Synthesis of Optically Active Tetrahedral Clusters through Ester Exchange Catalyzed by Lipase

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Reactions of the monoanions $[(\eta^5\text{-}C_5H_4R)M_2(CO)_3]^-$ with $ArCH(Me)COOCH_2C_2H(\mu_3\text{-}C)Co_2(CO)_6$ (**4**) in THF at 60 °C gave the functional cluster derivatives $ArCH(Me)COOCH_2C_2H(\mu_3\text{-}C)CoM_2(CO)_5(\eta^5\text{-}C_5H_4R)$ (**1a**−**d**: M_2 = Mo, W; R = CO_2Me, C(O)Me). Similarly, reactions of $\{[(\eta^5\text{-}C_5H_4)C(O)OCH_2(OH)CH_3]M_2(CO)_3\}^-$ (M_2 = Mo, W) with $(\mu_3\text{-}S)M_1Co_2(CO)_9$ (M_1 = Fe, Ru) gave the tetrahedral metal clusters $(\mu_3\text{-}S)CoM_2M_1(CO)_8[(\eta^5\text{-}C_5H_4)C(O)OCH_2(OH)CH_3]$ (**8a**−**d**: M_1 = Fe, Ru; M_2 = Mo, W). Treatment of the two metal clusters **1a**−**d** and three metal clusters **8a**−**d** with methanol respectively in the presence of lipase at 50 °C for 1 h afforded the optically active cluster derivatives $HOCH_2C_2H(\mu_3\text{-}C)CoM_2(CO)_5(\eta^5\text{-}C_5H_4R)$ (**6a**−**d**: M_2 = Mo, W; R = CO_2Me, C(O)Me) and $(\mu_3\text{-}S)CoM_2M_1(CO)_8[(\eta^5\text{-}C_5H_4)C(O)OCH_3]$ (**9a**−**d**: M_1 = Fe, Ru; M_2 = Mo, W)**.** The products were separated by silica gel chromatography. The conditions of the lipase reactions were discussed. All the compounds in the global process were characterized by element analysis, and IR and ^{1}H NMR spectroscopy. The structures of clusters **8c** and **9c** have been determined by single-crystal X-ray diffraction.

1. Introduction

In the last two decades, the synthesis of chiral clusters has been studied extensively, and various types of chiral tetrahedral clusters are accessible.[1] The metal exchange procedure, which Richter and Vahrenkamp pioneered,[2] was considered to be the most efficient and versatile way to prepare tetrahedral mixed-metal clusters. The unambiguous evidence that the chiral metal cluster frameworks serve as the catalysts is obtaining the chiral products when they have been involved in an asymmetric reaction.[3]

However, the enantiomeric resolution of the tetrahedral clusters remains a major problem.[3b] A single pure enantiomer could be obtained by introducing an optically active phosphine into a chiral cluster.[4] However, it was found that the optically active enantiomers can racemize under a CO atmosphere when the auxiliary phosphine is removed.[5] To obtain the optically active tetrahedral clusters, the synthesis was carried out in the presence of the chiral phase transfer catalyst, but only much less optically active clusters were obtained.[6] Later, the reaction of the chiral reagents with functional groups (such as aldehyde, ketone, and ester) on the cyclopentadienyl ligand in tetrahedral cluster molecules was investigated by our group under warmer conditions. Although two chiral auxiliaries have been introduced into the racemic clusters, the pairs of diastereoisomers cannot be separated successfully.[7]

In recent years, lipases have been attracting great interest because of their broad substrate specificity, good enantioselectivity, and thermal stability in organic solvents. Their application in organic syntheses has been shown to be a powerful technique for the preparation of chiral compounds.[8] The earliest application of lipases to metal compounds was the resolution of the derivatives of tricarbonylchromium and tricarbonyliron.[9] It was shown that the lipases kept good activity in globally reactive processes; the reaction only occurred on the side chain with no influence on the precursor of the carbonyl complexes. In 1979, Harald et al. confirmed the energetic separation of metal−metal and metal−ligand bonding by interpreting the HOMO−LUMO nature of metal−metal interactions.[10] In tetrahedral metal cluster molecules, all the carbon monoxide ligands and cyclopentadienyl ligands are coordinated stably to metal atoms; the number of electrons of the three metal

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(1) (a) Vahrenkamp, H. *J. Organomet. Chem*. **1989**, *370*, 65. (b) Stone, F. G. A. *Angew. Chem., Int. Ed. Engl*. **1984**, *23*, 89. (c) Zhang, J.; Zhang, Y.-H.; Yin, Y.-Q. *J. Mol. Catal. (China)* **1999**, *13*, 70.

(2) Richter, F.; Vahrenkamp, H. *Chem. Ber*. **1982**, *115*, 3224.

(3) (a) Pittman, C. U.; Richmond, G. M.; Absi-Halabi, M.; Beurich, H.; Richter, F.; Vahrenkamp, H. *Angew. Chem., Int. Ed. Engl*. **1982**, *21*, 786. (b) Whyman, R. *Surface Organometallic Chemistry: Molecular Approaches to Surface Catalysis*; Kluwer Academic: Dordrecht, The Netherlands, 1988; pp 75−95. (c) Adams, R. D.; Cotton, F. A. *Catalysis by Di- and Polynuclear Metal Cluster Complexes*; Wiley-VCH: Weinheim, Germany, 1998; p 27.

(4) Richter, F.; Vahrenkamp, H. *Chem. Ber*. **1982**, *115*, 3243.

(5) Planalp, R. P.; Vahrenkamp, H. *Organometallics* **1987**, *6*, 492.

