{1}{2}D_2 + HCl(H_2O) \rightleftharpoons \tfrac{1}{2}H_2 + DCl(D_2O) \qquad (8)$$

of reaction (9) and the free energy of transfer of chloride

$$D_2 + H_2O(l) \rightleftharpoons H_2 + D_2O(l) \qquad (9)$$

ions between H_2O and D_2O [reaction (10)], yields L.

$$D_2O + Cl^-(H_2O) \rightleftharpoons Cl^-(D_2O) + H_2O \qquad (10)$$

Of the data used by Salomaa and Aalto the e.m.f. values of Gary *et al.*[24] are still applicable, but improved measurements for reactions (9) and (10) are now available. For the isotope exchange between hydrogen gas and water (9), Rolston, *et al.* have made measurements at low atom fractions of deuterium[25] to obtain 3.81 as equilibrium constant at 25° for the exchange (11), which, when combined with K 3.26 for the disproportionation constant of HD (12), calculated from Bron *et al.*'s convenient tabulation of isotopic partition function ratios and their temperature dependence,[26] and 3.80 for the disproportionation constant of HDO (13), based on the average of gas phase measurements[27] corrected to the liquid state,[28] gives an equilibrium constant for (9) of 12.39.

$$HD + H_2O(l) \rightleftharpoons H_2 + HDO(l) \qquad (11)$$

$$2HD \rightleftharpoons H_2 + D_2 \qquad (12)$$

$$2HDO \rightleftharpoons H_2O + D_2O \qquad (13)$$

Taking Voice's measurement of 172 cal mol^{-1} for sodium chloride as the molar transfer free energy of the chloride ion[29] gives L 9.85, which differs little from Salomaa and Aalto's original value of 9.0 and agrees well with Gold's n.m.r. determination[9] of 9.7 and Heinzinger and Weston's[7,10,30] value of 9.6 from measurements of isotope separation factors between aqueous perchloric acid solutions and water vapour, although the last value is for 13.5 °C and would be smaller (*ca.* 9.0) at 25°. The data also allow calculation of the temperature dependence of L between 0 and 50° as equation (14), where

$$\Delta\bar{G}^0 = -3\,126 - 14.08T + .02724T^2 \qquad (14)$$

$\Delta\bar{G}^0$ is the standard molar free energy change for reaction (7) in cal mol^{-1} and T is in degrees Kelvin.

The value of $L^{1/2}$ may now be combined with one of the recent measurements of $K_W^{H_2O}/K_W^{D_2O}$,[12,20-23] of which those of Gold and Lowe[12] and Covington *et al.*[20] are perhaps the most satisfactory.[31] From Gold and Lowe's value of 7.28 at 25° one obtains $\phi_a\phi_b^3$ 0.431. A similar combination using the value of Covington *et al.*

however, leads to a cancellation of redundant terms because common e.m.f. data are used for the calculations of $K_W^{H_2O}/K_W^{D_2O}$ and L. Most directly $\phi_a\phi_b^3$ is obtained from e.m.f. measurements for the cell H_2,NaOH,NaCl-(H_2O),AgCl;Ag[32] and its D_2–D_2O counterpart.[20] E.m.f.s corresponding to the net reaction (15) have been

$$\tfrac{1}{2}D_2 + NaOD(D_2O) + NaCl(H_2O) + H_2O \rightleftharpoons \tfrac{1}{2}H_2 + NaOH(H_2O) + NaCl(D_2O) + D_2O \quad (15)$$

listed by Goldblatt and Jones,[21] and combination with $\Delta\bar{G}^0$ for the D_2–water exchange (8) and the transfer free energy of chloride ions (10) yields at 25° $\phi_a\phi_b^3$ 0.434, which compares satisfactorily with Goldblatt and Jones's own measurement at 25° giving $\phi_a\phi_b^3$ 0.444. It should be noted that these values contain a, probably very small, contribution from the transfer free energy of sodium ions.

