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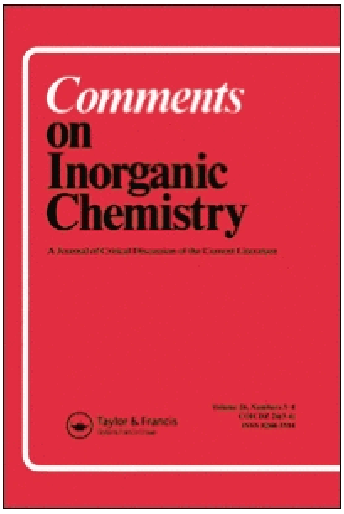

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Reactions of Cyclopropylcarbene-Chromium Complexes

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Reactions of Cyclopropylcarbene-Chromium Complexes

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The reactions of Fischer-carbene complexes containing a cyclopropane ring as one of the carbene substituents have been examined. Reaction of these complexes with alkynes leads to cyclopentenone derivatives in good–excellent yields. The reaction proceeds through a cyclopentadienone intermediate, which is reduced to the corresponding cyclopentenone derivative by chromium (0) and water. The cyclopropane ring opens at a relatively late stage of the reaction with alkynes, and does not occur until after insertion of the alkyne. Cyclopropylcarbene complexes having an alkenyl substituent at the 2-position of the cyclopropane ring undergo facile ring expansion reactions. The cyclopropane ring-opening steps of these reactions resemble classical pericyclic organic reactions, and thus the reactivity of these systems has been attributed to orbital symmetry considerations.

Key Words: *cyclopropane, cyclopropylcarbene-metal complexes, alkynes, cycloaddition, cyclopentenones, cyclopentadienones, Cope rearrangement, divinylcyclopropane rearrangement, vinylcyclopropane rearrangement, orbital symmetry*

INTRODUCTION

Metal-carbene complexes were first discovered in 1964,[1] and since that time exploration into the reactivity of these complexes has

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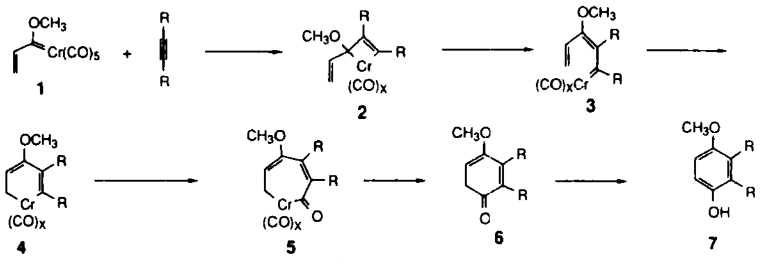
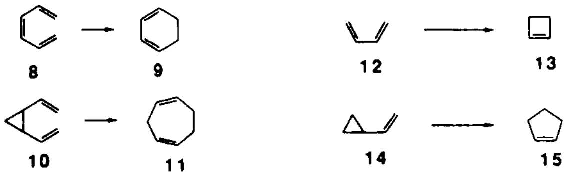


SCHEME 1

been a highly active area of research. Metal-carbene complexes are key intermediates in the industrially important olefin-metathesis reaction,[2] and are also very important compounds for synthetic organic chemistry. The more useful transformations accomplished by these complexes include the conversion of alkenes to cyclopropanes,[3] the conversion of carbonyl compounds to alkenes,[4] and novel constructions of highly substituted aromatic rings from alkynes.[5] In addition, metal-carbene complexes have been implicated in various biological processes such as cytochrome reductions/oxidations[6] and vitamin B_{12}-induced processes,[7] and in iron-catalyzed hydrocarbon oxidations.[8]

One of the most intensely studied reactions of metal-carbene complexes is the coupling of α,β-unsaturated carbene-chromium complexes with alkynes. It has been reported that cyclobutenones,[9] aromatic rings,[5] cyclopentenones and/or indenes,[10] vinylketenes,[11] and furans[1b,c] have resulted from these reactions, and aromatic rings are the most commonly observed products (Scheme 1). The mechanism suggested for the formation of aromatic rings is outlined in Scheme 1.[5] Although there is little direct evidence for this mechanism it is supported by the fact that all types of the above products can form from intermediates along this reaction pathway. In addition, all of these processes do have some precedent in other organotransition metal systems. Many of the conversions suggested bear a remarkable resemblance to classical pericyclic organic reactions.

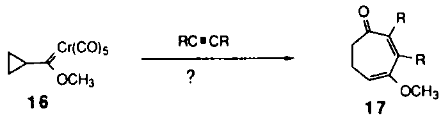
The aromatic ring-forming reaction requires the presence of an alkene (or aromatic ring) as one of the carbene substituents. In many organic transformations, the reactivity of an alkene can often be emulated by a cyclopropane ring.[12] For example, cyclopropane rings can replace alkenes in electrocyclic ring closure reactions



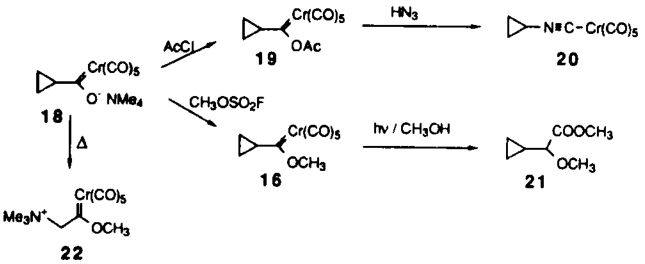
SCHEME 2

giving products with an extra carbon in the newly formed ring (Scheme 2). By analogy to the reactions in Schemes 1 and 2, the expected product of a reaction between cyclopropylcarbene complex **16** and an alkyne would be the cycloheptadienone **17** (Scheme 3). The reaction in Scheme 3 represents a versatile synthesis of seven-membered ring derivatives from alkynes and easily attainable cyclopropylcarbene-chromium complexes.[13] Since there are a wide variety of medicinally important seven-membered ring-containing compounds,[14] and since few practical cycloaddition reactions producing a seven-membered ring have been reported,[15] we undertook a study of the reactions of cyclopropylcarbene-metal complexes.

