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Chromium Carbene Complex Photochemistry in Organic Synthesis

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INTRODUCTION

Although the thermal reaction[1] chemistry of heteroatom-stabilized group 6 carbene complexes **1** (hereafter referred to as Fischer carbene complexes) has been studied almost since their advent over 30 years ago,[2] their photochemical reactions, particularly those of interest to synthetic organic chemists, have a much briefer history.[3] Since photochemical reactions involve excited-state chemistry, the electronic spectral characterization and electronic structures of Fischer carbene complexes are central to a consideration of this topic. The visible spectra of Fischer carbene complexes consist of three discernible absorptions; a very weak band above 500 nm, assigned as a spin-forbidden metal-to-ligand charge transfer band (MLCT); a moderately intense band between 350-450 nm assigned as a spin-allowed MLCT; and a somewhat weaker band at 300-350 nm assigned as a ligand-field (LF) transition.[4] A lower energy LF transition is usually masked by the intense MLCT, although it has been observed in the non-heteroatom stabilized carbene complex $(CO)_5W{=}CPh(p\text{-}MeOPh)$.[5]

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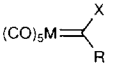
A simplified one-electron energy level diagram for the tungsten(methoxy)(phenyl)carbene complex[4,6] is shown in Figure 1. From this diagram it can be seen that the MLCT band corresponds to promotion of an electron from a non-bonding metal-centered orbital to a π^* orbital that is carbene-carbon p-orbital centered, while the LF band(s) result in population of a metal centered dx^2-y^2 orbital (or the dz^2-σ-Csp^2 σ^* orbital). As expected from the visible spectra, Fischer carbene complexes are highly colored, ranging from yellow to orange to red. Strongly donating heteroatom substituents on the carbene carbon (eg. N vs. O) cause a blue shift in the spectrum, while π-accepting carbon substituents (eg. Ph- or PhCHCH- vs. Me) result in a red shift.



1

M = Cr, Mo, W
X = OR', NR_2', SR', etc.

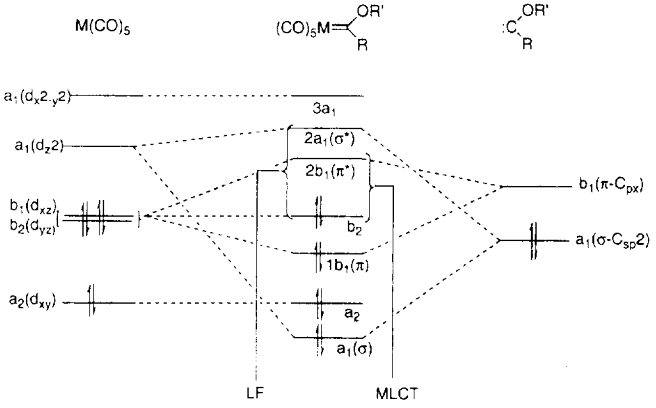


Figure 1

A number of photochemical studies of Fischer carbene complexes have been carried out.[4,5,7,8] Most of these have centered on the effects of irradiation into the LF bands, for which photoejection of a metal-bound CO has been universally observed. The MLCT states of these complexes have been reported to be not appreciably photosensitive, with any reactivity observed being attributed to the low-energy LF band overlapping with the MLCT band.[4] The results of a solution-phase time-resolved resonance Raman flash-photolysis study of $(CO)_5W{=}C(OMe)Me$ with irradiation into the MLCT band (405 nm) were interpreted as involving the generation of a transient species (microseconds) in which the site vacated by photoejection of CO was "blocked" in some manner.[7] This transient species decayed back to the starting complex by recapture of CO (Figure 2). In contrast, the results of a matrix photolysis study with irradiation into the MLCT band of the corresponding chromium complex were interpreted as involving the reversible isomerization of the OMe group from the more stable syn isomer to the less stable anti isomer (Figure 2). (There is a ≈12 kcal/mol barrier to rotation about the carbene carbon-oxygen bond.) Neither of these processes would appear to be useful for organic synthesis.

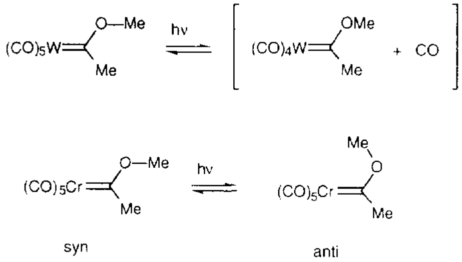
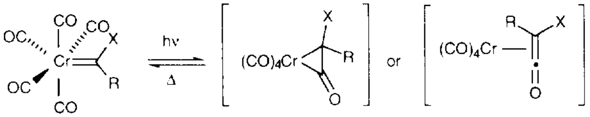


Figure 2

In spite of this, Michael McGuire, then a graduate student in the author's research group, discovered that irradiation of chromium and molybdenum (but not tungsten) Fischer carbene complexes into the MLCT band resulted in the transient generation of a species which had ketene-like reactivity.[9] Subsequent studies[10] led to the suggestion that irradiation into the MLCT band of chromium carbene complexes actually promoted the reversible insertion of one of the four *cis*-CO groups into the metal carbon double bond to generate a short lived metallacyclopropanone/metal-bound ketene, which in the presence of substrates reactive with ketenes was consumed, but in the absence of reactive substrates, thermally deinserted CO to regenerate the carbene complex (Eq. 1). Since the MLCT transition corresponds to a one-electron oxidation of the metal [promotion of an electron from a metal d-centered HOMO to a π^*-carbene-carbon centered LUMO (see Figure 1)], and since oxidation is known to drive insertion of CO into metal-carbon bonds,[11] this is reasonable.


(Eq. 1)

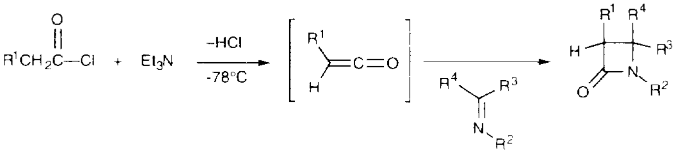
A number of stable group 6 metal-ketene complexes have been characterized,[12] and photochemically driven insertion of carbon monoxide into a tungsten-carbon triple bond is well-documented,[13] affording some precedent for the process expressed in Eq. 1. Indeed, photolysis of a wide range of heteroatom-stabilized chromium carbene complexes into the MLCT (visible light, Pyrex) in the presence of substrates that normally undergo reactions with ketenes results in the transfer of a ketene fragment from the metal to the substrate. Because chromium carbene complexes with a variety of heteroatom groups – OR, NH_2, NHR, NR_2, SR, PR_2 – as well as highly functionalized organic side chains are readily synthesized and easily handled, this visible photolysis process makes a wide array of unusual, electron-rich, functionalized ketenes potentially readily accessible for use in organic synthesis. Further, this ketene moiety appears to remain coordinated to the metal until freed by reaction with the substrate, and free ketene or self reaction products thereof, are not detected. Synthetic applications of this process are the topic of this report.

