JOC The Journal of Organic Chemistry

Article

pubs.acs.org/joc

Synthesis of Rare Earth Catalysts and Their Applications for Enantioselective Synthesis of Heterocyclic β-Amino Alcohols

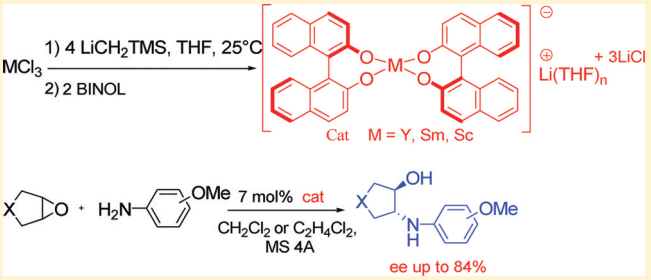
Myriam Martin,[†] Ahmad El Hellani,[†] Jing Yang,[†] Jacqueline Collin,*[,†,‡] and Sophie Bezzenine-Lafollée*[,†]

[†]Equipe de Catalyse Moléculaire, ICMMO, UMR 8182, Bâtiment 420, Université Paris-Sud, 91405 Orsay, France

[‡]CNRS, F-91405 Orsay, France

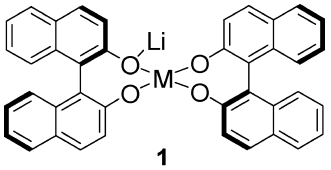
Supporting Information

ABSTRACT: A new family of chiral lanthanide complexes derived from (*R*)-binaphthol has been synthesized by a one-pot procedure using only commercially available substrates. These complexes were evaluated for the aminolysis of *meso*-epoxides and proved to be efficient enantioselective catalysts. The samarium complex coordinated by two (*R*)-binaphthoxide ligands was the most enantioselective catalyst of this series. β-Amino alcohols including heterocycles have been isolated with enantiomeric excesses up to 84%.



INTRODUCTION

Asymmetric catalysis provides highly economic access to optically active compounds. The development of efficient methods to obtain new chiral catalysts for enantioselective carbon−carbon and carbon−nitrogen bond formation is an important goal nowadays. In the last decades, heterobimetallic catalysts have received particular attention since they enable highly efficient asymmetric reactions. Shibasaki et al. have developed various bifunctional asymmetric catalysts based on binaphtholate ligands and rare earths.[1] They have extended this concept to another metal center and reported a new chiral catalyst **1** containing aluminum and lithium, by reacting $LiAlH_4$ with 2 equiv of binaphthol (Figure 1, M = Al).[2] This complex



1

M = Al, B, Ga, In, Sc

Figure 1. Structure of complexes **1**.

catalyzed Michael and tandem Michael−aldol reactions with enantiomeric excesses up to 99% and 91%, respectively. The Shibasaki team has also synthesized heterobimetallic complexes using group 13 elements (B, Ga, In) (Figure 1).[3] These complexes catalyzed the asymmetric ring-opening of *meso* epoxides by thiols to give β-hydroxy sulfides with enantiomeric excesses up to 97% in the case of gallium catalyst. Vallée et al.[4] have reported the preparation of a similar chiral scandium complex (Figure 1, M = Sc) which has been successfully used for enantioselective Strecker reaction although its structure has not been determined.

In our laboratory, a family of ionic rare earth amides based on (*R*)-1,1′-binaphthyl-2,2′-bis(alkylamine) ligands with various metals and *N*-alkyl substituents has been synthesized and characterized.[5] These complexes contain a complex anion with a discrete $[Li(THF)_4]^+$ as counterion. They exhibit high activities and enantioselectivities for asymmetric intramolecular hydroaminations. Moreover, these catalysts are easily and rapidly prepared from commercially available sources. This led us to envisage the preparation of similar rare earth ate complexes based on binaphtholate ligands as readily available catalysts that could be evaluated for enantioselective carbon−nitrogen bond formation such as the aminolysis of *meso*-epoxides.