Prior to the initiation of these studies, few examples of the reactivity of cyclopropylcarbene-chromium complexes had ever appeared in the literature. The first example of a cyclopropylcarbene-metal complex was cyclopropylcarbene-chromium complex **16**, synthesized by Connor.[13] The reactivity of this complex with alkynes was not reported. The acetoxy complex was reported to be unstable above − 10°C, but could be captured by hydrogen azide[16] to give the isocyanide complex **20** in a reaction analogous to the Curtius rearrangement (Scheme 4). The corresponding acylate salt undergoes thermolysis to give the alkylammonium-substituted carbene complex **22**. While this work was in progress, complex **16** was reported to undergo conversion to the α-methoxy acid **21** upon photolysis in methanol; this reaction proceeds through a ketene intermediate.[17] Brookhart[18] reported that the cationic-iron complex **23** undergoes a cyclopropanation reaction with electron-rich



SCHEME 3

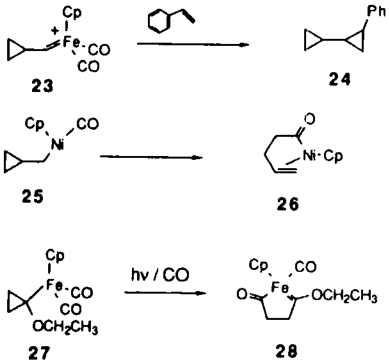


Scheme 4

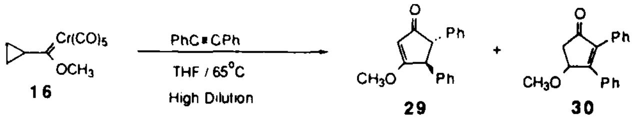
alkenes to give cyclopropylcyclopropanes (Scheme 5). This process is difficult to carry out with free carbenes due to competing rearrangement reactions.[19] The above studies suggest that the cyclopropane ring in these complexes is quite reluctant to undergo ring-opening reactions. Other transition metal complexes which contain cyclopropane rings, such as cyclopropylcarbinyl-metal complexes[20] and cyclopropyl-metal complexes,[21] undergo facile ring-opening or ring-expansion reactions. Some representative reactions of these classes of compounds are shown in Scheme 5.

REACTION OF CYCLOPROPYLCARBENE-CHROMIUM COMPLEXES WITH ALKYNES

Reaction of carbene complex **16** with diphenylacetylene was the first reaction attempted. When this reaction was conducted under



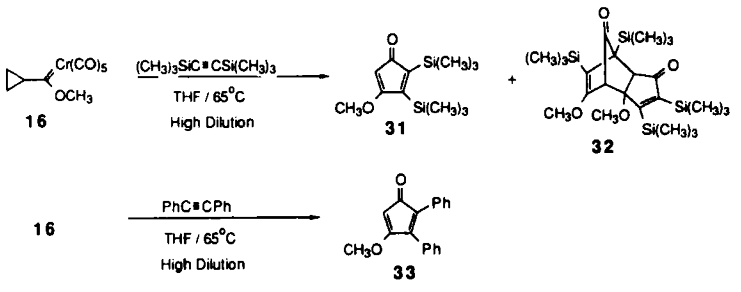
Scheme 5



SCHEME 6

the standard conditions established by Wulff,[22] heating a solution of both components (ca. 0.1 M) in THF until the reaction had gone to completion, an intractable reaction mixture was obtained. Simple carbene complexes have been reported to induce the polymerization of diphenylacetylene,[23] and a similar situation could be occurring in this case. In one previous instance, competing polymerization reactions were successfully suppressed by keeping the concentration of alkyne to a minimum throughout the reaction.[23b] When the reaction was performed under high dilution conditions (syringe pump addition of diphenylacetylene to a refluxing THF solution of carbene complex **16**) two products were obtained from the reaction in low yield (Scheme 6).[24] The major product was assigned as **29** (30%), and the minor product was assigned as **30** (6%). When the reaction was conducted in refluxing dioxane, only compound **29** was obtained from the reaction in 38% yield. When the reaction was conducted in THF, longer reflux times led to diminished amounts of **30** and higher yields of **29**, suggesting that perhaps **29** results from a thermodynamic equilibration of **30** to the more stable vinylogous ester. Conditions could not be found where **30** was the major product of the reaction, but **30** will rearrange to **29** upon treatment with chromium hexacarbonyl or sodium methoxide/methanol.

