hemagglutination of erythrocytes 10^3–10^4 times more than Neu5Acα2Me.[22]

In summary, it appears that bidentate binding occurs to different HA trimers on influenza virus. From the relative binding affinities of our bivalent compounds, the distance between SA binding sites on different HA trimers must be less than about 55 Å. Interestingly, the effects we have observed are not unique to influenza virus: G(4,4) inhibits the agglutination of erythrocytes by polyoma virus some 500-fold better than Neu5Acα2Me.[23] While we do not know if inhibition of hemagglutination correlates with blockade of viral infectivity, further experiments with defined polyvalent ligand analogues should clarify the nature of viral recognition and may suggest routes to new antiviral agents.

Acknowledgment. This work was supported by the National Institutes of Health as a collaboration among the groups of M. Karplus, J. R. Knowles, G. M. Whitesides, and D. C. Wiley and by the Howard Hughes Medical Institute. We are especially grateful to P. L. Toogood for practical help and discussions, to J. E. Hanson and N. K. Sauter for assistance with the NMR binding assay, and to J. J. Skehel for generous supplies of BHA and virus.

(22) Roy, R.; Laferrière, C. A. *Carbohydr. Res.* **1988**, *177*, 1. Matrosovich, M. N.; Mochalova, L. V.; Marinina, V. P.; Byramova, N. E.; Bovin, N. V. *FEBS Lett.* **1990**, *272*, 209. Spaltenstein, A.; Whitesides, G. M. *J. Am. Chem. Soc.* **1991**, *113*, 686.

(23) Glick, G. D.; Zhao, H.-C., unpublished results.

Chemical Reactivity of a Metallabenzene[1]

John R. Bleeke,* Yun-Feng Xie, Laura Bass, and Michael Y. Chiang

Department of Chemistry, Washington University St. Louis, Missouri 63130

Received February 5, 1991

In addition to its effects on molecular structure and spectroscopy, aromaticity strongly influences chemical reactivity. Studies of reduction, oxidation, and substitution reactions involving benzene and heterobenzene derivatives form a central component of organic chemistry.[2] However, related studies on metallabenzenes have not been pursued because of the scarcity of metal-containing aromatic systems.[3] We recently reported the synthesis of a rare, stable metallabenzene complex, (IrCH=C(Me)CH=C(Me)CH)(PEt$_3$)$_3$ (**1**).[4] Structural and spectroscopic data for **1** clearly indicated the presence of an aromatic ring system. We now report initial findings on the reactivity of **1**, which parallels in some respects the reactivity of conventional benzene derivatives, and in others does not.

Unlike organic arenes, **1** reacts with H_2 at room temperature and 1 atm of pressure, generating the partially hydrogenated iridacyclohexadiene complex *mer*-(IrCH$_2$C(Me)=CHC(Me)=CH)(PEt$_3$)$_3$(H) (**2**)[5] (see Scheme I). This reaction probably proceeds via dissociation of a PEt$_3$ ligand from **1**, producing 16 e$^-$ (IrCH=C(Me)CH=C(Me)CH)(PEt$_3$)$_2$. Oxidative addition of H_2, followed by hydride migration from the iridium center to the ortho carbon of the ring and readdition of PEt$_3$, yields the observed product.

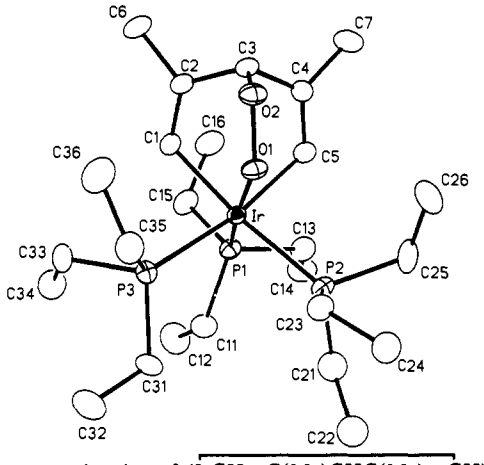
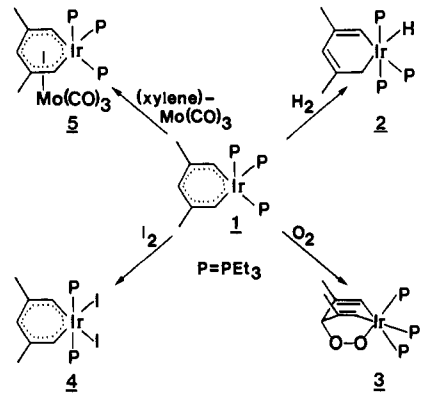


