

Mechanistic Insights into the Reactions of Co(III) Salens with Diazoacetates

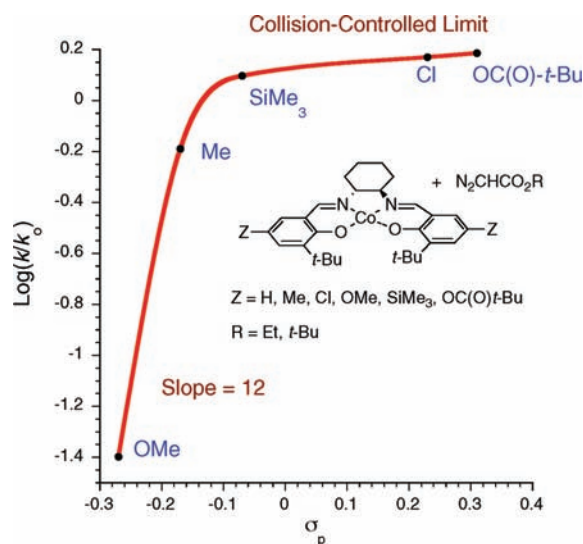
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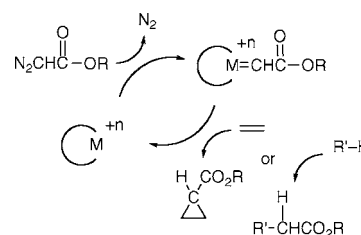
ABSTRACT



The rates and products from the gas-phase reactions of Co(III) salens with ethyl and *t*-butyl diazoacetate were examined. Addition with loss of N_2 is observed, and substituent effects as well as DFT calculations indicate that addition is rate determining. Calculations suggest that the carbene species involve novel structures with the carbenic carbon bridging between the cobalt and a salen oxygen. Collision-induced dissociation leads to an unusual, bridged metal/ketene species.

Metal carbenes derived from the reactions of diazoacetates and metal-centered catalysts are useful synthetic intermediates that can be used for C–H insertion reactions or cyclopropanations (Scheme 1).^{1–8} Despite the widespread

Scheme 1. Generic Catalytic Cycle



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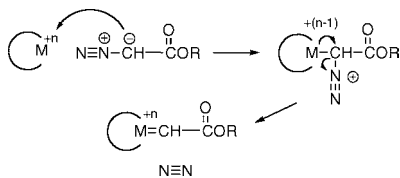
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use of these species, mechanistic information related to metal carbene formation has been limited. This is not surprising because it is difficult to isolate and characterize reaction intermediates in the carbene formation process. Here, we report a gas-phase study of the reaction of a series of substituted Co(III) salens with ethyl diazoacetate. The experimental and computational results provide insight into the rate-determining step and the unusual structures of the metal carbene species.

The mechanism of metal carbene formation from a diazoacetate involves two steps: first, addition of the α -carbon to the metal, and then expulsion of N_2 (Scheme 2). To date, there has not been a detailed mechanistic study

Scheme 2. Mechanistic Steps in Carbene Formation



of the reactions of Co(III) salens with diazoacetates,⁹ although there is substantial data on the reactions of cobalt porphyrins with diazoacetates.^{10–14}

In any case, it has not been possible to examine the rate-determining step in the formation of the cobalt carbene species or to isolate a carbene derived from a cobalt salen and examine its properties in detail. However, Hengge and Wu¹⁵ recently showed that in related dirhodium reactions with diazo esters ¹⁵N isotope effects as well as substituent effects suggest that the N_2 loss step is rate determining in the formation of the metal carbene.

Gas-phase studies offer unique opportunities in catalytic systems because in the absence of solvent and other reagents it often is possible to isolate highly reactive intermediates on the catalytic cycle and probe their properties. Examples of work by Chen,¹⁶ Plattner,¹⁷ O'Hair,¹⁸ McIndoe,¹⁹ Schwarz,²⁰ and others demonstrate the value of gas-phase

work in this respect. In the present study, electrospray ionization (ESI) in a Finnigan LCQ quadrupole ion trap mass spectrometer was used to cleanly generate cationic Co(III) salens from chloride precursors (Figure 1) dissolved in

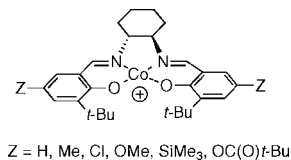


Figure 1. Cobalt salen systems.