When bis-trimethylsilylacetylene was allowed to react with complex **16** in refluxing THF under conditions of high dilution, a new compound was isolated whose structure was assigned as the cyclopentadienone **31** (Scheme 7).[25] Compounds such as this are known to be very unstable,[26] and are often stabilized by the presence of bulky substituents such as trimethylsilyl.[27] In fact, **31** was converted to the dimeric compound **32** upon standing. We suspected that cyclopentadienones might also be intermediates in the reaction of complex **16** with diphenylacetylene. In order to test for this possibility, complex **16** was allowed to react with diphenylacetylene,



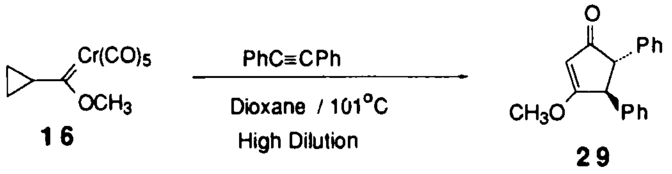
SCHEME 7

and immediately after the addition was complete, the refluxing was stopped. Under these conditions, the corresponding cyclopentadienone **33** could be isolated in 24% yield. Compound **33** also underwent dimerization upon standing. These results strongly suggest that cyclopentadienones are intermediates in the formation of **29** and **30**.

We now must address the issue of the conversion of cyclopentadienones to the observed cyclopentenones. It was not clear as to the identity of the hydrogen source. In our first studies, we tested to see if the yield of formation of **29** could be improved substantially by the addition of an external source of hydrogen. Thus, the reaction of diphenylacetylene with complex **16** was conducted in the presence of a variety of hydrogen sources in refluxing dioxane. The results are summarized in Table I. Table I indicates that both proton and hydride sources seem to increase the yield to some extent. The combination of a proton source with a hydride source was more effective than if either was used alone (Entry 7). This reduction system is similar to that used in a recently reported method for the hydrogenation of enones using chromium or molybdenum hexacarbonyl and triethylsilane/water.[28] The best yields of the reaction were obtained when the reaction was conducted in 1% aqueous dioxane. Interestingly, hydrogen gas alone did not assist the reduction to any extent. When the reaction was conducted in the presence of D_2O, compound **29** was obtained deuterated at the 2-position (30%), 4-position (85%) and the 5-position (85%). What is the hydrogen source when no additive is present? We suggest that the hydrogen source may actually be the carbene complex since the proton alpha to the carbene carbon

TABLE I

Reaction of diphenylacetylene with complex **16** in the presence of external hydrogen sources



Entry	Additive	Yield **29**
1	None	38
2	Et_3SiH	47
3	$(MeO)_3SiH$	16
4	Me_3COH	45
5	MeOH	43
6	CH_3COOH	49
7	Et_3SiH/MeOH	63
8	H_2O	79[a]
9	H_2	38
10	1,3-Cyclohexadiene	39

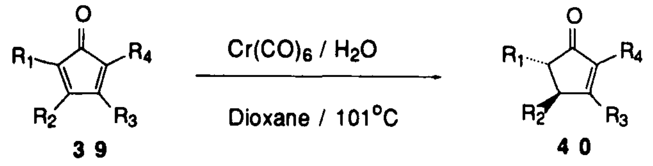
[a] A 4% yield of cyclopentenone **30** was also obtained.

would be predicted to have a pKa of 8,[29] and thus is itself a proton source. Consistent with this hypothesis is the fact that the yields are never above 50% if a proton source is not present.

In this next section, we will speculate on the mechanism for the reduction of cyclopentadienones to cyclopentenones by chromium hexacarbonyl and a proton source. After the reaction was over, the color of the solutions was intensely green, which is highly suggestive of chromium (III) species. The cyclopentadienones were reduced to the corresponding cyclopentenones upon treatment with chromium hexacarbonyl in refluxing 1% aqueous dioxane (Table II). Treatment of diphenylcyclopentadienone **33** with chromium hexacarbonyl/water led to the cyclopentenone **29** in 61% yield. The reduction of trimethylsilyl-substituted cyclopentadienone **31** was not nearly so efficient. Competing protiodesilylation was a significant problem, and after treatment of the reaction mixture with KF/DMF, 3-methoxy-2-cyclopentenone (**40**, R_1, R_2, R_4 = H, R_3 = OCH_3) could be isolated in 24% yield. Tetraphenylcyclopentadienone was also reduced to the corresponding cyclopenten-

TABLE II

Reduction if cyclopentadienones using chromium hexacarbonyl/water

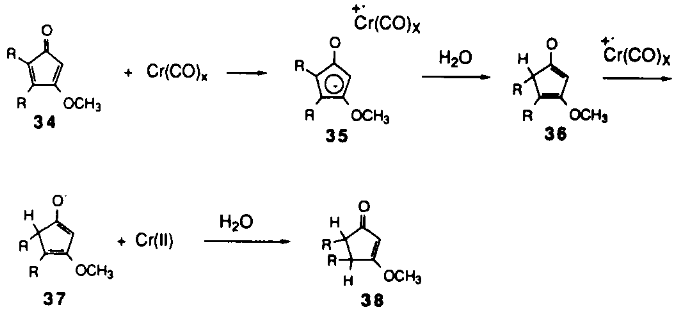


Entry[a]	R_1	R_2	R_3	R_4	Yield
A	Ph	Ph	OCH_3	H	61%
B	$Si(CH_3)_3$	$Si(CH_3)_3$	OCH_3	H	14%[b]
C	Ph	Ph	Ph	Ph	92%

[a] Table entry letters define R_1, R_2, R_3, R_4 for compounds **39** and **40**.

