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Gold(I)-Catalyzed Asymmetric Induction of Planar Chirality by Intramolecular Nucleophilic Addition to Chromium-Complexed Alkynylarenes: Asymmetric Synthesis of Planar Chiral (1*H*-Isochromene and 1,2-Dihydroisoquinoline)chromium Complexes

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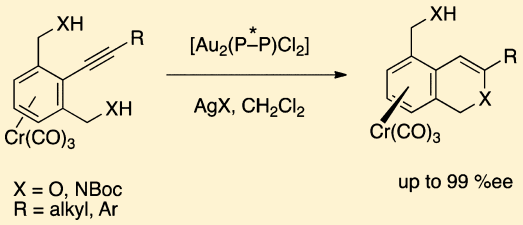
Supporting Information

ABSTRACT: Gold(I)-catalyzed asymmetric intramolecular cyclization of prochiral 1,3-dihydroxymethyl-2-alkynylbenzene or 1,3-bis(carbamate)-2-alkynylbenzene tricarbonylchromium complexes with axially chiral diphosphine ligand gave planar chiral tricarbonylchromium complexes of 1*H*-isochromene or 1,2-dihydroisoquinoline with high enantioselectivity. An enantiomeric excess of the planar chiral arene chromium complexes was largely affected by a combination of axially chiral diphosphine$(AuCl)_2$ precatalysts and silver salts. In the case of 1,3-dihydroxymethyl-2-alkynylbenzene chromium complexes, a system of segphos$(AuCl)_2$ with $AgBF_4$ resulted in the formation of the corresponding antipode.



INTRODUCTION

Transition metal π-complexes exist in two enantiomeric forms based on a planar chirality when the arene or Cp ring is substituted with different groups at the *ortho*- or *meta*-position. Planar chiral tricarbonyl(arene)chromium complexes have been widely employed in asymmetric synthesis and natural product synthesis[1,2] and increasingly find application as chiral ligands in asymmetric catalysis.[1,3] For the preparation of the planar chiral arene chromium complexes, optical resolution[4,5] and asymmetric synthesis are employed. The latter method includes diastereoselective complexation,[6] diastereoselective or enantioselective lithiation/electrophilic quenching[7,8] and nucleophilic addition/hydride abstraction.[9] In contrast to these methods, efforts to perform catalytic asymmetric synthesis of the planar chiral arene tricarbonylchromium complexes have met with little success. We reported the first catalytic asymmetric desymmetrization of *o*-dichlorobenzene chromium complex with alkenyl- and arylboronic acids by Suzuki–Miyaura cross-coupling reaction with chiral palladium catalyst.[10] However, both yield and enantiomeric excess of the monocoupling product were moderate. Palladium-catalyzed methoxycarbonylation of same substrate along this procedure gave an enantiomeric excess of about 60% in 47% yield. Increasing reaction time afforded the product in up to 95% ee albeit in lower yield (30%) accompanied with 48% yield of bis-coupling product.[11] The increased enantioselectivity is based on a kinetic resolution. Also, palladium-catalyzed asymmetric intramolecular Heck reaction afforded the cyclization products with moderate enantioselectivity.[12] Asymmetric reduction of a dibromonaphthalene chromium complex gave monobromonaphthalene chromium complex with good enantioselectivity.[13] In addition, rhodium(II)-catalyzed aryl C–H insertion of α-diazoacetamide chromium complex employing Doyle's carboxamide catalyst afforded planar chiral indolinone complex by distinguishing the enantiotopic *ortho* protons.[14] Moreover, asymmetric mono-reduction of 2,3-dihydronaphthalene-1,4-dione chromium complex with (*R*)-oxazaborolidine catalyst in the presence of catecholborane gave 8-hydroxy-5-tetralone chromium complex with high enantioselectivity.[15] Further satisfactory results regarding both yield and optical purity are still required in the catalytic asymmetric synthesis of the planar chiral arene chromium complexes.

The number of applications on the utility of gold(I) complexes as homogeneous catalysts for organic transformations has become increasingly common over the past decade.[16] Furthermore, effective gold(I)-catalyzed enantioselective reactions based on the π-activation of carbon–carbon multiple bond have been developed.[17] Although the Au cation displayed superior reactivity with regard to electrophilic activation of alkynes and allenes, stereoinduction based on gold catalysis has been considered an extremely challenging task. The linear coordination geometry of Au(I) represented an unconventional obstacle to delivery of the chiral environment from remote ligands to reaction site. Particularly, gold(I)-catalyzed intramolecular asymmetric addition of heteroatom and carbon nucleophiles to allenes has been achieved with high enantioselectivity.[18] On the other hand, in the nucleophilic addition reactions of heteroatoms to the alkyne bond, the chiral center should be created at the position other than the heterocyclic part for the generation of chiral compounds, since the heterocyclic compounds are planar compounds.[19] Along

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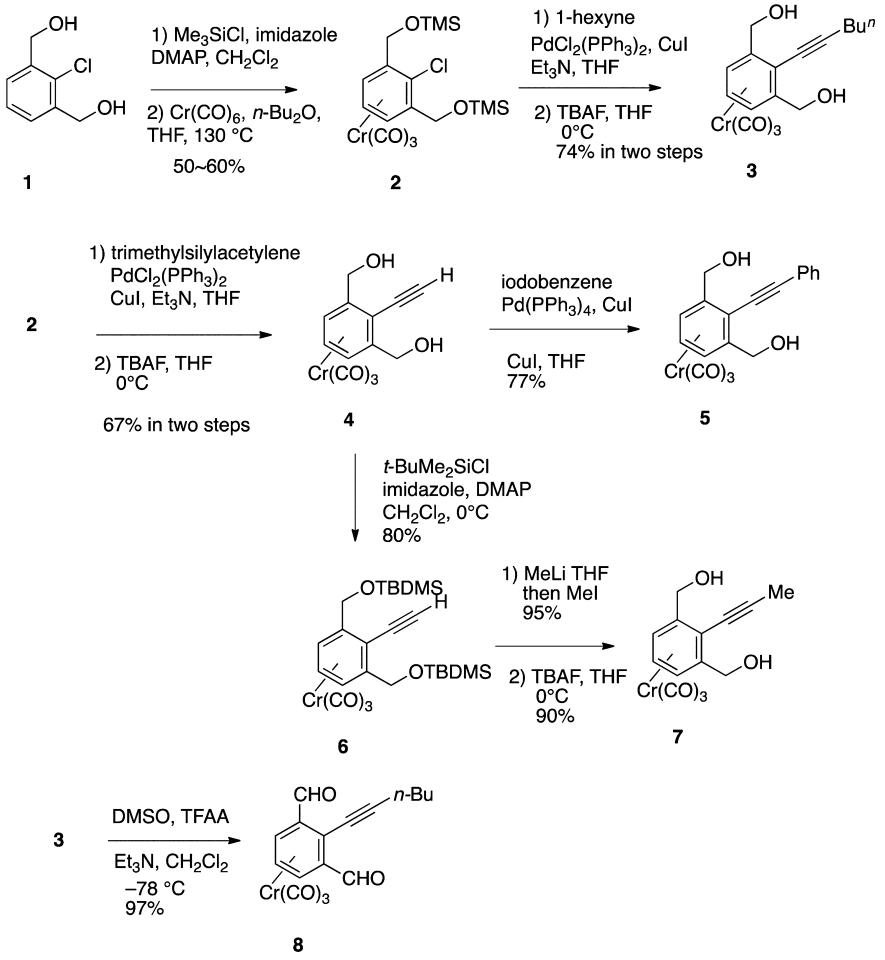
Scheme 1. Preparation of Prochiral [Bis(1,3-hydroxymethyl)-2-alkynylbenzene]tricarbonylchromium and [2-(Hex-1-yn-1yl)isophthalaldehyde]tricarbonylchromium

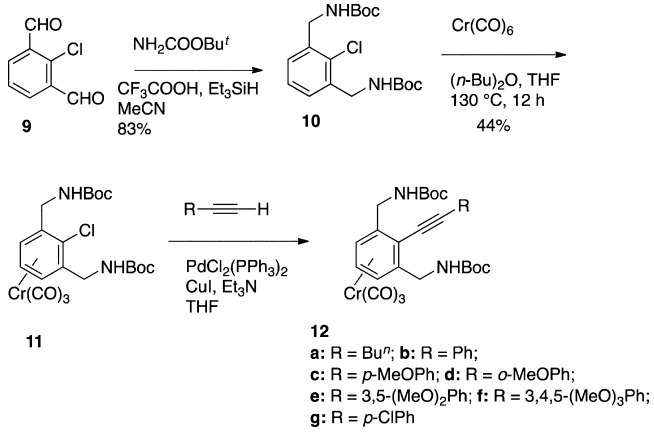


this idea, we reported an asymmetric induction of the planar chiral arene chromium complexes by gold(I)-catalyzed intramolecular cyclization of 1,3-bis-hydroxymethyl2-alkynylbenzene chromium complexes.[20] Herein, we would like to report full details of the gold-catalyzed asymmetric induction of planar chirality by an intramolecular hydroalkoxylation and hydroamination to the alkyne bond of prochiral alkynylbenzene chromium complexes.

