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Hydrogen Isotope Fractionation Factors for Benzylamine and Benzylammonium Ion. Comparison of Fractionation Factors for Neutral and Positively-Charged Nitrogen–Hydrogen Bonds

C. H. Arrowsmith,[†] H.-X. Guo,[‡] and A. J. Kresge*,[‡]

Contribution from the Department of Chemistry, University of Toronto, 80 St. George Street, Toronto, Ontario M5S 1A1, Canada, and Ontario Cancer Institute and Department of Medical Biophysics, University of Toronto, 500 Sherbourne Street, Toronto, Ontario M4X 1K9, Canada

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Abstract: Deuterium–protium fractionation factors were determined for benzylamine and benzylammonium ion by the traditional ^{1}H NMR method and for the benzylammonium ion by a newly devised ^{13}C NMR method. The results, $\phi_{\mathrm{PhCH_2NL_2}} = 0.958 \pm 0.070$ and $\phi_{\mathrm{PhCH_2NL_3^+}} = 1.081 \pm 0.019$, when combined with the solvent isotope effect on the ionization of benzylammonium ion, also determined here, $K_H/K_D = 3.36 \pm 0.13$, give $\Phi_{\mathrm{PhCH_2NL_3^+}} = 0.80 \pm 0.13$ as the medium effect for transfer of this ion from H_2O to D_2O. These results show that introduction of a positive charge into an N–L bond does not decrease its fractionation factor as is the case for O–L bonds, where $\phi_{\mathrm{OL^+}}/\phi_{\mathrm{OL}} = 0.7$. This difference is attributed to the tetrahedral structure of ammonium ions and the consequent stiffness of their bond-bending vibrations.

Hydrogen isotope fractionation factors have played a central role in the development of our understanding of solvent isotope effects. For example, they form the basis of a formalism that relates isotope effects in H_2O–D_2O mixtures to the deuterium content of the solvent.[1] This formalism allows separation of isotope effects into contributions from individual hydrogens, and it is therefore commonly called the "proton inventory" method; because of the capability implied by this name, the method has received especially widespread use in the study of enzyme-catalyzed reactions.[2]

Deuterium fractionation factors are deuterium to protium ratios at specific sites in a system compared to deuterium to protium ratios of some reference. In solvent isotope effect applications, the reference is usually taken to be the solvent, and the fractionation factor for site i, ϕ_i, then becomes the deuterium to protium ratio as that site, $(D/H)_i$, divided by the deuterium to protium ratio of the solvent, $(D/H)_s$, as shown in eq 1. Deuterium

$$\phi_i = (D/H)_i/(D/H)_s \qquad (1)$$

fractionation factors may also be viewed as equilibrium constants for isotope exchange reactions such as that given as eq 2, where LZ_i[3] represents the site under examination and LS is the solvent, *i.e.* $\phi_i = K_i$. Since it is a general characteristic of isotope exchange

$$\mathrm{HZ_i + DS \overset{K_i}{\rightleftharpoons} DZ_i + HS} \qquad (2)$$

reactions that the heavier isotope concentrates where it is more tightly bound,[4] deuterium fractionation factors also provide information, through their magnitude, about hydrogenic binding, with $\phi < 1$ denoting looser and $\phi > 1$ denoting tighter binding of hydrogen than that in the oxygen–hydrogen bonds of water.

The deuterium fractionation factor for the hydronium ion in aqueous solution is $\phi \equiv \ell$[5] = 0.69.[6] Its less than unit value signifies looser binding of the hydrogens in this substance than the hydrogens in water, which is consistent with the lower vibrational frequencies of the hydronium ion than those of water.[7] It is generally believed that this looser binding is a consequence of the positive charge on the central atom of this ion, which draws electron density out of the oxygen–hydrogen bonds and makes them weaker, and the fractionation factor $\phi = 0.7$ is consequently commonly assigned to all positively charged hydrogen–oxygen bonds. That raises the question of whether introduction of a positive charge loosens the binding and lowers ϕ for bonds between hydrogen and atoms other than oxygen. The ready availability of amines and the corresponding ammonium ions makes nitrogen–hydrogen bonds a good place to seek an answer to this question.

