Hydride Abstraction from η^3-Allylic Molybdenum Complexes Exploring Various Diaryl Carbenium Ion Precursors. A Study toward Enantioselective Hydride Abstraction

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Received November 26, 2001

The efficiency of trityl bromide (**4**) and diaryl carbenium ion precursors **5**−**7** in hydride abstraction from a series of cyclohexenyl molybdenum complexes (**2**) was investigated. The novel nonracemic hydride abstractors **14a**,**b** were designed and prepared and were shown to effectuate hydride abstraction from prochiral substrate **15** with modest enantioselectivity.

Introduction

Cationic diene molybdenum complexes of the type η^5L-(diene)Mo(CO)$_2$X constitute a valuable class of electrophiles in organic synthesis. In particular, the temporary complexation of carbo- or heterocyclic dienes to molybdenum has been utilized for enantioselective syntheses of *cis*-disubstituted targets such as piperidines[1] and dihydro- or tetrahydropyrans[2] as well as for the construction of quaternary centers.[3] Preparative routes forming cationic diene molybdenum complexes involve either direct complexation or, the more frequently used, oxidative addition of an allylic halide followed by hydride abstraction.

Despite the obvious synthetic applicability of nonracemic diene molybdenum complexes, enantioselective routes for their preparation have only recently been considered. Chiral carbenium ions offer an opportunity to distinguish prochiral hydrides in a neutral η-metal complex, forming a cationic complex with increased hapticity upon hydride abstraction. Enantioselective hydride abstraction from (tricarbonyl)(diene)iron complexes has very recently been described utilizing chiral trityl cation analogues (Figure 1) as hydride acceptors.[4] Pettus et al.[4a] presented the first enantioselective hydride abstraction employing *meso*-(tricarbonyl)(1,4-dialkoxycyclohexadiene) iron complexes as substrates (Figure 1).

We previously reported that hydride abstraction from the model system (η^5-cyclopentadienyl)dicarbonyl[(1−3-η)-1-cyclohexen-3-yl]molybdenum could be effectuated using trityl bromide or chloride, (4-MeOC$_6$H$_4$)$_2$CHBr, or their polymer-bound analogues, as carbenium ion precursors. The presence of HFiP as a cosolvent in those reactions was crucial.[5,6] Good yields of (η^5-cyclopentadienyl)dicarbonyl[(1−4-η)-cyclohexadiene]molybdenum halides were obtained in both homogeneous and heterogeneous reactions. We hypothesized that stable benzhydryl halides or diarylcarbinols might offer a convenient source of new chiral carbenium ions for use in enantioselective hydride abstraction. Herein, we disclose an extended study involving a series of allylic substrates and additional carbenium ion precursors. Further, via structural evolution of a chiral diaryl carbenium ion precursor, we report the first enantioselective hydride abstraction involving a molybdenum complex substrate.

Results and Discussion

Hydride Abstraction Employing Various Carbenium Ion Precursors. To investigate steric effects in the hydride abstraction reaction, in which the hydrogen *anti* to the metal becomes abstracted, the allylic complexes **2a**−**e** (Table 1) were synthesized. The methyl- and phenyl-substituted molybdenum complexes **2a**[7] and **2d**[5] were prepared according to literature procedures in yields of 95% and 90%, respectively. The isopropyl analogue **2b** was synthesized by addition of ^{i}PrMgCl to **1**, giving an 88% isolated yield, and **2e** was isolated in 40% yield upon adding freshly prepared 1-naphthylmagnesium bromide to **1**.

Attempted addition of ^{t}BuMgCl to **1** resulted in hydride transfer[8] from the Grignard reagent rather than alkylation, and (cyclopentadienyl)dicarbonyl[(1−3-η)-1-

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(1) Moretto, A. F.; Liebeskind, L. S. *J. Org. Chem.* **2000**, *65*, 7445.
(2) (a) Rubio, A.; Liebeskind, L. S. *J. Am. Chem. Soc.* **1993**, *115*, 891. (b) Hansson, S.; Miller, J. F.; Libeskind, L. S. *J. Am. Chem. Soc.* **1990,** *112*, 9660.
(3) Reviews: (a) Pearson, A. J. In *Comprehensive Organometallic Chemistry II.*; Abel, E. W., Stone, E. G. A. Wilkinson, G., Eds.; Pergamon: Oxford, U.K., 1995; Vol. 12, Chapter 6.3. (b) Liu, R.-S. *Adv. Met.-Org. Chem.* **1998**, *6*, 145. (c) Li, C.-L.; Liu, R.-S. *Chem. Rev.* **2000**, *100*, 3127.
(4) (a) Magdziak, D.; Pettus, L. H.; Pettus, T. R. R. *Org. Lett.* **2001,** *3*, 557. (b) Older, J. E. J. Ph.D. Thesis, University of East Anglia, UK, 2001
(5) Bjurling, E.; Björkman, A.; Andersson, C.-M. *Organometallics* **2001**, *20*, 990.
(6) Bjurling, E.; Andersson, C.-M. *Tetrahedron Lett.* **1999**, *40*, 1981.
(7) Faller, J. W.; Murray, H. H.; White, D. L.; Chao, K. H. *Organometallics* **1983**, *2*, 400.
(8) Cabiddu, S.; Secci, M.*J. Organomet. Chem.* **1975**, *88*, 121.

10.1021/om011016g CCC: $22.00
Publication on Web 03/20/2002

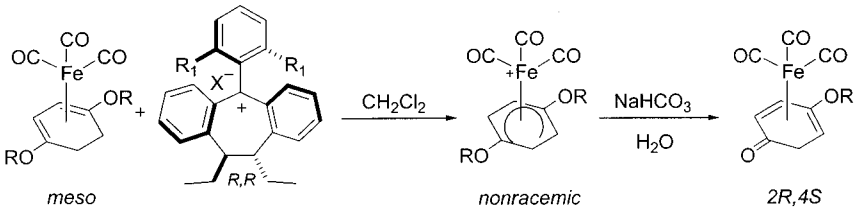
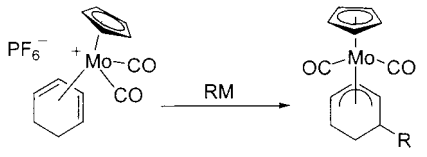


Figure 1.

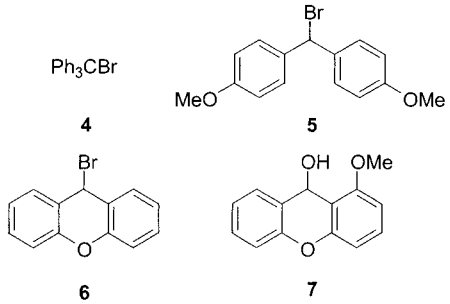
Table 1. Nucleophilic Addition to Cationic Complex 1 Forming Allylic Complexes 2



1 2

compound	RM	yield (%)
2a	MeMgBr	95
2b	^{i}PrMgCl	88
2c	^{t}BuMgCl	
2d	PhMgBr	90
2e	1-naphthylMgBr	40

Chart 1



4 5 6 7

cyclohexen-3-yl]molybdenum was isolated in 74% yield as the sole product. Prereacting $CeCl_3$ and ^{t}BuMgCl in order to increase nucleophilicity[9] by using the in situ-produced cerium reagent similarly failed to give the desired allylic product.

