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Origins of Selectivity in a Colorimetric Charge-Transfer Sensor for Diols

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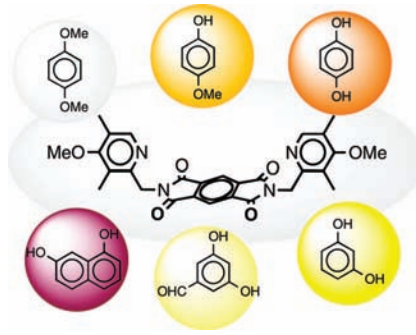
ABSTRACT



Bispyridyl hydrogen bonding receptor 1 forms colored charge transfer (CT) complexes with complementary phenols and naphthols. Despite its low association constants of ~10^1 M^{-1}, receptor 1 was highly selective forming CT complexes of varying color and intensity with different diol guests. The selectivity of 1 was correlated with the ability of its CT band to simultaneously yield information about the association constant and the electronic structure of the phenols and naphthols.

Colorimetric molecular sensors are attractive because they can be implemented into simple low-cost devices and can often be monitored by the naked eye.[1] A range of different mechanisms have been used to produce color changes in colorimetric sensors including protonation/deprotonation, hydrogen bonding, metal coordination, indicator displacement, nanoparticle, and bond formation/breaking.[2] One of the less studied mechanisms to produce changes in color is intermolecular charge transfer (CT).[3] This is probably due to the low association constants and extinction coefficients of CT complexes that limit the selectivity and sensitivity of CT sensors. However, the CT-sensing mechanism has some unique advantages that can yield highly selective colorimetric sensors. For example, Shinkai recently reported an electron-poor organogelator that was able to differentiate the positional isomers of naphthalene diols via the formation of different colored organogels through a combination of hydrogen bonding and CT.[4] In this work, we developed a soluble hydrogen bonding CT receptor **1** to demonstrate and study the origins of the excellent selectivity of CT sensors. We hypothesized that this selectivity arises from the ability of the CT band to simultaneously yield information about

(1) (a) Martinez-Manez, R.; Sancenon, F. *Chem. Rev.* **2003**, *103*, 4419. (b) de Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; Huxley, A. J. M.; McCoy, C. P.; Rademacher, J. T.; Rice, T. E. *Chem. Rev* **1997**, *97*, 1515. (c) Nguyen, B. T.; Anslyn, E. V. *Coord. Chem. Rev.* **2006**, *250*, 3118.

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(3) Most of these examples rely entirely on donor−acceptor interactions to provide affinity and selectivity: (a) Guo, Y.; Shao, S. J.; Xu, H.; Shi, Y. P.; Jiang, S. X *Tetrahedron Lett.* **2004**, *45*, 6477. (b) Issa, Y. M.; Abou-Attia, F. M.; Abdel-Hamid, F. M.; Abdel-Hamid, S. M. *Anal. Lett.* **2002**, *35*, 451. (c) Taha, E. A.; Soliman, S. M.; Abdellatef, H. E.; Ayad, M. M. *Mikrochim. Acta* **2002**, *140*, 175. (d) Yoon, K. B.; Huh, T. J.; Kochi, J. K. *J. Phys. Chem.* **1995**, *99*, 7042.

(4) Mukhopadhyay, P.; Iwashita, Y.; Shirakawa, M.; Kawano, S.; Fujita, N.; Shinkai, S. *Angew. Chem., Int. Ed.* **2006**, *45*, 1592.

