Observation by UV−Visible and NMR Spectroscopy and Theoretical Confirmation of 4-Isopropyltropolonate Ion, 4-Isopropyltropolone (Hinokitiol), and Protonated 4-Isopropyltropolone in Acetonitrile[†]

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Protonated 4-isopropyltropolone (H_2L^+) was produced by the addition of methanesulfonic or trifluoromethanesulfonic acid to 4-isopropyltropolone (hinokitiol: HL) dissolved in a protophobic aprotic solvent, acetonitrile, with poor solvation of anions and cations. The formation was confirmed by UV−visible and ^{13}C NMR spectroscopy as well as theoretical calculations using the Gaussian03 quantum chemistry package. The ^{13}C chemical shifts of all C-atoms in the seven-membered ring were properly assigned for H_2L^+ and HL as well as for the deprotonated species, L^-. The influence of residual water in the organic solvent was regarded as negligible because such a water is in the “dihydrogen ether” condition.

Introduction

Strong electrolytes include some mineral acids (HCl, $HClO_4$) and alkali metal and alkaline earth metal salts (LiCl, $MgCl_2$). These electrolytes can be completely dissociated into ions in aqueous solution of moderate concentration ($\sim 0.1\ \mathrm{mol \cdot dm^{-3}}$).[1] However, in nonaqueous solution, especially in aprotic and protophobic solvents, “strong electrolytes” (as regarded in aqueous solution) are often not completely dissociated even though the relative permittivities of these solvents seem to be high enough ($\varepsilon_r > 20$). Protophobic aprotic solvents have poor solvation abilities toward both anions and cations, compared with that of bulk water. We have demonstrated that alkali metal and alkaline earth metal cations can interact with many simple anions (except ClO_4^- and so on) not only through Coulombic forces but also by coordination provided the solute ions are not subject to strong solvation.[2]

We have explained the large salt effects on the indicator acidity (or Hammett acidity function)[3] using 4-(dimethylamino)azobenzene[4] and on the proton transfer from tropolone[5] or nitrophenols[6] toward amine bases in acetonitrile solution in terms of the direct chemical interaction between the anions and M^+ or M^{2+} and not merely as ion-exchange reactions or the alternation between contact ion pairs (CIP) and solvent-separated ion pairs (SSIP).[6] At last, we obtained decisive ^1H NMR evidence of the formation of “reverse-coordinated”[2,5] species, $(Li^+)_2L^-$, for the anions (L^-) of tropolone and hinokitiol (4-isopropyltropolone) in acetonitrile-d_3 but not in DMF-d_6 (dimethylformamide-d_6).[7] The successive formation of ML_2 and ML^+ ($M^{2+} = Mg^{2+}$ or Ba^{2+} and $L^- = C_6H_5CO_2^-$) in acetonitrile, which is based on the chemical interaction in addition to the Coulombic force, has been also reported.[8]

In the present paper, we report the observations of the 4-isopropyltropolonate ion, 4-isopropyltropolone (hinokitiol), and the protonated 4-isopropyltropolone in acetonitrile by UV−visible and NMR spectroscopy and theoretical confirmation.

Also, we have proposed that, upon the addition of concentrated salts, the properties of bulk water can be altered as if it was that of a nonaqueous solvent. Reichardt et al.[9] described, using the solvation model of Frank and Wen,[10] that “at high salt concentrations ($c > 5$ mol/L), region **C** can be abolished and only regions **A** and **B** survive, resulting in an aqueous solvent called ‘dihydrogen ether’”.[1−13]

Experimental Section

The preparation method of tetrabutylammonium 4-isopropyltropolonate was described previously.[7] The “glassy state” salt from 4-isopropyltropolone (hinokitiol) was found to be twice hydrated ($n\text{-}Bu_4N^+\ 4\text{-}C_3H_7{-}C_7H_4O_2^-\ 2H_2O$) on the basis of ^1H NMR analysis, where tropolone is 2-hydroxycyclohepta-2,4,6-triene-1-one. Other chemicals and equipments employed in the present study are the same as those in the previous study.[7]

Results and Discussion

UV−Visible and NMR Spectroscopy. The ^{13}C NMR results of the tropolone ion, tropolone, and the protonated tropolone in acetonitrile-d_3 (CD_3CN) have been reported in the previous paper.[7] Scheme 1 shows the molecular structure of 4-isopropyltropolone, HL (hinokitiol), and the numbering system for HL and its related species (L^-, HL, and H_2L^+). All ^1H NMR signals of 4-isopropyltropolonate ($n\text{-}Bu_4N^+\ 4\text{-}C_3H_7{-}C_7H_4O_2^-\ 2H_2O$), except for the 9,10-H signal, shift slightly toward the

