Solubility of Calix[4]resorcinarene in Water from (278.15 to 308.15) K

Lina S. Franco,[†] Yina P. Salamanca,[†,‡] Mauricio Maldonado,[‡] and Edgar F. Vargas*[,†]

Laboratorio de Termodinámica de Soluciones, Departamento de Química, Universidad de los Andes, Bogotá D.C., Colombia, and Departamento de Química, Facultad de Ciencias, Universidad Nacional de Colombia, Ciudad Universitaria, Bogotá D.C., Colombia

The solubility of 2,8,14,20-tetramethyl-4,6,10,12,16,18,22,24-octahidroxyresorci[4]arene, calix[4]resorcinarene, in water has been measured for temperatures ranging from (278.15 to 308.15) K. The experimental data were correlated with the van't Hoff equation, quadratic equation, and Apelblat equation. The thermodynamic functions of free energy and the enthalpy and entropy of solution were evaluated. The results showed that the main contributor to the standard free energy of solution is the enthalpy.

1. Introduction

Calix[4]resorcinarene are compounds obtained from the condensation reaction of resorcinol and aldehydes, generally in an acidic medium. The importance and applications of these macrocyclic compounds in fields such as electrochemical sensors, optical sensors, chiral recognition devices, and stationary phases in high-performance liquid chromatography have been the subject of study for several authors.[1−4] The high yields in the preparation and the facile derivatization of these compounds have particular importance in supramolecular chemistry. The cone shape of the calix[4]resorcinarene has a hydrophobic cavity with electron-rich aromatic walls which makes them particularly suitable for the investigation of interactions in solution (Figure 1).[5]

The aim of this work is to study the solubility of 2,8,14,20-tetramethyl-4,6,10,12,16,18,22,24-octahidroxyresorci[4]arene in water from (278.15 to 308.15) K at atmospheric pressure. The thermodynamic properties of this compound in solution have received little attention, and the solubility data in aqueous solutions have not been reported.

2. Experimental Section

2.1. Materials. 2,8,14,20-Tetramethyl-4,6,10,12,16,18,22,24-octahidroxyresorci[4]arene, calix[4]resorcinarene, was synthesized according to published procedure.[6,7] The water used in the experiments was double-distilled, and its conductivity was 2 μS·cm^{-1}.

2.2. Apparatus and Procedure. The solubility of calix[4]resorcinarene in water was measured using experimental equipment similar to that used by Lee and Huang.[8] The experiments were carried out in a magnetically stirred, jacketed glass cell of 25 mL. A constant temperature was maintained by circulating water through the outer jacket from a Julabo refrigerated circulating bath at temperatures between (278.15 to 308.15) ± 0.05 K. Saturated solutions of calix[4]resorcinarene were obtained by following the procedure: 15 mL of water and a small amount of the solid solute were added to glass cell. Then, the mixture was stirred during 1 h at intervals of 6 h over a period for 48 h followed by 24 h of rest at the desired temperature. After, the supernatant solution was analyzed by spectrophotometry after proper dilution. The concentration for the saturated solutions of calix[4]resorcinarene in water were determined on a Genesys 5 UV spectrophotometer at 283 nm.

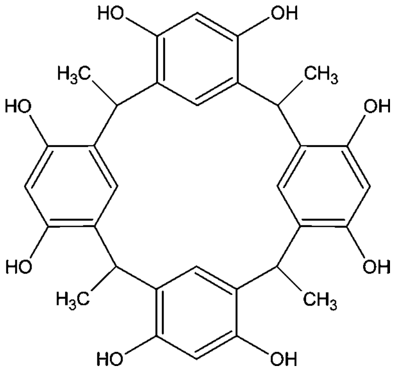

Figure 1. Structure of the 2,8,14,20-tetramethyl-4,6,10,12,16,18,22,24-octahidroxyresorci[4]arene, calix[4]resorcinarene.

