for the calculated ordering 3d > 4d > 5d for the M-CO bond strength in the nonrelativistic limit. Four-electron two-orbital interactions, including those encountered in the metal carbonyls between occupied metal orbitals and σ_{CO} orbitals, are, as already mentioned, destabilizing. The destabilization is in part due to an increase in the electronic kinetic energy caused by the node in the out-of-phase combination from the two-orbital interaction. Relativistic effects can, as it is explained in ref 12, to some degree reduce the electronic kinetic energy by increasing the electronic mass through the socalled mass-velocity term. The stabilizing relativistic effect will be larger for carbonyls of 5d metals than for carbonyls of 4d metals. The calculated ordering of the M-CO bond strength is as a result, after relativistic effects have been included, 3d > 5d > 4d.

We have attempted as well to assess the relative importance of σ-donation and π-back-donation for the strength of the synergic M-CO bond. The conclusions from such an assessment depend on the operative definition of σ-donation and π-back-donation. It depends, in addition, on whether one considers ΔH or D(M-CO) as a measure for the M-CO bond strength. We conclude, based on the definition for σ-donation and π-back-donation given in this work, that π-back-donation is the more important factor in D-(M-CO), whereas both σ-donation and π-back-donation are of importance for ΔH. It should, however, be noted that σ_{CO} largely has a repulsive role in metal carbonyls and that σ-donation only serves to reduce the repulsive role. The π_{CO}^* orbitals on the other hand serve exclusively to stabilize the M-CO bond.

Acknowledgment. This investigation was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) as well as the Alberta Research Council (through a scholarship to V.T.). We thank Professor E. J. Baerends for a copy of the newest version of the HFS-program system and the University of Calgary for providing time on its Cyber-205 installations. We also thank Professor A. Becke (Queens University, Kingston, Canada) for numerous useful discussions.

A Versatile New Synthesis of Organic Compounds with Chiral Methyl Groups: Stereochemistry of Protolytic Rhenium-Carbon Bond Cleavage in Chiral Alkyl Complexes (η^5-C_5H_5)Re(NO)(PPh_3)(R)

Edward J. O'Connor,[1] Motomasa Kobayashi,[2] Heinz G. Floss,*[2] and J. A. Gladysz*[1]

Contribution from the Departments of Chemistry, University of Utah, Salt Lake City, Utah 84112, and The Ohio State University, Columbus, Ohio 43210.
Received December 12, 1986

Abstract: Reaction of (η^5-C_5H_5)Re(NO)(PPh_3)(CO_2CH_3) (**1**) with (3,5-dimethoxyphenyl)magnesium iodide gives 3,5-dimethoxybenzoyl complex (η^5-C_5H_5)Re(NO)(PPh_3)(CO(3,5-$C_6H_3(OCH_3)_2$)) (**2**, 97%). Reaction of **2** with BH_3·THF gives 3,5-dimethoxybenzyl complex (η^5-C_5H_5)Re(NO)(PPh_3)(CH_2(3,5-$C_6H_3(OCH_3)_2$)) (**3**, 86%). Reaction of **3** with $Ph_3C^+PF_6^-$ at -80 °C gives a 62:38 mixture of the *sc* and *ac* Re=C geometric isomers (**4k**, **4t**) of 3,5-dimethoxybenzylidene complex [(η^5-C_5H_5)Re(NO)(PPh_3)(=CH(3,5-$C_6H_3(OCH_3)_2$))]$^+PF_6^-$; workup gives **4t** (89%). Reaction of **4t** with Li(C_2H_5)$_3$BD or $NaBD_4$ gives addition product (*SS*,*RR*)-**3**-α-d_1. Optically active (+)-(*S*)-**1** and (-)-(*R*)-**1** (≥98% ee) are similarly treated with (3,5-dimethoxyphenyl)magnesium iodide, BD_3·THF, and $Ph_3C^+PF_6^-$ to give (+)-(*S*)- and (-)-(*R*)-**4t**-α-d_1. Addition of $NaBT_4$ gives (+)-(*SS*)- and (-)-(*RR*)-**3**-α-d_1t_1. Reaction with HBr gives (*S*)- and (*R*)-dimethoxytoluene-α-d_1t_1, and (+)-(*R*)- and (-)-(*S*)-(η^5-C_5H_5)Re(NO)(PPh_3)(Br) (retention of configuration at carbon and rhenium). The former are treated with O_3 to give chiral acetate salts (*S*)- and (*R*)-CHDTCOO$^-$Na$^+$ of 93% and 86% ee, as established by an enzymatic assay. The mechanisms of these transformations, and the utility of this route to chiral acetic acid, are discussed.

Asymmetric organic synthesis has evolved in sophistication to the stage where several classes of chiral molecules are now easily synthesized in optically pure form. Both chemical and enzymatic methodologies have been developed, and the former, which are often more amenable to laboratory study, have provided important insights into the mechanisms of biological stereogenesis. In this paper, we describe a versatile, convenient, metal-mediated synthesis of molecules containing the most fundamental unit of organic asymmetry, the chiral methyl group, -CHDT.[3] Such chiral-by-isotopic-substitution derivatives of proprochiral compounds have seen practical use in the elucidation of enzymatic reaction mechanisms and are also of value, as illustrated below, in the study of abiological reaction mechanisms.[3,4]

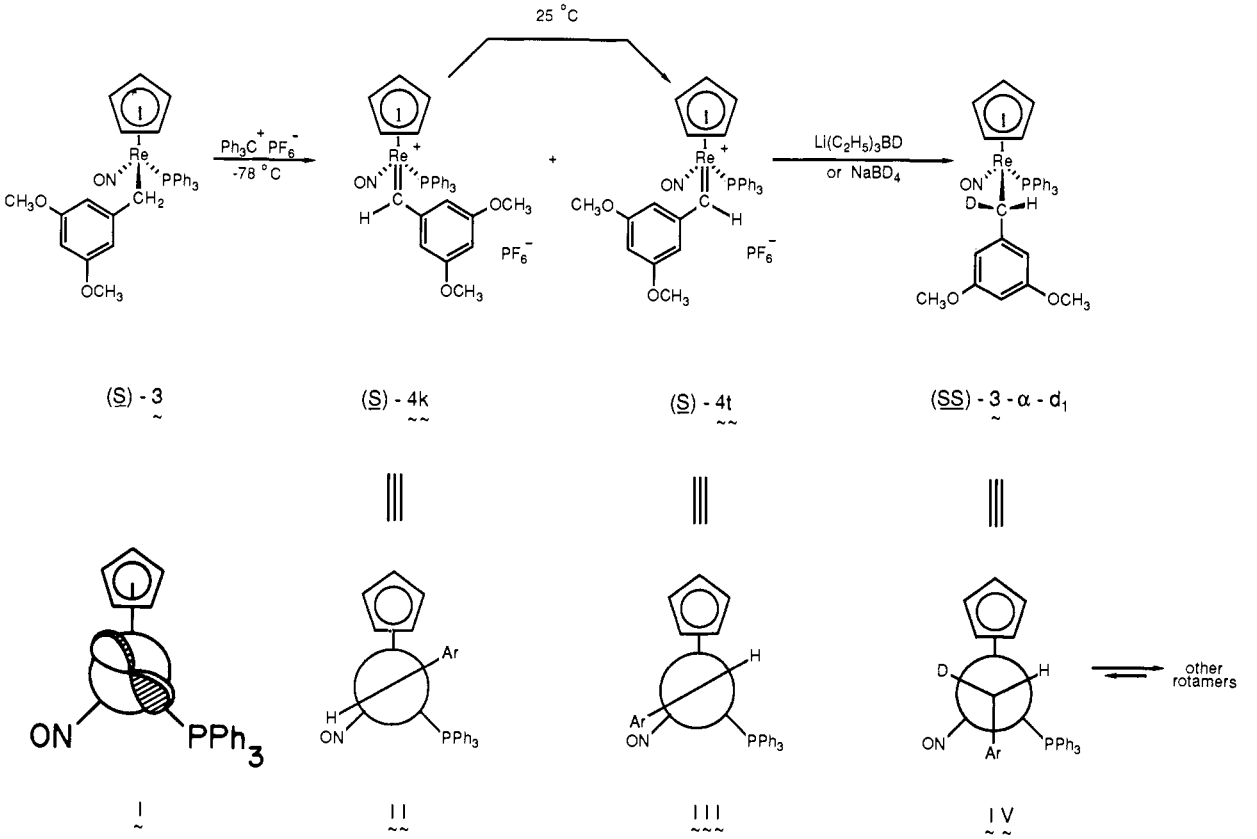
The first preparations of compounds containing chiral methyl groups were reported in landmark communications by Cornforth and Arigoni in 1969.[5a,6a] Since then, additional elegant syntheses have been developed. These include purely chemical routes,[5] and ones involving enzymatic steps.[6] Most have been directed at the preparation of chiral acetic acid (CHDTCOOH), for which an

(1) University of Utah.
(2) Ohio State University.
(3) Floss, H. G.; Tsai, M.-D.; Woodward, R. W. *Top. Stereochem.* **1984**, *15*, 253.
(4) (a) Lowe, G. *Acc. Chem. Res.* **1983**, *16*, 244. (b) Buchwald, S. L.; Pliura, D. H.; Knowles, J. R. *J. Am. Chem. Soc.* **1984**, *106*, 4916.