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Scheme 1. Numbering System for ^1H and ^{13}C NMR of 4-Isopropyltropolone, HL (Hinokitiol), and Its Related Species (L^-, HL, and H_2L^+)

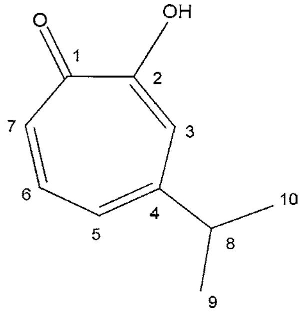

Table 1. ^1H and ^{13}C NMR Chemical Shift Values (vs Tetramethylsilane, TMS) of Tetrabutylammonium 4-Isopropyltropolonate (Dihydrate), Measured at Various Concentrations in CD_3CN at 25 °C

	$[n\text{-}Bu_4N^+\ 4\text{-}C_3H_7{-}C_7H_4O_2^-\ 2H_2O]/mol\cdot dm^{-3}$			
	$1\cdot10^{-3}$	0.01	0.1	1.0
	^1H NMR (δ/ppm)			
$H_2O{-}H$ signal	2.146	2.244	2.776	3.952
6-H	6.70	6.71	6.71	6.76
3-H	6.46	6.47	6.48	6.58
7-H	6.29	6.31	6.32	6.43
5-H	5.99	6.29	6.02	6.10
8-H	2.60	2.60	2.61	2.63
9,10-H	1.18	1.18	1.17	1.18
	^{13}C NMR (δ/ppm)			
C-1		183.8	183.8	183.4
C-2		183.4	183.3	182.9
C-4		155.4	155.4	155.6
C-6		134.6	134.6	134.9
C-7		121.8	122.0	122.6
C-3		120.6	120.7	121.2
C-5		114.2	114.4	115.4
C-8		39.5	39.5	39.5
C-9,10		24.3	24.4	24.5

lower magnetic field with increasing concentration [$(1\cdot10^{-3}$ to $1.0)\ mol\cdot dm^{-3}$] of L^- in CD_3CN (cf. Table 1). Coincidentally, the ^1H NMR signal of H_2O, which stems from the residual water in the solvent as well as from the dihydrate salt, shifts toward the lower magnetic field. A similar downfield shift of the ^1H NMR signal of H_2O was observed for the binary water−CD_3CN mixture with an increasing amount of water.[2]

With an increasing concentration of the 4-isopropyltropolonate salt [c = (0.01 to 1.0) $mol\cdot dm^{-3}$], the ^{13}C signals of C-1 and C-2 of 4-isopropyltropolonate shift just slightly toward the higher magnetic field, whereas other ^{13}C signals in the seven-membered ring are shifted oppositely; the signals out of the seven-membered ring (C-8 and C-9,10) remain constant. The assignment of the signals of the 4-isopropyltropolonate ion was performed with the assistance of theoretical calculations, as described later. We would like to stress that the water brought in by the hydrated salt scarcely affects the ^{13}C NMR chemical shift of the 4-isopropyltropolonate ion in CD_3CN. The reason is that the properties of residual water in organic solvents should be close to that of a "dihydrogen ether",[2] being far from those of bulk water.

Figure 1 shows the shifts of the ^{13}C NMR signals of the 4-isopropyltropolonate ion (c = 0.10 $mol\cdot dm^{-3}$) after the addition of CF_3SO_3H in CD_3CN at 25 °C. With increasing concentration of the strong proton donor, CF_3SO_3H, the signals of C-1 and C-2 are shifted toward a higher magnetic field even though a positive charge was added to the anionic compound.

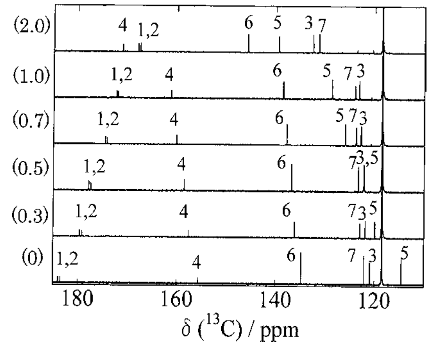

Figure 1. Shifts of ^{13}C NMR signals of the 4-isopropyltropolonate ion (c = 0.10 $mol\cdot dm^{-3}$, $n\text{-}Bu_4N^+\ 4\text{-}C_3H_7{-}C_7H_4O_2^-\ 2H_2O$) after addition of CF_3SO_3H in CD_3CN at 25 °C; the chemical shift values δ (^{13}C) versus TMS. The figures in parentheses show the concentration ratios of the added CF_3SO_3H to the 4-isopropyltropolonate ion.

