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Role of the Conformational Freedom of the Skeleton in the Complex Formation Ability of Resorcinarene Derivatives toward a Neutral Phenol Guest

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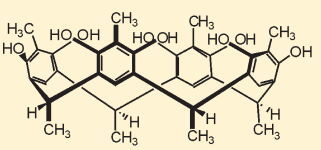
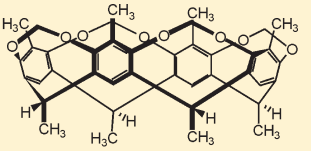
Supporting Information

ABSTRACT: The interaction of phenol guest molecules with 2-methylresorcinarene and its methylene-bridged cavitand derivative has been investigated in methanol. The host molecules were selected according to the flexibility of their cavities by varying the conformational freedom of the molecular skeleton prior to molecular association. The results show stronger host−phenol interactions when the host molecule possesses a rigid molecular skeleton (i.e., cavitand) compared to that of the flexible resorcinarene with phenol. Although the enthalpy change associated with the molecular interactions was found to be the same in both cases, higher negative entropy change was obtained when the resorcinarene interacted with the phenol molecules at room temperature. As a result, stronger host−guest complexes are formed at room temperature when the host molecules, possessing a rigid molecular skeleton, participated in the complex formation. Furthermore, since the higher entropy change results in higher temperature-dependence of the interactions, the stability of the complexes formed with the flexible resorcinarene is smaller at higher temperature. These results highlight that the decreasing flexibility of the host molecular skeleton itself can determine the entropy change during the complexation process; therefore, the temperature dependence of the complex stabilities highly depends on the flexibility of the host's molecular skeleton. This information might contribute to the development of selective and sensitive sensor molecules toward phenol derivatives.



1a

Host with flexible cavity



1b

Host with rigid cavity

INTRODUCTION

Calixarenes[1] and the related resorcinarenes[2] are members of a fascinating class of macrocycles which have potential applications in sensor chemistry. This property is due to the ability of these molecules to form complexes with both cations and anions and also with neutral molecules. Calixarenes are widely used as electrochemical,[3] fluorescent sensors,[4] and their sensing potential ranges from toxic metals[5] to proteins.[6] Resorcinarenes were shown to possess good sensitivity toward aliphatic alcohols,[7] while the structurally more rigid cavitands have been successfully employed in the detection of gases and organic vapors.[8,9] Recent studies show their application on deposited films[10] and on silicon grafting.[11]

These molecules show considerable photoluminescence (PL) properties according to their aromatic moieties.[12] Their PL properties show characteristic changes during the interactions with other species, which makes the examination of these molecular interactions possible by the highly sensitive PL methods.[13,14] Several factors that control the sensitivity and the selectivity characters of these host molecules have been studied during the last decades.[15−18] These investigations revealed that compounds with appropriate host properties can be developed. That is, the type and strength of host−guest interactions can be finely tuned by the systematic variation of the molecular skeleton.

In our previous works, the effects of the cavity shape[19,20] and also the solvent effect[21] on the stability of calixarene, phenol or calixarene, benzotrifluoride complexes were determined. The effects of the solvent permittivity were examined in detail for primary alcohols.[22] The dependence of the molecular interactions on the electron density of the guest molecules highlighted the intricate behavior of the complex formation between species possessing aromatic moieties.[23,24] In particular, the solvent itself can significantly modify the interactions due to the entropy term associated with the thermodynamic equilibrium. This property becomes more complex when the solvation shell of the interacted species is built up by the molecules of protic solvents.[25,26] The overall entropy change of the interactions is determined as a competitive effect between the entropy change of the interacting species and the entropy change of the solvent molecules.