Two types of chromium carbene complexes fail to undergo this photochemical ketene-generating reaction. Those having *two* heteroatoms on the carbene carbon [e.g., $(CO)_5Cr{=}C(OMe)_2$, $(CO)_5Cr{=}C(OMe)(NR_2)$] are almost colorless and are inert to visible photolysis, being recovered unchanged after one week of exposure. However, they decompose when subjected to ultraviolet radiation. Complexes having good π-acceptor groups on the carbene carbon (e.g., PhCH=CH-, PhC≡C-) are a deep, intense red, and also fail to undergo photochemical reactions when subjected to visible light. Finally, all tungsten carbene complexes studied to date, regardless of their substitution patterns or UV-visible spectra, are photochemically unreactive. The reason for this is not known.

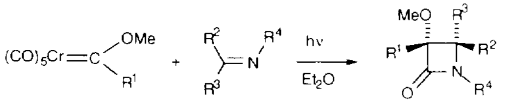
REACTIONS[14]

1. *Cycloaddition Reactions*

a. With Imines to Give β-Lactams. A classic approch to the biologically important β-lactams is the reaction of ketenes, usually generated from treatment of acid chlorides with triethylamine at low temperature, with imines, in what is thought to be a stepwise 2+2 cycloaddition (Eq. 2).[15,16] Because ketenes are highly reactive, and by necessity are generated in the absence of the imine, this reaction is sometimes inefficient, producing by-products from ketene self-reactions and multiple ketene incorporation. As anticipated from Eq. 1, photolysis of chromium alkoxycarbene complexes in the presence of a wide range of imines also produced β-lactams, in good to excellent yield, and free of by-products (Eq. 3).[17-19] The process was highly diastereoselective, usually producing a single diastereoisomer, and was not restricted to simple imines. A variety of heterocyclic imines also produced structurally more complex β-lactams efficiently (Eq. 3). A particularly interesting case is the reaction of N-protected imidazolines with chromium alkoxycarbene complexes (Eq. 4).[20-22] After deprotection, azapenams, a new class of β-lactam, were produced. When bis-carbene complexes were used, bis-azapenams were produced (Eq. 5).[23] Surprisingly, imidazolines failed to produce β-lactams when exposed to ketenes generated from acid chlorides and triethylamine. Rather, complex mixtures of uncyclized material, and material having multiple ketene-derived units were obtained. This is one of several systems for which chromium carbene photochemistry and classical ketene chemistry differ and are complementary.

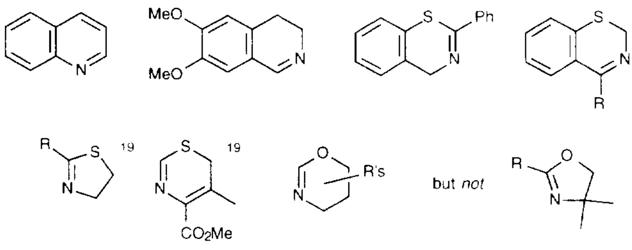


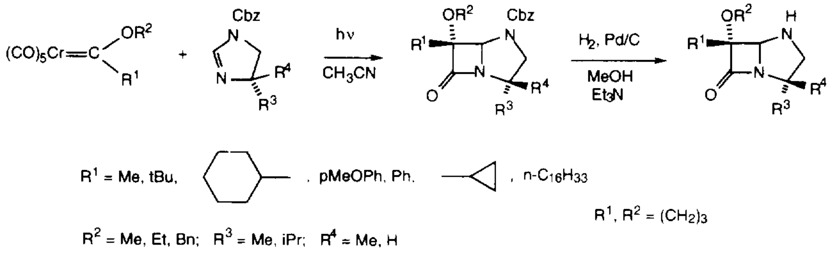
(Eq. 2)



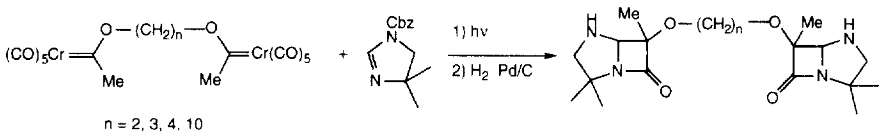
(Eq. 3)

R^1 = Me, Ph; R^2 = H, Ph, Me; R^3 = Me, Ph, pMeOPh, H, Bn, $CH_2P(O)(OEt)_2$,[19] $CH(CO_2Me)P(O)(OEt)_2$,[19], $CH{=}CH_2$,[19] PhCO,[19] also





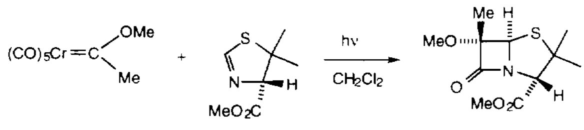
(Eq. 4)



(Eq. 5)

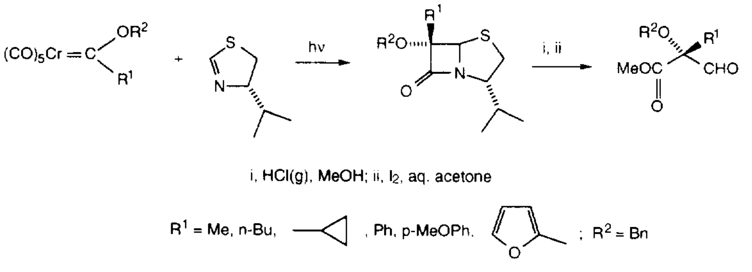
(1:1 mix of diastereoisomers)

Attempts to induce asymmetry into the reaction of chromium alkoxycarbene complexes with imines met with mixed results. In most cases, chiral auxilliaries on the nitrogen of the imine were ineffective, resulting in low to moderate diastereoselectivity.[18] Exceptions to this were with rigid, cyclic imines such as thiazolines (Eq. 6)[18] and imidazolines,[20] for which very high (essentially 100%) de's were observed. Although these particular β-lactams were not of biological interest, they provided chiral templates for the synthesis of highly functionalized quaternary systems (Eq. 7).[24]



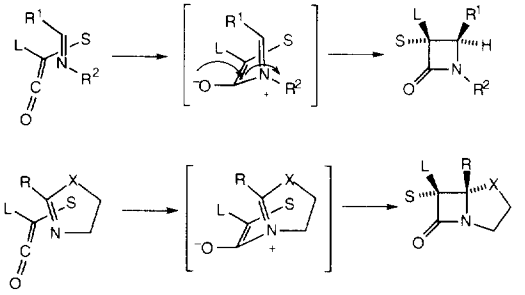
(Eq. 6)

(1 diast.)