From the e.m.f. measurements[21,23] the temperature dependence of $\phi_a\phi_b^3$ may be calculated as equation (16),

$$\Delta\bar{G}^0 = -820 - 0.456T + 0.000\,56T^2 \quad (16)$$

where $\Delta\bar{G}^0 = 2RT\ln\,(\phi_a\phi_b^3)$ [or, more generally, $2RT\ln\left(\prod_i \phi_i\right)$] is the standard molar free energy change for reaction (17) in which the hydroxide ion is written

$$2DO^- + H_2O \rightleftharpoons 2HO^- + D_2O \quad (17)$$

formally without its solvation shell. At 25° the equilibrium constant for this reaction is 5.31.

(b) *Ionisation of* 1,8 *bis(dimethylamino)naphthalene.* For 1,8-bis(dimethylamino)naphthalene the ratio of basic ionisation constants in D_2O and H_2O may be written in terms of fractionation factors as equation (18), where ϕ_P refers to the ionising hydrogen of the protonated

$$K_{D_2O}/K_{H_2O} = \phi_a\phi_b^3\phi_P\Phi_S \quad (18)$$

base [*cf.* equation (1)] and Φ_S is the contribution of medium effects arising from transfer of free and protonated base from H_2O to D_2O.[6] Since ionisation occurs at concentrations of hydroxide ion (0.1—0.001M) determinable by titration or dilution no correction is required for the difference of pH from pD. The measured values of K_{H_2O}/K_{D_2O} and ϕ_P were 2.64 ± 0.04 and 0.901 ± 0.014, respectively

Because Φ_S is unknown $\phi_a\phi_b^3$ cannot in this case be determined directly. However, with $\phi_a\phi_b^3$ 0.434, we obtain ϕ_S 1.03, and it becomes possible to make transfer corrections and derive values of ϕ_a and ϕ_b from measurements in H_2O–D_2O mixtures. The nearness of Φ_S to 1.0 suggests cancellation of transfer free energies between free and pronated base (plausibly because hydrogen bonding between the ionising species and solvent is weak), and this small correction for medium effects should be an advantage in evaluating ϕ_a and ϕ_b.

Measurements in H_2O-D_2O *Mixtures.*—To obtain ϕ_a and ϕ_b separately the value of $\phi_a\phi_b^3$ must be combined with suitable measurements in H_2O-D_2O mixtures. Again, previous measurements may be reviewed before considering results for 1,8-bis(dimethylamino)naphthalene.

(a) *Liquid–vapour isotope separation factors.* Weston and Heinzinger measured the fractionation of H and D isotopes between liquid water and aqueous hydroxide solutions and water vapour.[33] Their measurements yield $(1 - \phi_a) + 3(1 - \phi_b)$ or, in model independent terms, $\sum_i (1 - \phi_i)$, where again the ϕ_i may include a contribution from a medium effect Φ_S. The relationship of fractionation factors to experimentally measured parameters is expressed by equation (19) where N is the mole

$$\sum_i (1 - \phi_i) - \ln \Phi_S = \frac{2 - N}{N}(1 - \alpha_B/\alpha_W) \quad (19)$$

fraction of NaOH or KOH, α_B and α_W are the liquid–vapour D-H separation factors for base solution and pure water respectively, and $-\ln\Phi_S$ separates medium from specific fractionation effects.* The separation factors are defined by $\alpha = x_V(1 - x_L)/x_L(1 - x_V)$ where x is the atom fraction of deuterium and the subscripts L and V denote liquid and vapour. Values of $\sum_i (1 - \phi_i)$ are shown in Table 3.

Table 3

$\sum_i (1 - \phi_i)$ [a] for the hydroxide ion from Heinzinger and Weston's isotope separation measurements [b]

Base	N	α_B/α_W [c]	$(1 - \phi_i)$ [d] Uncorrected	$(1 - \phi_i)$ [d] Corrected [f]	σ [e]
NaOH	7.84	0.9638	0.442	0.442	0.021
NaOH	10.20	0.9567	0.480	0.480	0.010
NaOH	12.12	0.9472	0.486	0.486	0.014
KOH	6.99	0.9626	0.573	0.519	0.011
KOH	10.30	0.9456	0.543	0.489	0.008

[a] For model (1), $4 - \phi_a - 3\phi_b$. [b] Ref. 33. [c] Ratio of isotope separation factors between base solution and water vapour (α_B) and liquid water and water vapour (α_W). [d] $(2-N)(1-\alpha_B/\alpha_W)/N$. [e] Average deviation. [f] The measurements for KOH are corrected for the difference in free energies of transfer of Na^+ and K^+ ions.