In this work, the particular role of the entropy change of two host molecules has been investigated: the conformationally flexible methylresorcinarene (**1a**) and its methylene-bridged cavitand analogue (**1b**). In the cavitand **1b**, the rigid molecular

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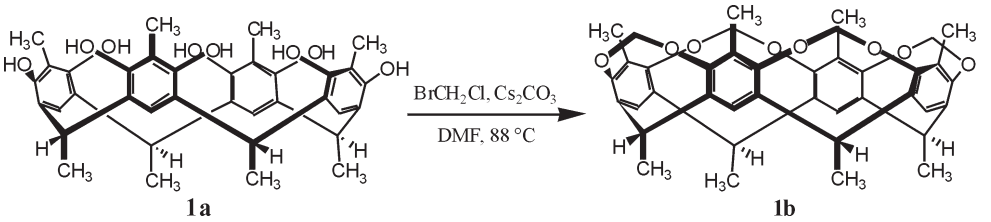

Figure 1. Complexation ability of host resorcinarene **1a** and cavitand **1b** toward phenol were investigated in this work.

cavity cannot change significantly during the molecular interactions, while in the resorcinarene **1a** significant decreases the freedom of the molecular skeleton that takes place during the interactions with the phenol guest. According to our previous investigations, PL methods and van't Hoff theory are applied to determine the thermodynamic parameters associated with the formation of the host−guest complexes.

MATERIALS AND METHODS

Resorcinarene **1a**[27] and cavitand **1b**[28] were synthesized according to literature procedures (see Figure 1). Phenol **2** (p.a. grade) and methanol were purchased from Merck (Germany) and from Panreac (Spain), respectively, and were used without further purification.

Photoluminescence Measurements. A highly sensitive Fluorolog τ3 spectrofluorometric system (Jobin-Yvon/SPEX) was used to investigate the photoluminescence (PL) spectra of different solutions. For data collection, a photon counting method with 0.2 s integration time was used. Excitation and emission bandwidths were set to 1 nm. A 1 mm layer thickness of the fluorescent probes with front face detection was used to eliminate the inner filter effect.

In order to investigate the interaction of the hosts (**1a** and **1b**) with guest (**2**), 10^{-3} M stock solutions were prepared in methanol. The stoichiometry of the complexes was checked by the Job's method: samples were prepared as mixture of the appropriate stock solutions of **1** and **2** with 1:9, ...9:1 molar ratios. The PL spectra were recorded at 5 different temperatures within the range from 288.16 to 308.16 K with 5 K steps.

The data evaluation method was described earlier.[19−24] However, because of the fact that in this particular case the complexes formed possess 1:1 stoichiometry (see below), the Benesi−Hildebrandt method was applied for data evaluations.[29] According to the Benesi−Hildebrand equation, if the complex formed possesses 1:1 stoichiometry, the plot of the reciprocal PL change against the reciprocal concentration of one of the reactant should show a straight line. Therefore, the equilibrium constant can be determined by the linear fitting of these data points using the following equation:

$$\frac{1}{I - I_0} = \frac{1}{[a]}\frac{1}{[p]}\frac{1}{K} + \frac{1}{[a]} \qquad (1)$$

where [p] and [a] represents the analytical concentration of phenol **2** and hosts **1a** or **1b**, respectively. I is the intensity of the samples containing both the reactants, while I_0 is the PL intensity of the host's solution in the absence of phenol.

The temperature dependence of the equilibrium constants were employed to determine the enthalpy and the entropy change of the association reaction using the van't Hoff theory. According to the van't Hoff equation, the logarithm of the equilibrium constants was plotted against the reciprocal temperature:

$$\ln K = -\frac{\Delta H}{R}\frac{1}{T} + \frac{\Delta S}{R} \qquad (2)$$

The enthalpy change can be obtained from the slope, while the entropy change can be determined from the intercept of the line fitted to the experimental data.

RESULTS

Figure 2 shows the PL spectra of the solutions of hosts (**1a** and **1b**) both in the absence and in the presence of guest phenol **2** molecules. Excitations at 280 and 380 nm were used for these studies, and the emission spectra were recorded within the 290−700 nm spectral range. Both host molecules show emission peaks at 305 and 460 nm using the appropriate excitations at 280 and 380 nm, respectively. The shapes of the emission bands are the same for both **1a** and **1b**. However, while the emission spectra at 305 nm are nearly the same for both macrocycles, much higher emission intensity of the flexible resorcinarene (**1a**) was obtained at 460 nm using the 380 nm excitation (Figure 2). The presence of phenol guest molecules changes the peak intensity of the host molecules at 305 nm due to the considerable emission of phenol molecules at the same wavelength. Since the intensities of the emission peaks observed at 460 nm show a significant decrease in the presence of phenol, this peak was used to determine the molecular interactions.