(5) See, inter alia: (a) Cornforth, J. W.; Redmond, J. W.; Eggerer, H.; Buckel, W.; Gutschow, C. *Nature (London)* **1969**, *221*, 1212. (b) Townsend, C. A.; Scholl, T.; Arigoni, D. *J. Chem. Soc., Chem. Commun.* **1975**, 921. (c) Kajiwara, M.; Lee, S.-F.; Scott, A. I.; Akhtar, M.; Jones, C. R.; Jordan, P. M. *Ibid.* **1978**, 967. (d) Fryzuk, M. D.; Bosnich, B. *J. Am. Chem. Soc.* **1979**, *101*, 3043. (e) Caspi, E.; Piper, J.; Shapiro, S. *J. Chem. Soc., Chem. Commun.* **1981**, 76. (f) Townsend, C. A.; Neese, A. S.; Theis, A. B. *Ibid.* **1982**, 116. (g) Kobayashi, K.; Jadhav, P. K.; Zydowsky, T. M.; Floss, H. G. *J. Org. Chem.* **1983**, *48*, 3510. (h) Caspi, E.; Aranachalam, T.; Nelson, P. A. *J. Am. Chem. Soc.* **1983**, *105*, 6987. (i) Kobayashi, K.; Kakinuma, K.; Floss, H. G. *J. Org. Chem.* **1984**, *49*, 1290. (j) Coates, R. M.; Kock, S. C.; Hegde, S. *J. Am. Chem. Soc.* **1986**, *108*, 2762. (k) Zydowsky, T. M.; Courtney, L. F.; Frasca, V.; Kobayashi, K.; Shimizu, H.; Yuen, L.-D.; Matthews, R. G.; Benkovic, S. J.; Floss, H. G. *Ibid.* **1986**, *108*, 3152.
(6) See, inter alia: (a) Lüthy, J.; Rétey, J.; Arigoni, D. *Nature (London)* **1969**, *221*, 1212. (b) Rose, I. A. *J. Biol. Chem.* **1970**, *245*, 6052. (c) Creighton, D. F.; Rose, I. A. *Ibid.* **1976**, *251*, 61. (d) Altman, L. J.; Han, C. Y.; Bertolino, A.; Handy, G.; Laungaini, D.; Muller, W.; Schwartz, S.; Shanker, D.; de Wolf, W. H.; Yang, F. *J. Am. Chem. Soc.* **1978**, *100*, 3235. (e) Rozell, J. D., Jr.; Benner, S. A. *J. Org. Chem.* **1983**, *48*, 1190.

0002-7863/87/1509-4837$01.50/0

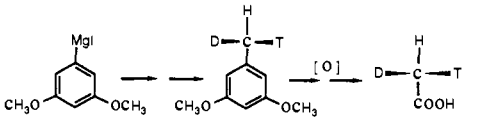
Scheme I. Synthesis and Reactions of Optically Active 3,5-Dimethoxybenzylidene Complexes



enzymatic assay for configuration and optical purity has been developed.[5a,6a,7]

We recently described a general method for the synthesis of diasteromerically and enantiomerically pure, pseudotetrahedral rhenium alkyl complexes of the formula $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CHDR)$, where R = aryl or *n*-alkyl.[8,9] These alkyl complexes have also been shown to react with protic acids HX to give complexes of the formula $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(X)$ and alkanes.[10] If the rhenium–carbon bond cleavage were to be stereospecific at carbon, use of a tritiated acid TX should provide a very general synthesis of enantiomerically pure RCHDT compounds.

Accordingly, we describe below the elaboration of the Grignard reagent derived from 3,5-dimethoxyiodobenzene to both enantiomers of chiral 3,5-dimethoxytoluene (eq 1). This target was

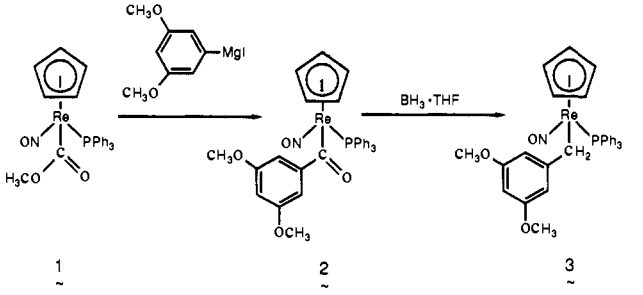


(1)

selected because we have previously shown it to be readily degradable to chiral acetic acid without loss of optical purity.[5g] However, the methodology developed should be applicable to any aryl or *n*-alkyl Grignard reagent. We also establish the stereochemistry of sp^3 carbon–rhenium bond protonolysis at both carbon and rhenium.

Results

Synthesis of Racemic Complexes. We have previously shown that reaction of the "methyl ester" $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CO_2CH_3)$ (**1**)[11] with Grignard reagents RMgX in THF provides a convenient route to acyl complexes $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(COR)$.[12] Accordingly, **1** and (3,5-dimethoxyphenyl)magnesium iodide reacted to give 3,5-dimethoxybenzoyl complex $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CO(3,5\text{-}C_6H_3(OCH_3)_2))$ (**2**) in 97% yield (eq 2). Reduction of **2** with BH_3·THF gave 3,5-dimethoxybenzyl complex $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CH_2(3,5\text{-}C_6H_3(OCH_3)_2))$ (**3**) in 86% yield after recrystallization (eq 2). The



(2)

structures of **2** and **3** followed readily from their spectroscopic properties, which are summarized in the Experimental Section. The two diastereotopic benzylic protons (H_α) in **3** exhibited different ^1H NMR chemical shifts (δ (CD_2Cl_2) 3.48 (dd), 2.85 (dd)), as shown in trace C of Figure 1.

Attention was turned to the generation of 3,5-dimethoxybenzylidene complexes from **3**. First, treatment of **3** with hydride abstraction agent $Ph_3C^+PF_6^-$ at −78 °C, followed by a room-temperature workup, gave the more stable Re=C geometric isomer *ac*-$[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(=CH(3,5\text{-}C_6H_3(OCH_3)_2))]^+PF_6^-$ (**4t**) in 89% yield. This is illustrated in Scheme I for the corresponding reaction with optically active substrate. Complex **4t** exhibited the low-field ^1H and ^{13}C NMR resonances

(7) Floss, H. G. *Methods Enzymol.* **1982**, *87*, 126.
(8) (a) Kiel, W. A.; Lin, G.-Y.; Constable, A. G.; McCormick, F. B.; Strouse, C. E.; Eisenstein, O.; Gladysz, J. A. *J. Am. Chem. Soc.* **1982**, *104*, 4865. (b) Kiel, W. A.; Lin, G.-Y.; Bodner, G. S.; Gladysz, J. A. *Ibid.* **1983**, *105*, 4958.
(9) See also: O'Connor, E. J.; Fernández, J. M.; Patton, A. T.; Gladysz, J. A., submitted for publication in *Inorg. Synth.*
(10) (a) Merrifield, J. H.; Fernández, J. M.; Buhro, W. E.; Gladysz, J. A. *Inorg. Chem.* **1984**, *23*, 4022. (b) Fernández, J. M.; Gladysz, J. A. *Ibid.* **1986**, *25*, 2672.
(11) Merrifield, J. H.; Strouse, C. E.; Gladysz, J. A. *Organometallics* **1982**, *1*, 1204.
(12) Buhro, W. E.; Wong, A.; Merrifield, J. H.; Lin, G.-Y.; Constable, A. G.; Gladysz, J. A. *Organometallics* **1983**, *2*, 1852.

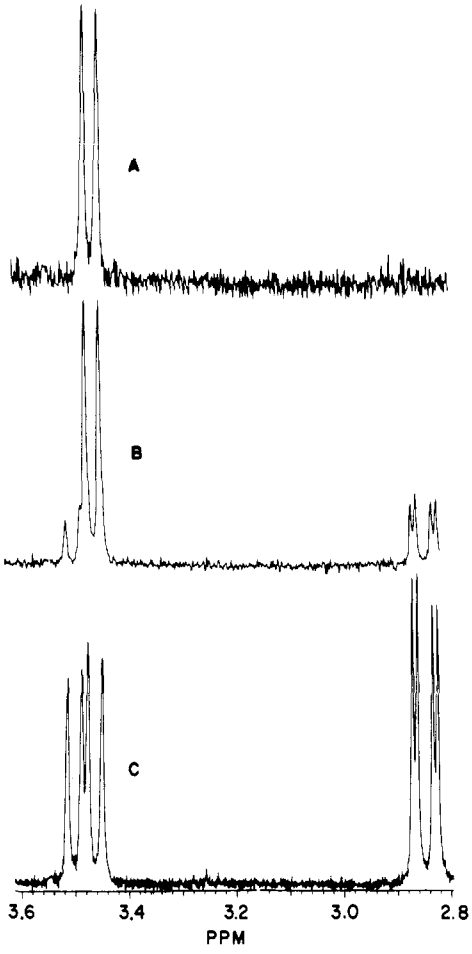


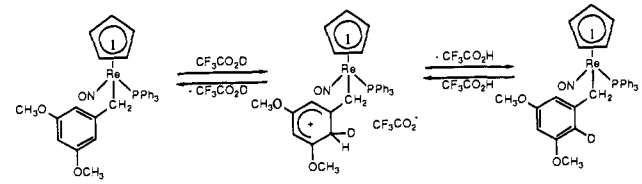
Figure 1. ^1H NMR spectra of the benzylic (C_α) protons of (C) **3**-α-d_0, (B) a 72:28 mixture of (*SS,RR*)-**3**-α-d_1 and **3**-α-d_0 prepared with $NaBD_4$ as described in the text, and (A) (*SS,RR*)-**3**-α-d_1.

for H_α and C_α that are characteristic of this class of compounds (Experimental Section).[8]

When the reaction of **3** with $Ph_3C^+PF_6^-$ was monitored by ^1H NMR at −80 °C, a (62 ± 2):(38 ± 2) mixture of the less stable Re=C geometric isomer, **4k**, and **4t** formed. Complex **4k** underwent a first-order isomerization to **4t** with k_{obsd} = (2.09 ± 0.2) × 10^{-4} s^{-1} at 24.6 °C. The orientations of the 3,5-dimethoxybenzylidene ligand in **4k** and **4t** are shown in Newman projections II and III in Scheme I. These Re=C conformations maximize the overlap of the rhenium fragment HOMO (shown in I, Scheme I) with the p acceptor orbital on C_α. Interestingly, in previous studies involving alkyl and unsubstituted benzyl complexes, we had found the less stable Re=C geometric isomers to be the exclusive kinetic products.[8] However, we had also found that ortho-substituted benzyl complexes gave appreciable quantities of the more stable Re=C geometric isomer among the kinetic products.[13] Apparently, meta-substituted benzyl complexes are intermediate in selectivity.