RESULTS AND DISCUSSION

Preparation of Prochiral Arene Chromium Complexes. For gold(I)-catalyzed asymmetric induction of the planar chirality, the following prochiral alkynylarene chromium complexes as stating materials were prepared (Schemes 1, 2). As a chromium complexation of 1,3-bis(hydroxymethyl)-2-chlorobenzene[21] (**1**) with $Cr(CO)_6$ under thermal condition gave dechlorinated [1,3-bis(hydroxymethyl)benzene]chromium complex, hydroxyl group was protected with chlorotrimethylsilane. Bis-trimethylsilylated compound was heated with $Cr(CO)_6$ in *n*-dibutylether and THF (10:1) at 130 °C for 24 h to afford chromium complexation product **2** as yellow crystals in 50−60% yield. Sonogashira coupling of **2** with 1-hexyne followed by desilylation gave alkyne substituted diol chromium complex **3** in good yield. But, the coupling reaction of **2** with phenylacetylene resulted in a recovery of the starting material. For the preparation of phenylalkyne substituted arene chromium complex, the complex **2** was converted to ethynyl

Scheme 2. Preparation of Prochiral 2-Alkynylated 1,3-Bis(carbamate)arene Chromium Complexes



substituted chromium complex. Palladium-catalyzed coupling of **2** with trimethylsilylacetylene followed by treatment with tetrabutylammonium fluoride gave an ethynyl substituted arene chromium complex **4**. The chromium complex **4** was easily converted to phenyl substituted alkyne chromium complex **5** by Sonogashira coupling with iodobenzene. Protection of diol as *t*-butyldimethylsilyl ether and subsequent methylation at the alkyne terminal position followed by desilylation gave propynyl

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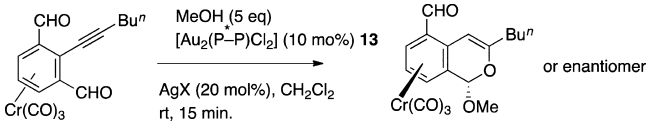
substituted prochiral arene chromium complex **7**. An oxidation of the hydroxyl group of chromium complex **3** gave [2-(hex-1-yn-1-yl)isophthalaldehyde]chromium complex (**8**) in good yield.

Similarly, the corresponding prochiral Boc-protected amine chromium complexes possessing an alkyne bond was easily prepared as shown in Scheme 2. Reductive amination[22] of **9** with *t*-butyl carbamate and subsequent chromium complexation gave bis-carbamate chlorobenzene chromium complex **11**. Sonogashira coupling of **11** with terminal alkynes produced the alkynylated chromium complexes **12a**−**12g**. Sonogashira coupling of bis-carbamate chlorobenzene chromium complex **11** with phenylacetylene was performed with satisfactory results in contrast to the corresponding trimethylsilyloxymethyl substituted chromium complex **2** as shown in Scheme 1.

Gold(I)-Catalyzed Asymmetric Reaction of Prochiral [2-(Hex-1-yn-1-yl)isophthalaldehyde]chromium Complex (8) with MeOH. We first studied gold(I)-catalyzed desymmetrical methoxy cycloisomerization of prochiral [2-(hex-1-yn-1-yl)isophthalaldehyde]chromium complex (**8**) with methanol. It was already reported that gold(I)-catalyzed reaction of *o*-alkynyl benzaldehyde chromium complexes with alcohol gave 1-*anti*-alkoxy isochromene tricarbonyl chromium complexes in good yields with 6-*endo*-*dig* cyclization fashion via chromium-complexed benzopyrynium ion intermediates.[23] This reaction was applied to the asymmetric desymmetrization of prochiral arene chromium complex **8** by using chiral gold(I) catalyst. The desymmetrization of **8** was performed by a combination of 10 mol % $[Au_2(P-P^*)Cl_2]$ precatalyst **13** and 20 mol % silver salt cocatalyst with 5 equiv of MeOH in CH_2Cl_2 at room temperature. The reaction results are summarized in Table 1. In this reaction, chiral center at the

Table 1. Gold-Catalyzed Asymmetric Reaction of [2-(Hex-1-yn-1-yl)isophthalaldehyde]chromium Complex (8) with MeOH



8 **14**

13a: (*R*)-BINAP(AuCl)$_2$
13b: (*R*)-XylylBINAP(AuCl)$_2$
13c: (*R*)-3,5-di-Me-4-MeOphenyl-BINAP(AuCl)$_2$
13d: (*R*)-SEGPHOS(AuCl)$_2$

entry	$Au_2(P^*-P)Cl_2$] (10 mol %) **13**	AgX	yield (%)	% ee[a]
1	**13a**	$AgBF_4$	46	16
2	**13a**	$AgNTf_2$	39	18
3	**13a**	AgOTf	42	22
4	**13b**	$AgBF_4$	64	8
5	**13b**	$AgNTf_2$	46	1
6	**13b**	AgOTf	67	2
7	**13b**	$AgSbF_6$	53	20
8	**13d**	$AgBF_4$	50	29

[a]Enantiomeric excess was determined by HPLC with Chiralcel OD-H.

benzylic position and the planar chirality are created. However, the asymmetric induction was low in all cases. Enantiotopic two formyl groups of the prochiral chromium complex **8** could not be clearly differentiated for the formation of the planar chiral chromium-complexed benzopyrynium ion intermediate. Therefore, sp^2 formyl group as the nucleophile was reduced to a hydroxymethyl group for a modification of the property of nucleophile.

Gold(I)-Catalyzed Asymmetric Cyclization of 1,3-Bis-(hydroxymethyl)-2-alkynylbenzene Chromium Complexes. The asymmetric induction of the planar chirality by an intramolecular cyclization of 1,3-bis(hydroxymethyl)-2-alkynylbenzene chromium complexes was next studied.[20] Fortunately, an intramolecular nucleophilic addition of a hydroxy group of the prochiral 1,3-bis(hydroxymethyl)-2-alkynylbenzene chromium complexes took place smoothly under the combination of axially chiral diphosphine$(AuCl)_2$ precatalyst **13** and silver salt cocatalyst with good to excellent enantioselectivity (Table 2). The reaction was readily performed at room temperature within 5 min with 10 mol % axially chiral diphosphine$(AuCl)_2$ catalyst **13** and 20 mol % silver salt in methylene chloride. It is noteworthy that enatioselectivities of the cyclized isochromene chromium complexes **15** are largely depending on the combination of gold precatalysts and silver salts. Particularly, excellent enantioselectivities were achieved by the use of $AgSbF_6$ regardless of the nature of gold precatalyst (entries, 4, 8, 9, 15, 19, 21, 29) except the reaction of phenyl substituted alkyne chromium complex **5** with binap$(AuCl)_2$ (entry 25). High enantioselectivities were also observed in the reaction with $AgNTf_2$ cocatalyst (entries, 6, 13, 17, 24, 27). The employment of AgOTf or $AgBF_4$ cocatalysts resulted in decreased enantioselectivities of the cyclized chromium complexes **15**. Interestingly, the combination of segphos$(AuCl)_2$ and $AgBF_4$ afforded the corresponding antipode of cyclized isochromene chromium complexes, although the reason is not clear (entries 10, 22, 31). In this way, a counterion of the silver salt controls the enantioselectivity dramatically in the gold(I)-catalyzed asymmetric cyclization of prochiral 1,3-bis(hydroxymethyl)-2-alkynylbenzene chromium complexes. Thus, the stereochemical information via ion pairs may have tremendous potential for the gold-catalyzed asymmetric reactions. Use of a lesser amount of the catalysts (e.g., 3 mol % of chiral gold and 6 mol % silver salt) required several hours until a disappearance of the starting material was observed. However, the chemical yield of the cyclized chromium complex **15** was less than 30% because of the labile chromium complex for an air-oxidation in a solution, although the enantioselectivity was still excellent. Therefore, short reaction time is essential for the achievement of high yield with excellent selectivity.