Figure 1. ORTEP drawing of (IrCH=C(Me)CHC(Me)=CH)(PEt$_3$)$_3$ (**3**). Selected bond distances: Ir–P(1), 2.279 (3) Å; Ir–P(2), 2.387 (2) Å; Ir–P(3), 2.395 (2) Å; Ir–C(1), 2.075 (8) Å; Ir–C(5), 2.062 (8) Å; Ir–O(1), 2.111 (6) Å; C(1)–C(2), 1.315 (11) Å; C(2)–C(3), 1.512 (11) Å; C(3)–C(4), 1.521 (13) Å; C(4)–C(5), 1.339 (12) Å; O(1)–O(2), 1.466 (7) Å; O(2)–C(3), 1.435 (10) Å.

Scheme I



In pentane solution reacts with atmospheric oxygen to produce the novel dioxygen-bridged species (IrCH=C(Me)CHC(Me)=CH)(PEt$_3$)$_3$ (**3**) (see Scheme I and ORTEP drawing, Figure 1).[6,7] The iridacyclohexa-2,5-diene ring in **3** is boat-shaped with Ir and C(3) residing 0.92 and 0.65 Å, respectively, out of the C(1)/C(2)/C(4)/C(5) plane. This reaction is reminiscent of the reaction of certain polycyclic aromatic compounds (e.g., anthracene) with O_2, which lead to internal peroxides.[8] However, unlike these organic reactions which require singlet oxygen, **1** reacts with ground-state (triplet) oxygen. Furthermore, unlike the reaction of **1** with H_2 (which requires PEt$_3$ loss and therefore proceeds relatively slowly), the O_2 reaction

(1) Metallacyclohexadiene and Metallabenzene Chemistry. 5. Previous paper in this series: Bleeke, J. R.; Haile, T.; Chiang, M. Y. *Organometallics* **1991**, *10*, 19.

(2) See, for example: March, J. *Advanced Organic Chemistry*, 3rd ed.; Wiley: New York, 1985; also references cited therein.

(3) Prior to our work, only one other family of stable metallabenzenes had been reported: Elliott, G. P.; Roper, W. R.; Waters, J. M. *J. Chem. Soc., Chem. Commun.* **1982**, 811. In addition, there was one report of a metallabenzene *coordinated* to a second metal center: Kralik, M. S.; Rheingold, A. L.; Ernst, R. D. *Organometallics* **1987**, *6*, 2612.

(4) Bleeke, J. R.; Xie, Y.-F.; Peng, W.-J.; Chiang, M. *J. Am. Chem. Soc.* **1989**, *111*, 4118.

(5) Bleeke, J. R.; Peng, W.-J. *Organometallics* **1987**, *6*, 1576.

