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New Oxidative Demetalation Protocol for Molybdenum π-Complexes: Enantiocontrolled Synthesis of Unsaturated Ketones and Lactones

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Received January 2, 2002

An efficient and general oxidative demetalation of (η^3-allyl)molybdenum complexes using pyridinium dichromate allows the introduction of a carbonyl group at an allylic terminus of the π-system. The process takes place with high regiocontrol and can lead to the preparation of unsaturated ketones and lactones of high enantiopurity.

Introduction

The ability of stoichiometric (η^3-allyl)molybdenum complexes of high enantiopurity to participate in multiple and sequential, regio- and stereocontrolled bond constructions render them potent chiral scaffolds for the asymmetric synthesis of complex organic molecules.[1] Given the efficient preparation and ease of manipulation of these air-stable, solid organometallic intermediates, their synthetic potential depends on efficient and general methods for decomplexation/functionalization that occur with high regio- and stereoselectivity.

A variety of demetalation protocols are known. In 1976 Faller reported that CpMo(CO)$_2$(η^3-allyl) (Cp = η^5-cyclopentadienyl) complexes are easily converted to allyl cation equivalents by replacement of one CO ligand with NO^+ using $NOBF_4$.[2,3] Treatment of the resulting [CpMo(CO)(NO)(π-allyl)]$^+$ cations with nucleophiles such as hydride,[4] deuteride,[5] hydroxyl,[4,5,6] enamines,[5b,7] thiolates,[4,8] dithiocarbamate,[5] malonate,[7b,9] and organocuprates[1h,9a,10] gave the corresponding η^2-alkene complexes which, after simple oxidation (air, ceric ammonium nitrate), afforded the corresponding α-functionalized olefins. Mo complexes carrying a pendant nucleophilic group undergo regiocontrolled, intramolecular nucleophilic addition using this protocol.[1b,8c,11,12] NO^+-based decomplexation protocols have also been extended to analogous TpMo(CO)$_2$(π-allyl) [Tp = hydridotris(1-pyrazolyl)borate] complexes, where oxidative decomplexation of the intermediate η^2-alkene complex occurs spontaneously.[1c,d,f,12]

In 1985 Pearson reported the decomplexation of CpMo(CO)$_2$(π-allyl) complexes by treatment with iodine[13] or bromine.[14] Iodo (or bromo) alkenes are formed by addition

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(1) For a recent review, see: (a) Li, C.-L.; Liu, R.-S. *Chem. Rev.* **2000**, *100*, 3127−3161. For recent examples, see also: (b) Pearson, A. J.; Mesaros, E. F. *Org. Lett.* **2002**, *4*, 2001−2004. (c) Shu, C.; Alcudia, A.; Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2001**, *123*, 12477−12487. (d) Arrayás, R. G.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2001**, *123*, 6185−6186. (e) Yin, J.; Llorente, I.; Villanueva, L. A.; Liebeskind, L. S. *J. Am. Chem. Soc.* **2000**, *122*, 10458−10459. (f) Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem.* **2000**, *65*, 7445−7455. (g) Malinakova, H. C.; Liebeskind, L. S. *Org. Lett.* **2000**, *2*, 4083−4686. (h) Christopher, J. A.; Kocienski, P. J.; Kuhl, A.; Bell, R. *Synlett.* **2000**, 463.

(2) (a) Faller, J. W.; Rosan, A. M. *J. Am. Chem. Soc.* **1976**, *98*, 3388−3389. (b) Faller, J. W.; Rosan, A. M. *J. Am. Chem. Soc.* **1977**, *99*, 4858. See also: (c) Cosford, N. D. P.; Liebeskind, L. S. *Organometallics* **1994**, *13*, 1498−1503.

(3) Faller also described that nucleophilic (π-allyl)Mo(NO)(X)Cp (X = halide) complexes, easily prepared from [(π-allyl)Mo(CO)(NO)Cp]$^+$ by treatment with LiX, reacted with aldehydes to give demetalated secondary homoallylic alcohols stereospecifically in high yields. However, this three-step demetalation protocol has been used only with few acyclic Mo complexes: (a) Faller, J. W.; Nguyen, J. T.; Ellis, W.; Mazzieri, M. R. *Organometallics* **1993**, *12*, 1434−1438 and references therein. See also: (b) Vong, W.-J.; Peng, S.-M.; Lin, S.-H.; Lin, W.-J.; Liu, R.-S. *J. Am. Chem. Soc.* **1991**, *113*, 573−582.

(4) Adams, R. D.; Chodosh, D. F.; Faller, J. W.; Rosan, A. M. *J. Am. Chem. Soc.* **1979**, *101*, 2570−2578.

(5) (a) Faller, J. W.; Chao, K. H.; Murray, H. H. *Organometallics* **1984**, *3*, 1231−1240. (b) Faller, J. W.; Chao, K.-H. *J. Am. Chem. Soc.* **1983**, *105*, 3893−3898.

(6) Faller, J. W.; Chao, K.-H. *Organometallics* **1984**, *3*, 927−932.

(7) (a) Faller, J. W.; Lambert, C. *Tetrahedron* **1985**, *41*, 5755−5760. (b) Faller, J. W.; Lambert, C.; Mazzieri, M. R. *J. Organomet. Chem.* **1990**, *383*, 161−177.

(8) (a) Liao, M.-F.; Lee, G.-H.; Peng, S.-M.; Liu, R.-S. *Organometallics* **1994**, *13*, 4973−4977. (b) Yeh, M.-C. P.; Tsou, C.-J.; Cuang, C.-N.; Lin, H.-C. *J. Chem. Soc., Chem. Commun.* **1992**, 890−891. (c) Wang, S.-H.; Cheng, Y.-C.; Lee, G.-H.; Peng, S.-M.; Liu, R.-S. *Organometallics* **1993**, *12*, 3282−3290.