The application of the Benesi−Hildebrand method assumes 1:1 stoichiometry of the complexes formed during the molecular interaction. The Job's method was applied to prove the 1:1 stoichiometry of the host−guest complexes. Stock solutions of 10^{-3} M of host molecules and 10^{-3} M of phenol were used for these studies as described in the Materials and Methods. Figure 3 shows the Job's plot of mixtures formed from the solutions of **1a** and **1b** with the solutions of phenol **2**. The temperature dependence of this plot validates the 1:1 stoichiometry of the complexes through the temperature range of the examinations (288.16 K ...308.16 K).

The thermodynamic parameters of the interactions between the hosts **1a** or **1b** and phenol **2** molecules were determined as follows. The stability constants of the host−guest complexes were determined at five different temperatures. Then, with application of the van't Hoff theory, the logarithm of the stability constants was plotted against the reciprocal temperature and a straight line was fitted to these data (Figure 4a,b). According to the results of the Job's method, the 1:1 stoichiometry of the complexes results in the linear dependence on the Benesi−Hildebrand plot. The stabilities of the complexes are decreased at elevated temperatures. Overall, the complexes formed with **1a** resorcinarene show smaller stability constants at all temperatures than the phenol complexes of **1b** cavitand. The thermodynamic parameters were determined by the van't Hoff theory,

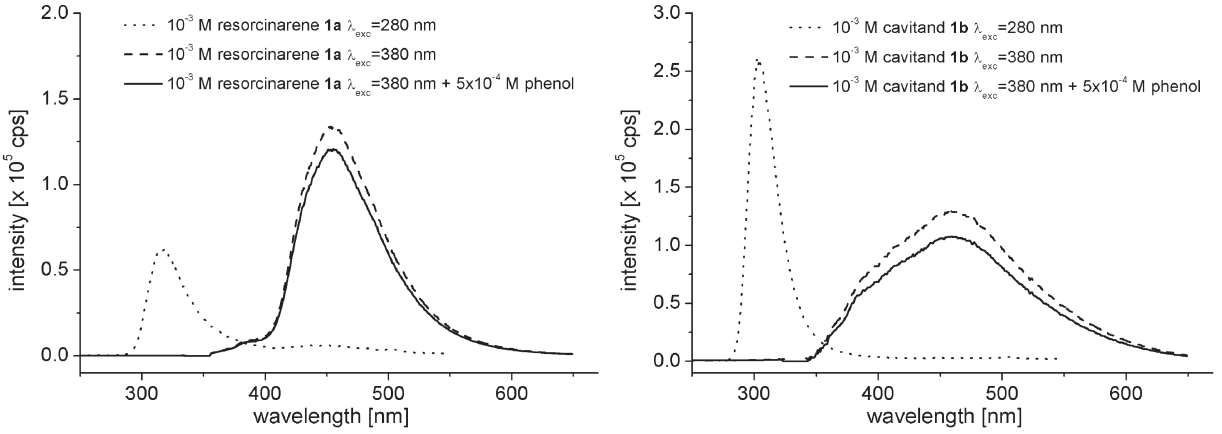

Figure 2. PL spectra of hosts **1a** (left) and **1b** (right) in the absence and in the presence of **2** phenol. Spectra were recorded at 298.16 K.