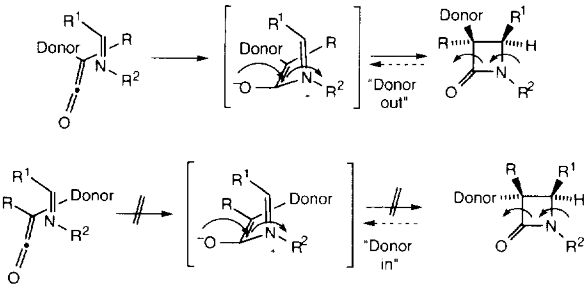


(Eq. 7)

The mechanism of the classic ketene-imine reaction to form β-lactams[15b,16] is thought to involve perpendicular attack of the imine nitrogen on the ketene carbonyl carbon from the side of the sterically smaller of the two groups, followed by conrotatory closure of the zwitterionic intermediate (Eq. 8). This places the large substituent of the ketene *cis* to the anti-substituent of the imine. In *all* the cases cited above, the observed stereochemistry was exactly opposite that expected on these steric grounds. Initially, this difference was thought to be due to the presence of the metal during the cycloadditions, biasing the process to produce the contrasteric product. However, subsequent considerations,[25] supported by theoretical calculations relating the closure step of β-lactam formation to the electronic bias observed ("torquoselectivity") in the ring opening of cyclobutenes bearing heteroatom substituents,[26] suggested that the observed stereoselectivity was rather due to the presence of the donor methoxy group on the ketene, which greatly lowers the energy for closure of the zwitterion resulting from attack over the large R group, from the face opposite the donor groups, leading to the contrasteric product (Eq. 9).

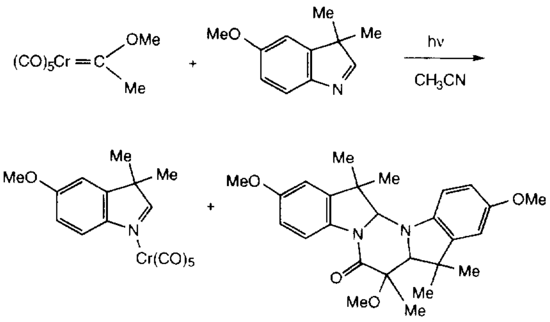


(Eq. 8)



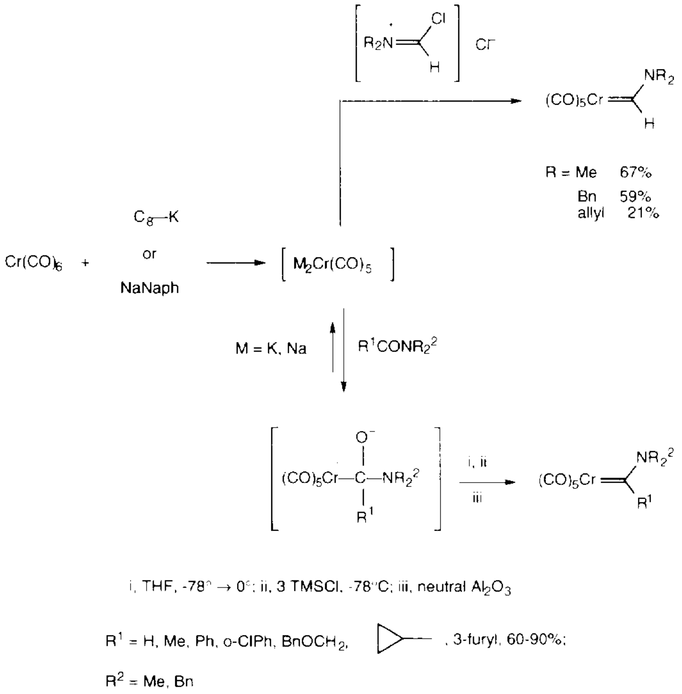
(Eq. 9)

Not all imines successfully react with chromium alkoxycarbene complexes, as evidenced by the example in Eq. 10.[27] However, these cases are rare.



(Eq. 10)

In contrast to the β-lactams presented above, most biologically active β-lactams do not have an alkyl and an alkoxy group α to the lactam carbonyl group, but rather they have an amino group and a hydrogen. The requisite aminocarbene complexes[28] were readily prepared by the reaction of $M_2Cr(CO)_5$ with iminium chlorides[29] or with amides with addition of trimethylsilyl chloride[30] (Eq. 11). Complexes derived from formamides (R^1 = H) underwent efficient photoreaction with a wide range of imines to produce α-amino β-lactams in good to excellent yields and, as is usual, with high diastereoselectivity (Eq. 12). In contrast, complexes for which R^1 was alkyl or aryl formed β-lactams in only low yields. An intramolecular version resulted in production of the unusual "anti-Bredt" amide rather than the expected β-lactam (Eq. 13).[32]



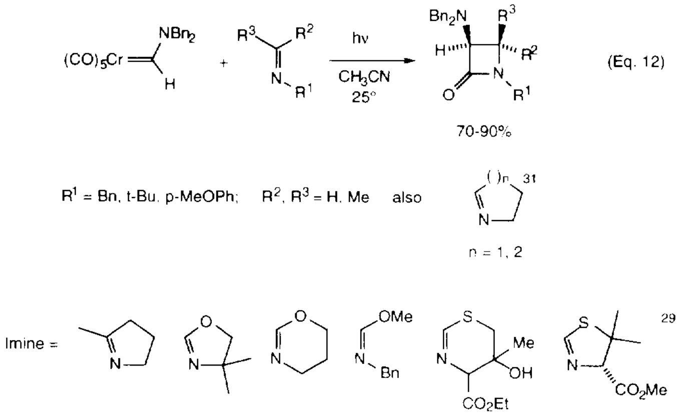
(Eq. 11)

i, THF, -78° → 0°; ii, 3 TMSCl, -78°C; iii, neutral Al_2O_3

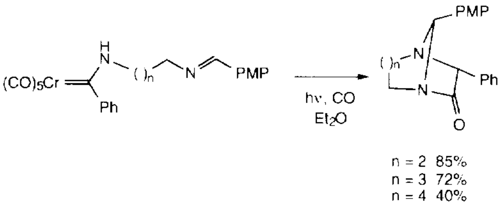
R^1 = H, Me, Ph, o-ClPh, $BnOCH_2$, , 3-furyl, 60-90%;