Hydride abstractions from complexes **2a**,**b** and **2d**,**e**, using di- or triarylhalides **4**−**7** (Chart 1) as carbenium ion precursors are presented in Table 2.[10] New diene complexes (**3**) were fully characterized after repeating hydride abstraction in larger scale under similar conditions (See Experimental Section for details). All reactions were performed in the NMR tube employing 5 mg of the substrates **2** in a deuterated solvent mixture of dichloromethane and HFiP (4:1). Tetramethylsilane was introduced as an internal standard, and yields were estimated via integration. Generally, the use of 2 equiv of the carbenium ion precursor turned out to be necessary to reach complete conversion.

For example, the use of 1 equiv of the hydride abstractor **4** or **5** in the reaction with **2d** gave 50% conversion, while the use of 2 equiv returned quantitative yield. Similar outcomes were observed in reactions with complex **2b**. This requirement for employing an excess of the carbenium ion precursor might be due to particular experimental conditions associated with small-scale NMR experiments.[11] Surprisingly, a direct comparison between trityl bromide (**4**) and the less sterically demanding bromodi(*p*-methoxyphenyl)methane (**5**) did not reveal any significant difference in the rate of reaction with **2a** (R = Me), **2d** (R = Ph), or **2e** (R = naphthyl). A striking difference was, however, noted in the reaction with **2b** (R = ^{i}Pr), where trityl bromide (**4**) gave a much better yield (90%) than **5** (40%).

Xanthenylium ions have been isolated and are known as stable carbenium ions.[12] The hydride affinity of the xanthenylium ion has been determined to be lower than that of trityl cation,[13] and it has, to our knowledge, not been used in hydride abstractions from organometallic compounds. We were interested in taking advantage of the potentially reduced sterical encumberance in this less flexible skeleton and decided to investigate whether the xanthenylium ion could abstract hydride from allylic molybdenum complexes. We were also intrigued by the possibility of applying the rigid xanthene scaffold in enantioselective hydride abstraction after installation of a chiral appendage. The carbenium ion precursor 9-bromoxanthene (**6**) was synthesized from 9-xanthenol by treatment with HBr.[14]

In the hydride abstraction reactions employing substrates **2** carbenium ion precursor **6** gave uniformly unsatisfactory yields. With the exception of an 80% yield using the allylic naphthyl complex **2e**, the yields were between 30 and 60%, possibly due to ineffective hydride abstraction in combination (for **2a** and **2b**) with competing reactions with substrate or product.

We concluded that it was necessary to introduce an alkoxy substituent in order to stabilize the intermediate xanthenylium ion. The introduction of a substituent at the 1-position was also desired for further functionalization with a chiral group, enabling the preparation of enantiomerically enriched cationic diene complexes. The requisite 1-methoxyxanthen-9-one was synthesized according to a literature procedure[15] and reduced with $LiAlH_4$ to form alcohol **7**, which was used crude together with *p*-TsOH as an aid to generate the carbenium ion. The yields of diene complexes were more satisfying (60−90%) using methoxyxanthenol (**7**) compared to the parent **6** and similar to the yields obtained with trityl precursor **4**. Importantly, decompostion of the allylic starting material as well as the cationic product was suppressed by the use of **7**. Control hydride abstraction

(9) Imamoto, T.; Takiyama, N.; Nakamura, K. *Tetrahedron Lett.* **1985**, *26*, 4763.

(10) New diene complexes (**3**) were fully characterized after repeating hydride abstraction in larger scale under similar conditions. See Experimental Section for details.

(11) We have previously obtained good yields of **1** from preparative scale reactions employing only a slight excess of **4**.

(12) Arnette, E. M.; Venimadhaven, S.; Amarnath, K. *J. Am. Chem. Soc.* **1992**, *114*, 5598.

(13) Arnette, E. M.; Flowers, R. A.; Ludwig, R. T.; Meekhof, A. E.; Walek, S. A. *J. Phys. Org. Chem.* **1997**, *10*, 499.

(14) Tadros, W.; Sakla, A. B.; Awad, S. B.; Abdul-Malik, N. F. *Helv. Chim. Acta* **1973**, *56*, 1829.

(15) Horne, S.; Rodrigo, R. *J. Org. Chem.* **1990**, *55*, 4520.

Table 2. Hydride Abstractions Employing Various Diarylcarbenium Ion Precursors

	carbenium ion precursors[a]							
	4		**5**		**6**		**7**[d]	
substrate	30 min	120 min	30 min	120 min	30 min	120 min	30 min	120 min
2a	90(0)	90(0)	80(0)	80(0)	60(0)	60(0)	60(−)	80(−)
2b	80(0)	90(0)	40(30)	40(trace)	30(0)	30(0)	80(10)	90(0)
	60(20)[b]	70(−)[b]	10(70)[b]	10(30)[b]	20(40)[b]	20(30)[b]		
2d	60(40)	100(0)	80(20)	100(0)	30(70)	40(20)	60(40)	80(20)
	20(60)[b]	50(30)[b]	50(50)[b]	50(40)[b]	20(80)[b]	50(50)[b]		
					30(70)[c]	60(30)[c]		
2e	80(20)	100(0)	90(10)	90(0)	40(60)	80(10)	50(50)	60(40)

[a] Percent yield (remaining substrate). The yields were estimated by integration of NMR spectra taken in $CD_2Cl_2/CF_3CDODCF_3$ and using 2 equiv of carbenium ion precursor. [b] Yield obtained using 1 equiv of carbenium ion precursor. [c] Reaction performed in 50% (v/v) HFiP. [d] Addition of 2 equiv of *p*-TsOH effected the reaction.

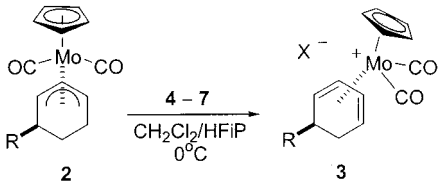


Figure 2.

using an alcohol (e.g., triphenyl carbinol with addition of $HBF_4 \cdot Et_2O$) as the trityl precursor in the absence of HFiP returned an inferior yield (14%).[16]

In an earlier publication, we established that indole-substituted cyclohexenyl complexes failed to undergo hydride abstraction and attributed the failure to steric hindrance in combination with protolytic degradation.[17] However, upon mixing (η^5-cyclopentadienyl)dicarbonyl-[(2−4-η)-(3-cyanoindol-1-yl)-2-cyclohexen-4-yl]molybdenum and **4**, **5**, or **6**, no reaction took place, suggesting the steric effect of the allylic indole substituent to be a minor factor, especially in view of the result obtained with complex **2e**.

In conclusion, the increase in sterical hindrance in the series of substrate complexes **2** did not affect the results from hydride abstractions employing various carbenium ion precursors. Trityl bromide was generally superior as the hydride abstractor. Stabilization of the presumed intermediate benzhydryl cations by introduction of electron-donating substituents in the aryl rings was important for an efficient hydride abstraction.

