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THERMODYNAMIC PROPERTIES OF ANTIPYRINE AND 4-AMINOANTIPYRINE

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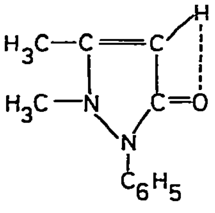
ABSTRACT

Variation with temperature of the thermodynamic properties of antipyrine and 4-aminoantipyrine has been studied using vapour pressure osmometry measurements. The results obtained indicate the existence of an association phenomenon. In order to explain the association mechanism, several theoretical models have been proposed. The excess properties G^E, H^E and S^E are also evaluated.

INTRODUCTION

Nowadays, thanks to the development of electronics, it is possible to get high sensibility vapour pressure osmometers. This offers new possibilities to the thermodynamic study of systems which cannot be studied by any other physical method [1]. Vapour pressure osmometry (VPO) allows calculation not only of the dissociation constants of acids and bases [2], but also molecular weights up to 3×10^4 g mole^{-1}, activity and osmotic coefficients of electrolytes and non-electrolytes [3,4] and consequently all the thermodynamic functions.

In this paper, the association of antipyrine(I) and 4-aminoantipyrine(II) and its thermal variation are examined. The different association constants and the number of associated molecules are also studied. Values of the osmotic coefficient, Φ, and the activity coefficient, γ, for antipyrine and 4-aminoantipyrine are also given, which allows calculation of both the mixing and excess thermodynamic functions.



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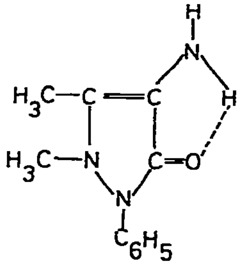


(II)

EXPERIMENTAL

Measurements were carried out on a Knauer 1974 model vapour pressure osmometer. Calibration of the probe, containing two thermistors, was made using, as standard, aqueous solutions of sodium chloride of well known activity coefficients, which are expressed as a function of molality in the expression

$$\ln \gamma = -A\sqrt{m}/(1 + B\sqrt{m}) + Cm + Dm^2 + \ldots \tag{1}$$

where A is the theoretical Debye—Huckel coefficient. The other coefficients are determined by trial and error.

The osmotic coefficients of NaCl were calculated from the expression

$$\Phi = 1 - (A/B^3m)\,|1 + B\sqrt{m} - 1/(1 + B\sqrt{m} - 2)\ln(1 + B\sqrt{m})| + Cm/2 + 3Dm^2/2 \tag{2}$$

The osmotic or experimental molality is calculated from the relation

$$\overline{m} = \nu\Phi m \tag{3}$$

where ν is the total number of ions in solution and m is the theoretical molality. The values of $\overline{m}$ and ΔR are directly determined by the osmometer for the different solutions; from these values the calibration curve of the probe representing ΔR as a function of the molality is obtained.

Later, and having prepared the different solutions of theoretical molality m, it is possible to calculate the experimental molality $\overline{m}$ carrying the values of ΔR to the calculated curve.

Using eqn. (3) it is possible to determine the osmotic coefficients. In this case $\nu = 1$ because antipyrine and 4-aminoantipyrine can be considered as non-electrolytes for osmotic studies in aqueous solutions.

The following method is used to calculate the association number and constants. As the osmotic or experimental molality for non-electrolytes can be considered equal to the addition of the equilibrium molalities, m_x, and the theoretical molality is equal to the addition of $x_1 m_x$, where x can vary from 1 to n, so

$$\overline{m} = m_1 + \sum_{x=2}^{n} \left(\prod_{j=2}^{x} k_j \right) m_1^x \tag{4}$$

and

$$m = m_1 + \sum_{x=2}^{n} x \left(\prod_{j=2}^{x} k_j \right) m_1^x \tag{5}$$

From eqns. (3)—(5)

$$m_1 = m \exp \left\{ \sum |(x + 1)/x| a_x m^x \right\} \tag{6}$$

Equations (4)—(6) are the basic relations for evaluation of the association of non-electrolytes from vapour pressure measurements, considering different association models [5].