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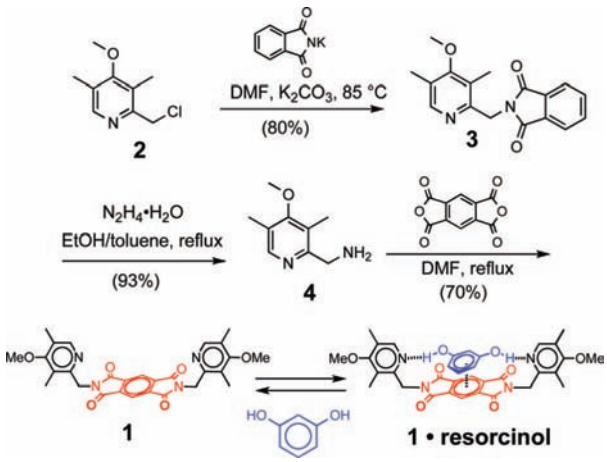
the hydrogen-bonding ability and electron-donating ability of the guest molecule. In contrast, the color of most colorimetric sensing systems corresponds to a single parameter, which is usually the receptor−guest association constant. Thus, a CT sensor can differentiate analytes that have similar association constants based on the differences in their electron-donating or -withdrawing abilities.[5] A CT sensor can also differentiate analytes with similar electron donating or accepting abilities based on the differences in their affinities for the sensor platform.

CT receptor **1** was designed to form hydrogen bond complexes with phenols and diols (Scheme 1). The two

Scheme 1. Synthesis and Binding Geometry of Receptor **1**



pyridine arms are positioned to form hydrogen bonds to a diol guest and position it over the electron-poor 1,2,4,5-benzenediimide surface.[6] Unlike the yellow 1,4,5,8-naphthalenediimide CT sensors, receptor **1** is colorless in solution, and thus the formation of colored CT complexes upon addition of diol guests was easily visualized. In addition, receptor **1** was readily soluble in organic solvents as an unaggregated structure and thus the association constants of its host−guest complexes could be easily measured via UV−vis titration studies and correlated to the color and intensity of the CT band.

Receptor **1** was easily prepared by condensation of 2 equiv of aminopyridine **4** with 1,2,4,5-benzene dianhydride. Pyridine **4** was prepared in two steps from chloromethylpyridine **2**. The methyl and methoxy groups on the pyridine **4** were necessary to enhance the solubility of receptor **1** in organic solvents.

First the structure and recognition abilities of receptor **1** were studied in the solid state. The receptor **1**•1,7-naphthalenediol crystal structure is shown in Figure 1. Both pyridine nitrogens of **1** form hydrogen-bonding interactions with a phenolic hydrogen of a 1,7-naphthalenediol. This positions the naphthalenediol over the electron-poor diimide surface

(5) (a) Foster, R. *Organic Charge Transfer Complexes*; Academic Press: New York, 1969. (b) Rathore, R.; Lindeman, S. V.; Kochi, J. K. *J. Am. Chem. Soc.* **1997**, *119*, 9393.

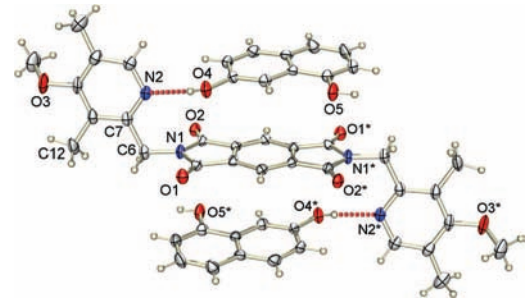


Figure 1. Crystal structure of receptor **1**•1,7-naphthalenediol cocrystal (1:2 complex).

in $\pi-\pi$ stacking distance. The exclusive formation of the more symmetrical *anti*-isomer in the solid state did not preclude the formation of the convergent *syn*-isomer in solution.[7] In solution, the pyridine arms are free to rotate and thus can adopt either the *syn*- or *anti*-conformers.[8] The crystal structure also revealed an additional degree of preorganization provided by the C12 methyl group on the pyridine arms. The C12 methyl group restricts the conformation about the C6−C7 bond to avoid steric interactions with the N1 imide nitrogen. This fixes the pyridine N2 nitrogens to point inward toward the central diimide surface.