[b] The compound was treated with KF/DMF prior to isolation; the yield refers to 3-methoxy-2-cyclopentenone (R_1, R_2, R_3, R_4 = H).

one under these conditions.[30] In none of these reactions was there any evidence of overreduction products such as cyclopentanones. The combination of chromium hexacarbonyl/water was effective only for the reduction of cyclopentadienones. Neither simple enones nor dienones such as 4,4-dimethyl-2,5-cyclohexadienone were reduced under these conditions. When nitrogen was continually bubbled through the solution, and the effluent gases were bubbled through a saturated barium hydroxide solution, the amount of carbon dioxide produced was only 0.06 eq. for every eq. of cyclopentadienone produced. Hydrogen gas does not appear to be responsible for the reduction. When hydrogen gas was continuously bubbled through the solution during the cycloaddition reaction with D_2O present, only products resulting from deuterium incorporation were observed. These results rule out a mechanism involving a hydrogenation or metal hydrides derived from the water-gas shift reaction.[31] We suggest that the mechanism shown in Scheme 8 is operative, which involves electron transfer followed by protonation followed by a second electron transfer and protonation. In this mechanism, both of the newly incorporated hydrogens arise from proton sources. This mechanism does not necessarily require that the kinetic product of the reaction be the cis isomer, as would be suggested from a metal-catalyzed hydrogenation reaction. The



SCHEME 8

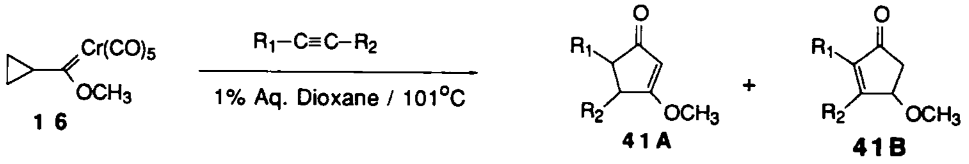
reduction potential of a cyclopentadienone is very low,[32] which might explain why the reduction reaction is limited to cyclopentadienones, and structurally similar compounds such as simple divinylketones are not reduced. Chromium (II) was also an effective reducing agent, but less so than chromium hexacarbonyl.

The cyclopentenone-forming reaction appears to be general for a wide variety of alkynes. The only limitation on the alkyne substituents appears to be that the reaction will not tolerate alkynes having electron-withdrawing substituents. When terminal alkynes were employed in the reaction, the reaction was highly regioselective, giving only the compound where the larger substituent is alpha to the carbonyl group in the product. When unsymmetrically disubstituted alkynes were employed in the reaction with complex **16**, mixtures of regioisomers were usually obtained (Table III, Entry C). The reaction appears to be controlled by steric effects, and the larger substituent ends up alpha to the carbonyl group in the product. Primarily the trans stereoisomers are formed in the reaction. The preponderance of the trans isomer increases with increasing reaction time, and treatment of the crude reaction mixtures with sodium methoxide/methanol leads to nearly complete isomerization to the trans isomer. A variety of functional groups appear to be tolerated by the reaction. The yields of cyclopentenones do not appear to be significantly affected by the presence of alcohol, ether, or vinyl groups.

In order for this reaction to be useful for synthetic organic chemistry, it would be desirable to have a method to control the regiochemistry with unsymmetrically substituted internal alkynes. Others[33]

TABLE III

Formation of cyclopentenones from the reaction of alkynes and carbene complex **16**

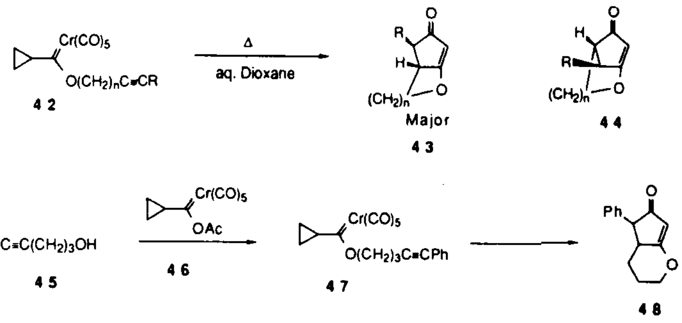


Entry[a]	R_1	R_2	Yield **41A**(%)	Trans/cis **41A**	Yield **41B**(%)
A	Ph	Ph	79	24:1	4
B	Ph	H	62		0
C	Ph	CH_3	73	9:1	12[b]
D	n-C_3H_7	n-C_3H_7	55	7:1	0
E	n-C_3H_7	H	68		0
F	$-(CH_2)_3OH$	H	54		0
G	$-(CH_2)_3OSiMe_2(t\text{-}Bu)$	H	58		0
H	$-CH{=}CHOMe$	H	42[c]		0

[a] Table entry letters define R_1 and R_2 for compounds **41A** and **41B**.

[b] In this compound R_1 and R_2 are reversed: CH_3 is at the 2-position and Ph is at the 3-position.

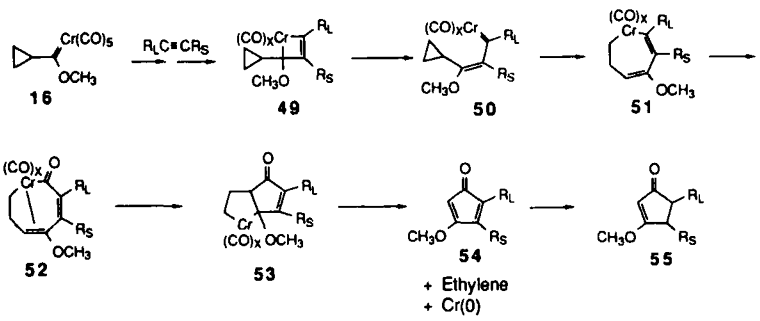
[c] The product was obtained as a 3:2 trans:cis mixture about the enol ether double bond.



