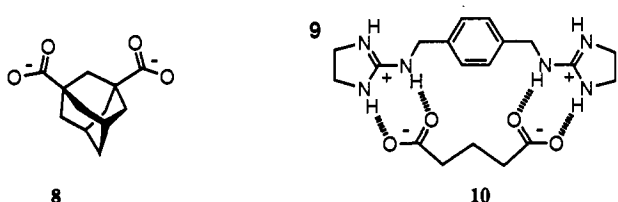


resonances on going from CDCl_3 to $\text{DMSO}-d_6$, which is smaller for the dialkylureas (1.65 ppm) than for the 2-(acylamino)pyridines (2.33 ppm). Nonetheless, the increase in binding strength in **6** is modest compared to **2a** ($\Delta G_{295} = -2.2 \text{ kcal mol}^{-1}$, $\Delta H = -2.7 \text{ kcal mol}^{-1}$, and $\Delta S = -1.7 \text{ cal mol}^{-1} \text{ K}^{-1}$), possibly reflecting that glutarate is binding in a higher energy conformation.¹⁴ This interpretation is supported by the very strong interaction between **4** and adamantane-1,3-dicarboxylate **8**, a rigid analog of glutarate ($\Delta G_{295} = -4.5 \text{ kcal mol}^{-1}$, $\Delta H = -5.6 \text{ kcal mol}^{-1}$, and $\Delta S = -2.6 \text{ cal mol}^{-1} \text{ K}^{-1}$). The entropies of association for **2a**, **6**, and **4:8** in $\text{DMSO}-d_6$ are all small despite the inherent entropic cost of bimolecular association and the greater flexibility of the xylylene spacer, compared to the terephthaloyl group in **1**. Binding must therefore involve an entropically favorable component to counterbalance these unfavorable factors. This may derive from displacement of DMSO molecules solvating the urea NH sites or ion-paired tetrabutylammonium cations on substrate binding. The resultant randomization of solvent or ions would lead to an increase in entropy, and similar effects have been seen with other synthetic receptors.^{5,15}



The complex **7** formed between bis-thiourea receptor **5** and glutarate-TBA in $\text{DMSO}-d_6$ shows a 15-fold increase in stability ($K_a = (1.0 \pm 0.2) \times 10^4 \text{ M}^{-1}$) over **6**.¹⁶ The corresponding bis-alkylguanidinium receptor **9**¹⁷ is formed by reaction of 1,4-bis(aminomethyl)benzene with 2-(methylthio)imidazoline hydroiodide. The association constant for the complex between **9** (as its bis-iodide salt) and glutarate-TBA in $\text{DMSO}-d_6$ was too large ($K_a > 5 \times 10^4 \text{ M}^{-1}$) to be measured by $^1\text{H NMR}$. Addition of D_2O to the DMSO solution led to the expected decrease in K_a , due to increased solvation of the carboxylate groups. However, binding was still clearly observable at 12% $\text{D}_2\text{O}/\text{DMSO}$ ($K_a = (8.5 \pm 1.5) \times 10^3 \text{ M}^{-1}$) and even 25% $\text{D}_2\text{O}/\text{DMSO}$ ($K_a = (4.8 \pm 2.5) \times 10^2 \text{ M}^{-1}$).¹⁸

In summary, we have shown that manipulation of both the location and charge of hydrogen-bonding sites can convert synthetic receptors that function only in nonpolar solvents into ones that bind strongly in highly competitive solvents. We are currently applying these designs to new catalytic systems.

Acknowledgment. We thank the National Institutes of Health (GM 35208) for financial support of this research, Prof. Steven Weber for many helpful discussions, and Prof. Craig Wilcox for his generous provision of the Hostest-II program.

(13) A similar proximity of H-bond donor sites is seen in the carboxylate-binding pocket of the antibiotic vancomycin. See: Kannan, R.; Harris, C. M.; Harris, T. M.; Waltho, J. P.; Skelton, N. N.; Williams, D. H. *J. Am. Chem. Soc.* **1988**, *110*, 2946.