There is some fragmentary information on this matter in the literature. An early determination of the acid dissociation constant of NL_4^+ in H_2O–D_2O mixtures plus the estimate of the fractionation factor for ammonium, $\phi_{\mathrm{NL_3}} = 1.04$, based upon a gas-phase value of the isotope exchange equilibrium constant converted to aqueous solution, led to $\phi_{\mathrm{NL_4^+}} = 1.08$.[8] A compilation of fractionation factors made somewhat later, however, listed $\phi_{\mathrm{NL}} = 0.92$ and $\phi_{\mathrm{NL^+}} = 0.97$ for neutral and positively charged nitrogen–hydrogen bonds in general but gave no information on how these values were obtained.[9] More recently, feasibility studies demonstrating new NMR methods for determining fractionation factors produced $\phi_{\mathrm{NL}} = 1.01$–$1.56$ and $\phi_{\mathrm{NL^+}} = 0.89$–$1.38$ for a

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[†] Ontario Cancer Institute and Department of Medical Biophysics.

[‡] Department of Chemistry.

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(1) Kresge, A. J. *Pure Appl. Chem.* **1964**, *8*, 243–258.

(2) (a) Schowen, R. L. In *Isotope Effects on Enzyme-Catalyzed Reactions*; Cleland, W. W., O'Leary, M. H., Northrup, D. B., Eds.; University Park Press: Baltimore, MD, 1976; pp 64–99. (b) Schowen, K. B. In *Transition States of Biochemical Processes*; Gandour, R. D., Schowen, R. L., Eds.; Plenum Press: New York, 1978; Chapter 6. Schowen, K. B.; Schowen, R. L. *Methods Enzymol.* **1982**, *87C*, 551–606. Venkatasubban, K. S.; Schowen, R. L. *Crit. Rev. Biochem.* **1984**, *17*, 1–44. Quinn, D. L.; Sutton, L. D. In *Enzyme Mechanisms from Isotope Effects*; Cook, P. F., Ed.; CRC Press: Boca Raton, FL, 1991; Chapter 3.

(3) The symbol "L" is used to denote either H or D.

(4) Kreevoy, M. M. In *Isotopes in Organic Chemistry. Volume 2. Isotopes in Hydrogen Transfer Processes*; Buncel, E., Lee, C. C., Eds.; Elsevier: Amsterdam, 1976; Chapter 1.

(5) The special symbol "ℓ" is generally used for the fractionation factor of the hydronium ion.

(6) (a) Kresge, A. J.; Allred, A. L. *J. Am. Chem. Soc.* **1963**, *85*, 1541. Gold, V. *Pure Chem. Soc.* **1963**, 141–143. (b) Kresge, A. J.; More O'Ferrall, R. A.; Powell, M. F. In *Isotopes in Organic Chemistry. Volume 7, Secondary and Solvent Isotope Effects*; Buncel, E., Lee, C. C., Eds.; Elsevier: Amsterdam, 1987; Chapter 4.

(7) More O'Ferrall, R. A.; Koeppl, G. W.; Kresge, A. J. *J. Am. Chem. Soc.* **1971**, *93*, 1–9, 9–20.

(8) Salomaa, P.; Schaleger, L. L.; Long, F. A. *J. Phys. Chem.* **1964**, *68*, 410–411.

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number of different amines and ammonium ion salts.[10] Even more recently, the ratio $\phi_{NL_4^+}/\phi_{NL_3} = 1.07 \pm 0.01$ was deduced from measurements of rates of hydrogen exchange between deuterated ammonium ions and water, on the assumption that the secondary isotope effect on this reaction is equal to the ratio of fractionation factors of ammonium ion and ammonia.[11]

In view of this lack of direct information and the importance of fractionation factors, we have determined the fractionation factors for an amine and its ammonium ion conjugate acid. We chose benzylamine for this purpose because we hoped to make the required deuterium-content measurements using the newly devised carbon-13 NMR method.[10a] This method is based upon the fact that substitution of deuterium for protium in an N–L bond produces an isotope effect on the chemical shift of nearby carbon atoms, and this isotope effect can be used to report the average deuterium content of N–L bonds of substrates in aqueous solution under conditions where the hydrogens of these bonds are exchanging rapidly with the solvent. This condition of rapid exchange is, of course, prevalent for amines and ammonium ions in aqueous solution, and it is this feature of the system, moreover, that impedes removal of these substrates from solution for isotopic analysis by more conventional means without disturbing their deuterium content. Benzylamine seemed ideally suited for this purpose because the chemical shift of its α-carbon atom appears in an isolated part of its NMR spectrum, which facilitates accurate determination of changes in this chemical shift, and the amine enriched with carbon-13 at this position can be readily synthesized from relatively inexpensive commercially available enriched benzoic acid. Unfortunately, we were able to apply this method only to benzylammonium ion and not to benzylamine itself (*vide infra*). We therefore also used the more traditional ^{1}H NMR method to determine fractionation factors for both the amine and the ammonium ion, and we supplemented this with pK_a determinations.