Next, the ability of receptor **1** to bind and form colored CT complexes with electron-rich guests in solution (4:1, $CHCl_3/CH_3CN$) was assessed (Figure 2). This mixed solvent system yielded the best balance between maximizing solubility of the diols without disrupting the host−guest hydrogen bonding interactions. The solutions varied widely in color and intensity and were easily visually differentiated, ranging from yellow (**e**, **f**, **g**) to orange (**b**, **k m**), to purple (**h**). A clear correlation between the ability of a guest to form hydrogen bonds to receptor **1** and the formation of a colored CT complex was observed. For example, diols **b**, **c**, **e**, **f**, and **g** form strong colored CT complexes. In comparison, guests that could not form hydrogen-bonding interactions such as *p*-dimethoxybenzene **d** and 1,7-dimethoxynaphthalene **j** showed little or no color, even though they have very similar electron-donating abilities to the diols.

There was also considerable variation in the color of the CT complexes even with diols with very similar structures. For example, the positional isomers hydroquinone **b**, catechol **e**, and resorcinol **f** formed orange, pale yellow, and bright yellow complexes, respectively. The differences in color were even more dramatic for the isomeric dihydroxynaphthalenes **h**, **k**, and ***l***. Perhaps the most remarkable was that guests

(6) (a) Kishikawa, K.; Iwashima, C.; Kohmoto, S.; Yamaguchi, K.; Yamamoto, M. *J. Chem. Soc., Perkin Trans. 1* **2000**, 2217. (b) Fallon, G.; Langford, S. J.; Lee, M. A. P. *Chem. Lett.* **2001**, 578. (c) Kato, S.; Matsumoto, T.; Ideta, K.; Shimasaki, T.; Goto, K.; Shinmyozu, T. *J. Org. Chem.* **2006**, *71*, 4723. (d) Iijima, T.; Vignon, S. A.; Tseng, H. R.; Jarrosson, T.; Sanders, J. K.; Marchioni, F.; Venturi, M.; Apostoli, E.; Balzani, V.; Stoddart, J. F. *Chem. Eur. J.* **2004**, *10*, 6375.

(7) This has been observed elsewhere: Barooah, N.; Sarma, R. J.; Batsanovq, A. S.; Baruah, J. B. *J. Mol. Struct.* **2006**, *791*, 122.

(8) Kacprzak, K.; Gawronski, J. *Chem. Commun.* **2003**, 1532.

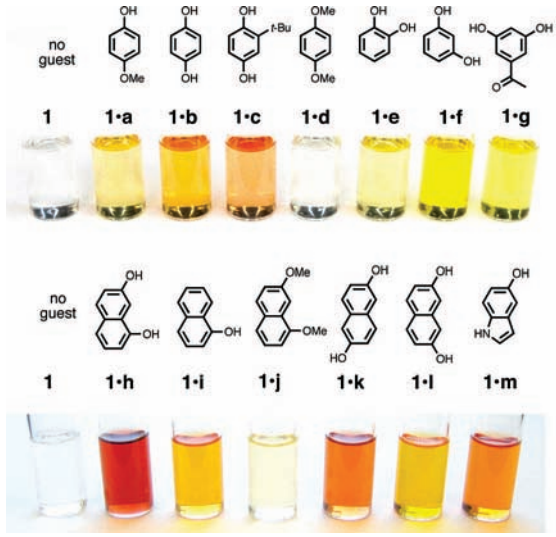


Figure 2. The addition of various guests to receptor **1** gives rise to different colored CT complexes. The concentration for receptor **1** was 4 mM and there was a 10-fold excess of each guest in 4:1 $CHCl_3/CH_3CN$.

with different functional groups attached to them were readily differentiated. For example, *tert*-butylhydroquinone **c** and hydroquinone **b** are easily distinguished as are acetylresorcinol **g** and resorcinol **f**.

