Synthesis of β-Lactones by the Photochemical Reactions of Chromium Alkoxycarbene Complexes with Aldehydes

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Photolysis of chromium alkoxycarbene complexes with aldehydes in the presence of Lewis acids produced β-lactones in low yield. Incorporation of the aldehyde into either side chain of the carbene complex resulted in intramolecular processes which were considerably more efficient.

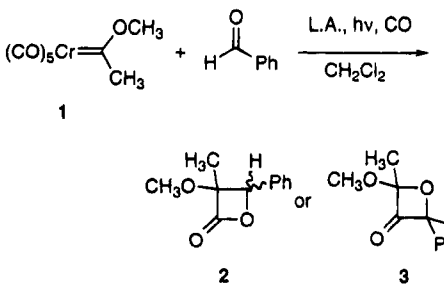
Introduction

2-Oxetanones (β-lactones) are of interest both because of their occurrence in a variety of naturally occurring, biologically active compounds and because of their intrinsic reactivity due to the strained lactone ring, making them useful synthetic intermediates.[1,2] Among the approaches to β-lactones, the 2 + 2 cycloaddition reaction of ketenes with aldehydes or ketones,[3] often in the presence of Lewis acids, has recently been extended by the use of very sterically hindered phenoxy aluminum compounds such as MABR[4] (methylaluminum bis(4-bromo-2,6-di-*tert*-butylphenoxide) and (trimethylsilyl)-ketene.

Research in these laboratories has centered on the development of a wide range of reactions based on the observation that photolysis of chromium carbene complexes generates short-lived species which have ketene-like reactivity.[5] Thus, photolysis of chromium carbene complexes with imines gives β-lactams,[6] with alkenes gives cyclobutanones,[7] and with nucleophiles gives carboxylic acid derivatives (α-amino acids,[8] peptides[9]). Herein, we report attempts to extend this reaction chemistry to cycloaddition reactions with aldehydes to produce β-lactones.

Results and Discussion

Initial studies involved the reaction of the (methoxy)-(methyl)carbene complex **1** with benzaldehyde in the presence of various Lewis acids (eq 1). In the absence of



Eq. 1

Lewis Acid	T	Products, yield
none	25°C	decomp.
BF_3•Et_2O (0.2 eq)	25°C	decomp.
MABR (0.2 eq)	25°C	**2a/2b** (6/4), 12%
MABR (0.2 eq)	0°C	**2a/2b** (6/4), 17%
MABR (0.2 eq)	-30°C	**2a/2b** (6/4), 18%
$(CH_3)_2AlCl$ (0.2 eq)	0°C	**2a/2b** (7/3), 22%
$ZnCl_2$ (0.5 eq)	25°C	**3**, 29%

a Lewis acid and in the presence of BF_3•etherate only decomposition products were obtained. In the presence of MABR under a variety of conditions low yields of the β-lactone, **2**, as a mixture of diastereoisomers, were obtained. The use of dimethylaluminum chloride as a Lewis acid led to similar results while, remarkably, zinc chloride caused a reversal of regioselectivity to give the 3-oxetanone **3** in modest yield. This stands in marked contrast to the reactions of trimethylsilyl ketene with aldehydes in the presence of MABR, which proceed in high yield and with excellent stereo- and regioselectivity.

Because photolysis of chromium carbene complexes generates the reaction intermediate reversibly and only in low concentrations, reactions tend to be slow, and consumption of carbene complex **1** required 12–24 h, in comparison to reaction of free ketenes, which are complete in a short time even at low temperatures.[4] Thus, the stability of the product lactone **2** to the reaction conditions becomes an issue. Indeed, while β-lactone **2** was stable to the photolytic conditions of the reaction, stirring overnight with the Lewis acid led to complete decomposition, implicating the requisite long reaction times as the cause of the low yield.

Intramolecular reactions usually proceed more quickly than intermolecular reactions, and processes to incorpo-

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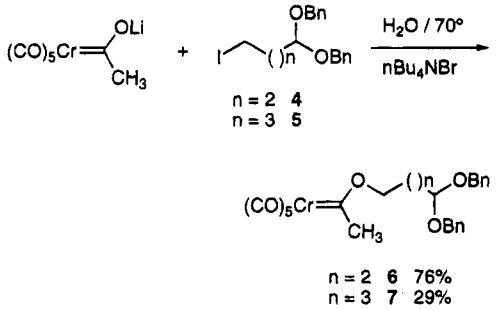
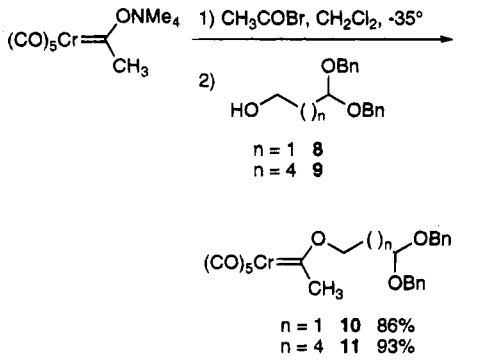
rate an aldehyde group into the alkoxy chain of the carbene complex were next developed. Two approaches, one involving O-alkylation with iodo acetals (eq 2)[10] and

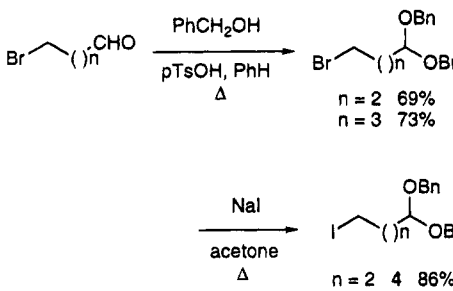


Eq. 2

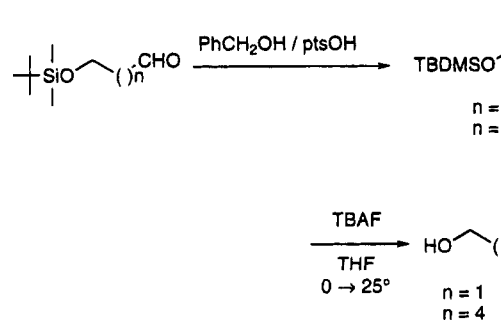
one involving O-acylation/exchange with hydroxy acetals (eq 3)[7d] were studied, with the latter being more efficient. The requisite starting materials were made by conventional procedures (eqs 4 and 5) from readily available starting materials.