Numerous synthetic routes have been reported for the preparation of enantioenriched α,β-amino alcohols.[6] The asymmetric ring-opening of epoxides by various nucleophiles to prepare 1,2-disubstituted derivatives including α,β-amino alcohols was reviewed in 2006.[7] New catalytic systems for the enantioselective aminolyzes of epoxides based on binol,[8] bipyridine,[9] or salen[10] ligands and different metal precursors have been developed in recent years. High enantiomeric excesses have been recorded by Schneider for the ring-opening of nonfunctionnalized epoxides by aromatic amines using $In(OTf)_3$ coordinated by a chiral bipyridine ligand[9a−c] and by Kobayashi with $Nb(OMe)_5$ coordinated by a tetradentate binol ligand[8d,e] (up to 98% and 96%, respectively), yet only a few examples of enantioselective ring-opening of functionnalized epoxides were described, and these involved aniline as the sole

Received: September 14, 2011
Published: October 22, 2011

   dx.doi.org/10.1021/jo2019015 | *J. Org. Chem.* 2011, 76, 9801−9808

amine. Both systems described above were efficient, with the highest enantioselectivities being recorded in niobium catalyzed reactions (up to 89% ee).[9a−c,8d,e,11]

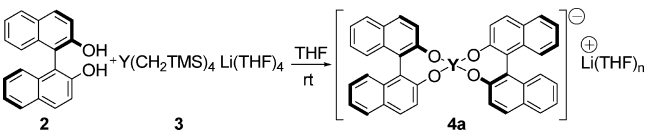
In our previous studies, we have reported the desymmetrization of cyclic *meso*-epoxides by aromatic amines catalyzed by samarium iodo binaphtholate.[12] These reactions allowed us to prepare the corresponding *β*-amino alcohols with enantiomeric excesses up to 93% as the highest values reported for these transformations. The ring-opening by aromatic amines of cyclic *meso*-epoxides containing *O* and *N* functionalities led to new heterocyclic *β*-amino alcohols with up to 70% ee.[13]

Herein we report a new route toward rare earth heterobimetallic derivatives which catalyze the synthesis of heterocyclic *β*-amino alcohols in high enantiomeric excesses.

RESULTS AND DISCUSSION

The synthesis of rare earth derivatives from amido or alkyl precursors has attracted an increased interest since it avoids the preparation of salts from ligands.[14] Tetraalkyl ate complexes of yttrium, lutetium, and scandium have been recently isolated and used for the synthesis of carbene complexes.[15] We thus considered that these ate complexes could be simple starting materials for preparing heterobimetallic rare earth complexes coordinated by two binaphtholate ligands. Yttrium was selected to investigate this route since heterobimetallic complexes YMB have been the focus of numerous studies by several teams.[16] The reaction of 2 equiv of binaphthol **2** with yttrium ate complex **3** in tetrahydrofuran at room temperature led to the formation of a new complex **4a** obtained as a white powder after evaporation of the solvent (Scheme 1). The ^{1}H NMR

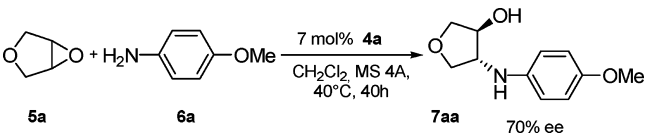
Scheme 1. Synthesis of 4a from Tetraalkyl Complex 3



spectrum of this product in C_6D_6 shows a large signal for aromatic protons indicating the coordination of binaphthol to yttrium and a binaphthol/THF ratio of 1/1. The coordination of binaphthol was confirmed by the absence of OH bond in the FT-IR spectrum. Elemental analysis correspond to a structure including two binol units, one lithium atom, and two molecules of THF per yttrium. The structure could be an ate complex with dissociation of the lithium cation or a structure similar to that proposed by Vallée for a scandium complex.[4,17]