Mechanistic Study Using ^{2}H NMR for the Determination of the Hydride Abstraction Pathway. Enantioselective hydride abstraction requires a highly stereospecific pathway. To confirm that the mechanism of our HFiP-dependent method for hydride abstraction was consistent with the established mechanism, using trityl salts as hydride abstractors, we decided to synthesize an *anti*-deuterated allylic complex (Figure 3) adopting a strategy published by Faller.[7] Surprisingly, when (η^5-cyclopentadienyl)dicarbonyl[(1−4-η)-cyclohexadiene]molybdenum bromide (**8**) was reacted with $LiEt_3BD$, the isolated allylic compound **9** was nearly exclusively the *syn*-deuterated product (**9b**),[18] as confirmed by ^{2}H NMR.[19]

When $Na(CN)BD_3$ was used as the deuteride source, the expected *anti*-product **9a** was formed. Hydride

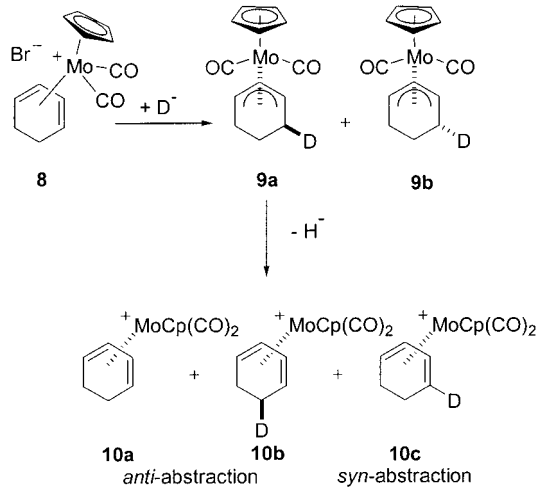


Figure 3.

abstraction from this complex with **4** in the presence of HFiP gave the cationic complexes **10a**,**b** in statistical distribution (1:1) with no trace of **10c** in keeping with earlier publications, which have established exclusive abstraction of hydrides *anti* to molybdenum.

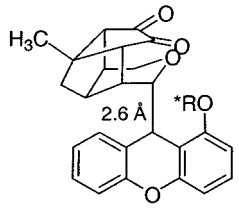
Synthesis of Chiral Carbenium Ion Precursors. The successful application of xanthenol **7** in hydride abstractions from substrates **2** provided an incentive to synthesize carbenium ion precursors with stereogenic alkoxy groups close to the reaction center. Deprotection of the methoxy group of 1-methoxyxanthen-9-one (**11**) with BBr_3 in dichloromethane gave the phenol **12** in 86% yield (Scheme 1). This phenol was alkylated with (*R*)-1-phenylethanol with good stereocontrol using Mitsunobu conditions and gave the xanthone **13a** in 54% yield and 98% ee, as established by chiral HPLC. Reduction of **13a** with $LiAlH_4$ gave carbinol **14a** in 78% yield and a diastereomeric ratio of approximately 1:1. Alkylation was similarly performed with (*R*)-1-indanol, returning **13b** in 52% yield and 86% ee. Here, reduction afforded a 67% yield of alcohol **14b**, which was used without purification in the hydride abstraction reaction.

(16) This experiment was performed with the substrate (η^5-cyclopentadienyl)dicarbonyl[(1−3-η)-1-cyclohexen-3-yl]molybdenum to control the utility of HFiP as co-solvent.

(17) Bjurling, E.; Johansson, M. H.; Andersson, C.-M. *Organometallics* **1999**, *18*, 5606.

(18) The stereospecificity of hydride addition can vary with the bulkiness of the reagent, the counterion to the metal complex, or the solvent used in the reaction. See: Morken, A. M.; Darrell, P. E.; Wolff, M. A.; Schauer, S. J. *Organometallics* **1993**, *12*, 725.

(19) ^{2}H NMR (CD_2Cl_2, 500 MHz) analysis of **9b** obtained from $LiEt_3BD$ gave two signals at 2.09 and 1.62 ppm in the relationship 3:100. Hydride abstraction from this complex gave deuterium signals at 5.99 (diene system) and 2.02 ppm. The use of $Na(CN)BD_3$ gave reduced intensity in the signal at 1.95 ppm (^{1}H NMR ($CDCl_3$, 300 MHz)), and the subsequent hydride abstraction did not result in reduced intensity of the signals assigned to the diene protons.



18

Figure 4.

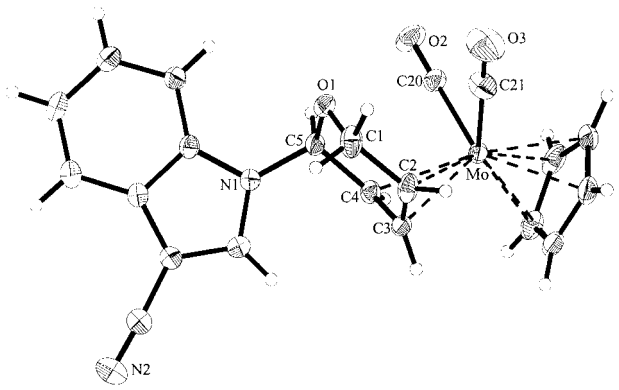
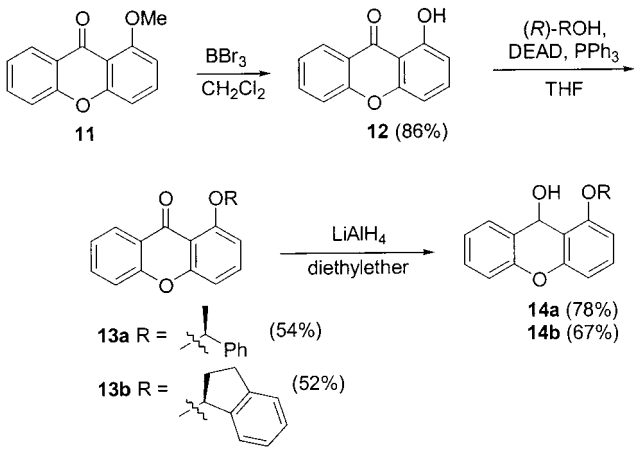


Figure 5.

Scheme 1



Synthesis of an Enantiomerically Enriched Cationic Diene Molybdenum Complex. Computational Modeling. Characterization of the hydride transfer transition states of molybdenum complexes using large xanthenyl cations was beyond our computational capacity. Instead, we tried the design of an isosteric model of the transition state, **18** (Figure 4), which could be easily exploited by excessive molecular mechanics modeling. A representative molybdenum complex structure, (η^5-cyclopentadienyl)dicarbonyl-[(3,4,5-η)-2-*anti*-(3-cyanoindol-yl)-5,6-dihydro-2*H*-pyran-5-yl]molybdenum, is shown in Figure 5. Figure 6 provides the superposition of the hydride-donating moiety of the isosteric model with the crystal structure (indole group removed for clarity).[17] The crucial carbon−carbon hydride shift entity was modeled as a covalent carbon−carbon bond of the length (2.65 Å) obtained in ab initio transition states of hydride transfer reactions[20] and kept at this length using the restricted motion option in MacroModel.[21]

Monte Carlo searches using the MM3* force field followed by energy minimization resulted in several

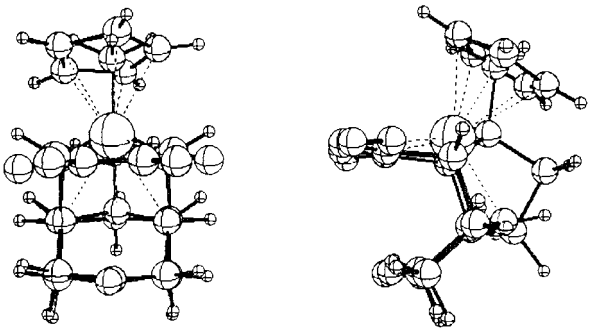


Figure 6.

conformations of each diastereomeric transition state model. The minimized transition states with carbenium ion precursors **14a**,**b** giving rise to the enantiomers are shown in Figure 7. With **14a** a difference in energy of 2.4 kJ/mol was obtained in the calculations between the two enantiomers. With **14b**, the energy difference was 3.3 kJ/mol, in this case, in fact, favoring the transition state leading to the *opposite enantiomer*.