Experimental Section

Materials. Benzylamine-α-^{13}C was prepared by converting benzoic acid-α-^{13}C (99 atom %, ISOTEC, Inc.) to benzamide-α-^{13}C via the acid chloride followed by reduction of the amide with lithium aluminum hydride. Methyl-^{13}C-trimethylammonium iodide was obtained by treating trimethylamine with methyl-^{13}C iodide (99 atom %, ISOTEC, Inc.). The identities of these substances were confirmed by their NMR spectra. All other materials were the best available commercial grades. Deuterium oxide (Norell) contained 99.9 atom % D.

NMR. NMR measurements were made with Varian Gemini 200 or Gemini 300 instruments operating at probe temperatures of 25 °C. Coaxial 5-mm sample tubes were used, with the sample solution containing benzylamine or benzylammonium ion substrate plus the tetramethylammonium iodide (0.001 M) reference placed in the outer compartment and D_2O (to provide a frequency lock) placed in the inner compartment. Because the reference and sample were present together in the same solution, no corrections for differences in magnetic susceptibility of the H_2O, HDO, and D_2O solvents were necessary.

pK_a Determination. The acid dissociation constant of benzylammonium ion was determined spectrophotometrically using the change in absorbance near $\lambda = 220$ nm that accompanies this ionization reaction. Measurements were made with a Cary 118 spectrometer, operating with the cell compartment at 25.0 ± 0.05 °C, on solutions of fixed stoichiometric benzylammonium ion concentration (3.86×10^{-4} M in H_2O and 3.97×10^{-4} M in D_2O) but variable, and known, hydrogen ion concentration. Equilibrium constants, K_a, were evaluated by nonlinear least squares fitting of eq 3, in which A_B and A_{BH} are absorbances of the substrate completely in its basic and acid forms, respectively.

$$A_{obs} = \frac{A_B K_a + A_{BH}[H^+]}{K_a + [H^+]} \qquad (3)$$

Results

Carbon-13 NMR. This method of determining fractionation factors requires measurement of the carbon-13 chemical shift of the carbon atom being used to report deuterium content under three different conditions: in H_2O solution (δ_H), in D_2O solution (δ_D), and in an H_2O–D_2O mixture of atom fraction $x(\delta_x)$. The deuterium to protium ratio of the substrate at the exchanging site is then given by the ratio $(\delta_H - \delta_x)/(\delta_x - \delta_D)$, and the fractionation factor is equal to this ratio divided by the deuterium to protium ratio of the solvent, $x/(1 - x)$ (eq 4).

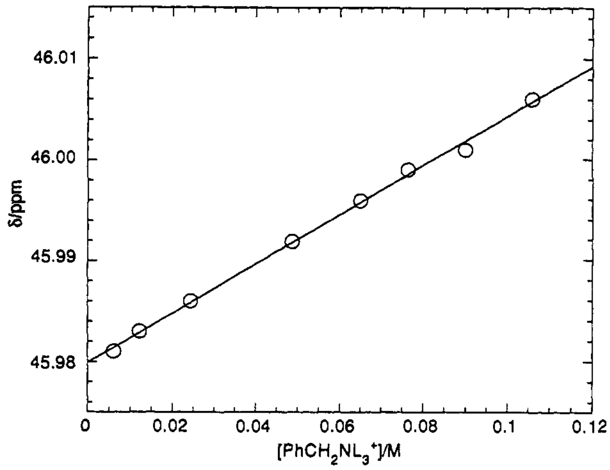

Figure 1. Relationship between chemical shifts of the α-carbon atom and concentration of benzylammonium ion in HDO solutions.

$$\phi = \left(\frac{\delta_H - \delta_x}{\delta_x - \delta_D}\right) \Big/ \frac{x}{(1 - x)} \qquad (4)$$

