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Volume of Association of Charge-Transfer Interaction of 1-Methyl-3-(carbomethoxy)pyridinium Iodide and Sodium 8-Chlorotheophyllinate in Aqueous Solution

R. Kenneth Williams

Department of Chemistry, University of Guelph, Guelph, Ontario, N1G 2W1 Canada

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Values have been obtained for the association constant for the interaction of sodium 8-chlorotheophyllinate with 1-methyl-3-(carbomethoxy)pyridinium iodide in aqueous solution at pH 7.0, $I = 0.20$, at various temperatures and pressures. From these data the apparent volume change on association is estimated to be $\Delta\bar{V} = -6.5\ (\pm 0.5)$ cm^3 mol^{-1} at 25 °C. Values for the compressibility increment were obtained within the range of $\Delta\kappa = (1.6\text{–}2.0) \times 10^{-9}$ Pa^{-1}. Values were also obtained for the association constant of sodium 8-chlorotheophyllinate with the methyl ester of *trans*-cinnamic acid in a methanol and water mixture at 1-atm pressure. The results are interpreted in terms of the volume change to be expected on association due to ion pairing, and the approach of aromatic rings in water.

Introduction

While important information has been gathered on the effect of pressure on charge-transfer complexes in nonaqueous solvents,[1,2] there are few recorded studies of their behavior in aqueous solution.[3,4] The association between the acceptor, 1-methyl-3-(carbomethoxy)pyridinium iodide, and the donor, sodium 8-chlorotheophyllinate, in aqueous solution was previously found to be characterized by a yellow charge-transfer band, and accompanied by a volume decrease.[4] This result was unusual in that the formation of an ion pair in water normally is associated with a volume increase.[5] Since these observations referred to solutions at relatively high ionic strength, where charge effects may be expected to be damped out, the work has now been extended to solutions of lower ionic strength, and higher pressure. For comparison, the association of 8-chlorotheophylline with the methoxy ester of *trans*-cinnamic acid was also measured in a methanol–water mixture.[6] In this case charge interaction should be absent.

Experimental Section

Methyl nicotinate (mp 42–43 °C) and 8-chlorotheophylline (mp 290 °C) were obtained from Aldrich Chemical Co. (Milwaukee, WI). Oxalyl chloride was obtained from Eastman Kodak Co. (Rochester, NY, 4650). all other chemicals were of reagent grade and obtained from Fischer Scientific Co. (Toronto, Ontario, Canada).

1-Methyl-3-(carbomethoxy)pyridinium iodide was prepared from methyl nicotinate on reaction with methyl iodide in methanol at 30 °C, as described previously.[4] The methyl ester of *trans*-cinnamic acid was prepared as follows. The sodium salt of *trans*-cinnamic acid was reacted with oxalyl chloride in benzene, yielding *trans*-cinnamoyl chloride. This was methylated by means of a solution of pyridine in methanol. The melting point was found to be 31.3–32.7 °C. The NMR spectra indicated an olefinic double bond and the presence of a methyl group in the trans position.

The pressure technique was essentially as reported before.[4] A high-pressure optical cell capable of holding a quartz cuvette of 1-cm path length was built for the purpose.[7] Pressures were measured by means of a Bourdon gauge, which was calibrated against a pressure balance reading to 10 000 lb in.$^{-2}$ Temperatures were read by means of a thermocouple attached to the optical cell and were accurate to 0.10 °C.

TABLE I: Association Constants for the Interaction of the Sodium 8-Chlorotheophyllinate and 1-Methyl-3-(carbomethoxy)pyridinium Iodide[a]

I, mol kg^{-1}	T, °C	K_m	$\Delta\epsilon_{380}$, mol kg^{-1} cm^{-1}
0.50	25.0	3.77 ± 0.4	376.6 ± 16
0.50	10.0	4.86 ± 0.5	361.9 ± 13
0.20	25.0	4.28 ± 0.4	355.6 ± 13
0.20	10.0	5.55 ± 0.6	369.0 ± 18

[a] Conditions of measurement were as follows. Absorbances were measured at a wavelength of 380 nm in aqueous solutions at a pH of 7.0, and a pressure of 1 atm. Concentrations are expressed as mol (kg of water)$^{-1}$.

The assay solution in a quartz cuvette was separated from the pressure fluid, hexane, inside the optical cell, by a Teflon membrane placed over the top of the cuvette and held in place by a Viton polyfluorocarbon O ring.

