Table II. Dihedral Angles (in deg) within Complexes 3 and 4

dihedral angle	complex 3	analogous angle in complex 4
O2-C2-Fe-C1	162.5	169
Fe-P-C11-C16	86.0	67
C2-Fe-P-C11	60.0	34

organolithium reagents was noticeably slower than analogous reactions using **1A** and **1B**, presumably due to the more electron-donating nature of alkylphosphine vs arylphosphine ligands.[8] Tetramethylethylene diamine (TMEDA) was necessary to obtain good yields of adducts in the addition of methyllithium to complex **1D**. Lower diastereoselectivities were obtained with TMEDA present, presumably due to disruption of methyllithium aggregates,[9] which would make methyllithium sterically smaller.

It is postulated that steric interaction between a phenyl ring, twisted out of plane, and the acetyl oxygen is the cause of the conformational locking of the acetyl ligand of complex **4**. As can be seen from the X-ray structure of complex **3**[10] (Figure 1), the acetyl oxygen is anti with respect to the carbonyl ligand, in spite of the absence of tilted phenyl rings (Table II; Fe-P-C11-C16 dihedral angle = 86° in complex **3**, compared to a value of 67° for the corresponding dihedral angle in complex **4**). Clearly, the stability associated with the anti conformation does not arise simply from steric interactions involving tilted phenyl rings. The phenyl ring in **3** is situated directly underneath the acetyl ligand, which presumably accounts for the high stereoselectivity observed in Michael addition reactions to complex **1C**. If steric interactions are not responsible for conformational locking of the acyl ligand, then similar conformational preferences can be expected in complex **1D** as well, where the bulky *n*-butyl groups can effectively block one face of the acyl ligand. As can be seen in entries 6 and 7, the Michael addition reaction is also highly diastereoselective with the tributylphosphine complex **1D**.

In summary, the reaction of organolithium reagents with α,β-unsaturated acyliron complexes of the type $Cp(CO)(PR_3)FeCOCH{=}CHR'$, is highly diastereoselective. This high diastereoselectivity can be obtained regardless which phosphine ligand is present at iron; a triphenylphosphine ligand is not required to obtain high diastereoselectivity. Contrary to earlier suggestions, conformational preferences of the acyl group in these complexes is clearly due to more than steric interactions between the acyl oxygen and the aryl groups of a triphenylphosphine ligand. We are further investigating the reasons for this conformational locking and its potential for further use in organic synthesis.

Acknowledgment. We thank the donors of Petroleum Research Fund, administered by the American Chemical Society, the State of Maryland, and the General Research Board of the University of Maryland for financial support of this work. Support by the NSF (CHE-84-02155) for purchase of the diffractometer system is gratefully acknowledged.

Registry No. **1** (L = CO, R = CH_3), 74087-37-9; **1** (L = CO, R = Ph), 72028-88-7; **1A** (R = CH_3), 96645-44-2; **1B** (R = CH_3), 114466-65-8; **1C** (R = CH_3), 114466-66-9; **1C** (R = Ph), 114466-67-0; **1D** (R = CH_3), 114466-68-1; **1D** (R = Ph), 114466-69-2; **1E** (R = CH_3), 114490-27-6; **2A** (R = CH_3, R′ = Ph, R″ = H), 41529-61-7; **2B** (R = CH_3, R′ = Ph, R″ = H), 114466-70-5; **2C** (R = CH_3, R′ = Ph, R″ = H), 114466-71-6; **2C** (R = CH_3, R′ = Ph, R″ = CH_3), 114466-72-7; **2C** (R = Ph, R′ = CH_3, R″ = H), 114529-74-7; **2D** (R = CH_3, R′ = Ph, R″ = H), 114466-73-8; **2D** (R = Ph, R′ = CH_3, R″ = H), 114529-75-8; **3**, 32993-87-6; **4**, 114529-76-9; PPh_3, 603-35-0; $P(C_6H_4CF_3)_3$, 13406-29-6; $P(CH_3)_2Ph$, 672-66-2; $P(n\text{-}C_4H_9)_3$, 998-40-3; $P(OPh)_3$, 101-02-0.

Supplementary Material Available: Spectral characterization for the products in Table I and X-ray data (atomic coordinates, temperature factors, bond lengths and angles) for complex **3** (6 pages); structure factors for complex **3** (19 pages). Ordering information is given on any current masthead page.