Experimental Results. To our knowledge, we present the first enantioselective hydride abstraction from a molybdenum complex making use of a chiral carbenium ion. The dihydropyranyl molybdenum complex **15** was used as the allylic substrate in the hydride abstraction reaction, since the expected cationic product had been synthesized in enantiomerically pure form by Liebeskind et al., and a procedure for estimating the enantiomeric purity of this material has been reported.[22] Substrate **15** was dissolved together with **14a** in dichloromethane and HFiP.

Hydride abstraction was initiated through addition of $HBF_4 \cdot Et_2O$ at 0 °C, whereupon the product **16** precipitated immediately and was isolated in 80% yield. After addition of MeMgBr to **16**, it was possible to determine the enantiomeric excess of complex **17** by NMR, using (−)Pr[hfc]$_3$ as the chiral shift reagent. Integration of the peaks assigned to the Cp-ligand suggested a 6% ee. A chromatographic determination using chiral HPLC indicated a 4% ee. A similar experiment utilizing **14b** as the carbenium ion precursor gave a 10% ee upon analogous NMR analysis, while chiral HPLC analysis indicated an 8% ee. Interestingly, consistent with calculations based on the isosteric model system, the two reactions favored opposite enantiomers. Thus, the experimental outcome was well in line with the results suggested by calculations, providing verification that the model that was used for molecular modeling should provide a useful system for directing future experiments.

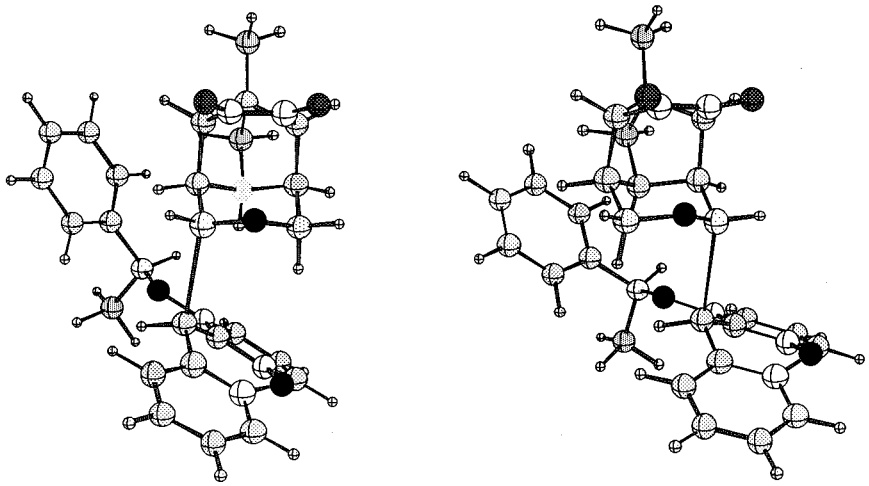
Conclusion

We have shown the first enantioselective hydride abstraction involving a molybdenum complex using chiral diaryl carbenium ions. Although the use of

(20) Ritzeler, O.; Parel, S.; Therrien, B.; Bensel, N.; Peymond, J.-L.; Schenk, K. *Eur. J. Org. Chem.* **2000**, 1365.

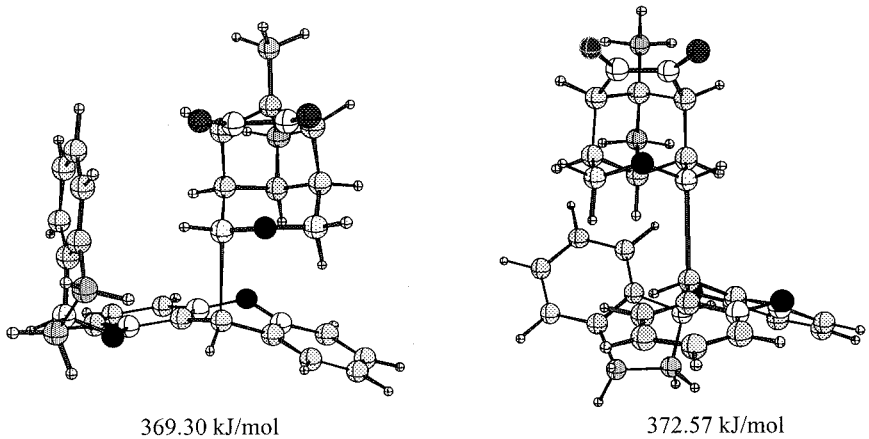
(21) Macromodel version 6.5: Mohamadi, F.; Richards, N. G. J.; Guida, W. C.; Liskamp, R.; Lipton, M.; Caufield, C.; Chang, G.; Hendrickson, T.; Still, W. C. *J. Comput. Chem.* **1990**, *11*, 440.

(22) See ref 2b. After addition of MeMgX and purification, the enantiomeric excess was determined in a 20 mM solution of the allylic complex in benzene-d_6 with 0.75 equiv of Pr[hfc]$_3$.



348.92 kJ/mol 346.48 kJ/mol

Transition states for **14a**.

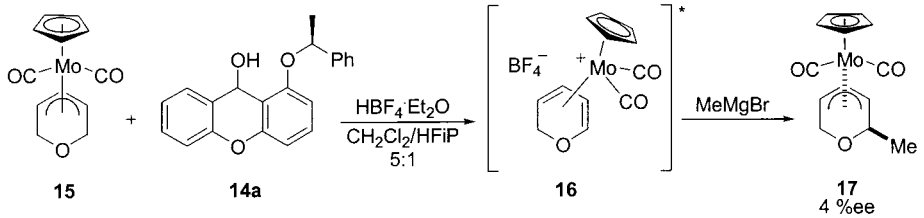


369.30 kJ/mol 372.57 kJ/mol

Transition states for **14b**.

Figure 7.

Scheme 2



15 **14a** **16** **17** 4 %ee

1-alkoxy xanthenols as carbenium ion precursors gave only very modest enantiomeric excess with (η^5-cyclopentadienyl)dicarbonyl[(3−5-η)-5,6-dihydropyranyl]-molybdenum as the substrate, the strategy holds promise for further development. Molecular mechanics calculations on the isosteric model were useful for predicting the reaction outcome of these transformations.