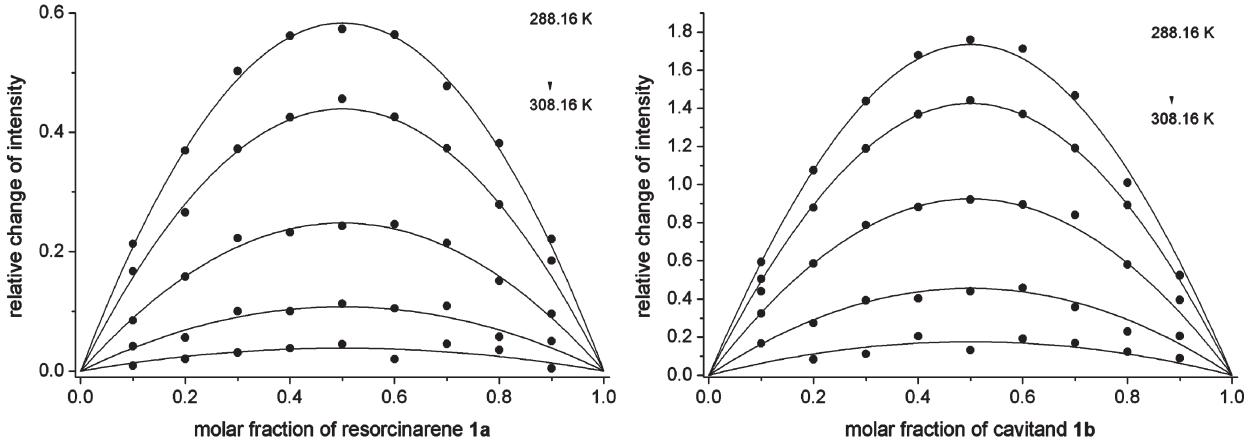

Figure 3. Job's plot of the interaction of hosts **1a** and **1b** with phenol **2** molecules. Stock solutions (10^{-3} M) of the hosts (**1a** and **1b**) and guest (**2**) were prepared in methanol, then the mixture of the appropriate stock solutions of **1** and **2** with 1:9, ...9:1 molar ratios were prepared. PL spectra of such samples were recorded in 5 different temperatures within the range from 288.16 to 308.16 K with 5 K steps (see Table 1). Differences between the intensities of the mixture and the pure host solutions measured at λ = 460 nm were divided by the PL intensities of the pure hosts and plotted against the molar fraction of the host. Temperatures associated with the curves are increased from the top down.

and the results are plotted in the insets of Figure 4a,b. Accordingly, quite the same enthalpy change obtained for the **1a**−**2** and **1b**−**2** complexes; they are $\Delta H = -47.4 \pm 0.7$ kJ mol^{-1} and $\Delta H = -47.11 \pm 1.1$ kJ mol^{-1}, respectively. However, very different entropy changes are associated with the molecular interactions. They are $\Delta S = -123$ J K^{-1} mol^{-1} for the **1a**−**2** complexes, and $\Delta S = -86$ J K^{-1} mol^{-1} for the **1b**−**2** complexes. These results show that for the **1a**−**2** complexes, the ordering of the system is much higher after the molecular association than in the **1b**−**2** complexes. Our explanation for these properties is the following: after the formation of the host−guest complexes, the skeletons of both **1a** and **1b** are fixed, i.e., the shape of the cavity molecule cannot change anymore after the inclusion of the phenol guest. However, in the case of resorcinarene **1a**, the shape of the molecular skeleton is determined only by the tetrahedral distortion of the carbon bonds in the ethylidene (CH_3CH) bridge between the aromatic walls. In contrast, the skeleton of **1b** cavitand is further reinforced by a second, methylenedioxy (OCH_2O) bridge. As a result, cavitand **1b** has much more rigid structure compared to resorcinarene **1b**. According to the complex formation with phenol molecules, the final state of the complexes has a similar entropy content to the initial states, resulting in a higher decrease of the entropy when the more flexible resorcinarene **1a** forms complexes with phenols. The appropriate free enthalpies calculated at room temperature are −10.7 kJ mol^{-1} and −21.5 kJ mol^{-1} for **1a**−**2** and **1b**−**2** complexes, respectively. This phenomenon shows the presence of weaker **1a**−**2** complexes compared to the **1b**−**2** complexes at room temperature. Therefore, **1b** cavitand possesses a higher sensitivity toward phenol around room temperature.

Taking into account the potential applications of these molecules in chemical sensors, the results described here have considerable consequences on the temperature dependence of the stability of the complexes formed. Because of the fact that the stability is determined by the free enthalpy change and since the temperature dependence of the free enthalpy is determined by the entropy term within a narrow temperature range, the devices prepared from **1a** resorcinarene will show higher temperature-dependence and less sensitivity at about room temperature, compared to the devices based on the **1b** cavitands.