(6) Spectroscopic data for **3**: ^{1}H NMR (C_6D_6, 17 °C, 300 MHz) δ 7.37 (m, 2, H1/H5), 4.59 (s, 1, H3), 2.32 (s, 6, ring CH$_3$'s), 1.95–1.77 (m, 6, PEt$_3$ CH$_2$'s), 1.71–1.53 (m, 12, PEt$_3$ CH$_2$'s), 1.10–0.97 (m, 18, PEt$_3$ CH$_3$'s), 0.82–0.69 (m, 9, PEt$_3$ CH$_3$'s); ^{13}C{^{1}H} NMR (C_6D_6, 17 °C, 75 MHz) δ 132.1 (d of t, J_{C-P} = 89.4, 9.2 Hz, C1/C5), 129.5 (s, C2/C4), 92.3 (s, C3), 26.5 (t, J_{C-P} = 4.7 Hz, ring CH$_3$'s), 19.8 (d, J_{C-P} = 32.2 Hz, PEt$_3$ CH$_2$'s), 16.1 (d, J_{C-P} = 22.8 Hz, PEt$_3$ CH$_2$'s), 8.8 (virtual t, J_{C-P} = 5.1 Hz, PEt$_3$ CH$_3$'s), 8.6 (d, J_{C-P} = 5.1 Hz, PEt$_3$ CH$_3$'s); ^{31}P{^{1}H} NMR (C_6D_6, 17 °C, 121 MHz, referenced to external H_3PO_4) δ −29.5 (t, J_{P-P} = 9.5 Hz, 1, PEt$_3$), −35.8 (d, J_{P-P} = 9.5 Hz, 2, equivalent PEt$_3$'s).

(7) Crystal data for **3**: monoclinic, space group $P2_1/c$, a = 16.713 (5) Å, b = 10.454 (3) Å, c = 17.609 (4) Å, β = 103.99 (2)°, V = 2985.3 (14) Å^3, Z = 4.

(8) Rigaudy, J. *Pure Appl. Chem.* **1968**, *16*, 169.

0002-7863/91/1513-4703$02.50/0

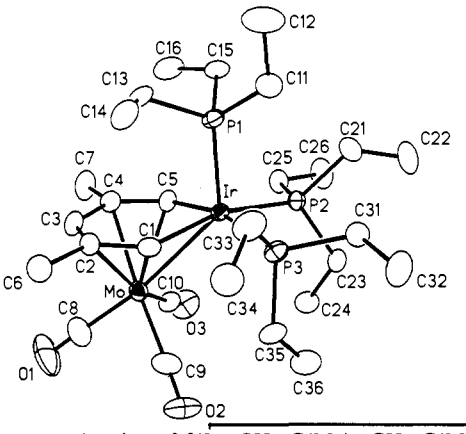


Figure 2. ORTEP drawing of $[(Ir{-}CH{-}C(Me){-}CH{-}C(Me){-}CH)(PEt_3)_3]Mo(CO)_3$ (**5**). Selected bond distances: Ir-Mo, 2.978 (1) Å; Ir-P(1), 2.274 (2) Å; Ir-P(2), 2.365 (2) Å; Ir-P(3), 2.369 (2) Å; Ir-C(1), 2.025 (8) Å; Ir-C(5), 2.038 (9) Å; C(1)-C(2), 1.399 (13) Å; C(2)-C(3), 1.411 (14) Å; C(3)-C(4), 1.429 (13) Å; C(4)-C(5), 1.393 (12) Å; Mo-C(1), 2.397 (8) Å; Mo-C(2), 2.404 (9) Å; Mo-C(3), 2.318 (10) Å; Mo-C(4), 2.355 (9) Å; Mo-C(5), 2.349 (9) Å.

is rapid (15 min) and probably involves initial transfer of an electron from **1** to O_2.

Treatment of **1** in acetone solution with iodine (I_2) leads to the rapid production of $(Ir{-}CH{-}C(Me){-}CH{-}C(Me){-}CH)(PEt_3)_2(I)_2$ (**4**), in which the aromatic ring is retained (see Scheme I).[9] Thus, **1** undergoes oxidative addition of I_2 at the iridium center rather than electrophilic aromatic substitution at carbon.[10] Although the detailed mechanism of this oxidative addition reaction is still unknown, both one-electron and two-electron processes can be envisaged. The ^1H NMR signals for ring protons H1/H5 and H3 in **4** are shifted dramatically downfield, appearing at δ 13.95 and 7.86, respectively. These shifts reflect the influence of a strong aromatic ring current, together with the electronic effect of two electronegative iodine atoms in the ring plane.