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(11) (a) Lin, S.-H.; Lush, S.-F.; Cheng, W.-J.; Lee, G.-H.; Peng, S.-M.; Liao, Y.-L.; Wang, S.-L.; Liu, R.-S. *Organometallics* **1994**, *13*, 1711−1719. (b) Lin, S.-H.; Cheng, W.-J.; Liao, Y.-L.; Wang, S.-L.; Lee, G.-H.; Peng, S.-M.; Liu, R.-S. *J. Chem. Soc., Chem. Commun.* **1993**, 1391−1393. (c) Yeh, M.-C.; Chaung, C.-N. *J. Chem. Soc., Perkin Trans. 1* **1996**, 2167−2172.

(12) The first general description of synthetically useful transformations of TpMo(CO)$_2$(η^3-allyl) and TpMo(CO)$_2$(η^4-diene) complexes is documented within the Supporting Information for: (a) Ward, Y. D.; Villanueva, L. A.; Allred, G. D.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1996**, *118*, 897−898. See also: (b) Pearson, A. J.; Douglas, A. R. *Organometallics* **1998**, *17*, 1446−1448. (c) Yin, J.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1999**, *121*, 5811−5812 and references 1c,d,f.

(13) (a) Pearson, A. J.; Khan, M. N. I.; Clardy, J. C.; Cun-Heng, H. *J. Am. Chem. Soc.* **1985**, *107*, 2748−2757. (b) Pearson, A. J.; Khan, M. N. I. *J. Org. Chem.* **1985**, *50*, 5276−5285.

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10.1021/jo020002x CCC: $22.00
Published on Web 07/11/2002

of halide to the intermediate cationic [CpMo(CO)(X)(η^3-allyl)]$^+$ complex, trans to the metal.[15] Poor regiocontrol results with unsymmetrically substituted η^3-allyl complexes.[13a,16] When combined with suitable nucleophiles, iodo and bromo demetalations provide access to nucleophilic substitution products that are conceptually related to the CO/NO$^+$ ligand exchange protocol.[13b,17] Complexes containing a pendant nucleophile such as a carboxylate[13] or hydroxyl group[18] produce cyclization products with high regio- and stereocontrol.

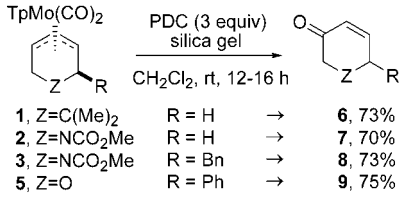
Protodemetalation of Cp and Tp (η^3-allyl)molybdenum complexes has also been achieved with TFA,[9b,12c,19] AcOH/$h\nu$,[1c,e] or HCl[1c,9b] and affords the corresponding alkenes.

Direct oxidative decomplexations are also known. Pearson described an oxidative method for the direct decomplexation of CpMo(CO)$_2$(π-allyl) complexes accompanied by introduction of an OH group.[13a] In a related transformation, cyclic Mo complexes bearing a methoxy group[1f,g,20] at a terminus of the π-allylic system have been oxidatively demetalated with ceric ammonium nitrate or $CuCl_2$ to afford the corresponding α,β-unsaturated ketones.[21,22] As a complement to the preceding demetalation procedures, we report herein a novel, efficient, and general oxidative demetalation of (η^3-allyl)molybdenum complexes that allows the introduction of a carbonyl group at an allylic terminus of the π-system. The process takes place with high regiocontrol and leads to unsaturated ketones and lactones. High enantiopurity (η^3-allyl)-molybdenum complexes lead to high enantiopurity unsaturated ketones and lactones.

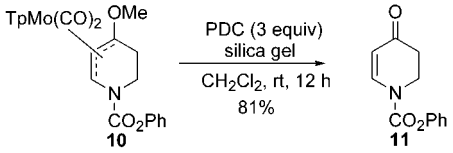
Results and Discussion

When various *non-electron-deficient* carbocyclic and heterocyclic (η^3-allyl)molybdenum complexes were treated with pyridinium dichromate (PDC)/silica gel,[23] demetalations occurred concurrent with oxidation of a terminal position of the π-system. The corresponding α,β-unsaturated ketones were obtained in good yields (Scheme 1).[24] Unsymmetrically substituted complexes (**3**[25] and **5**[26]) gave enones in good yields with the carbonyl group situated at the sterically less hindered terminal position of the allylic system.

SCHEME 1



SCHEME 2



Oxidation of η^3-allyl systems bearing a terminal electron-donating alkoxy substituent occurs at the alkoxy-substituted terminus. For example, the 4-methoxytetrahydropyridinyl−Mo complex **10**[27] was oxidatively demetalated to the tetrahydropyridone **11**[28] in 81% yield and with complete regiocontrol (Scheme 2).

Related alkoxy-directed oxidative demetalations led to the synthesis of the α,β-unsaturated lactones shown in Scheme 3 and Table 1. A range of variously substituted (η-2,3,4-pyranyl)molybdenum (**12**, **13**)[29] and (η-2,3,4-chromenyl)molybdenum complexes (**16**−**20**)[30] were con-

(15) When the anti attack of iodide is sterically disfavored, the metal can deliver the iodo intramolecularly to the face of the π-ligand syn to the molybdenum (see ref 12c).

(16) Chou, S.-S. P.; Sheng, H.-T. *Organometallics* **1996**, *15*, 4113−4115.

(17) Bjurling, E.; Johansson, M. H.; Andersson, C.-M. *Organometallics* **1999**, 5606−5613.

(18) Liao, M. F.; Lee, G.-H.; Peng, S.-M.; Liu, R.-S. *Organometallics* **1994**, *14*, 4973.

(19) Rubio, A.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1993**, *115*, 891−901.

(20) Malinakova, H.; Liebeskind, L. S. *Org. Lett.* **2000**, *2*, 3909−3911.