James W. Herndon,*[1a] Chao Wu[1a]
Herman L. Ammon[1a,b]
Department of Chemistry and Biochemistry and Center for Advanced Research in Biotechnology
University of Maryland
College Park, Maryland 20742
Received December 30, 1987

(8) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. W. *Principles and Applications of Organotransition Metal Chemistry*, 2nd ed.; University Science Books: Mill Valley, CA, 1987; pp 66-72.
(9) Fraenkl, G.; Henrichs, M.; Hewitt, J. M.; Su, B. M.; Geckle, M. J. *J. Am. Chem. Soc.* **1980**, *102*, 3345-3350.
(10) X-ray intensity data collected from a 0.2 × 0.3 × 0.3 mm crystal sealed in a glass capillary on an Enraf Nonius CAD-4 diffractometer (Mo Kα, λ = 0.71069 Å graphite monochromator). Triclinic, $P\bar{1}$, Z = 2, a = 7.494 (2) Å, b = 8.665 (2) Å, c = 12.957 (4) Å, α = 106.85 (3)°, β = 97.96 (3)°, γ = 93.24 (2)°. 3304 total data measured to θ_{max} of 26°; 3261 unique data; 2724 data with $I > 3\sigma(I)$. Structure refinement by full-matrix least-squares with anisotropic temperatures for Fe, P, C, and O and isotopic terms for H. Final R and weighted R values of 0.034 and 0.056. Calculations were performed on a MicroVax II computer with the TEXSAN system of programs.
(11) Davies, S. G.; Dordor-Hedgecock, I. M.; Warner, P. *J. Organomet. Chem.* **1985**, *285*, 213-233. The conformation of the acyl ligand in **4** is virtually identical with that in a similar simple acetyl complex (C_5H_5 ligand replaced by a 1-CH_3-3-$C_6H_5C_5H_3$ ligand).[12]
(12) Attig, T. G.; Teller, R. G.; Wu, S.-M.; Bau, R.; Wojcicki, A. *J. Am. Chem. Soc.* **1979**, *101*, 619-628.

Rhodium Carbenoid Induced Cycloadditions of Substituted 1-Diazo-2,5-pentanediones

Summary: Treatment of substituted 1-diazo-2,5-pentanediones with rhodium(II) acetate results in cyclization of the intermediate rhodium carbenoid to give a six-ring carbonyl ylide which readily undergoes both inter- and intramolecular dipolar cycloadditions.

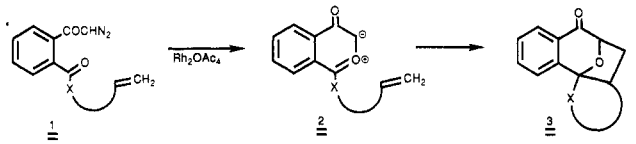
Sir: The role of α-diazo carbonyl compounds in organic synthesis is well established and in recent years much effort has been devoted to the study of the effect of different transition-metal catalysts on these reactions.[1-6] We recently reported that the rhodium metal induced reaction of (enoxycarbonyl)-α-diazoacetophenones results in carbonyl ylide formation followed by intramolecular 1,3-dipolar cycloaddition across the neighboring π-bond.[7] Our initial forays into this tandem cyclization-cycloaddition chemistry involved systems in which the keto rhodium carbenoid and the remote carbonyl were attached in a

(1) Doyle, M. P. *Acc. Chem. Res.* **1986**, *19*, 348. Doyle, M. P.; Dorrow, R. L.; Buhro, W. E.; Griffin, J. H.; Tamblyn, W. H.; Trudell, M. L. *Organometallics* **1984**, *3*, 44. Doyle, M. P.; Van Leusen, D.; Tamblyn, W. H. *Synthesis* **1981**, 787.
(2) Burke, S. D.; Grieco, P. A. *Org. React. (N.Y.)* **1979**, *26*, 361.
(3) Moody, C. J.; Pearson, C.; Lawton, G. *Tetrahedron Lett.* **1985**, 3171.
(4) Hudlicky, T.; Reddy, D. B.; Govindan, S. V.; Kulp, T.; Still, B.; Sheth, J. P. *J. Org. Chem.* **1983**, *48*, 3422.
(5) Wenkert, E.; Alonso, M. E.; Buckwalter, B. L.; Sanchez, E. L. *J. Am. Chem. Soc.* **1983**, *105*, 2021.
(6) Taber, D. F.; Petty, E. H. *J. Org. Chem.* **1982**, *47*, 4808. Taber, D. F.; Petty, E. H.; Raman, K. *J. Am. Chem. Soc.* **1985**, *107*, 196.
(7) Padwa, A.; Carter, S. P.; Nimmesgern, H. *J. Org. Chem.* **1986**, *51*, 1157. Padwa, A.; Carter, S. P.; Nimmesgern, H.; Stull, P. D. *J. Am. Chem. Soc.*, in press.