(6) Wu, S.-L.; Ding, E. R.; Li, Q. S.; Yin, Y.-Q. *J. Mol. Catal. (China)* **1998**, *12*(3), 161−162.

(7) (a) Wu, H.-P.; Zhao, Zh.−Y.; Liu, Sh.-M.; Ding, E.-R.; Yin, Y.-Q. *Polyhedron* **1996**, *15*, 4117. (b) Ding, Er.-R.; Wu, Sh.-L.; Xia, Ch.-G.; Yin, Y.-Q.; Sun, J. *J. Organomet. Chem*. **1999**, *568*, 157. (c) Ding, E.-R.; Yin, Y.-Q.; Sun, J. *J. Organomet. Chem*. **1998**, *559*, 157.

(8) (a) Jones, J. B. *Tetrahedron* **1986**, *42*, 3351. (b) Yamada, H.; Shimizu, S. *Angew. Chem., Int. Ed. Engl*. **1988**, *27*, 622.

(9) (a) Nicolosi, G.; Patti, A.; Morronc, R.; Piottelli, M. *Tetrahedron: Asymmetry* **1994**, *5*(7), 1275−1280. (b) Nakamura, K.; Ishihara, K.; et al. *Tetrahedron Lett*. **1990**, *31*(25), 3603−3604.

(10) Beurich, H.; Madach, T.; Richter, F.; Vahrenkamp, H. *Angew. Chem., Int. Ed. Engl*. **1979**, *18*(9), 690−691.

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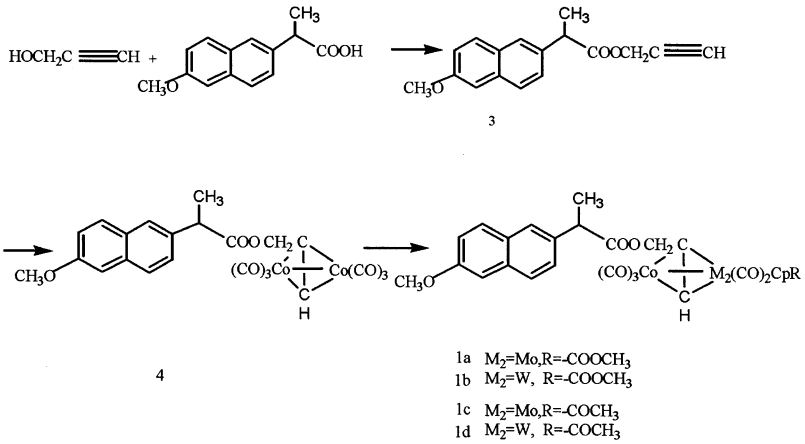
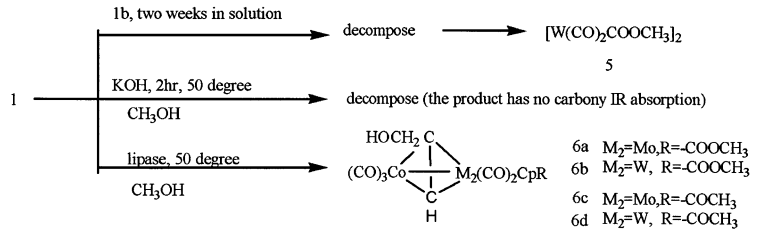
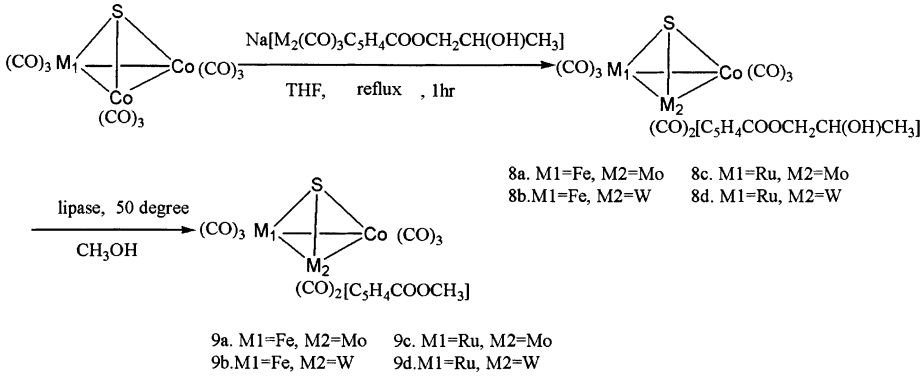
Scheme 1





Scheme 2



atoms all satisfy the 18-electron rule. Therefore, the resolution of stable tetrahedral clusters through ester exchange reactions taking place on the functional group of the cyclopentadienyl ligand is quite possible. Here, we report the preliminary results of ester exchange reactions of the tetrahedral metal clusters in the presence of Novozym 435. During the reactions the lipase remained active and showed a good selectivity. Finally, eight optically active clusters (with percent ee value) have been obtained.

2. Results and Discussion

2.1. Synthesis, Characterization, and Properties. The metal exchange reactions of the (substituted cyclopentadienyl)tricarbonylmetal anions $[M(CO)_3(\eta^5\text{-}C_5H_4R)]^-$ with prochiral clusters, such as $(\mu_3\text{-S})FeCo_2(CO)_9$, can give rise to the formation of chiral clusters containing functional groups.[11] On the basis of this theory, two classes of tetrahedral chiral clusters containing novel functional groups at the cyclopentadienyl ligand were prepared, and we investigated their properties and biotransformation. The reactions described in this work are summarized in Schemes 1 and 2.