Experimental Section

General Considerations. All reactions were performed under an argon atmosphere. Solvents and reagents were used as received from commercial sources, unless otherwise indicated. HFiP was purchased from Lancaster Synthesis. Degassing of solvents was accomplished through ultrasound irradiation for approximately 1 h. NMR spectra were recorded on a Bruker ARX400 instrument at 400.132 MHz (^{1}H) or 100.6 MHz (^{13}C) or on a Bruker ARX300 instument at 300.135 MHz (^{1}H) or 75.5 MHz (^{13}C). The chemical shifts are given relative to $CDCl_3$ (δ 7.27, residual ^{1}H; δ 77.0, ^{13}C), CD_2Cl_2 (δ 5.32, residual ^{1}H; δ 54.0, ^{13}C), acetone-d_6 (δ 2.04, residual ^{1}H), benzene-d_6 (δ 7.16, residual ^{1}H), and CD_3CN (δ 1.94, residual ^{1}H; δ 118.7, ^{13}C). HPLC analyses were performed on a Diacel OD-H (250 × 4.6 mm id, 5 μm particle size) column. Determination of the enantiomeric excess by HPLC showed an interexperimental variability of a few percent, in the integrated peak areas. IR spectra were recorded on an FT-IR Nicolet Impact 410. (η^5-Cyclopentadienyl)dicarbonyl[(1−4-η)-cyclohexadien]molybdenum hexafluorophosphate,[7] (η^5-cyclopentadienyl)dicarbonyl[(2−5-η)-6*H*-dihydropyranyl]molybde-

num tetrafluoroborate,[2a] and 1-methoxyxanthen-9-one[15] were prepared according to the literature.

The calculations were carried out on a Silicon Graphics O2 workstation. The Polak-Ribiere conjugate gradient algorithm was applied in all minimizations with 1000 iterations limit, and a cutoff of 12 Å was used for the nonbonded interactions. Energy convergence criterion was 0.05 kJ/Å mol.

(η^5-Cyclopentadienyl)dicarbonyl[(2−4-η)-1-isopropyl-2-cyclohexen-4-yl]molybdenum (2b). In a dry, two-necked flask were placed (η^5-cyclopentadienyl)dicarbonyl[(1−4-η)cyclohexadiene]molybdenum hexafluorophospate (0.25 g, 0.57 mmol) and dry THF (10 mL). The suspension was cooled to 0 °C, whereupon a 2 M solution of ^{i}PrMgCl in THF (0.5 mL, 1.0 mmol, 2 equiv) was added. The reaction mixture was stirred for 40 min at 0 °C. Saturated aqueous NH_4Cl (20 mL) was added, and the reaction mixture was extracted with 2 × 20 mL of dichloromethane. The combined organic phases were dried over Na_2SO_4, filtered, and evaporated, and the crude product was subjected to flash chromatography (CH_2Cl_2, collection of the yellow band) to give 0.17 g (88%) of a yellow solid. ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 5.31 (s, 5H), 4.31 (t, J = 7.2 Hz, 1H), 3.70−3.75 (m, 1H), 3.64 (dm, J = 7.2 Hz, 1H), 1.91−2.01 (m, 1H), 1.63 (sep, J = 6.8 Hz, 1H), 1.50−1.58 (m, 2H) partly obscured by the water signal, 1.02 (d, J = 6.8 Hz, 3H), 0.96 (d, J = 6.8 Hz, 3H), 0.89−0.95 (m, 1H) obscured by the doublet at 0.96 ppm, 0.32−0.43 (m, 1H). ^{13}C NMR (CD_3CN, 400 MHz): δ 238.8, 238.0, 93.7, 60.1, 58.6, 56.6, 39.4, 36.6, 21.9, 21.5, 21.5, 21.3. IR (KBr): 1903, 1817 cm^{-1}. HRMS (FAB+): m/z calcd for $C_{16}H_{20}MoO_2$, 340.0517; found M$^+$, 340.0522.

(η^5-Cyclopentadienyl)dicarbonyl[(2−4-η)-1-naphthyl-2-cyclohexen-4-yl]molybdenum (2e). In a dry, two-necked flask were placed (η^5-cyclopentadienyl)dicarbonyl[(1−4-η)cyclohexadiene]molybdenum hexafluorophospate (**1**) (0.26 g, 0.59 mmol) and dry THF (10 mL). The suspension was cooled to 0 °C, whereupon a freshly prepared 1 M solution of naphthylmagnesium bromide[23] in THF (5.0 mL, 5.0 mmol, 8.5 equiv) was added. The reaction mixture was stirred for 1.5 h at 0 °C. After addition of water (20 mL) the reaction mixture was extracted with 2 × 20 mL of dichloromethane. The combined organic phases were dried over Na_2SO_4, filtered, and evaporated, and the crude product was subjected to flash chromatography (CH_2Cl_2/heptane, 1:4, R_f = 0.47) to give 0.10 g (40%) of a yellow solid. ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 8.06 (d, J = 8.3 Hz, 1H), 7.98 (d, J = 7.2 Hz, 1H), 7.84−7.83 (m, 1H), 7.73 (d, J = 8.2 Hz, 1H), 7.44−7.53 (m, 3H), 5.39 (s, 5H), 4.62 (t, J = 7.2 Hz, 1H), 3.99 (dd, J = 7.2, 2.9 Hz, 1H), 3.86−3.92 (m, 1H), 3.72 (dq, J = 7.0, 1.5 Hz, 1H), 1.98−2.08 (m, 1H), 1.67 (dm, J = 15 Hz, 1H), 1.10 (dd, J = 14.0, 6.0 Hz, 1H), 0.91−1.02 (m, 1H). ^{13}C NMR (CD_2Cl_2, 400 MHz): δ 237.6, 236.1, 143.9, 134.6, 131.9, 129.3, 127.1, 126.5, 125.9, 125.9, 124.2, 123.8, 93.0, 58.9, 56.7, 56.1, 33.1, 25.7, 19.7. IR (CH_2Cl_2): 1928, 1844 cm^{-1}. HRMS (FAB+): m/z calcd for $C_{23}H_{20}MoO_2$, 426.0517; found M$^+$, 426.0522.

Hydride Abstractions Performed in the NMR Tube. General Procedure. The substrate **2** (approximately 5 mg) was dissolved in CD_2Cl_2 containing $CF_3CDODCF_3$ (20 vol %) and TMS (0.5−2.0 equiv). A reference spectrum was recorded before the sample was transferred into a vial containing 1 or 2 equiv of the carbenium ion precursor (**4**−**7**). After complete dissolution had occurred, the reaction mixture was reintroduced into the NMR tube. NMR spectra were recorded after the time intervals indicated in Table 2. Conversions were estimated through comparison of the integrals of the resonances arising from the Cp ligands of **2** and **3** with the reference TMS.