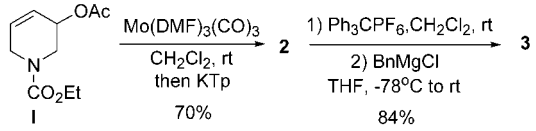
(21) Birch has also reported the transformation of functionalized tricarbonyl(3-methoxycyclohexa-2,4-dien-1-yl)iron complexes into demetalated 5-substituted-2-cyclohexenones using Jones' reagent or PCC: (a) Kelly, L. F.; Dahler, P.; Narula, A. S.; Birch, A. J. *Tetrahedron Lett.* **1981**, *22*, 1433−1436. See also: (b) Pearson, A. J.; Khetani, V. D.; Roden, B. A. *J. Org. Chem.* **1989**, *54*, 5141−5147.

(22) Mo complexes bearing a methyl substituent at an allyl terminus of the π-system can also be demetalated with CAN/Et_3N to afford a diene (see ref 12c).

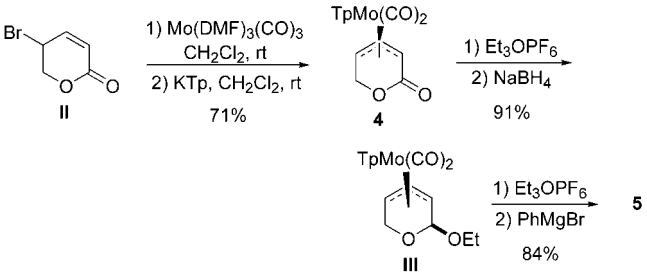
(23) For the use of PCC−silica gel system for oxidation of alcohols to carbonyl compounds, see: Adams, L. L.; Luzzio, F. A. *J. Org. Chem.* **1989**, *54*, 5387−5390.

(24) For synthesis and characterization data for the molybdenum complex **1**, see: McCallum, J. S.; Sterbenz, J. T.; Liebeskind, L. S. *Organometallics* **1993**, *12*, 927−932.

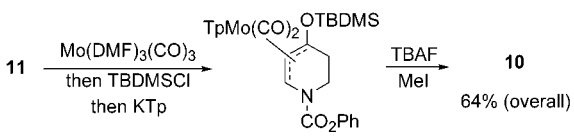
(25) Compounds **2** and **3** were prepared by following the synthetic sequence shown below (see Supporting Information for details). 3-(Acetyloxy)-1-(ethoxycarbonyl)-1,2,3,6-tetrahydropyridine (**I**) was prepared by following a previously described procedure: (a) Imanishi, T.; Shin, H.; Hanaoka, M.; Momose, T.; Imanishi, I. *Chem. Pharm. Bull.* **1982**, *30*, 3617−3623. (b) Imanishi, T.; Imanishi, I.; Momose, T. *Synth. Commun.* **1978**, *8*, 99−102.



(26) Molybdenum complex **5** was prepared from 5-bromo-5,6-dihydro-2*H*-pyran-2-one, **II**, as shown below (see Supporting Information for experimental details and characterization data). For the synthesis of (+)-**4**, (−)-**4**, and (+)-**III**, see ref 12a. For the synthesis of **II**, see: Nakagawa, M.; Saegusa, J.; Tonozuka, M.; Obi, M.; Kiuchi, M.; Hino, T.; Ban, Y. *Org. Synth.* **1977**, *56*, 49.

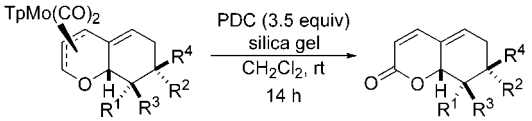


(27) Molybdenum complex **10** was prepared from **11** by following the one-pot sequence shown (see Supporting Information for experimental details and characterization data):



(28) For previous synthesis of **11**, see: (a) Comins, D. L.; Chung, G.; Foley, M. A. *Heterocycles* **1994**, *37*, 1121−1140. (b) Comins, D. L.; Foley, M. A. *Tetrahedron Lett.* **1988**, *29*, 6711−6714.

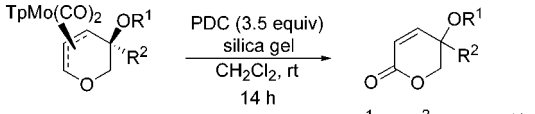
TABLE 1. Oxidative Demetalation of (η^3-Allyl)molybdenum Complexes



cmpd	product	R^1	R^2	R^3	R^4	%	ee (%)[a]
(−)-**16**[b]	(+)-**21**	CO_2Me	H	H	H	85	98
(−)-**17**[b]	(+)-**22**	COMe	H	H	H	80	98
(−)-**18**[c]	(+)-**23**	CHO	H	*n*-Bu	H	72	99.8
(±)-**19**	(±)-**24**	CHO	H	Me	Me	70	
(±)-**20**	(±)-**25**	−CON(Me) CO−		H	H	60	

[a] Measured by chiral HPLC. [b] 98% ee. [c] 99.8% ee.

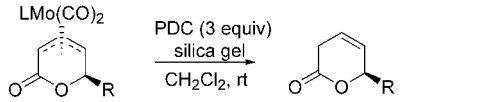
SCHEME 3



12, R^1=H, R^2=vinyl
13, R^1=Ac, R^2=Me

14, R^1=H, R^2=vinyl, 75%
15, R^1=Ac, R^2=Me, 75%

SCHEME 4



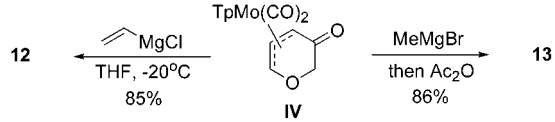
(±)-**4**, L=Tp; R=H	12 h	(±)-**29**, (R=H), 50%
(+)-**26**, L=Tp; R=CH_2OAc	20 h	(-)-**30**, (R=CH_2OAc), 71%
(+)-**27**, L=Cp; R=CH_2OAc	12 h	(-)-**30**, (R=CH_2OAc), 70%
(+)-**28**, L=Tp; R=CH_2OH	15 h[a]	(-)-**31**, (R=CH_2OH), 82%

a) 2 equivalents of PDC were used

verted into the corresponding 5,5-disubstituted dihydropyranones and tetrahydrochromen-2-ones (**21**−**25**),[30] respectively, in good yields. These combined results demonstrate the compatibility of this method with various functional groups.