The structure and stoichiometry of the receptor•guest complexes in solution were characterized. Job plots of receptor **1**•guest complexes were measured with representative benzene (**f**) and naphthalene (**h**) diols (Supporting Information, Figures S11 and S12) confirming the formation of 1:1 complexes. To verify that the receptor **1**•guest complexes involved both pyridine arms, recognition abilities of receptors **1**, **5**, and **6**, having two, one, and zero pyridine arms, were compared (Figure 3). Figure 3 shows the CT band of each receptor in the presence of 1,7-naphthalene diol **h**. Receptor **1** displays a much stronger CT band than control receptors **5** and **6**. All three receptors contained the same

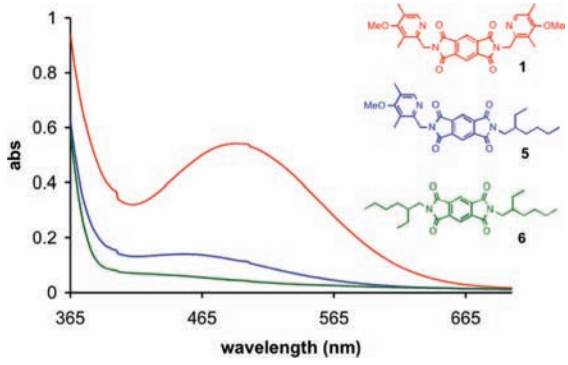


Figure 3. UV−vis spectrum for receptors **1**, **5**, and **6** (4 mM) in the presence of 1,7-naphthalene diol **h** (40 mM) in 4:1 $CHCl_3/CH_3CN$.

electron-deficient 1,2,4,5-benzenediimide core, and thus, the differences can be attributed to the ability of both pyridine arms of **1** to form hydrogen bonds to the diol guest. Additional evidence for the participation of both pyridine arms in **1** comes for the comparison of the CT complexes of guests that can form two (**b**), one (**a**), and zero (**d**) hydrogen bonds (Figure 2). Again, the intensity of the CT band correlates to the number of hydrogen-bonding interactions the guests can form with receptor **1**. Finally, ^{1}H NMR titration studies between receptor **1** and naphthalene diol **h** showed an excellent fit to a 1:1 binding isotherm (Supporting Information, Figure S17) with a binding constant of 115 M^{-1}. Upon formation of the complex, the receptor diimide spacer protons shifted upfield due to π-stacking of the naphthalene guest, and the guest OH hydrogens shifted downfield due to hydrogen bonding as expected.

Next, the origins of the impressive colorimetric selectivity of receptor **1** were investigated. The color (λ_{CT}) and intensity (abs at λ_{CT}) of the CT bands were measured under similar conditions and correlated with the association constant (K_a) and ionization potential (IP) of the respective guests (Table 1). The binding constants for each guest with receptor **1** were

Table 1. The CT Absorption Wavelength (λ_{CT}), Association Constant (K_a), and Ionization Potential (IP) for Complexes of Receptor **1** with Electron-Rich Guests **a**−**m**

complex	λ_{CT} (nm)	K_a[a] (M^{-1})	abs (at λ_{CT})	IP[b] (eV)
1·a	428	5.7	0.24	7.96
1·b	440	10.6	0.45	8.12
1·c	462	5.9	0.35	7.91
1·d		≪1		7.82
1·e	402	5.5	0.31	8.24
1·f	392	19.0	1.16	8.46
1·g	378	14.3	1.46	8.61
1·h	480	65.4	1.76	7.67
1·i	424	3.1	0.95	7.81
1·j		≪1		7.47
1·k	463	11.0	1.07	7.73
1·*l*	415	16.1	1.48	7.90
1·m	450	12.9	1.17	7.72

[a] Measured in $CHCl_3/CH_3CN$ (4:1), using Benesi−Hildebrand analysis. [b] The ionization potentials were calculated by using semiempirical AM1 in SPARTAN.

measured by UV−vis titration studies. The binding constants were calculated from the binding isotherms by Benesi−Hildebrand analyses.[9] The association constants of the naphthalene guests were generally higher than those of the benzene guests suggesting that there was a π-stacking or electrostatic component to the binding interaction.[10] The ionization potentials (IP) were calculated by using SPARTAN.