RESULTS AND DISCUSSION

There are two basic types of association mechanism [6]: the closed and the open or unlimited. The first is expressed by

$$n\,A_1 \overset{k}{\rightleftharpoons} A_n$$

and the second by

$$A_1 + A_1 \overset{k_2}{\rightleftharpoons} A_2$$

$$A_1 + A_2 \overset{k_3}{\rightleftharpoons} A_3$$

....

$$A_1 + A_{n-1} \overset{k_n}{\rightleftharpoons} A_n$$

where A_1, A_2, ..., A_n are the monomer, dimer, ..., n-mer, respectively, and k_1, k_2 ... k_n are the association constants of the different processes. From these two basic types of association the following models can be assumed.

Model 1. The association follows a closed-type mechanism. The association equilibrium is $nA_1 \rightleftharpoons A_n$, where only a single associated species is formed, composed of n molecules, and the osmotic molality can be calculated by means of eqn. (4), giving $\bar{m}_{\text{cal}} = m_1 + km_1^n$, where $k = m_n/m_1^n$.

Model 2. In this model and in models 3—5, an open type of association mechanism is supposed, where n association processes occur. Here all the association constants are considered equal: $k_2 = k_3 = ... = k_n = k$.

Model 3. In this case the dimerization constant is considered independent, while the other association constants are identical.

Model 4. k_2 is considered to be independent and the rest are correlated by means of the expression $k_n = q/n$, where q is an empirical parameter. The association constants decrease when n increases, following the above relation.

Model 5. This model is similar to the previous one, but the relation between the constants is $k_n = q(n-2)/(n-1)$. The constants increase and when $n \to \infty$, $k \to q$.

To determine which is the best model to explain our system, the function U, expressed as

$$U = \sum_{x=1}^{s} (\bar{m}_{x,\text{obs}} - \bar{m}_{x,\text{calc}})^2$$

(where s represents the used number of experimental values) was minimized. In order to compare the different models the following expression was

$$\sigma = \left|\frac{U_{\min}}{s-p}\right|^{1/2}$$

where p is the number of independent association constants, and is equal to 1 in models 1 and 2, and 2 in models 3—5.

In Tables 1—4 the values of n, k_2, q and σ for the different models studied are summarized. As can be seen, model 5 best adjusts to the experimental and theoretical values for both antipyrine and 4-aminoantipyrine in the temperature range studied.

Another parameter which can be calculated from the data obtained by VPO is the activity coefficient. Following the Gibbs—Duhem equation

$$S\,\mathrm{d}T - V\,\mathrm{d}p + \sum n_i\, d\mu_i = 0$$

at constant T and p

$$\sum n_i\, d\mu_i = 0 \tag{7}$$

where the chemical potential, μ_i, is

$$\mu_i = \mu_i^*(T, p) + RT\Phi_i \ln x_i \tag{8}$$

where Φ_i is the osmotic coefficient of the solvent. Derivation of eqn. (8) and using its value in the Gibbs—Duhem equation gives

$$x_1 \ln x_1\, \mathrm{d}\Phi_1 + x_1\Phi_1\, \mathrm{dln}\, x_1 + x_2\, \mathrm{dln}\, x_2 + x_2\, \mathrm{dln}\, \gamma_2 = 0 \tag{9}$$

Differentiating eqn. (9) with respect to x_2 and considering $\mathrm{d}x_1 = -\mathrm{d}x_2$ gives

$$x_1 \ln x_1\left(\frac{\mathrm{d}\Phi_1}{\mathrm{d}x_2}\right) + x_2\left(\frac{\mathrm{dln}\,\gamma_2}{\mathrm{d}x_2}\right) - \Phi_1 + 1 = 0 \tag{10}$$

For dilute solutions, $x_1 \approx 1$, and consequently $\ln x_1 = \ln(1 - x_2) \approx -x_2$. Using this result in eqn. (10) gives

$$(1 - \Phi_1) - x_2\left(\frac{\mathrm{d}\Phi_1}{\mathrm{d}x_2}\right) + x_2\left(\frac{\mathrm{dln}\,\gamma_2}{\mathrm{d}x_2}\right) = 0 \tag{11}$$