SCHEME 9

have reported that the regiochemistry of addition in the aromatic ring-forming reaction involving α,β-unsaturated carbene complexes can be controlled through an intramolecular version of the chromium carbene cyclization reaction. Presumably, a similar tick could be employed in these systems as well (Scheme 9). Provided that the carbon chain connecting the alkyne and alcohol is reasonably small, the major product of the reaction should the fused-ring isomer **43** and not the bridged-ring isomer **44**. The requisite alkyne-containing carbene complexes are easily synthesized from the reaction of alkynols with acetoxycarbene complex **46**.[34] Thermolysis of compound **47** at 100°C in 1% aqueous dioxane leads to the bicyclic compound **48** as a 5:1 trans:cis mixture. Further studies into the scope and limitations of this reaction, as well as methods to open the newly formed heterocyclic rings, are presently underway in our laboratories.

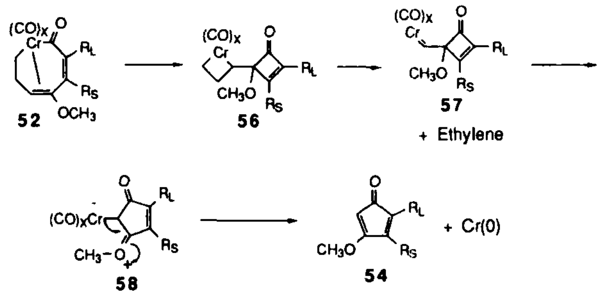
We envisage that two different mechanistic pathways might be involved in the reaction of cyclopropylcarbene-chromium complexes and alkynes. We have to date determined that cyclopentadienones are intermediates in the reaction, and that the two secondary carbons in cyclopropylcarbene complex **16** are converted to ethylene during the course of the reaction. In mechanism 1 (Scheme 10), the reaction begins much like all the other reported reactions between metal carbene complexes and alkynes,[5] and results in carbene complex **50**, which can undergo an electrocyclic ring closure to the metallacycloheptadiene **51**. Carbon monoxide insertion followed by alkene insertion gives the metallacyclopen-



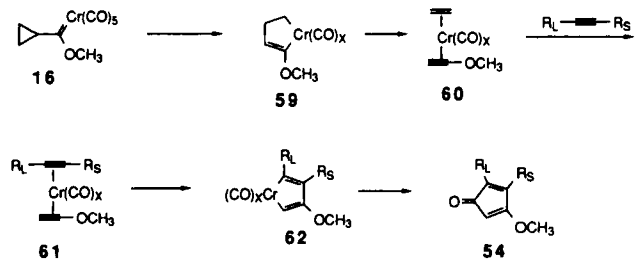
SCHEME 10

tane **53**, which can fragment with loss of ethylene to give the cyclopentadienone **54**,[35] which is then converted to the cyclopentenone product by the action of Cr(0) and water. A model has suggested that the correct geometry for the alkene insertion is somewhat difficult to attain; thus we propose an alternative route (Scheme 11) for the conversion of metallacycloctadienone **52** to cyclopentadienone **54**. In this case, compound **52** undergoes an intramolecular alkene insertion to give the metallacyclobutane **56**. Ethylene loss from fragmentation of the metallacyclobutane gives intermediate carbene complex **57**. Carbene complexes such as **57** which lack heteroatom stabilization are extremely electrophilic,[36] and alkyl migration to the electrophilic carbene carbon gives the five-membered ring-containing compound **58**,[37] which loses chromium to give the cyclopentadienone.

In mechanism 2 (Scheme 12), the first step of the mechanism



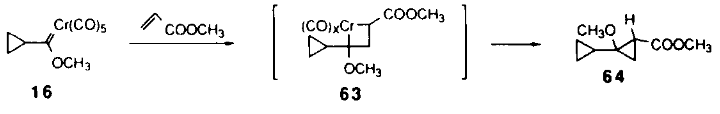
SCHEME 11



SCHEME 12

involves a ring expansion of the starting carbene complex to the metallacyclopentene **59**. Metallacyclopentene fragmentation[35] followed by ligand exchange provides bis alkyne complex **61**, expelling ethylene in the process. Oxidative ligand coupling[38] followed by CO insertion and reductive elimination leads to cyclopentadienone **54**.

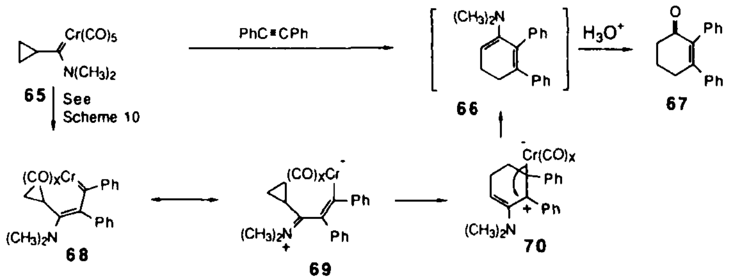
Although we have by no means proven any mechanism to date, most of the data available support the mechanism in Scheme 10(11). In Scheme 10(11), the regiochemistry is set in the formation of metallacyclobutene **49**. In this type of reaction, others have noted that the reaction puts the larger alkyne substituent alpha to the metal. This is the regiochemistry observed in the examples in Table III as well. In the mechanism detailed in Scheme 12, the regiochemistry is set in the formation of metallacyclopentadiene **62**. Although the regiochemistry of this process has been well worked-out for cobalt,[38] few examples have been reported with chromium.[39] The mechanisms in Scheme 10(11) suggest that the cyclopropane ring opens at a relatively late stage on the reaction pathway, whereas the mechanism in Scheme 12 suggests that it opens in the very first step of the reaction. The reaction of complex **16** with electron-deficient alkenes has recently been examined and was found to produce cyclopropylcyclopropane derivatives such as **64** (Scheme 13).[40] Cyclopropanation of electron-deficient alkenes