Clusters **1a**−**d**, **6a**−**d**, **8a**−**d**, and **9a**−**d** are brown to dark red oils or solids. Their structures are all in agreement with those expected. Their IR spectra showed terminal carbonyl absorption bands in the range of 2089−1880 cm^{-1} and bridging or semibridging carbonyl bands between 1900 and 1800 cm^{-1}. Meanwhile, the IR spectra of **1a**−**d**, **6a**,**b**, **8a**−**d**, and **9a**−**d** displayed

(11) (a) Song, L.-C.; Dong, Y.-B.; Hu, Q.-M.; Li, Y.-K.; Sun, J. *Polyhedron* **1998**, *17*, 1579. (b) Song, L.-C.; Hu, Q.-M.; Yang, J.-S.; Shen, J.-Y. *J. Chem. Res., Synop.* **1998**, 344.

corresponding ester absorption bands in the range of 1717−1724 cm^{-1}; absorption bands around 1665−1685 cm^{-1} for **1c**,**d** and **6c**,**d** are ketone stretching vibrations. Absorption bands around 3025−3429 cm^{-1} in the spectra of **6a**−**d** and **8a**−**d** are characteristic of the hydroxyl group. The wavenumbers at 1725 and 1723 cm^{-1} in the spectrum of **1a** belong to the two esters.

In the ^1H NMR spectra of the clusters, chemical shifts of four protons in the cyclopentadienyl ligand appeared as a multiplet in the range of 4.93−6.03 ppm, resulting from the interaction between the electron-withdrawing effects of functional groups and the chirality of the frameworks. For clusters **1a**,**b**, **6a**,**b**, and **9a**−**d**, the signals in the range 3.73−3.93 ppm are for the protons in the methoxy group. In the ^1H NMR spectra of **1a**−**d**, the terminal proton chemical shifts in alkynol are observed as singlets at 5.66−5.67 ppm, while in the ^1H NMR spectra of **6a**−**d**, the corresponding proton appeared at 6.38−6.48 ppm. It should be pointed out that two diastereoisomeric proton signals should appear in the ^1H NMR spectra of clusters **1a**−**d** due to a chiral auxiliary on their side chains, but we have not found their signals in detail; this might be caused by cobalt atom paramagnetism. As far as clusters **8a**−**d** are concerned, there are some distinct signals of diastereoisomers in ^1H NMR spectra. For example, in the spectrum of cluster **8a**, the two doublets at 1.15 and 1.26 ppm were assigned to the three protons in the methyl group; their appearances result from shared effects between framework chirality and the chiral carbon on the side chain. The same phenomenon occurred with the proton in the hydroxyl group, which was confirmed by D_2O exchange. Two wide singlets at 1.85 and 2.05 ppm were observed, respectively, and their integral areas are equal. It is unfortunate that all of the signals of the methyl group in the four diastereoisomers of **8a**−**d** could not be observed clearly, unlike the singlet for the methoxy group in the two enantiomers of **9a**−**d**, which is possibly away from the chiral framework.

Clusters **1a**−**d**, suggested by their analogues as being the intermediates of catalysis,[12] were much more unstable and highly sensitive to air, acid, and base. The clusters **1a**−**d** in solution decompose on their own at room temperature in 2 weeks; moreover, their tetrahedral framework can be destroyed in 2 h in THF containing KOH and methanol. However, clusters **8a**−**d** kept their frameworks intact in solution over 1 month at room temperature. To further investigate the decomposition process of the clusters **1a**−**d**, the main decomposed product of the cluster **1b**, **5**, was analyzed, and its crystal structure was determined. The data show that it is the same compound as reported by Song.[13] The compound **5** is composed of two identical metal units. Possibly, it was formed from metal radical anions produced in the course of decomposition. Interestingly, the clusters **6a**−**d** were more stable than the clusters **1a**−**d**, and the clusters **9a**,**b** were similar to the clusters **8a**−**d**.

To further confirm the structures of the clusters **8a**−**d** and **9a**,**b**, X-ray single-crystal structure analyses of **8c** and **9c** were undertaken. Crystal data and structure refinement details for **8c** and **9c** are given in Table 1. The final atomic coordinates and thermal parameters of the non-hydrogen atoms for **8c** are presented in the Supporting Information, and selected bond lengths and angles are given in Table 2. The molecular structures of **8c** and **9c** are presented in Figures 1 and 2, respectively.

As seen in Figures 1 and 2, both of the clusters **8c** and **9c** contain a common tetrahedral skeleton which is composed of Ru, Co, Mo, and S. The slightly distorted triangle Ru−Co−Mo is capped by a sulfur ligand. The acute angles in the tetrahedral core of cluster **8c** about the basal atoms range from 50.08 to 75.09°, and those about the S atom average 73.12°. The distances from the S atom to the metals are not equal. All the atoms