The absolute configuration of the asymmetric gold(I)-catalyzed cyclization product was determined by a comparison with authentic compound (Scheme 3). Stereodefined (−)-(1*R*)-*o*-chlorobenzaldehyde tricarbonylchromium[24] (**16**) was converted to (+)-*t*-butyldimethylsilyl ether of 2-chloro-3-formylbenzylalcohol chromium complex **18** by reduction of the formyl group and subsequent protection followed by *ortho* lithiation of the chromium complex **17** and a trap of lithiated intermediate with DMF. Sonogashira coupling of (+)-chromium complex **18** with 1-hexyne followed by reduction of formyl group gave (−)-alkyne chromium complex **19** in good yield. The cyclization of **19** with 10 mol % $(PPh_3)AuNTf_2$ in CH_2Cl_2 at room temperature and subsequent desilylation afforded (+)-isochromene chromium complex **15b**. An optical rotation value and chiral HPLC behavior of the authentic isochromene chromium complex were completely consistent with those of the gold(I)-catalyzed asymmetric cyclized product **15b**, and thus, the absolute configuration of planar chirality of

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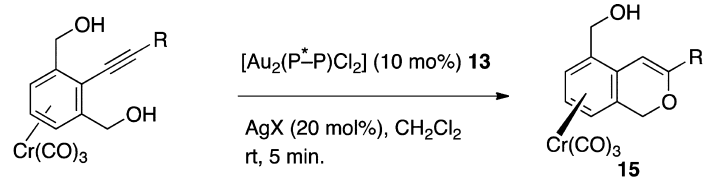
Table 2. Gold(I)-Catalyzed Intramolecular Asymmetric Hydroalkoxylation of (1,3-Dihydroxymethyl-2-alkynyl)benzene Chromium Complexes



3: R = Bu^n, **5:** R = Ph, **7:** R = Me **a**: R = Me, **b**: R = Bu^n, **c**: R = Ph

entry	complex	$[Au_2(P–P)Cl_2]$ **13**	AgX	yield **15** (%)	% ee[a]
1	7	(*R*)-binap$(AuCl)_2$	$AgBF_4$	86	62
2	7	(*R*)-binap$(AuCl)_2$	$AgNTf_2$	86	95
3	7	(*R*)-binap$(AuCl)_2$	AgOTf	78	47
4	7	(*R*)-binap$(AuCl)_2$	$AgSbF_6$	67	95
5	7	(*R*)-xylylbinap$(AuCl)_2$	$AgBF_4$	69	90
6	7	(*R*)-xylylbinap$(AuCl)_2$	$AgNTf_2$	76	99[b]
7	7	(*R*)-xylylbinap$(AuCl)_2$	AgOTf	91	75
8	7	(*R*)-xylylbinap$(AuCl)_2$	$AgSbF_6$	87	99
9	7	(*R*)-3,5-di-Me-4-MeOphenylbinap$(AuCl)_2$	$AgSbF_6$	91	99
10	7	(*R*)-segphos$(AuCl)_2$	$AgBF_4$	69	−27
11	7	(*R*)-segphos$(AuCl)_2$	$AgNTf_2$	60	80
12	3	(*R*)-binap$(AuCl)_2$	$AgBF_4$	86	47
13	3	(*R*)-binap$(AuCl)_2$	$AgNTf_2$	87	96
14	3	(*R*)-binap$(AuCl)_2$	AgOTf	89	51
15	3	(*R*)-binap$(AuCl)_2$	$AgSbF_6$	55	93
16	3	(*R*)-xylylbinap$(AuCl)_2$	$AgBF_4$	75	90
17	3	(*R*)-xylylbinap$(AuCl)_2$	$AgNTf_2$	75	98
18	3	(*R*)-xylylbinap$(AuCl)_2$	AgOTf	93	75
19	3	(*R*)-xylylbinap$(AuCl)_2$	$AgSbF_6$	87	99[c]
20	3	(*R*)-3,5-diMe-4-MeObinap$(AuCl)_2$	$AgBF_4$	86	77
21	3	(*R*)-3,5-diMe-4-MeObinap$(AuCl)_2$	$AgSbF_6$	91	98
22	3	(*R*)-segphos$(AuCl)_2$	$AgBF_4$	67	−48
23	3	(*R*)-segphos$(AuCl)_2$	$AgNTf_2$	86	83
24	5	(*R*)-binap$(AuCl)_2$	$AgNTf_2$	79	99
25	5	(*R*)-binap$(AuCl)_2$	$AgSbF_6$	80	70
26	5	(*R*)-xylylbinap$(AuCl)_2$	$AgBF_4$	73	97
27	5	(*R*)-xylylbinap$(AuCl)_2$	$AgNTf_2$	89	99[d]
28	5	(*R*)-xylylbinap$(AuCl)_2$	AgOTf	79	93
29	5	(*R*)-xylylbinap$(AuCl)_2$	$AgSbF_6$	70	97
30	5	(*R*)-3,5-diMe-4-MeObinap$(AuCl)_2$	$AgBF_4$	92	96
31	5	(*R*)-segphos$(AuCl)_2$	$AgBF_4$	88	−48
32	5	(*R*)-segphos$(AuCl)_2$	$AgNTf_2$	35	71

[a]Enantiomeric excess was determined by HPLC with Chiralpak AD-H. [b]$[\alpha]_D^{20}$ = 1116 (c = 0.41, $CHCl_3$). [c]$[\alpha]_D^{20}$ = +893 (c = 0.27, $CHCl_3$). [d]$[\alpha]_D^{20}$ = +821 (c = 0.27, $CHCl_3$).

the gold-catalyzed asymmetric cyclizazation compounds **15** was determined as R_p.

Gold(I)-Catalyzed Asymmetric Cyclization of Prochiral [1,3-Bis(*t*-butyl carbamate)-2-alkynylbenzene]-chromium Complexes. Furthermore, the gold(I)-catalyzed asymmetric cyclization of the corresponding prochiral 1,3-di-*tert*-butoxycarbonylaminomethyl-2-alkynylbenzene chromium complexes **12** was studied, and the reaction results are summarized in Table 3. Prior to the asymmetric reaction, the reactivity on the effect of the substituent at the alkyne terminal position was initially examined. The reaction of *n*-butyl substituted alkyne chromium complex **12a** with 10 mol % achiral $(PPh_3)Au(NTf_2)$ reagent in CH_2Cl_2 at room temperature resulted in a recovery of the starting material without formation of the cyclization product (entry 1). But, the corresponding phenyl substituted chromium complex **12b** produced the desired cyclized 1,2-dihydroisoquinoline chromium complex in a moderate yield. Therefore, the asymmetric version using chiral gold(I) catalyst was carried out with phenyl substituted chromium complexes at the alkyne terminal position. Prochiral phenylethynyl substituted chromium complex **12b** was treated with the combination of (*R*)-binap$(AuCl)_2$ precatalyst **13a** and $AgNTf_2$ at 0 °C for 20 min to give a planar chiral 1,2-dihydroisoquinoline chromium complex **20b** in 29% yield with 99% ee (entry 3), and the yield increased slightly at room temperature (entry 4). However, the isolated yield of **20** decreased under the conditions of a longer reaction time or higher reaction temperature (entries 2, 5), since the cylization product **20** was a labile chromium complex for air oxidation in a solution. The major compound under these conditions was 1,2-dihydroisoquinoline derivative with loss of $Cr(CO)_3$ fragment. The reactivity of bis(*tert*-butylcarbamate)

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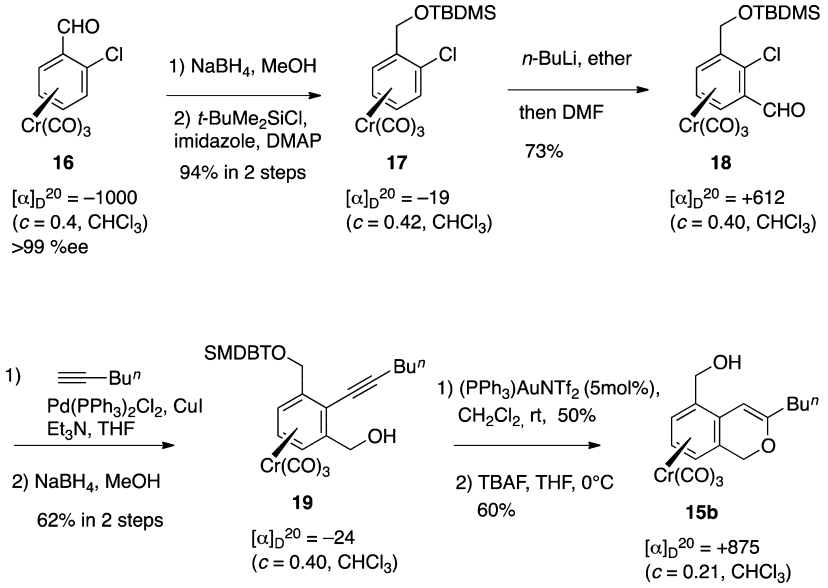
Scheme 3. Determination of Absolute Configuration



chromium complex **12b** with gold catalyst was lower than the corresponding prochiral 1,3-bis(hydroxymethyl)-2-alkynylbenezene chromium complexes as shown in Table 2. The isolated yield of the compound **20** was low under the employment of 10 mol % gold precatalyst and 20 mol % silver salt. For the improvement of yield, an employment of much catalyst in short reaction time, 20 mol % gold catalyst, and 40 mol % silver cocatalyst were used in the asymmetric cyclization in Table 3. The effect on the aromatic ring was next examined for the asymmetric cyclization. With the prochiral chromium complexes **12c** and **12d** with an electron-rich OMe group, the yield increased (entries 8−11, 13−16). 3,5-Dimethoxyphenyl substituted alkyne chromium complex **12e** afforded the planar chiral dihydroisoquinoline chromium complex **20e** with excellent enantioselectivity (entries 18−22). Also, 3,4,5-trimethoxyphenyl substituted alkyne chromium complex **12f** afforded planar chiral complex **20f** with high enantioselectivity (entries 23−25), while an electron-withdrawing *para* chlorobenzene substituted complex **12g** gave the cyclization product in less than 5% yield along with a recovery of the starting material as major isolated compound. Thus, the electron-rich substituents at the alkyne terminal position is significant factor for the gold(I)-catalyzed cyclization of chromium complexes **12**. Furthermore, it is a sharp contrast that the combination of (*R*)-segphos$(AuCl)_2$ and $AgBF_4$ gave the enantiomerically identical planar chiral arene chromium complex with other combinations of gold precatalyst and silver cocatalyst (entries, 12, 17, 22), while the corresponding 1,3-bis(hydroxymethyl) substituted chromium complexes gave the optical antipode of isochromene chromium complexes under the conditions of the combination of (*R*)-segphos$(AuCl)_2$ and $AgBF_4$ (Table 2, entries 10, 22, 31).