The required chemical shifts proved to be concentration dependent, for both benzylamine and benzylammonium ion, in all three solvents used, H_2O, D_2O, and a mixture, "HDO", made up of equal volumes of H_2O and D_2O.[12] Measurements were therefore made over a range of concentrations, 0.01–0.3 M for benzylamine and 0.05–0.1 M for benzylammonium ion. The ionic strength of the solutions was maintained at 0.10 M by adding $NaClO_4$ as required. These data are summarized in Table S1.[13]

The relationship between chemical shift and concentration was linear for benzylammonium ion, as is illustrated in Figure 1. The data could therefore be readily extrapolated to zero concentration in order to give precise concentration-independent chemical shift values. The results produced the fractionation factor $\phi = 1.084 \pm 0.020$ for the benzylammonium ion.

For benzylamine, however, the relationship between chemical shift and concentration was not linear but curved, as is shown in Figure 2. The data were found to fit a model in which benzylamine is in equilibrium with a dimeric species whose chemical shift is different from that of the monomer. Least squares fitting of such a model to the data gave chemical shifts and dimer-formation equilibrium constants that reproduced the data well, as is illustrated by the line in Figure 2 which was drawn using the set of parameters appropriate to this solution. The parameters obtained for all solutions examined are listed in Table S1.[13]

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(9) Schowen, R. L. *Prog. Phys. Org. Chem.* **1972**, *9*, 281–332. Note added in proof based on personal communication from Professor Schowen: These fractionation factors are values calculated by F. J. Karol using estimates of vibration frequencies of the relevant species in light and heavy water solution, see: Karol, F. J. Ph.D. Thesis, M.I.T., Cambridge, MA, 1962.

(10) (a) Jarret, R. M.; Saunders, M. *J. Am. Chem. Soc.* **1985**, *107*, 2648–2654. (b) *Ibid.* **1986**, *108*, 7549–7553.

(11) Perrin, C. L.; Engler, R. E. *J. Phys. Chem.* **1991**, *95*, 8431–8433.

(12) The deuterium to protium ratio of this mixture was found to be D/H = 0.991 ± 0.012 by comparing the magnitude of its ^{1}H NMR signal with that of a known amount of added dioxane. This result was used in the calculation of fractionation factors.

(13) Supplementary material; see paragraph at the end of this paper regarding availability.

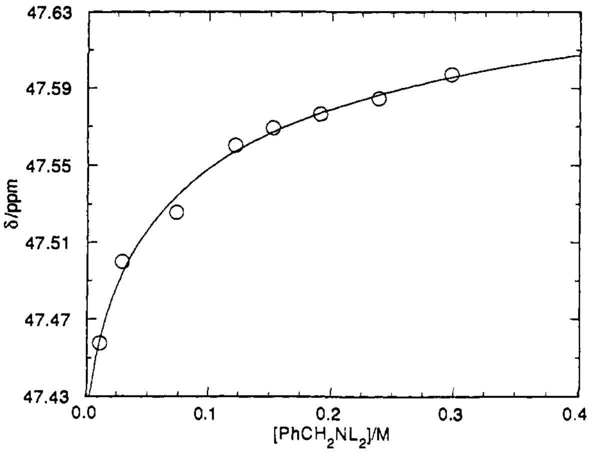

Figure 2. Relationship between chemical shifts of the α-carbon atom and concentration of benzylamine in HDO solutions.

Unfortunately, extrapolation to zero concentration down a curve such as that shown in Figure 2 does not give a very precise intercept and the concentration-independent chemical shift of monomeric benzylamine needed for evaluation of the fractionation factor was not well determined. The fractionation factor obtained therefore had an unacceptably large statistical uncertainty: $\phi = 0.81 \pm 0.53$. This fractionation factor was consequently also determined by the ^{1}H NMR method (*vide infra*).

The dimer-formation equilibrium constants obtained by this least-squares fitting had rather large associated statistical uncertainties as well, but they were nevertheless quite similar for all three media (H_2O, D_2O, and "HDO"). Their weighted average value, $K = 19.5 \pm 6.1$ M^{-1}, corresponds to a free energy of reaction for dimer formation of $\Delta G° = -1.8 \pm 0.2$ kcal mol^{-1}.