(14) Adipic acid binds to the bis-(acylamino)pyridine receptor **1** in a less stable conformation.⁴

(15) For a discussion of related effects in cyclophane receptors, see: Stauffer, D. A.; Barrans, R. E., Jr.; Dougherty, D. A. *J. Org. Chem.* **1990**, *55*, 9412.

(16) The stronger binding of anions by thioureas compared to ureas has also been observed by C. S. Wilcox and his group. A detailed analysis of this effect will be the subject of a future paper.

(17) For other examples of guanidinium-containing synthetic receptors, see: Dietrich, B.; Fyles, D. L.; Fyles, T. M.; Lehn, J. M. *Helv. Chim. Acta* **1979**, *62*, 2763. Müller, M.; Riede, J.; Schmidtchen, F. P. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1516. Echaverran, A.; Galan, A.; Lehn, J. M.; de Mendoza, J. *J. Am. Chem. Soc.* **1989**, *111*, 4994. Schmidtchen, F. P. *Tetrahedron Lett.* **1989**, 4493. Dixon, R. P.; Geib, S. J.; Hamilton, A. D. *J. Am. Chem. Soc.* **1992**, *114*, 365. Ariga, K.; Ansllyn, E. V. *J. Org. Chem.* **1992**, *57*, 419.

(18) Binding was monitored by following the upfield shifts of the benzylic proton resonances and was further supported by the observation of an NOE between the aromatic and glutarate protons.

Multidentate Lewis Acids. Simultaneous Coordination of a Carbonyl Oxygen Atom by Four Lewis Acids

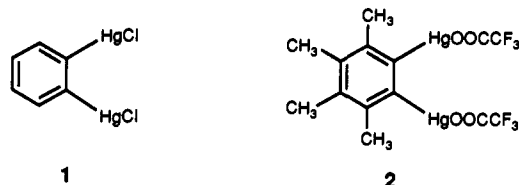
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Basic oxygen atoms in neutral organic molecules are able to accept multiple hydrogen bonds at the same time.³ These multiple interactions play a chemically important role by helping determine structure and reactivity. In contrast, the simultaneous interaction of basic oxygen atoms with multiple sites of Lewis acidity is a more elusive phenomenon. Complexes in which the oxygen atom of an ether or a carbonyl compound is bound by two Lewis acids are rare,⁵⁻⁸ and higher degrees of association are unknown. In this communication, we describe the unprecedented structure of a complex in which the oxygen atom of a simple amide interacts simultaneously with four Lewis acidic atoms of mercury.

Phenylenedimercury dichloride **1**, a bidentate Lewis acid,⁹ is known to form a 1:1 complex with dimethylformamide in which the carbonyl oxygen atom is bonded to both atoms of mercury at once.^{5c} A partial structure is shown in Figure 1a, along with selected geometric parameters. We have now found that crystallization of the more strongly Lewis acidic bis(trifluoroacetate) **2**^{5b} from dimethylformamide or diethylformamide produces complexes in which the bidentate Lewis acid and the amide are present in a 2:3 molar ratio.¹⁰ The structures of these two complexes were determined by X-ray crystallography and proved to be very similar;¹¹ the structure of the diethylformamide adduct is illustrated in Figures 1 and 2, along with selected interatomic distances and angles.



Two of the three bound amides are complexed in the expected manner. Each carbonyl oxygen atom interacts with two Lewis

(1) Fellow of the Natural Sciences and Engineering Research Council of Canada, 1988-1992.

(2) Killam Research Fellow, 1992-1994.

(3) A dramatic example is provided by the carbonyl oxygen atom of crystalline urea, which accepts four hydrogen bonds.⁴

(4) Swaminathan, S.; Craven, B. M.; McMullan, R. K. *Acta Crystallogr., Sect. B* **1984**, *B40*, 300.