Eq. 3

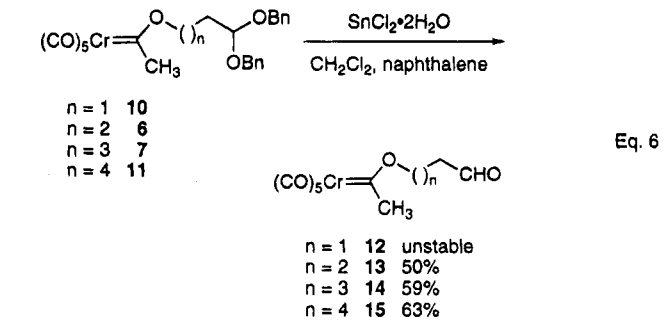


Eq. 4



Eq. 5

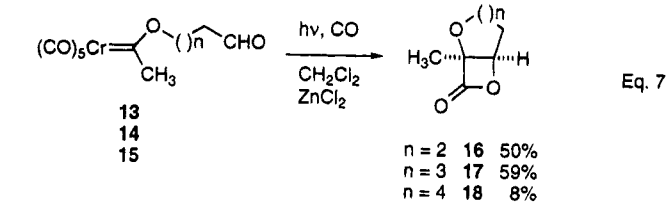
Deprotection of the acetal in carbene complexes **6**, **7**, **10**, and **11** proved problematic, since carbene complexes are generally not stable to the acidic conditions required for this transformation. Standard procedures (1 M HCl/THF, $MgSO_4$/wet benzene) as well as less conventional ones ($PdCl_2(CH_3CN)_2$/acetone)[11] resulted in decomposition of the carbene complexes, as did hydrogenolysis of the benzyl groups (H_2, Pd/C). However, the recently reported[12] procedure involving $SnCl_2 \cdot 2H_2O$ in the presence of naphthalene as a promoter was successful, giving aldehyde-containing carbene complexes **12**–**15** (eq 6).



Eq. 6

Complex **12**, having a single methylene group between the aldehyde and alkoxy group, was unstable and decomposed upon attempted purification. The longer chain complexes **13**–**15** were more easily handled and were obtained in 50–63% yield, along with ≈25% of unreacted starting material which could be recycled.

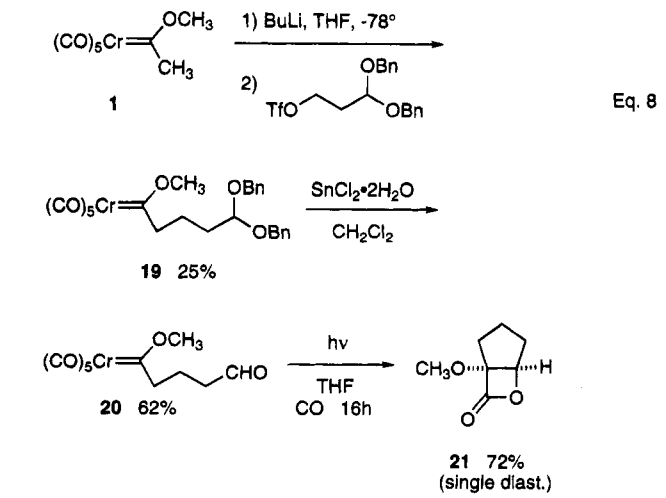
Photolysis of complexes **13** and **14** in the presence of 0.2 equiv of zinc chloride as the Lewis acid produced bicyclic β-lactones **16** and **17** in 50% and 59% yield, respectively (eq 7). In contrast, only traces of β-lactone



Eq. 7

were obtained when complex **15** was treated under the same conditions, perhaps because of the difficulty with forming an eight-membered ring. This yield increased to 8% when dimethylaluminum chloride was used as the Lewis acid, but this reaction remained synthetically useless. In all cases, only a single diastereoisomer was obtained.

A single carbene complex with an aldehyde group in the alkyl side chain was also prepared and photolyzed (eq 8). This one underwent efficient bicyclic β-lactone formation, giving a 72% yield of **21**.



Eq. 8

All β-lactones reported had characteristic absorptions in the infrared spectrum at 1830 cm^{-1} for the carbonyl stretching frequency and a characteristic carbonyl carbon signal at 170 ppm in the ^{13}C NMR. All bicyclic β-lactones were obtained as single diastereoisomers and were assigned *cis* stereochemistry on the basis of NOE studies (see Experimental Section).

Experimental Section

General Procedure. ^1H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were obtained on a Brucker ACE-300 spectrometer. NMR spectra were recorded in $CDCl_3$, and chemical shifts are reported in ppm relative to $(CH_3)_4Si$ (0 ppm, ^1H) and $CDCl_3$ (77 ppm, ^{13}C). IR spectra were recorded on a Perkin-Elmer 1600 series FTIR. Elemental analyses were perfomed by M-H-W Laboratories, Phoenix, AZ. All reactions were performed under an atmosphere of argon except as specified and for reactions involving chromium carbenes, the solvents were degassed by a vacuum/argon process.

The crude reaction mixtures were purified by flash column chromatography with silica gel (ICN Biomedicals Silitech 32–63 μm).

[(Methoxy)(methyl)carbene]pentacarbonylchromium,[13] [[(tetramethylammonium)oxy)](methyl)carbene]pentacarbonylchromium,[14] 4-bromobutanal,[15] 5-bromopentanal,[16] 3-[(*tert*-butyldimethylsilyl)oxy]propanal,[17] and 6-[(*tert*-butyldimethylsilyl)oxy]hexanal[18] were prepared according to published methods.