Measurements were made for KOH and NaOH solutions, and their comparison requires a correction to be made for the difference in transfer free energies between potassium and sodium ions, $\Delta\bar{G}_t^0$, which from Voice's measurements[29] amounts to 31 cal mol^{-1}. Taking $\ln\Phi_S = \Delta\bar{G}_t^0/RT$ and subtracting from $\sum_i (1 - \phi_i)$ for KOH gives the corrected values shown in the right hand column of Table 3. Agreement between KOH and NaOH measurements is significantly improved.

In a later discussion of the results, Gold and Grist[13] noted that a trend in Heinzinger and Weston's measurements with concentration of base could perhaps be discerned, and suggested extrapolation to zero base concentration. They made no correction, however, for the difference in free energies of transfer of Na^+ and K^+ ions and a linear extrapolation leads to a significantly higher value of $(1 - \phi_a) + 3(1 - \phi_b)$ without the correction (0.561) than with it (0.490 ± 0.064). Indeed Grist and Gold considered a higher value still (0.656) not inconsistent with the result.

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* In terms of fractionation, $\Phi_S = \phi^n$, where n is large and $\phi \rightarrow 1.0$. The contribution to $\sum_i (1 - \phi)$ is thus $n\,(1 - \phi) \cong -n\ln\phi = -\ln\Phi_S$.

Further corrections may be made because the measurements were made at 13.5° rather than 25° and to take account of departures from the Rule of the Geometric Mean.[6,27] In practise these were found to be so small (2%) as to be sensibly neglected.

Values of ϕ_a and ϕ_b may be obtained by combining Heinzinger and Weston's measurements with $\phi_a\phi_b^3 = 0.434$. The sensitivity of the values to the precision of the measurements is best shown by plotting $(1 - \phi_a) + 3(1 - \phi_b)$ against a range of values of ϕ_a with $\phi_b = \sqrt[3]{0.434/\phi_a}$ as in Figure 1. A smooth curve is obtained with a maximum at $\phi_a = \phi_b$, as shown by the full line in Figure 1. The 'observed' value of $(1 - \phi_a) + 3(1 - \phi_b) = 0.490$, extrapolated to infinite dilution and corrected to 25°, is shown as the horizontal line, with the limits of the standard deviation of its mean indicated by cross hatching. Also shown, as an extreme comparison, is the value favoured by Gold and Grist,[13] which lacks corrections for the difference in transfer free energies of Na^+ and K^+.

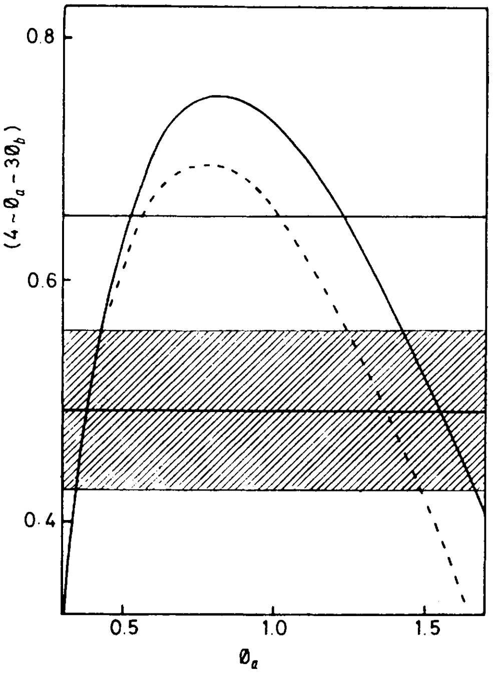

FIGURE 1 Full curve, plot of $4 - \phi - 3\phi_b$ *versus* ϕ_a with $\phi_a\ \phi_b^3$ 0.434. Dashed curve, the same including a medium effect ϕ 1.3. The patched area shows an experimental value and standard deviation based on the data of ref. 35. The upper line shows a value from the same data derived by Gold and Grist