(5) (a) Sharma, V.; Simard, M.; Wuest, J. D. *J. Am. Chem. Soc.* **1992**, *114*, 7931. (b) Nadeau, F.; Simard, M.; Wuest, J. D. *Organometallics* **1990**, *9*, 1311. (c) Beauchamp, A. L.; Olivier, M. J.; Wuest, J. D.; Zacharie, B. *Organometallics* **1987**, *6*, 153. (d) Wuest, J. D.; Zacharie, B. *J. Am. Chem. Soc.* **1987**, *109*, 4714.

(6) Adams, R. D.; Chen, G.; Chen, L.; Wu, W.; Yin, J. *J. Am. Chem. Soc.* **1991**, *113*, 9406. Derunov, V. V.; Shilova, O. S.; Batsanov, A. S.; Yanovskii, A. I.; Struchkov, Yu. T.; Kolobova, N. E. *Metalloorg. Khim.* **1991**, *4*, 1166.

(7) Seebach, D.; Müller, H.-M.; Bürger, H. M.; Plattner, D. A. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 434. Waymouth, R. W.; Potter, K. S.; Schaefer, W. P.; Grubbs, R. H. *Organometallics* **1990**, *9*, 2843. Erker, G.; Dorf, U.; Czisch, P.; Petersen, J. L. *Organometallics* **1986**, *5*, 668. Adams, H.; Bailey, N. A.; Gauntlett, J. T.; Winter, M. J. *J. Chem. Soc., Chem. Commun.* **1984**, 1360. Rao, C. P.; Rao, A. M.; Rao, C. N. R. *Inorg. Chem.* **1984**, *23*, 2080. Verbist, J.; Meulemans, R.; Piret, P.; Van Meersehe, M. *Bull. Soc. Chim. Belg.* **1970**, *79*, 391. Palm, J. H.; MacGillavry, C. H. *Acta Crystallogr.* **1963**, *16*, 963.

(8) Grdenič, D.; Korpar-Čolig, B.; Sikirica, M.; Bruvo, M. *J. Organomet. Chem.* **1982**, *238*, 327.

(9) For other recent studies of multidentate Lewis acidic compounds of mercury, see: Yang, X.; Knobler, C. B.; Hawthorne, M. F. *J. Am. Chem. Soc.* **1992**, *114*, 380. Yang, X.; Knobler, C. B.; Hawthorne, M. F. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1507. Shur, V. B.; Tikhonova, I. A.; Yanovsky, A. I.; Struchkov, Yu. T.; Petrovskii, P. V.; Panov, S. Yu.; Furin, G. G.; Vol'pin, M. E. *J. Organomet. Chem.* **1991**, *418*, C29. Korpar-Čolig, B.; Popović, Z.; Sikirica, M.; Grdenič, D. *J. Organomet. Chem.* **1991**, *405*, 59.