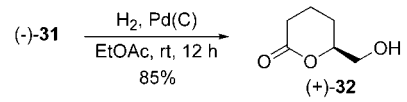
In contrast to the PDC/silica gel mediated oxidation of *non-electron-deficient* (η^3-allyl)molybdenum complexes, treatment of *electron-deficient* (η^3-allyl)molybdenum complexes with PDC/silica gel (CH_2Cl_2, room temperature, 24 h) followed a protodemetalation course. As shown in Scheme 4, three different β,γ-unsaturated lactones (**29**−**31**)[31] were obtained in good yields[32] from the corresponding lactonylmolybdenum complexes (**4** and **26**−**28**)[33] using the PDC/SiO_2 protocol. Surprisingly, no aldehyde was detected by NMR analysis of the crude reaction mixture of (−)-**31**. The hydridotris(pyrazolyl)borate ligand (Tp) does not seem to be a requirement for the success of this procedure, since (+)-**27**[19] (Cp = cyclopentadienyl)

(29) Mo complexes **12** (ref 1d) and **13** (see Supporting Information for experimental details and characterization data) were prepared from **IV** (ref 12c) as shown:



(30) The oxidative demetalation of molybdenum complexes **16**−**19** was previously communicated (ref 1d). A complete description of the synthesis and characterization data for compounds **16**−**19** is found within the Supporting Information for ref 1d. For synthesis and characterization data for compound **20**, see the Supporting Information.

SCHEME 5



$[\alpha]_D^{20}$ = + 35.1 (c 1.3, CH_2Cl_2)
lit $[\alpha]_D^{20}$ = + 34.7 (c 1.3, CH_2Cl_2)

underwent oxidative demetalation as efficiently as its Tp analogue (+)-**26**.

No racemization was observed in the demetalation of the enantiomerically pure Mo complexes **26**−**28**, prepared from D-glucose. Lactone (−)-**31** was transformed into (+)-5-(hydroxymethyl)-δ-valerolactone, (+)-**32**, a versatile intermediate in Corey's synthesis of leukotriene B (Scheme 5).[31i,34]

The mechanism of this oxidative demetalation must accommodate the disparate demetalation paths followed by the electron-deficient and non-electron-deficient (η^3-allyl)molybdenum complexes and account for the observed regioselectivities. Oxidation of the non-electron-deficient (η^3-allyl)molybdenum complexes by PDC would generate a cationic allylmolybdenum (Scheme 6). Those η^3-allyl complexes with a directly attached electron-donating substituent should suffer addition of water anti to the $TpMo(CO)_2$ moiety and adjacent to the electron-donating substituent; for those not bearing an electron-donating substituent, the incoming water would be

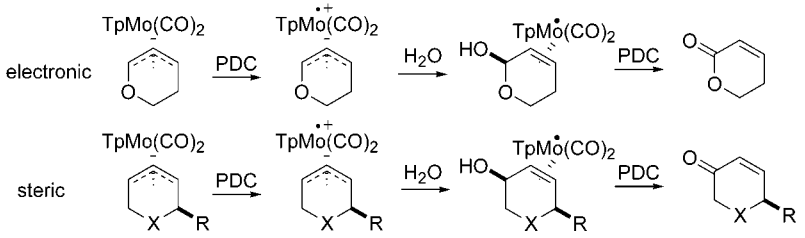
(31) For previous syntheses of **29**, see: (a) Hattori, T.; Suzuki, Y.; Uesugi, O.; Shuichi, O.; Miyano, S. *Chem. Commun.* **2000**, 73−74. (b) Yamada, S.; Matsumoto, M. *Chem. Lett.* **1992**, 2273−2276. (c) Smadja, W.; Zahouily, M.; Malacria, M. *Tetrahedron Lett.* **1992**, *33*, 5511−5514. (d) Stensen, W.; Svedsen, J. S.; Hofer, O.; Sydnes, L. K. *Acta Chem. Scand., Ser. B* **1988**, *B42*, 259−268. (e) Suzuki, M.; Takada, H.; Noyori, R. J. *J. Org. Chem.* **1982**, *47*, 902−904. (f) Nakashima, Y.; Imagawa, T.; Kawanisi, M. *Synth. Commun.* **1979**, *9*, 889−894. (g) Aumann, R.; Ring, H.; Krueger, C.; Goddard, R. *Chem. Ber.* **1979**, *112*, 3644−3671. (h) Bonjouklian, R.; Ruden, R. A. *J. Org. Chem.* **1977**, *42*, 4095−40103. Only one synthesis of (−)-**30** has been described: (i) Corey, E. J.; Pyne, S. G.; Su, W. G. *Tetrahedron Lett.* **1983**, *24*, 4883−4886.

(32) The moderate isolated yield of **29** was attributed to its low boiling point.

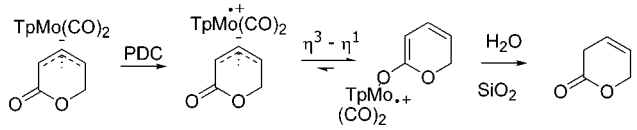
(33) Compound (+)-**28** was obtained from (+)-**26** (ref 12a) after basic hydrolysis of the acetate [LiOH, EtOH, room temperature, 97% (see Supporting Information for details)]. For the synthesis of (+)-**27**, see ref 19.

(34) For previous enantioselective syntheses of (+)-**32**, see: (a) Liu, Z.-Y.; Ji, J.-X.; Li, B.-G. *J. Chem. Soc., Perkin Trans. 1* **2000**, 3519−3521. (b) Coutrot, Ph.; Grison, C.; Bomont, C. *Tetrahedron Lett.* **1994**, *35*, 8381−8384. (c) Lees, W. J.; Whitesides, G. M. *J. Org. Chem.* **1993**, *58*, 1887−1894. (d) Sugita, Y.; Sakaki, J.; Sato, M.; Kaneko, C. *J. Chem. Soc., Perkin Trans. 1* **1992**, 2855−2861. (e) Blaser, F.; Deschenaux, P. F.; Kallimopoulos, T.; Gacot-Guillarmod, A. *Helv. Chim. Acta* **1991**, *74*, 141−145. (f) Leggeri, P.; Azzolina, O.; Pirillo, D.; Traverso, G. *Farmaco* **1989**, *44*, 303−313. (g) Pianetti, P.; Pougny, J. R. *J. Carbohydr. Chem.* **1988**, *7*, 811−815. (h) Gerth, D. B.; Giese, B. *J. Org. Chem.* **1986**, *51*, 3726−3729.