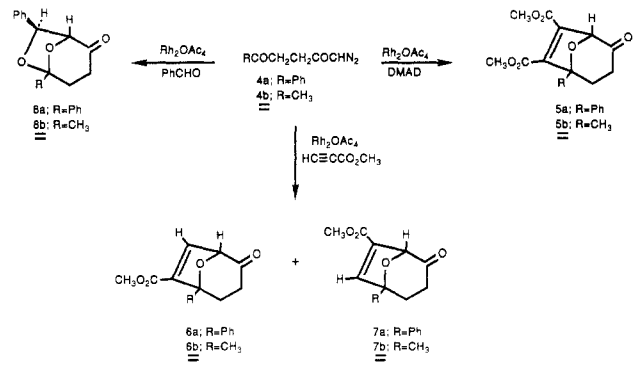
0022-3263/88/1953-2875$01.50/0

1,2-fashion on a benzene ring.[7,8] This arrangement provides interatomic distances and bond angles that are ideal for dipole formation. Our ongoing interest in this procedurally simple methodology brought several questions into focus. What are the geometric and electronic requirements of the remote carbonyl for dipole formation? What sort of stereo- and regioselectivity can be expected in the cycloaddition of these carbonyl ylides? How sensitive are these dipoles to the electronic nature of the dipolarophile? Preliminary results addressing these questions are reported herein.

The initial studies (1→3) utilized relatively nucleophilic carbonyls (i.e., amides and esters) to trap the rhodium carbenoid and form the carbonyl ylide.[8,9] To simultaneously test the geometric and electronic requirements of dipole formation, the 1-diazo-2,5-pentanedione backbone was targeted. Note that in this system the carbonyl ylide is being formed by attack of a less nucleophilic ketonic carbonyl and that the tether in this system is a simple dimethylene chain, introducing a conformational "floppiness" not available in the previously studied benzo systems.

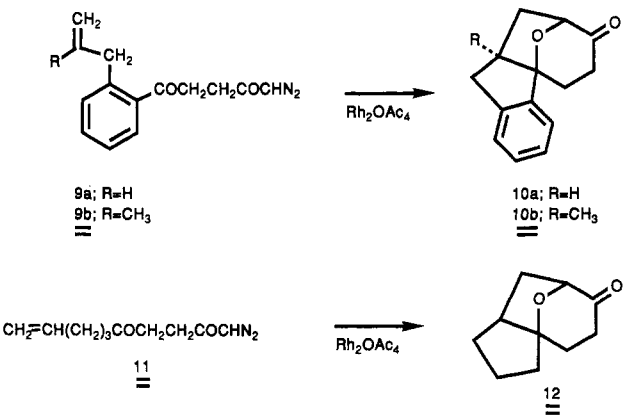


As a consequence of the ready availability of 3-benzoylpropionic acid, 1-diazo-5-phenyl-2,5-pentanedione (**4a**; R = Ph) was the initial system selected for study. Treatment of **4a** with a catalytic amount of rhodium(II) acetate (0.005 mmol) at 25 °C in benzene with dimethyl acetylenedicarboxylate (10% mol excess) afforded cycloadduct **5a** in 93% yield.[10] Similar treatment of **4a** with methyl propiolate produced a 15:1 mixture of bicyclo keto esters **6a** and **7a** (89%), clearly demonstrating the high degree of regioselectivity possible in these reactions.[10] Cycloaddition of the metallocarbenoid derived from **4a** was also carried out in the presence of benzaldehyde. Bicyclic ketal **8a** was the only product isolated.[10] The regioselectivity encountered here correlates nicely with the methyl propiolate cycloaddition.