Treatment of **4t** with $Li(C_2H_5)_3BD$ in THF gave deuteride addition product (*SS,RR*)-(η^5-C_5H_5)Re(NO)(PPh_3)(CHD(3,5-$C_6H_3(OCH_3)_2$)) ((*SS,RR*)-**3**-α-d_1)[14] of >99% diastereomeric purity (Scheme I), as assayed by integration of the H_α NMR resonances shown in trace A of Figure 1. This stereochemical assignment was based upon the previous demonstration of nucleophilic attack from a direction anti to the PPh_3 ligand in phenyl and alkyl analogues of III.[8]

Scheme II. Proposed Mechanism of Deuterium Incorporation into Arene Rings



In order to achieve maximum flexibility in the sequence of hydrogen isotope introduction and in view of the ready availiability of tritiated $NaBH_4$ (and considerable cost of tritiated $Li(C_2H_5)_3BH$),[15] the reaction of **4t** with $NaBD_4$ (98% D) in THF was also investigated. This gave a (72 ± 2):(28 ± 2) ratio of (*SS,RR*)-**3**-α-d_1 and **3**-α-d_0, as determined from the ^1H NMR spectrum shown in trace B of Figure 1.[16] No evidence for the opposite diastereomer, (*SR,RS*)-**3**-α-d_1, was noted. This shows that the stereospecificity of deuteride addition is independent of the size of the ligands on the boron reductant.

Synthesis of 3,5-Dimethoxytoluene. Attention was next turned to the generation of 3,5-dimethoxytoluene and 3,5-dimethoxytoluene-α-d_1 by protonolysis and deuterolysis of the rhenium–carbon bond in **3**. We first examined acids that could be readily generated by hydrolysis of the corresponding anhydride. By conducting the hydrolyses with T_2O, these acids would be obtained in tritiated form.

First, reaction of **3** with 1.0 equiv of CF_3CO_2H (CH_2Cl_2) gave 3,5-dimethoxytoluene in 76% yield by GLC analysis. Product was easily isolated by silica gel or gas chromatography. Reaction of **3** with 2.0 equiv of CF_3CO_2D gave deuteriated 3,5-dimethoxytoluene. However, mass spectrometric analysis of the product gave a *m/e* 152:153:154 ratio of 80.0:100.0:60.0. Under identical conditions the *m/e* 151:152:153 ratio for natural abundance 3,5-dimethoxytoluene was 3.6:100.0:8.8, indicating that multiple deuteriation had occurred. A ^2H NMR spectrum of this sample (61.4 MHz, ppm, $CDCl_3$: 6.26, 2.17 (12:1)) showed that deuterium had been incorporated almost exclusively into the aromatic ring. Reaction of **3** with 6.0 equiv of CF_3CO_2D gave 3,5-dimethoxytoluene that had a greater fraction of deuterium in the methyl group, as assayed by ^2H NMR (ppm, $CDCl_3$: 6.20, 2.17 (2:1)). In order to determine if a phenyl ring less activated toward electrophilic attack would be deuteriated, benzyl complex (η^5-C_5H_5)Re(NO)(PPh_3)($CH_2C_6H_5$) and 1.0 equiv of CF_3CO_2D were reacted. This gave toluene that was exclusively deuteriated on the methyl group, $C_6H_5CH_2D$, as assayed by ^2H NMR (61.4 MHz, ppm, CH_2Cl_2: 2.31). However, reaction of both **3** and (η^5-C_5H_5)Re(NO)(PPh_3)($CH_2C_6H_5$) with 1.0 equiv of the stronger acid 48% aqueous DBr gave arene products with predominant deuterium incorporation on the aromatic ring.

The above data are best accomodated by the hydrogen/deuterium exchange pathway exemplified in Scheme II. This label scrambling would be a significant complication when the rhenium–carbon bond of **3** is cleaved with a tritiated acid, since much of the radiolabel would be incorporated into the aromatic ring and not productively used to generate a chiral methyl group. We therefore revised our synthetic plan to introduce tritium in the *penultimate* step and conduct the rhenium–carbon bond cleavage with a protiated acid.

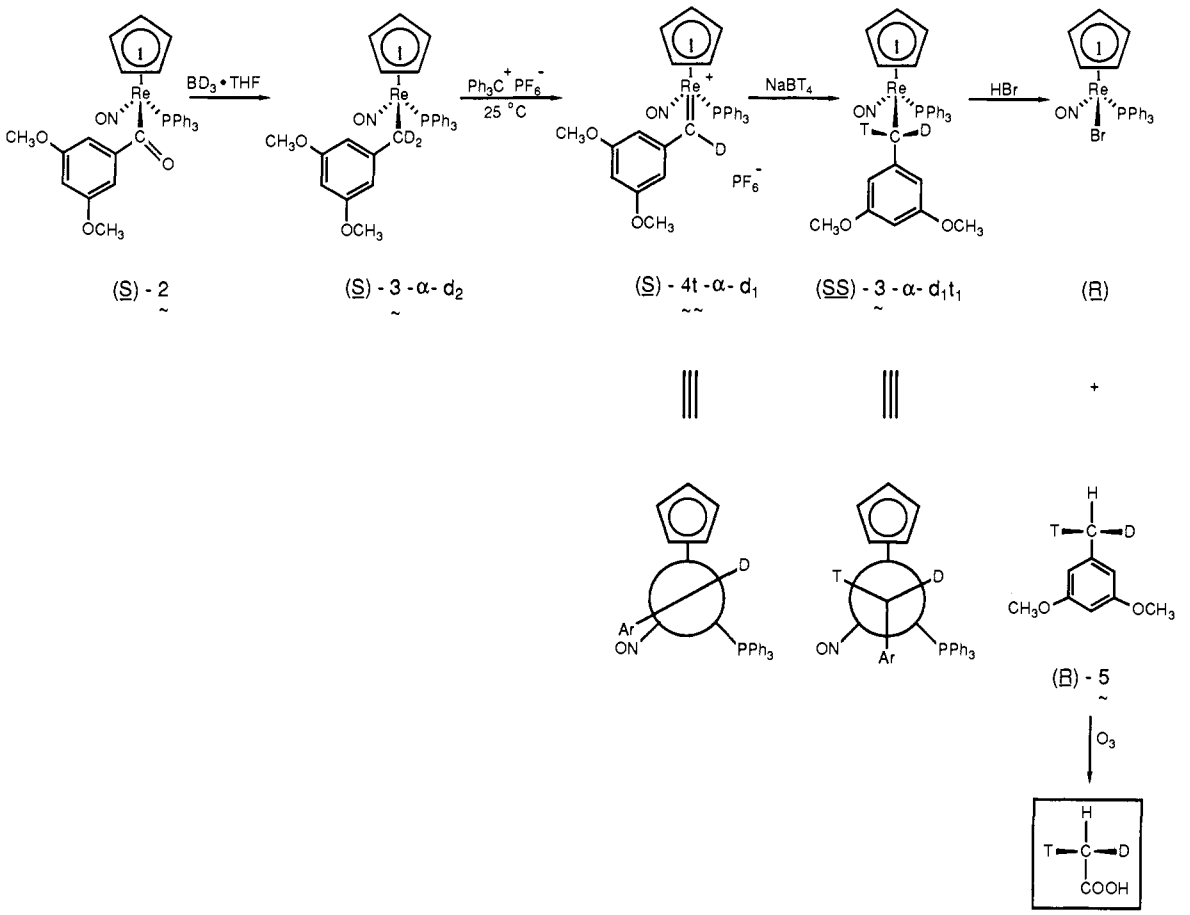
(13) Kiel, W. A.; Buhro, W. E.; Gladysz, J. A. *Organometallics* **1984**, *3*, 879.

(14) (a) Absolute configurations are assigned according to the Baird/Sloan modification of the Chan–Ingold–Prelog priority rules. The η^5-C_5H_5 ligand is considered to be a pseudoatom of atomic number 30, which gives the following sequence: Br > η^5-C_5H_5 > PPh_3 > NO > COOR, COR, CH_2R, =CHR. Stanley, K.; Baird, M. C. *J. Am. Chem. Soc.* **1975**, *97*, 6598. Sloan, T. E. *Top. Stereochem.* **1981**, *12*, 1. (b) In complexes with more than one chiral center, the rhenium configuration is specified first. (c) Prefixes (+) and (−) refer to rotations at 589 nm. All measurements are in CH_2Cl_2 with *c* in the range of 0.3–0.6 mg/mL.

(15) Hegde, S.; Coates, R. M.; Pearce, C. J. *J. Chem. Soc., Chem. Commun.* **1983**, 1484.

(16) We often find that $NaBD_4$ gives lower deuterium incorporation than $Li(C_2H_5)_3BD$ in addition reactions. The former reagent is commonly used at a higher D^-/substrate ratio, providing a greater pool of H^- impurity. Any kinetic isotope effect therefore causes the transfer of more H^- to the substrate in the $NaBD_4$ reaction, lowering the amount of deuterium incorporation but not the stereospecificity. The lower isotope incorporation is not important in this instance as $NaBT_4$ need incorporate tritium only at tracer levels. The important requirements is that the isotope be introduced stereospecifically.