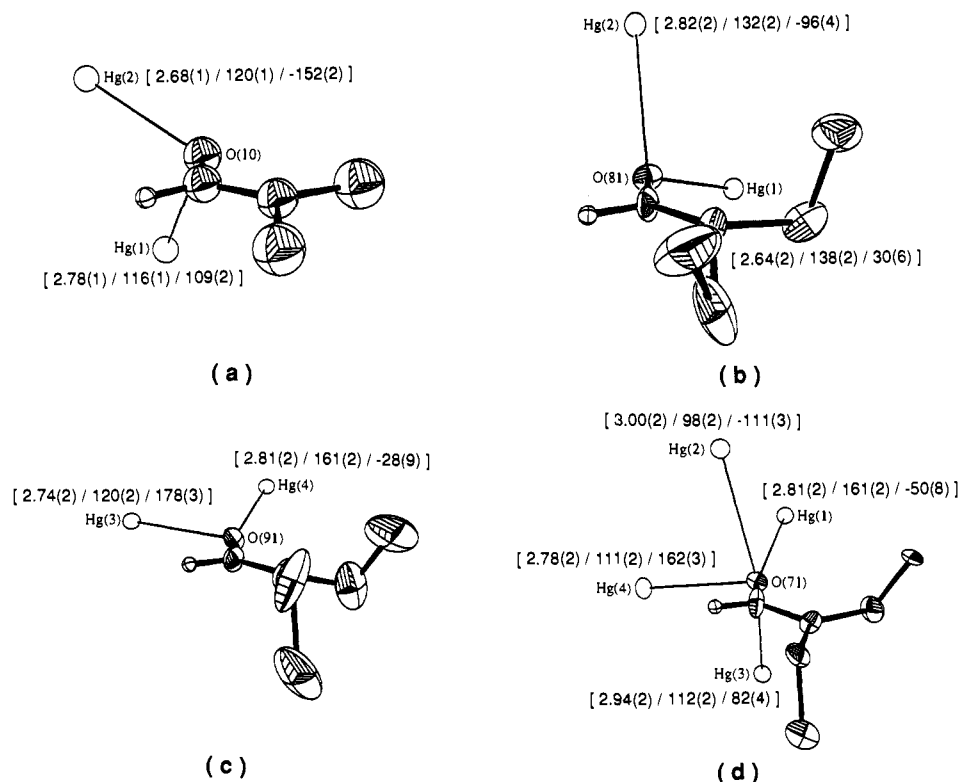


Figure 1. ORTEP drawings of the structures of amide complexes of phenylenedimercury dichloride **1** (a) and bis(trifluoroacetate) **2** (b–d) showing only the bound amides and the associated atoms of mercury. To facilitate comparison, each structure is viewed along the carbonyl C=O axis from slightly above the carbonyl plane. The three geometric parameters that appear next to each mercury atom correspond to the carbonyl O...Hg distance (Å)/C=O...Hg angle (deg)/N—C=O...Hg dihedral angle (deg). The formyl hydrogen atoms appear as spheres of arbitrary size, while other hydrogen atoms are omitted for simplicity. Other atoms are represented by ellipsoids corresponding to 30% probability.

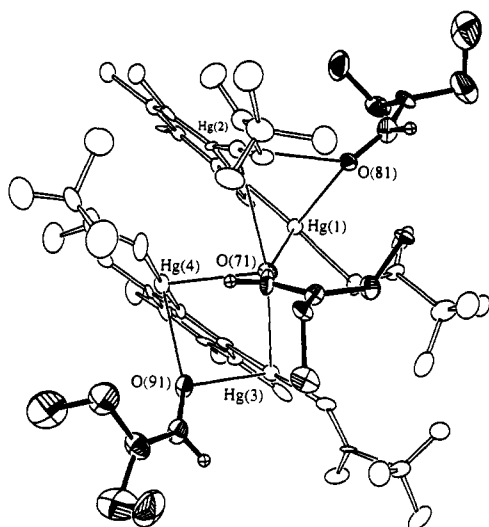


Figure 2. ORTEP drawing of the structure of the 2:3 complex of phenylenedimercury bis(trifluoroacetate) **2** with diethylformamide. The formyl hydrogens appear as spheres of arbitrary size, while other hydrogen atoms are omitted for simplicity. Other atoms are represented by ellipsoids corresponding to 30% probability. Important interatomic distances not shown in Figure 1 include C(71)—O(71) = 1.25 (5), C(81)—O(81) = 1.19 (4), C(91)—O(91) = 1.19 (4), C(71)—N(71) = 1.33 (4), C(81)—N(81) = 1.31 (4), and C(91)—N(91) = 1.28 (5) Å.

acidic atoms of mercury derived from a single molecule of bis(trifluoroacetate) **2**, producing motifs that resemble the structure of the 1:1 complex of dichloride **1** and dimethylformamide. For comparison, partial structures are shown in Figure 1b,c. The lengths of the dative Hg—O bonds, which vary only within the narrow range 2.64(2)–2.82(2) Å, resemble those found in related complexes.^{5c,8,12} Other features of the complex, including the

tendency of mercury to form two essentially collinear primary bonds and to accept coordinative interactions in the plane perpendicular to these bonds, have been noted in related structures.^{5b} In addition, the average lengths of the primary Hg—O and Hg—C bonds (2.10 (2) and 2.06 (3) Å, respectively) have normal values.^{5b,13}