We also studied the cyclization–cycloaddition chemistry of the closely related 1-diazo-2,5-hexanedione system (R = CH_3) and encountered similar results. Thus, the reaction of **4b** with DMAD in the presence of rhodium(II) acetate afforded **5b** in 88% yield. Treatment of **4b** with methyl propiolate in benzene at 25 °C (Rh_2OAc_4) produced a 4:1 mixture (80%) of the regioisomeric cycloadducts **6b** and **7b**.[10] Reaction with benzaldehyde afforded **8b** in high yield. The orientation observed with these systems can readily be rationalized in terms of maximum overlap of the dipole HOMO–dipolarophile LUMO.[11] MNDO calculations on the carbonyl ylide derived from **4** clearly indicate that the largest coefficient in the HOMO resides on the enolate carbon.[12] This site becomes linked with the less substituted carbon atom of the alkyne.

Among [4 + 2]-cycloadditions, intramolecular 1,3-dipolar cycloadditions are of considerable value and have been applied successfully in the synthesis of many classes of compounds.[13] In this spirit we decided to further explore the synthetic potential of the rhodium carbenoid induced intramolecular cycloaddition of several substituted 1-diazo-2,5-pentanediones. Tetracyclic ketone **10a** was isolated in 98% yield from the tandem cyclization reaction of diazo ketone **9a**. The NMR spectrum of cycloadduct **10a** was a bit complicated since a number of overlapping peaks were present. In order to simplify the spectrum, the reaction of **9b** with rhodium(II) acetate was carried out. The reaction proceeded quite smoothly producing cycloadduct **10b** in 88% yield (NMR ($CDCl_3$, 300 MHz) δ 1.29 (s, 3 H), 1.90 (d, 1 H, J = 13.4 Hz), 2.17 (ddd, 1 H, J = 13.4, 7.1, and 3.1 Hz), 2.56–2.70 (m, 3 H), 2.7–2.9 (m, 1 H), 2.88 (d, 1 H, J = 15.9 Hz), 3.21 (d, 1 H, J = 15.9 Hz), 4.48 (d, 1 H, J = 8.6 Hz), and 7.16–7.41 (m, 4 H)). Molecular mechanics calculations clearly indicate that the isomer containing the endo methyl group at C_7 is less strained (ca. 16 kcal) and so this is the assumed stereochemistry at this position in **10b**.[14] The metal-catalyzed reaction of the closely related diazo ketone **11** was also examined. We found that an analogous reaction occurred to give cycloadduct **12** in good yield.



In contrast to the results obtained earlier with the (enoxycarbonyl)-α-diazoacetophenone system **1**, no bimolecular trapping product was observed when the reaction of **9** was carried out in the presence of an activated dipolarophile (i.e., DMAD). In the benzo system, a second

(8) Padwa, A.; Stull, P. D. *Tetrahedron Lett.* **1987**, 5407.

(9) For some related cases, see: Taylor, K. G. *Tetrahedron* **1982**, *38*, 159. Ibata, T.; Toyoda, J.; Sawada, M.; Takai, Y.; Tanaka, T. *Tetrahedron Lett.* **1988**, 317.

(10) Compound **5a**: NMR ($CDCl_3$, 300 MHz) δ 2.52–2.75 (m, 2 H), 2.77–3.01 (m, 2 H), 3.64 (s, 3 H), 3.78 (s, 3 H), 5.06 (s, 1 H), 7.15–7.55 (m, 5 H). Compound **6a**: NMR δ 2.50–2.90 (m, 4 H), 3.62 (s, 3 H), 4.89 (d, 1 H, J = 2.3 Hz), 7.10 (d, 1 H, J = 2.3 Hz), 7.2–7.5 (m, 5 H). Compound **7b**: NMR δ 1.50 (s, 3 H), 1.9–2.7 (m, 4 H), 3.80 (s, 3 H), 4.78 (s, 1 H), and 7.01 (s, 1 H).

(11) Fleming, I. *Frontier Orbitals and Organic Chemical Reactions*; Wiley: New York, 1976.