CONCLUSION

The gold(I)-catalyzed asymmetyric cyclization of prochiral 1,3-bis(hydroxymethyl)-2-alkynylbenzene tricarbonylchromium complexes and the corresponding *N*-boc-protected 1,3-bis-(aminomethyl)-2-alkynylbenzene chromium complexes gave planar chiral isochromene and dihydroisoquinoline tricarbonylchromium complexes, respectively, with high enantioselectivity. Enantioselectivities of the cyclized chromium complexes are largely depending on the combination of gold precatalysts and silver salts. In the asymmetric cyclization of [bis(1,3-hydroxymethyl)-2-alkynylbenzene]tricarbonyl chromium complexes, the combination of segphos$(AuCl)_2$ and $AgBF_4$ afforded the corresponding antipode of cyclized isochromene chromium complexes.

EXPERIMENTAL SECTION

[1,3-Bis(trimethylsilyloxymethyl)-2-chlorobenzene]-tricarbonylchromium (2). A mixture of bis-trimethylsilyl ether of **1** (2.80 g, 8.83 mmol) and $Cr(CO)_6$ (3.90 g, 17.7 mmol) in dibutyl ether (100 mL) and THF (10 mL) was heated at 130 °C for 24 h. The solvent was evaporated under reduced pressure, and the residue was dissolved in ether, filtered, and washed with ether. The organic solvent was removed. The residue was purified by column chromatography with hexane/ether (6/1) to the title compound as crystals. 2.20 g (55%): mp 59−60 °C; ^{1}H NMR (400 MHz) δ 5.68 (2H, d, J = 6.3 Hz), 5.23 (1H, d, J = 6.3 Hz), 4.70 (2H, d, J = 13.6 Hz), 4.55 (2H, d, J = 13.6 Hz), 0.22 (18H, s); ^{13}C NMR (100 MHz) δ 231.9 (3C), 108.9, 108.0 (2C), 91.0, 89.3 (2C), 61.3 (2C), −0.6 (6C); IR 1901 cm^{-1}. Anal. Calcd for $C_{17}H_{25}ClCrO_5Si_2$: C, 45.07; H, 5.56. Found: C, 45.08; H, 5.42.

[1,3-Bis(hydroxymethyl)-2-(hex-1-yn-1-yl)benzene]-tricarbonylchromium (3). To a mixture of **2** (200 mg, 0.44 mmol), CuI (4.3 mg, 0.0022 mmol), and $PdCl_2(PPh_3)_2$ (15.5 mg, 0.0022 mmol) in THF (5 mL) was added triethylamine (1.2 mL) and 1-hexyne (0.152 mL, 1.32 mmol), and the reaction mixture was refluxed gently for 30 min. The organic layer was evaporated. The residue was purified by column chromatography with hexane/ether to collect the yellow band. The solution was evaporated to leave yellow liquid (198 mg). The residue was immediately used without further purification for next desilylation step. To a solution of the above residue in THF (15 mL) was added tetrabutylammmonium fluoride (4.40 mL, 1.0 M in THF, 4.40 mmol) at 0 °C, and the reaction mixture was stirred for 2 h. Usual workup and purification by column chromatography with 50% ether in hexane gave **3** as crystals. 115.2 mg (74% in two steps): mp 67 °C; ^{1}H NMR (300 MHz) δ 5.55 (2H, d, J = 6.3 Hz), 5.42 (1H, t, J = 6.3 Hz), 4.74 (2H, dd, J = 13.8, 6.6 Hz), 4.58 (2H, dd, J = 13.8, 6.6 Hz), 2.45 (2H, t, J = 7.2 Hz), 2.06 (2H, t, J = 6.6 Hz), 1.58−1.46 (4H, m) 0.96 (3H, t, J = 7.2 Hz); ^{13}C NMR (125 MHz) δ 232.3 (3C), 126.4, 111.9 (2C), 91.3 (2C), 89.3, 88.7, 72.1, 62.7 (2C), 30.5, 22.01, 19.2, 13.5; IR 3349, 1964, 1888 cm^{-1}. Anal. Calcd for $C_{17}H_{18}CrO_5$: C, 57.63; H, 5.12. Found: C, 57.70; H, 5.19.

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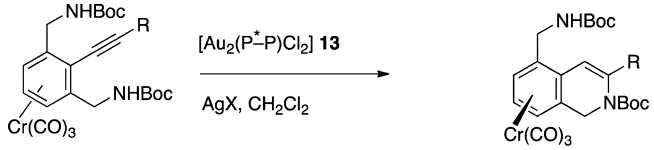
Table 3. Gold-Catalyzed Asymmetric Induction of Planar Chiral Arene Chromium Complexes of 1,3-Bis(aminomethyl)-2-alkynylbenzene Chromium Complexes



12 **20**

a: R = Bu^n; **b:** R = Ph; **c:** R = *p*-MeOPh; **d:** R = *o*-MeOPh; **e:** R = 3,5-(MeO)$_2$Ph; **f:** R = 3,4,5-(MeO)$_3$Ph; **g:** R = *p*-ClPh

entry	complex **12**	[Au$_2$(P*–P)Cl$_2$] **13**	AgX	conditions (temp, time)	yield (%)	% ee[a]
1	**12a**	Au(I)[b]	–	rt, 20 min	0	–
2	**12b**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	reflux, 60 min	<5[c]	–
3	**12b**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	0° C, 20 min	29	99
4	**12b**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	40	99
5	**12b**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	rt, overnight	<5[c]	–
6	**12b**	(*R*)-binap(AuCl)$_2$	AgSbF$_6$	rt, 20 min	52	99
7	**12b**	(*R*)-xylylbinap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	83	99
8	**12c**	(*R*)-binap(AuCl)$_2$	AgSbF$_6$	rt, 20 min	70	99
9	**12c**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	61	99
10	**12c**	(*R*)-segphos(AuCl)$_2$	AgSbF$_6$	rt, 20 min	60	99
11	**12c**	(*R*)-segphos(AuCl)$_2$	AgNTf$_2$	rt, 20 min	53	99
12	**12c**	(*R*)-segphos(AuCl)$_2$	AgBF$_4$	rt, 20 min	70	99
13	**12d**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	55	99
14	**12d**	(*R*)-binap(AuCl)$_2$	AgSbF$_6$	rt, 20 min	48	99
15	**12d**	(*R*)-xylylbinap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	30	92
16	**12d**	(*R*)-segphos(AuCl)$_2$	AgSbF$_6$	rt, 20 min	37	94
17	**12d**	(*R*)-segphos(AuCl)$_2$	AgBF$_4$	rt, 20 min	34	96
18	**12e**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	55	99
19	**12e**	(*R*)-binap(AuCl)$_2$	AgSbF$_6$	rt, 20 min	65	99
20	**12e**	(*R*)-xylylbinap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	62	99
21	**12e**	(*R*)-segphos(AuCl)$_2$	AgSbF$_6$	rt, 20 min	61	99
22	**12e**	(*R*)-segphos(AuCl)$_2$	AgBF$_4$	rt, 20 min	39	99
23	**12f**	(*R*)-binap(AuCl)$_2$	AgSbF$_6$	rt, 20 min	70	99
24	**12f**	(*R*)-binap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	52	96
25	**12f**	(*R*)-xylylbinap(AuCl)$_2$	AgNTf$_2$	rt, 20 min	45	99
26	**12g**	Au(I)[b]	–	rt, 20 min	0	–

[a]Enantiomeric excess was determined with HPLC with following chiral column. Chiralcel OF for chromium complexes **20b** and **20d**; Chiralcel OD-H for complexes **20c** and **20e**; Chiralpak AD-H for complex **20f**. [b]10 mol % achiral (PPh$_3$)Au(NTf$_2$) reagent was used for study of the reactivity. [c]A major compound was de-Cr(CO)$_3$ product of **20b**.

[1,3-Bis(hydroxymethyl)-2-(1-ethynyl)benzene]-tricarbonylchromium (4). Palladium-catalyzed reaction of chromium complex **2** (0.500 mg, 1.10 mmol) with trimethylsilylacetylene (432 mg, 2.2 mmol) gave coupling product (392 mg). To the obtained yellow liquid in THF (15 mL) was added tetrabutylammmonium fluoride (4.40 mL, 1.0 M in THF, 4.40 mmol) at 0 °C. The reaction mixture was stirred for 2 h, quenched with aqueous NH_4Cl, and extracted with ether. Usual workup and purification gave the title compound as crystals (220 mg, 67% for 2 steps): mp 107 °C; ^{1}H NMR (300 MHz) δ 5.54–5.51 (3H, m), 4.87–4.60 (4H, m), 3.31 (1H, s), 2.10 (2H, t, J = 6.0 Hz); ^{13}C NMR (125 MHz) δ 231.7 (3C), 112.5, 97.4 (2C), 92.0 (2C), 88.5, 84.5, 75.5, 62.5 (2C); IR 3393, 1963, 1884 cm^{-1}. Anal. Calcd. for $C_{13}H_{10}CrO_5$: C, 52.36; H, 3.38. Found: C, 52.47; H, 3.92.