Table 1. Crystal Data and Structure Refinement Details for 8c and 9c

	8c	9c
formula	$C_{17}H_{11}O_{11}S$-CoMoRu	$C_{15}H_7O_{10}S$-CoMoRu
fw	679.26	635.21
temp (K)	293(2)	293(2)
cryst syst	monoclinic	triclinic
space group	$P2_1/n$	$P\bar{1}$
a (Å)	10.3072(9)	7.6714(6)
b (Å)	9.2771(9)	8.4559(7)
c (Å)	22.895(2)	16.2292(13)
α (deg)	90	85.9890(10)
β (deg)	91.089(2)	76.5010(10)
γ (deg)	90	74.1830(10)
V (Å^3)	2188.9(3)	984.90(14)
Z	4	2
D_c (Mg m^{-3})	2.061	2.412
F(000)	1320	612
θ (deg)	2.15−28.28	2.50−25.50
limiting indices	$-9 \le h \le 13$ $-12 \le k \le 12$ $-30 \le l \le 28$	$-9 \le h \le 9$ $-7 \le k \le 10$ $-19 \le l \le 19$
no. of rflns collected/unique	13 097/5148 (R(int) = 0.0899)	6056/4383 (R(int) = 0.0817)
no. of data/restraints/params	5148/5/291	4383/5/263
goodness of fit on F^2	0.824	1.071
R ($I > 2\sigma(I)$)	R1 = 0.0457, wR2 = 0.0879	R1=0.0457, wR2= 0.0879
R	R1 = 0.0795, wR2 = 0.0948	R1=0.0795, wR2= 0.0948
largest diff peak and hole (e Å^{-3})	0.887, −0.574	0.7842, 0.23

Table 2. Bond Lengths (Å) and Angles (deg) for 8c[a]

Ru−S	2.3220(15)	Mo−C(10)	2.381(6)
Mo−C(4)	1.963(6)	Co−C(7)	1.788(7)
Mo−C(12)	2.288(6)	Ru−Mo	2.8652(7)
Mo−S	2.3792(15)	Mo−C(13)	2.282(5)
Co−C(8)	1.747(7)	Mo−C(11)	2.343(6)
Ru−Co	2.6128(9)	Mo−Co	2.7457(9)
Mo−C(5)	1.980(6)	Co−C(6)	1.818(7)
Mo−C(9)	2.325(5)		
Co−S	2.1946(17)	O(9)−C(14)	1.201(7)
C(15)−C(16′)	1.375(15)	C(15)−C(16)	1.452(16)
C(16)−C(17)	1.423(16)	C(16′)−C(17′)	1.374(16)

S−Ru−Co	52.41(4)	S−Co−Mo	56.26(4)
S−Mo−Co	50.08(4)	Co−S−Mo	73.66(5)
S−Co−Ru	56.97(4)	Co−Ru−Mo	59.95(2)
Co−S−Ru	70.62(5)	Co−Mo−Ru	55.46(2)
S−Ru−Mo	53.36(4)	Ru−Co−Mo	64.59(2)
S−Mo−Ru	51.55(4)	Ru−S−Mo	75.09(4)
C(16′)−C(15)−O(10)	110.0(11)	C(16)−C(15)−O(10)	106.5(7)
C(16′)−C(15)−H(5)	87(4)	C(16)−C(15)−H(5)	141(4)
C(17)−C(16)−C(15)	103.9(12)	C(15)−C(16′)−C(17′)	98.5(15)

[a] Symmetry transformations were used to generate equivalent atoms:

(12) Albiez, T.; Vahrenkamp, H. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*(6), 572−573.
(13) Song, L.-C.; et al. *Chem. J. Chinese University* **1992**, *13*, 1227.

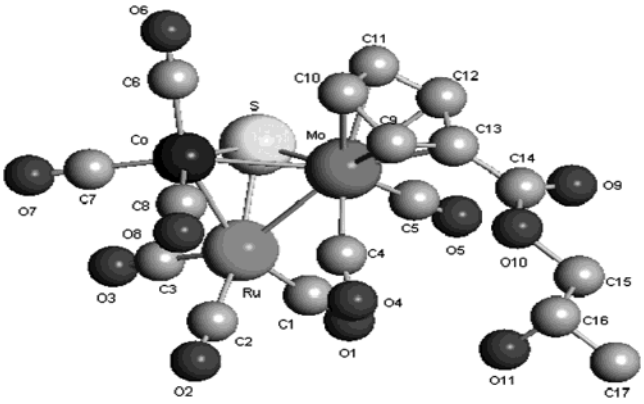


Figure 1. Molecular structure of cluster **8c**.

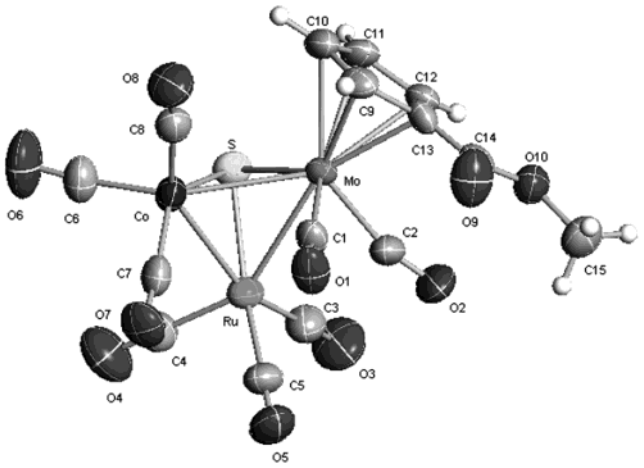


Figure 2. Molecular structure of cluster **9c**.

in the cyclopentadienyl ligand together with C(14), O(10), and O(9) in the substituent are incompletely located in one plane. The torsion angle C(9)−C(13)−C(14)−O(10) is 2.9(9)°, and the bond length C(13)−C(14) (1.467 Å) is shorter than a normal C−C bond (1.54 Å); thus, the π-system of the substituent is partly conjugated with the cyclopentadienyl π-system. It should be noted that the carbonyl C(4)−O(4) bound to the Mo atom is semibridging, because the asymmetric parameter α (0.41) is well within the range for semibridging carbonyls.[14] The properties of the cluster **9c** are similar to those of **8c**. However, it is found that C(16) and C(17) in the cluster **8c** have two different orientations; their ratio is 3:2. This might be caused by the tetrahedral chiral framework. The special torsion angle C(14)−O(10)−C(15)−C(16′) is 76.2(12)°, and C(14)−O(10)−C(15)−C(16) = 174.7(18)°, O(15)−C(15)−C(16)−C(17) = 177.8(10)°, and O(15)−C(15)−C(16′)−C(17′) = 69.5(16)°. These results are consistent with ^{1}H NMR data.