R^2 = Me, Bn

Most biologically active β-lactams are also optically active, and chromium carbene complex photochemistry also offers approaches to these important classes of compounds in high yield and with high diastereoselectivity (Eq. 14).[33] The high stereoselectivity in the reaction with oxazoles was put to use in an efficient synthesis of α-alkyl α-aminoacids (Eq. 15).[37] This chromium-derived ketene bearing an oxazolidine chiral auxilliary is closely related to an acid chloride-derived ketene bearing an *oxazolidinone* chiral auxilliary. Despite this close relationship, the reactivity of these two species was dramatically different and complementary.[38] The oxazolidine ketene (Eq. 14) gave excellent chemical yields of single diastereoisomers of β-lactams with imidates, oxazines, thiazines and cyclic and acyclic aliphatic imines, but only modest yields of mixtures of *cis* and *trans*

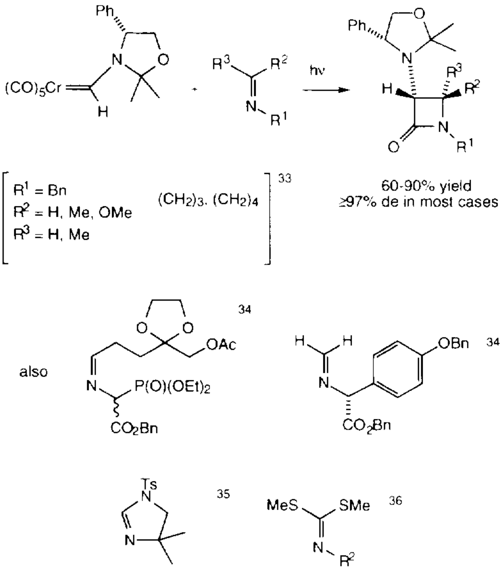


(Eq. 12)

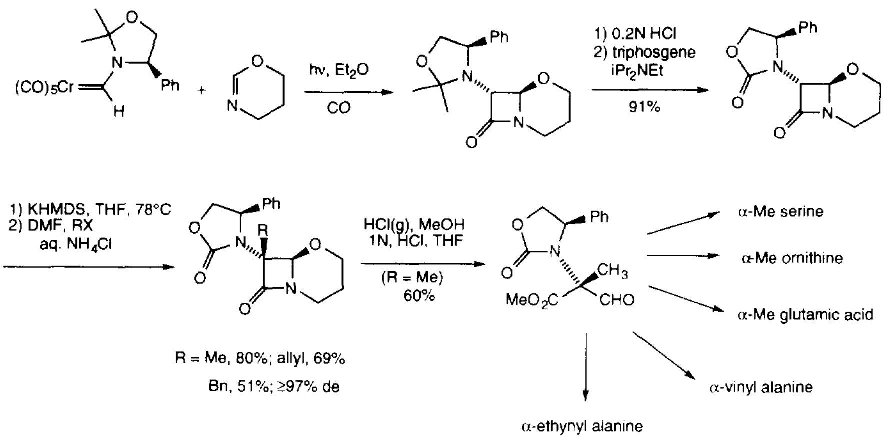


(Eq. 13)

diastereoisomers of β-lactams with imines of benzaldehyde and cinnamaldehyde. In contrast, the oxazolidinone ketene gave excellent chemical yields of single *cis* diastereoisomers of β-lactams with imines of benzaldehyde and cinnamaldehyde, but very low yields of β-lactams with other imines.



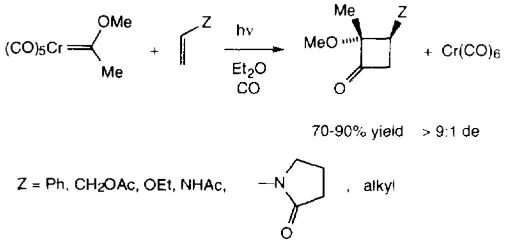
(Eq. 14)



(Eq. 15)

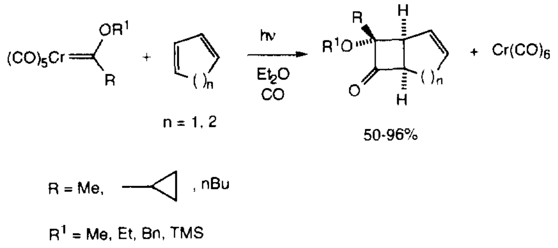
β-Lactams were also produced from pyrrolocarbene complexes, although in modest yield,[39] while O-acylimidatocarbene complexes underwent photochemical reaction with imines to give a host of different compounds, with β-lactams being minor components.[40]

b. With Olefins to Give Cyclobutanones. Ketenes undergo highly stereoselective [2+2] cycloadditions to electron-rich olefins to give cyclobutanones,[14] highly reactive substrates of use in organic synthesis.[41] Both inter- and intramolecular versions are efficient, and a wide range of systems have been studied.[42] Similarly, photolysis of chromium alkoxycarbene complexes in the presence of electron-rich alkenes produced cyclobutanones efficiently and with high diastereoselectivity.[43] The intermolecular reaction was efficient with a wide range of electron-rich olefins (Eq. 16) and dienes (Eq. 17), and the intramolecular version proceeded in high yield as well (Eq. 18).[44] Even carbon-tethered systems underwent efficient intramolecular cycloaddition, making strained [2.1.1] bicyclic systems (Eq. 19).[45] When fused to a cyclopropyl system, a thermally allowed [(π2s + π2s) + σ2s] rearrangement occurred (Eq. 20).[45]