Scheme III. Synthesis of Chiral Acetic Acid



Synthesis of Optically Active Compounds. Attention was next given to the synthesis of optically active complexes. Optically active "methyl ester" (+)-(*S*)-**1**[11] (≥98% ee) and (3,5-dimethoxyphenyl)magnesium iodide were reacted at −24 °C. This gave optically active 3,5-dimethoxybenzoyl complex (+)-(*S*)-**2** in 85% yield after workup. Complex (+)-(*S*)-**2** was treated with BH_3·THF and BD_3·THF to give 3,5-dimethoxybenzyl complexes (+)-(*S*)-**3** and (+)-(*S*)-**3**-α-d_2, respectively. The latter reaction is shown in Scheme III. Absolute configurations of (+)-(*S*)-**2** and (+)-(*S*)-**3** were assigned on the basis of previously described stereochemical cycles involving analogous rhenium complexes.[12]

Optically active 3,5-dimethoxybenzyl complex (+)-(*S*)-**3**-α-d_2 was treated with aqueous HBr. This gave previously reported bromide complex (+)-(*R*)-(η^5-C_5H_5)Re(NO)(PPh_3)(Br)[10] (see Scheme III) in 93% yield and 96% ee, as well as 3,5-dimethoxytoluene-α-d_2. This established the optical purity of (+)-(*S*)-**3**-α-d_2 as ≥96% ee and that HBr cleavage of the rhenium–carbon bond proceeds with retention of configuration at rhenium.

Optically active 3,5-dimethoxybenzyl complexes (+)-(*S*)-**3** and (+)-(*S*)-**3**-α-d_2 were treated with Ph_3C^+ PF_6^- to give, after workup, 3,5-dimethoxybenzylidene complexes (+)-(*S*)-**4t** and (+)-(*S*)-**4t**-α-d_1 (Scheme III). The preceding chemistry was duplicated with enantiomeric complexes and analogously gave (−)-(*R*)-**4t**-α-d_1, which contained ca. 6% of the undeuteriated complex (−)-(*R*)-**4t** as assayed by (+)-FAB mass spectrometry. This arose from incomplete labeling in the BD_3·THF reduction step (see Experimental Section).[16]

Optically active 3,5-dimethoxybenzylidene complex (+)-(*S*)-**4t**-α-d_1 was treated with $NaBT_4$ to give the α-deuteriated, α-tritiated 3,5-dimethoxybenzyl complex (+)-(*SS*)-(η^5-C_5H_5)-Re(NO)(PPh_3)(CDT(3,5-$C_6H_3(OCH_3)_2$)) ((+)-(*SS*)-**3**-α-d_1t_1), as shown in Scheme III. An identical reaction was conducted with the enantiomer (−)-(*R*)-**4t**-α-d_1 to give (−)-(*RR*)-**3**-α-d_1t_1. The stereochemistry of these products was assigned as described above for (*SS*,*RR*)-**3**-α-d_1. Both (−)-(*RR*)-**3**-α-d_1t_1 and (+)-(*SS*)-**3**-α-d_1t_1 were treated with aqueous HBr. This gave (*S*)-3,5-dimethoxytoluene-α-d_1t_1 ((*S*)-**5**) and (*R*)-3,5-dimethoxytoluene-α-d_1t_1 ((*R*)-**5**), respectively, in >94% yields after workup (Scheme III).

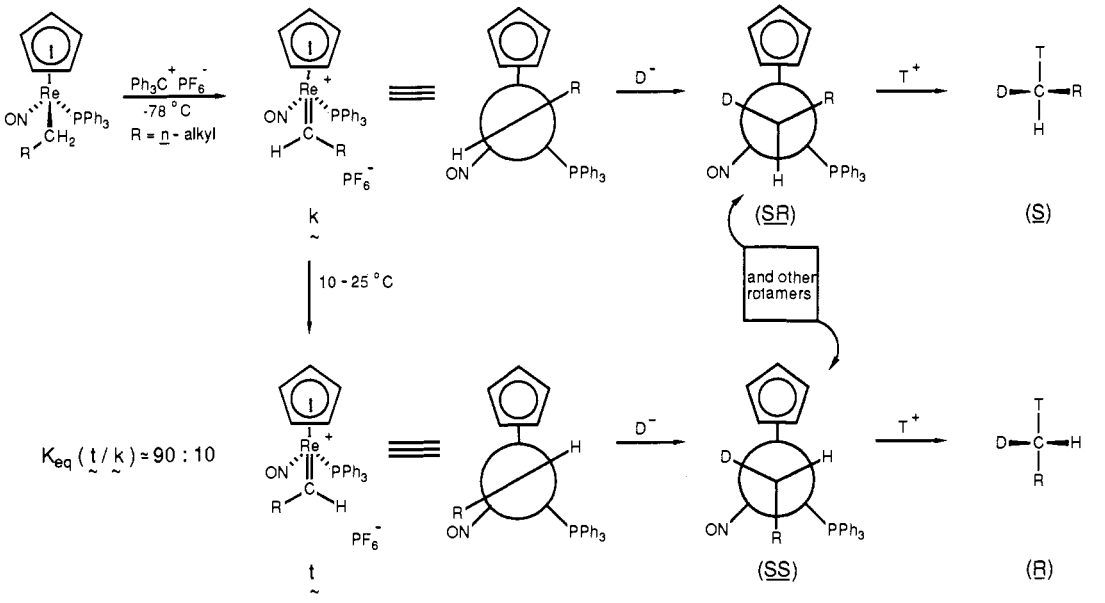
The absolute configurations and optical purities of (*S*)-**5** and (*R*)-**5** were assigned via the malate/fumarase enzymatic assay.[7] First, degradative ozonolysis gave the required substrates, chiral acetate salts (*S*)-CHDTCOO$^-$Na$^+$ and (*R*)-CHDTCOO$^-$Na$^+$, respectively.[5g] Enzymatic analysis of the former yielded an *F* value of 23, indicating an *S* absolute configuration and an optical purity of 93% ee. Identical analysis of the latter yielded an *F* value of 75, indicating an *R* absolute configuration and an optical purity of 86% ee.[7] This establishes that HBr cleavage of the rhenium–carbon bond in **3** proceeds with retention of configuration at carbon.

Discussion

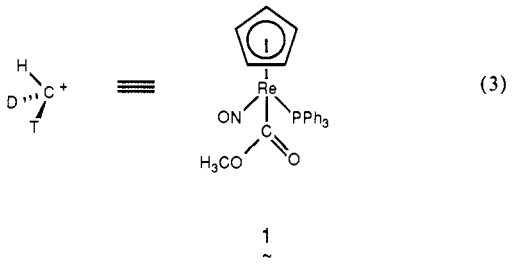
Given the successful synthesis of both enantiomers of chiral 3,5-dimethoxytoluene described above, we extrapolate that identical methodology can be used to synthesize nearly any chiral *n*-alkane or aryl methyl compound in high enantiomeric purity. Furthermore, the synthesis of chiral *n*-alkanes, which is outlined in Scheme IV, should be significantly more flexible, since (1) either of the two Re=C geometric isomers exemplified by **k** and **t** (Scheme IV) can be generated in >90% isomeric purity, thereby allowing the synthesis of either RCHDT enantiomer from the same enantiomer of the precursor alkyl complex (η^5-C_5H_5)Re(NO)-(PPh_3)(CHDR)[8b] and (2) the tritium can be introduced in the rhenium–carbon bond cleavage step without competing attack upon an arene ring. Only the absence of an established optical purity assay for other RCHDT compounds deterred us from reporting additional syntheses.

Our chiral methyl group synthesis is the first in which a transition metal fully participates in and *completely* directs the stereospecificity of the introduction of each isotope. In the earlier synthesis of Bosnich, Rh(I)-catalyzed asymmetric hydrogenation was used to introduce the final hydrogen isotope.[5d] Our synthesis

Scheme IV. Optimal Synthesis of *n*-Alkanes Containing a Chiral Methyl Group



is also the first in which the chiral methyl group carbon is not in the initial organic substrate. The net synthetic transformation may be represented as the methylation of a carbanion, as shown in eq 1. In this perspective, the "methyl ester" **1** functions as a synthetic equivalent of a chiral, pyramidal methyl carbocation (eq 3).



(3)

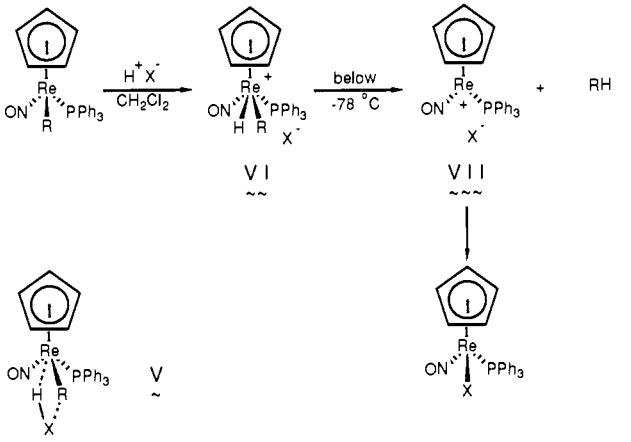
1

At this time, the only recognizable limitation of our methodology is in the synthesis of chiral branched alkanes of the formula RR′CHCHDT. Here, the precursor rhenium alkyl complexes $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CH_2CHRR')$ undergo β-hydride abstraction to give alkene complexes when treated with $Ph_3C^+PF_6^-$ instead of the α-hydride abstraction required in Schemes I and IV.[8b]

The rhenium alkylidene chemistry shown in Schemes I and III proceeds analogously to reactions that we have previously reported.[8,13] The key features that enable the stereospecific introduction of the second hydrogen isotope into **4** are (1) the Re=C geometric isomer with its substituent syn to the small NO ligand (**4t**) is greatly preferred thermodynamically and is thus obtainable in pure form and (2) the bulky PPh_3 ligand shields one Re=C face of **4t** from nucleophilic attack.