The measurements of enthalpy of fusion, ΔH_m^0, and the melting point, T_m, of the calix[4]resorcinarene were determined using a Netzsch TG-DTA/DSC STA 409, in the temperature range between (288 and 820) K. The applied scan rate was 5 K·min^{-1}; nitrogen as a purge gas was used, and the flow rate was 60 mL·min^{-1}. The mass of the chemical compound was 7.14 mg.

3. Results and Discussion

3.1. Experimental Uncertainties. The molar extinction coefficient of the calix[4]resorcinarene was found as 6772 ± 40 L·mol^{-1}·cm^{-1}, the uncertainty in absorbance was found as ± 0.003, each experiment was repeated three times, and the deviation of the determined solubility data was within 2 %.

The measured solubilities of calix[4]resorcinarene in water at different temperatures are presented in Table 1 with their respective uncertainties, σ_{X_2}. Uncertainty values were calculated according to the law of propagation of uncertainties.[9]

3.2. Ideal Solubility. The ideal solubility of a solute in a liquid solvent can be calculated by eq 1:

$$\ln X^i = -\frac{\Delta H_m(T_m - T)}{RT_mT} \qquad (1)$$

where X^i is the ideal solubility of solute as mole fraction and ΔH_m and T_m are the molar enthalpy of fusion and the melting

---

* Corresponding author. E-mail: edvargas@uniandes.edu.co.

[†] Universidad de los Andes.

[‡] Universidad Nacional de Colombia.

10.1021/je9005097 CCC: $40.75

Table 1. Solubilities of Calix[4]resorcinarene in Water

			1000 X_{C2}		
T/K	1000 X_2	1000 σ_{X_2}	eq 2	eq 3	eq 4
278.15	0.00322	0.00007	0.00355	0.00326	0.00325
283.15	0.00429	0.00008	0.00414	0.00415	0.00416
288.15	0.00486	0.00009	0.00481	0.00508	0.00509
293.15	0.00626	0.00011	0.00555	0.00596	0.00596
298.15	0.00659	0.00012	0.00638	0.00672	0.00671
303.15	0.00716	0.00012	0.00730	0.00729	0.00727
308.15	0.00768	0.00013	0.00831	0.00758	0.00760

Table 2. Parameters of Calix[4]resorcinarene in Water by Equations 2 to 4

equation	parameter			10^5 rmsd	10^2 AAD
2	A^V	B^V			
	−3.82	−2427.59		0.043	5.59
3	A	B	C		
	−89.36	0.50	−0.000804	0.018	2.69
4	A'	B'	C'		
	810.22	−38090.06	−121.87	0.018	2.54

point, respectively. The values were measured by differential scanning calorimetry obtaining a value of 38.20 kJ·mol^{-1} and 578.6 K, respectively. The activity coefficient can be calculated by expression: $\gamma_2 = X^i/X$. The values obtained for this study are 71262 to 149200 in the range of (278.15 to 308.15) K, respectively.

3.3. Correlation Equations. The temperature dependence of solubility of a solute in a given solvent has been described by several equations such as van't Hoff, quadratic,[10] and Apelblat:[11] eqs 2, 3, and 4, respectively.

$$\ln X = A^V + \frac{B^V}{T/\mathrm{K}} \tag{2}$$

$$\ln X = A + B(T/\mathrm{K}) + C(T/\mathrm{K})^2 \tag{3}$$

$$\ln X = A' + \frac{B'}{T/\mathrm{K}} + C' \ln(T/\mathrm{K}) \tag{4}$$

where B^V has been associated with enthalpy of solution, and A^V, A, A', B, B', C, and C' are the model parameters. The values of these parameters together with the root-mean-square deviation (rmsd) and the absolute average deviations (AAD) are listed in Table 2. The rmsd and the AAD are defined as

$$\mathrm{rmsd} = \left[\frac{1}{N}\sum_{i=1}^{N}(X_{Ci} - X_i)^2\right]^{1/2} \tag{5}$$

and

$$\mathrm{AAD} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{X_i - X_{Ci}}{X_i}\right| \tag{6}$$

where N is the number of experimental points, X_{Ci} is the solubility calculated from eqs 2, 3, or 4, and X_i represents the experimental solubility values. The calculated solubilities X_C of calix[4]resorcinarene by eqs 2 to 4 are also given in Table 1.