Similar phenomena have been observed for the tropolonate ion, $C_7H_5O_2^-$, in CD_3CN.[7] All other signals in the seven-membered ring gave, more or less, magnetic downfield shifts. The shift of C-5 was most remarkable: without acid, the C-5 signal was observed in the highest magnetic field among the signal of the seven-membered ring carbons. However, the signal approached or even exceeded the C-3 signals in the presence of a half-equivalent amount (0.5) of the acid. With the addition of the equivalent amount of CF_3SO_3H to 4-isopropyltropolonate (L^-), all of the ^{13}C signals turned out to be those of 4-isopropyltropolone (HL); see Table 2 for 4-isopropyltropolone.

Figure 2 shows UV−visible spectra of 4-isopropyltropolone ($c = 1.0\cdot10^{-3}\ mol\cdot dm^{-3}$) in the presence of methanesulfonic acid (CH_3SO_3H) in CH_3CN at room temperature. The spectrum of 4-isopropyltropolone, without acid, gave two peaks at λ_{max} = (322 and 349) nm. With an increasing concentration of CH_3SO_3H, however, the peak at 349 nm decreased, but a new peak appeared at 336 nm. In the presence of (0.2 or 0.5) $mol\cdot dm^{-3}$ CH_3SO_3H, the absorbance at 336 nm reached its maximum value, suggesting the complete formation of the protonated 4-isopropyltropolone (H_2L^+). The addition of trifluoromethanesulfonic acid (CF_3SO_3H) to 4-isopropyltropolone solution caused similar spectral changes at much lower acid concentrations. It should be mentioned that the acidity of CF_3SO_3H ($pK_a = 2.6$)[14] is much higher than that of CH_3SO_3H ($pK_a = 10.0$)[15] in acetonitrile. Hosoya and Nagakura[16] have examined the basicity of tropolone in concentrated sulfuric acid solutions, and they found a pK_a value of −0.86 for the protonated tropolone (H_2L^+). In their experiment, the formation of the protonated tropolone seems to be completed at −3.38 of the acidity constant, H_0,[3] of the solvent (50 % H_2SO_4) or more concentrated H_2SO_4 solution.

Figure 3 shows the changes in the ^{13}C NMR chemical shift values of 0.01 $mol\cdot dm^{-3}$ 4-isopropyltropolone after addition of trifluoromethanesulfonic acid in CD_3CN. With an increasing concentration of the acid CF_3SO_3H, the C-1 and C-2 signals are shifted toward the higher magnetic field, while other signals show normal downfield shifts. All of the signals reached almost constant values at 0.01 $mol\cdot dm^{-3}$ CF_3SO_3H (in the presence of equivalent amounts of the acid). The complete formation of the protonated 4-isopropyltropolone (H_2L^+) has been achieved at $c(CF_3SO_3H) = 0.02\ mol\cdot dm^{-3}$, judging from the experimental fact that all of the signals remained almost constant even in the presence of (0.02 to 0.2) $mol\cdot dm^{-3}$ CF_3SO_3H (see Table 2).

The intrinsic acidity and basicity of tropolone in the gas phase have been determined experimentally, and the results have been compared with those observed by the ab initio calculation.[17]

Table 2. Changes in the ^{13}C NMR Chemical Shift Values of 4-Isopropyltropolone (Hinokitiol, $c = 0.010$ mol·dm^{-3}) after the Addition of Trifluoromethanesulfonic Acid in CD_3CN at 25 °C

	concentration of added CF_3SO_3H/mol·dm^{-3}								
	0	0.002[a]	0.005[a]	0.0075[a]	0.01	0.02	0.05	0.1	0.2
C-1	172.1	171.1	169.7	168.3	166.7	166.5	166.4	166.3	166.3
C-2	171.8	170.8	169.4	168.6	167.4	167.1	167.1	167.0	167.0
C-3	122.9	124.9	127.4	129.2	132.6	133.0	133.1	133.2	133.2
C-4	161.0	163.4	166.5	168.8	171.2	171.7	171.8	171.9	171.9
C-5	128.4	131.0	134.4	136.7	139.8	140.3	140.4	140.5	140.6
C-6	138.3	140.1	142.3	143.8	145.7	146.1	146.1	146.1	146.1
C-7	123.8	125.8	128.5	130.3	131.1	131.7	131.8	131.8	131.8
C-8	39.5	39.7	40.0	40.3	40.5	40.5	40.6	40.6	40.6
C-9,10	23.5	23.5	23.5	23.6	23.6	23.6	23.6	23.6	23.6

[a] The concentrations of CF_3SO_3H were (0.02, 0.05, and 0.075) mol·dm^{-3} for 0.10 mol·dm^{-3} 4-isopropyltropolone.

