lifetime, a calculated rate constant of 3 × 10^8 s^{-1} was determined for the reaction of **7**. Similar values are derived from the results with **4a–c**.[5]

The photolytic reactions of benzoin phosphates yield a relatively stable, inert rearrangement product and released phosphate with rate constants of 10^8 s^{-1}, much higher than the rate constants reported for the *o*-nitrophenyl cage.[4c,f] We are further pursuing this general approach to *cage* ligands.

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Activation of Organic Carbonyl Compounds by Lewis Acids: Relative Reactivities of σ and π Adducts toward Nucleophiles and Implications for Enantioselective Addition Reactions

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A variety of protocols for enantioselective additions to aldehyes and ketones have now been developed.[1] These usually involve intermediate Lewis acid adducts, for which a multitude of potentially reactive binding motifs are possible.[2] Thus, little is known regarding mechanisms of enantioselection, and similar ambiguities attend other Lewis acid mediated reactions of organic carbonyl compounds.[3] We have undertaken a detailed study of complexes of the chiral rhenium Lewis acid $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)]^+$ with aldehydes and ketones. This has included the structural characterization of, and diastereoselective hydride and cyanide additions to, both π and σ adducts.[4-6] In this communication, we report the first determination of the relative reactivity of π and σ isomers of Lewis acid/O=CRR′ complexes toward nucleophiles.

The previously reported pentafluorobenzaldehyde complex $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(O{=}CHC_6F_5)]^+BF_4^-$ (**1a**) shows no detectable amount of a σ isomer in CH_2Cl_2 at 26 °C by IR or UV/visible spectroscopy,[5a] and π/σ ratios for these compounds further increase upon cooling. Complex **1a** exists as a 98:2 mixture of two configurational diastereomers, $\mathbf{1a}_\pi$ and $\mathbf{1a}_{\pi'}$ (Scheme I),[7] which slowly interconvert via σ isomers $\mathbf{1a}_\sigma$ ($\Delta G^\ddagger_{300K} \geq 15$ kcal/mol).[5b] The reaction of $\mathbf{1a}_\pi$ and PPN^+CN^- was monitored by ^{31}P NMR spectroscopy ($CDCl_2F$, −83 °C) under pseudo-first-order conditions ($[CN^-] > [\mathbf{1a}_\pi]$). Rate data are summarized

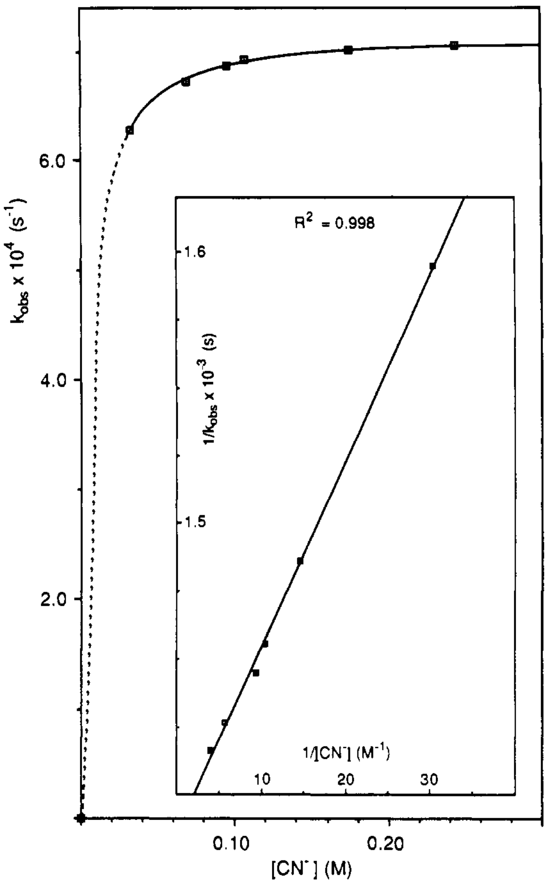
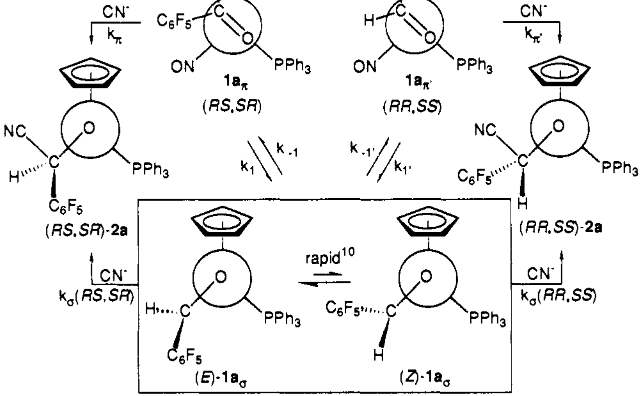