According to Table 2 and Figure 2, it is found that there is a good agreement between eqs 3 and 4 with the experimental data. The rmsd's are $1.83 \cdot 10^{-7}$ and $1.78 \cdot 10^{-7}$, respectively, while by the van't Hoff equation the rmsd is $4.25 \cdot 10^{-7}$. The relative deviations by eqs 3 and 4 do not exceed 5 %, which indicates that the quadratic and the Apelblat equations are fit to correlate the solubility data of calix[4]resorcinarene in water. The relative deviations by the van't Hoff equation (eq 2) were between 1 % and 12 %. These values show that eq 2 is not adequate for correlation of the solubility of calix[4]resorcinarene in water.

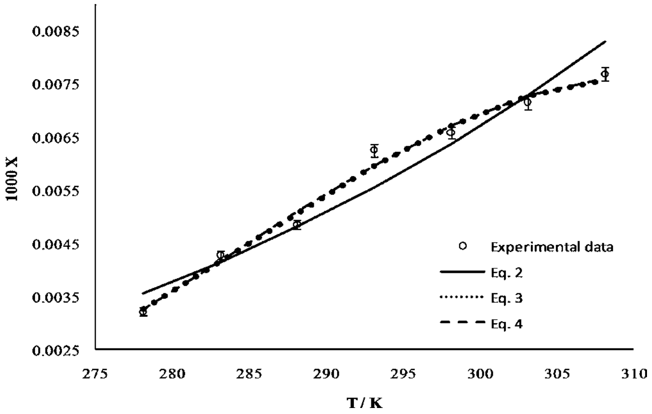

Figure 2. Solubility of calix[4]resorcinarene in water as a function of temperature.

3.4. Thermodynamic Functions of Solution. According to van't Hoff equation, the enthalpy of solution can be calculated from the slope of ln X_2 versus $1/T$ plot. However, Krug et al.[12] have proposed modifications in the van't Hoff equation to diminish the propagation of uncertainty. This modification consists in the use of the mean harmonic temperature (T_{mh}) in the van't Hoff equation. The T_{mh} is calculated as $T_{mh} = n/\sum_1^n T^{-1}$, where n is the number of temperatures studied. The modified van't Hoff equation most widely used is[12,13]

$$\left(\frac{\partial \ln X_2}{\partial(1/T - 1/T_{mh})}\right)_P = -\frac{\Delta H^0_{sol}}{R} \tag{7}$$

In this study the T_{mh} calculated is 292.81 K. The data were fitted to a second-order regression, and the intercept and the fit standard error obtained were calculated as 12.03 ± 0.02 and 0.04, respectively, where $r^2 > 0.99$.

The standard free energy and the standard entropy of solution, considering the approach proposed by Krug et al.,[12] is calculated according to

$$\Delta G^0_{sol} = -RT_{mh} \cdot \mathrm{intercept} \tag{8}$$

$$\Delta S^0_{sol} = \frac{\Delta H^0_{sol} - \Delta G^0_{sol}}{T_{mh}} \tag{9}$$

where the intercept correspond to 12.03 ± 0.02. The values of the thermodynamic function of the solution of calix[4]resorcinarene are 29.29 ± 0.05 kJ·mol^{-1}, 19.2 ± 1.0 kJ·mol^{-1}, and −34.4 ± 3.6 J·K^{-1}·mol^{-1} for ΔG^0_{sol}, ΔH^0_{sol}, and ΔS^0_{sol}, respectively.