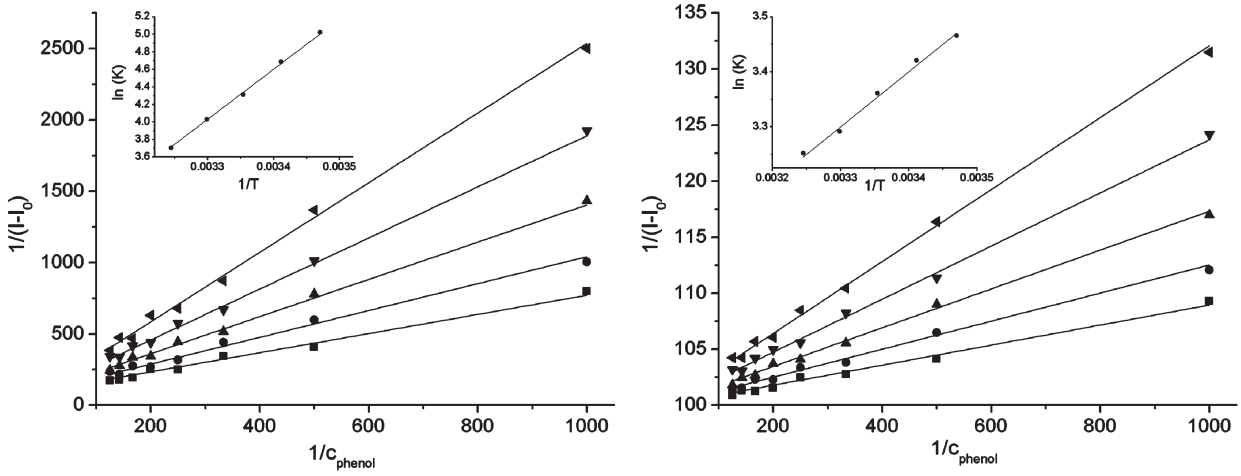

Figure 4. Benesi−Hildebrand plot of the interaction of hosts **1a** and **1b** with phenol **2** molecules. PL spectra of 10^{-3} M of **1a** (left) or **1b** (right) were recorded in the presence of **2** guest, then the $1/(I - I_0)$ were plotted against the reciprocal concentration of **2**. (I and I_0 are the PL intensities measured at λ_{em} = 460 nm of the **1** + **2** samples and the pure **1**, respectively.) Temperatures associated with the curves are increased from the top down. Van't Hoff plots of the stability constants were inserted as insets.

Table 1. Temperature-Dependence of the Stability Constants Associated with the Interaction of Hosts 1a or 1b with Phenol 2

	Stability constants (dm^3/mol)	
temperature (K)	resorcinarene **1a** + phenol **2**	cavitand **1b** + phenol **2**
288.16	151.4 ± 4	1071.7 ± 7
293.16	108.6 ± 4	667.8 ± 7
298.16	74.5 ± 3	506.3 ± 5
303.16	56.2 ± 2	329.4 ± 4
308.16	40.7 ± 2	251.2 ± 3

CONCLUSIONS

The complexation ability of methylresorcinarene and its cavitand derivative as hosts toward a phenol guest molecule was investigated in methanol. The two host molecules differ remarkably in their complexation properties due to the difference in the rigidity of their molecular skeleton. The results show stronger complex formation when the host possessing a more rigid cavity (i.e., cavitand) is interacted with the phenol guest. These results can be applied to the development of selective and sensitive host molecules for application in sensor chemistry.