SCHEME 6



SCHEME 7



directed to the sterically least hindered η^3-allyl terminus. In both cases the intermediate allylic alcohols would be oxidized to enones by the excess PDC.

Electron-deficient (η^3-allyl)molybdenum complexes **4** and **26**−**28** followed an unexpected oxidation-induced protodemetalation path (Scheme 7).[35] This can be rationalized by the presumed tendency of the electron-deficient (η^3-allyl)molybdenum complexes to undergo an $\eta^3 \angle \eta^1$ slippage, particularly after oxidation of Mo by PDC diminishes stabilization of the η^3 form through back-bonding. The η^1-molybdenum dienolate should then undergo a well-established kinetic α-protonation.

Conclusions

An efficient and general procedure for the demetalation of molybdenum π-complexes using pyridinium dichromate is reported. The reaction with non-electron-deficient (η^3-allyl)molybdenum complexes allows the introduction of a carbonyl group at an allylic terminus of the π-system, while electron-deficient complexes undergo an oxidation-induced protodemetalation. In both cases the process takes place with good yields and high regiocontrol and leads to the preparation of unsaturated ketones and lactones of high enantiopurity.

Experimental Section[36]

General Procedure for the Demetalation with PDC. To a solution (or suspension) of the molybdenum complex (0.20 mmol) in CH_2Cl_2 (2.0 mL) was added a mixture of PDC (241 mg, 0.64 mmol) and silica gel (241 mg, 0.64 mmol) in one portion as a solid. The mixture was stirred at room temperature for 12−20 h. It was then passed through a short pad of Celite with a thin layer of silica gel on the top (eluted with 2:1 CH_2Cl_2−EtOAc). After concentration, the residue was purified by flash chromatography to afford the corresponding pure demetalated product.

(±)-5,5-Dimethylhex-2-en-1-one (6).[37] Following the general procedure, **1** (200 mg, 0.42 mmol) was demetalated to afford, after chromatographic purification (7:1 *n*-hexanes−EtOAc), the known **6** (38.1 mg, 73%) as a colorless oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 6.86 (dt, J = 10.1, 4.1 Hz, 1H), 6.02 (dt, J = 10.1, 1.9 Hz, 1H), 2.27 (s, 2H), 2.24 (dd, J = 4.1, 1.9 Hz, 2H), 1.04 (s, 6H).

(±)-1-(Ethoxycarbonyl)-1,2,3,6-tetrahydro-3-pyridone (7).[25a−b,38] Following the general procedure, **2** (250 mg, 0.48 mmol) was demetalated to afford, after chromatographic purification (4:1 *n*-hexanes−EtOAc), the known **7** (56.7 mg, 70%) as a colorless oil. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.03 (m, 1H), 6.16 (dt, J = 10.2, 2.2 Hz, 1H), 4.27 (m, 2H), 4.16 (q, J = 7.0 Hz, 2H), 4.14 (s, 2H), 1.26 (t, J = 7.0 Hz, 3H).

(±)-1-(Ethoxycarbonyl)-6-benzyl-1,2,5,6-tetrahydro-3-pyridone (8). Following the general procedure, **3** (248 mg, 0.4 mmol) was demetalated to afford, after chromatographic purification (11:1 *n*-hexanes−EtOAc), **8** (77.2 mg, 73%) as a colorless oil. TLC (7:1 *n*-hexanes−EtOAc): R_f = 0.4. IR (neat, cm^{-1}): 2934 (br), 2860 (w), 1737 (s), 1698 (s), 1428 (w), 1374 (m), 1336 (w), 1243 (s), 1173 (w), 1108 (w), 1077 (w), 1023 (m), 980 (w). ^{1}H NMR (50:50 mixture of rotamers): δ 7.34−7.14 (m, 5H), 6.90 (dd, J = 10.2, 4.8 Hz, 1H), 6.12 (d, J = 4.8 Hz, 1H), 5.07 (bs, 0.5 H), 4.95 (bs, 0.5 H), 4.67 (bd, J = 19.5 Hz, 0.5H), 4,49 (bd, J = 18.4 Hz, 0.5H), 4.24−3.98 (m, 2H), 3.64−3.46 (m, 1H), 3.08−2.95 (m, 2H), 1.24 (m, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 192.9, 155.0, 150.5, 149.6, 136.4, 129.5, 128.9, 127.3, 127.1, 70.6, 70.3, 62.2, 53.9, 53.4, 49.5, 48.9, 39.0, 38.5, 29.9, 29.5, 22.9, 14.7. HRMS (FAB): calcd for $C_{15}H_{17}NO_3Li$ [M^++Li], 259.1208; found, 259.1204.

(±)-2-Phenyl-5,6-dihydro-2*H*-pyran-3-one (9). Following the general procedure, **5** (460 mg, 0.85 mmol) was demetalated to afford, after chromatographic purification (1:2 *n*-hexanes−CH_2Cl_2), **9** (120 mg, 75%) as a colorless oil. TLC (1:2 *n*-hexanes−CH_2Cl_2 1:2): R_f = 0.15. IR (neat, cm^{-1}): 3034 (w), 2822 (w), 1695 (s), 1258 (m), 1096 (m). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.42−7.37 (m, 5 H), 7.12 (dd, J = 10.5, 2.2 Hz, 1H), 6.28 (dd, J = 10.5, 2.2 Hz, 1H), 5.39 (m, 1H), 4.32 (d, J = 16.3, Hz, 1H), 4.25 (dd, J = 16.3, 1.6 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 194.3, 150.6, 137.7, 128.9, 128.8, 127.4, 126.9, 75.8, 70.9. HRMS [M^+]: calcd for $C_{11}H_{10}O_2$, 174.0681; found, 174.0673.