2.2. Ester Exchange Reaction Catalyzed by Lipase. From more than 30 lipases containing SRuCoM (M = W, Mo) framework clusters as reactants, we picked out eight lipases showing better selectivity. Finally, Novozym 435 was used, because it was heat tolerant in the range 70−80 °C.[15] It was found that Novozym 435 showed better activities in DIPE (diisopropyl ether), lower activities in cyclehexane, and no activities in THF and dichloromethane. The mixture of dichloromethane and DIPE was used in order to increase the solubility of the clusters. The clusters **1a**−**d** and the clusters **8a**−**d** were transferred into the clusters **6a**−**d** and **9a**−**d**, respectively, catalyzed by Novozym 435. The highest yields of the clusters **6a**−**d** and **9a**−**d** were 33.41% and 21.32%, respectively, with a specific rotation between −55 and −250°. From the specific rotation, it can be concluded that the selectivities of the lipase with identical framework clusters are similar. Furthermore, the final products, **6a**−**d** and **9a**−**d**, might have the same configuration. Meanwhile, it was found that methanol can affect the rotation value of the product. More methane results in a lower specific rotation. In addition, the rotation values were affected by temperature and the solubility of the reactants.

In the total process of the reaction catalyzed by the lipase, metal groups decomposed from the clusters can make the lipase denatured and inactive. In fact, the lipase is a kind of protein composed of a series of amino acids. The lipase has not only a primary structure but also a space structure which keeps its space configuration stable. Some functional groups in amino acid residues, such as hydroxyl (−OH), amino ($-NH_2$), and mercapto (−SH), are necessary functional groups at the lipase active center. Metal ions can make the lipase denatured and inactive because many coordination bonds formed between the d orbitals of metal ions and isolated pair electrons of amino acid residues will cause the space structure of the lipase to be destroyed. However, the tetrahedral metal clusters cannot make lipase inactive, because the d orbitals of the metal ions are full, and no coordination occurred. Therefore, the lipase is active in the presence of tetrahedral metal clusters. This is why the cluster compounds are still stable under the reaction conditions. The reaction mixtures of Novozym 435 and **8a**,**b** became darker as the reaction proceeded; this phenomenon was not found in reaction mixtures containing Ru atom clusters. This may be the reason some of the clusters **8a**,**b** were decomposed into metal groups.

The percent ee (the enantiomeric excess) values of all the products were not obtained, because we have not found an effective way to determine them. At present, there are two methods, but a chemical shift reagent did not show distinctly separate effects, all of the signals of protons instead shifting downfield. HPLC is an effective tool to determine the percent ee value, but the kind of chiral column that would be suitable for the clusters has not yet been found.[16] This problem remains to be solved.

3. Experimental Section

All reactions were carried out under an atmosphere of pure nitrogen by using standard Schlenk techniques. Methanol (AR grade) and DIPE (isopropyl ether, CP grade) were dried using 4 Å molecular sieves. The other solvents were thoroughly dried and distilled immediately before used. Novozym 435 (im-

(14) The asymmetric parameter is defined as $\alpha = (d_2 - d_1)/d_1$, where d_2 is the long M···C distance and d_1 is the short M−C distance. If $0.1 \leq \alpha \leq 0.6$, a semibridging carbonyl can be designated according to Curtis' suggestion: Curtis, M. D.; Han, K. R.; Butler, W. M. *Inorg. Chem.* **1980**, *19*, 2096.

(15) Vorde, C.; Hogberg, H. E.; Hedenstrom, E. *Tetrahedron: Asymmetry* **1996**, *7*(5), 1507−1513.

(16) (a) Han, X.-Q.; Liu, Y.-Q.; Zhang, Y.-H.; Zhang, W.-Q.; Li, Y.-M.; Chen, L.-R. *Chromatographia* **2002**, *56*(5/6), 319−322. (b) Zhu, X.-Y.; Cai, Y.-C.; Zhang, W.-Q.; Chen, L.-R.; Li, Y.-M. *J. Chromatogr., A* **2003**, *1002*(1/2), 231−236.

mobilized lipase from *Candida antarctica*) is registered trademark of Novo Nordisk. Column chromatography was carried out using 160−200 mesh silica gel. Specific rotations were determined on a J-20 (Japan) circular dichroism spectrometer. IR spectra were recorded on a Nicolet FT-IR 10DX spectrophotometer and ^{1}H NMR spectra on a Bruker AM 400 MHz spectromer. Elemental analyses were performed on an 1106-type analyzer. $Mo(CO)_6$, $W(CO)_6$, $RuCo_2(CO)_9(\mu_3\text{-S})$, $FeCo_2(CO)_9(\mu_3\text{-S})$,[17] $Na[C_5H_4C(O)Me]$, and $Na[C_5H_4C(O)O\,Me]$[18] were prepared according to literature methods or slight modifications thereof.