At the outset of this work, there was only a single published study[17] of the stereochemistry of sp^3 carbon–transition-metal bond protonolysis at carbon.[18,19] This investigation, conducted by Baird, showed that iron alkyl complexes of the formula $(\eta^5\text{-}C_5H_5)Fe(CO)_2(c\text{-}C_6H_{10}CH_3)$ react with CF_3CO_2D and DCl to give deuteriated methylcyclohexanes with >85% retention of configuration at carbon.[17] It is essential that rhenium–carbon bond protonolysis of alkyl complexes $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(R)$ proceed stereospecifically at carbon, since this is used to introduce the third hydrogen isotope of the chiral methyl group. Fortunately, we observe retention of configuration at both carbon and rhenium. This can be visualized as a net addition of HX across the rhenium–carbon σ bond as shown in V (Scheme V). However, a more likely protonolysis mechanism would involve initial attack of H^+ upon the d orbital HOMO of the rhenium fragment (analogous to I, Scheme I) to give square-pyramidal intermediate VI (Scheme V). We are unable to detect VI by NMR at −78 °C. However, such species have been previously proposed as intermediates in the electrophilic cleavage of metal–carbon bonds in other d^6 metal alkyl complexes of the formula $(\eta^5\text{-}C_5H_5)M(L)(L')(R)$,[17,18] and the square-pyramidal geometry is common for organorhenium compounds of the formula $(\eta^5\text{-}C_5H_5)ReLL'L''L'''$.[20] More recently, Baird has found that reaction of osmium alkyl complex $(\eta^5\text{-}C_5Me_5)Os(CO)(PPhMe_2)(CH_3)$ with electrophiles Br_2 and $HgBr_2$ gives observable adducts $[(\eta^5\text{-}C_5Me_5)Os(CO)(PPhMe_2)(CH_3)(X)]^+Br^-$ (X = Br, HgBr) that readily convert to osmium–carbon bond cleavage products and can be isolated as PF_6^- salts.[21] We similarly find that reactions of rhenium complexes $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(R)$ with electrophiles E^+ (R = H, $E^+ = H^+$; R = CH_3, $E^+ = Br^+$) can occur via observable $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(R)(E)]^+$ intermediates.[10b,22]

Scheme V. Proposed Mechanism of Protonolysis of the Rhenium–Carbon Bond



(17) Rogers, W. N.; Baird, M. C. *J. Organomet. Chem.* **1979**, C65.
(18) Flood, T. C. *Top. Stereochem.* **1981**, *12*, 37.
(19) Merrifield, J. M. PhD. Thesis, UCLA, 1983.
(20) (a) Hoyano, J. K.; Graham, W. A. G. *Organometallics* **1982**, *1*, 783. (b) Yang, G. K.; Bergman, R. G. *J. Am. Chem. Soc.* **1983**, *105*, 6500. (c) Einstein, F. W. B.; Klahn-Oliva, A. H.; Sutton, D.; Tyers, K. G. *Organometallics* **1986**, *5*, 53.
(21) Sanderson, L. J.; Baird, M. C. *J. Organomet. Chem.* **1986**, *307*, C1.
(22) O'Connor, E. J., University of Utah, unpublished results. *Abstracts of Papers*, 192nd National Meeting of the American Chemical Society, Anaheim, CA; American Chemical Society: Washington, DC, 1986; INOR 347.

Once formed, the square-pyramidal intermediate VI should undergo reductive elimination of RH to give the coordinatively unsaturated (16 electron) cation $[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)]^+X^-$ (VII, Scheme V) or a CH_2Cl_2 complex thereof. We have independently shown that VII is configurationally stable at low temperature and readily combines with Br^- to give optically active bromide complex $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(Br)$ with retention of configuration at rhenium.[10b] In rhodium(I)-catalyzed aldehyde decarbonylation and asymmetric alkene hydrogenation, it is commonly assumed that the reductive elimination of alkanes from intermediate alkyl hydride complexes proceeds with retention of configuration at carbon.[22]

By analogy to reactions of other $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(X)$ complexes,[10] optically active bromide complex (+)-(*R*)-$(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(Br)$ (Scheme III) can likely be recycled to carbonyl complex (+)-(*S*)-$[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CO)]^+$ without racemization (Ag^+/CO). Since the carbonyl complex is the precursor to "methyl ester" (+)-(*S*)-**1**,[11] the $(\eta^5\text{-}C_5H_5)\text{-}Re(NO)(PPh_3)$– moiety can in principle function as a recycleable chiral auxiliary.

We were initially surprised by the incorporation of deuterium into the arene ring during attempted deuterolysis of the rhenium–carbon bond of **3**. This had not been observed earlier in control reactions involving benzyl complex $(\eta^5\text{-}C_5H_5)Re(NO)\text{-}(PPh_3)(CH_2C_6H_5)$. However, similar label incorporation had been previously noted by Johnson upon deuterolysis of a variety of benzyl complexes L_nMCH_2Ar.[24] He showed that L_nMCH_2– substituents strongly donate electrons, both inductively and hyperconjugatively, into an arene ring. For example, the Hammett constant σ_p^+ for $(\eta^5\text{-}C_5H_5)Fe(CO)_2CH_2$– is between that of methoxy and amino substituents.[24]

In summary, we have determined the stereochemistry of protolytic cleavage of the rhenium–carbon bond at both the metal and carbon centers. In so doing, we have developed a versatile new synthesis of organic compounds with chiral methyl groups. Our simple metal system stereospecifically introduces all hydrogen isotopes and mimics the specificity expected of enzymes. In addition, it permits a higher degree of flexibility since in most cases we expect that opposite chiral methyl group enantiomers can be generated from the *same* enantiomer of rhenium. We have clearly demonstrated the effectiveness of the $(\eta^5\text{-}C_5H_5)Re\text{-}(NO)(PPh_3)$– moiety as a stereogenic transmitter and are continuing to explore applications of this capability in asymmetric organic synthesis.

Experimental Section

General Data. All reactions were conducted under a dry nitrogen atmosphere. IR spectra were recorded on a Perkin-Elmer 1500 FT-IR spectrometer. ^1H, ^{13}C, and ^{31}P NMR spectra were recorded on Varian XL-300 and FT-80A spectrometers. ^2H NMR spectra were recorded on a Varian XL-400 spectrometer with a ^{19}F lock. Optical rotations were measured on a Perkin-Elmer 241 MC polarimeter.[14c] Mass spectra were obtained on a VG 7070E spectrometer. Microanalyses were conducted by Galbraith and Schwarzkopf Laboratories. The radioactivity counting was done in Insta-Fluor (United Technologies Packard) on a Packard Tri-Carb 4530 scintillation spectrometer.

Solvents were purified as follows: THF and benzene, distilled from Na/benzophenone; hexane and toluene, distilled from Na; CH_2Cl_2, distilled from P_2O_5; ethyl acetate, used as received; $CDCl_3$, vacuum transferred from P_2O_5; CD_2Cl_2, vacuum transferred from CaH_2.

Substrate 3,5-dimethoxyphenyl iodide was prepared from KI and the diazonium salt derived from 3,5-dimethoxyaniline (Aldrich; sublimed prior to use).[25,26] Reagent $Ph_3C^+PF_6^-$ (Aldrich) was recrystallized from CH_2Cl_2/ethyl acetate before use. Reagents BH_3/THF (Aldrich), $NaBD_4$ (Aldrich, 98% D), $Li(C_2H_5)_3BD$ (Aldrich), BD_3·THF (Alfa), $NaBT_4$ (Amersham), 48% aqueous HBr (Fisher), and DBr (48% in D_2O, Aldrich, 98% D) were used without purification. Acid CF_3CO_2D was prepared from $(CF_3CO)_2O$ (Aldrich; distilled from P_2O_5) and D_2O (Aldrich, 99.8% D).

Preparation of (3,5-Dimethoxyphenyl)magnesium Iodide. A round-bottom flask was charged with 3,5-dimethoxyphenyl iodide (1.3 g, 4.92 mmol), freshly scraped magnesium wire (0.583 g, 24 mmol), and THF (15 mL) and was fitted with a reflux condenser. The reaction was refluxed (under N_2) for 24 h. Product formation was monitored by quenching aliquots with saturated aqueous $NH_4^+Cl^-$ and GLC analysis of the 1,3-dimethoxybenzene/starting material ratio (10% SE-30 on Chromasorb P/AW).

Preparation of $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CO(3,5\text{-}C_6H_3(OCH_3)_2))$ (2). A Schlenk flask was charged with $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CO_2CH_3)$ (**1**, 0.760 g, 1.26 mmol),[9,12] toluene (60 mL), and a stir bar. Then (3,5-dimethoxyphenyl)magnesium iodide (4.92 mmol in 15 mL of THF) was added with stirring. The yellow solution immediately turned amber, and after 1 h solvent was removed by rotary evaporation. The resulting dark brown oil was extracted several times with acetone, and the combined extracts were filtered through a 3-cm silica gel plug. The filtrate was concentrated by rotary evaporation and chromatographed on a 40 × 100 mm silica gel column using 60:40 (v/v) hexanes/ethyl acetate. The yellow band was collected. Solvent was removed by rotary evaporation, and the resulting residue was dried under vacuum to give **2** (0.866 g, 1.22 mmol, 97%) as a yellow powder. A toluene solution of **2** was layered with hexanes. Fine yellow needles of **2** formed, which were collected by filtration and dried under vacuum: mp 211–212 °C dec; **IR** (cm^{-1}, KBr) $\nu_{N\equiv O}$ 1653 s, $\nu_{C=O}$ 1535 m; ^1H NMR (δ, CD_2Cl_2) 7.54–7.29 (m, PPh_3), 6.38 (t, J_{AB_2} = 2.4 Hz, H_p), 6.31 (d, J_{AB_2} = 2.4 Hz, $2H_o$), 5.34 (s, C_5H_5), 3.69 (s, $2OCH_3$); $^{13}C\{^1H\}$ NMR (ppm, CD_2Cl_2) 254.2 (d, J_{CP} = 11.1 Hz, C=O), dimethoxyphenyl at 160.4 ($COCH_3$), 159.6 (C_{ipso}), 101.9 (C_p), 105.3 (C_o), 55.6 (OCH_3), PPh_3 at 135.9 (d, J_{CP} = 55.0 Hz, C_{ipso}), 134.1 (d, J_{CP} = 11.0 Hz, C_o),[27] 130.8 (s, C_p), 128.8 (d, J_{CP} = 9.5 Hz, C_m); 93.3 (C_5H_5); $^{31}P\{^1H\}$ NMR (δ, CD_2Cl_2) 15.9; mass spectrum (*m/e* (relative intensity) 70 eV, ^{187}Re) 709 (M^+, 13), 572 ($M^+ - C_6H_3(OCH_3)_2$, 57), 544 ($M^+ - CO - C_6H_3(OCH_3)_2$, 31), 262 ($Ph_3P^+$, 100). Anal. Calcd for $C_{32}H_{29}NO_4PRe$: C, 54.23; H, 4.23. Found: C, 54.43; H, 4.23.