(12) Calculations were performed with the Ampac program (QCPE 506) using the AM1 Hamiltonian. The calculations show that the HOMO is located at −7.83 eV and the LUMO at −1.43 eV for the carbonyl ylide derived from **4a** with coefficients of +0.66 (C_2) and −0.51 (C_4) in the HOMO.

(13) *1,3-Dipolar Cycloaddition Chemistry*; Padwa, A., Ed.; Wiley-Interscience: New York, 1984, Chapter 12.

(14) We have used the MMX88 program as parameterized by Gajewski and Gilbert and implemented in the program Model 2.9 to calculate the total energy of the endo (37.64 kcal) and exo (54.01 kcal) methyl isomers.

heteroatom (O or N from the ester or amide) is present, which further stabilizes the formal cationic terminus of the dipole. This stabilization sufficiently retards the rate of intramolecular cycloaddition with the tethered olefin to allow bimolecular cycloaddition with an activated alkyne to predominate. In the case of **9**, however, this stabilization is absent and the intramolecular cycloaddition to the internal π-bond is too rapid to allow bimolecular trapping of the intermediate carbonyl ylide.

The high efficiency of the cycloaddition coupled with the simplicity of the procedure promises to provide an efficient route to a variety of oxapolycycles. The tandem cyclization–cycloaddition sequence allows for the creation of three new rings containing two (or more) contiguous quaternary centers with fixed stereochemistry in a single step. We are continuing to explore the scope and mechanistic details of the reaction and will report additional findings at a later date.

Acknowledgment. We gratefully acknowledge the National Cancer Institute for generous support of this work.

Registry No. **4a**, 114491-32-6; **4b**, 114491-34-8; **5a**, 114491-33-7; **5b**, 114491-35-9; **6a**, 114491-36-0; **6b**, 114491-43-9; **7a**, 114491-37-1; **7b**, 114491-44-0; **8a**, 114491-38-2; **8b**, 114491-45-1; **9a**, 114491-39-3; **9b**, 114491-46-2; **10a**, 114491-40-6; **10b**, 114491-47-3; **11**, 114491-41-7; **12**, 114491-42-8; $Rh_2(OAc)_4$, 15956-28-2; $HC{\equiv}CCO_2CH_3$, 922-67-8; PhCHO, 100-52-7.

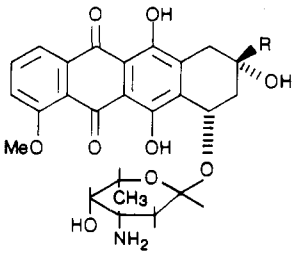
Albert Padwa,* Glen E. Fryxell, Lin Zhi
Department of Chemistry
Emory University
Atlanta, Georgia 30322
Received January 29, 1988

Photodemethylation of Methoxy-Substituted 9,10-Anthraquinones in Methanol

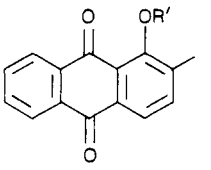
Summary: Irradiation of methoxy-substituted 9,10-anthraquinones with visible or ultraviolet light results in a demethylation reaction involving free radical intermediates.

Sir: 9,10-Anthraquinones comprise an important class of compounds that are used as dyes,[1] function as catalysts in the delignification of wood,[2] and bear a substitution pattern reminiscent of the clinically important antitumor anthracyclines **1**. As a result, considerable effort has been directed toward the synthesis of not only anthraquinones[3] but also anthracyclines[4] and their analogues.[5]

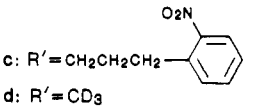
We recently prepared a variety of methoxy-substituted 9,10-anthraquinones as models for the antitumor anthracyclines daunorubicin (**1a**) and adriamycin (**1b**).[6] Solutions of several of these compounds in methanol became intensely yellow upon exposure to room light. In this report we present our preliminary findings on this photochemical process which appears to involve free radical intermediates.