Figure 1. Plot of k_{obs} vs $[CN^-]$ and (inset) $1/k_{obs}$ vs $1/[CN^-]$ for the reaction of (*RS,SR*)-$[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(O{=}CHC_6F_5)]^+BF_4^-$ ($\mathbf{1a}_\pi$) and PPN^+CN^- in $CDCl_2F$ at −83 °C ($[CN^-] > [\mathbf{1a}_\pi]$).

Scheme I. Possible Pathways for CN^- Addition to Pentafluorobenzaldehyde Complex $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(O{=}CHC_6F_5)]^+BF_4^-$ (**1a**)



$$\frac{d[\mathbf{1a}_\pi]}{dt} = -\underbrace{\left[\frac{k_1 k_\sigma[CN^-]}{k_{-1} + k_\sigma[CN^-]} + k_\pi[CN^-]\right]}_{k_{obs}}[\mathbf{1a}_\pi]$$

$$k_\sigma = k_\sigma(RS,SR) + k_\sigma(RR,SS)$$

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in Figure 1 and the supplementary material. The cyanohydrin alkoxide complex $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(OCH(CN)C_6F_5)$ (**2a**) formed in quantitative NMR yields as 96–97:3–4 mixtures of (*RS*,*SR*)/(*RR*,*SS*) diastereomers.[8] The dominant diastereomer is consistent with (among possibilities analyzed earlier)[4,6] CN^- attack upon (1) **1a**$_\pi$ from a direction opposite to rhenium or (2) the trans σ isomer (*E*)-**1a**$_\sigma$ from a direction opposite to the bulky PPh_3 ligand (Scheme I).

Figure 1 shows that the rate of reaction of **1a**$_\pi$ depends upon $[CN^-]$ at lower $[CN^-]$ but approaches zero order in $[CN^-]$ at higher $[CN^-]$. Such behavior ("saturation kinetics") requires an intermediate[9] and is readily interpreted in the context of the model in Scheme I and the attendant expression for k_{obs}. First, any residual slope in Figure 1 at high $[CN^-]$ provides an upper bound on k_π, the rate constant for the direct reaction of **1a**$_\pi$ and CN^- to give **2a** ($<7.3 \times 10^{-5}$ M^{-1} s^{-1}). Thus, k_{obs} reduces to $k_1k_\sigma[CN^-]/(k_{-1} + k_\sigma[CN^-])$, which depending upon the relative magnitudes of k_{-1} and $k_\sigma[CN^-]$ gives either a first- or zero-order dependence upon $[CN^-]$ (low $[CN^-]$, k_σ rate determining; high $[CN^-]$, k_1 rate determining). Data can be extracted by a double reciprocal plot of $1/k_{obs}$ vs $1/[CN^-]$ (Figure 1 inset), which gives $k_1 = 7.2 \times 10^{-4}$ s^{-1} (from the intercept) and $k_{-1}/k_1k_\sigma = 6.9$ Ms (from the slope).[10] If k_1/k_{-1}, the equilibrium constant for **1a**$_\pi$ $\rightleftarrows$ **1a**$_\sigma$ is then assumed to be $<10^{-2}$, then k_σ must be >15 M^{-1} s^{-1}. Thus, the relative reactivity of **1a**$_\sigma$ and **1a**$_\pi$ toward CN^- (k_σ/k_π) is *>10^5 in CDCl$_2$F at −83 °C!*