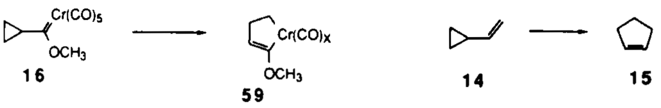
SCHEME 13

by Fischer carbene complexes has been reported to proceed through the intermediacy of metallacyclobutanes.[41] The reaction in Scheme 13 is another example of a reaction where a metallacyclobutane is formed without opening of a cyclopropane ring. If the mechanism in Scheme 12 were operative, it is difficult to see how cyclopropanation of alkenes could occur, since the cyclopropane ring is destroyed in the first step of the reaction.

In the mechanisms in Scheme 10(11) the organic products form at a very late stage of the reaction, after ample transformations involving organotransition metal intermediates. All of the intermediates of the reaction except carbene complex **50** are in theory directly susceptible to reductive elimination (possibly accompanied by CO insertion) reactions, giving organic products. Thus, by variance of the structure of the complex or reaction conditions, it may be possible to generate three-, four-, five-, six-, or seven-membered ring systems as well as the bicyclo[3.2.0]heptane or bicyclo[3.3.0]octane ring systems. Recently the reaction of (cyclopropyl)aminocarbene-chromium complexes with alkynes has been examined. The reaction of carbene complex **65** with diphenylacetylene leads after aqueous workup to the cyclohexenone derivative **67** in 20% yield. The simplest mechanism for the formation of this compound is outlined in Scheme 14. It has recently been reported that aminocarbene complexes do not lead to products resulting from CO insertion.[9,42] Yamashita has recently suggested an intriguing alternative mechanism to be operative for cycloadditions involving alkynes and aminocarbene-chromium complexes,[42a] which involves a Nazarov cyclization. In this system, the



SCHEME 14



SCHEME 15

final ring closure reaction (**69** → **70**) might be described as a "homo-Nazarov" cyclization. Further examination into the scope and utility of these processes, as well as studies of other structural variations of the parent complex **16**, are presently underway.

THERMAL REACTIVITY OF CYCLOPROPYLCARBENE-CHROMIUM COMPLEXES

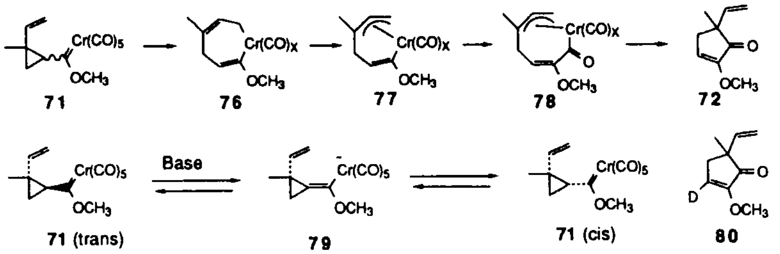
As a probe for the viability of the conversion of **16** to metallacyclopentane **59** (Scheme 15), we undertook a study of the thermal reactions of cyclopropylcarbene-chromium complexes.[43] Complex **16** does not undergo any rearrangement upon heating to 101°C for a period of 2 h. The conversion of **16** to **59** can be viewed as an analog of the vinylcyclopropane rearrangement[44] (**14** → **15**), where a carbon-chromium double bond replaces a carbon-carbon double bond. The vinylcyclopropane rearrangement is typically a very sluggish reaction and usually requires high temperatures. This analogy might help to explain the reluctance of **16** to convert to **59** (see below). Further attempts to activate the thermal cyclopropane ring opening for compounds such as **16** have recently been undertaken. Compound **71** was prepared as an inseparable 57:43 cis:trans mixture and its thermal reactivity examined. This compound undergoes a rapid thermal reaction at 65°C, converting to the cyclopentenone **72** (Scheme 16). When this reaction was stopped prior to completion, it was noticed that the unreacted starting material had become enriched in the trans isomer. The rate of

SCHEME 16

disappearance of the cis isomer at 52°C was 3.5×10^{-5} $\sec^{-1}$, while the rate of disappearance for the trans isomer was 0.8×10^{-5}; the relative rate for disappearance of cis:trans isomers at 52°C was 4.4.

This reaction appears to be general for all 2-alkenylsubstituted cyclopropylcarbene-chromium complexes (Table IV). Only in one case, the thermolysis of complex **73E**, does the reaction fail. When carbene complexes containing a H atom at the 2-position are thermalized, some of the product obtained is the α,β-unsaturated ketone **75** which results from an isomerization of the double bond. The reaction appears to go with retention of configuration in the limited amount of examples studied (Entries F, H, I), although in these systems the reaction is heavily biased for retention. The analogous 2-phenylsubstituted cyclopropylcarbene complexes are very reluctant to undergo the analogous rearrangement reaction. In the case of Entry C, the reaction does not proceed to any extent after 2 days at 95°C, but proceeds slowly at 101°C.