[1,3-Bis(hydroxymethyl)-2-phenylethynyl]-tricarbonylchromium (5). Sonogashira coupling of **4** with phenylacetylene gave 532 mg (77%) of **5**: Crystalline; mp 133 °C; ^{1}H NMR (300 MHz) δ 7.52–7.49 (2H, m), 7.39–7.38 (3H, m), 5.60 (2H, d, J = 6.3 Hz), 5.52 (1H, t, J = 6.3 Hz), 4.88 (2H, dd, J = 6.3, 14.1 Hz), 4.71 (2H, dd, J = 6.3, 14.1 Hz), 2.11 (2H, t, J = 6.3 Hz); ^{13}C NMR (125 MHz) δ 232.1 (3C), 131.8 (2C), 131.5, 129.5, 128.6 (2C), 126.4, 112.1 (2C), 91.7 (2C), 88.8, 86.8, 80.6, 62.6 (2C); IR 3019, 1971, 1901 cm^{-1}. Anal. Calcd. for $C_{19}H_{14}CrO_5$: C, 60.97; H, 3.77. Found: C, 61.21; H, 3.61.

[1,3-Bis(dimethyl-*t*-butylsilyloxymethyl)-2-ethynylbenzene]-tricarbonylchromium (6). Chromium complex **4** (220 mg, 0.74 mmol) was converted to **6** by treatment with TBDMSCl (330 mg, 2.2 mmol), *N*-dimethylaminopyridine (4.5 mg) and imidazole (150 mg) in CH_2Cl_2 (15 mL). 310 mg (80%): Crystalline; mp 112–113 °C; ^{1}H NMR (300 MHz) δ 5.55 (2H, d, J = 6.3 Hz), 5.49 (1H, t, J = 6.3 Hz), 4.76 (2H, d, J = 13.8 Hz), 4.64 (2H, d, J = 13.8 Hz), 3.28 (1H, s), 0.95 (18H, s), 0.16 (6H, s), 0.14 (6H, s); ^{13}C NMR (125 MHz) δ 232.1 (3C), 113.2, 91.6 (2C), 88.1 (2C), 84.7, 83.3, 75.4, 62.2 (2C), 25.8 (6C), 18.3 (2C), −5.40 (2C), −5.44 (2C); IR 1946, 1871 cm^{-1}. Anal. Calcd for $C_{25}H_{38}CrO_5Si_2$: C, 57.01; H, 7.27. Found: C, 56.78; H, 7.01.

[1,3-Bis(hydroxymethyl)-2-(propy-1-nyl)benzene]-tricarbonylchromium (7). To a solution of **6** (404 mg, 0.765 mmol) in THF (3 mL) was added MeLi (3.0 M in dimethoxyethane, 0.53 mL, 1.6 mmol) at −50 °C, and the mixture was stirred for 1 h. MeI (0.15 mL, 3.825 mmol) was added to the above mixture at −50 °C and warmed to rt over 30 min. The reaction mixture was quenched with aqueous NH_4Cl, and usual workup gave methylated complex as crystals (393 mg, 95%). The obtained methylated complex was treated with TBAF (1 M in THF, 1.46 mL, 1.46 mmol) in THF (5 mL) to give **7**. 221 mg (95%): Crystalline; mp 121–122 °C; ^{1}H NMR (300

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MHz) δ 5.53 (2H, d, J = 5.4 Hz), 5.44 (1H, t, J = 5.4 Hz), 4.77 (2H, dd, J = 5.7, 13.5 Hz), 4.58 (2H, dd, J = 5.7, 13.5 Hz), 2.11 (3H, s), 2.07 (2H, t, J = 6.3 Hz); ^{13}C NMR (125 MHz) δ 232.3 (3C), 112.2, 94.2 (2C), 91.5 (2C), 89.2, 88.5, 71.2, 62.7 (2C), 4.54; IR 3303, 1946, 1879 cm^{-1}. Anal. Calcd for $C_{14}H_{12}CrO_5$: C, 53.85; H, 3.87. Found: C, 54.19; H, 4.06.

[2-(1-Hexynyl)isophthalaldehyde]tricarbonylchromium (8). 38.5 mg (97%): Crystalline; mp 70 °C; ^{1}H NMR (300 MHz) δ 10.11 (2H, s), 6.43 (2H, d, J = 6.3 Hz), 5.29 (1H, t, J = 6.3 Hz), 2.58 (2H, t, J = 7.2 Hz), 1.71−1.43 (4H, m), 0.97 (3H, t, J = 7.2 Hz); ^{13}C NMR (125 MHz) δ 227.35 (3C), 187.48 (2C), 105.47, 99.01 (2C), 92.95 (2C), 92.60, 85.52, 69.20, 30.20, 22.10, 19.27, 13.47; IR 1990, 1931, 1678 cm^{-1}. Anal. Calcd for $C_{17}H_{14}CrO_5$: C, 58.29; H, 4.03. Found: C, 58.18; H, 4.22.

Di-*t*-butyl (2-chloro-1,3-phenylene)bis(methylene)-dicarbamate (10). 2-Chloroisophthalaldehyde (**9**)[21] was converted to the title compound **10** by reported procedure.[22] 5.48 g (83%): Crystalline; mp 137−138 °C; ^{1}H NMR (400 MHz) δ 7.32 (2H, d, J = 7.2 Hz), 7.23 (1H, t, J = 7.2 Hz), 4.99 (2H, brs), 4.41 (4H, d, J = 5.2 Hz), 1.45 (18H, s); ^{13}C NMR (100 MHz) δ 155.7 (2C), 136.9 (2C), 132.7, 128.6 (2C), 127.0, 79.7 (2C), 42.8 (2C), 28.4 (6C); IR 3456, 1708 cm^{-1}. Anal. Calcd for $C_{18}H_{27}ClN_2O_4$: C, 58.29; H, 7.34; N, 7.55. Found: C, 58.42; H, 7.16; N, 7.38.

[Di-*tert*-butyl((2-chloro-1,3-phenylene)bis(methylene))-dicarbamate]tricarbonylchromium (11). Chromium complexation of **10** was performed by above-mentioned procedure. 1.2 g (44%): Crystalline; mp 139−140 °C; ^{1}H NMR (400 MHz) δ 5.56 (2H, d, J = 6.0 Hz), 5.18 (1H, t, J = 6.0 Hz), 5.09 (2H, brs), 4.37 (2H, dd, J = 5.2, 16.0 Hz), 4.18 (2H, dd, J = 5.2, 16.0 Hz), 1.47 (18H, s); ^{13}C NMR (100 MHz) δ 231.5 (3C), 155.9 (2C), 111.6, 106.2 (2C), 92.4 (2C), 89.9, 80.5 (2C), 42.3 (2C), 28.5 (6C); IR 3453, 1712 cm^{-1}. Anal. Calcd $C_{21}H_{27}ClCrN_2O_7$: C, 49.76; H, 5.37; N, 5.53. Found: C, 49.44; H, 5.16; N, 5.25.

Tricarbonyl[1,3-di-*tert*-butoxycarbonylaminomethyl-2-(hexy-1-nyl)benzene]chromium (12a). Sonogashira coupling of **11** was performed by above-mentioned procedure. 163 mg (74%): Crystalline; mp 100−101 °C; ^{1}H NMR (400 MHz) δ5.38−5.35 (3H, m), 5.03 (2H, brs), 4.43 (2H, dd, J = 6.2, 16.0 Hz), 4.15 (2H, dd, J = 6.2, 16.0 Hz), 2.45 (2H, t, J = 7.1 Hz), 1.64−1.60 (4H, m), 1.47 (18H, s), 0.96 (3H, t, J = 7.3 Hz); ^{13}C NMR (100 MHz) δ 232.3 (3C), 155.8 (2C), 110.7 (2C), 99.1, 91.7, 89.9 (3C), 80.2 (2C), 72.6, 42.7 (2C), 30.5, 28.3 (6C), 22.1, 19.2, 13.5; IR 3453, 2400, 1711 cm^{-1}. Anal. Calcd for $C_{27}H_{36}CrN_2O_7$; C, 58.69; H, 6.57; N, 5.07. Found: C, 58.99; H, 6.49; N, 5.09.

Tricarbonyl[1,3-di-*tert*-butoxycarbonylaminomethyl-2-(phenylethy-1-nyl)benzene]chromium (12b). 215 mg (92%): Crystalline; mp 163−165 °C; ^{1}H NMR (400 MHz) δ 7.53 (1H, d, J = 2.0 Hz), 7.51 (1H, d, J = 2.4 Hz), 7.41−7.37 (3H, m), 5.48−5.44 (3H, m), 5.08 (2H, brs), 4.54 (2H, dd, J = 5.2, 16.8 Hz), 4.25 (2H, dd, J = 5.2, 16.8 Hz), 1.47 (18H, s); ^{13}C NMR (100 MHz) δ 232.1 (3C), 155.9 (2C), 132.1 (2C), 129.5, 128.6 (2C), 121.2, 110.7 (2C), 96.9 (2C), 92.2, 89.5 (2C), 81.2 (2C), 80.3, 42.8 (2C), 28.4 (6C); IR 3452, 2341, 1710 cm^{-1}. Anal. Calcd for $C_{29}H_{32}CrN_2O_7$: C, 60.83; H, 5.63; N, 4.89. Found: C, 60.61; H, 5.35; N, 4.88.