3.1. Preparations of (*S*)-Naproxen Propionate (3). A solution of (*S*)-(2-propynyl)-2-(6-methoxy-2-naphthyl)formyl chloride prepared from thionyl chloride (2 mL) and (*S*)-naproxen (3 g, 13 mmol) was added dropwise to a solution of propargyl alcohol (2 mL) and triethylamine (2 mL) at room temperature. After continual stirring for 2 h, the mixture was filtered, the precipitate was rinsed with dichloromethane, and the combined filtrates were evaporated. The resulting oil was chromatographed with CH_2Cl_2/hexane (2:1), and the solid obtained was recrystallized from hexane: yield 2.87 g (82%); colorless crystals; mp 69−70 °C. Anal. Calcd for $C_{17}H_{16}O_3$: C, 76.11; H, 6.02. Found: C, 75.6; H, 6.18. IR (KBr disk): 3255, 2131, 1729, 1179, 2997, 1457 cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.60 (d, 3H, ^3J = 7.2 Hz, CH_3), 2.43 (t, ^4J = 2.4 Hz, 1H, $-C_2H$), 3.90 (S, 3H, OCH_3), 3.91 (q,1H,Ar−CH), 4.63−4.59(dd,2H,-OCH_2),7.11−7.72(m,6H,Ar−H).

3.2. Preparations of 4. A total of 10 mmol of the alkynol derivative **3** (2.68 g) was dissolved in 30 mL of dry THF, and 3.60 g (12 mmol) of dicobalt octacarbonyl was added. The reaction mixture was stirred for 12 h at room temperature. The solvent was removed in vacuo, the residue was extracted by a small amount of CH_2Cl_2, and the extract was subjected to 2.5 × 25 cm silica gel column chromatography. Ethyl acetate/hexane (1:10) eluted the main red band, from which 3.08 g (48%) of cluster **4** as a brown-red oil was obtained. Anal. Calcd for $C_{23}H_{16}O_9Co_2$: C, 49.8; H, 2.92. Found: C, 50.20; H, 3.06. IR (KBr disk): 3255, 2131, 1729, 1179, 2997, 1457 cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.62 (d, 3H, ^3J = 6.3 Hz, CH_3), 6.00 (s, 1H, $-C_2H$), 3.92 (S, 3H, OCH_3), 3.91 (q, 1H, Ar−CH), 5.12−5.40 (dd, 2H, OCH_2), 7.11−7.72 (m, 6H, Ar−H).

3.3. Preparations of 1a,c and 8a,c. General Method. $Mo(CO)_6$ (264 mg, 1.0 mmol) was added to a solution of Na-[η^5-C_5H_4R] (R = $COCH_3$, $COOCH_3$, $C(O)OCH_2CH(OH)CH_3$; 1.0 mmol) in THF (25 mL). The mixture was refluxed for 16 h and cooled to room temperature. Then 1.0 mmol of the cluster **4** or the cluster (μ_3-S)$MCo_2(CO)_9$ (M = Fe, Ru) was added, and the mixture was stirred at 60 °C for another 1−2 h. The solvent was removed in vacuo, the residue was extracted by a small amount of CH_2Cl_2, and the extract was subjected to 2.5 × 25 cm silica gel column chromatography. Et_2O/CH_2Cl_2/hexane (1:4:5) or Et_2O/CH_2Cl_2/hexane (1:1:1) was the eluent.

1a: 309 mg (45.72%) of the cluster obtained as a black-red oil. Anal. Calcd for $C_{29}H_{23}O_{10}CoMo$: C, 51.48; H, 3.40. Found: C, 51.46; H, 3.43. IR (KBr disk): 2049 vs, 2012 vs, 1947 vs, 1725 s, 1722 s cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.50 (s, 3H, CH_3), 3.87 (S, 3H, $COOCH_3$), 2.11 (m, 1H, ArCH), 3.82 (d, 5H, OCH_2,-OCH_3), 4.96−5.46 (m, 4H, C_5H_4), 5.66 (s, 1H, CH), 7.02−7.72 (m, 6H, Ar).

1c: 308 mg (46.60%) of the cluster obtained as a dark red oil. Anal. Calcd for $C_{29}H_{23}O_{10}CoMo$: C, 52.73; H, 3.48. Found: C, 52.71; H, 3.47. IR (KBr disk): 2058 vs, 2030 vs, 2001 vs, 1943 vs, 1881 s, 1734 s, 1682 m cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.50 (s, 3H, CH_3), 2.08 (s, 3H, $COCH_3$), 2.11(m, 1H, ArCH), 3.82 (d, 5H, OCH_2,OCH_3), 4.98−5.45 (m, 4H, C_5H_4), 5.66 (s, 1H, CH), 7.03−7.62 (m, 6H, Ar).

8a: 320 mg (50.42%) of the cluster obtained as a black-red solid. Anal. Calcd for $C_{17}H_{11}O_{11}CoMoFeS$: C, 32.18; H, 1.74. Found: C, 32.15; H, 1.76. IR (KBr disk): 3429 br, 2077 vs, 2031 vs, 1894 s, 1722 s cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.15 (d, 3H, CH_3), 1.26 (d, 3H, CH_3), 1.85 (br, 1H, OH), 2.05 (br, 1H, OH), 3.69 (t, 1H, CH), 4.14 (dd, 2H, OCH_2), 4.93−6.03 (m, 4H, C_5H_4).

8c: 364 mg (53.61%) of the cluster obtained as a black-red solid. Anal. Calcd for $C_{17}H_{11}O_{11}CoMoRuS$: C, 30.04; H, 1.62. Found: C, 30.03; H, 1.64. IR (KBr disk): 3442 br, 2089 vs, 2041 vs, 2010 vs, 1895 s, 1723 m cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.35 (d, 3H, CH_3), 1.49 (d, 3H, CH_3), 1.71 (br, 1H, OH), 2.25 (br, 1H, OH), 4.06(t, 1H, CH), 4.71 (dd, 2H, OCH_2), 5.51−6.04 (dd, 4H, C_5H_4).