Figure 1 illustrates the two solutions [13,15] associated with measurements of $(1 - \phi_a) + 3(1 - \phi_b)$, and Table 4 lists pairs of values of ϕ_a and ϕ_b. The vulnerability of ϕ_a and ϕ_b to errors is indicated by the difference between the values of ϕ_a of 0.39 or 1.54 obtained using the fully corrected results and of $\phi_a = 0.5$ or 1.24 considered possible by Gold and Grist.[12] While it is now clear that the latter values have a poorer experimental basis, their lesser divergence from 1.0 makes them more consistent with measurements of other OH fractionation factors.[34]

TABLE 4

Fraction factors for the hydroxide ion [a]

Method	Medium effect [b] Φ_S	Solution 1 ϕ_a	Solution 1 ϕ_b	Solution 2 ϕ_a	Solution 2 ϕ_b
Vapour–liquid isotope separation	1.0	0.39	1.04	1.54	0.26
	1.3	0.39	0.95	1.37	0.63
	1.0	(0.50) [c]	(0.95) [c]	(1.24) [c]	(0.70) [c]
Autoprotolysis constant	1.0	0.55	0.92	1.15	0.72
	1.3	0.58	0.83	1.00	0.69

[a] Corrections for deviations from the Rule of the Mean are not included. Normally these amount to <3%. [b] When $\Phi_S = 1.0$, there is no medium effect. [c] Values in parentheses are those suggested by Gold and Grist [13] (see text)

(b) *Autoprotolysis measurements.* The second source of results suitable for determining ϕ_a and ϕ_b are Gold and Lowe's measurements of the autoprotolysis constant of water in H_2O–D_2O mixtures.[12] If $K_W{}^x$ is the autoprotolysis constant for a solvent of deuterium atom fraction x, $K_W{}^x/K_W{}^{H_2O}$ may be expressed in terms of fractionation factors as equation (20). Following Albery

$$K_W{}^x/K_W{}^{H_2O} = (1 - x + xl)^3(1 - x + x\phi_b)^3 (1 - x + x\phi_a) \quad (20)$$

and Davies,[35] this expression may be rearranged to a function y_x isolating terms in ϕ_a and ϕ_b (21). Focusing

$$y_x = \frac{K_W{}^x/K_W{}^{H_2O}}{(1 - x + xl)^3} = (1 - x + x\phi_b)^3(1 - x + x\phi_a) \quad (21)$$

on y_x at $x = \frac{1}{2}$ one obtains for $y_{\frac{1}{2}}$ equation (22), or, if a

$$y_{\frac{1}{2}} = \frac{K_W{}^{\frac{1}{2}}}{K_W{}^{H_2O}} \frac{8}{(1 + l)^3} = \frac{(1 + \phi_b)^3(1 + \phi_a)}{16} \quad (22)$$

specific model for the hydroxide ion is not used, $y_{\frac{1}{2}}$ takes the general form of (23).

$$y_{\frac{1}{2}} = \prod_i (1 + \phi_i)/2 \quad (23)$$

Solutions of ϕ_a and ϕ_b are obtained as before by plotting $y_{\frac{1}{2}}$ as a function of ϕ_a for $\phi_a\phi_b^3 = 0.434$ and reading off values of ϕ_a and ϕ_b corresponding to the measured $y_{\frac{1}{2}}$. In practice what is plotted in Figure 2 is not $y_{\frac{1}{2}}$ but the 'percentage curvature' c, representing the deviation from linearity of a plot of $K_W{}^x/K_W{}^{H_2O}$ against x at $x = 0.5$, defined by (24) where y_1 is the value of y in pure

$$\%c = \left\{1 - \frac{2y_{\frac{1}{2}}}{(1 + y_1)}\right\} \times 100 \quad (24)$$

D_2O, *i.e.* $\phi_a\phi_b^3$ (=0.434). Expressed in this form the precision required of the measurements to define the fractionation factors is directly indicated.