^{1}H NMR. The proton NMR method of determining fractionation factors for solutes whose hydrogens are undergoing rapid exchange with the solvent[6,14] is based upon the fact that the ^{1}H NMR signal from such a system consists of a composite line whose position depends upon the relative concentrations of protium at each of the exchanging sites. Introduction of deuterium into the system will change these relative concentrations (unless the fractionation factor is unity), and that will change the position of the NMR signal. From this change in signal position and knowledge of the stoichiometry of the system, fractionation factors may be calculated.

The relationship governing this phenomenon for a single solute is given in eq 5,[6,14] where δ_o is the chemical shift of the solvent and δ_s is that of the solute. The observed chemical shift, δ_{obs}, is

$$\delta_{obs} = \delta_o + \frac{\delta_s[S]}{1 - x + x\phi} \qquad (5)$$

thus expected to be a linear function of solute concentration. The slope of this linear relationship determined in H_2O solution, where $x = 0$, provides δ_s, and that in combination with the slope determined in an H_2O–D_2O mixture of deuterium atom fraction x gives ϕ. We accordingly measured δ_{obs} in H_2O and our "HDO" mixture for benzylamine over the concentration range 0.02–0.25 M and for benzylammonium ion over the range 0.01–0.1 M. The data are summarized in Table S2.[13] We found that improved precision could be obtained using chemical shifts referenced to the methylene groups of the substrates rather than to tetramethylammonium ion, and the data are consequently reported as such.

As Figure 3 illustrates, the expected linear relationship between observed chemical shift and substrate concentration is observed. Least squares analysis gave slopes which led to the fractionation factor $\phi = 0.961 \pm 0.071$ for benzylamine and $\phi = 1.032 \pm 0.074$ for benzylammonium ion.

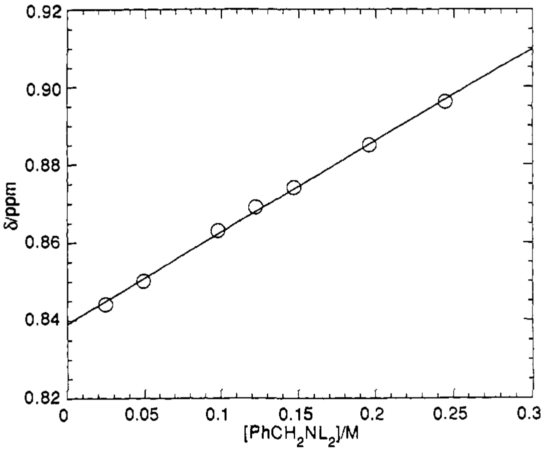

Figure 3. Relationship between benzylamine concentration and the benzylamine–water composite signal in the ^{1}H NMR spectrum of benzylamine in HDO solution; chemical shifts are referred to the substrate methylene group resonance.

Both of these results are consistent with the values obtained by the carbon-13 method, $\phi = 0.81 \pm 0.53$ and $\phi = 1.084 \pm 0.020$ for benzylamine and benzylammonium ion, respectively. Although the agreement in the former case is hardly meaningful because of the large uncertainty in the carbon-13 value, that for the latter is significant, both because this carbon-13 value is well determined and also because a difference might have been expected. The composite chemical shift measured by the ^{1}H NMR method contains contributions from all exchanging protons, including those of the solvation shell surrounding the substrate, and also those solvating the counterion if the substrate is ionic. If the water molecules of these solvation shells have chemical shifts sufficiently different from those of bulk solvent and fractionation factors sufficiently different from unity, they will contribute additional terms of the form $\delta_i[S_i]/(1 - x + x\phi_i)$ to eq 5.[6b,14] The fractionation factor obtained by a simple application of eq 5 will then not be the true value for the substrate itself but rather some composite of that fractionation factor and those for the various solvation shells. The carbon-13 NMR method, on the other hand, should be free of these difficulties, for it uses a chemical shift isotope effect to report D/H ratios and this isotope effect will, to a very good approximation, be independent of the isotopic nature of the solvent. Any dependence would be an isotope effect upon an isotope effect, also known as a departure from the rule of the geometric mean.[15] Such departures are produced by coupling of vibrational motions of bonds involving the isotopically substituted atoms. The effects are small even when these bonds are in the same molecule,[6b] and they will be even smaller, and consequently negligible, in a situation such as the present where one bond is in the substrate and the other is in the solvent. The concordance of ^{13}C and ^{1}H results observed here for the benzylammonium ion thus indicates that isotopic fractionation in solvation shells had no significant disturbing influence on the present determination of the fractionation factor for this species by the ^{1}H NMR method.