(±)-1-((Phenyloxy)carbonyl)-1,2,3,4-tetrahydro-4-pyridone (11).[28] Following the general procedure, **10** (450 mg, 0.75 mmol) was demetalated to afford, after chromatographic purification (8:1 *n*-hexanes−EtOAc), **11** (132 mg, 81%) as a colorless oil. TLC (4:1 *n*-hexanes−EtOAc 4:1): R_f = 0.4. IR (neat, cm^{-1}): 2362 (br), 2343 (br), 1741 (s), 1671 (s), 1602 (s), 1420 (w), 1351 (m), 1332 (m), 1305 (s), 1200 (s), 1181 (s), 1081 (w), 984 (w), 810 (w), 748 (w), 690 (w). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.97 (d, J = 7.9 Hz, 1H), 7.44−7.15 (m, 5H), 5.60−5.39 (bs, 1H), 4.21−4.00 (bs, 2H), 2.75−2.50 (m, 2H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 193.1, 150.3, 143.4, 142.6, 129.6, 126.4, 121.2, 108.3, 77.3, 77.0, 76.6, 42.7, 35.6. HRMS (FAB): cald for $C_{12}H_{11}N_1O_3$ [M^+], 217.0743; found, 217.0739. Anal. Calcd

(35) The protodemetalation is not simply due to the acidic nature of PDC, since neither HCl nor TFA induced protodemetalation of complex (±)-**16** under the same conditions.

(36) For general methods, see the Supporting Information.

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for $C_{12}H_{11}NO_3$: C, 66.35; H, 5.10; N, 6.45. Found: C, 66.08; H, 5.23; N, 6.54.

(±)-5-Hydroxy-5-vinyl-5,6-dihydro-2*H*-pyran-2-one (14). Following the general procedure, **12** (275 mg, 0.56 mmol) was demetalated to afford, after chromatographic purification (2:1 *n*-hexanes−EtOAc), **14** (59.0 mg, 75%) as a colorless oil. TLC (2:1 *n*-hexanes−EtOAc 2:1): $R_f = 0.12$. IR (neat, cm^{-1}): 3424 (s), 2930 (w), 1749 (s), 1208 (m). ^1H NMR ($CDCl_3$, 400 MHz): δ 7.43 (d, $J = 5.7$ Hz, 1H), 6.12 (d, $J = 5.7$ Hz, 1H), 5.92 (dd, $J = 17.4$, 10.6 Hz, 1H), 5.43 (d, $J = 17.4$ Hz, 1H), 5.33 (d, $J = 10.6$ Hz, 1H), 3.88 (d, $J = 12.1$ Hz, 1H), 3.78 (d, $J = 12.1$ Hz, 1H), 2.65 (bs, 1H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 172.5, 155.9, 131.9, 121.7, 118.4, 91.2, 65.3. HRMS $[M - OH]^+$: calcd for $C_7H_7O_2$, 123.0446; found, 123.0447.

(±)-5-(Acetyloxy)-5-methyl-5,6-dihydro-2*H*-pyran-2-one (15). Following the general procedure, **13** (400 mg, 0.77 mmol) was demetalated to afford, after chromatographic purification (9:1 *n*-hexanes−EtOAc), **15** (98 mg, 75%) as a colorless oil. TLC (8:1 *n*-hexanes−EtOAc 8:1): $R_f = 0.31$. IR (neat, cm^{-1}): IR (neat, cm^{-1}): 1733 (s), 1235 (s), 1131 (m), 1100 (m), 1061 (m), 1015 (w), 829 (w). ^1H NMR ($CDCl_3$, 400 MHz): δ 7.18 (dd, $J = 10$ Hz, $J = 1.44$ Hz, 1H), 5.99 (d, $J = 10$ Hz, 1H), 4.51 (dd, $J = 12$ Hz, $J = 1.44$ Hz, 1H), 4.21 (d, $J = 12$ Hz, 1H), 2.02 (s, 3H), 1.59 (s, 3H). ^{13}C NMR ($CDCl_3$, 100 MHz): 169.9, 162.2, 147.2, 120.7, 73.6, 72.1, 21.3, 20.3. HRMS (FAB): Cald for $C_8H_{10}O_4Li$ $[M^+ + Li]$, 177.0739; found, 177.0741. Anal. Calcd for $C_8H_{10}O_4$: C, 56.47; H, 5.92. Found: C, 56.45; H, 5.60.

(+)-(8*S*,8a*S*)-8-(Methoxycarbonyl)-6,7,8,8a-tetrahydro-2*H*-chromen-2-one [(+)-21].[1d] Following the general procedure, a 98% ee sample of (−)-**16** (136 mg, 0.24 mmol) was demetalated to afford, after chromatographic purification (CH_2Cl_2), (+)-**21** (43.0 mg, 85%) in 98% ee {$[\alpha]_D$ +438.5 (*c* 0.6, CH_2Cl_2)} as a white solid. TLC (4:1 *n*-hexanes−EtOAc 4:1) $R_f = 0.07$. Mp: 117−118 °C. IR (cm^{-1}): 2953 (w), 1714 (s), 1644 (m), 1436 (w), 1239 (w), 1197 (m), 1166 (m), 1119 (w), 1054 (m). ^1H NMR: δ 6.98 (d, $J = 9.8$ Hz, 1H), 6.09 (m, 1H), 5.85 (d, $J = 9.8$ Hz, 1H), 5.21 (m, 1H), 3.70 (s, 3H), 3.30 (q, $J = 5.4$ Hz, 1H), 2.47−2.36 (m, 1H), 2.32−2.82 (m, 1H), 2.20−2.13 (m, 1H), 2.03−1.95 (m, 1H). ^{13}C NMR: δ 171.1, 163.6, 143.4, 133.9, 128.5, 117.2, 74.3, 51.8, 41.8, 23.2, 23.0. HRMS $[M^+]$: calcd for $C_{11}H_{12}O_4$, 208.0736; found, 208.0742.