Although Gold and Lowe did not measure K_W at $x = 0.5$ directly, the value can be interpolated from their measurements at other values of x. The derived curvature is shown as the horizontal line aa' in Figure 2 and it is apparent that again two solutions exist. The values of ϕ_a and ϕ_b are also listed in Table 4, and it can be seen that compared with Heinzinger and Weston's measurements ϕ_a (0.55 or 1.15) is significantly closer to unity.

It should be mentioned that these results have previously been analysed by Albery's γ method to give γ 0.43 ± 0.14.[6]

(c) 1,8-*Bis(dimethylamino)naphthalene.* Ionisation of 1,8-bis(dimethylamino)naphthalene was studied in the expectation that one or other of the previous measurements might be confirmed. The ratio of ionisation constants in 1 : 1 H_2O–D_2O and pure H_2O, $K_{\frac{1}{2}}/K_{H_2O}$ may be written in terms of ϕ_a, ϕ_b, the fractionation factor of the exchangeable hydrogen of the protonated base, ϕ_P, and a correction $(\Phi_S)^{\frac{1}{2}}$ for the small net medium effect upon transferring free and protonated base from pure H_2O to the mixed isotopic solvents, as in equation (25). Rearrangement then gives the same expression

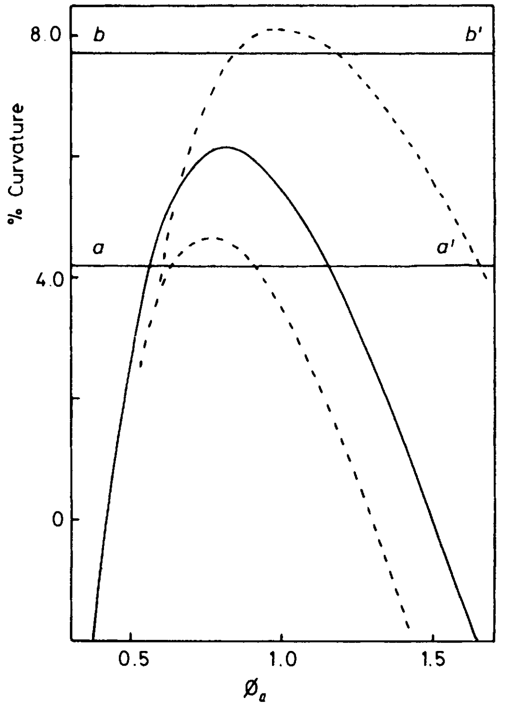

FIGURE 2 Full curve, percentage deviation from linearity (%c) of a plot of $(1 - x + x\,\phi_a)(1 - x + x\,\phi_b)^3$ *versus* x at $x = 0.5$ for various ϕ_a with $\phi_a\phi_b^3$ 0.434. Dashed curves, the same including medium effects, Φ 0.434 (upper curve) or 1.3 (lower curve). The lines represent experimental measurements from autoprotolysis constants (aa') and from the ionisation of proton sponge (bb')

$$\frac{K_{\frac{1}{2}}}{K_{H_2O}} = \frac{(1 + \phi_a)(1 + \phi_b)^3(1 + \phi_P)\Phi_S^{\frac{1}{2}}}{32} \qquad (25)$$

for $y_{\frac{1}{2}}$ in terms of fractionation factors ϕ_a and ϕ_b as from the autoprotolysis measurements, *i.e.* equation (26). It

$$y_{\frac{1}{2}} = \frac{K_{\frac{1}{2}}}{K_{H_2O}} \times \frac{2}{(1 + \phi_P)\Phi_S^{\frac{1}{2}}} = \frac{(1 + \phi_b)^3(1 + \phi_a)}{16} \qquad (26)$$

follows that if the curvature, %c, is calculated ϕ_a and ϕ_b may be read from Figure 2, as before.