Preparation of $(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(CH_2(3,5\text{-}C_6H_3(OCH_3)_2))$ (3). A Schlenk flask was charged with **2** (0.866 g, 1.22 mmol), THF (100 mL), and a stir bar and was fitted with a reflux condenser. Then BH_3·THF (15 mL, 0.5 M in THF) was added, and the solution was refluxed for 4 h. The reaction was then allowed to cool, and methanol (4 mL) was added. Solvent was removed by rotary evaporation, and the resulting orange brown residue was extracted with benzene. The extract was filtered through a 3-cm plug of silica gel, and solvent was removed from the filtrate by rotary evaporation. This gave an orange solid, which was recrystallized from benzene/hexanes to give orange needles of **3**, which were collected by filtration and dried under vacuum (0.729 g, 1.05 mmol, 86%): mp 177–179 °C; **IR** (cm^{-1}, KBr) $\nu_{N=O}$ 1621 s; ^1H NMR (δ, CD_2Cl_2) 7.62–7.34 (m, PPh_3), 6.21 (d, J_{AB_2} = 2.3 Hz, $2H_o$), 6.00 (t, J_{AB_2} = 2.3 Hz, H_p), 4.83 (s, C_5H_5), 3.74 (s, $2OCH_3$), 3.41 (dd, J_{HH} = 11.3 Hz, J_{HP} = 9.0 Hz, $ReCH_\alpha$), 2.85 (dd, J_{HH} = 11.3 Hz, J_{HP} = 2.5 Hz, $ReCH_{\alpha'}$); $^{13}C\{^1H\}$ NMR (ppm, CD_2Cl_2) dimethoxyphenyl at 162.3 (d, J_{CP} = 3.4 Hz, C_{ipso}), 160.8 ($COCH_3$), 105.5 (C_o), 94.8 (C_p), 55.3 (OCH_3), PPh_3 at 136.9 (d, J_{CP} = 51.4 Hz, C_{ipso}), 134.2 (d, J_{CP} = 10.8 Hz),[27] 130.7 (s, C_p), 129.0 (d, J_{CP} = 10.7 Hz, C_m); 90.9 (C_5H_5), -3.86 (d, J_{CP} = 5.2 Hz, ReC_α); $^{31}P\{^1H\}$ NMR (δ, CD_2Cl_2) 23.3; mass spectrum (*m/e* (relative intensity) 70 eV, ^{187}Re) 695 (M^+, 1), 544 ($M^+ - CH_2(C_6H_3(OCH_3)_2)$, 10), 262 ($Ph_3P^+$, 100). Anal. Calcd for $C_{32}H_{31}NO_3PRe$: C, 55.32; H, 4.50. Found: C, 55.26; H, 4.55.

Preparation of *ac*-$[(\eta^5\text{-}C_5H_5)Re(NO)(PPh_3)(=CH(3,5\text{-}C_6H_3(OCH_3)_2))]^+PF_6^-$. A. A septum-capped NMR tube was charged with **3** (0.0170 g, 0.0202 mmol) and CD_2Cl_2 (0.5 mL) and was cooled to −78 °C. Then solid $Ph_3C^+PF_6^-$ (0.009 g, 0.0232 mmol) was added. The tube was shaken vigorously, and the contents turned from orange to red-orange. The tube was quickly transferred to a −80 °C NMR probe. A (62 ± 2):(38 ± 2) mixture of **4k** and **4t** had cleanly formed. The tube was kept at room temperature for 4 h, after which only **4t** remained. ^1H NMR (δ, CD_2Cl_2, 80 MHz): **4k**, 15.89, 6.09; **4t**, 15.33, 5.94. ^{31}P NMR (δ, CD_2Cl_2): **4k**, 21.01; **4t**, 19.56. **B.** A Schlenk tube was charged with **3** (0.0580 g, 0.0834 mmol), CH_2Cl_2 (3 mL), and a stir bar and was cooled to −78 °C. Then solid $Ph_3C^+PF_6^-$ (0.0390 g, 0.100 mmol) was added. The resulting deep red-orange solution was stirred for 0.5 h at −78 °C and then 12 h at room temperature. Solvent was removed under oil pump vacuum to give a yellow-brown oil that was triturated with

(23) (a) Halpern, J. *Acc. Chem. Res.* **1982**, *15*, 332. (b) Doughty, D. N.; Pignolet, L. H. In *Homogeneous Catalysis with Metal Phosphine Complexes*; Pignolet, L. H. Ed.; Plenum: New York, 1983; pp 343–375. (c) See also: Suggs, J. W.; Jun, C.-H. *J. Am. Chem. Soc.* **1986**, *108*, 4679.

(24) Anderson, S. N.; Cooksey, C. J.; Holton, S. G.; Johnson, M. D. *J. Am. Chem. Soc.* **1980**, *102*, 2312.

(25) Heaney, H.; Millar, I. T. *Organic Synthesis*; Wiley: New York, 1973; Collect. Vol. V p 1120.

(26) Schram, A. C.; Christenson, C. P. *Texas J. Sci.* **1977**, *28*, 253.

(27) Assignments of ipso, para, meta, and ortho carbon resonances were made as described in footnote *c* of Table I in: Buhro, W. E.; Georgiou, S.; Fernández, J. M.; Patton, A. T.; Strouse, C. E.; Gladysz, J. A. *Organometallics* **1986**, *5*, 956.

hexanes to remove Ph_3CH. The remaining solid was extracted several times with benzene, and the combined extracts were filtered through Whatman No. 1 filter paper. Solvent was removed from the light yellow filtrate under oil pump vacuum to give **4t** (0.062 g, 0.744 mmol, 89%) as a light yellow powder. A CH_2Cl_2 solution of **4t** was layered with hexanes. Yellow needles of **4t** formed, which were collected by filtration and dried under vacuum: mp 168–171 °C dec; IR (cm^{-1}, KBr) $\nu_{N=O}$ 1704 s; ^1H NMR (δ, CD_2Cl_2) 15.33 (d, J_{HP} = 1.4 Hz, Re=CH_α), 7.60–7.17 (m, PPh_3), 6.60 (s, 3 H_{aryl}), 6.09 (s, C_5H_5), 3.71 (s, $2OCH_3$); $^{13}C\{^1H\}$ NMR (ppm, CD_2Cl_2) 288.7 (d, J_{CP} = 7.2 Hz, Re=C_α), dimethoxyphenyl at 161.2 ($COCH_3$), 153.7 (C_{ipso}), 108.8 (C_o), 107.1 (C_p), 55.9 (OCH_3), PPh_3 at 133.4 (d, J_{CP} = 11.4 Hz, C_o),[27] 132.5 (s, C_p), 129.7 (d, J_{CP} = 12.2 Hz, C_m), 128.7 (d, J_{CP} = 61.5 Hz, C_{ipso}); 100.0 (C_5H_5); $^{31}P\{^1H\}$ NMR (δ, CD_2Cl_2) 19.6; (+)-FAB (*m/z* (relative intensity) Ar, 3-nitrobenzyl alcohol, 7 kV, ^{187}Re) 694 (M^-, 100), 544 ($M^+ - CH(C_6H_3(OCH_3)_2)$, 50). Anal. Calcd. for $C_{32}H_{30}F_6NO_3P_2Re$: C, 45.83; H, 3.61. Found: C, 45.62; H, 3.92.

Preparation of (*SS,RR*)-(η^5-C_5H_5)Re(NO)(PPh_3)($CHD(3,5\text{-}C_6H_3(OCH_3)_2)$) ((*SS,RR*)-3-$\alpha$-$d_1$). **A.** A Schlenk tube was equipped with a magnetic stir bar and charged with **4t** (62.0 mg, 0.0739 mmol) and CH_2Cl_2 (10 mL). Then $Li(C_2H_5)_3BD$ (80 μL, 0.0813 mmol) was added, and the reaction was stirred for 1 h. Solvent was then removed by rotary evaporation, and the resulting orange residue was extracted with benzene. The extracts were filtered through a plug of silica gel, and solvent was removed from the filtrate by rotary evaporation. The orange oil was dissolved in benzene, and hexane was slowly introduced by vapor diffusion. Bright orange crystals of (*SS,RR*)-**3**-α-d_1 (42.4 mg, 0.061 mmol, 82%) formed and were collected by filtration. Analysis by ^1H NMR (Figure 1A) indicated stereospecific deuterium incorporation with a α-d_1/α-d_0 ratio of >99:1. **B.** A Schlenk tube was equipped with a magnetic stir bar and charged with **4t** (54.5 mg, 0.650 mmol) and THF (10 mL). The yellow solution was cooled to −78 °C, and $NaBD_4$ (3.0 mg, 0.0717 mmol) was added. The solution was stirred for 8 h and gradually allowed to warm to room temperature. Solvent was removed by rotary evaporation. The resulting orange-brown oily solid was extracted with benzene, and the extracts were filtered through a plug of silica gel. Solvent removal by rotary evaporation gave (*SS,RR*)-**3**-α-d_1 as an orange solid (36.6 mg, 0.053 mmol, 81%). Analysis by ^1H NMR (Figure 1B) indicated stereospecific deuterium incorporation with a α-d_1/α-d_0 ratio of (72 ± 2):(28 ± 2).