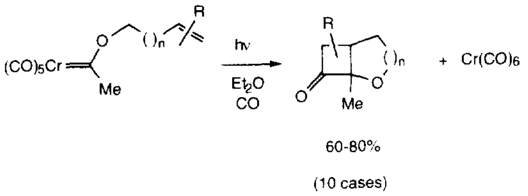


(Eq. 16)

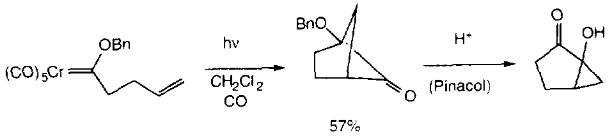
A comparison of the [2+2] reaction of ketenes derived from acid chlorides, and the same ketenes derived from photolysis of the corresponding chromium carbene complex, with alkenes showed identical stereochemical behavior, but better yields for the chromium-derived ketenes



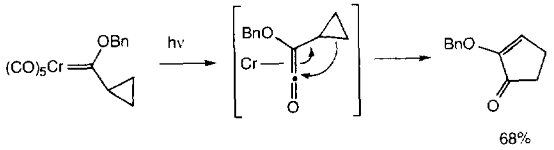
(Eq. 17)



(Eq. 18)



(Eq. 19)

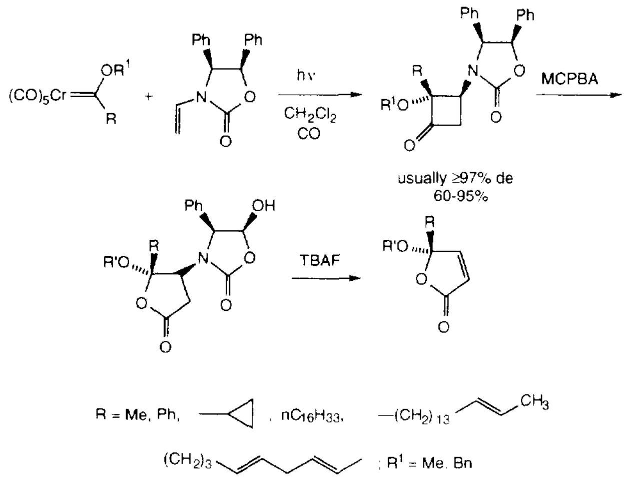


(Eq. 20)

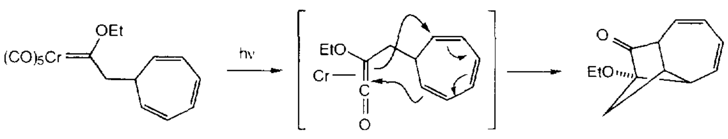
because the reaction conditions were milder. In addition, chromium thiocarbene complexes also underwent this cycloaddition reaction efficiently.[46]

With optically active ene carbamates[47] as substrates, optically active cyclobutanones were produced in good yield, and with high diastereoselectivity (Eq. 21).[48] These underwent efficient Baeyer-Villiger oxidation to the lactone with complete retention of stereochemistry of the migrating center, and efficient elimination of the oxazolidinone to give optically active butenolides (Eq. 22).[49] These were valuable intermediates in the synthesis of (+)-tetrahydrocerulenin,[49] (+)-cerulenin,[50] as well as a wide variety of more highly functionalized lactones.[51]

(Cycloheptatrienylmethyl)(ethoxy) carbene complexes underwent a related [6+2] cycloaddition when photolyzed (Eq. 22).[52]

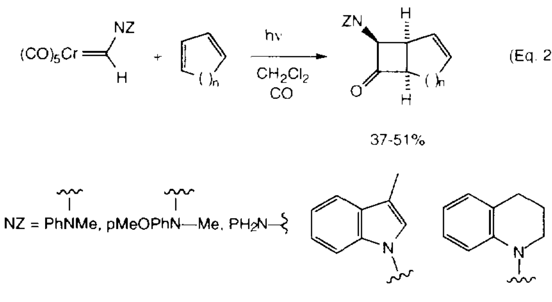


(Eq. 21)



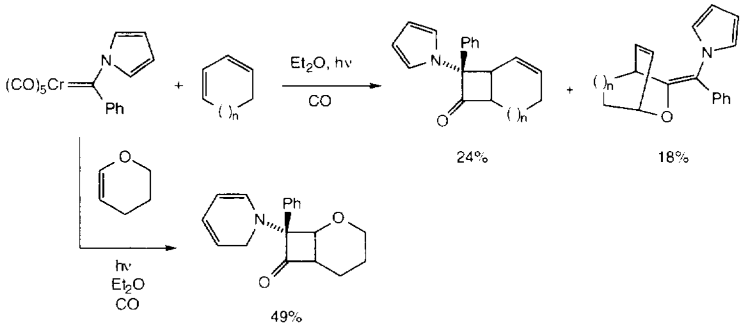
(Eq. 22)

In contrast to alkoxycarbene complexes, which underwent photochemical [2+2] cycloaddition with olefins with facility, N-alkylaminocarbene complexes failed to react at all. It was reasoned that the aminoketenes thus generated were too electron-rich to undergo the requisite nucleophilic attack by the alkene, since the sp carbon of the aminoketene has enamine character. Replacement of the N-alkyl group by an N-aryl group substantially reduces the basicity of amines ($\approx 10^6$) and consequently increases the electrophilicity of aminoketenes, allowing them to form cyclobutanones, although the yields were only modest (Eq. 23).[53]



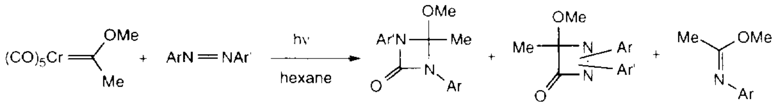
(Eq. 23)

Pyrrolocarbene complexes were also considered as sources of electron-poor aminoketenes, since the nitrogen lone pair is delocalized into the aromatic system. Photolysis of these complexes in the presence of electron-rich olefins produced cyclobutanones, as expected. Surprisingly, dienes underwent a [4+2] cycloaddition across the *carbonyl group* of the ketene, in addition to the normal [2+2] process (Eq. 24).[39] This is unusual but not unprecedented behavior for ketenes.