Finally, **1** cleanly displaces *p*-xylene from (*p*-xylene)$Mo(CO)_3$ in tetrahydrofuran (THF) solvent, producing the metal-coordinated metallabenzene complex, $[(Ir{-}CH{-}C(Me){-}CH{-}C(Me){-}CH)(PEt_3)_3]Mo(CO)_3$ (**5**) (see Scheme I and ORTEP drawing, Figure 2).[11,12] As is normally the case when arenes coordinate to metal fragments, the ^1H NMR signals for the ring protons in **5** shift upfield from their positions in the parent metallabenzene, **1**. Protons H1/H5 in **5** appear at δ 8.16 (vs δ 10.91 in **1**), while H3 resonates at δ 6.31 (vs δ 7.18 in **1**).[11] Furthermore, the metallabenzene moiety in **5** rotates with respect to the $Mo(CO)_3$ fragment. Hence, the carbonyl carbon atoms in **5** give rise to just one signal in the $^{13}C\{^1H\}$ NMR spectrum, even at -80 °C.

The infrared CO stretching bands exhibited by **5** in THF solution appear at very low energies (1918, 1836 cm^{-1}) compared to other (arene)$Mo(CO)_3$ complexes,[13] reflecting the extremely electron-rich nature of **1**. Since the stability of (arene)$Mo(CO)_3$ complexes increases with increasing arene basicity, it is not surprising that **1** readily displaces organic arenes from (arene)-$Mo(CO)_3$ complexes in THF solvent.[14]

Through this preliminary study, several reactivity features of metallabenzene complex **1** have emerged. First, the electron-rich metal center directs much of the chemistry by undergoing ligand-dissociation, oxidative-addition, and electron-transfer processes. Second, the aromaticity of the ring system appears to be quite fragile and is, in fact, disrupted in several of the reactions reported herein. Future work will continue to explore the chemistry of metallabenzenes via-ã-vis their conventional organic counterparts.

Acknowledgment. Support from the National Science Foundation (Grants CHE-8520680 and CHE-9003159), the donors of the Petroleum Research Fund, administered by the American Chemical Society, and Johnson-Matthey, Inc. ($IrCl_3 \cdot 3H_2O$ loan) is gratefully acknowledged. Washington University's X-ray Crystallography Facility was funded by the NSF Chemical Instrumentation Program (Grant CHE-8811456).

Supplementary Material Available: Detailed descriptions of syntheses and spectra of compounds **2-5**, structure determination summaries, ORTEP drawings, and tables of final atomic coordinates, thermal parameters, bond lengths, and bond angles for **3** and **5** (22 pages); listings of observed and calculated structure factor amplitudes for **3** and **5** (53 pages). Ordering information is given on any current masthead page.

(9) Spectroscopic data for **4**: ^1H NMR ($CD_3C(O)CD_3$, 17 °C, 300 MHz) δ 13.95 (s, 2, H1/H5), 7.86 (s, 1, H3), 2.37 (s, 6, ring CH_3's), 2.12-1.90 (m, 12, PEt_3 CH_2's), 1.00-0.78 (m, 18, PEt_3 CH_3's); $^{13}C\{^1H\}$ NMR ($CD_3C(O)CD_3$, 17 °C, 75 MHz) δ 215.1 (s, C1/C5), 161.6 (s, C3), 134.8 (s, C2/C4), 25.4 (s, ring CH_3's), 19.3 (virtual t, J_{C-P} = 36.4 Hz, PEt_3 CH_2's), 8.6 (s, PEt_3 CH_3's); $^{31}P\{^1H\}$ NMR ($CD_3C(O)CD_3$, 17 °C, 121 MHz, referenced to external H_3PO_4) δ -22.6 (s). The structure of **4** has been confirmed by an X-ray diffraction study.

(10) The same product is obtained when the reaction is run in the presence of a Friedel-Crafts catalyst.