ASSOCIATED CONTENT

Supporting Information. Raw data of the PL intensities measured during the interaction of hosts resorcinarene **1a** or cavitand **1b** with the phenol **2** guest molecules and statistics about the data evaluation plotted in Figure 4. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) Bohmer, V. *Angew. Chem., Int. Ed.* **1995**, *34*, 713–745.
(2) Timmerman, P.; Verboom, W; Reinhoudt, D. N. *Tetrahedron* **1996**, *52*, 2663–2704.
(3) El Nashar, R. M.; Wagdy, H. A. A.; Aboul-Enein, H. Y. *Curr. Anal. Chem.* **2009**, *5* (3), 249–270.
(4) Kim, J. S.; Quang, D. T. *Chem. Rev.* **2007**, *107* (9), 3780–3799.
(5) Leray, I.; Valeur, B. *Eur. J. Inorg. Chem.* **2009**, *24*, 3525–3535.
(6) Coleman, A. W.; Perret, F.; Moussa, A.; Dupin, M.; Guo, Y.; Perron, H. *Top. Curr. Chem.* **2007**, *277*, 31–88.
(7) Koshets, I. A.; Kazantseva, Z. I.; Belyaev, A. E.; Kalchenko, V. I. *Sens. Actuators, B* **2009**, *140*, 104–108.
(8) Hartmann, J.; Hauptmann, P; Levi, S.; Dalcanale, E. *Sens. Actuators, B* **1996**, *35*−*36*, 154–157.
(9) Feresenbet, E. B.; Dalcanale, E.; Dulcey, C.; Shenoy, D. K. *Sens. Actuators, B* **2004**, *97*, 211–220.
(10) Tonezzer, M.; Melegari, M.; Maggioni, G.; Milan, R.; Della Mea, G.; Dalcanale, E. *Chem. Mater.* **2008**, *20*, 6535–6542.
(11) Condorelli, G. G.; Motta, A.; Favazza, M.; Gurrieri, E.; Betti, P.; Dalcanale, E. *Chem. Commun.* **2010**, *46*, 288–290.
(12) Ree, M.; Kim, J.-S.; Kim, J. J.; Kim, B. H.; Yoon, J.; Kim, H. *Tetrahedron Lett.* **2003**, *44*, 8211–8215.
(13) Kunsági-Máté, S.; Nagy, G.; Kollár, L. *Anal. Chim. Acta* **2001**, *428*, 301–307.
(14) Kunsági-Máté, S.; Nagy, G.; Kollár, L. *Sens. Actuators, B* **2001**, *76*, 545–550.
(15) Kolthoff, I. M. *Anal. Chem.* **1979**, *51*, 1R–22R.
(16) Popov, A. I.; Lehn, J. M. In *Coordination Chemistry of Macrocyclic Compounds*; Melson, G. A., Ed.; Plenum: New York, 1979; pp 537−602.
(17) Izatt, R. M.; Bradshaw, S. J.; Nielsen, S. A.; Lamb, J. D.; Christensen, J. J.; Sen, D. *Chem. Rev.* **1985**, *85*, 271–339.
(18) Izatt, R. M.; Pawlak, K.; Bradshaw, J. S.; Bruening, R. L. *Chem. Rev.* **1991**, *91*, 1721–2085.
(19) Kunsági-Máté, S.; Bitter, I.; Grün, A.; Nagy, G.; Kollár, L. *Anal. Chim. Acta* **2001**, *443*, 227–234.
(20) Kunsági-Máté, S.; Nagy, G.; Jurecka, P.; Kollár, L. *Tetrahedron* **2002**, *58*, 5119–5124.
(21) Kunsági-Máté, S.; Bitter, I.; Grün, A.; Nagy, G.; Kollár, L. *Anal. Chim. Acta* **2002**, *461*, 273–279.
(22) Kunsági-Máté, S.; Csók, Zs.; Tuzi, A.; Kollár, L. *J. Phys. Chem. B* **2008**, *112*, 11743–11749.

(23) Kunsági-Máté, S.; Szabó, K.; Lemli, B.; Bitter, I.; Nagy, G.; Kollár, L. *Thermochim. Acta* **2005**, *425*, 121–126.
(24) Kunsági-Máté, S.; Szabó, K.; Lemli, B.; Bitter, I.; Nagy, G.; Kollár, L. *J. Phys. Chem. A* **2005**, *109*, 5237–5242.
(25) Kunsági-Máté, S.; Iwata, K. *Chem. Phys. Lett.* **2009**, *473*, 284–287.
(26) Matisz, G.; Fabian, W. M. F.; Kelterer, A.-M.; Kunsági-Máté, S. *J. Mol. Struct. (THEOCHEM)* **2010**, *956*, 103–109.
(27) Tunstad, L. M.; Tucker, J. A.; Dalcanale, E.; Weiser, J.; Bryant, J. A.; Sherman, J. C.; Helgeson, R. C.; Knobler, C. B.; Cram, D. J. *J. Org. Chem.* **1989**, *54*, 1305–1312.
(28) Roman, E.; Peinador, C.; Mendoza, S.; Kaifer, A. E. *J. Org. Chem.* **1999**, *64*, 2577–2578.
(29) Benesi, H.; Hildebrand, J. *J. Am. Chem. Soc.* **1949**, *71*, 2703–2707.