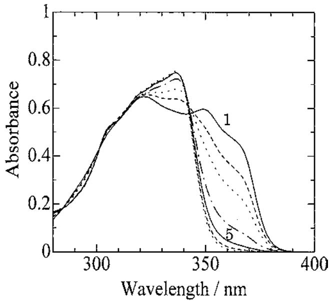

Figure 2. UV−visible spectra of 1.0·10^{-3} mol·dm^{-3} 4-isopropyltropolone (0.1 cm path length) in CH_3CN as a function of CH_3SO_3H concentration: (1) 0; dashed line, 1.0·10^{-2}; dotted line, 2.0·10^{-2}; dash−dot−dashed line, 5.0·10^{-2}; (5) 0.1; dashed line, 0.2; dotted line, 0.5 mol·dm^{-3} of CH_3SO_3H.

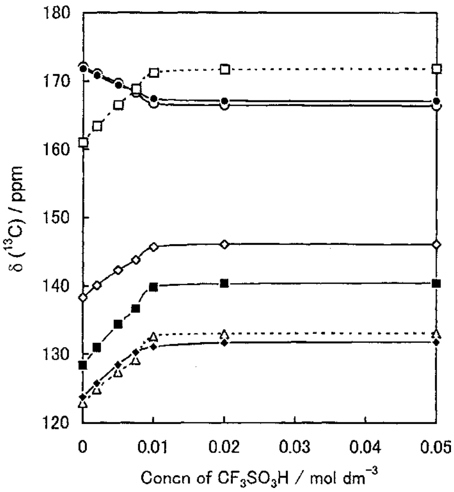

Figure 3. Changes in ^{13}C NMR chemical shift values (vs TMS) for 4-isopropyltropolone (hinokitiol, $c = 0.010$ mol·dm^{-3}) with increasing concentration of CF_3SO_3H in CD_3CN at 25 °C: ○, C-1; ●, C-2; △, C-3; □, C-4; ■, C-5; ◇, C-6; ◆, C-7.

The analysis showed that both the protonated and the deprotonated species are stabilized by resonance. We have demonstrated that tropolone[7] and 4-isopropyltropolone are ready to accept a proton from CF_3SO_3H and even from CH_3SO_3H, whereas benzoic acid does accept a proton just partly in acetonitrile. Ola and Calin[18] have reported the ^{1}H NMR spectrum of protonated tropolone in "magic acids," $SbF_5 + FSO_3H + SO_2$ and $FSO_3H + SO_2$ solutions at −60 °C.

Careful examination of the experimental results revealed that the signals of C-3 and C-7 might intersect each other at around a 75 % equivalent amount of CF_3SO_3H to 4-isopropyltropolone. Theoretical calculations verified the intersection between the C-3 and the C-7 signals. The intersection between C-1 and C-2 was also suggested on the basis of both experimental and theoretical evidence.

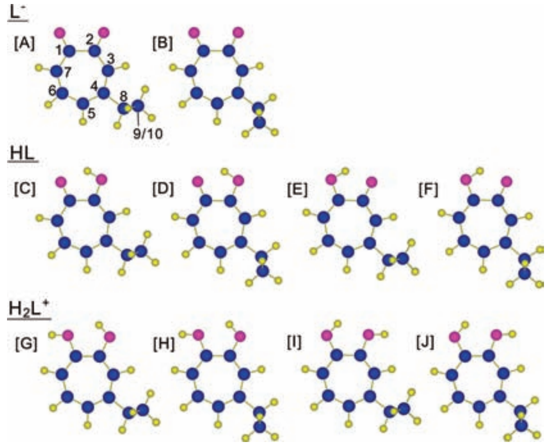

Figure 4. Optimized geometries of isomers of L$^-$ ([A], [B]), HL ([C] to [F]), and H_2L^+ ([G] to [J]).