methanol ($\sim 10^{-5}$ M).^{21,22} Our instrument has been modified by the addition of a custom gas-handling system that allows for the quantitative introduction of reagents into the helium buffer gas of the ion trap.^{23–25} The system has been employed in many studies,²⁴ and the neutral reagent pressure is calculated based on its mixing ratio with the helium buffer gas, the estimated helium pressure in the ion trap (1.75 mTorr), and a correction for differential effusion.²³ The effective temperature is approximately 300 K in the ion trap.²⁵ When diazoacetates are added to the buffer gas, they smoothly react with the Co(III) salen to give addition with the loss of N_2 , thus producing the putative cobalt carbene intermediate (Figure 2a).²⁶

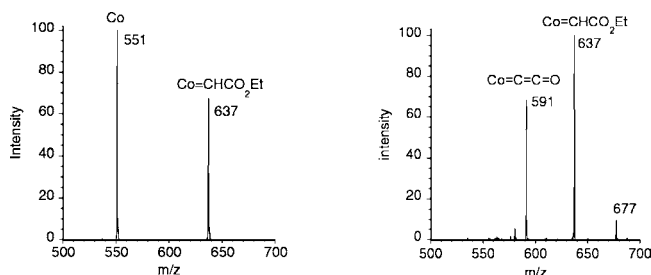


Figure 2. (a) Spectrum of reaction of ethyl diazoacetate with Co(III) salen where $Z = OCH_3$. (b) CAD spectrum of the carbene complex of Co(III) salen where $Z = OCH_3$. Peak at m/z 677 is the secondary reaction product of m/z 591 with ethyl diazoacetate (addition $-N_2$). “Co” represents the cationic cobalt salen complex.

The rates of the reaction can be determined by varying the residence time of the reactants in the ion trap. Pressures

(21) The salens were provided by Eric Jacobsen of Harvard University.

(22) Variations in solvent or ESI conditions did not appreciably affect ion production.

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(26) Decomposition of the diazoacetate is unlikely because it is vaporized at room temperature in a fast flow of helium. However, if a small amount decomposes during the introduction to the vacuum manifold, it should not affect the observed results. Given the mean free paths in the instrument system, any free carbene generated in this way is expected to be captured on the walls of the apparatus.

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of approximately 10^{-7} to 10^{-8} torr are used for the diazoacetates, which leads to pseudo first-order conditions (neutral/ion ratios of 10^4 – 10^6). Data for the reactions with ethyl

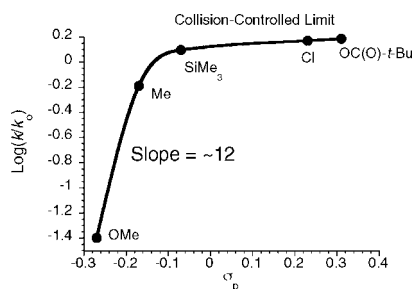


Figure 3. Hammett plot of reaction of ethyl diazoacetate with Co(III) salens. Curve added to facilitate data interpretation.

diazoacetate are presented in Figure 3 in the form of a Hammett plot. The reactions are generally fast and for substituents with a positive σ value reach the collision-controlled limit ($\sim 2 \times 10^{-9}$ cm³ molecule⁻¹ s⁻¹). This leads to a sharply curved plot with a limited linear section that can be used for estimating a ρ value of approximately 12, indicating that the reaction is very sensitive to substituents on the salen and disfavored by electron-donating groups.

This result suggests that the first step in the carbene formation process is rate determining because electron-donating groups on the ligand are expected to make the metal less susceptible to nucleophilic addition by the diazoacetate. In contrast, one would expect that electron-donating groups would enhance the back-bonding interaction involved in displacing the N₂. The fact that no addition products are observed in the reactions that are below the collision-controlled limit also supports this conclusion (every addition leads to N₂ loss). This is the opposite of the dirhodium system noted above where the second step was believed to be rate determining.¹⁵

To gain more insight into the mechanism, DFT calculations were completed at the B3LYP/6-311+G(d,p) level²⁷ with a simplified model system (diazoacetic acid reacting with the parent, underivatized Co(III) salen) in a singlet state. It is known that metal carbenes of this general type can adopt unusual structures, and bridging from the metal to a pyrrole nitrogen is known in carbenes derived from cobalt porphyrins.^{11,12,14} In the salen, a bridged structure is also preferred with the carbenic carbon bridging to the salen oxygen (Figure 4a). This is 12.4 kcal/mol more stable than nitrogen bridging and 28.2 kcal/mol better than the conventional metal carbene structure (i.e., M=C).