Integrating between the limits 0 and x_2 gives the activity coefficient as a function of the osmotic coefficient

$$\ln \gamma_2 = (\Phi_1 - 1) + \int_0^{x_2} (\Phi_1 - 1)\, \mathrm{dln}\, x_2 \tag{12}$$

TABLE 1

Values of the degree of association, dimerization constant, and q and σ parameters for antipyrine at 40 and 50°C

Model	40°C				50°C			
	n	k_2	k, q *	$\pm\sigma \times 10^3$	n	k_2	k, q *	$\pm\sigma \times 10^3$
1	3		8.36	5.88	3		8.30	5.67
2	12		1.45	3.27	12		1.38	2.99
3	12	1.28	1.68	1.80	12	1.23	1.61	1.73
4	8	1.17	6.50 *	2.04	8	1.11	6.48 *	1.99
5	13	1.34	2.45 *	1.68	13	1.30	2.43 *	1.62

* q Values are indicated by an asterisk.

TABLE 2

Values of the degree of association, dimerization constant, and q and σ parameters for antipyrine at 60 and 70°C

Model	60°C				70°C			
	n	k_2	k, q *	$\pm\sigma \times 10^3$	n	k_2	k, q *	$\pm\sigma \times 10^3$
1	3		8.07	5.59	3		8.03	5.55
2	12		1.33	2.95	11		1.30	2.91
3	11	1.20	1.57	1.71	9	1.15	1.52	1.65
4	6	1.10	6.45 *	1.83	6	1.07	6.38 *	1.77
5	11	1.27	2.40 *	1.55	10	1.24	2.33 *	1.42

* q Values are indicated by an asterisk.

TABLE 3

Values of the degree of association, dimerization constant, and q and σ parameters for 4-aminoantipyrine at 40 and 50°C

Model	40°C				50°C			
	n	k_2	k, q *	$\pm\sigma \times 10^3$	n	k_2	k, q *	$\pm\sigma \times 10^3$
1	3		11.00	3.73	3		10.93	3.65
2	12		1.72	8.16	12		1.66	7.97
3	13	1.07	2.33	1.46	13	1.05	2.31	1.41
4	10	0.88	10.53 *	1.92	10	0.87	10.50 *	1.88
5	11	1.23	3.33 *	1.33	11	1.21	3.28 *	1.25

* q Values are indicated by an asterisk.

On the other hand, we have $\Phi = 1 + \sum^{i} a_i m^i$, where m is the theoretical molality and a_i is the coefficient of the polinomy which better adjusts to the previous equation. Integrating and introducing this value of the osmotic

TABLE 4

Values of the degree of association, dimerization constant, and q and σ parameters for 4-aminoantipyrine at 60 and 70°C

Model	60°C				70°C			
	n	k_2	k, q *	$\pm\sigma \times 10^3$	n	k_2	k, q *	$\pm\sigma \times 10^3$
1	3		10.90	3.63	3		10.71	3.51
2	12		1.64	7.91	11		1.47	7.83
3	13	1.03	2.30	1.40	11	1.00	2.20	1.30
4	10	0.86	10.49 *	1.83	8	0.82	10.37 *	1.71
5	11	1.20	3.26 *	1.23	9	1.17	3.19	1.12

* q Values are indicated by an asterisk.

coefficient finally gives

$$\ln \gamma = \sum_{i=1}^{j} \left(\frac{i+1}{i}\right) a_i m^i \tag{13}$$

It is also possible to calculate the entropy increase of the association process using the data from Tables 1—4 and combining the equations of van't Hoff and Gibbs.

Figure 1 is a plot of the dimerization constant, k_2, and the parameter q vs. temperature, obtained using model 5. Table 5 gives the values of ΔS for antipyrine and 4-aminoantipyrine in the temperature range studied. As can be observed, ΔS is always negative and almost constant with temperature, because when dimerization occurs a greater ordering of the system takes place and logically a decrease in the entropy. However, the number of molecules is maintained nearly constant with temperature, which explains the small entropy decrease observed.