We propose the mechanism depicted in Scheme 17 to account for these observations. First, a Cope rearrangement[45] occurs to give the metallacycloheptadiene **76** followed by $\sigma \rightarrow \pi$-allyl interconversion and CO insertion to give π-allyl complex **78**. Reductive elimination provides cyclopentenone **72**. Since the reaction is inhibited by CO, the first step of the reaction might actually be CO-dissociation and/or alkene coordination; however, the reaction does appear to follow clean first order kinetics in the absence of external CO pressure. Consistent with this mechanism is the fact that phenyl



SCHEME 17

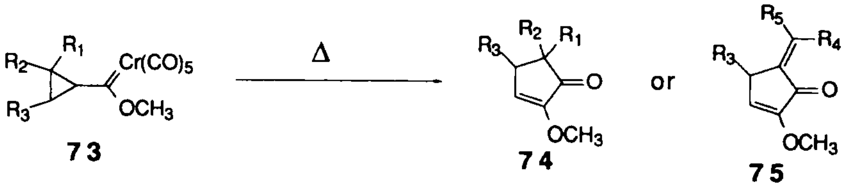
is not a good replacement for vinyl. If the vinyl group were simply weakening the cyclopropane carbon-carbon which is broken in the reaction, thus activating the system for the rearrangement in Scheme 15, then phenyl groups and vinyl groups should have a similar effect. Also consistent is the observation that the cis isomer reacts faster than the trans. This is the same order of reactivity as is observed in the divinylcyclopropane rearrangement[45] (Scheme 19, **10** → **11**), although the relative rate differences are considerably less. In the divinylcyclopropane rearrangement, it has been postulated that the trans isomer converts to the cis isomer prior to rearrangement.[46] In complex **71**, the cis and trans isomers could interconvert through a deprotonation-protonation sequence since the carbene complex has a highly acidic proton in the alpha position.[29] In DMF solution, such a process does indeed happen. When carbene complex **71** was heated to 80°C in 99:1 DMF:D_2O, deuterated cyclopentenone **80** was obtained from the reaction. When the same thermolysis reaction was performed in 99:1 THF:D_2O at 80°C in a pressure bottle, only undeuterated cyclopentenone **72** was obtained. Presumably, the deprotonation is assisted by the slightly basic nature of DMF. The reaction appears to be both faster and more efficient in DMF solution, which we attribute to a higher concentration of the more reactive cis isomer.

Complex **73E** fails to rearrange under any conditions. The synthesis of this complex provided only the exo isomer, which should be less reactive in the Cope rearrangement than the corresponding endo isomer. In the endo isomer, a model suggests that there are severe steric interactions between the chromium pentacarbonyl group and the six-membered ring. This reluctance to form the more reactive endo isomer might explain the failure of this complex to convert to the cyclopentenone **75E** upon thermolysis. Further studies of the conversion of **73** to **75** are currently underway.

The reactions of cyclopropylcarbene-chromium complexes seem to be subject to control by orbital symmetry considerations. For example, the conversion of **50** to **51** or **71** to **76** appears to be a facile process, while the conversion of **16** to **59** is a very slow process (Scheme 19). While this work was in progress, studies on the related N-aziridinylcarbene-chromium complex **81** were reported[47] (Scheme 18). In these systems as well, cyclopropane ring opening

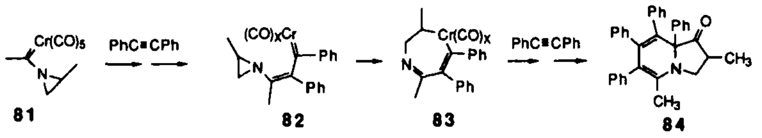
TABLE IV

Thermolysis of 2-alkenylcyclopropylcarbene-chromium complexes



Entry[a]	R_1	R_2	R_3	R_4	R_5	Trans:cis Complex[b]	Reaction time/temperature[c,d]	Yield 13[c]
A	vinyl	CH_3	H			42:58	3 h/101°C	43
B	Ph	H	H			46:54	14 h/101°C[f]	22
C	Ph	CH_3	H			68:32	14 h/101°C[f]	27
D[k]	1-cyclopentenyl	H	H	$R_4,R_5 = -(CH_2)_4-$		–	1 h/101°C	69[i]
E	H;	$R_2,R_3 = -CH{=}CH(CH_2)_2-$				100:0	4.5 h/101°C[i]	0
F	1-propenyl	H	CH_3	CH_2CH_3	H	53:47[g]	1 h/100°C	53[g–i,l]
G	vinyl	H	H	CH_3	H	49:51	2.0 h/100°C	49[i,j,m]
H	vinyl;	$R_2,R_3 = -(CH_2)_4-$				41:59	1.5 h/101°C	67[n]
I	vinyl	$R_2,R_3 = -(CH_2)_5-$				78:22	1.5 h/100°C	57[h,n]