This is consistent with IR data that suggest a metal carbon single bond in related carbene systems.²⁸ However, we are unaware of previous reports of bridging in carbene salen systems. We have also computed the barriers on the potential energy surface. In each case, the identified transition state has a single imaginary frequency, and an intrinsic reaction coordinate (IRC) calculation indicates that it links the appropriate intermediates. A reaction

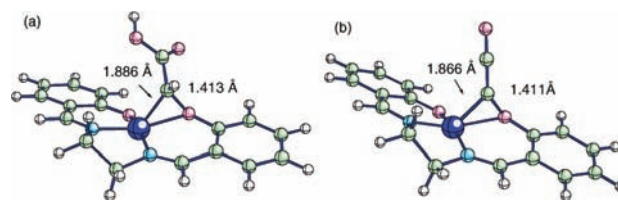


Figure 4. B3LYP/6-311+G(d,p) structures of the underivatized Co(III) salen complex with (a) carbene from diazoacetic acid and (b) C=C=O (proposed fragmentation product). Cobalt is blue; carbon is green; oxygen is red; and nitrogen is teal.

profile is given in Figure 5. As suggested by the Hammett plot, the addition transition state has the highest energy

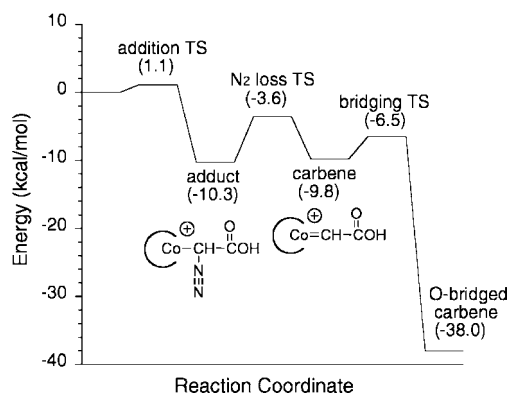


Figure 5. B3LYP/6-311+G(d,p) potential energy surface (0 K with zero-point energy corrections) for the addition of diazoacetic acid to unsubstituted Co(III) salen. Energies relative to separated reactants.

and will therefore be rate determining because we are operating in a pressure regime (~ 1 mTorr) where collisions are rare for reaction complexes, so the appropriate reference energy for the system is that of the separated reactants (i.e., intermediates are not collisionally cooled on the time scale of the reaction). The potential energy surface also indicates that bridging is a strong thermodynamic driving force. A transition state with a modest barrier separates the conventional from the bridged carbene. A concerted transition state (N₂ loss along with bridging) could not be found. A natural population analysis (NPA)²⁹ of the B3LYP wave function confirms our assumption that the addition step involves an increase in ligand electron density and should be sensitive to electron-donating groups. The computed negative charges on the salen oxygens increase from -0.60 to -0.69 , and the overall salen negative charge increases from -0.03 to

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-0.56 as a result of addition. In contrast, the N₂ loss step decreases the negative charges on the salen to -0.61 on the salen oxygens and -0.26 on the entire ligand. Finally, we have computationally investigated the effect of substituents by calculating the reaction energy for adduct formation when the salen has hydroxyl groups at the para positions (relative to the salen phenolate). With the hydroxyl substituents, the addition is favorable by only 4.9 kcal/mol, as compared to 10.3 kcal/mol in the parent system. This also supports our conclusion that electron-donating groups disfavor the addition step.

We also have examined the fragmentation behavior of the cobalt carbenes from the ethyl diazoacetate reaction. Under collision-activated dissociation conditions (CAD), loss of 46 mass units is observed (Figure 2b). This is most likely ethanol loss³⁰ and corresponds to the formation of a cobalt ketene species (Co=C=C=O), but DFT calculations indicate that

(30) The carbene derived from *t*-butyl diazoacetate gives a small loss of 74, *t*-butyl alcohol, but mainly 56, isobutene, a common neutral loss for *t*-butyl esters.

a bridged structure is more stable (Figure 4b). Again, this represents a highly unusual structure.

In summary, we have shown that cobalt salens react readily in the gas phase to give carbene species through a mechanism that involves rate-determining addition followed by N₂ expulsion. DFT calculations indicate that bridging of the carbene to an oxygen in the salen ligand is very favorable. Further studies of the reactivity of the carbene and its fragmentation products are underway.

Acknowledgment. Support from the National Science Foundation (CHE-0716147) is acknowledged. We thank Eric Jacobsen of Harvard University for generously providing the cobalt salens.

Supporting Information Available: Tables of computed structures and their energies. Full citation for ref 27. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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