The general similarity of the three motifs shown in Figure 1a–c confirms that derivatives of 1,2-phenylenedimercury hold two sites of Lewis acidity in an orientation particularly well suited for the cooperative binding of carbonyl substrates. Although the three motifs are similar, the angular distributions of the two Lewis acidic atoms of mercury vary widely. This suggests that carbonyl oxygen atoms do not have very strong steric or electronic preferences for bonding to atoms of mercury along specific directions.¹⁴ We

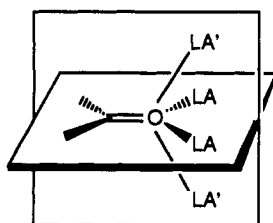
(10) The structures assigned to all new compounds are consistent with their IR, ¹H NMR, ¹³C NMR, and ¹⁹⁹Hg NMR spectra and their elemental analyses. These data are included in the supplementary material.

(11) (a) Crystals of the 2:3 complex of phenylenedimercury bis(trifluoroacetate) **2** with diethylformamide belong to the monoclinic space group *P*2₁/*c* with *a* = 10.922 (7) Å, *b* = 18.166 (8) Å, *c* = 28.955 (12) Å, *V* = 5672 (5) Å³, *D*_{calc} = 2.134 g cm⁻³, and *Z* = 4. Data were collected at 220 K, and the structure was solved by direct methods and refined to *R*_f = 0.053, *R*_w = 0.050 for 3420 reflections with *I* > 2.50σ(*I*). A full description of the structure is provided in the supplementary material. (b) To establish that adducts of bis(trifluoroacetate) **2** with other amides have similar structures, we also studied the 2:3 complex with dimethylformamide but did not refine its structure as extensively. Bélanger-Gariépy, F.; Vaugois, J.; Wuest, J. D. Unpublished results. (c) Crystals of the 2:3 complex of phenylenedimercury bis(trifluoroacetate) **2** with dimethylformamide belong to the triclinic space group *P*-1 with *a* = 10.3970 (10) Å, *b* = 13.642 (3) Å, *c* = 18.280 (5) Å, α = 89.29 (2)°, β = 77.68 (2)°, γ = 74.74 (21)°, *V* = 2441.1 (9) Å³, *D*_{calc} = 2.308 g cm⁻³, and *Z* = 2. Data were collected at 220 K, and the structure was solved by direct methods and refined to *R*_f = 0.098, *R*_w = 0.107 for 4820 reflections with *I* > 3.0σ(*I*). Additional information is provided in the supplementary material.

(12) Lechat, J. R.; Francisco, R. H. P.; Airoldi, C. *Acta Crystallogr., Sect. B* 1980, *B36*, 930. Birker, P. J. M. W. L.; Freeman, H. C.; Guss, J. M.; Watson, A. D. *Acta Crystallogr., Sect. B* 1977, *B33*, 182. Majeste, R. J.; Trefonas, L. M. *Inorg. Chem.* 1972, *11*, 1834. Carrabine, J. A.; Sundaralingam, M. *Biochemistry* 1971, *10*, 292.

conclude that the Hg–O interactions have a significant electrostatic component. In addition, the data in Figure 1a–c provide evidence for an important covalent component as well, since the shortest dative Hg–O bonds are those that lie closest to the carbonyl plane, in the direction of the carbonyl lone pairs.¹⁵