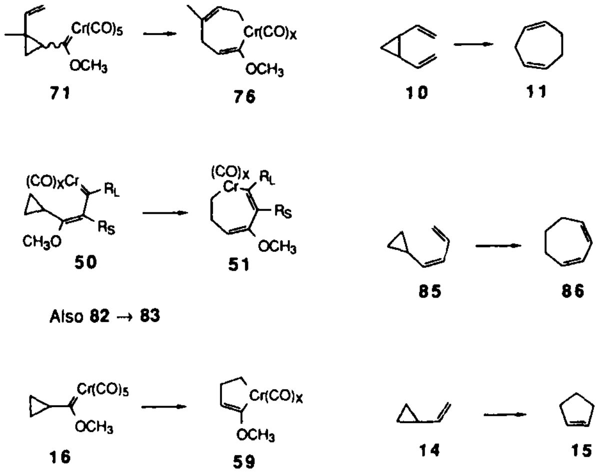
[a] Table entry letters define R_1, R_2, R_3 for compounds **73–75**.
[b] The trans:cis designation refers to the relative stereochemistry of the chromium carbene and the alkenyl (aryl) substituents in the starting carbene complex.
[c] The reaction was performed in anhydrous p-dioxane unless otherwise noted.
[d] All reactions were allowed to proceed until the carbene complex had completely disappeared unless otherwise noted.
[e] The yields refer to products obtained after chromatographic purification.
[f] The starting material had not disappeared when the reaction was stopped.
[g] The relative stereochemistry of the methyl and propenyl groups is trans.
[h] The reaction was conducted in DMF.
[i] The yield refers to the product isolated after isomerization of the double bond (compound **75**).
[j] The reaction was conducted in THF in a pressure bottle.
[k] The starting carbene complex was stereoisomerically pure, a cis or trans assignment was not possible.
[l] The E/Z ratio is 26:74.
[m] The E/Z ratio is 36:64.
[n] The ring fusion has been assigned as cis based on NOE results.



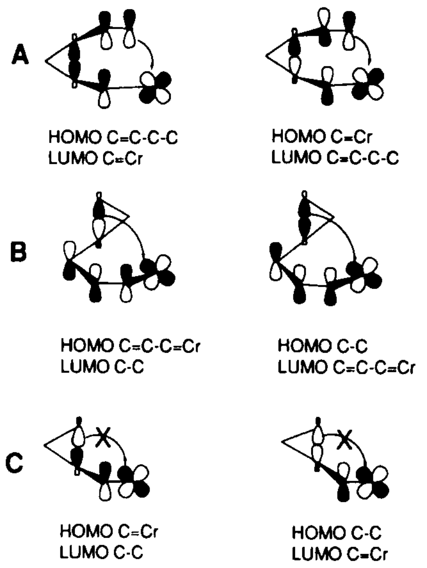
SCHEME 18

appears to be occurring at a rather late stage of the reaction, and the suggested mechanism involves cyclopropane ring opening after insertion of the first alkyne. In this system, the proposed ring opening step (**82** → **83**) is analogous to the conversion of **50** to **51**. Interestingly, the ring-opening reactions of **50**, **71**, and **82** are all organometallic analogs of pericyclic organic reactions which are suprafacially allowed in the ground state due to orbital symmetry considerations. The conversion of **16** to **59** is an organometallic analog of the vinylcyclopropane rearrangement, which is not allowed in a suprafacial fashion.

Can ground-state HOMO-LUMO interactions explain the trends observed here? The simple pictures of Scheme 20[48] suggest that there might be an orbital symmetry component to these reaction processes. The pictures in Scheme 20 depict the ground state HOMO-LUMO interactions for the cyclopropyl ring expansion reactions



SCHEME 19



SCHEME 20

of **71** (Scheme 20A), **50** and **82** (Scheme 20B), and **16** (Scheme 20C). In these systems, the pictures are derived from the expected ground state interactions for the corresponding all-carbon system, and one of the carbon-carbon π-bonds has been replaced by a chromium-carbon double bond arising from a pπ-dπ interaction. In Scheme 20A, both of the ground state HOMO-LUMO interactions depicted allow for suprafacial interaction of the migrating alkene carbon and the chromium. Likewise, in the migration depicted by Scheme 20B, a suprafacial migration of the cyclopropane carbon to the chromium is possible. Scheme 20C depicts the ground state HOMO-LUMO interactions having the correct orbital symmetry for formation of the carbon-carbon double bond. Suprafacial migration to the chromium must proceed with an antibonding interaction and thus this process is not allowed. This process could conceivably happen if the carbon attaches itself to the rear lobe of the chromium d-orbital; however, this site is not as easy to access as the front lobe. Also, orbital symmetry violations could be overcome if the migrating carbon attaches itself to a d-orbital at chromium not involved in the dπ-pπ bond.[49] This picture suggests that the type of rearrangement depicted by Scheme 20C might happen more readily than the corresponding vinylcyclopropane rearrangement since these alternate sites of attachment are available. Further examination of orbital symmetry control of metal-carbene reactions is currently being investigated.

CONCLUSION

In summary, chromium-carbene complexes with cyclopropane rings directly attached undergo a wide variety of interesting transformations, including a versatile new cycloaddition reaction for the formation of cyclopentenone derivatives from alkynes. The 2-alkenylcyclopropylcarbene-chromium complexes undergo a facile conversion to 5-alkenyl-2-methoxy-2-cyclopentenone derivatives when heated. For the mechanistic steps of these reactions which involve opening of the cyclopropane ring, an interesting parallel is observed with pericyclic reactions of simple organic molecules. We are further examining the reactions of cyclopropylcarbene-metal complexes in anticipation that new and synthetically useful transformations will continue to arise from these highly underexplored compounds.

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