Isotopic fractionation in solvation shells is equivalent to a medium effect on transfer of a substance from H_2O to D_2O.[6b,16] Such medium effects can, and often do, make significant, if small, contributions to solvent isotope effects involving ions, and the lack of a disturbing influence on the present fractionation factor determination for benzylammonium ion does not necessarily mean that a medium effect is absent here. This lack of a significant

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(14) Kresge, A. J.; Tang, Y. C. *J. Phys. Chem.* **1979**, *83*, 2156–2159.

(15) Bigeleisen, J. *J. Chem. Phys.* **1955**, *23*, 2264–2267.

(16) Albery, W. J. In *Proton Transfer Reactions*; Caldin, E. F., Gold, V., Eds.; Chapman and Hall: London, 1975; Chapter 9.

disturbing influence could be due instead to offsetting medium effects produced by other ions in the solution or to chemical shifts of solvating waters insufficiently different from that of bulk solvent.

Medium effects are believed to be limited to ionic solutes.[6b,16] The fractionation factor determined here for benzylamine by the ^{1}H NMR method should consequently be free of any disturbance caused by such effects.

pK_a. Solvent isotope effects on acid–base equilibria can be expressed in terms of fractionation factors;[1] for example, that on the ionization of benzylammonium ion (eq 6) is equal to the collection of fractionation factors given by eq 7. In this expression,

$$\mathrm{PhCH_2NL_3{}^+ + L_2O \overset{K_a}{\rightleftharpoons} PhCH_2NL_2 + L_3O^+} \qquad (6)$$

$$\frac{\mathrm{K_D}}{\mathrm{K_H}} = \frac{(\phi_{\mathrm{PhCH_2NL_2}})^2 \ell^3}{(\phi_{\mathrm{PhCH_2NL_3{}^+}})^3 \Phi_{\mathrm{PhCH_2NL_3{}^+}}} \qquad (7)$$

the fractionation factors for benzylamine, $\phi_{\mathrm{PhCH_2NL_2}}$, benzylammonium ion, $\phi_{\mathrm{PhCH_2NL_3{}^+}}$, and hydronium ion, ℓ, are each raised to powers equal to the number of relevant equivalent hydrogens; the medium effect for the benzylammonium ions, $\Phi_{\mathrm{PhCH_2NL_3{}^+}}$, on the other hand, is a composite factor produced by all of the (unknown number of) hydrogens responsible for this effect. (Following Albery,[16] we use lower case ϕ for individual-site fractionation factors and upper case Φ for the medium effect.) The medium effect for the hydronium ion is included in the fractionation factor ℓ.[6b]

Medium effects are generally quite small,[6b,16] and $\Phi_{\mathrm{PhCH_2NL_3{}^+}}$ can be expected to have a value close to unity. The isotope effect on the acid ionization of benzylammonium ion will consequently be determined largely by ℓ, whose value is known,[6] and the two fractionation factors produced by the present NMR experiments. This isotope effect can therefore serve as a check on the validity of the present results.

We have consequently measured this isotope effect, using the UV absorbance of benzylamine to determine the relative concentrations of its protonated and unprotonated forms in H_2O and D_2O solutions of known acidity. Measurements were made at two wavelengths, $\lambda = 218$ and 220 nm, in perchloric acid and sodium hydroxide solutions as well as in boric acid and bicarbonate buffers. Ionic strength was maintained at 0.10 M by adding $NaClO_4$ as required. Hydrogen ion concentrations of the buffers were obtained by calculation using $\mathrm{p}K_a(H_2O) = 9.223$ and $K_a(H_2O)/K_a(D_2O) = 3.28$ for boric acid[17] and $\mathrm{p}K_a(H_2O) = 10.329$ and $K_a(H_2O)/K_a(D_2O) = 5.07$ for bicarbonate ion,[18] plus activity coefficients recommended by Bates;[19] the isotope effect on the autoprotolysis of water was taken to be $K_a(H_2O)/K_a(D_2O) = 7.28$.[20] The data are summarized in Table S3.[13]