1a: R=$COCH_3$
b: R=$COCH_2OH$



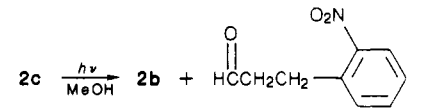
2a: R'=CH_3
b: R'=H



c: R'=$CH_2CH_2CH_2$
d: R'=CD_3

Exposure of solutions of 1-methoxy-2-methyl-9,10-anthraquinone (**2a**) in methanol (0.5–1.0 mM) to a tungsten lamp or xenon chloride eximer laser (308 nm) in the presence or absence of oxygen led to nearly a quantitative yield of 1-hydroxy-2-methyl-9,10-anthraquinone (**2b**) following removal of solvent. This photodemethylation does not occur in $CHCl_3$ or CCl_4 or in the absence of solvent, but does occur in other protic solvents such as ethanol, 1-propanol, 2-propanol, and 2-methyl-2-propanol, albeit at slightly lower rates.

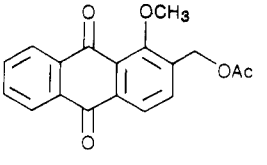
We were unable to determine the fate of the methyl group in this reaction using standard analytical techniques. Consequently, anthraquinone **2c** was prepared to facilitate isolation and identification of the other cleavage product. The 3-(*o*-nitrophenyl)propyl group, which is stable toward tungsten light, was chosen as a substitute for CH_3 in **2a** because it absorbs strongly in the ultraviolet and is relatively nonvolatile. Photolysis of **2c** (0.5 mM in methanol) with a 300-W tungsten lamp for 15 h led to greater than 80% isolated yields of **2b** and 3-(*o*-nitrophenyl)propanal (eq 1). Plots of ln [**2b**] vs time for the photolysis of **2a**



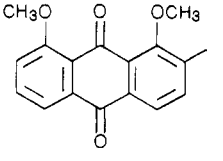
(1)

and **2c** under identical conditions were linear and had comparable slopes. Thus, it is likely that similar mechanisms are operative in the photolysis of these compounds.

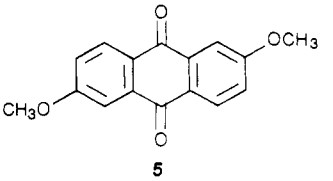
How general is this photodemethylation? Anthraquinone **3** cleanly demethylates to 1-hydroxy-2-(acetoxymethyl)-9,10-anthraquinone with a quantum yield of 0.050. Anthraquinone **4**, which possesses two methoxy groups, demethylates stepwise when a 308-nm laser is used, but at a much lower rate than **2a**. Anthraquinone **5**, also undergoes photolysis slowly like **4**, but produces a complex mixture of products that have not been identified. In-



3



4



5

(1) Lubs, H. A., Ed. *The Chemistry of Synthetic Dyes and Pigments*; Reinhold: New York, 1955; Chapter 7.
(2) Holton, H. H. *Pulp Paper Can.* **1977**, *78*, T218.
(3) (a) Banville, J.; Brassard, P. *J. Chem. Soc., Perk. Trans. 1* **1976**, *613*. (b) Brisson, C.; Brassard, P. *J. Org. Chem.* **1981**, *46*, 1810. (c) Russell, R. A.; Warrener, R. N. *J. Chem. Soc., Chem. Commun.* **1981**, 108. (d) Savard, J.; Brassard, P. *Tetrahedron* **1984**, *40*, 3455. (e) Roberge, G.; Brassard, P. *J. Org. Chem.* **1981**, *46*, 4161. (f) Krohn, K. *Tetrahedron Lett.* **1980**, *21*, 3557. (g) Kelly, T. R.; Parekh, N. D.; Trachtenberg, E. N. *J. Org. Chem.* **1982**, *47*, 5009.
(4) (a) Kraus, G. A.; Fulton, B. S. *J. Org. Chem.* **1985**, *50*, 1782. (b) Wulff, W. D.; Jung, P.-C. *J. Am. Chem. Soc.* **1984**, *106*, 434 and references therein.
(5) (a) Kelly, J. R.; Vaya, J.; Ananthasubramonian, L. *J. Am. Chem. Soc.* **1980**, *102*, 5983. (b) Israel, M.; Potti, P. G.; Seshadri, R. *J. Med. Chem.* **1985**, *28*, 1223 and references therein.
(6) Blankespoor, R. L.; Schutt, D. L.; Tubergen, M. B.; De Jong, R. L. *J. Org. Chem.* **1987**, *52*, 2059.

0022-3263/88/1953-2877$01.50/0