3.4 Preparations of 1b,d and 8b,d. General Method. $W(CO)_6$ (352 mg, 1.0 mmol) was added to a solution of Na[η^5-C_5H_4R] (R = $COCH_3$, $COOCH_3$, $C(O)OCH_2CH(OH)CH_3$; 1.0 mmol) in DMF (15 mL). The mixture was refluxed for 3 h and cooled to room temperature. After the solvent was removed under reduced pressure, 1.0 mmol of the cluster **4** or the cluster (μ_3-S)$MCo_2(CO)_9$ (M = Fe, Ru) and 25 mL of THF were added, the mixture was stirred at 60 °C for 1−2 h. The solvent was removed in vacuo, the residue was dissolved in 5 mL of CH_2Cl_2, and the extract was subjected to 2.5 × 25 cm silica gel column chromatography. Et_2O/CH_2Cl_2/hexane (5:4:1) or Et_2O/CH_2Cl_2/hexane (1:1:1) was the eluent.

1b: 369 mg (48.30%) of a dark red oil was obtained. Anal. Calcd for $C_{29}H_{23}O_{10}CoW$: C, 45.55; H, 3.01. Found: C, 45.53; H, 3.04. IR (KBr disk): 2053 vs, 2010 vs, 1942 vs, 1726 s, 1720 s cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.51 (s, 3H, CH_3), 3.87 (s, 3H, $COOCH_3$), 2.11 (m, 1H, Ar−CH), 3.82 (d, 5H, OCH_2,OCH_3), 4.95−5.52 (m, 4H, C_5H_4), 5.67 (s, 1H, CH), 7.02−7.72 (m, 6H, Ar).

1d: 330 mg (44.10%) of the compound, obtained as a black-red oil. Anal. Calcd for $C_{29}H_{23}O_9CoW$: C, 46.52; H, 3.07. Found: C, 46.49; H, 3.10. IR (KBr disk): 2054 vs, 2005 vs, 1944 s, 1881 s, 1730 s, 1685 m cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.59 (s, 3H, CH_3), 2.16 (s, 3H, $COCH_3$), 2.17 (m, 1H, ArCH), 3.91 (d, 5H, OCH_2, OCH_3), 5.10−5.54 (m, 4H, C_5H_4), 5.70 (s, 1H, CH), 7.13−7.70 (m, 6H, Ar).

8b: 359 mg (49.71%) of the compound, obtained as a black-red solid. Anal. Calcd for $C_{17}H_{11}O_{11}CoFeSW$: C, 28.25; H, 1.52. Found: C, 28.26; H, 1.55. IR (KBr disk): 3422 br, 2075 vs, 2028 vs, 1895 s, 1723 s cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.29 (d, 3H, CH_3), 1.59 (br, 1H, OH), 1.94 (br, 1H, OH), 3.72 (t, 1H, CH), 4.22 (dd, 2H, OCH_2), 5.21−6.03 (q, 4H, C_5H_4).

8d: 385 mg (50.23%) of the compound, obtained as a red solid. Anal. Calcd for $C_{17}H_{11}O_{11}CoRuSW$: C, 26.60; H, 1.43. Found: C, 26.59; H, 1.47. IR (KBr disk): 3426 br, 2082 vs, 2040 vs, 2001 vs, 1895 s, 1723 m cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 1.31 (d, 3H, CH_3), 1.41 (d, 3H, CH_3), 2.01 (br, 1H, OH), 2.21 (br, 1H, OH), 3.72 (t, 1H, CH), 4.22 (dd, 2H, OCH_2), 5.18−5.98 (dd, 4H, C_5H_4).

3.5. Preparation of Chiral Clusters 6a−d and 9a−d. General Method. The clusters **1a−d** and **8a−d** (0.2 mmol) were dissolved in 0.5 mL of CH_2Cl_2, 30 mL of DIPE was added, the mixture was stirred at room temperature for 10 min, and then 100 μL of methanol was added; 10 min later, 50 mg of Novozym 435 was added at 50 °C for 8 h while the mixture was stirred very slowly. During the procedure, reaction changes were examined by TLC. The solvent was removed, and the residue was separated on a silica gel column. Elution with CH_2Cl_2/petroleum ether/Et_2O (2:1:1 v/v/v; bp 60−90 °C) gave **6a−d**, and elution with CH_2Cl_2/hexane (3:1) gave **9a−d**.

6a: 29 mg (30.30% yield) of the compound as a dark brown oil. Anal. Calcd for $C_{15}H_{11}O_8CoMo$: C, 37.97; H, 2.32. Found: C, 37.41; H, 2.35. IR (KBr disk): 3024 br, 2058 vs, 2030 vs, 2001 vs, 1892 s, 1741 s cm^{-1}. ^{1}H NMR ($CDCl_3$, δ): 3.73 (s, 3H, OCH_3), 3.71 (s, 2H, OCH_2), 6.38 (s, 1H, CH), 5.42−5.84 (m, 4H, C_5H_4), 2.15 (s, 1H, OH). $[\alpha]_D^{22} = -87°$ (c = 0.30, CH_2Cl_2).

(17) Roland, E.; Bernhardt, W.; Vahrenkamp, H. *Chem. Ber.* **1986**, *119*, 2566.

(18) (a) Hart, W. P.; Dong, S.; Rausch, M. D. *J. Organomet. Chem.* **1985**, *282*, 111. (b) Busetto, L.; Cristina, M.; Mazzoni, R.; et al. *Organometallics* **2002**, *21*, 4993.