(+)-(8*S*,8a*S*)-8-Acetyl-6,7,8,8a-tetrahydro-2*H*-chromen-2-one [(+)-22].[1d] Following the general procedure, a 98% ee sample of (−)-**17** (57 mg, 0.10 mmol) was demetalated to afford, after chromatographic purification (22:1 CH_2Cl_2−EtOAc), (+)-**22** (16.1 mg, 80%) in 98% ee {$[\alpha]_D$ +285 (*c* 1, CH_2Cl_2)} as a white solid. TLC (1:1 *n*-hexanes−EtOAc 1:1): $R_f = 0.21$. Mp: 104−105 °C. IR (cm^{-1}): 2930 (w), 1710 (s), 1644 (m), 1355 (w), 1239 (m), 1162 (m), 1504 (m). ^1H NMR: δ 6.98 (d, $J = 10.1$ Hz, 1H), 6.08 (m, 1H), 5.84 (d, $J = 10.1$ Hz, 1H), 5.25 (m, 1H), 3.33 (q, $J = 4.4$ Hz, 1H), 2.46−2.34 (m, 1H), 2.28−2.19 (m, 1H), 2.25 (s, 3H), 2.14−2.07 (m, 1H), 1.99−1.90 (m, 1H). ^{13}C NMR: δ 206.7, 163.8, 143.5, 134.3, 128.5, 117.1, 74.7, 47.9, 30.8, 23.3, 22.3. HRMS $[M^+]$: calcd for $C_{11}H_{12}O_3$, 192.0786; found, 192.0790.

(+)-(8*R*,8a*S*)-8-Butyl-8-formyl-6,7,8,8a-tetrahydro-2*H*-chromen-2-one [(+)-23].[1d] Following the general procedure, a 99.8% ee sample of (−)-**18** (77 mg, 0.13 mmol) was demetalated to afford, after chromatographic purification (6:1 *n*-hexanes−EtOAc), (+)-**23** (22.2 mg, 72%) in 99.8% ee {$[\alpha]_D$ +256.5 (*c* 0.5, CH_2Cl_2)} as a white solid. TLC (6:1 *n*-hexanes−EtOAc 6:1): $R_f = 0.11$. Mp: 78−80 °C. IR (cm^{-1}): 2961 (m), 2934 (m), 2868 (w), 1718 (s), 1644 (m), 1401 (w), 1235 (m), 1046 (m). ^1H NMR: δ 9.88 (d, $J = 1.6$ Hz, 1H), 6.97 (d, $J = 9.5$ Hz, 1H), 6.10 (bs, 1H), 5.88 (d, $J = 9.5$ Hz, 1H), 5.11 (m, 1H), 2.47−2.35 (m, 1H), 2.32−2.22 (m, 1H), 2.19 (dd, $J = 14.0$, 6.3 Hz, 1H), 1.95−1.88 (m, 1H), 1.73−1.65 (m, 1H), 1.54−1.45 (m, 1H), 1.38−1.27 (m, 3H), 1.22−1.13 (m, 1H), 0.91 (t, $J = 7.3$ Hz, 3H). ^{13}C NMR: δ 203.0, 163.9, 143.4, 136.5, 128.5, 116.9, 78.2, 51.0, 32.2, 25.4, 25.1, 23.5, 23.1, 13.9.

(±)-(7*R*,8*S*,8a*R*)-7,8-Dimethyl-8-formyl-6,7,8,8a-tetrahydro-2*H*-chromen-2- one [(±)-24].[1d] Following the general procedure, (±)-**19** (65 mg, 0.12 mmol) was demetalated to afford, after chromatographic purification (5:1 *n*-hexanes−EtOAc), (±)-**24** (18 mg, 75%) as a white solid. TLC (3:1 *n*-hexanes−EtOAc): $R_f = 0.20$. Mp: 112−113 °C. IR (cm^{-1}): 2980 (w), 2918 (w), 2883 (w), 1718 (s), 1698 (s), 1648 (m), 1455 (w), 1401 (m), 1243 (m), 1023 (m). ^1H NMR: δ 9.91 (s, 1H), 7.01 (d, $J = 9.5$ Hz, 1H), 6.11 (m, 1H), 5.91 (d, $J = 9.5$ Hz, 1H), 5.00 (m, 1H), 2.56 (bd, $J = 20.6$ Hz, 1H), 2.27 (pent, $J = 6.7$ Hz, 1H), 2.05 (dd, $J = 20.6$, 5.1 Hz, 1H), 1.31 (s, 3H), 1.00 (d, $J = 7.0$ Hz, 3H). ^{13}C NMR: δ 203.4, 164.2, 143.2, 135.0, 127.8, 117.6, 77.7, 50.5, 33.0, 31.4, 17.4, 15.9. HRMS $[M^+]$: calcd for $C_{12}H_{14}O_3$, 206.0944; found, 206.0943.

(±)-(3a*S*,9a*S*,9b*S*)-2-Methyl-1,2,3-trioxo-3a,8,9a,9b-tetrahydro-2*H*,4*H*-pyrano[2,3-e]isoindole [(±)-25]. Following the general procedure, (±)-**20** (75 mg, 0.13 mmol) was demetalated to afford, after chromatographic purification (9:1 CH_2Cl_2−EtOAc), (±)-**25** (25.0 mg, 83%) as a white solid. TLC (1:1 *n*-hexanes−EtOAc): $R_f = 0.06$. Mp: >200 °C. IR (cm^{-1}): 2957 (w), 2926 (w), 1938 (w), 1849 (w), 1725 (s), 1695 (s), 1436 (m), 1386 (m), 1289 (m), 1231 (m), 1092 (m). ^1H NMR: δ 6.91 (d, $J = 9.8$ Hz, 1H), 6.10 (m, 1H), 5.93 (d, $J = 9.8$ Hz, 1H), 5.26 (dt, $J = 6.0$, 2.8 Hz,1H), 3.65 (dd, $J = 8.9$, 6.7 Hz, 1H), 3.24 (bt, $J = 8.9$ Hz, 1H), 2.97 (ddd, $J = 16.5$, 7.0, 1.3 Hz, 1H), 2.92 (s, 3H), 2.10−2.02 (m, 1H). ^{13}C NMR: δ 178.1, 174.3, 161.2, 139.5, 131.1, 127.9, 118.1, 74.3, 44.1, 36.9, 25.2, 25.0.