Tricarbonyl[1,3-di-*tert*-butoxycarbonylaminomethyl-2-(*p*-methoxyphenylethy-1-nyl)benzene]chromium (12c). 260 mg (87%): Crystalline; mp 164−165 °C; ^{1}H NMR (400 MHz) δ 7.45 (2H, d, J = 9.2 Hz), 6.91 (2H, d, J = 9.2 Hz), 5.43 (3H, s), 5.08 (2H, brs), 4.53 (2H, dd, J = 6.4, 16.0 Hz), 4.25 (2H, dd, J = 6.4, 16.0 Hz), 3.85 (3H, s), 1.47 (18H, s); ^{13}C NMR (100 MHz) δ 232.24 (3C), 160.55, 155.81 (2C), 133.47 (2C), 114.23 (2C), 110.56, 99.54, 97.23 (2C), 89.66 (2C), 83.31, 80.27 (2C), 79.95 (2C), 55.39, 42.75 (2C), 28.34 (6C); IR 3451, 1710, 1509 cm^{-1}. Anal. Calcd for $C_{30}H_{34}CrN_2O_8$: C, 59.79; H, 5.69; N, 4.65. Found: C, 59.61; H, 5.43; N, 4.46.

Tricarbonyl[1,3-di-*tert*-butoxycarbonylaminomethyl-2-(*o*-methoxyphenylethy-1-nyl)benzene]chromium (12d). 226 mg (75%): Crystalline; mp 138−139 °C; ^{1}H NMR (400 MHz) δ 7.47 (1H, d, J = 7.6 Hz), 7.39 (1H, t, J = 7.6 Hz), 7.01−6.93 (2H, m), 5.68 (2H, brs), 5.47 (2H, d, J = 7.2 Hz), 5.40 (1H, t, J = 7.2 Hz), 4.38 (2H, dd, J = 6.0, 16.4 Hz), 4.24 (2H, dd, J = 6.0, 16.4 Hz), 3.97 (3H, s), 1.46 (18H, s); ^{13}C NMR (100 MHz) δ 232.3 (3C), 162.3, 155.94 (2C), 133.0, 131.1, 121.2, 110.5, 110.2 (2C), 102.0, 92.2 (2C), 90.9 (2C), 89.9, 86.1, 80.4 (2C), 55.7, 43.3 (2C), 28.7 (6C); IR 3447, 1706 cm^{-1}. Anal. Calcd for $C_{30}H_{34}CrN_2O_8$: C, 59.79; H, 5.69; N, 4.65. Found: C, 59.60; H, 5.52; N, 4.51.

Tricarbonyl[1,3-di-*tert*-butoxycarbonylaminomethyl-2-(3,5-dimethoxyphenylethy-1-nyl)benzene]chromium (12e). 202 mg (81%): Crystalline; mp 139−140 °C; ^{1}H NMR (400 MHz) δ 6.65 (2H, d, J = 2.3 Hz), 6.52 (1H, t, J = 2.3 Hz), 5.46 (1H, t, J = 6.1 Hz), 5.42 (2H, d, J = 6.1 Hz), 5.07 (2H, brs), 4.54 (2H, dd, J = 6.8, 15.6 Hz), 4.24 (2H, dd, J = 6.8, 15.6 Hz), 3.82 (6H, s), 1.47 (18H, s); ^{13}C NMR (100 MHz) δ 232.1 (3C), 160.7 (2C), 155.8 (2C), 122.6, 110.9 (2C), 109.7 (2C), 102.8, 96.8, 92.2 (2C), 89.4 (2C), 88.0, 80.3 (2C), 55.6 (2C), 42.7 (2C), 28.3 (6C); IR 3451, 1710 cm^{-1}. Anal. Calcd for $C_{31}H_{36}CrN_2O_9$: C, 58.86; H, 5.74; N, 4.43. Found: C, 59.14; H, 5.50; N, 4.21.

Tricarbonyl[1,3-di-*tert*-butoxycarbonylaminomethyl-2-(3,4,5-trimethoxyphenylethy-1-nyl)benzene]chromium (12f). 82 mg (62%): Crystalline; mp 175−176 °C; ^{1}H NMR (400 MHz) δ 6.74 (2H, s), 5.47 (1H, t, J = 6.6 Hz), 5.42 (2H, d, J = 6.6 Hz), 5.07 (2H, brs), 4.57 (2H, dd, J = 6.0, 16.4 Hz), 4.24 (2H, dd, J = 6.0, 16.4 Hz), 3.90 (6H, s), 3.88 (3H, s), 1.47 (18H, s); ^{13}C NMR (100 MHz) δ 232.2 (3C) 155.8, 153.32C), 116.3 (2C), 112.7, 110.9 (2C), 107.2, 97.1 (2C) 92.2, 89.3 (2C) 88.3 (2C) 80.2 (2C) 61.1, 56.4 (2C) 42.7 (2C) 28.3 (6C); IR 3450, 1709 cm^{-1}. Anal. Calcd for $C_{32}H_{38}CrN_2O_{10}$: C, 58.00; H, 5.78; N, 4.23. Found: C, 57.83; H, 5.65; N, 4.04.

Tricarbonyl[1,3-di-*tert*-butoxycarbonylaminomethyl-2-(*p*-chlorophenylethy-1-nyl)benzene]chromium (12g). 109 mg (36%): Crystalline; mp 72−74 °C; ^{1}H NMR (400 MHz) δ 7.45 (2H, d, J = 10.4 Hz), 7.36 (2H, d, J = 10.4 Hz), 5.47 (1H, t, J = 6.3 Hz), 5.41 (2H, d, J = 6.3 Hz), 5.05 (2H, brs), 4.55 (2H, dd, J = 6.0, 16.0 Hz), 4.23 (2H, dd, J = 6.0, 16.0 Hz), 1.47 (18H, s); ^{13}C NMR (100 MHz) δ 232.0 (3C), 155.8 (2C), 135.7, 133.1 (2C), 129.0 (2C), 119.8, 110.8 (2C), 95.6 (2C), 89.3, 87.6, 82.2 (2C), 80.4 (2C), 42.7 (2C), 28.3 (6C); IR 3452, 1710, 1506, 1091 cm^{-1}. Anal. Calcd for $C_{29}H_{31}ClCrN_2O_7$: C, 57.38; H, 5.15; N, 4.61. Found: C, 57.84; H, 5.46; N, 4.59.

(R_p)-Tricarbonyl(3-methyl-5-hydroxymethyl-1*H*-isochromene)chromium (15a). A mixture of [(*R*)-xylyl-binap(AuCl)$_2$] (5.8 mg, 0.0048 mmol) and $AgSbF_6$ (3.3 mg, 0.0096 mmol) in CH_2Cl_2 (1 mL) was stirred at room temperature for 10 min. A solution of complex **7** (15.0 mg, 0.048 mmol) in CH_2Cl_2 (2.0 mL) was added to the reaction mixture at rt. After 5 min, ether was added to the reaction mixture and filtered through a short layer of silica gel. Concentration of the organic layer and purification by silica gel column chromatography (5% ether in hexane) gave 12.8 mg (85%) of **15a**: Crystalline; mp 75 °C; $[\alpha]_D^{20}$ +1116 (c 0.41, $CHCl_3$); ^{1}H NMR (300 MHz) δ 5.52 (1H, d, J = 6.3 Hz), 5.48 (1H, s), 5.29 (1H, d, J = 6.3 Hz), 5.16 (1H, t, J = 6.3 Hz), 4.94 (1H, d, J = 13.2 Hz), 4.86 (1H, d, J = 13.2 Hz), 4.58 (1H, dd, J = 6.3, 13.2 Hz), 4.48 (1H, dd, J = 6.3, 13.2 Hz), 1.97 (3H, s), 1.80 (1H, t, J = 6.3 Hz); ^{13}C NMR (125 MHz) δ 233.2 (3C), 159.9, 102.5, 101.9, 99.3, 94.0, 92.9, 89.3, 88.6, 67.1, 61.4, 20.0; IR 3389, 1951, 1868 cm^{-1}. Anal. Calcd for $C_{14}H_{12}CrO_5$: C, 53.85; H, 3.87. Found: C, 54.11; H, 4.09. HPLC (Chiralcel AD-H), Hexane:*i*-PrOH = 9:1, flow rate 1.0 mL/min; retention time = 15.7, 22.1 min; 99% ee.