The measurement of absorbance increments was affected as described previously,[4] a 1.0-cm cuvette or a 2-mm cuvette being used according to the total absorbance. Absorbance was measured at 380 nm in the case of the 8-chlorotheophyllinate–pyridinium cation complex. For the complex between the methyl ester of *trans*-cinnamic acid and sodium 8-chlorotheophyllinate measurements were made at 320 nm. Absorbance increments at 1 atm were measured in a Unicam SP 1700 UV spectrometer, and under pressure in a Cary 118 double-beam UV spectrometer.

No buffer was used in any solution since none of the rejections studied involved a hydrogen ion equilibrium. Solutions were adjusted to pH 7.0, at 25 °C, by using a Radiometer, Model 26, expanded-scale pH meter and sodium chloride was added to bring to the required ionic strength. Concentrations of all species were expressed in molal units (mol (kg of water)$^{-1}$).

Solutions of the methyl ester of *trans*-cinnamic acid in methanol were prepared by dissolving the solid crystalline material in a measured volume of anhydrous methanol. A 5-cm^3 sample of this solution was mixed with a sufficient volume of the solution of sodium 8-chlorotheophyllinate to contain 20 g of water. The mole ratio of methanol to water was therefore 1:9.

Data were therefore treated essentially as described before to obtain the volume change ΔV, and the compressibility increment $\Delta\kappa$.[4]

Results

Interaction of Sodium 8-Chlorotheophyllinate with 1-Methyl-3-(carbomethoxy)pyridinium Iodide in Aqueous Solution.

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TABLE II: Association Constants as a Function of Pressure, and Derived Values of Volume Change and of Compressibility Increment, for Mixtures of Sodium 8-Chlorotheophyllinate and 1-Methyl-3-(carbomethoxy)pyridinium Iodide in Aqueous Solution[a]

P, MPa	K_m	$\Delta\bar{V}$, cm^3 mol^{-1}	$10^9\Delta\kappa$, Pa^{-1}
	T = 25 °C		
0.1	4.27 ± 0.1	−6.5 ± 0.5	1.6 ± 0.5
7.0	4.37 ± 0.1		
14.0	4.49 ± 0.2		
34.9	4.72 ± 0.1		
69.8	5.14 ± 0.2		
139.7	6.12 ± 0.5		
209.5	6.65 ± 0.6		
279.4	7.47 ± 1.1		
314.3	8.18 ± 1.1		
349.2	8.34 ± 1.3		
	T = 10 °C		
0.1	5.55 ± 0.4	−6.2 ± 0.6	2.0 ± 0.3
7.0	5.70 ± 0.3		
14.0	5.86 ± 0.1		
34.9	6.11 ± 0.4		
69.8	6.59 ± 0.5		
139.7	7.53 ± 0.5		
209.5	8.34 ± 0.4		
279.4	9.43 ± 0.6		
314.3	9.78 ± 0.6		
349.2	10.19 ± 0.4		

[a] Conditions of measurement are as follows: aqueous solution at pH 7.0, I = 0.20. Concentrations are expressed as mol (kg of water)$^{-1}$.

In Table I are shown values for the association constant, K_m, at different temperatures and ionic strengths for the interaction of the donor, sodium 8-chlorotheophyllinate, and the acceptor, 1-methyl-3-(carbomethoxy)pyridinium iodide, in aqueous solution at a pH of 7.0. Also shown are derived values for the increment in extinction coefficient, $\Delta\epsilon$, at a wavelength of 380 nm. The change in apparent value of K_m with ionic strength is within experimental error, whereas the variation in K_m with temperature is outside of the experimental error. The variation in donor concentration, at lower ionic strength, was from 0.180 to 0.040, as compared with an acceptor concentration of 5.0 × 10^{-3} mol kg^{-1}, whereas the variation in donor concentration at higher ionic strength was from 0.40 to 0.05, at the same acceptor concentration.

In Table II are shown values of the association constants, K_m, for the interaction of the donor with the acceptor in aqueous solutions of ionic strength I = 0.20, pH 7.0 at different temperatures and pressures. Absorbances are measured at 380 nm, in cuvettes of 10-mm path length.

In the plot of reciprocal absorbance increment against reciprocal donor concentration, no appreciable change in the intercept on the reciprocal absorbance axis occurred with change in either temperature or pressure, and hence no appreciable change in the increment in the extinction coefficient, $\Delta\epsilon$, occurred.