The most remarkable feature of the structure of the 2:3 complex of bis(trifluoroacetate) **2** with diethylformamide is the binding of the third amide. Its oxygen atom interacts simultaneously with four Lewis acidic atoms of mercury, creating the unprecedented partial structure shown in Figure 1d. All four dative Hg–O distances are significantly shorter than the sum of the van der Waals radii of oxygen (1.40 Å)¹⁶ and mercury (1.73 Å).¹⁷ Each 1,2-phenylenedimercury unit forms one short and one long dative Hg–O bond. The two shortest bonds are those that lie closest to the carbonyl plane, while the two longest bonds lie in an approximately orthogonal plane. The resulting motif therefore resembles the quadruply hydrogen-bonded structure of crystalline urea,⁴ since in both cases the carbonyl oxygen atom is surrounded by four electrophilic sites disposed in two approximately perpendicular planes. This suggests that other adducts of carbonyl compounds with four neutral main group Lewis acids will attempt to attain the idealized structure **3**, in which the carbonyl oxygen



3

atom forms strong, partly covalent bonds to two Lewis acids (LA) lying in the carbonyl plane along the directions of the sp^2 lone pairs and accepts weaker, largely electrostatic interactions with two other Lewis acids (LA') in an orthogonal plane.¹⁸

(13) Deguire, S.; Beauchamp, A. L. *Acta Crystallogr., Sect. C* **1990**, *C46*, 27.

(14) The ease of distorting the geometries of complexes of carbonyl compounds with Lewis acids is discussed by LePage, T. J.; Wiberg, K. B. *J. Am. Chem. Soc.* **1988**, *110*, 6642.

In principle, quadruple bonding of the third amide should have a conspicuous effect on its structure and reactivity.^{5a,19} Unfortunately, the standard deviations in the structural parameters are too high to permit detailed comparison of the three bound amides, so we cannot confirm that the C–O and C–N distances in the quadruply bonded amide are significantly longer and shorter, respectively, than those in its doubly bonded neighbors or in free diethylformamide.²⁰ Nevertheless, this structure provides a dramatic illustration of the ability of the oxygen atom of carbonyl compounds to accommodate multiple sites of Lewis acidity when they are linked together to form multidentate units that are structurally and electronically complementary.

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Supplementary Material Available: Listings of spectroscopic and analytical data for the 2:3 complexes of phenylenedimercury bis(trifluoroacetate) **2** with dimethylformamide and diethylformamide, descriptions of the structure determinations, and tables of X-ray crystallographic data, including atomic coordinates, interatomic distances and angles, anisotropic thermal parameters, and calculated hydrogen atom coordinates (23 pages); table of observed and calculated structure factors (45 pages). Ordering information is given on any current masthead page.

(15) For comparisons of $\eta^1(\sigma)$ and $\eta^2(\pi)$ bonding of carbonyl compounds by Lewis acids, see: Corcoran, R. C.; Ma, J. *J. Am. Chem. Soc.* **1992**, *114*, 4536. Delbecq, F.; Sautet, P. *J. Am. Chem. Soc.* **1992**, *114*, 2446. Klein, D. P.; Dalton, D. M.; Méndez, N. Q.; Arif, A. M.; Gladysz, J. A. *J. Organomet. Chem.* **1991**, *412*, C7. Shambayati, S.; Crowe, W. E.; Schreiber, S. L. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 256.

(16) Pauling, L. *The Nature of the Chemical Bond*; Cornell University Press: Ithaca, NY, 1960; p 514.

(17) Canty, A. J.; Deacon, G. B. *Inorg. Chim. Acta* **1980**, *45*, L225.

(18) Prominent deviations from this ideal geometry in the quadruple bonding of the third amide by bis(trifluoroacetate) **2** can be attributed to steric factors and to the rigidity of the phenylenedimercury skeleton.

(19) Wuest, J. D.; Zacharie, B. *J. Am. Chem. Soc.* **1985**, *107*, 6121.

(20) Attempts to use spectroscopic methods to probe the unusual bonding of the amides were unsuccessful. In IR spectra, for example, carbonyl bands characteristic of the bound amides could not be distinguished from those of the trifluoroacetate ligands. Moreover, NMR spectroscopy in solution could not be used to study the bonding because the complexes are readily soluble only in solvents that displace the bound amides. We are now trying to make derivatives of 1,2-phenylenedimercury with significantly higher solubilities.