(R_p)-Tricarbonyl(3-*n*-butyl-5-hydroxymethyl-1*H*-isochromene)chromium (15b). Liquid; 13 mg (87%): $[\alpha]_D^{20}$ +893 (c 0.27, $CHCl_3$); ^{1}H NMR (300 MHz) δ 5.52 (1H, d, J = 5.4 Hz), 5.47 (1H, s), 5.29 (1H, d, J = 5.4 Hz), 5.16 (1H, t, J = 5.4 Hz), 4.91 (1H, d, J = 12.9 Hz), 4.85 (1H, d, J = 12.9 Hz), 4.58 (1H, d, J = 12.6 Hz), 4.48 (1H, d, J = 12.6 Hz), 2.21 (2H, t, J = 6.9 Hz), 1.85 (1H, brs), 1.56−1.25 (4H, m), 0.92 (3H, t, J = 6.6 Hz); ^{13}C NMR (125 MHz) δ 233.2 (3C), 163.9, 102.5, 102.0, 99.7, 93.5, 92.8, 89.2, 88.6, 67.1, 61.4, 33.8, 29.0, 22.2, 13.8; IR 3377, 1957, 1880 cm^{-1}; EI-MS (70 eV) m/z (relative intensity) 354 (14, M$^+$), 298 (70), 270 (70), 52 (100); HRMS (ESI) calcd for $C_{17}H_{18}CrO_5$ 354.0559, found 354.0554. HPLC (Chiralcel AD-H), Hexane:*i*-PrOH = 9:1; flow rate 0.5 mL/min; retention time = 24.1, 27.4 min; 99% ee.

(R_p)-Tricarbonyl(3-phenyl-5-hydroxymethyl-1*H*-isochromene)chromium (15c). 11 mg (70%): Crystalline; mp 118 °C; $[\alpha]_D^{20}$ +821 (*c* 0.27, $CHCl_3$); ^{1}H NMR (300 MHz) δ 7.71−7.68 (2H, m), 7.40−7.38 (3H, m), 6.26 (1H, s), 5.55 (1H, d, *J* = 6.0 Hz), 5.36 (1H, d, *J* = 6.0 Hz), 5.25 (1H, t, *J* = 6.0 Hz), 5.10 (1H, d, *J* = 13.2 Hz), 5.05 (1H, d, *J* = 13.2 Hz), 4.72 (1H, dd, *J* = 12.9, 6.9 Hz), 4.61 (1H, dd, *J* = 12.9, 6.9 Hz), 1.91 (1H, t, *J* = 6.9 Hz); ^{13}C NMR (125 MHz) δ 233.0 (3C), 158.0, 133.1, 130.0 (2C), 128.5 (2C), 125.5, 103.0, 101.4, 100.6, 93.9, 92.4, 89.1, 88.9, 67.6, 61.6; IR 3347, 1939, 1864 cm^{-1}. Anal. Calcd for $C_{19}H_{14}CrO_5$: C, 60.97; H, 3.77. Found: C, 61.00; H, 3.93. HPLC (Chiralcel AD-H); Hexane:*i*-PrOH = 9:1; flow rate 1.0 mL/min; retention time = 24.0, 27.2 min; 99% ee.

Tricarbonyl(1-methoxy-3-*n*-butyl-5-formyl-1*H*-isochromene)chromium (14). Red oil; 9 mg (53%): ^{1}H NMR (300 MHz) δ 9.82 (1H, s), 6.37 (1H, s), 6.07 (1H, d, *J* = 6.3 Hz), 5.78 (1H, d, *J* = 6.3 Hz), 5.57 (1H, s), 5.11 (1H, t, *J* = 6.3 Hz), 3.58 (3H, s), 2.34 (2H, t, *J* = 7.2 Hz), 1.60−1.26 (4H, m), 0.94 (3H, t, *J* = 7.2 Hz); ^{13}C NMR (125 MHz) δ 230.1 (3C), 187.0, 162.8, 106.5, 97.9, 95.6, 93.7, 92.9, 92.0, 87.1, 85.7, 56.2, 34.2, 29.1, 22.1, 13.8; IR 1974, 1900, 1638 cm^{-1}; EI-MS (70 eV) *m*/*z* (relative intensity) 382 (18, M$^+$), 351 (5), 326 (5), 298 (57), 52 (100); HRMS (ESI) calcd for $C_{18}H_{18}CrO_6$ 382.0508, found 382.0514. HPLC (Chiralcel AD-H); Hexane:*i*-PrOH = 95:5; flow rate 0.5 mL/min; retention time = 23.9, 25.8 min; 29% ee.

Tricarbonyl[*N*,*N*′-di-*tert*-butoxycarbonyl 5-aminomethyl-3-phenyl-1,2-dihydroisoquinoline]chromium (20b). 7.8 mg (40%): Crystalline; mp 82−83 °C; $[\alpha]_D^{20}$ +923.7 (*c* 0.05, $CHCl_3$); ^{1}H NMR (400 MHz) δ7.43 (2H, d, *J* = 3.7 Hz), 7.36−7.35 (3H, m), 6.19 (1H, s), 5.42 (2H, d, *J* = 6.1 Hz), 5.25 (1H, t, *J* = 6.1 Hz), 4.97 (1H, d, *J* = 15.1 Hz), 4.95 (1H, brs), 4.53 (1H, dd, *J* = 5.2, 15.2 Hz), 4.41 (1H, d, *J* = 15.1 Hz), 4.13 (1H, dd, *J* = 5.2, 15.2 Hz), 1.48 (9H, s), 1.07 (9H, s); ^{13}C NMR (100 MHz) δ232.55 (3C), 155.63, 145.18, 138.02, 128.73, 128.24 (2C), 126.46, 107.18 (2C), 102.60, 91.97 (2C), 90.42, 89.49 (2C), 82.01 (2C), 80.36, 46.48, 41.43, 28.34 (3C), 27.41 (3C); IR 3447, 1613, 1704 cm^{-1}. Anal. Calcd for $C_{29}H_{32}CrN_2O_7$: C, 60.83; H, 5.63; N, 4.89. Found: C, 60.57; H, 5.69; N, 4.65. HPLC (Chiralcel OF); Hexane:*i*-PrOH = 40:3; flow rate 0.5 mL/min; retention time = 56.2, 70.3 min; 99% ee.

Tricarbonyl[*N*,*N*′-di-*tert*-butoxycarbonyl 5-aminomethyl-3-(*p*-methoxyphenyl)-1,2-dihydroisoquinoline]chromium (20c). 14 mg (70%): Crystalline; mp 80−82 °C; $[\alpha]_D^{20}$ +554 (*c* 0.05, $CHCl_3$); ^{1}H NMR (400 MHz) δ 7.37 (2H, d, *J* = 8.8 Hz), 6.89 (2H, d, *J* = 8.8 Hz), 6.13 (1H, s), 5.43 (1H, d, *J* = 6.6 Hz), 5.41 (1H, d, *J* = 6.6 Hz), 5.22 (1H, t, *J* = 6.6 Hz), 4.93 (1H, d, *J* = 15.0 Hz), 4.92 (1H, brs), 4.52 (1H, dd, *J* = 7.2, 16.0 Hz), 4.38 (1H, d, *J* = 15.0 Hz), 4.11 (1H, dd, *J* = 7.2, 16.0 Hz), 3.84 (3H, s), 1.48 (9H, s), 1.11 (9H, s); ^{13}C NMR (100 MHz) δ 232.7 (3C), 160.3, 155.2, 145.1, 130.5, 127.8 (2C), 113.6 (2C), 105.8, 102.3, 102.0, 92.3 (2C), 90.7 (2C), 89.1 81.8, 80.3, 55.4, 46.5, 41.4, 28.3 (3C), 27.5 (3C); IR 3450, 1705 cm^{-1}. Anal. Calcd for $C_{30}H_{34}CrN_2O_8$: C, 59.79; H, 5.69; N, 4.65. Found: C; 59.96; H, 5.67; N; 4.75. HPLC (Chiralcel OD-H), Hexane:*i*-PrOH = 9:1; flow rate 1.0 mL/min; retention time = 16.4, 22.3 min; 99% ee.

Tricarbonyl[*N*,*N*′-di-*tert*-butoxycarbonyl 5-aminomethyl-3-(*o*-methoxyphenyl)-1,2-dihydroisoquinoline]chromium (20d). 6.8 mg (34%): Crystalline; mp 87−89 °C; $[\alpha]_D^{20}$ +646 (*c* 0.21, $CHCl_3$) ^{1}H NMR (400 MHz) δ7.32 (2H, t, *J* = 7.5 Hz), 6.96 (1H, t, *J* = 7.5 Hz), 6.85 (1H, d, *J* = 7.5 Hz), 5.92 (1H, s), 5.36 (2H, d, *J* = 6.2 Hz), 5.30 (1H, t, *J* = 6.2 Hz), 4.96 (1H, brs), 4.87 (1H, d, *J* = 14.8 Hz), 4.50−4.41 (1H, m), 4.45 (1H, d, *J* = 14.8 Hz), 4.12 (1H, dd, *J* = 5.6, 15.6 Hz), 3.81 (3H, s), 1.47 (9H, s), 1.05 (9H, s); ^{13}C NMR (100 MHz) δ 232.9 (3C), 156.3, 155.7, 142.6, 129.8, 129.5, 127.3, 120.6, 110.1, 107.8, 103.2, 100.6, 91.0 (2C), 90.5 (2C), 89.6, 81.2, 80.3, 55.6, 45.8, 41.4, 28.3 (3C), 27.5 (3C); IR 1966, 1897, 1700 cm^{-1}. Anal. Calcd for $C_{30}H_{34}CrN_2O_8$: C, 59.79; H, 5.69; N, 4.65. Found: C, 60.05; H, 5.72; N, 4.35. HPLC (Chiralcel OF), Hexane:*i*-PrOH = 9:1; flow rate 0.75 mL/min; retention time = 38.01, 64.05 min; 96% ee.