Also shown in Table II are values for the volume of association, $\Delta\bar{V}$, and compressibility increment, $\Delta\kappa$, derived from the pressure dependence of the association constant. The value of $\Delta\bar{V}$ obtained is negative and greater in magnitude than the value obtained previously for this complex,[4] at ionic strength of 0.50, which was −4.0 cm^3 mol^{-1}. the value of the compressibility increment was positive, indicating that the complex was more compressible than that of the separate entities, donor and acceptor.

Interaction of Sodium 8-Chlorotheophyllinate and the Methyl Ester of *trans-Cinnamic Acid in a Mixture of Methanol and Water.* In Table III are shown the values of the association constant, K_m, for the interaction of the donor, 8-chlorotheophylline, and the acceptor, the methyl of *trans*-cinnamic acid, in aqueous methanol solutions, at pH 7.0, at different temperatures, and 1 atm pressure. The mole ratio of methanol to water was 1:9. Concentrations are expressed as mol (kg of water)$^{-1}$. The ionic strength was adjusted to I = 0.20 by addition of sodium chloride. Also shown in Table III are derived values of the increment in the extinction coefficient, $\Delta\epsilon$, at the wavelength of 320 nm.

TABLE III: Association Constants for the Interaction of Sodium 8-Chlorotheophyllinate, with the Methyl Ester of *trans*-Cinnamic Acid in a Methanol-Water Mixture[a]

T, °C	K_m	$\Delta\epsilon_{320}$, mol kg^{-1} cm^{-1}
25.0	11.5 ± 0.2	832 ± 22
10.0	15.1 ± 0.2	

[a] The conditions of measurement were as follows. The solvent was a methanol-water mixture in a 1:9 mole ratio, at a pH of 7.0, I = 0.20, and a pressure of 1 atm. Concentrations were expressed as mol (kg of water)$^{-1}$. Absorbance was measured at a wavelength of 320 nm.

From the variation of the association constant with temperature, it may be estimated that the entropy of association is greater for the complex of the donor, sodium 8-chlorotheophyllinate, with the pyridinium salt, having a value of approximately −27.8 ± 15 J mol^{-1} K^{-1} at 25 °C, I = 0.20, than for its complex with the methyl ester of Trans-cinnamic acid, where the value is −22.6 ± 5 J mol^{-1} K^{-1}. The enthalpies of association were much the same, −11.9 ± 4 and −12.8 ± 2 kJ mol^{-1}, respectively. This suggests that charge interaction is a factor in the association of 8-chlorotheophylline with the pyridinium salt.

Discussion

In the case of molecules bearing charges of opposite sign, it might have been expected that, on association, the dominating factor would be the reduction in electrostriction, due to the approach of opposite charges to form an ion pair, with consequent release of solvent molecules and increase in volume.[4] Since the volume change was negative, it was concluded that the dominating factor was the association of two aromatic rings in water,[8,9] the effect of charge being damped out by the high ionic strength of the solvent. In contrast to this, one notes that at lower ionic strength, where charge interaction would be more important, the volume change would be more positive. The results here show that the volume change is more negative.[4]

One explanation for the change in volume of exists which has not been considered previously. This is that volume of complexing results not from the association of two rings of opposite charge but from the exchange of one ion pair for another.[10-13] Ewald[2] has shown that the ion pair of pyridinium iodide undergoes self-association, in acetone as solvent, with charge-transfer interaction, and that the volume change is positive, being 16.0 cm^3 mol^{-1}. This leads to less association with increasing pressure. This appears to be due to the decrease in electrostriction caused by the approach of two ions of opposite charge during complexing. A similar behavior might be expected of the ion pair between the 8-chlorotheophyllinate anion, and the pyridinium cation; however, in this case the anion has a delocalized charge which would bind solvent less strongly than iodide ion would be expected to. The decrease in electrostriction on binding would not be as great, so that the volume change would be smaller, though still positive.

The effect of pressure of the equilibrium between the pyridinium iodide ion pair and the 8-chlorotheophyllinate–pyridinium ion pair would be expected to favor the one with a lesser volume change on self-association, which would be the ion pair formed between two rings of delocalized charge, 8-chlorotheophyllinate anion and pyridinium cation.[10-13] These volume changes would presumably

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be greater at lower ionic strength, where the masking of ions by a gegenion atmosphere would be less, so that the result that the measured volume of association of sodium 8-chlorotheophyllinate and pyridinium iodide is more negative at lower ionic strength is not unexpected.

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Registry No. Sodium 8-chlorotheophyllinate, 46264-79-3; 1-methyl-3-(carbomethoxy)pyridinium iodide, 4685-10-3; *trans*-cinnamic acid methyl ester, 1754-62-7.