As Figure 4 illustrates, the results gave well-defined titration curves. Least squares fitting of eq 3 produced $K_a(H_2O) = (4.36 \pm 0.16) \times 10^{-10}$ M for measurements at $\lambda = 218$ nm and $K_a(H_2O) = (4.42 \pm 0.18) \times 10^{-10}$ M for measurements at $\lambda = 220$ nm; the weighted average of these results is $K_a = (4.39 \pm 0.12) \times 10^{-10}$ M, $\mathrm{p}K_a = 9.358 \pm 0.012$, in good agreement with the literature value, $\mathrm{p}K_a = 9.35$.[21,22] The measurements in D_2O solution gave $K_a = (1.25 \pm 0.06) \times 10^{-10}$ M ($\lambda = 218$ nm) and $K_a = (1.35 \pm 0.05) \times 10^{-10}$ M ($\lambda = 220$ nm), whose weighted average is $K_a = (1.30 \pm 0.04) \times 10^{-10}$ M, $\mathrm{p}K_a = 9.885 \pm 0.013$. These results provide the isotope effect $K_H/K_D = 3.36 \pm 0.13$, which is a reasonable value for an acid of this strength.[23]

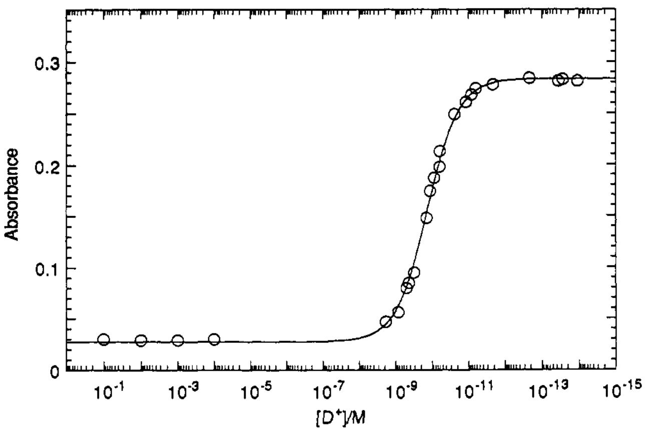

Figure 4. Titration curve for the ionization of benzylammonium ion in D_2O solution using absorbance data measured at 220 nm.

Table 1. Summary of Fractionation Factors

	species	
fractionation factor	$PhCH_2NL_2$	$PhCH_2NL_3{}^+$
ϕ, ^{13}C NMR	0.81 ± 0.53	1.084 ± 0.020
ϕ, ^{1}H NMR	0.961 ± 0.071	1.032 ± 0.074
ϕ, weighted average	0.958 ± 0.070	1.081 ± 0.019
Φ[a]		0.804 ± 0.130

[a] Medium effect.

A convenient way of employing this isotope effect to test the fractionation factors determined here is to use eq 7 to calculate $\Phi_{\mathrm{PhCH_2NL_3{}^+}}$ and see whether it has the expected near-unity value. The results, based on the weighted average fractionation factors listed in Table 1, is $\Phi_{\mathrm{PhCH_2NL_3{}^+}} = 0.804 \pm 0.130$. This is sufficiently near unity, and also quite similar to $\Phi = 0.70$ for the not too dissimilar tetra-*n*-butylammonium ion,[16] to lend confidence to the validity of the presently determined fractionation factors.

Discussion

The present results, summarized in Table 1, provide a ratio of benzylammonium ion to benzylamine fractionation factors that is slightly greater than unity: $\phi_{\mathrm{PhCH_2NL_3{}^+}}/\phi_{\mathrm{PhCH_2NL_2}} = 1.128 \pm 0.086$. This agrees well with the ratio for ammonium ion to ammonia, $\phi_{\mathrm{NL_4{}^+}}/\phi_{\mathrm{NL_3}} = 1.07 \pm 0.01$, estimated from rates of hydrogen exchange[11] and is consistent with the earlier estimate for the same pair, $\phi_{\mathrm{NL_4{}^+}}/\phi_{\mathrm{NL_3}} = 1.04$.[8] The fractionation factors for positively charged and neutral N–L bonds in general also give a ratio greater than unity, $\phi_{\mathrm{NL^+}}/\phi_{\mathrm{NL}} = 1.05$.[9] It would seem, therefore, that introducing a positive charge into a neutral N–L bond does not lower its fractionation factor as it does for the O–L bond in the hydronium ion–water system, where $\phi_{\mathrm{OL^+}}/\phi_{\mathrm{OL}} = 0.69$.