Tricarbonyl[*N*,*N*′-di-*tert*-butoxycarbonyl 5-aminomethyl-3-(3, 5-dimethoxyphenyl)-1,2-dihydroisoquinoline]chromium (20e). 12 mg (61%): Crystalline; mp 83−85 °C; $[\alpha]_D^{20}$ +445 (*c* 0.08, $CHCl_3$); ^{1}H NMR (400 MHz) δ 6.59 (2H, d, *J* = 2.0 Hz), 6.47 (1H, t, *J* = 2.0 Hz), 6.22 (1H, s), 5.40 (2H, t, *J* = 5.8 Hz), 5.27 (1H, t, *J* = 5.8 Hz), 4.94 (1H, d, *J* = 14.9 Hz), 4.92 (1H, brs), 4.56 (1H, dd, *J* = 6.8, 15.6 Hz), 4.42 (1H, d, *J* = 14.9 Hz), 4.08 (1H, dd, *J* = 6.8, 15.6 Hz), 3.82 (6H, s), 1.47 (9H, s), 1.14 (9H, s); ^{13}C NMR (100 MHz) δ 232.5 (3C), 160.7 (2C), 144.8 (2C), 134.1, 129.0, 107.4 (2C), 106.9, 104.6 (2C), 102.8 (2C), 101.0, 100.7, 91.6, 90.1, 82.0, 55.5 (2C), 46.5, 41.4, 28.4 (3C), 27.5 (3C); IR 3435, 1707 cm^{-1}. Anal. Calcd for $C_{31}H_{36}CrN_2O_9$: C, 58.86; H, 5.74; N, 4.43. Found: C, 59.12; H, 5.61; N, 4.37. HPLC (Chiralcel OD-H), Hexane:*i*-PrOH = 9:1; flow rate 1.0 mL/min; retention time = 14.6, 18.4 min; 99% ee.

Tricarbonyl[*N*,*N*′-di-*tert*-butoxycarbonyl 5-aminomethyl-3-(3,4,5-trimethoxyphenyl)-1,2-dihydroisoquinoline]chromium (20f). 14 mg (70%): Crystalline; mp 80−82 °C; $[\alpha]_D^{20}$ +800 (*c* 0.05, $CHCl_3$); ^{1}H NMR (400 MHz) δ 6.68 (2H, s), 6.23 (1H, s), 5.42 (1H, d, *J* = 6.1 Hz), 5.38 (1H, d, *J* = 6.1 Hz), 5.27 (1H, t, *J* = 6.1 Hz), 4.94 (1H, d, *J* = 15.2 Hz), 4.92 (1H, brs), 4.63 (1H, dd, *J* = 8.5, 15.0 Hz), 4.43 (1H, d, *J* = 15.2 Hz), 4.03 (1H, dd, *J* = 8.5, 15.0 Hz), 3.90 (6H, s), 3.87 (3H, s), 1.45 (9H, s), 1.14 (9H, s); ^{13}C NMR (100 MHz) δ 232.5 (3C), 155.6, 153.2 (2C), 144.8, 138.8, 133.8, 131.7, 106.7, 103.7 (2C), 102.6, 91.8 (2C), 90.3 (2C), 89.6, 82.0, 80.3, 61.0, 56.3 (2C), 46.6, 41.5, 28.3 (3C), 27.6 (3C); IR 1967, 1898, 1702 cm^{-1}. Anal. Calcd for $C_{32}H_{38}CrN_2O_{10}$: C, 58.00; H, 5.78; N, 4.23. Found: C, 58.12; H, 5.68; N, 4.17. HPLC (Chiralpak AD-H), Hexane:*i*-PrOH = 9:1; flow rate 1.0 mL/min; retention time = 19.98, 38.03 min; 99% ee.

(−)-Tricarbonyl(2-chlorobenzyl *t*-butyldimethylsilyl ether) chromium (17). A mixture of optically pure (*o*-chlorobenzylalcohol)-$Cr(CO)_3$ (200 mg, 0.718 mmol), imidazole (73 mg, 1.08 mmol), *N*,*N*-dimethylaminopyridine (4.4 mg, 0.36 mmol), and TBDMSCl (119 mg, 0.79 mol) in CH_2Cl_2 (3 mL) was stirred at 0 °C for 1.5 h. Usual workup gave 266 mg (95%) of **17**: Crystalline; mp 80−81 °C; $[\alpha]_D^{20}$ −19 (*c* 0.42, $CHCl_3$); ^{1}H NMR (300 MHz,) δ 5.78 (1H, d, *J* = 6.0 Hz), 5.48 (1H, d, *J* = 6.0 Hz), 5.33 (1H, t, *J* = 6.0 Hz), 5.13 (1H, t, *J* = 6.0 Hz), 4.70 (1H, d, *J* = 13.8 Hz), 4.58 (1H, d, *J* = 13.8 Hz), 0.97 (9H, s), 0.18 (3H, s), 0.16 (3H, s); ^{13}C NMR (125 MHz) δ 231.7 (3C), 110.5, 108.2, 91.9, 91.7, 91.4, 88.8, 61.4, 25.8 (3C), 18.3, −5.4, −5.5; IR 1977, 1907 cm^{-1}. Anal. Calcd for $C_{16}H_{21}ClCrO_4Si$: C, 48.91; H, 5.39. Found: C, 48.93; H, 5.68.

(+)-[(2-Chloro-3-*t*-butyldimethylsilyloxymethyl)-benzaldehyde]tricarbonylchromium (18). To a solution of (−)-complex (**17**) (1.6g, 4.07 mmol) in ether (30 mL) was added *n*-BuLi (1.56 M in hexane, 3.1 mL, 4.88 mmol) at −35 °C, and the mixture was stirred for 2 h. DMF (6.3 mL, 81 mmol, 20 equiv) was added to the mixture, and the reaction mixture was warmed to 0 °C over 2 h and quenched with aqueous NH_4Cl. Usual workup and purification with chromatography gave **18**. 1.493g (87%): Crystalline; mp 77−78 °C; $[\alpha]_D^{20}$ +612 (*c* 0.40, $CHCl_3$); ^{1}H NMR (300 MHz) δ 10.08 (1H, s), 6.13 (1H, d, *J* = 5.1 Hz), 6.11 (1H, d, *J* = 5.1 Hz), 5.18 (1H, t, *J* = 5.1 Hz), 4.73 (1H, d, *J* = 13.8 Hz), 4.58 (1H, d, *J* = 13.8 Hz), 0.98 (9H, s), 0.18 (3H, s), 0.17 (3H, s); ^{13}C NMR (125 MHz) δ 229.2 (3C), 186.1, 115.7, 105.8, 92.9, 92.7, 91.9, 86.2, 61.1, 25.8 (3C), 18.3, −5.49, −5.54; IR 1974, 1905, 1688 cm^{-1}. Anal. Calcd for $C_{17}H_{21}ClCrO_5Si$: C, 48.51; H, 5.03. Found: C, 48.56; H, 5.07.

(−)-[(3-(((*tert*-butyldimethylsilyl)oxy)methyl)-2-(hex-1-yn-1-yl)phenyl)methanol]tricarbonylchromium (19). (+)-Chromium complex **18** was converted to **19** by Sonogashira coupling and subsequent reduction of formyl group. Liquid. 89 mg (78%): $[\alpha]_D^{20}$ −24 (*c* 0.24, $CHCl_3$); ^{1}H NMR (300 MHz) δ 5.63 (1H, d, *J* = 6.3 Hz), 5.48 (1H, d, *J* = 6.3 Hz), 5.41 (1H, t, *J* = 6.3 Hz), 4.80−4.53 (4H, m), 2.45 (2H, t, *J* = 7.2 Hz), 2.03 (1H, t, *J* = 6.6 Hz), 1.64−1.43 (7H, m), 0.96 (9H, s), 0.16 (3H, s), 0.15 (3H, s); ^{13}C NMR (125 MHz) δ 232.6 (3C), 113.2, 111.4, 98.9, 91.1, 89.2, 89.0, 88.0, 72.1, 62.8, 62.3, 30.5, 25.8 (3C), 21.9, 19.2, 18.3, 13.5, −5.4, −5.5; IR 3391, 1965, 1892 cm^{-1}; EI-MS (70 eV) *m*/*z* (relative intensity) 468 (7, M$^+$), 384 (32), 252 (26), 52 (100, Cr); HRMS (ESI) calcd for $C_{23}H_{32}CrO_5Si$ 468.1418, found 468.1424.

Preparation of 15b. (−)-Chromium complex **19** was treated with 5 mol % $(PPh_3)AuNTf_2$ in CH_2Cl_2, and subsequent desilylation with TBAF in THF to give (+)-**15b**.

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■ ASSOCIATED CONTENT

Supporting Information

Copies of NMR (^{1}H and ^{13}C) spectra of all new compounds and HPLC charts of compounds **14**, **15a**−**15c**, and **20b**−**20f**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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