Theoretical Calculation of ^{13}C NMR Chemical Shifts for L^-, HL, and H_2L^+. We assigned the ^{13}C NMR chemical shifts of the 4-isopropyltropolonate ion (L^-), 4-isopropyltropolone (HL), and protonated 4-isopropyltropolone (H_2L^+) with the help of quantum-chemical calculations using the Gaussian03 quantum chemistry package.[19] There are two stable conformers for L^- derived from the isopropyl group. For HL and H_2L^+, we consider four isomers issuing from the position and/or direction of the hydroxyl and isopropyl groups. These isomers are depicted in Figure 4. All geometries were optimized with the density functional theory (DFT) employing a PBE1PBE hybrid functional[20,21] at C_s symmetry. Dunning's correlation-consistent polarized triple-ζ (cc-pVTZ) basis set[22] was adopted. The relative energies with respect to the most stable species of each molecule and their existing probabilities at 298.15 K (= 25 °C) evaluated from Boltzmann distribution are summarized in Table 3. We have evaluated the ^{13}C NMR chemical shift of L^-, HL, and H_2L^+ by the thermal average of these isomers at 298.15 K. Magnetic shielding tensors of these molecules at the optimized geometries were evaluated by using the gauge-including atomic orbital (GIAO) method[23,24] at the PBE1PBE/cc-pVTZ level. To evaluate ^{13}C chemical shifts, the magnetic shielding calculation of the tetramethylsilane (TMS) standard was also performed.

The calculated ^{13}C NMR chemical shifts (vs TMS) for L^-, HL, and H_2L^+ are listed in Table 4 and depicted in Figure 5. The shifts of each species ([A] to [J]) are available in Table S1 (Supporting Information). The results are in accord with the experimental data of Figure 1 or Tables 1 and 2: (i) As the number of H-atoms bonded to oxygen atoms (i.e., the concentration of a proton donor) increases, the chemical shifts of C-1

Table 3. Relative Energy (Δ*E*) and Existing Probability at 298.15 K (*P*) of L^-, HL, and H_2L^+

molecule	structure	Δ*E* kJ·mol^{-1}	*P*
L^-	[A]	0.000	0.526
	[B]	0.258	0.474
HL	[C]	0.000	0.433
	[D]	2.844	0.139
	[E]	2.695	0.147
	[F]	1.083	0.281
H_2L^+	[G]	0.000	0.319
	[H]	0.134	0.302
	[I]	1.038	0.210
	[J]	1.591	0.169

Table 4. Calculated ^{13}C NMR Chemical Shifts of 4-Isopropyltropolonate Ion (L^-), 4-Isopropyltropolone (HL), and Protonated 4-Isopropyltropolone (H_2L^+) in ppm

	chemical shift, *δ*/ppm		
	L^-	HL	H_2L^+
C-1	187.5	176.5	165.2
C-2	187.4	175.3	166.6
C-3	120.2	122.7	137.4
C-4	152.6	166.5	185.0
C-5	105.3	128.3	147.8
C-6	135.1	142.7	150.3
C-7	121.2	124.5	133.3
C-8	44.8	45.2	48.1
C-9,10	26.3	25.1	26.1

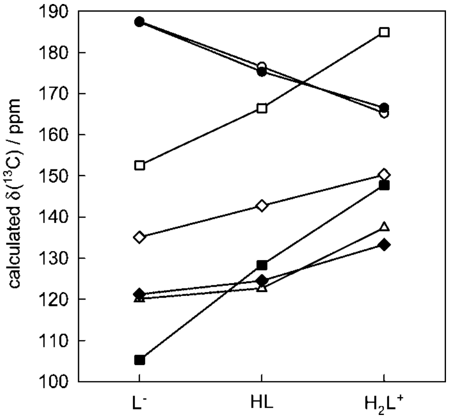

Figure 5. Calculated ^{13}C NMR chemical shift values (*δ*) of L^-, HL, and H_2L^+: ○, C-1; ●, C-2; △, C-3; □, C-4; ■, C-5; ◇, C-6; ◆, C-7.

and C-2 decrease. (ii) The opposite is true for the other seven-membered ring carbons. (iii) The shift of C-5 is the most remarkable. (iv) The order of C-3 and C-7 changes between HL and H_2L^+. These theoretical results support the above assignments of the experimental ^{13}C NMR chemical shifts of 4-isopropyltropolone derivatives.

Conclusions

The protonation of 4-isopropyltropolone (hinokitiol) with methanesulfonic or trifluoromethanesulfonic acid takes place rather easily in acetonitrile as a solvent. The reactivity of a chemical reaction can differ much in different solvent conditions. We propose that not only the Coulombic force but also "direct" chemical interactions between many anions and protons, alkali metal, or alkaline earth metal cations should be taken into account for many reactions in "aqueous" solution containing concentrated salts.

Acknowledgment

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Supporting Information Available:

Calculated ^{13}C NMR chemical shift values of 4-isopropyltropolone and related species. This material is available free of charge via the Internet at http://pubs.acs.org.

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