It has been suggested that the tetrahedral structure of ammonium ions may increase the resistance to bending of their N–H bonds, raising the net binding of hydrogen in these species relative to that in the trigonal hydronium ion.[2a] This idea receives support from a comparison of vibrational frequencies of the two ions. Ideally, such a comparison should be based upon values measured in the same medium as that in which the fractionation factors were determined, *i.e.* aqueous solution. Unfortunately, aqueous solution values are not available, but the solid state

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(17) Gold, V.; Lowe, B. M. *J. Chem. Soc. A* **1968**, 1923–1932.

(18) Paabo, M.; Bates, R. G. *J. Phys. Chem.* **1969**, *73*, 3014–3017.

(19) Bates, R. G. *Determination of pH. Theory and Practise*; Wiley-Interscience: New York, 1973; p 49.

(20) Gold, V.; Lowe, B. M. *J. Chem. Soc. A* **1967**, 936–943.

(21) Robinson, R. A.; Kiang, A. K. *Trans. Faraday Soc.* **1956**, *52*, 327–331.

(22) Our result is a concentration quotient applicable at ionic strength = 0.10 M, whereas it is not clear whether the literature value[21] refers to zero or some unspecified ionic strength; ionic strength effects on the ionization of ammonium ions, however, are likely to be small.

(23) Laughton, P. M.; Robertson, R. E. In *Solute-Solvent Interactions*; Coetzee, J. F.; Ritchie, C. D., Eds.; M. Dekker: New York, 1969; Chapter 7.

(24) Nakamoto, K. *Infrared and Raman Spectra of Inorganic and Coordination Compounds*, 4th ed.; Wiley-Interscience: New York, 1986.

Table 2. Comparison of Vibrational Frequencies (ω, cm^{-1})[a]

H_2O	H_3O^+	NH_3	NH_4^+
3400	3285	3378	3145
3220	3100	3223	3040
1620	1577	1646	1680
	1175	1060	1400

[a] Values taken from ref 24.

frequencies listed in Table 2 might not be an unreasonable substitute. It may be seen that the frequencies of the two bending vibrations of NH_4^+ at ω = 1680 and 1400 cm^{-1} are roughly comparable to that of the bending vibration of H_3O^+ at ω = 1577 cm^{-1} but that the remaining bending vibration of H_3O^+ at ω = 1175 cm^{-1} is indeed markedly lower.

A further instructive comparison may be made of the H_2O–H_3O^+ and NH_3–NH_4^+ systems. The stretching vibrations of H_2O are each reduced by *ca.* 100 cm^{-1} in going over to H_3O^+, and one bending vibration of H_3O^+ is weaker by almost 500 cm^{-1} than the bending vibration of H_2O. The binding of hydrogens in H_3O^+ is thus considerably weaker than that in H_2O, and the fractionation factor of H_3O^+ is consequently significantly less than that of H_2O. In the NH_3–NH_4^+ pair, on the other hand, although each of the stretching vibration frequencies decreases by some 200 cm^{-1} in going from the neutral to the charged species, this is compensated for almost completely by increases in bending vibration frequencies. The net result is that the overall binding of hydrogens in NH_4^+ is of similar strength to that in NH_3, and the fractionation factors of these substances are consequently also similar.

The bond weakening expected as a consequence of introducing a positive charge is thus reflected in loosened stretching vibrations for both the O–L and N–L systems. In the N–L system, however, its effect is offset by stiffened bending vibrations. This is a consequence of the tetrahedral structure of the ammonium ion whose three additional hydrogen atoms restrict the bending motion of a given N–L bond in all directions. The hydronium ion, on the other hand, is trigonal with a very flat pyramidal structure;[25] "out-of-plane" bending of its O–L bonds is therefore less restricted by the presence of other atoms, and this vibration is correspondingly weaker.

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Supplementary Material Available: Tables S1–S3 of ^{13}C NMR, ^1H NMR, and acid dissociation data (8 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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(25) Bell, R. P. *The Proton in Chemistrry*, 2nd ed.; Cornell University Press: Ithaca, NY, 1973; pp 14–15.