Another interesting application is to calculate the thermal variation of the activity coefficient of the solute. Dividing eqn. (7) by T and differentiating it with respect to the temperature gives

$$\left(\frac{\partial \ln \gamma_2}{\partial T}\right)_{p,m_2} = \frac{h_2^\infty - h_2}{RT^2} = -\frac{\bar{L}_2}{RT^2} \tag{14}$$

where h_2 and h_2^∞ are the partial molar enthalpy of the solute in the solution and the partial molar enthalpy of the solute at infinite dilution, respectively, and $\bar{L}_2$ is the relative partial molar enthalpy of the solute.

Figure 2 shows the value of $(\partial \ln \gamma_2/\partial T)_{p,m_2}$ for antipyrine and 4-aminoantipyrine of different molalities. As this magnitude depends on the concentration of the solution, extrapolation to $m_2 \rightarrow 0$ gives the standard partial

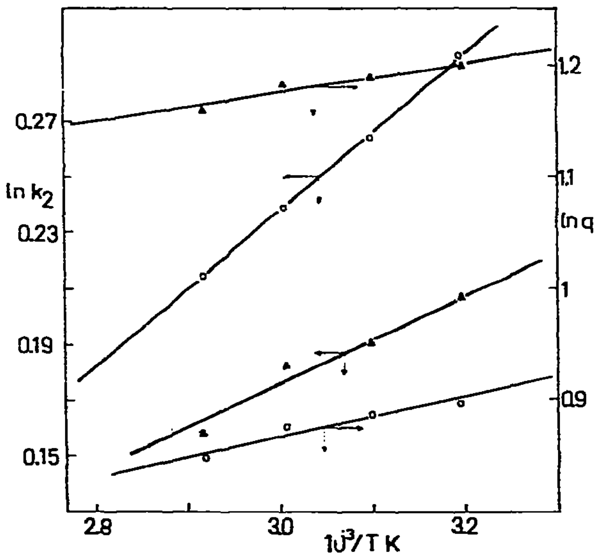


Fig. 1. Plot of $\ln k_2$ and $\ln q$ vs. $1/T$ for antipyrine (○) and 4-aminoantipyrine (▲).

TABLE 5

Variation of entropy with temperature for antipyrine and 4-aminoantipyrine

T (K)	ΔS (cal deg^{-1} mole^{-1})	
	Antipyrine	4-Aminoantipyrine
313	−1.22	−0.61
323	−1.21	−0.61
333	−1.20	−0.60
343	−1.20	−0.61

molar enthalpy, h_2^∞. For antipyrine and 4-aminoantipyrine, h_2^∞ takes the values 2.30 and 1.52 kJ mole^{-1}, respectively. As can be observed in Fig. 2, the slope of the curve of antipyrine has a different sign to that of the 4-aminoantipyrine. At first, it may be thought that both substances follow the same behaviour. But if antipyrine and 4-aminoantipyrine are observed it is seen that 4-aminoantipyrine is intramolecularly associated, forming a ring of five links between an amine group and a carboxylic group which are very close. However, this intramolecular interaction is not probable in antipyrine because the ring so formed would be composed of four links and the tensions between them would be greater.

On the other hand, if the enthalpies of these two substances are calculated by means of the van 't Hoff equation, values of $\Delta H = 2.32$ kJ mole^{-1} for antipyrine and 1.32 kJ mole^{-1} for 4-aminoantipyrine are obtained. If these values are compared with those obtained from ln γ_2, it is seen that they are coincident, which proves the consistency of the values obtained.

It is possible to calculate the excess Gibbs function from

$$G^E = RT(n_1 \ln \gamma_1 + n_2 \ln \gamma_2) \qquad (15)$$

where it is necessary to calculate γ_1 in the Gibbs—Duhem equation, because the values of γ_2 are known. Knowing G^E values for different temperatures, it is possible to calculate the entropy and enthalpy excess functions. Tables 6—11 give the values of γ_1, G^E and $-TS^E$ of antipyrine and 4-aminoantipyrine for all temperatures studied.