β-Lactone 2. A solution of dimethylaluminum chloride (0.20 mmol, 0.20 mL, 1 M in hexane) was added to a solution of benzaldehyde (0.20 g, 2.00 mmol) and a solution of (methyl)(methoxy) chromium carbene complex **1** (0.25 g, 1.00 mmol) in CH_2Cl_2 (25 mL, anhydrous, degassed) at 25 °C. The mixture was saturated with CO and irradiated (450-W Conrad Hanovia 7825 medium-pressure mercury lamp) under 60 psi of CO at 0 °C for 24 h. The mixture was concentrated under reduced pressure, diluted with pentane (20 mL), filtered through Celite, washed with a saturated solution of $NaHCO_3$ (15 mL), with a saturated solution of sodium sulfite (3 × 15 mL), and with a saturated solution of $NaHCO_3$ (15 mL), dried with $MgSO_4$, filtered, and concentrated. Chromatography [SiO_2 (30 g), elution hexane, EtOAc 20%] afforded isomeric β-lactones **2a** (0.028 g, 15%) and **2b** (0.014 g, 7%) as pale yellow liquids. **2a**: ^1H NMR δ 1.08 (s, 3H, CH_3), 3.57 (s, 3H, OCH_3), 5.62 (s, 1H, CH), 7.23–7.45 (m, 5H, C_6H_5); ^{13}C NMR δ 15.88, 53.55, 80.79, 92.37, 125.09, 128.62, 128.74, 134.13 (Ar), 170.33 (C=O); IR (NaCl film) ν 1835 cm^{-1} (C=O). **2b**: ^1H NMR δ 1.73 (s, 3H, CH_3), 3.13 (s, 3H, OCH_3), 5.29 (s, 1H, CH), 7.34–7.41 (m, 5H, C_6H_5); ^{13}C NMR δ 18.58, 53.53, 84.31, 89.40, 126.58, 128.37, 128.93, 133.37 (Ar), 170.36 (C=O); IR (NaCl film) ν 1828 cm^{-1} (C=O).

2-Oxetanone 3. Benzaldehyde (0.31 g, 3.00 mmoles) and a solution of (methyl) (methoxy) chromium carbene complex **1** (0.25 g, 1.00 mmole) in CH_2Cl_2 (5 mL, anhydrous, degassed) were added at 25 °C to a solution of $ZnCl_2$ (0.50 mmol prepared from a 1 M solution in Et_2O by removing the solvent under reduced pressure). Glass beads were added, and the mixture was saturated with CO and irradiated (450-W Conrad Hanovia 7825 medium-pressure mercury lamp) under 60 psi of CO at 25 °C for 11 h. The mixture was filtered through Celite and concentrated under reduced pressure. Chromatography [SiO_2 (30 g), elution hexane, EtOAc 20%] afforded 3-oxetanone **3** (0.025 g, 29%) as a pale yellow liquid: ^1H NMR δ 2.09 (s, 3H, CH_3), 3.36 (s, 3H, OCH_3), 4.58 (s, 1H, CH), 7.32–7.38 (m, 5H, C_6H_5); ^{13}C NMR δ 25.05, 57.13, 89.37, 126.93, 128.56, 128.78, 135.80(Ar), 206.59 (C=O); IR (NaCl film) ν 1719 cm^{-1}. Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.96; H, 6.86. Found: C, 75.13; H, 7.00.

General Procedure for the Preparation of Carbene Acetals. Method A. A solution of methyllithium (1.2 equiv) was added to a suspension of $Cr(CO)_6$ (1.05 equiv) in Et_2O (anhydrous, 1 M) at 25 °C. The brown mixture was stirred for 1 h at 25 °C, concentrated under reduced pressure, cooled to 0 °C, and diluted with water (degassed, cold, *n* mmol, *n* mL). Iodo acetal (1 equiv) and tetramethylammonium bromide (0.1 equiv) were then added, the flask was sealed, and the mixture was heated at 70 °C for 1 h, cooled to 25 °C, and extracted with CH_2Cl_2. The organic layer was washed with brine, dried with $MgSO_4$, filtered, and concentrated under reduced pressure. **Method B.** Acetyl bromide (1.15 equiv, freshly distilled) was added to a solution of the tetramethylammonium salt of the methyl carbene complex **1** (1.3 equiv) in CH_2Cl_2 (0.08–0.1 M, anhydrous, degassed) at −40 °C. The red mixture was stirred at −35 °C (±5 °C) for 1 h, and a solution of hydroxyl acetal (1 equiv) in CH_2Cl_2 (0.8–1 M, anhydrous, degassed) was added. The mixture was stirred at −30 °C (±5 °C) for 2 h and held at 25 °C for 10 min, and a saturated solution of $NaHCO_3$ (*n* mmol, 6*n* mL) was added. The organic layer was washed with brine (*n* mmol, 2 × 10*n* mmol) dried with $MgSO_4$, filtered, and concentrated under reduced pressure.

Iodo Acetal 4. A solution of 4-bromobutanal (0.61 g, 4.00 mmol), benzyl alcohol (1.04 g, 9.00 mmol), and *p*-toluenesulfonic acid (catalytic amount) in benzene (50 mL) was heated at reflux (Dean Stark trap), cooled to 25 °C, washed with a saturated solution of $NaHCO_3$, dried with $MgSO_4$, filtered, and concentrated under reduced pressure. Chromatography [SiO_2 (30 g), elution hexane, EtOAc 10%] afforded the bromo acetal (0.97 g, 69%) as a liquid. This bromo acetal (0.97 g, 2.76 mmol) was added to a solution of sodium iodide (0.83 g, 5.50 mmol) in acetone (10 mL). After addition, the mixture was heated at reflux for 1 h, cooled to 25 °C, concentrated, diluted with EtOAc, washed with brine and a saturated solution of sodium thiosulfate, dried with $MgSO_4$, filtered, and concentrated. Chromatography [SiO_2 (30 g), elution hexane, EtOAc 10%] afforded compound **4** (0.944 g, 86%) as a pale yellow liquid: ^1H NMR δ 1.86–1.93 (m, 4H, CH_2), 3.17 (t, 2H, J = 6.6 Hz, CH_2I), 4.55 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.65 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.74 (t, 1H, J = 5.5 Hz, CHOBn), 7.24–7.34 (m, 10H, Ar); ^{13}C NMR δ 6.65, 28.53, 34.01, 67.30 (OCH_2-Ph), 100.87 (CHOBn), 127.55, 127.65, 128.09, 137.89 (Ar). Anal. Calcd for $C_{18}H_{21}IO_2$: C, 54.56; H, 5.34. Found: C, 54.33; H, 5.41.