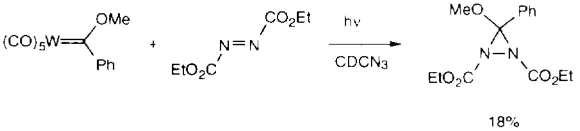
(Eq. 24)

c. With Azoarenes. Photolysis of chromium alkoxycarbene complexes with azoarenes produced 1,3- and 1,2-diazetidinones along with imidates from formal metathesis of the azoarene (Eq. 25).[54] This is a mechanistically complex reaction,[55] of little synthetic value because of the inability to control the product distribution. The elegant mechanistic work of McElwee-White[56] revealed that the primary photoprocess is *trans*-to-*cis* isomerization of the azoarene, followed by *thermal* reaction of the *cis* azoarene (which can be independantly prepared) with the carbene complex. Apparently, only the 1,2-diazetidinone is a primary photoproduct of this reaction. Photolysis of tungsten alkoxycarbene complexes with diethyl diazodicarboxylate gave three-membered rings (Eq. 26),[57] although in low yield.



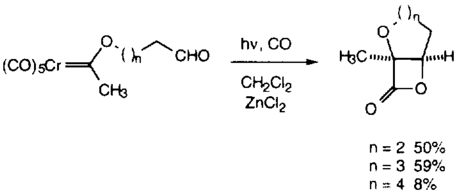
(Eq. 25)

Ar = Ar' = Ph	16%	16%	31%
Ar = Ph, Ar' = p-MeOPh	45%	0%	25%
Ar = Ph, Ar' = p-Me$_2$NPh	29%	0%	45%



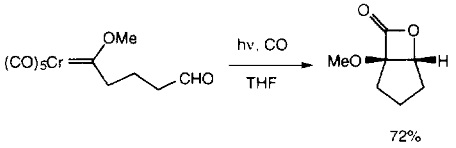
(Eq. 26)

d. With Aldehydes to Produce β-Lactones. Ketones and aldehydes undergo reaction with ketenes in the presence of Lewis acids to produce β-lactones.[58] Although the intermolecular reaction between chromium alkoxycarbene complexes and aldehydes did produce β-lactones, the yields were low, mainly because of the long reaction times required and the relative instability of the product β-lactones to long term exposure to Lewis acids. However, the intramolecular version was more efficient and could be used to make bicyclic β-lactones in reasonable yield (Eq. 27).[59]

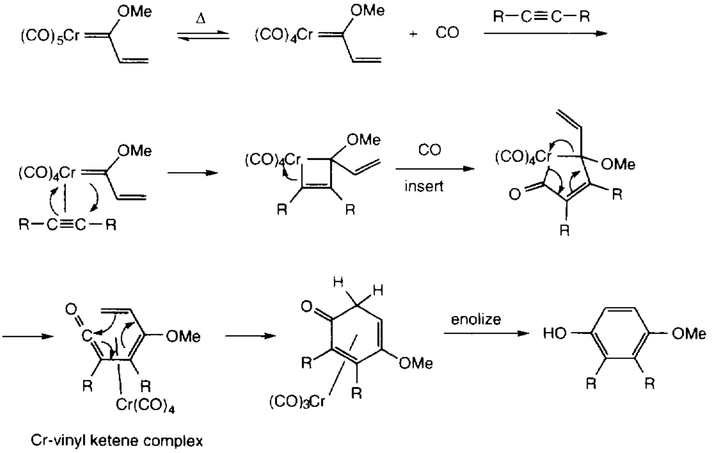


(Eq. 27)

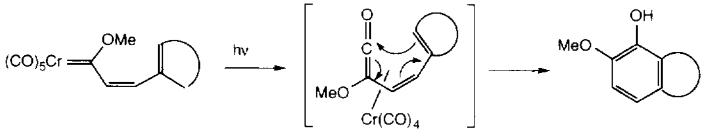
and



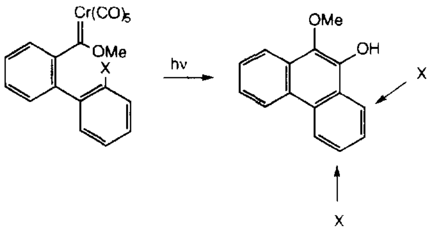
e. Photochemical Benzannulation Reactions.[1] Perhaps the most synthetically used *thermal* reaction of Group 6 metal carbene complexes is the Dötz benzannulation reaction, which results from the reaction of an alkyne with a carbene complex, and is thought to proceed through a vinyl ketene intermediate (Eq. 28).[60] The realization that CO insertion into metal-carbon double bonds could be photochemically driven,[10] led to a useful and general photochemical variant of the Dötz reaction utilizing diene carbene complexes, allowing the facile synthesis of a range of substituted aromatics (Eqs. 29 and 30).[61,62] N-Acylaminocarbenes also underwent this reaction making amine-substituted arenes available (Eq. 31).[61b] The same types of arenes were available from the thermal reaction of isonitriles with diene-carbene complexes.[63]



(Eq. 28)

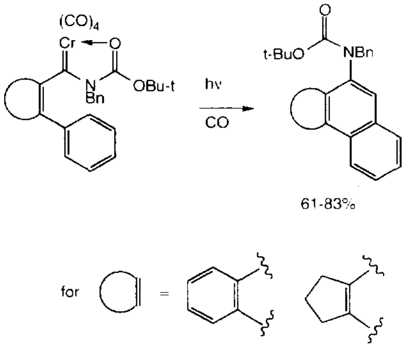


(Eq. 29)



(Eq. 30)

X = OH, Me, CHO, CH(OMe)2, F, OMe, Cl, CF3

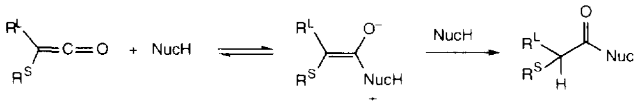


(Eq. 31)

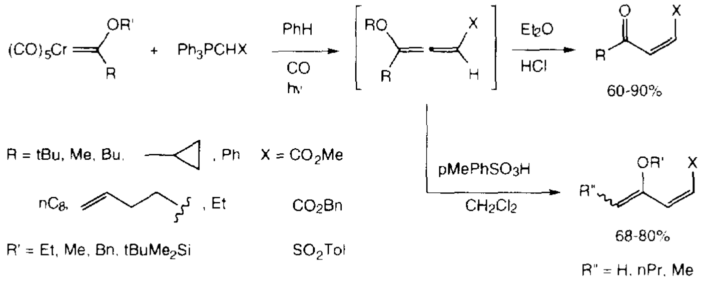
Although not in Group 6, manganese carbene complexes also underwent both inter-[64] and intramolecular[65] photochemical benzannulations with alkynes.