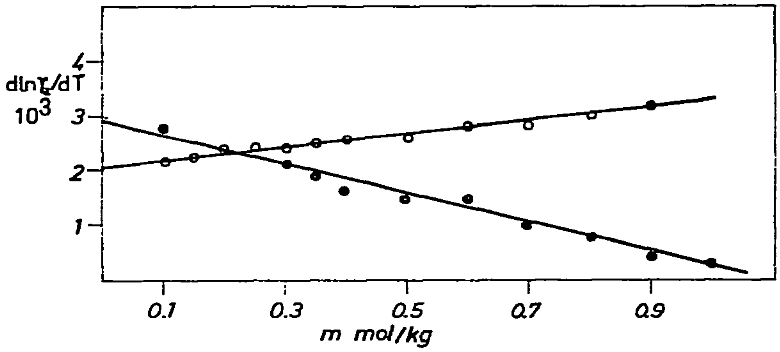


Fig. 2. Plot of d ln γ_2/dT vs. molality for antipyrine (●) and 4-aminoantipyrine (○).

TABLE 6

Values of γ_1, G^E and $-TS^E$ at 313 K and their variation with molality for antipyrine

m (mole kg^{-1})	γ_1	G^E (cal mole^{-1})	$-TS^E$ (cal mole^{-1})
0.1	1.00016	−0.060	0.903
0.2	1.00066	−0.212	0.99
0.3	1.00137	−0.443	0.836
0.4	1.00256	−0.672	0.32
0.5	1.00403	−0.900	0.012
0.6	1.00583	−1.105	0.05
0.7	1.00780	−1.335	−0.15
0.8	1.0103	−1.470	−1.25
0.9	1.0129	−1.654	−2.69
1.0	1.016	−1.672	−3.27

TABLE 7

Values of γ_1, G^E and $-TS^E$ at 333 K and their variation with molality for antipyrine

m (mole kg^{-1})	γ_1	G^E (cal mole^{-1})	$-TS^E$ (cal mole^{-1})
0.1	1.00016	−0.013	0.96
0.2	1.00064	−0.136	1.05
0.3	1.00134	−0.380	0.89
0.4	1.00250	−0.654	0.34
0.5	1.00393	−0.897	0.013
0.6	1.00568	−1.095	0.053
0.7	1.00764	−1.330	−0.156
0.8	1.0100	−1.560	−1.33
0.9	1.0126	−1.852	−2.86
1.0	1.0156	−1.945	−3.48

TABLE 8

Values of γ_1, G^E and $-TS^E$ at 343 K and their variation with molality for antipyrine

m (mole kg^{-1})	γ_1	G^E (cal mole^{-1})	$-TS^E$ (cal mole^{-1})
0.1	1.00016	0.031	0.99
0.2	1.0064	−0.120	1.08
0.3	1.00132	−0.365	0.92
0.4	1.00247	−0.641	0.35
0.5	1.00389	−0.098	0.014
0.6	1.00563	−1.102	0.055
0.7	1.00756	−1.353	−0.16
0.8	1.00993	−1.590	−1.37
0.9	1.0125	−1.905	−2.95
1.0	1.0155	−1.97	−3.59

TABLE 9

Values of γ_1, G^E and $-TS^E$ at 323 K and their variation with molality for 4-aminoantipyrine

m (mole kg^{-1})	γ_1	G^E (cal mole^{-1})	$-TS^E$ (cal mole^{-1})
0.1	1.00018	−0.056	0.442
0.2	1.00074	−0.227	0.633
0.3	1.00154	−0.544	0.407
0.4	1.00288	−0.854	−0.257
0.5	1.00452	−1.200	−1.161
0.6	1.00655	−1.418	−2.110
0.7	1.00880	−1.815	−3.022
0.8	1.0126	−2.029	−5.18
0.9	1.0145	−2.232	−8.01
1.0	1.0180	−2.177	−11.85