(η^5-Cyclopentadienyl)dicarbonyl[(1−4-η)-5-methylcyclohexadiene]molybdenum Bromide (3a). In a flask were placed degassed 1,1,1,3,3,3-hexafluoro-2-propanol (1.0 mL), degassed dichloromethane (4.0 mL), and **2a**[7] (0.20 g, 0.62 mmol). The flask was cooled to 0 °C, whereupon **4** (0.62 g, 1.9 mmol, 3.1 equiv) was added, and the reaction mixture was stirred at 0 °C for 15 min followed by 30 min at room temperature. The product was precipitated by dropwise addition of the reaction mixture to degassed diethyl ether (100 mL), and inert filtration gave, after trituration with 2 × 10 mL of diethyl ether, 0.14 g (57%) of **3a**. ^{1}H NMR (acetone-d_6, 400 MHz): δ 6.48−6.54 (m, 1H), 6.31−6.37 (m, 1H), 6.15 (s, 5H), 4.95 (dm, J = 7.3 Hz, 1H), 4.86−4.91 (m, 1H), 2.38−2.50 (m, 2H), 1.93 (d, J = 14.8 Hz, 1H), 1.12 (d, J = 6.7 Hz, 3H). ^{13}C NMR (CD_3CN, 400 MHz): δ 224.4, 224.2, 95.8, 85.8 (br), 85.7 (br), 84.2 (br), 66.7, 34.1, 33.3, 26.4 (gradual decomposition made the ^{13}C NMR determination difficult). IR (CH_2Cl_2): 2011, 1945 cm^{-1}. HRMS (FAB+): m/z calcd for $C_{14}H_{15}MoO_2$, 313.0126; found M$^+$, 313.0137.

(η^5-Cyclopentadienyl)dicarbonyl[(1−4-η)-5-isopropylcyclohexadien]molybdenum Bromide (3b). In a flask were placed degassed 1,1,1,3,3,3-hexafluoro-2-propanol (1.0 mL), degassed dichloromethane (4.0 mL), and **2b** (0.13 g, 0.52 mmol). The flask was cooled to 0 °C, whereupon **4** (0.40 g, 1.2 mmol, 3.0 equiv) was added, and the reaction mixture was stirred for 30 min at room temperature. The product was precipitated by dropwise addition of the reaction mixture to degassed diethyl ether (100 mL), and inert filtration gave, after trituration with 2 × 10 mL of diethyl ether, 72 mg (44%) of **3b**. ^{1}H NMR (CD_3CN, 400 MHz): δ 5.95−5.92 (m, 2H), 5.74 (s, 5H), 4.62 (br s, 1H), 4.57 (br d, J = 6 Hz, 1H), 2.07−2.2 (m, 3H) obscured by water signal, 1.58 (sep, J = 6.8 Hz, 1H), 0.86 (d, J = 6.8 Hz, 3H), 0.81 (d, J = 6.8 Hz, 3H). ^{13}C NMR (CD_3CN, 400 MHz): δ 225.2 (impurity) 224.8, 224.3, 101.9 (impurity) 96.5, 90.1, 89.7 (br), 86.6 (br), 86.0 (br), 45.7, 35.9, 28.8, 20.9, 20.1 (gradual decomposition made the ^{13}C NMR determination difficult). IR (CH_2Cl_2): 2013, 1955 cm^{-1}. HRMS (FAB+): m/z calcd for $C_{16}H_{19}MoO_2$, 341.0439; found M$^+$, 341.0448.

(η^5-Cyclopentadienyl)dicarbonyl[(1−4-η)-5-(1-naphthyl)cyclohexadien]molybdenum Bromide (3e). In a flask were placed degassed 1,1,1,3,3,3-hexafluoro-2-propanol (1.0 mL), degassed dichloromethane (4.0 mL), and **2e** (76 mg, 0.18 mmol). The flask was cooled to 0 °C, whereupon **4** (0.13 g, 0.39 mmol, 2.2 equiv) was added, and the reaction mixture was stirred at 0 °C for 15 min followed by 1 h at room temperature. The product was precipitated by addition of degassed diethyl ether (100 mL) followed by inert filtration. After trituration with 2 × 10 mL of diethyl ether, 20 mg (22%) of **3e** was isolated. ^{1}H NMR (acetone-d_6, 300 MHz): δ 8.08 (d, J = 7.5 Hz, 1H), 7.94 (d, J = 8.6 Hz, 1H), 7.82 (d, J = 7.7 Hz, 1H), 7.45−7.63 (m, 4H) 6.62−6.52 (m, 2H), 6.17 (s, 5H), 4.86−5.01 (m, 2H), 4.59 (dm, J = 9.2 Hz, 1H), 3.00−3.30 (m, 2H) obscured by water signal, 2.43 (d, J = 16.5 Hz, 1H). ^{13}C NMR (CD3CN, 400 MHz): 222.7, 222.4, 142.1, 135.3,132.6, 130.3, 129.0, 128.0, 127.4, 127.1, 124.3, 124.3, 95.9, 86.5, 85.6, 84.4, 55.9, 40.0, 34.2 (decomposition complicated ^{13}C NMR determination). IR (CH_2Cl_2): 2009, 1957 cm^{-1}. HRMS (FAB+): m/z calcd for $C_{23}H_{19}MoO_2$, 425.0439; found M$^+$, 425.0443.

9-Hydroxy-1-methoxyxanthene (7). In a flask were placed 1-methoxyxanthone[15] (0.31 g, 1.3 mmol) and dry diethyl ether (10 mL). The flask was cooled to 0 °C, whereupon $LiAlH_4$ (0.18 g, 4.7 mmol, 3.6 equiv) was added in three portions, and the reaction mixture was stirred at room temperature for 3 h. Aqueous sodium bisulfate (5% solution, 25 mL) was added, and the reaction mixture was extracted with 3 × 20 mL of diethyl ether. The combined organic phases were dried over Na_2SO_4, filtered, and evaporated, giving 0.19 g (61%) of the title product. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.62 (d, J = 7.7 Hz, 1H), 7.15−7.38 (m, 4H), 6.83 (d, J = 8.2 Hz, 1H), 6.68 (d, J = 8.2 Hz, 1H), 6.15 (s, 1H), 3.98 (s, 3H). IR (CH2Cl2): 3386, 2962, 1653, 1603, 1471, 1263 cm^{-1}. HRMS (FAB+): m/z calcd for $C_{14}H_{11}O_2$, 211.0757; found (M − OH)$^+$, 211.0740. HRMS

(23) The freshly distilled naphthyl bromide was dissolved in THF and added dropwise to magnesium at such a rate that the mixture was kept at reflux.

(CI+): *m*/*z* calcd for $C_{17}H_{19}O_3Si$, 299.1140; found (M + TMS − 1)$^+$, 299.1100. Further characterization was prevented by disproportionation of the alcohol into the corresponding xanthone and xanthene in solvents such as $CDCl_3$.[24]

Dissolution of alcohol **7** in dihloromethane and diethyl ether followed by treatment with HBF_4·Et_2O gave the xanthenylium ion as a red solid.[25] ^{1}H NMR (CD_2Cl_2, 300 MHz): δ 10.45 (s, 1H), 8.52−8.63 (m, 3H), 8.27 (d, J = 8.8 Hz, 1H), 8.06 (ddd, J = 8.2, 7.2, 1.0 Hz, 1H), 7.81 (d, J = 8.8, 1H), 7.33 (d, J = 8.2, 1H), 4.30 (s, 3H). IR (KBr): 1598, 1483, 1469, 1250, 1084 cm^{-1}. HRMS (FAB+): *m*/*z* calcd for $C_{14}H_{11}O_2$, 211.0759; found M$^+$, 211.0752.