(11) Spectroscopic data for **5**: ^1H NMR ($CD_3C(O)CD_3$, 17 °C, 300 MHz) δ 8.16 (br d, J_{H-P} = 20.4 Hz, 2, H1/H5), 6.31 (s, 1, H3), 2.10 (s, 6, ring CH_3's), 2.20-2.00 (m, 12, PEt_3 CH_2's), 1.83-1.71 (m, 6, PEt_3 CH_2's), 1.29-1.20 (m, 18, PEt_3 CH_3's), 0.96-0.85 (m, 9, PEt_3 CH_3's); $^{13}C\{^1H\}$ NMR (C_4D_8O, 17 °C, 75 MHz) δ 229.8 (s, CO's), 135.7 (d of d, J_{C-P} = 74.5, 9.4 Hz, C1/C5), 107.9 (s, C2/C4), 99.5 (s, C3), 29.3 (s, ring CH_3's), 24.8-24.3 (m, PEt_3 CH_2's), 22.0-21.6 (m, PEt_3 CH_2's), 10.4 (s, PEt_3 CH_3's), 9.0 (s, PEt_3 CH_3's); $^{31}P\{^1H\}$ NMR ($CD_3C(O)CD_3$, 17 °C, 121 MHz, referenced to external H_3PO_4) δ 19.9 (t, J_{P-P} = 3.5 Hz, 1, axial PEt_3), -19.4 (d, J_{P-P} = 3.5 Hz, 2, basal PEt_3's).

(12) Crystal data for **5**: monoclinic, space group $P2_1/n$, a = 9.897 (1) Å, b = 16.213 (3) Å, c = 20.937 (3) Å, β = 96.68 (1)°, V = 3336.7 (9) Å^3, Z = 4.

(13) By comparison, the ν(CO) bands for (hexamethylbenzene)$Mo(CO)_3$ come at 1958 and 1882 cm^{-1}: Barbeau, C.; Turcotte, J. *Can. J. Chem.* **1976**, *54*, 1612.

(14) Muetterties, E. L.; Bleeke, J. R.; Sievert, A. C. *J. Organomet. Chem.* **1979**, *178*, 197.

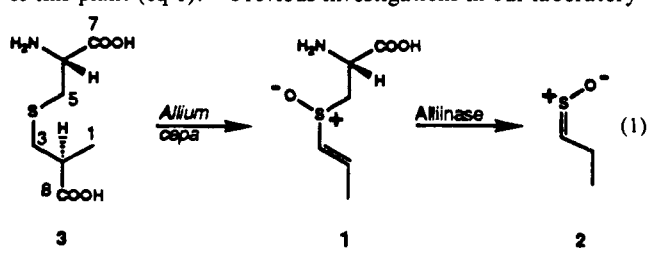
Investigations of the Biosynthesis of *trans*-(+)-*S*-1-Propenyl-L-cysteine Sulfoxide. Elucidation of the Stereochemistry of the Oxidative Decarboxylation Process

Ronald J. Parry* and Fwu-Lin Lii

Department of Chemistry, Rice University
Houston, Texas 77251

Received February 19, 1991

The novel amino acid *trans*-(+)-*S*-1-propenyl-L-cysteine sulfoxide (**1**) (PCS) is the constituent of the onion plant (*Allium cepa*)[1] that has been shown[1] to be the precursor of (*Z*)-propanethial *S*-oxide (**2**), the lachrymatory substance characteristic of this plant (eq 1).[2] Previous investigations in our laboratory[3]



(1)

3 **1** **2**

have demonstrated that **1** is derived from (2*S*,6*R*)-(-)-*S*-(2-carboxy-*n*-propyl)cysteine (CPC) (**3**) by an oxidative decarboxylation process that proceeds with the loss of one hydrogen atom from C-3 of CPC and none from C-2. This observation indicated

(1) Spare, C.-G.; Virtanen, A. I. *Suom. Kemistil.* **1961**, *B34*, 72; **1962**, *B35*, 28.

(2) Block, E.; Penn, R. E.; Revelle, L. K. *J. Am. Chem. Soc.* **1979**, *101*, 2200.

(3) Parry, R. J.; Sood, G. R. *J. Am. Chem. Soc.* **1989**, *111*, 4514.

0002-7863/91/1513-4704$02.50/0