Preparation of 3,5-Dimethoxytoluene-d_x. **A.** A 5-mL Schlenk flask was equipped with a magnetic stir bar and then charged with **3** (17.7 mg, 0.025 mmol) and CH_2Cl_2 (1.0 mL). Then CF_3CO_2H (1.96 μL, 0.025 mmol) was added, and the solution turned from orange to red. The reaction was stirred for 8 h. Then GLC analysis (Carbowax 20M; 1,3-dimethoxybenzene internal standard) showed that 3,5-dimethoxytoluene had formed in 76% yield. Solvent was removed by rotary evaporation, and the resulting maroon oil was extracted with hexanes. The extracts were filtered through a plug of silica gel, and solvent was removed from the filtrate by rotary evaporation. The residue was purified by preparative GLC to give 3,5-dimethoxytoluene-d_0 that was identical with a commercial sample (Alfa) and pure by ^1H NMR (δ, $CDCl_3$): 6.34 (br s, 2 H), 6.29 (br s, 1 H), 3.77 (s, 6 H), 2.31 (s, 3 H). **B.** 3,5-Dimethoxytoluene-α-d_1 was prepared from (+)-(S)-(η^5-C_5H_5)Re(NO)(PPh_3)($CHD(3,5\text{-}C_6H_3(OCH_3)_2)$) ((+)-(*S*)-**3**-$\alpha$-$d_1$; 18 mg, 0.0259 mmol) and 48% aqueous HBr (3.0 μL, 0.0278 mmol) in a manner identical with the preparation of 3,5-dimethoxytoluene-d_0. Mass spectrometric analysis (70 eV) showed a *m/e* 152:153:154 ratio of 4.2:100:12.7. Under identical conditions the *m/e* 151:152:153 ratio for natural abundance 3,5-dimethoxytoluene was 3.6:100:8.8. These data indicate a α-d_1/α-d_0 ratio of (99 ± 2):(1 ± 2). **C.** 3,5-Dimethoxytoluene-d_x was prepared from **3**-α-d_0 (17.7 mg, 0.025 mmol) and CF_3CO_2D (3.9 μL; 0.051 mmol) in a manner identical with the preparation of 3,5-dimethoxytoluene-d_0. Mass spectrometric and ^2H NMR analysis: see text.

Preparation of (+)-(*S*)-(η^5-C_5H_5)Re(NO)(PPh_3)($CO(3,5\text{-}C_6H_3(OCH_3)_2)$) ((+)-(*S*)-2). This compound was prepared from (+)-(*S*)-**1** (0.720 g, 1.20 mmol, ≥98% ee)[9,11] in toluene (50 mL) and (3,5-dimethoxyphenyl)magnesium iodide (5.0 mmol in 25 mL of THF) in a manner similar to the preparation of (±)-**2**, except that the solution of (+)-(*S*)-**1** was cooled to −24 °C prior to reaction. Recrystallization from toluene/hexanes gave (+)-(*S*)-**2** as a yellow microcrystalline solid (0.723 g, 1.02 mmol, 85%): mp 174–175 °C; $[\alpha]^{22}_{589}$ +30°.[14c] The enantiomer (−)-(*R*)-**2** was prepared identically from (−)-(*R*)-**1**, $[\alpha]^{24}_{589}$ −28°.

Preparation of (+)-(*S*)-(η^5-C_5H_5)Re(NO)(PPh_3)($CH_2(3,5\text{-}C_6H_3(OCH_3)_2)$) ((+)-(*S*)-3). This compound was prepared from a THF (30 mL) solution of (+)-(*S*)-**2** (0.290 g, 0.409 mmol) and BH_3·THF (5.0 mL, 0.5 M in THF) in a manner identical with the preparation of (±)-**3**. Workup gave (+)-(*S*)-**3** as a bright orange powder (0.270 g, 0.389 mmol, 95%). Recrystallization from benzene layered with hexanes afforded bright orange plates: mp 204–205 °C dec; $[\alpha]^{21}_{589}$ +116°.[14c]

Preparation of (+)-(*S*)-(η^5-C_5H_5)Re(NO)(PPh_3)($CD_2(3,5\text{-}C_6H_3(OCH_3)_2)$) ((+)-(*S*)-3-$\alpha$-$d_2$). This compound was prepared from (+)-(*S*)-**2** (0.171 g, 0.241 mmol) and BD_3·THF (0.720 mL, 0.720 mmol) in a manner identical with the preparation of **3**. The product was dissolved in benzene, and hexanes was slowly added by vapor diffusion. This gave bright orange needles of (+)-(*S*)-**3**-α-d_2 (141 mg, 2.02 mmol, 84%): mp 202–204 °C; $[\alpha]_{589}^{24}$ +108°.[14c] Mass spectrometric analysis (70 eV) showed a *m/e* 695:696:697 ratio of 57.5:34.0:100. Under identical conditions, the *m/e* 693:694:695 ratio for natural abundance **3** was 57.6:22.0:100. These data indicate ca. 10% of the product to be incompletely labeled. The enantiomer (−)-(*R*)-**3**-α-d_2 was prepared identically from (−)-(*R*)-**2**, $[\alpha]^{24}_{589}$ −110°. Mass spectrometric analysis (70 eV) showed a *m/e* 695:696:697 ratio of 58.3:48.0:100. This indicates ca. 22% of the product to be incompletely labeled (see analyses of **4t**-α-d_1 below).

Conversion of (+)-(*S*)-3-α-d_2 to (+)-(*R*)-(η^5-C_5H_5)Re(NO)(PPh_3)(Br). A 10-mL round-bottom flask was equipped with a magnetic stir bar and charged with (+)-(*S*)-**3**-α-d_2 (0.050 g, 0.072 mmol) and CH_2Cl_2 (2 mL). The orange homogeneous mixture was freeze–thaw–degassed (3×) and placed in a −24 °C bath. Then 48% aqueous HBr (16.6 μL, 0.154 mmol) was added, and the reaction was stirred for 1 h. Solvent was then removed under oil pump vacuum, and the resulting red oil was extracted with CH_2Cl_2/acetone (90:10 v/v) and filtered through a plug of silica gel. Solvent was removed from the filtrate under oil pump vacuum, and the resulting red oil was taken up in CH_2Cl_2 (5 mL), dried over anhydrous $MgSO_4$, and filtered through Whatman No. 1 filter paper. Solvent was removed from the filtrate by rotary evaporation, and the resulting purple powder was dried under oil pump vacuum to give (+)-(*R*)-(η^5-C_5H_5)Re(NO)(PPh_3)(Br) (0.041 g, 0.065 mmol, 93%): $[\alpha]^{18}_{589}$ 361°[14c] (lit.[10a] $[\alpha]^{24}_{589}$ 375°); $^{31}P\{^1H\}$ NMR (δ, CD_2Cl_2) 15.5 (lit.[10a] $^{31}P\{^1H\}$ NMR (δ, $CDCl_3$) 15.8).

Preparation of (+)-(*S*)-*ac*-[(η^5-C_5H_5)Re(NO)(PPh)(=$CH(3,5\text{-}C_6H_3(OCH_3)_2)$)]$^+PF_6^-$ ((+)-(*S*)-(4t)). This compound was prepared from (+)-(*S*)-**3** (0.145 g, 0.209 mmol) and $Ph_3C^+PF_6^-$ (0.0892 g, 0.230 mmol) in a manner identical with the preparation of (±)-**4t**. This gave (+)-(*S*)-**4t** (0.147 g, 0.176 mmol, 84%).

Preparation of (+)-(*S*)-*ac*-[(η^5-C_5H_5)Re(NO)(PPh)(=$CD(3,5\text{-}C_6H_3(OCH_3)_2)$)]$^+PF_6^-$ ((+)-(*S*)-4t-α-d_1). This compound was prepared from (+)-(*S*)-**3**-α-d_2 (0.110 g, 0.158 mmol) and $Ph_3C^+PF_6^-$ (0.0670 g, 0.174 mmol) in a manner identical with the preparation of (±)-**4t**. Workup gave (+)-**4t**-α-d_1 as a yellow microcrystalline solid (0.121 g, 0.144 mmol, 91%), $[\alpha]^{24}_{589}$ +141°.[14c] Mass spectrometric analysis ((+)-FAB) showed a *m/e* 693:694:695 ratio of 89.7:25.1:100. Under identical conditions, the *m/e* 692:693:694 ratio for natural abundance **4t** was 57.8:23.4:100. These data indicate a α-d_1/α-d_0 ratio of >99:1. The enantiomer (−)-(*R*)-**4t**-α-d_1 was prepared identically from (−)-(*R*)-**3**-α-d_2: mp 189–192 °C dec; $[\alpha]^{24}_{589}$ −142°. Mass spectrometric analysis showed a *m/e* 693:694:695 ratio of 61.9:31.4:100. This indicates a α-d_1/α-d_0 ratio of (94 ± 2):(6 ± 2).

Preparation of (+)-(*SS*)-(η^5-C_5H_5)Re(NO)(PPh_3)($CDT(3,5\text{-}C_6H_3(OCH_3)_2)$) ((+)-(*SS*)-3-$\alpha$-$d_1t_1$). A Schlenk tube was charged with (+)-(*S*)-**4t**-α-d_1 (0.0823 g, 0.091 mmol), THF (15 mL), and a stir bar. The yellow homogeneous mixture was freeze–thaw–degassed (3×) and placed in a −78 °C bath. Then solid $NaBT_4$ (25 mCi, 0.088 mmol; 283 mCi/mmol) was added, and the reaction mixture was stirred for 12 h while gradually warming to room temperature. Then $NaBH_4$ (0.002 g) was added, and stirring was continued for an additional 2 h. Methanol (2 mL) was added to the flask and the solvent then removed under a stream of nitrogen. The remaining orange-brown oily solid was extracted with benzene and filtered through a plug of silica gel. Solvent was removed under a nitrogen stream, giving a bright orange oily solid. The solid was dissolved in benzene under nitrogen, and hexanes were slowly added by vapor diffusion. This gave clusters of bright orange needles of (+)-(*SS*)-**3**-α-d_1t_1, which were isolated by filtration, washed with cold hexanes, and dried under a stream of nitrogen (0.0551 g, 0.079 mmol; 87% chemical yield, 43% radiochemical yield).