For the purpose of comparing the relative contributions of enthalpy (% ζ_H) and entropy (% ζ_{TS}) to the solution process, the following equation can be employed:

$$\%\ \zeta_H = \frac{|\Delta H^0_{sol}|}{|\Delta H^0_{sol}| + |T\Delta S^0_{sol}|} \tag{10}$$

$$\%\ \zeta_{TS} = \frac{|T\Delta S^0_{sol}|}{|\Delta H^0_{sol}| + |T\Delta S^0_{sol}|} \tag{11}$$

By using these equations, values for % ζ_H and % ζ_{TS} are 65.6 and 34.4, respectively. It follows that in the process of solubility of calix[4]resorcinarene in water the main contributor to the standard Gibbs energy of solution is the enthalpy.

Literature Cited

(1) Timmerman, P.; Verboom, W.; Reinhoudt, D. N. Resorcinarenes. *Tetrahedron* **1996**, *52*, 2663–2704.

(2) He, M.; Johnson, R. J.; Escobedo, J. O.; Beck, P. A.; Kim, K. K.; St. Luce, N. N.; Davis, C. J.; Lewis, P. T.; Fronczek, F. R.; Melancon, B. J.; Mrse, A. A.; Treleaven, W. D.; Strongin, R. M. Chromophore Formation in Resorcinarene solutions and the visual detection of mono- and oligosaccharides. *J. Am. Chem. Soc.* **2002**, *124*, 5000–5009.

(3) McMahon, G.; O'Malley, S.; Nolan, K. Important calixarene derivatives - their synthesis and applications. *ARKIVOC (Gainesville, FL, U.S.)* **2003**, (vii), 23–31.

(4) Danil de Namor, A. F.; Chaaban, J. K.; Piro, O. E.; Castellano, E. E. Resorcarene-based receptor: versatile behavior in its interaction with heavy and soft metal cations. *J. Phys. Chem. B* **2006**, *110*, 2442–2450.

(5) Atwood, J. L.; Szumna, A. Cation-pi interactions in neutral calix[4]resorcinarenes. *J. Supramol. Chem.* **2002**, *2*, 479–482.

(6) Abis, L.; Dalcanale, E.; Du vosel, A.; Sperala, S. Structurally new macrocycles from the resorcinol-aldehyde condensation. Configurational and conformational analyses by means of dynamic NMR, NOE, and T1 experiments. *J. Org. Chem.* **1988**, *53*, 5475–5479.

(7) Hedidi, M.; Hamdi, S. M.; Mazari, T.; Boutemeur, B.; Rabia, C.; Chemat, F.; Hamdi, M. *Tetrahedron* **2006**, *62*, 5652–5655.

(8) Lee, L. S.; Huang, H. Y. Solubility of Tetrabutylamonium bromide in benzene between 298.15 and 323.15 K. *J. Chem. Eng. Data* **2002**, *47*, 1135–1139.

(9) *Guidelines for evaluating and expressing the uncertainty of NIST measurement results*; adapted from NIST technical note 1297; NIST: Gaithersburg, MD, 1994.

(10) Li, H.; Guo, F.; Zhao, L. Measurement and correlation for solubility of 2-bromopropane and thiourea in water. *J. Chem. Eng. Data* **2009**, *54*, 2386–2388.

(11) Apelblat, A.; Manzurola, E. Solubilities of o-acetylsalicylic 4-aminosalicylic, 3,5-dinitrosalicylic, and p-toluic acid, and magnesium-DL-aspartate in water from T = (298 to 348) K. *J. Chem. Thermodyn.* **1999**, *31*, 85–91.

(12) Krug, R. R.; Hunter, W. G.; Grieger, R. A. Enthalpy-entropy compensation. Separation of the chemical from the statistical effect. *J. Phys. Chem.* **1976**, *80*, 2341–2351.

(13) Bustamante, P.; Romero, S.; Peña, A.; Escalera, B.; Reillo, A. Nonlinear enthalpy-entropy conpensation for the solubility of drugs in solvent mixtures: paracetamol, acetanilide and nalidixic acid in dioxane-water. *J. Pharm. Sci.* **1998**, *87*, 1590–1596.

Received for review June 16, 2009. Accepted October 29, 2009.

JE9005097