TABLE 10

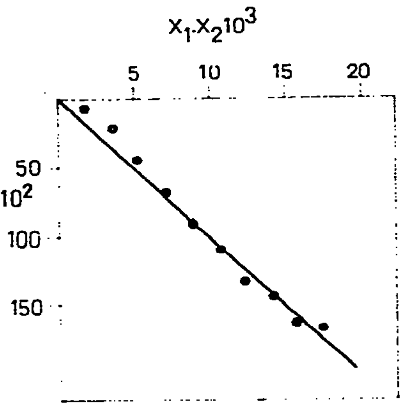
Values of γ_1, G^E and $-TS^E$ at 333 K and their variation with molality for 4-aminoantipyrine

m (mole kg^{-1})	γ_1	G^E (cal mole^{-1})	$-TS^E$ (cal mole^{-1})
0.1	1.00017	−0.049	0.456
0.2	1.00068	−0.224	0.653
0.3	1.00143	−0.546	0.420
0.4	1.00266	−0.973	−0.265
0.5	1.00419	−1.256	−1.197
0.6	1.00606	−1.517	−2.173
0.7	1.00814	−1.960	−3.115
0.8	1.0107	−2.268	−5.341
0.9	1.0134	−2.558	−8.258
1.0	1.0167	−2.593	−12.221

TABLE 11

Values of γ_1, G^E and $-TS^E$ at 343 K and their variation with molality for 4-aminoantipyrine

m (mole kg^{-1})	γ_1	G^E (cal mole^{-1})	$-TS^E$ (cal mole^{-1})
0.1	1.00016	−0.028	0.47
0.2	1.00062	−0.188	0.67
0.3	1.00130	−0.519	0.43
0.4	1.00243	−0.870	−0.273
0.5	1.00382	−1.271	−1.23
0.6	1.00553	−1.548	−2.24
0.7	1.00744	−2.002	−3.21
0.8	1.00976	−2.350	−5.50
0.9	1.01226	−2.730	−8.51
1.0	1.0152	−2.911	−12.59



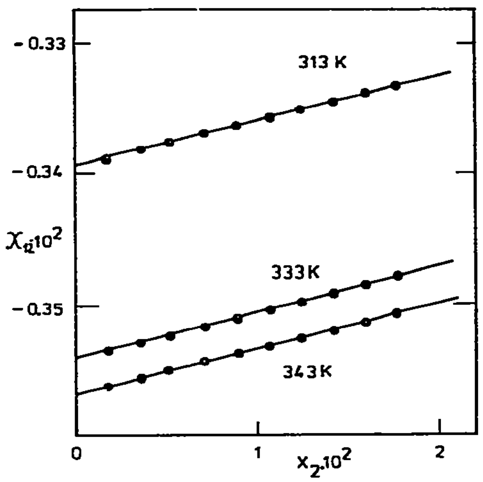


Fig. 3. Variation of excess Gibbs energy, G^E, with x_1x_2 for antipyrine at 313 K.

Fig. 4. Variation of interaction solute—solvent parameter χ_{12} with solute molar fraction, x_2, at several temperatures for antipyrine.

Another interesting parameter from the thermodynamic point of view is the interaction solute—solvent parameter, χ_{12}, which can be obtained from

$$G^E = NRTx_1x_2\chi_{12} \tag{16}$$

where N is the total number of moles; if G^E is plotted against x_1x_2 (Fig. 3) the value of χ_{12} is obtained from the slope. In Figs. 4 and 5 the values of χ_{12} for antipyrine and 4-aminoantipyrine are shown as a function of molar fraction, x_2, at several temperatures. As can be seen in both cases, the solute—solute interactions are favoured (χ_{12} increases) when increasing the solute molar fraction, while the solvent—solute interactions are those most

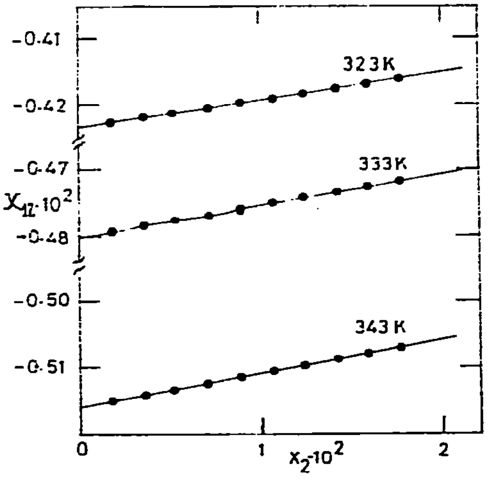


Fig. 5. Variation of interaction solute—solvent parameter χ_{12} for 4-aminoantipyrine.

favoured (χ_{12} decreases) when increasing temperature at constant concentration.

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