(±)-3,6-Dihydro-2*H*-pyran-2-one [(±)-29].[31a−h] Following the general procedure, (±)-**4** (370 mg, 0.79 mmol) was demetalated to afford, after chromatographic purification (4:1 *n*-hexanes−EtOAc), the known (±)-**29** (39 mg, 50%) as a colorless oil. ^1H NMR (300 MHz): δ 3.12 (m, 2H), 4.93 (m, 2H), 5.92 (m, 2H).

(−)-(6*S*)-6-((Acetyloxy)methyl)-3,6-dihydro-2*H*-pyran-2-one [(−)-30].[39] Following the general procedure, (+)-**26** (360 mg, 0.66 mmol) was demetalated to afford, after chromatographic purification (5:1 *n*-hexanes−EtOAc), (−)-**30** (79 mg, 71%) as a colorless oil: $[\alpha]_D$ −112 (*c* 2.1, $CHCl_3$) {lit. $[\alpha]_D$ −113.2 (*c* 1.25, $CHCl_3$)}.[31i] TLC (4:1 *n*-hexanes−EtOAc): $R_f = 0.30$. IR (cm^{-1}): 1741 (s) 1378 (m), 1220 (s), 1166 (w), 1104 (m), 1046 (m), 714 (w). ^1H NMR (300 MHz): δ 5.99−5.91 (m, 1H), 5.86−5.75 (m, 1H), 5.15 (bs, 1H), 4.35−4.17 (m, 1H), 3.08 (bs, 1H), 2.08 (s, 3H). ^{13}C NMR: δ 170.4, 167.9, 123.9, 122.1, 77.3, 64.9, 29.7, 20.6. HRMS (FAB): cald for $C_8H_{10}O_4Li$ $[M^+ + Li]$, 177.0739; found, 177.0740. Anal. Calcd for $C_8H_{10}O_4$: C, 56.47; H, 5.92. Found: C, 56.40; H, 5.74.

(−)-(6*S*)-6-(Hydroxymethyl)-3,6-dihydro-2*H*-pyran-2-one [(−)-31]. Following the general procedure, (+)-**28** (475 mg, 0.95 mmol) was demetalated to afford, after chromatographic purification (2:1 *n*-hexanes−EtOAc), (−)-**31** (99 mg, 82%) as a colorless oil: $[\alpha]_D$ −48 (*c* 0.8, $CHCl_3$). TLC (2:1 *n*-hexanes−EtOAc): $R_f = 0.16$. IR (cm^{-1}): 3424 (br), 2922 (br), 2856 (w), 2362 (br), 1729 (s), 1459 (w), 1417 (w), 1382 (w), 1247 (m), 1166 (m), 1054 (m), 934 (w). ^1H NMR: δ 6.06−5.78 (m, 2H), 5.05 (m, 1H), 3.85 (dd, $J = 13.7$, 4.0 Hz, 1 H), 3.65 (dd, $J = 13.7$, 7.1 Hz, 1 H), 3.11−2.89 (m, 2H), 3.84 (bs, 1H). ^{13}C NMR: δ 171.6, 81.1, 64.7, 29.5, 23.5, 18.2. HRMS (FAB): cald for $C_8H_{10}O_4Li$ $[M^+ + Li]$, 135.0687; found, 135.0633. Anal. Calcd for $C_6H_8O_3$: C, 56.25; H, 6.29; N, 37.46. Found: C, 56.47; H, 6.49; N, 37.24.

(+)-(6*S*)-6-(Hydroxymethyl)-3,4,5,6-tetrahydro-2*H*-pyran-2-one [(+)-32].[39] To a solution of (−)-**31** (160 mg, 1.25 mmol) in 1.5 mL of ethyl acetate was added 10 wt % Pd/C (50 mg, 0.11 mmol), and the mixture was stirred at room temperature under H_2 (1 atm) for 12 h. The reaction mixture was passed through a pad of Celite, and the filtrate was concentrated to give pure (+)-**32** (14 mg, 85%) as a colorless oil: $[\alpha]_D$ +35.2 (*c* 1.3, $CHCl_3$) {lit. $[\alpha]_D$ +34.68 (*c* 1.25, $CHCl_3$)}.[31i] TLC (2:1 *n*-hexanes−EtOAc): $R_f = 0.37$. ^1H NMR (300 MHz): δ

(39) Although compounds (−)-**30** and (+)-**32** are known (see ref 31i), their analytical and spectroscopic data have not been reported.

4.45−4.38 (m, 1H), 3.78 (dd, J = 12.1, 3.2 Hz, 1H), 3.66 (dd, J = 12.1, 5.5 Hz, 1H), 2.66−2.57 (m, 1H), 2.49−2.41 (m, 1H), 1.97−1.82 (m, 1H), 1.73−1.68 (m, 1H). ^{13}C NMR: δ 171.5, 81.1, 64.8, 29.5, 23.5, 18.2.

Acknowledgment. This work was supported by Grant No. GM43107, awarded by the National Institute of General Medical Sciences, DHHS. A.A. and R.G.A. thank the Secretaría de Estado de Educación y Universidades (Spain) and NATO, respectively, for postdoctoral fellowships. We also thank Drs. Almudena Rubio, Isidro Llorente, and Jingjun Yin for their earlier preparation of samples of molybdenum complexes (+)-**27**, **10**, and **13**, respectively.

Supporting Information Available: A complete description of the synthesis and analytical and spectral characterization data of all molybdenum complexes used in this study and copies of proton and carbon NMR spectra of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

JO020002X