1-((*S*)-1-Phenylethoxy)xanthone ((*S*)-13a). In a flask were placed 1-methoxyxanthone (0.99 g, 4.2 mmol) and dry dichloromethane (10 mL). The flask was cooled to −78 °C, whereupon a 1 M solution of BBr_3 (8.5 mL, 8.5 mmol, 2.0 equiv) was added. The reaction mixture was stirred at room temperature for 2 h. Ice−water (50 mL) was added, and the reaction mixture was extracted with 2 × 20 mL of dichloromethane. The combined organic phases were washed with brine (20 mL) and water (20 mL), dried over Na_2SO_4, filtered, and evaporated, giving 0.78 g (87%) of 1-hydroxyxanthone.[26] ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.66 (s, 1H), 8.30 (ddd, J = 8.0, 1.7, 0.4 Hz, 1H), 7.77 (ddd, J = 8.5, 7.1, 1.7 Hz, 1H), 7.61 (t, J = 8.3 Hz, 1H), 7.50 (ddd, J = 8.5, 1.1, 0.4 Hz, 1H), 7.42 (ddd, J = 8.0, 7.1, 1.1 Hz, 1H), 6.96 (dd, J = 8.3, 0.9 Hz, 1H), 6.82 (dd, J = 8.3, 0.9 Hz, 1H). A mixture of triphenyl phosphine (1.2 g, 4.8 mmol, 2.0 equiv) and dry THF (14 mL) was cooled to 0 °C, whereupon DEAD (0.75 mL, 4.8 mmol, 2.0 equiv) was added dropwise over 15 min. The reaction mixture was then allowed to warm to room temperature. After stirring for 1.5 h at room temperature 1-hydroxyxanthone (0.50 g, 2.3 mmol) and (*R*)-1-phenetyl alcohol (0.6 mL, 5.0 mmol, 2.2 equiv) were added, and the mixture was stirred for 84 h. The reaction mixture was evaporated and thereafter triturated with diethyl ether to yield a white solid. Filtration, evaporation, and purification by flash chromatography (EtOAC/heptane, 3:1, R_f = 0.22) gave 0.40 g (54%) of 1-((*S*)-1-phenylethoxy)xanthone. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 8.38 (ddd, J = 8.0, 1.7, 0.4 Hz, 1H), 7.66 (ddd, J = 8.5, 7.1, 1.7 Hz, 1H), 7.52−7.57 (m, 2H), 7.33−7.43 (m, 5H), 7.24−7.31 (m, 1H), 6.97 (dd, J = 8.4, 1.0 Hz, 1H), 6.67 (d, J = 8.3 Hz, 1H), 5.54 (q, J = 6.4 Hz, 1H), 1.84 (d, J = 6.4 Hz, 3H). ^{13}C NMR ($CDCl_3$, 400 MHz): δ 176.2, 158.8, 158.0, 154.9, 142.5, 134.2, 133.9, 128.5, 127.3, 126.6, 125.6, 123.5, 122.6, 117.06, 113.2, 109.6, 108.8, 77.4, 24.3. IR (CH_2Cl_2): 3062, 2979, 2929, 1658, 1618, 1603, 1486, 1358, 1273 cm^{-1}. HRMS (FAB+): *m*/*z* calcd for $C_{21}H_{17}O_3$, 317.1178; found (M + 1)$^+$, 317.1184. HPLC analysis was performed with ^{i}PrOH/hexane, 15:85, as the eluent (flow rate 0.5 mL/min); enantiomer *S*, t_R = 13 min, 93%; enantiomer *R*, t_R = 17 min, 7%.

Racemic 1-(1-Phenylethoxy)xanthone (*rac*-13a). This material was prepared according to the procedure used for enantiomerically pure 1-(1-phenylethoxy)xanthone from triphenyl phosphine (0.26 g, 1.0 mmol, 2.1 equiv), DEAD (160 μL, 1.0 mmol, 2.2 equiv), 1-hydroxyxanthone (0.10 g, 0.47 mmol), and 1-phenetyl alcohol (116 μL, 1.0 mmol, 2.0 equiv), yielding, after purification, 75 mg (51%) of 1-(1-phenylethoxy)-xanthone. HPLC analysis was recorded with ^{i}PrOH/hexane, 15:85, as the solvent (flow rate 0.5 mL/min); enantiomer *S*, t_R = 13 min, 49%; enantiomer *R*, t_R = 17 min, 51%.

1-((*S*)-1-Indanyloxy)xanthone ((*S*)-13b). In a flask were placed triphenyl phosphine (0.79 g, 3.0 mmol, 2.2 equiv) and dry THF (9 mL). The flask was cooled to 0 °C, whereupon DEAD (0.45 mL, 2.8 mmol, 2.1 equiv) was added dropwise over 15 min. The reaction mixture was then allowed to warm to room temperature. After stirring for 30 min at room temperature, 1-hydroxyxanthone (0.29 g, 1.4 mmol) and (*R*)-1-indanol (0.40 g, 2.8 mmol, 2.0 equiv) were added and stirring was continued for 4 days. The reaction mixture was evaporated and thereafter triturated with diethyl ether to give a white solid. Filtration, evaporation, and purification by flash chromatography (EtOAC/heptane, 3:1, R_f = 0.29) gave 0.24 g (52%) of 1-((*S*)-1-indanyloxy)xanthone. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 8.28 (dd, J = 8.0, 1.4 Hz, 1H), 7.57−7.69 (m, 3H), 7.42 (d, J = 7.8 Hz, 1H), 7.29−7.35 (m, 4H), 7.11 (dd, J = 8.4, 0.99 Hz, 1H), 7.00 (d, J = 7.8 Hz, 1H), 5.93 (dd, J = 6.5, 5.4 Hz, 1H), 3.18−3.30 (m, 1H), 2.92−3.03 (m, 1H), 2.62−2.76 (m, 1H), 2.32−2.47 (m, 1H). ^{13}C NMR ($CDCl_3$, 400 MHz): δ 170.2, 159.6, 158.3, 155.0, 143.7, 141.4, 134.5, 134.1, 128.8, 126.8, 126.8, 125.6, 124.8, 123.7, 123.1, 117.2, 113.7, 110.4, 109.6, 83.7, 32.8, 30.3. IR (CH_2Cl_2): 3070, 2939, 1718, 1660, 1618, 1601, 1466, 1356, 1271 cm^{-1}. HRMS (FAB+): *m*/*z* calcd for $C_{22}H_{16}O_3$, 329.1178; found (M + 1)$^+$, 329.183. HPLC analysis was recorded with ^{i}PrOH/hexane, 15:85, as the eluent (flow rate 0.5 mL/min); enantiomer *S*, t_R = 20 min, 99%; enantiomer *R*, t_R = 23 min, 1%.

Racemic 1-(1-Indanyloxy)xanthone (*rac*-13b). 13b was prepared according to the procedure used for enantiomerically pure 1-(1-indane)xanthone from triphenyl phosphine (0.26 g, 1.0 mmol, 2.1 equiv), DEAD (160 μL, 1.0 mmol, 2.2 equiv), 1-hydroxyxanthone (0.10 g, 0.47 mmol), and 1-indanol (116 μL, 1.0 mmol, 2.0 equiv), yielding, after purification, 75 mg (51%) of the title compound. HPLC analysis was performed as above; enantiomer *S*, t_R = 20 min, 50%; enantiomer *R*, t_R = 23 min, 50%.