2. *Nucleophilic Additions*

a. With Ylides to Form Captodative Allenes. Ketenes undergo reaction with a wide range of nucleophiles in a mechanistically complex[14,66] process involving nucleophilic attack at the carbonyl (sp) carbon in the plane of the subsituents and from the less-hindered side of the ketene, followed by a slow, bimolecular protonation (Eq. 32). Photolysis of chromium carbene complexes in the presence of a variety of nucleophiles also resulted in products derived from nucleophilic attack on the photogenerated-ketene complex. With stabilized ylides as the nucleophile, captodative allenes - those having a donor on one end and an acceptor on the other - were formed. These were not very stable, and readily underwent acid-catalyzed hydrolysis or rearrangement (Eq. 33).[66]



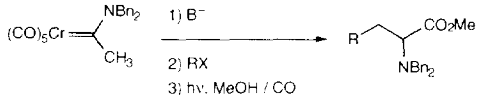
(Eq. 32)



(Eq. 33)

b. Formation of Amino Acids and Peptides.[67] The synthesis of "unnatural" amino acids, and their incorporation into peptides, to change the biological and physical properties thereof, has been the object of substantial research efforts recently, and many new approaches to this important class of compounds have been developed. Chromium carbene photochemistry offers an unusual route to amino acids, as well as a method to introduce unusual amino acid residues directly into peptides, that is complementary to many standard methods.

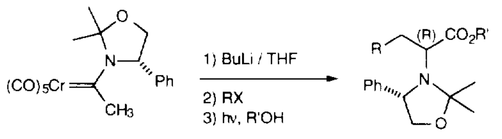
Chromium aminocarbene complexes were readily synthesized from amides and $Cr(CO)_5^{=}$ (Eq. 11). Their α-protons are acidic and α-alkylation with a range of electrophiles is facile. Photolysis of these complexes in the presence of alcohols as nucleophiles produced α-amino acid esters in good yield, presumably via the aminoketene (Eq. 34).[68] However, racemic amino acids are of little synthetic interest. To induce asymmetry into this process, the optically active oxazolidine chiral auxilliary used in β-lactam synthesis (Eqs. 14 and 15) and derived from phenyl glycine, again proved effective (Eq. 35).[68] Since both enantiomers of phenyl glycine are readily available and of comparable cost, either the natural (S) or unnatural (R) amino acid esters were available by this procedure. By using the chiral carbene complex from the N-formyl oxazolidine (as in Eq. 13) with deuterated alcohols as the nucleophile, optically active glycine ($[2\text{-}^2H_1]$ glycine) was synthesized.[69] By starting with $Cr(^{13}CO)_6$, easily produced by ligand exchange of $Cr(CO)_6$ with ^{13}CO, 1,2-bis-^{13}C-2-^2H-labelled optically active amino acid esters were synthesized in good yield.[70] This is one of the more direct ways to introduce isotopic labels into amino acids and peptides.



(Eq. 34)

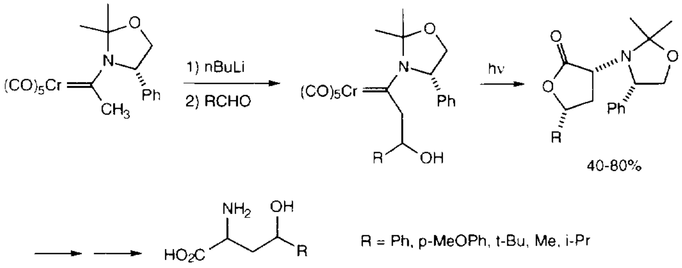
R = n-Bu, 48%; Bn, 72%; allyl, 72%;
p-MeOPhCH$_2$, 73%; EtO$_2$CCH$_2$, 66%

Chromium aminocarbene complexes also underwent α-alkylation with aldehydes to produce β-hydroxy aminocarbene complexes, wherein the pendant OH group could intramolecularly trap photogenerated amino ketenes. This provided a moderately efficient stereoselective route to α-amino butyrolactones, and ultimately homoserines (Eq. 36).[71]



(Eq. 35)

R = $PhCH_2$, R' = t-Bu,
42% yield, ≥93% de
R = $t\text{-}BuO_2CCH_2$, R' = Me
52% yield, ≥93% de



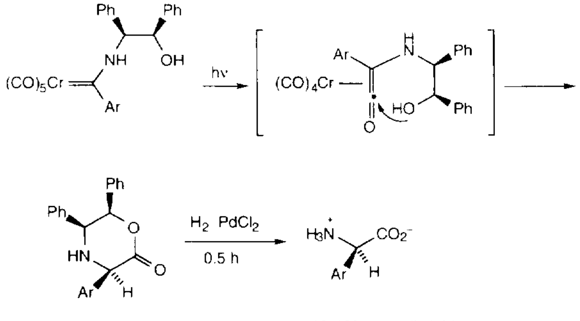
(Eq. 36)

40-80%

R = Ph, p-MeOPh, t-Bu, Me, i-Pr

60-80%

Aryl glycines were not directly available by the route shown in Eq. 35, since the corresponding arylcarbene complexes could not be synthesized. An alternative route involving intramolecular trapping of the ketene by an appended chiral alcohol provided an effective approach to a variety of these important amino acids (Eq. 37).[72] Again, the absolute configuration of the aryl glycine produced was determined by the absolute configuration of the amino alcohol, both enantiomers of which are commercially available.

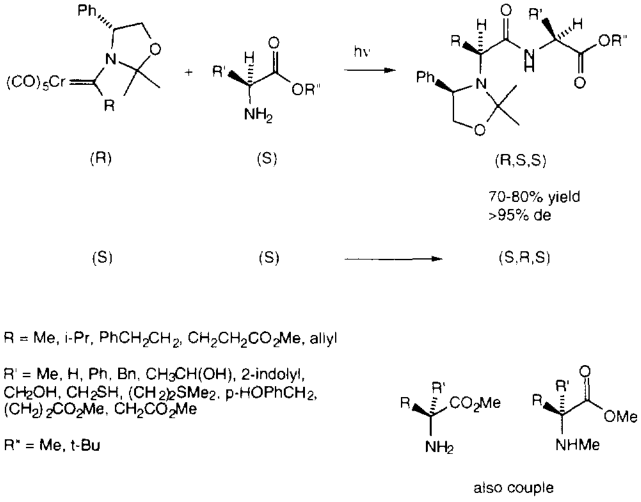


(Eq. 37)