For the observed values of $K_{H_2O}/K_{\frac{1}{2}}$ 1.61_5, ϕ_P 0.90 and Φ_S 1.03, the curvature for y_1 0.434 is 7.7 ± 1.6%, and this is included in Figure 2 as the line bb'. Thus, far from confirming previous values of ϕ_a and ϕ_b the departure of K_x/K_H from a linear dependence upon the atom fraction of deuterium x at x 0.5 actually exceeds the maximum theoretical value of 6.1% consistent with our model (1) for the hydroxide ion!

In view of the small range of allowed curvatures for 1,8-bis(dimethylamino)naphthalene we may ask whether the measurements are sensitive to small corrections hitherto neglected. It is shown in an Appendix that there is little influence from deviations from the Rule of the Mean, but the measured curvature can be reproduced if the fractionation model for the hydroxide ion is modified to include a sufficiently large medium effect. Thus if the effect of transferring a hydroxide ion from H_2O to D_2O is denoted $\Phi_S{}^{OH}$ we can write $\phi_a\phi_b{}^3\Phi_S{}^{OH}$ 0.434 and equation (22) as (27). Maximum positive

$$y_{\frac{1}{2}} = \frac{(1 + \phi_b)^3(1 + \phi_a)(\Phi_S{}^{OH})^{\frac{1}{2}}}{16} \qquad (27)$$

curvature results when the isotope effect is entirely a medium effect, and this is shown in the upper dashed curve of Figure 2, for which $\Phi_S{}^{OH} = 0.434$. However, values consistent with the experimental measurement, represented by the line bb' are only just achieved and since the medium effect accounts only for fractionation effects beyond the four innermost hydrogens of the solvated hydroxide ion it is unlikely to be as strong as would be required.*

Conclusions.—Almost certainly the discrepancy for 1,8-bis(dimethylamino)naphthalene, and indeed between Gold and Grist's and Heinzinger and Weston's measurements, reflects an intrinsic difficulty in separating sets of fractionation factors from measurements of the curvature of plots of K_x/K_H against x when solutions occur in an insensitive range, even when, as here, the measurements are made with considerable care. This is particularly true when a plot of curvature as a function of ϕ has an extremum close to its solutions as in Figure 2. Thus despite the large difference in solutions of ϕ_a and ϕ_b implied, the values of $y_{\frac{1}{2}}$ on which the curvatures of the autoprotolysis measurements and ionisation of proton sponge are based differ by only 5%.

Probably the most reliable values of ϕ_a and ϕ_b are those based on Heinzinger and Weston's measurements,[33] *i.e.* ϕ_a 0.39 and ϕ_b 1.04 or ϕ_a 1.54 and ϕ_b 0.66, but the more moderate values from Gold and Lowe's autoprotolysis measurements[12] appear more reasonable.† Our own results may add weight to values of ϕ_a close to unity, but Taylor and Tomlinson's n.m.r. measurements of hydroxide solutions in H_2O–D_2O mixtures, while not yielding values of ϕ_a and ϕ_b directly, suggest the contrary.[14] The combined measurements reflect the recognised uncertainty of the individual values of ϕ_a and ϕ_b.

Nevertheless, ' moderate ' solutions for ϕ_a and ϕ_b are implied by the calculations of the following paper, and it is worth examining further the sensitivity of the

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* The value of Albery's $\gamma \cong -0.3$ also indicates the poor fit to the hydroxide model; $\gamma = 0$ corresponds to the whole isotope effect being a medium effect.

† The more limited autoprotolysis data in H_2O–D_2O mixtures of Pentz and Thornton[22] give ϕ_a 0.44 or 1.45.

measurements to medium effects. The dashed curve of Figure 1 and the lower dashed curve of Figure 2 incorporate mild medium effects of Φ_S^{OH} 1.3, and it can be seen from the Figures and from Table 4 that for the solution with $\phi_a > 1.0$, ϕ_a is significantly reduced: for the isotope separation measurements, from 1.54 to 1.37. A similar effect is produced by a minor fractionation contribution from the three outer hydrogens of the water molecules in the hydroxide solvation shell (1), *i.e.* with ϕ^3 1.3.

With Φ_S^{OH} 1.3 the medium effect on ϕ_a for the second solution of ϕ_a and ϕ_b is small. This solution is sensitive to additional fractionation but more so to a single fractionation site than to a medium effect which, in terms of a structural model, seems less likely.