9-Hydroxy-1-((*S*)-1-phenylethoxy)xanthene (14a). In a flask were placed **(*S*)-13a** (0.35 g, 1.1 mmol) and dry diethyl ether (10 mL). The flask was cooled to 0 °C, whereupon $LiAlH_4$ (0.18 g, 4.7 mmol, 4.3 equiv) was added in three portions, and the reaction mixture was stirred at room temperature for 3 h. Aqueous sodium bisulfate (a 5% solution, 25 mL) was added, and the reaction mixture was extracted with 3 × 20 mL of diethyl ether. The combined organic phases were washed with water (20 mL), dried over Na_2SO_4, filtered, and evaporated, giving 0.27 g (78%) of **14a**. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.63 (d, J = 7.6 Hz, 1H), 7.53−7.12 (m, 9H), 6.73 (t, J = 7.2 Hz, 1H), 6.50 (q, J = 7.5 Hz, 1H), 6.27 (s, 1H), 5.41−5.57 (m, 1H), 1.77 (d, J = 6.9 Hz, 1.5 H), 1.74 (d, J = 6.9 Hz, 1.5 H). Decomposition prohibited IR and ^{13}C NMR. HRMS (FAB+): *m*/*z* calcd for $C_{21}H_{17}O_2$, 301.1229; found (M − OH)$^+$, 301.1237. HRMS (CI+): *m*/*z* calcd for $C_{24}H_{25}O_3Si$, 389.1573; found (M + TMS − 1)$^+$, 389.1569.

9-Hydroxy-1-((*S*)-1-indanyloxy)xanthene (14b). In a flask were placed **(*S*)-13b** (0.22 g, 0.7 mmol) and dry diethyl ether (10 mL). The flask was cooled to 0 °C, whereupon $LiAlH_4$ (0.22 g, 5.9 mmol, 9.0 equiv) was added in three portions, and the reaction mixture was stirred at room temperature for 3 h. Aqueous sodium bisulfate (a 5% solution, 25 mL) was added, and the reaction mixture was extracted with 3 × 20 mL of diethyl ether. The combined organic phases were washed with water (20 mL), dried over Na_2SO_4, filtered, and evaporated, giving 0.15 g (67%) of **14b**. The product was immediately used in the reaction with **15**.

(η⁵-Cyclopentadienyl)dicarbonyl[(3−5-η)-5,6-dihydropyranyl]molybdenum (15). In a dry, two-necked flask were placed (η⁵-cyclopentadienyl)dicarbonyl[(2−5-η)-6*H*-dihydropyranyl]molybdenum tetrafluoroborate[2a] (0.24 g, 0.63 mmol) and dry THF (10 mL) under argon atmosphere. The suspension was cooled to −78 °C, whereupon a 1 M solution of $LiEt_3BH$ in THF (4.0 mL, 4.0 mmol, 6.3 equiv) was added. The reaction mixture was stirred for 2 h at −78 °C. The reaction mixture was filtered through a pad of silica, which was rinsed with dichloromethane, and the solvent was evaporated. The crude product was subjected to flash chromatography (EtOAc/heptane, 1:1, R_f = 0.36) to give 0.11 g (58%) of an orange solid. ^{1}H NMR (CD_2Cl_2): δ 5.35 (s, 5H), 4.30 (t, J = 6.8 Hz, 1H), 3.70

(24) Fozze, M. R. *Ann. Chim.* **1916,** *6*, 56. Zhu, Z.; Espenson, J. H. *J. Org. Chem.* **1996,** *61*, 324.
(25) Convert, O.; Le Roux, J.-P.; Desbene, P.-L.; Defoin A. *Bull. Soc. Chim. Fr.* **1975**, *9*−*10*, 2023.
(26) Gabbutt, C. D.; Hepworth, J. D.; Urquhart, M. W. J. Vazquez de Miguel, L. M. *J. Chem. Soc., Perkin Trans. 1* **1997,** *1819*.

(d, J = 11.9 Hz, 2H), 3.43−3.49 (m, 4H). ^{13}C NMR (CD_2Cl_2, 400 MHz): δ 235.8, 92.68, 61.72, 54.0 (obscured by the solvent signal), 53.0. IR (KBr): 1927, 1859 cm^{-1}. HRMS (FAB+): m/z calcd for $C_{12}H_{12}MoO_3$, 301.9841; found M^+, 301.9852.

(η^5-Cyclopentadienyl)dicarbonyl[(3−5-η)-2-methyl-5,6-dihydropyranyl]molybdenum (17). In a flask under inert atmosphere were placed degassed 1,1,1,3,3,3-hexafluoro-2-propanol (1.0 mL), degassed dichloromethane (4.0 mL), **15** (0.11 g, 0.37 mmol), and **14a** (0.22 g, 0.70 mmol, 1.9 equiv). Degassed diethyl ether (100 mL) was added, and the flask was cooled to 0 °C, whereupon HBF_4·Et_2O (0.10 mL, 0.73 mmol, 2.0 equiv) was added dropwise, and a precipitation was immediately formed. After 30 min inert filtration and trituration with 2 × 10 mL of diethyl ether returned 0.12 g (86%) of crude **16**. In a flask fitted with an argon inlet were placed crude **16** and dry THF (10 mL). The flask was cooled to −78 °C, whereupon a 3 M solution of MeMgBr in THF (1.4 mL, 4.2 mmol, 13 equiv) was added. The reaction mixture was stirred for 1 h at −78 °C followed by 30 min stirring at room temperature. Saturated aqueous NH_4Cl (20 mL) was added, and the reaction mixture was extracted with 2 × 20 mL of dichloromethane. The combined organic phases were dried over Na_2SO_4, filtered, and evaporated, and the crude product was subjected to flash chromatography (EtOAc/heptane, 3:1) to give 0.36 g (30%) of a yellow oil. The enantiomeric excess was determined by HPLC as well as according to a literature procedure[2b] using (−)-Pr[hfc]$_3$ (0.75 equiv) as the chiral shift reagent. Integration of the two Cp singlets indicated an enantiomeric excess of 6%. The enantiomer with the more downfield NMR shift in the presence of the chiral shift reagent was favored. HPLC analysis was performed with ^{i}PrOH/hexane, 20:80, as the eluent (flow rate 0.5 mL/min); enantiomer A, t_R = 22 min, 52%; enantiomer B, t_R = 27 min, 48%. A similar experiment using **15** (67 mg, 0.23 mmol) and **14b** (0.15 g, 0.44 mmol, 1.9 equiv) provided 88 mg (100%) of crude **16** contaminated with **14b**. Addition of MeMgBr (1.5 mL, 4.5 mmol, 20 equiv) gave, after filtration through a pad of silica gel, 54 mg (64% crude yield). Additional chromatographic purification allowed the isolation of analytically pure **17** (3.3 mg). The enantiomeric excess of this material was determined by NMR (10% ee) and HPLC; enantiomer A, t_R = 22 min, 46%; enantiomer B, t_R = 27 min, 54%. The enantiomer with the more upfield NMR shift in the presence of the chiral shift reagent was favored.

Acknowledgment. This work was supported by the Swedish Natural Science Research Council and Kungliga Fysiografiska Sällskapet i Lund.

OM011016G