Preparation of (−)-(*RR*)-(η^5-C_5H_5)Re(NO)(PPh_3)($CDT(3,5\text{-}C_6H_3(OCH_3)_2)$) ((−)-(*RR*)-3-$\alpha$-$d_1t_1$. This compound was prepared from (−)-(*R*)-**4t**-α-d_1 (0.105 g, 0.125 mmol), $NaBT_4$ (25 mCi, 0.05 mmol; 500 mCi/mmol), and $NaBH_4$ (0.003 g) in a manner identical with the preparation of (*SS*)-**3**-α-d_1t_1. Workup gave bright clusters of orange needles of (−)-(*RR*)-**3**-α-d_1t_1 (0.0710 g, 0.102 mmol; 83% chemical yield, 50% radiochemical yield).

Preparation of (*R*)-3,5-Dimethoxytoluene-α-d_1t_1 ((*R*)-5). A 10-mL pear-shaped flask was charged with (+)-(*SS*)-**3**-α-d_1t_1 (0.0098 g, 0.014 mmol, 380 μCi) and CH_2Cl_2 (1 mL). The orange homogeneous solution was freeze–thaw–degassed (3×) and placed in a bath at −78 °C. Then 48% aqueous HBr (2.3 μL, 0.21 mmol) was added, and the solution was stirred for 12 h while gradually warming to room temperature. The solvent was removed under a nitrogen stream, leaving a maroon oil. Hexanes were added to the flask, and after the mixture was stirred for

0.5 h, (+)-(*R*)-(η^5-C_5H_5)Re(NO)(PPh_3)(Br) precipitated as a purple powder. The combined hexane extracts were passed through a pipette containing a small plug of silica gel. Solvent was removed by blowing a stream of nitrogen into the receiving vial, leaving a clear colorless oil. Then nonlabeled carrier dimethoxytoluene (31.3 mg, 0.206 mmol) was added, and the mixture was purified by column chromatography (silica gel 60, 230-400 mesh, Merck; 10 g) using 1:1 (v/v) hexanes/$CHCl_3$. Solvent was removed under a nitrogen stream to give (*R*)-**5** as a colorless oil (332 μCi, 87% radiochemical yield, 85% chemical yield).

Preparation of (*S*)-3,5-Dimethoxytoluene-α-d_1t_1 ((*S*)-5). A 10-mL pear-shaped flask was charged with (-)-(*RR*)-**3**-α-d_1t_1 (0.035 g, 0.050 mmol, 1.29 mCi), and CH_2Cl_2 (2 mL). The homogeneous solution was freeze-thaw-degassed (3×) and placed in a bath at -78 °C. Then 48% aqueous HBr (7 μL, 0.65 mmol) was added and the solution stirred for 12 h while gradually warming to room temperature. The solvent was removed by blowing a stream of nitrogen into the flask leaving a maroon oil. Hexanes were added to the flask, and after the mixture was stirred for 0.5 h, (-)-(*S*)-(η^5-C_5H_5)Re(NO)(PPh_3)(Br) precipitated as a purple powder. The combined hexane extracts were passed through a pipette containing a small plug of silica gel. Solvent was removed under nitrogen stream to give (*S*)-**5** as a colorless oil (7.20 mg, 0.0471 mmol, 94% chemical yield).

Preparation of (*S*)-CHDTCOO$^-$Na$^+$ and (*R*)-CHDTCOO$^-$Na$^+$. Nonlabled carrier 3,5-dimethoxytoluene (45 mg, 0.30 mmol) was added to a sample of (*S*)-**5**, and the mixture was passed through a silica gel column (silica gel 60, 230-400 mesh, Merck; 10 g) using hexane/$CHCl_3$ (1:1 v/v). To a solution of the resulting (*S*)-**5** (0.2 mmol, 1.0×10^8 dpm, 48 μCi) in *n*-hexane (5 mL) was added silicic acid (3 g, 100 mesh, Mallinckrodt), and the solvent was removed in vacuo. The resulting silicic acid with absorbed substrate was stirred for 2 h at -78 °C under a stream of ozone. The sample was kept at room temperature for 1 h, and the ozonolysis was repeated (2 h, -78 °C). The mixture was warmed to 4 °C, and water (10 mL) was added. The suspension was kept at 4 °C overnight and then steam distilled. The distillate (120 mL) was neutralized with 0.1 N NaOH and evaporated to dryness. The residue was dissolved in water (90 mL), mixed with $HgSO_4$ (0.9 g) and concentrated H_2SO_4 (1.5 mL), and steam distilled. Neutralization of the distillate and evaporation to dryness as above gave (*S*)-CHDTCOO$^-$Na$^+$ (5.2×10^7 dpm) in 50% radiochemical yield. The *F* value of this material was found to be 23.[7] Similarly, (*R*)-**5** (0.2 mmol, 0.051 μCi) gave (*R*)-CHDTCOO$^-$Na$^+$ (9.6×10^3 dpm) with $F = 75$.

Acknowledgment. We thank the NIH for support of this research (Utah, GM 31280-05; Ohio State, GM 32333-04) and the C. D. Poulter group for helpful discussions and use of their radiochemical laboratory. The NMR spectrometers utilized were acquired via NSF, DOD, and NIH instrumentation grants.

Cation Distributions within a Cluster Framework. Synthesis and Structure of the Carbon- and Boron-Centered Zirconium Cluster Compounds $KZr_6Cl_{15}C$ and $CsKZr_6Cl_{15}B$

Robin P. Ziebarth and John D. Corbett*

Contribution from the Department of Chemistry, Iowa State University, Ames, Iowa 50011.
Received December 24, 1986

Abstract: The structures of the isotypic $KZr_6Cl_{15}C$ and $CsKZr_6Cl_{15}B$ have been established by single-crystal X-ray diffraction in space group *Pmma*, $Z = 4$ ($R = 3.1$, 3.9%; $R_w = 3.2$, 3.6%, respectively). These contain a matrix of Z-centered $Zr_6Cl_{12}Z$ clusters linked together by trans-chlorine atoms to form separate linear and zigzag chains that are interconnected into a three-dimensional network by four additional bridging chlorides. This $(Zr_6Cl_{12}Z)Cl_{6/2}$ framework affords three types of chloride environments for the cations, a smaller one (a) of ten-coordination occupied by potassium or rubidium and a pair of larger sites (b) with lower multiplicity that are utilized by cesium etc. The two b-type metal sites exhibit (1) an elongated square-pyramidal environment which, for the matrix studied, leaves the cesium closer to four-coordinate and (2) a more distorted 6 + 2 position of $2/m$ symmetry. Some evident cation disorder especially in the b(2) site and a possible small distortion of the anion matrix are noted. Compounds of this type are made by the reaction of stoichiometric amounts of $ZrCl_4$ and Zr with C, B, or ZrNCl and the appropriate MCl in welded Ta containers at 850 °C. These reactions give, according to Guinier powder diffraction, >95% yields of $KZr_6Cl_{15}Z$, Z = C or N, with occupancy of cation site a, the isotopic (Cs or Rb)$Zr_6Cl_{15}C$ utilizing site b, and (CsK, Rb_2, or CsRb)$Zr_6Cl_{15}B$ with a and b site occupancy. All but the nitride involve 14 cluster-bonding electrons, the most preferred state according to the MO scheme. The cluster framework and the cation bonding in this structure are compared with those in four other structure types that are known for $M_6X_{12}X_{6/2}$-type compounds.

Over the past several years, an increasing number of octahedral metal clusters that require a heteroatom within the cluster for stability have been reported within rare-earth-metal and early-transition-metal halides.[1-6] As a result of these investigations, it is becoming increasingly evident that many, but not all, of the previously prepared clusters and condensed clusters of these elements that were implicitly presumed to be empty actually are interstitially stabilized by small nonmetals. Prime examples are Zr_6Cl_{15}, Sc_5Cl_8, and the rare-earth-metal monohalides which are now recognized to be the halide mononitride, carbide, and hydrides, respectively.[1,7-9]

These results also suggest that a vast and largely untapped potential exists for the preparation of new cluster compounds by the purposeful and systematic addition of potential interstitial elements to cluster-forming reactions. The potential lies not only

(1) Ziebarth, R. P.; Corbett, J. D. *J. Am. Chem. Soc.* **1985**, *107*, 4571.
(2) Smith, J. D.; Corbett, J. D. *J. Am. Chem. Soc.* **1985**, *107*, 5704.
(3) Smith, J. D.; Corbett, J. D. *J. Am. Chem. Soc.* **1986**, *108*, 1927.
(4) Hwu, S.-J.; Corbett, J. D. *J. Solid State Chem.* **1986**, *64*, 331.
(5) Dudis, D. S.; Corbett, J. D. *Inorg. Chem.* **1986**, *25*, 3434.
(6) Hughbanks, T. R.; Rosenthal, G.; Corbett, J. D. *J. Am. Chem. Soc.* **1986**, *108*, 8289.
(7) Hwu, S.-J.; Dudis, D. S.; Corbett, J. D. *Inorg. Chem.* **1987**, *26*, 469.
(8) Simon, A. *J. Solid State Chem.* **1985**, *57*, 2.
(9) Meyer, G.; Hwu, S.-J.; Wijeyesekera, S.; Corbett, J. D. *Inorg. Chem.* **1986**, *25*, 4811.

0002-7863/87/1509-4844$01.50/0