It is perhaps regrettable that a more precise dissection of ϕ_a and ϕ_b and potential medium effects is not possible. How critical this is to the interpretation of kinetic measurements in H_2O–D_2O mixtures will be examined in a further paper. For the present the distinction between the two solutions for ϕ_a and ϕ_b is sufficient to offer a basis for the calculations of the following paper.

APPENDIX

Deviations from the Rule of the Mean.—Values of $y_{\frac{1}{2}}$ for proton sponge may be corrected for deviations from the Rule of the Mean as follows. It is assumed, and the results of the following paper confirm, that corrections for water molecules in the solvation shell of the hydroxide ion cancel with those of solvent water molecules. Corrections then arise only for the hydrogens of OH^- itself and of the solvent water molecule that in the ionisation equilibrium (1) is the counterpart of the hydroxide ion and the fractionating hydrogen of proton sponge.

Adapting Albery and Davies' procedure,[36] the simple expression for $y_{\frac{1}{2}}$ of equation (26) is modified by multiplying $(1 + \phi_b)^3(1 + \phi_a)/16$ by the term $[1 - 0.25(3\delta_{ab} - 2\delta_{HDO})]$, in which the δ values are correction factors representing interactions of fractionating hydrogens attached to a common atom[11] which enter as differences of contributions between reactants and product; $\delta_{HDO} = 1 - K/4$, where K is the equilibrium constant for disproportionation of HDO to H_2O and D_2O (13), corrects for interaction of the two hydrogens of a water molecule, and $3\delta_{ab}$, defined in the following paper,[17] corrects for interaction of the hydroxide hydrogen a with the three neighbouring hydrogens of its solvation shell. For reaction in an H_2O–D_2O mixture of atom fraction x the corrections enter as $\delta x(1 - x)$ and for 1 : 1 H_2O–D_2O, for which $x = 0.5$, as 0.25δ.[36]

The magnitudes of the corrections reflect the bending force constants between the bonds to the interacting atoms, and calculations[17] suggest that the value of δ_{ab} depends on which solution is adopted for ϕ_a and ϕ_b, since larger values of ϕ_a are associated with larger hydrogen bond bending force constants for the hydroxy group. For ϕ_a 1.2—1.5, $3\delta_{ab}$ approaches $\delta_{HDO}/2$ and the correction largely cancels with that for a water hydrogen, while for $\phi_a < 0.6$ δ_{ab} is small and the hydroxy-group is sensibly treated as an isolated fractionating hydrogen (δ_{ab} 0). The latter case leads to the larger correction and with δ_{HDO} 0.05, $y_{\frac{1}{2}}$ is now given by equation (28). However, the corrected value of

$$y_{\frac{1}{2}} = \frac{K_{HDO}}{K_{H_2O}} \times \frac{1.975}{(1 - \phi_R)\Phi_S^{\frac{1}{2}}} \qquad (28)$$

the curvature is 8.9% which differs little from the uncorrected value of 7.7%. The magnitude of the correction is thus quite small, and its direction is such as to increase rather than decrease the discrepancy between observed and allowed values.

Similar correction of the autoprotolysis measurements introduces an interaction term δ_{H_2DO} for the hydronium ion, as shown in equation (29). From model calculations[37] $\delta_{H_2DO} \cong \frac{3}{4}\delta_{HDO}$, which with δ_{HDO} 0.05, gives a value close to

$$\frac{K_W^{\frac{1}{2}}}{K_W^{H_2O}} = (1 + \phi_a)(1 + \phi_b)^3(1 + l)^3 \{1 - 0.25(3\delta_{ab} + 3\delta_{H_2DO} - 2\delta_{HDO})\} \qquad (29)$$

the measured value of δ 0.03 for NH_3.[38] For the solution of the hydroxide fractionation factors with $\phi_a < 1.0$ ($\delta_{ab} = 0$) the corrections cancel, while for $\phi_a > 1.0$ the curvature is reduced slightly, from 3.8 to 3.2%. Again the correction is very small.

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