Iodo Acetal 5. A solution of 5-bromopentanal (5.50 g, 33.00 mmol), benzyl alcohol (7.20 g, 73.00 mmol), and *p*-toluenesulfonic acid (catalytic amount) in benzene (200 mL) were heated at reflux (Dean Stark trap), cooled to 25 °C, washed with a saturated solution of $NaHCO_3$, dried with $MgSO_4$, filtered, and concentrated under reduced pressure. Chromatography [SiO_2 (120 g), elution hexane, EtOAc 10%] afforded the bromo acetal (8.80 g, 73%) as a liquid. This bromoacetal (8.80 g, 24.00 mmol) was added to a solution of sodium iodide (7.30 g, 48.00 mmol) in acetone (110 mL). After addition, the mixture was heated at reflux for 1 h, cooled to 25 °C, concentrated, diluted with EtOAc, washed with brine and a saturated solution of sodium thiosulfate, dried with $MgSO_4$, filtered, and concentrated. Chromatography [SiO_2 (120 g), elution hexane, EtOAc 10%] afforded compound **5** (9.70 g, 97%) as a pale yellow liquid: ^1H NMR δ 1.47–1.55 (m, 2H, CH_2), 1.72–1.84 (m, 4H, CH_2) 3.15 (t, 2H, J = 6.9 Hz, CH_2I), 4.55 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.65 (d, 2H, J = 11.7 Hz, OCH_2-Ph), 4.73 (t, 1H, J = 5.7 Hz, CHOBn), 7.24–7.35 (m, 10H, Ar); ^{13}C NMR δ 6.59, 25.59, 32.11, 33.04, 67.19 (OCH_2Ph), 101.71 (CHOBn), 127.53, 127.68, 128.34, 138.06 (Ar). Anal. Calcd for $C_{19}H_{23}IO_2$: C, 55.62; H, 5.65. Found: C, 55.39; H, 5.61.

Carbene Complex 6. Following the general procedure (method A), carbene complex **6** was prepared from $Cr(CO)_6$

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(2.31 g, 10.50 mmol), MeLi (8.40 mL, 12.60 mmol, 1.5 M in Et_2O), $(nBu)_4NBr$ (0.32 g, 1.00 mmol,) and iodo acetal **8** (4.00 g, 10.00 mmol). Chromatography [SiO_2 (200 g), elution hexane, EtOAc 20%] afforded carbene complex **6** (3.84 g, 76%) as an orange oil: ^1H NMR δ 1.94–1.99 (m, 2H, CH_2), 2.05–2.12 (m, 2H, CH_2), 2.89 (s, 3H, CH_3), 4.58 (d, 2H, J = 11.7 Hz, OCHPh), 4.69 (d, 2H, J = 11.7 Hz, OCHPh), 4.81 (t, 1H, J = 5.4 Hz, CHOBn), 4.90 (s (broad), 2H, Cr=$COCH_2$), 7.24–7.38 (m, 10H, Ar); ^{13}C NMR δ 24.92, 30.19, 68.12 (OCH_2Ph), 101.81 (CHOBn), 128.14, 128.85, 138.33 (Ar), 216.83 (C≡O), 223.70 (C≡O), 358.36 (Cr=C). Anal. Calcd for $C_{25}H_{24}O_8Cr$: C, 59.52; H, 4.80. Found: C, 59.58; H, 5.00.

Carbene Complex (7). Following the general procedure (method A), carbene complex **7** was prepared from $Cr(CO)_6$ (1.15 g, 5.20 mmol), MeLi (4.20 mL, 6.20 mmol, 1.5 M in Et_2O), $(nBu)_4NBr$ (0.161g, 0.5 mmol), and iodo acetal **5** (2.00 g, 4.80 mmol). Chromatography [SiO_2 (200 g), elution hexane, EtOAc 20%] afforded carbene complex **7** (0.778 g, 29%) as an orange oil: ^1H NMR δ 1.58–1.67 (m, 2H, CH_2), 1.80–1.86 (m, 2H, CH_2), 1.92–2.03 (m, 2H, CH_2), 2.90 (s, 3H, CH_3), 4.56 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.67 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.76 (t, 1H, J = 5.6 Hz, CHOBn), 4.86 (s (broad), 2H, Cr=$COCH_2$), 7.24–7.38 (m, 10H, Ar); ^{13}C NMR δ 21.15, 29.05, 32.87, 67.43 (OCH_2Ph), 101.77 (CHOBn), 127.65, 127.75, 128.41, 138.09 (Ar), 216.46 (C≡O), 223.33 (C≡O), 357.76 (Cr=C). Anal. Calcd for $C_{26}H_{26}O_8Cr$: C, 60.23; H, 5.66. Found: C, 60.46; H, 5.29.