Refractive Index Increment of a Colloidal Dispersion of Small Spheroidal Particles

Yoh Sano and Masayuki Nakagaki*

Institute for Plant Virus Research, Tsukuba Science City, Yatabe, Ibaraki 305, Japan, and Faculty of Pharmaceutical Sciences, Kyoto University, Sakyoku, Kyoto 606, Japan (Received: February 15, 1983; In Final Form: May 20, 1983)

Using the light scattering theory of Rayleigh–Gans for spheroids, we derive theoretical expressions for the refractive index increment, dn/dc, of a dispersion in which small spheroidal particles are dispersed in a medium. The dn/dc depends on the axial ratio p, the intrinsic anisotropy p_m, and the relative refractive index of the spheroid to the solvent m in the general case. Even if the particle is made of optically isotropic material ($p_m = 1$), the dn/dc depends on p as well as m, and the well-known equation $(\mathrm{d}n/\mathrm{d}c)_{p_g=1} = (3n_0/2\rho)[(m^2-1)/(m^2+2)]$ is correct only in the case of isotropic spherical particles ($p_g = 1$). The deviation of (dn/dc) from $(\mathrm{d}n/\mathrm{d}c)_{p_g=1}$ is larger, the larger the m is and the larger the p is.

Introduction

The measurement of the refractive index increment for a colloidal dispersion or a macromolecular solution in which particles or macromolecules are dissolved in transparent liquid solvent is a relatively simple experiment for which several commercial refractometers are available.[1] Expressions for the refractive index increment based on theories of the refractive index of mixtures of transparent substances give generally fairly accurate refractive index increment values.[1]

For a spherical particle, it has been shown theoretically by the Mie theory and verified experimentally for suspensions of monodisperse polystyrene lattices that the refractive index of colloidal dispersions is strongly size dependent.[2] The anomalous diffraction approximation agrees closely with the exact Mie theory and a general result of both these theories is that the refractive index increment of dispersed spheres tends to zero in an oscillatory fashion as the sphere diameter increases.[3-5] For spheroidal particles, Meeten has recently investigated theoretically the dependence of the refractive index of colloidal dispersions on shape and size using the Rayleigh theory and the Rayleigh–Gans–Debye theory, which involves the restrictive assumption that the refractive index of the particles is close to that of the surrounding medium ($m \simeq 1$), and anomalous diffraction approximations, and shown that departures from particle sphericity modify the refractive index of the dispersion, both size and shape being generally of importance.[6] However, he did not take the effect of the optical anisotropy on the refractive index increment into consideration. To our knowledge, no theory exists for calculating the refractive index increment from the axial ratio and the degree of anisotropy, as well as the density and the refractive indices of the colloidal and continuous phases.

The subject of this work is to derive expressions whereby the refractive index increment may be related to the optical properties of the dispersed and continuous phases. This work is useful in the interpretation of light scattering measurements for colloidal dispersions of spheroidal particles, where light scattering theory generally requires either the refractive index increment or the relative refractive index of the scatterer to the solvent. Differing from the treatments quantitatively correct only for limiting conditions such as (a) for infinitely thin rods or infinitely thin disks or (b) for bodies whose refractive index differs very little from that of the surrounding medium, we derive here a general treatment by using the general theory given by Rayleigh[7] and Gans[8] for the scattered light intensity of spheroidal particles. The treatment derived here will be referred to as the Rayleigh–Gans theory of spheroids (RGS theory) in order to avoid confusion with the well-known Rayleigh–Gans (RG) theory of scattering which involves the restrictive assumption that the refractive index of the particles is close to that of the surrounding medium.

Theory

General Considerations. For small molecules, or flexible polymer chains, dissolved in a solvent of small molecules, a variety of expressions exist for the refractive index of the solution in terms of the refractive indices, polarizabilities, and densities of each component.[1] These expressions are derived from the assumption that each molecule is small enough to be regarded as a point dipole. The polarizability of each molecule is assumed to be independent of its environment and the induced electric dipole moment is assumed to result from the internal electric field.

Van de Hulst[9] showed that the real part of the refractive index n of an assembly of independent scatterers of any size or shape in a medium of refractive index n_0 is given generally by

$$m = n/n_0 = 1 + 2\pi N k^{-3}\,\mathrm{Im}\,S(0) \qquad (1)$$

$$k = 2\pi/\lambda \qquad (2)$$

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