Additional rate experiments were conducted. First, k_{obs} ($\simeq k_1$) was measured at $[CN^-] \geq 0.20$ M at −78, −83, −88, −93, and −98 °C. An Eyring plot gave $\Delta H^\ddagger_{\pi\to\sigma} = 12.3 \pm 0.3$ kcal/mol, and $\Delta S^\ddagger_{\pi\to\sigma} = 7 \pm 3$ eu. Also, rates of reaction of the *p*-(trifluoromethyl)benzaldehyde complex $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(O{=}CH\text{-}p\text{-}C_6H_4CF_3)]^+BF_4^-$ (**1b**) and PPN^+CN^- showed a similar saturation effect. Complex **1b** exists as a 91:9 mixture of diastereomers (**1b**$_\pi$, **1b**$_{\pi'}$), and a small amount of a σ isomer can be detected by UV/visible spectroscopy (<4% by IR) in CH_2Cl_2 at 26 °C.[5] Accordingly, the rate of disappearance of **1b**$_\pi$ at high $[CN^-]$ at −98 °C ($k_{obs} = 1.56 \times 10^{-3}$ s^{-1} $\simeq k_1$) was 50 times that of **1a**$_\pi$.

Rates of reaction of analogous *p*-chlorobenzaldehyde, benzaldehyde, *p*-methylbenzaldehyde, and *p*-methoxybenzaldehyde complexes (**1c,d,e,f**)[5] with PPN^+CN^- were too fast to measure at −120 °C. Thus, competition experiments were conducted with 1:10:10 molar ratios of PPN^+CN^- and pairs of aldehyde complexes. A **1b**/**1c** mixture gave a 20:80 ratio of the corresponding cyanohydrin alkoxide complexes **2b**/**2c** (CD_2Cl_2, in situ, −80 °C). Similarly, **1c**/**1d** and **1d**/**1e** yielded 35:65 mixtures of **2c**/**2d** and **2d**/**2e**. Finally, **1e**/**1f** gave a <1:99 mixture of **2e**/**2f** ($CHCl_2F$, −130 °C). Thus, the progressively more electron-releasing aryl substituents in this series of compounds *enhance* the rate of CN^- attack, in contrast to the deactivation that might have been intuitively expected. Importantly, however, the equilibrium proportions of σ isomers also increase (π/σ, CH_2Cl_2, 26 °C: **1c,d,e,f** 83:17, 84:16, 53:47, 15:85).[5a] Hence, this reactivity trend provides further support for the greater electrophilicity of σ isomers.

In summary, the preceding data constitute compelling evidence that σ isomers of **1** are more reactive toward CN^- than π isomers. We predict that this result will prove general for a variety of other nucleophiles and Lewis acids. However, Corcoran has recently examined $TiCl_4$-catalyzed Diels–Alder reactions of enones containing alkoxy groups capable of promoting π and σ chelates.[3] In contrast, he finds enones disposed toward π chelate formation to be more reactive. Finally, the σ adduct manifold in Scheme I can now be confidently assigned as the progenitor of diastereoselection. However, certain observations suggest other subtleties that must be incorporated into any comprehensive model of the reaction coordinate. Study of these secondary effects is in progress.

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Supplementary Material Available: Experimental procedures and tables of rate and characterization data (3 pages). Ordering information is given on any current masthead page.

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(8) Complexes **2a,b** were characterized by NMR (^{1}H, ^{13}C, ^{31}P) and IR spectroscopy (supplementary material). Configurational assignments were made by analogy to nine related cyanohydrin alkoxide complexes reported recently.[6]

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Accessibility to the Active Site of Methane Monooxygenase: The First Demonstration of Exogenous Ligand Binding to the Diiron Cluster

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Methane monooxygenase (MMO) catalyzes the oxidation of many hydrocarbons.[1,2] The soluble, 245 kDa methane monooxygenase hydroxylase (MMOH) component from *Methylosinus trichosporium* OB3B contains two diiron clusters believed to be the sites of dioxygen activation.[1,3] Although the structure of the diiron cluster[4] in MMOH is not known, spectroscopic[1,5,6] studies suggest that it is related to, but distinct from, the (μ-oxo)diiron clusters found in hemerythrin[4,7] and the R2-protein of ribonucleotide reductase.[4,8] Unlike MMOH, which is colorless,[1,6c]

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