Hydroxy Acetal 8. $MgSO_4$ (2.00 g) was added to a solution of 3-[(*tert*-butyldimethylsilyl)oxy]propanal (1.45 g, 7.60 mmol), benzyl alcohol (1.71 g, 16.7 mmol), and *p*-toluenesulfonic acid (catalytic amount) in CH_2Cl_2 (40 mL), the mixture was stirrred at 25 °C for 10 h, $NaHCO_3$ (catalytic amount) was added, and the mixture was filtered and concentrated under reduced pressure. Chromatography [SiO_2 (30 g), elution hexane, EtOAc 10%] afforded the acetal **8** (1.28 g, 43%) as a liquid: ^1H NMR δ 0.01 (s, 6H, CH_3Si), 0.85 (s, 9H, CH_3CSi), 1.96 (q, 2H, J = 6.0 Hz, CH_2), 3.71 (t, 2H, J = 6.2 Hz, CH_2OSi), 4.57 (d, 2H, J = 11.4 Hz, OCH_2Ph), 4.66 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.91 (t, 1H, J = 5.5 Hz, CHOBn), 7.24–7.37 (m, 10H, Ar); ^{13}C NMR δ −5.42, 18.20, 25.87, 36.74, 59.13, 67.53 (OCH_2Ph), 99.91 (CHOBn), 127.53, 127.72, 128.37, 138.24 (Ar). Anal. Calcd for $C_{23}H_{34}O_3Si$: C, 71.46; H, 8.86. Found: C, 71.28; H, 8.73.

A solution of tetrabutylammonium fluoride (5.3 mL, 5.30 mmol, 1 M in THF) was added to a solution of silyl ether acetal (1.66 g, 4.20 mmol) in THF (45 mL) at 0 °C. The mixture was slowly warmed to 25 °C and monitored by TLC. After total conversion, a saturated solution of ammonium chloride (40 mL) was added. The aqueous layer was extracted with EtOAc (2 × 25 mL), the organic layers were combined and washed with brine (2 × 40 mL), dried with $MgSO_4$, filtered, and concentrated. Chromatography [SiO_2 (120 g), elution hexane, EtOAc 20%] afforded compound **8** (0.596 g, 86%) as a colorless liquid: ^1H NMR δ 2.00 (dd, 2H, J = 5.5, 11.2 Hz, CH_2), 2.21 (t, 1H, J = 5.7 Hz, HO), 3.74 (dd, 2H, J = 5.6, 11.2 Hz, CH_2-OH), 4.57 (d, 2H, J = 11.4 Hz, OCH_2Ph), 4.66 (d, 2H, J = 11.7Hz, OCH_2Ph), 4.91 (t, 1H, J = 5.5 Hz, CHOBn), 7.24–7.37 (m, 10H, Ar); ^{13}C NMR δ 35.68, 58.81, 67.88 (OCH_2Ph), 101.24 (CHOBn), 127.67, 128.39, 137.72 (Ar). Anal. Calcd for $C_{17}H_{20}O_3$: C, 71.16; H, 8.53. Found: C, 71.37; H, 8.71.

Hydroxy Acetal 9. A solution of 6-[(*tert*-butyldimethylsilyl)oxy]hexanal (1.38 g, 6.00 mmol), benzyl alcohol (1.56 g, 14.4 mmol), and pyridinium *p*-toluenesulfonic acid (catalytic amount) in benzene (80 mL) was heated at reflux (Dean Stark trap), cooled to 25 °C, washed with a saturated solution of $NaHCO_3$, dried with $MgSO_4$, filtered, and concentrated under reduced pressure. Chromatography [SiO_2 (60 g), elution hexane, EtOAc 10%] afforded the acetal (1.63 g, 63%) as a colorless liquid: ^1H NMR δ 0.03 (s, 6H, CH_3Si), 0.87 (s, 9H, CH_3CSi), 1.29–1.54 (m, 6H, CH_2), 1.71–1.79 (m, 2H, CH_2), 3.57 (t, 2H, J = 6.5 Hz, CH_2OSi), 4.54 (d, 2H, J = 11.7 Hz, OCHPh), 4.64 (d, 2H, J = 11.7 Hz, OCHPh), 4.72 (t, 1H, J = 5.8 Hz, CHOBn), 7.24–7.34 (m, 10H, Ar); ^{13}C NMR δ −5.30, 18.31, 24.52, 25.62, 25.94, 32.73, 33.27, 63.07, 67.04 (OCH_2Ph), 102.12 (CHOBn), 127.49, 127.71, 128.34, 138.28 (Ar).

A solution of tetrabutylammonium fluoride (2.70 mL, 2.70 mmol, 1 M in THF) was added to a solution of silyl ether acetal **9** (0.90 g, 2.10 mmol) in THF (30 mL) at 0 °C. The mixture was slowly warmed to 25 °C and monitored by TLC. After total conversion, a saturated solution of ammonium chloride (30 mL) was added. The aqueous layer was extracted with EtOAc (2 × 20 mL), the organic layers were combined and washed with brine (2 × 30 mL), dried with $MgSO_4$, filtered, and concentrated. Chromatography [SiO_2 (120 g), elution hexane, EtOAc 20%] afforded compound **9** (0.57 g, 87%) as a colorless liquid: ^1H NMR δ 1.19 (t, 1H, J = 5.3 Hz, OH), 1.32–1.45 (m, 4H, CH_2), 1.50–1.57 (m, 2H, CH_2), 1.72–1.79 (m, 2H, CH_2), 3.60 (dd, 2H, J = 6.5, 5.6 Hz, CH_2OH), 4.54 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.64 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.73 (t, 1H, J = 5.8 Hz, CHOBn), 7.24–7.34 (m, 10H, Ar); ^{13}C NMR δ 24.43, 25.46, 32.52, 33.15, 62.60, 67.08 (OCH_2Ph), 102.01 (CHOBn), 127.50, 127.70, 128.33, 138.17 (Ar). Anal. Calcd for $C_{20}H_{26}O_3$: C, 76.40; H, 8.33. Found: C, 76.52; H, 8.21.