6b: 37 mg (33.41%) of the compound as a brown-red oil. Anal. Calcd for $C_{15}H_{11}O_8CoW$: C, 26.00; H, 1.36. Found: C, 25.97; H, 1.39. IR (KBr disk): 3025 br, 2054 s, 2027 vs, 1994 vs, 1880 s, 1728 s cm^{-1}. ^1H NMR ($CDCl_3$, δ): 3.73 (s, 3H, OCH_3), 3.71 (s, 2H, OCH_2), 6.48 (s, 1H, CH), 5.25−5.90 (m, 4H, C_5H_4), 2.14 (s, 1H, OH). $[\alpha]_D^{22} = -100°$ ($c = 0.20$, CH_2Cl_2).

6c: 27 mg (28.94%) of the compound, obtained as a brown solid. Anal. Calcd for $C_{15}H_{11}O_7CoMo$: C, 39.30; H, 2.40. Found: C, 39.32; H, 2.42. IR (KBr disk): 3030 br, 2064 s, 2003 vs, 1954 vs, 1886 s, 1665 m cm^{-1}. ^1H NMR ($CDCl_3$, δ): 2.25 (s, 3H, $COCH_3$), 3.54 (s, 2H, OCH_2), 6.47 (s, 1H, CH), 5.32−5.89 (m, 4H, C_5H_4), 2.17 (s, 1H, OH). $[\alpha]_D^{22} = -55°$ ($c = 0.28$, CH_2Cl_2).

6d: 33 mg (30.20%) of the compound, obtained as a brown-red oil. Anal. Calcd for $C_{15}H_{11}O_7CoW$: C, 32.97; H, 2.01. Found: C, 25.97; H, 1.39. IR (KBr disk): 3028 br, 2063 vs, 2015 vs, 1967 vs, 1896 s, 1667 m cm^{-1}. ^1H NMR ($CDCl_3$, δ): 2.24 (s, 3H, $COCH_3$), 3.56(s, 2H, OCH_2), 6.46 (s, 1H, CH), 5.22−5.89 (m, 4H, C_5H_4), 2.16 (s, 1H, OH). $[\alpha]_D^{22} = -90°$ ($c = 0.18$, CH_2Cl_2).

9a: 20 mg (16.30%) of the compound, obtained as a brown solid. Anal. Calcd for $C_{15}H_7O_{10}CoFeMoS$: C, 30.51; H, 1.19. Found: C, 30.48; H, 1.22. IR (KBr disk): 2079 vs, 2031 vs, 2003 vs, 1947 vs, 1864 s, 1717 s cm^{-1}. ^1H NMR ($CDCl_3$, δ): 3.98 (s, 3H, OCH_3), 5.47−5.98 (t, 4H, C_5H_4,). $[\alpha]_D^{22} = -75°$ ($c = 0.30$, CH_2Cl_2).

9b: 25 mg (18.42%) of the compound, obtained as a brown solid. Anal. Calcd for $C_{15}H_7O_{10}CoFeWS$: C, 26.55; H, 1.03. Found: C, 26.53; H, 1.05. IR (KBr disk): 2078 vs, 2029 vs, 2007 vs, 1946 vs, 1861 s, 1717 s cm^{-1}. ^1H NMR ($CDCl_3$, δ): 3.93 (s, 3H, OCH_3), 5.55−5.97 (t, 4H, C_5H_4,). $[\alpha]_D^{22} = -250°$ ($c = 0.24$, CH_2Cl_2).

9c: 31 mg (21.32%) of the compound, obtained as a brown-red solid. Anal. Calcd for $C_{15}H_7O_{10}CoRuMoS$: C, 28.35; H, 1.10. Found: C, 28.37; H, 1.13. IR (KBr disk): 2085 s, 2037 vs, 1999 vs, 1926 s, 1881 s, 1720 s cm^{-1}. ^1H NMR ($CDCl_3$, δ): 3.86 (s, 3H, OCH_3), 5.45−5.97 (t, 4H, C_5H_4,). $[\alpha]_D^{22} = -194°$ ($c = 0.22$, CH_2Cl_2).

9d: 29 mg (20.34%) of the compound, obtained as a brown solid. Anal. Calcd for $C_{15}H_7O_{10}CoRuWS$: C, 24.90; H, 0.97. Found: C, 24.92; H, 1.01. IR (KBr disk): 2082 s, 2029 vs, 2001 vs, 1963 vs, 1945 s, 1880 s, 1721 s cm^{-1}. ^1H NMR ($CDCl_3$, δ): 3.88 (s, 3H, OCH_3), 5.55−5.96 (t, 4H, C_5H_4,). $[\alpha]_D^{22} = -167°$ ($c = 0.18$, CH_2Cl_2).

3.6. X-ray Crystallography of Clusters 8c and 9c. Crystals used for X-ray determination were obtained from hexane/CH_2Cl_2 at −20 °C. The crystals were mounted on a glass fiber. Preliminary examination and data collection were performed with Mo Kα radiation ($\lambda = 0.710\ 73$ Å) on an Enraf-Nonius CAD4 diffractometer equipped with a graphite monochromator. An empirical absorption correction was applied for the two clusters.

All the structures were solved by direct methods and expanded using Fourier techniques. The non-hydrogen atoms were refined by the full-matrix least-squares method anisotropically; hydrogen atoms were included but not refined. All calculations were performed using the TEXSAN program system. Crystal data and experimental details for **8c** and **9c** are collected in Tables 1 and 2.

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Supporting Information Available: Crystallographic data as CIF files. This material is available free of charge via the Internet at http://pubs.acs.org.

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