Ar = Ph, p-MeOPh, p-ClPh, p-FPh,
$p\text{-}CF_3Ph$, o-MeOPh, 2,6-F_2Ph,
1-Naphth

10-40% overall yield
of optically pure material
from $Cr(CO)_6$ + ArLi or
$Cr(CO)_5^{=}$ + ArCOCl

The main interest in synthesizing unusual amino acids is to incorporate them into peptides. Chromium carbene photochemistry provides a direct way to do this, by simply using the amino group of an α-amino acid ester as the nucleophile (Eq. 38).[73] This process was unique in that the peptide bond and the stereogenic center on the newly introduced α-amino acid residue were created in the same step. The process was efficient with a wide range of side-chain functionalized (e.g. serine, tyrosine, tryptophan) amino acid esters without requiring protection of these nucleophilic groups. Even sterically hindered α,α-dialkyl- and N-alkyl-α,α-dialkyl amino acid esters coupled in good yield,[74] since the electrophile in the reaction was the very unhindered carbonyl (sp) carbon of the ketene. By this procedure amino acid residues having "unnatural" side chains, "unnatural" configurations (R), and/or isotopic labels, could be effectively introduced into peptides. Di-, tri- and tetrapeptides having N-terminal NH_2 groups also trapped these photogenerated amino ketenes efficiently, allowing the introduction of chromium carbene complex-derived amino acid residues into polypeptides as well. Even Merrifield resin-supported peptides[75] and peptides supported on soluble poly(ethylene glycol) (PEG) polymers[76] underwent this photo-coupling efficiently, making this reaction chemistry potentially suitable for combinatorial chemistry applications. This method is *not* suitable for *iterative* introduction of several amino acid residues into supported peptides since it is not 100% diastereoselective (de's range from 80-96%) and the minor diastereoisomer cannot be separated from the major since both remain attached to the support.



$R = Me, i\text{-}Pr, PhCH_2CH_2, CH_2CH_2CO_2Me$, allyl

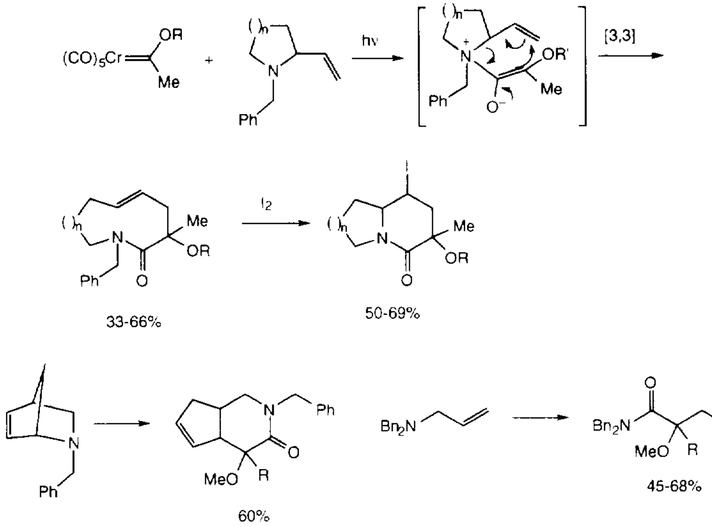
$R' = Me, H, Ph, Bn, CH_3CH(OH)$, 2-indolyl, $CH_2OH, CH_2SH, (CH_2)_2SMe_2, p\text{-}HOPhCH_2, (CH_2)_2CO_2Me, CH_2CO_2Me$

$R'' = Me, t\text{-}Bu$

(Eq. 38)

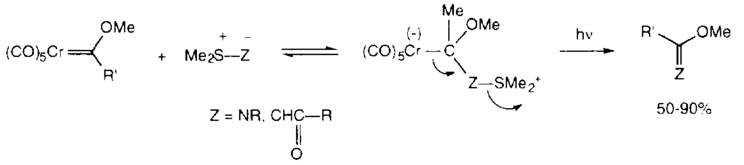
3. *Miscellaneous Reactions*

Tertiary allylic amines undergo reaction with ketenes to form zwitterionic intermediates which undergo a facile [3,3]-sigmatropic rearrangement in the presence of Lewis acids to ultimately form amides.[77] Photolysis of chromium alkoxycarbene complexes in the presence of these substrates resulted in similar chemistry (Eq. 39).[78] Cyclic and acyclic amines underwent this reaction fairly efficiently, and the resulting cyclic unsaturated amides underwent halolactamization.

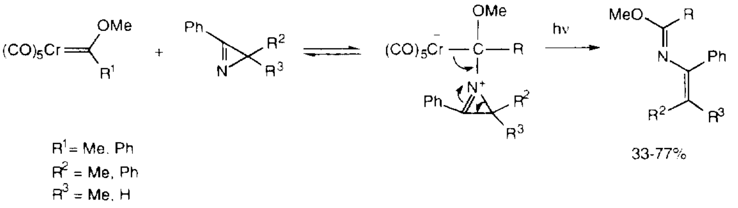


(Eq. 39)

Sulfilimines underwent reaction with chromium carbene complexes to give imidates,[79] while stabilized sulfur ylides produced β-alkoxyenones (Eq. 40)[80] in reactions which required photolysis but did *not* involve insertion of CO or reaction out of the ketene manifold. Similarly, azirines underwent reactions to give N-vinyl imidates (Eq. 41)[81]



(Eq. 40)



(Eq. 41)

CONCLUSIONS

Despite early photochemical studies which suggested that irradiation into the MLCT band of Fischer carbene complexes resulted in no useful reactions, further studies have shown that this area of photochemistry is very rich in its potential for synthetically useful reactions. It permits the production of a wide range of short-lived complexes of electron-rich ketenes which undergo all of the reactions for which classically generated free ketenes are famous, and often enjoys greater selectivity and tolerance for the presence of functionality.

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Biographical Sketch

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Lou Hegedus was born in 1943 in Cleveland, Ohio, but grew up in rural Ohio, away from big city temptations. He did his undergraduate studies at Pennsylvania State University, where he studied aqueous chromium redox chemistry with Professor Albert Haim. After PhD studies at Harvard on nickel carbonyl chemistry with E.J. Corey (1970) and a postdoctoral year at Stanford with J.P. Collman studying polymer supported homogeneous catalysis, he moved to Colorado State University, where he remains today as Professor of Chemistry. His research interests center on the use of transition metals in organic synthesis.