Carbene Complex 10. Following the general procedure (method B), carbene complex **10** was prepared from [[(tetramethylammonium)oxy](methyl)carbene]pentacarbonylchromium complex (0.55 g, 1.80 mmol), acetyl bromide (0.20 g, 1.60 mmol) and hydroxyl acetal **8** (0.39 g, 1.40 mmol). Chromatography [SiO_2 (120 g), elution hexane, EtOAc 20%] afforded carbene complex **10** (0.602 g, 86%) as an orange oil: ^1H NMR δ 2.39 (q, 2H, J = 6.1 Hz, CH_2), 2.80 (s, 3H, CH_3), 4.59 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.72 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.93 (s (broad), 2H, Cr=$COCH_2$), 4.99 (t, 1H, J = 5.5 Hz, CHOBn), 7.24–7.38 (m, 10H); ^{13}C NMR δ 33.48, 68.08 (OCH_2Ph), 98.76 (CHOBn), 127.85, 128.48, 137.61 (Ar), 216.36 (C≡O), 223.31 (C≡O), 358.50 (Cr=C).

Carbene Complex 11. Following the general procedure (method B), carbene complex **11** was prepared from [[(tetramethylammonium)oxy](methyl)carbene]pentacarbonylchromium complex (1.00 g, 3.25 mmol), acetyl bromide (0.35 g, 2.86 mmol), and hydroxyl acetal **9** (0.78 g, 2.49 mmol). Chromatography [SiO_2 (120 g), elution hexane, EtOAc 20%] afforded carbene complex **11** (1.27 g, 93%) as an orange oil: ^1H NMR δ 1.48–1.53 (m, 4H, CH_2), 1.76–1.81 (m, 2H, CH_2), 1.93–2.04 (m, 2H, CH_2), 2.91 (s, 3H, CH_3), 4.56 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.66 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.75 (t, 1H, J = 5.7 Hz, CHOBn), 4.88 (s (broad), 2H, Cr=$COCH_2$), 7.24–7.38 (m, 10H, Ar); ^{13}C NMR δ 24.30, 25.67, 29.20, 33.14, 67.29 (OCH_2Ph), 101.95 (CHOBn), 127.73, 128.38, 138.19 (Ar), 216.47 (C≡O), 223.33 (C≡O), 357.56 (Cr=C).

General Procedure for the Hydrolysis of the Acetals. A solution of carbene complex (1 equiv) in CH_2Cl_2 (0.18–0.2 M) was added to a suspension of $SnCl_2{\cdot}2H_2O$ (1 equiv) or $SnCl_2{\cdot}2H_2O$ (1 equiv) and naphthalene (1 equiv) in CH_2Cl_2 (0.18–0.2 M) at 0 °C. The mixture was held to 25 °C and stirred for 1 h at this temperature, and $NaHCO_3$ (1 equiv) was added. After 0.5 h of stirring at 25 °C, the mixture was filtered through a short pad of silica gel and concentrated under reduced pressure.

Carbene Complex 13. Following the general procedure, aldehyde complex **12** was prepared from carbene complex **6** (0.60 g, 1.12 mmol), $SnCl_2{\cdot}2H_2O$ (0.32 g, 1.12 mmol), naphthalene (0.151 g, 1.12 mmol), and $NaHCO_3$ (0.09 g, 1.12 mmol). Chromatography [SiO_2 (120 g), elution hexane, EtOAc 10%] afforded carbene complex **6** (0.15 g, 25%) and aldehyde complex **13** (0.20 g, 50%) as an orange oil: ^1H NMR δ 2.31 (td, 2H, J = 6.6 Hz, CH_2), 2.73 (t, 2H, J = 6.9 Hz, CH_2), 2.93 (s, 3H, CH_3), 4.90 (s (broad), 2H, Cr=$COCH_2$), 9.84 (s, 1H, CH=O); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 21.85, 40.01, 200.36 (CH=O), 216.32 (C≡O), 223.26 (C≡O), 359.00 (Cr=C). Anal. Calcd for $C_{11}H_{10}O_7Cr$: C, 43.15; H, 3.29. Found: C, 42.95; H, 3.38.

Carbene Complex 14. Following the general procedure, aldehyde complex **14** was prepared from carbene complex **7** (0.75 g, 1.43 mmol), $SnCl_2{\cdot}2H_2O$ (0.32 g, 1.43 mmol), naphthalene (0.18 g, 1.43 mmol), and $NaHCO_3$ (0.12 g, 1.43 mmol). Chromatography [SiO_2(120 g), elution hexane, EtOAc 10%] afforded carbene complex **7** (0.20 g, 26%) and aldehyde complex **14** (0.28 g, 59%) as an orange oil: ^1H NMR δ 1.80–1.90 (m, 2H, CH_2), 1.97–2.05 (m, 2H, CH_2), 2.57 (t, 2H, J = 6.8 Hz, CH_2), 2.93 (s, 3H, CH_3), 4.90 (s (broad), 2H, Cr=$COCH_2$), 9.80 (s, 1H, CH=O); ^{13}C NMR δ 18.47, 28.68, 43.16, 49.35 (broad), 80.61 (broad), 201.39 (CH=O), 216.43 (C≡O), 223.36 (C≡O),

358.32 (Cr=C). Anal. Calcd for $C_{12}H_{12}O_7Cr$: C, 45.01; H, 3.78. Found: C, 45.09; H, 4.00.

Carbene Complex 15. Following the general procedure, aldehyde complex **15** was prepared from carbene complex **11** (0.54 g, 1.00 mmol), $SnCl_2{\cdot}2H_2O$ (0.22 g, 1.00 mmol), naphthalene (0.12 g, 1.00 mmol), and $NaHCO_3$ (0.08 g, 1.00 mmol). Chromatography [SiO_2 (120 g), elution hexane, EtOAc 10%] afforded carbene complex **11** (0.16 g, 29%) and aldehyde complex **15** (0.22 g, 63%) as an orange oil: ^{1}H NMR δ 1.51–1.60 (m, 2H, CH_2), 1.73 (tt, 2H, J = 7.3 Hz, CH_2), 2.00 (tt, 2H, J = 7.3 Hz, CH_2), 2.50 (dt, 2H, J = 1.5, 7.1 Hz, CH_2), 2.92 (s, 3H, CH_3), 4.88 (s (broad), 2H, Cr=$COCH_2$), 9.77 (t, 1H, J = 1.5 Hz, CH=O); ^{13}C NMR δ 21.45, 25.36, 28.99, 43.46, 49.00 (broad), 80.74 (broad), 201.82 (CH=O), 216.38 (C≡O), 223.33 (C≡O), 357.84 (Cr=C).