The measured binding constants were surprisingly low especially considering the excellent levels of colorimetric discrimination displayed by receptor **1**. Most of the binding constants were around 10^1 M^{-1} with the highest K_a being 65 M^{-1} for 1,7-naphthalene diol (**h**). The colorimetric selectivity appears to arise from the ability of the CT band to simultaneously yield information about recognition prop-

erties and electron-donating abilities of the guest molecules. Thus, guests with similar association constants can be differentiated via their different donating abilities. Similarly, guests with similar donating abilities can be differentiated by their association constants.

We hypothesized that the intensity of the CT band correlated with the hydrogen-bonding abilities and the color (λ_{CT}) of the CT band correlated with the donating abilities of the guests. This hypothesis was tested via correlation plots (Figure 4). Although the intensity of the CT band is known

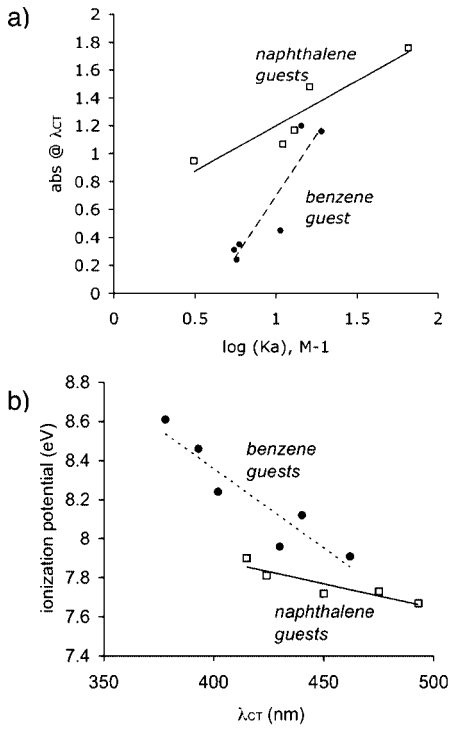


Figure 4. (a) Plot of absorbance vs log K_a (M^{-1}). (b) A plot of the ionization potential versus λ_{max} for the CT complexes formed between diimide-**1** and the variously substituted naphthalene and benzene guests.

to be proportional to K_a *times* the extinction coefficient (ϵ_{CT}),[9,11] a reasonable correlation was still observed between the intensity of the CT band and the binding energy (log K_a) (Figure 4a). Separate trend lines were observed for the naphthalene and benzene guests.

A linear correlation was also observed between the IP of the guest and the color (λ_{CT}) of the CT complex (Figure 4b).[12] Again, different trend lines were seen for the benzene and naphthalene guests. The naphthalenes and indole had lower ionization potentials and on average higher λ_{max} values compared to those of their benzene counterparts. The differences in the slopes of the trend lines reveal that receptor **1** is more sensitive to differences in the ionization potential of the naphthalene guests.

This study demonstrates that very selective colorimetric sensors can be developed by using intermolecular charge transfer even with receptors with very low association constants. The CT band can simultaneously report multiple characteristics about a guest such as size, recognition ability, and electronic structure.[5] The differences in the colorimetric responses are due to a combination of the abilities of the guests to form stable hydrogen-bonded complexes and the electronic structure of the guest. This multivariate aspect of the CT band enables receptor **1** to be highly selective despite its relatively low binding constants. Future CT-based receptors with higher association constants should have correspondingly higher sensitivities and also selectivities.[13]

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Supporting Information Available: Experimental procedures, spectroscopic data for all new compounds, and crystallographic data for **1·h**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(9) (a) Connors, K. A. *Binding Constants: The Measurement of Complex Stability*; John Wiley & Sons: New York, 1987. (b) Similar K_a values were also calculated by using curve-fitting analysis.

(10) Cubberley, M. S.; Iverson, B. L. *J. Am. Chem. Soc.* **2001**, *123*, 7560.

(11) The Benesi−Hildebrand equation predicts that the intensity of the CT band is proportional to K_a times the extinction coefficient (ϵ_{CT}). Indeed a much stronger correlation was observed between the CT band intensity and $K_a\epsilon_{CT}$ (Supporting Information, Figure S18).

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