General Procedure for the Photolysis Reactions. A solution of $ZnCl_2$ (0.3 equiv, 1 M in Et_2O) was added to a solution of carbene complex (1 equiv) in CH_2Cl_2 or THF (0.05 M) in a pressure tube at 25 °C. The tube was fitted with a pressure head, and the mixture was saturated with CO and irradiated (450-W Conrad Hanovia 7825 medium-pressure mercury lamp) under 60 psi of CO at 25 °C. The mixture was filtered through Celite and concentrated under reduced pressure.

β-Lactone 16. Following the general procedure β-lactone **16** was prepared from carbene complex **13** (0.16 g, 0.49 mmol) and $ZnCl_2$ (0.15 mL, 0.15 mmol, 1 M in CH_2Cl_2 in Et_2O) in CH_2Cl_2 after 6 h of photolysis. Chromatography (SiO_2, elution hexane, EtOAc 20%) afforded β-lactone **16** (0.035 g, 50%) as a colorless liquid: ^{1}H NMR δ 1.50 (s, 3H, CH_3), 1.66–1.88 (m, 2H, CH_2), 2.05 (dddd, 1H, J = 15.5, 4.3, 6.8, 9.4 Hz, CH_2), 2.23 (dddd, 1H, J = 15.5, 2.6, 5.5, 6.0 Hz, CH_2), 3.89 (t, 2H, J = 6.7 Hz, OCH_2), 4.52 (dd, 1H, J = 2.6, 4.2 Hz, CH); ^{13}C NMR δ 16.15, 19.93, 22.89, 63.43, 77.16, 84.86, 172.64 (C=O); IR (NaCl film) ν 1830 cm^{-1} (C=O). Anal. Calcd for $C_7H_{10}O_3$: C, 59.14; H, 7.09. Found: C, 59.00; H, 6.86.

β-Lactone 17. Following the general procedure β-lactone **17** was prepared from carbene complex **14** (0.17 g, 0.5 mmol) and $ZnCl_2$ (0.15 mL, 0.15 mmol, 1 M in Et_2O) in CH_2Cl_2 after 8 h of photolysis. Chromatography (SiO_2, elution hexane, EtOAc 20%) afforded β-lactone **17** (0.045 g, 58%) as a colorless liquid: ^{1}H NMR δ 1.56 (s, 3H, CH_3), 1.57–1.81 (m, 5H, CH_2), 2.25–2.31 (m, 1H, CH_2), 3.55 (ddd, 1H, J = 12.9, 10.9, 1.9 Hz, OCH_2), 4.01 (dt, 1H, J = 13.2, 3.3 Hz, OCH_2), 4.61 (dd, 1H, J = 5.4, 1.9 Hz, CH); NOE experiments showed a strong effect between the methyl at 1.56 ppm and the methine at 4.61 ppm in good accord with a cis stereochemistry; ^{13}C NMR δ 21.61, 21.79, 29.95, 32.54, 70.67, 85.99, 90.84, 171.78 (C=O); IR (NaCl film) ν 1823 cm^{-1} (C=O). Anal. Calcd for $C_8H_{12}O_3$: C, 61.52; H, 7.74. Found: C, 61.36; H, 7.94.

β-Lactone 18. A solution of $(CH_3)_2AlCl$ (0.03 mL, 0.03 mmol, 1 M in hexane) was added to a solution of carbene complex **15** (0.05 g, 0.14 mmol) in CH_2Cl_2 (15 mL) in a pressure tube at 25 °C. The tube was fitted with a pressure head, and the mixture was saturated with CO, stirred, and irradiated (450-W Conrad Hanovia 7825 medium-pressure mercury lamp) under 60 psi of CO for 6 h at 25 °C. The mixture was concentrated under reduced pressure, diluted with pentane/Et_2O 10%, filtered through Celite, and concentrated under reduced pressure. Chromatography [SiO_2 (10 g), elution hexane, EtOAc 20%] afforded β-lactone **18** (0.002 g, 8%) as a colorless liquid: ^{1}H NMR δ 1.20–1.35 (m, 2H, CH_2), 1.45 (ddd, 1H, J = 3.3, 9.1, 12.9 Hz, CH_2), 1.53–1.75 (m, 1H, CH_2), 1.66 (s, 3H, CH_3), 1.76–1.90 (m, 2H, CH_2), 1.97 (m, 1H, CH_2), 2.11 (dtt, 1H, J = 13.4, 2.9, 6.1 Hz, CH_2), 3.66 (ddd, 1H, J = 3.1, 10.1, 13.3 Hz, OCH_2), 3.80 (dt, 1H, J = 4.2, 12.7 Hz, OCH_2), 4.24 (dd, 1H, J = 2.8, 11.3 Hz, CH); NOE experiments showed a strong effect between the methyl at 1.66 ppm and the methine at 4.21 ppm in good accord with a cis stereochemistry; ^{13}C NMR δ 16.99, 25.77, 28.88, 29.01, 65.44, 84.60, 86.43, 171.51 (C=O); IR (NaCl film) ν 1833 cm^{-1} (C=O).

Carbene Complex 19. Pyridine (0.08 g, 1.05 mmol) was added to a solution of hydroxy acetal **8** (0.24 g, 1.00 mmol) in CH_2Cl_2 (2.5 mL) at −78 °C. After 10 min of stirring at −78 °C, triflic anhydride (0.30 g, 1.05 mmol) was added and the mixture stirred for 5 min at −78 °C. H_2O (3 mL) was added, and the mixture was transferred to a separatory funnel. The organic layer was dried with $MgSO_4$ at 0 °C, filtered, and concentrated under reduced pressure to afforded the triflate (0.36 g) as an unstable oil which was used directly in the alkylation reaction:[19] ^{1}H NMR δ 2.21 (q, 2H, J = 6.3 Hz, CH_2), 4.55 (d, 2H, J = 11.6Hz, OCHPh), 4.62 (t, 2H, J = 6.4 Hz, $TfOCH_2$), 4.68 (d, 1H, J = 11.6 Hz, OCHPh), 4.88 (t, 1H, J = 5.5 Hz, CHOBn), 7.24–7.39 (m, 10H, Ar).

A solution of butyllithium (0.44 mL, 0.70 mmol, 1.6 M in hexane) was added to a solution of carbene complex **1** (0.17 g, 0.70 mmol) in THF (10 mL) at −78 °C. After 10 min of stirring at −78 °C, a solution of triflate in THF (1 mL) was added. The mixture was held at 0 °C and stirred for 20 min at this temperature. A saturated solution of $NaHCO_3$ (10 mL) was added, and the mixture was stirred at 25 °C for 2 h, diluted with Et_2O (20 mL), washed with brine (30 mL), dried with $MgSO_4$, filtered, and concentrated under reduced pressure. The crude mixture was adsorbed on silica gel, and chromatography [SiO_2 (120 g), elution hexane, EtOAc 10%] afforded carbene complex **1** (0.025 g, 15%), carbene complex **19** (0.086 g, 25%), and the dialkylated carbene complex (0.026 g, 5%).[20] Carbene complex **19**: orange oil; ^{1}H NMR δ 1.50–1.58 (m, 2H, CH_2), 1.59–1.76 (m, 2H, CH_2), 3.32 (t, 2H, J = 7.6 Hz, Cr=CCH_2), 4.53 (d, 2H, J = 11.7 Hz, OCH_2Ph), 4.64 (d, 2H, J = 11.8 Hz, OCH_2Ph), 4.70 (t, 1H, J = 5.5 Hz, CHOBn), 4.73 (s, 3H, Cr=$COCH_3$), 7.24–7.37 (m, 10H, Ar); ^{13}C NMR δ 21.27, 32.65, 62.49, 67.37, 101.62 (CHOBn), 127.60, 127.70, 128.38, 138.04 (Ar), 216.29 (C≡O), 223.00 (C≡O), 362.61 (Cr=C).

Dialkylated carbene complex: orange oil; ^{1}H NMR δ 1.24–1.35 (m, 2H, CH_2), 1.55–1.70 (m, 4H, CH_2), 1.75–1.81 (m, 2H, CH_2), 3.95 (quint, 1H, J = 6.3 Hz, Cr=CCH), 4.48–4.54 (m, 4H, OCH_2Ph), 4.58–4.66 (m, 6H, CHOBn and OCH_2Ph), 4.72 (s, 3H, Cr=$COCH_3$), 7.24–7.37 (m, 20H); ^{13}C NMR 26.83, 31.26, 67.07, 67.50, 67.95, 70.25, 101.93 (CHOBn), 127.63, 127.72, 128.41, 138.04 (Ar), 216.23 (C≡O), 222.78 (C≡O), 367.67 (Cr=C).

Carbene Complex 20. Following the general procedure, aldehyde complex was prepared from carbene complex **19** (0.20 g, 0.40 mmol), $SnCl_2{\cdot}2H_2O$ (0.09 g, 0.40 mmol), and $NaHCO_3$ (0.035 g, 0.40 mmol). Chromatography [SiO_2 (30 g), elution hexane, EtOAc 10%] afforded carbene complex **19** (0.031 g, 16%) and aldehyde complex **20** (0.076 g, 62%) as an orange oil: ^{1}H NMR δ 1.80 (tt, 2H, J = 7.5 Hz, CH_2), 2.45 (t, 2H, J = 7.3 Hz, CH_2CHO), 3.34 (t, 2H, J = 7.7 Hz, Cr=CCH_2), 4.78 (s, 3H, CH_3), 9.74 (s, 1H, CHO); ^{13}C NMR δ 18.36, 42.82, 61.80, 67.75, 201.06 (CH=O), 216.18 (C≡O), 222.90 (C≡O), 362.06 (Cr=C).

β-Lactone 21. Following the general procedure β-lactone **21** was prepared from carbene complex **20** (0.040 g, 0.013 mmol) and $ZnCl_2$ (0.03 mL, 3.5 × 10^{-3} mmol, 1 M in Et_2O) in THF after 20 h of photolysis. The mixture was diluted with Et_2O (10 mL), washed with a 2% solution of $NaHCO_3$, dried with $MgSO_4$, filtered, and concentrated. Chromatography [SiO_2 (15 g), elution hexane, EtOAc 20%] afforded β-lactone **21** (0.013 g, 72%) as a colorless liquid: ^{1}H NMR δ 1.61–1.84 (m, 3H, CH_2), 1.90–1.98 (m, 1H, CH_2), 2.14–2.20 (m, 1H, CH_2), 2.23–2.30 (m, 1H, CH_2), 3.51 (s, 3H, OCH_3), 5.15 (d, 1H, J = 2.7 Hz, CH); ^{13}C NMR δ 20.70, 29.80, 31.92, 55.54, 80.16, 99.87, 170.52 (C=O); IR (NaCl film) ν 1825 cm^{-1} (C=O). Anal. Calcd for $C_7H_{10}O_3$: C, 59.14; H, 7.09. Found: C, 59.00; H, 7.12.

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(19) For similar transformation see Beard, C. D.; Baum, K.; Grakauskas, V. *J. Org. Chem.* **1973**, *38*, 3673.

(20) For similar transformation see: Xu, Y.-C.; Wulf, W. D. *J. Org. Chem.* **1987**, *52*, 3263.