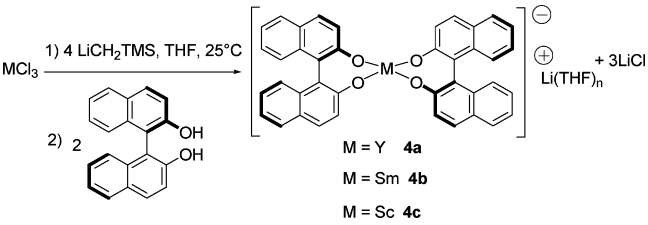
To evaluate the catalytic activity of complex **4a** for the enantioselective aminolysis of epoxides we examined first the ring-opening of 2,5-dihydrofuran oxide **5a** by *p*-anisidine. We previously studied this reaction using samarium iodobinaphtholate as catalyst and obtained 70% ee as the highest enantiomeric excess.[13] The reaction was thus performed under the same conditions (at 40 °C) using catalytic amounts of **4a** (Scheme 2).

Scheme 2. Aminolysis of Epoxide 5a Catalyzed by 4a



We were delighted to find a total conversion in *β*-amino alcohol **7aa** with 70% enantiomeric excess, the same value as using samarium iodobinaphtholate. In order to simplify the preparation of the catalyst, we decided to prepare **4a** directly from yttrium chloride without isolating ate alkylyttrium complex **3** (Scheme 3).

Scheme 3. Synthesis of Complexes 4 by a One-Pot Procedure



Addition of 4 equiv lithium trimethylsilyl methide on yttrium chloride in THF was followed by the addition of 2 equiv of binaphthol. Solvent was evaporated, the residue was dissolved in toluene and centrifugated to eliminate lithium chloride, and after evaporation of toluene the solid was washed with hexane. The resulting product exhibited the same ^{1}H NMR spectrum as **4a** prepared from **3**, and it catalyzed the aminolysis of 2,5-dihydrofuran oxide by *p*-anisidine affording *β*-amino alcohol **7aa** with the same enantiomeric excess as above. Thus, an efficient catalyst can be prepared directly from commercially available yttrium chloride and lithium trimethylsilylmethide without isolating the alkyl ate lithium rare earth complex. Following the same route, we next tried to prepare a complex of a metal of higher ionic radius for which the ate complex similar to **3** has not been isolated to the best of our knowledge. Performing the reaction as described above with samarium chloride led to **4b** as a yellow powder. Compound **4b** was evaluated for the enantioselective ring-opening of epoxides under the same conditions as samarium iodobinaphtholate catalyzed reactions (Scheme 4). The results are indicated in

Scheme 4. Aminolysis of Epoxide 5 Catalyzed by 4

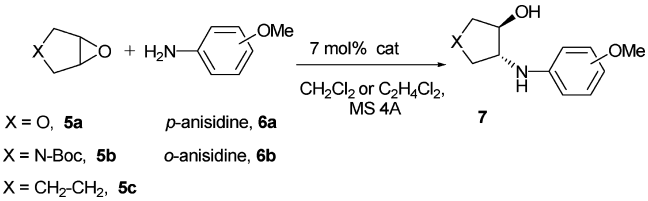


Table 1. Yttrium- and samarium-based catalysts **4a** and **4b** yielded similar results for the ring-opening of 2,5-dihydrofuran oxide by *p*-anisidine (Table 1, entries 1 and 2). We next examined the aminolysis of other epoxides **5b** and **5c** by *o*-anisidine using samarium compound **4b** as catalyst (entries 6 and 7). All of the above reactions afforded enantiomeric excesses similar to those given by samarium iodobinaphtholate under the same conditions (68% for **7aa**, 58% for **7bb**, 52% for **7cb**). Temperature has been shown to have a dramatic influence on the asymmetric induction for the rare earth-catalyzed ring-opening of epoxides. Thus, the influence of temperature on the reaction of *N*-heterocycle-containing epoxide with *o*-anisidine catalyzed by **4b** has been examined

dx.doi.org/10.1021/jo2019015 | J. Org. Chem. 2011, 76, 9801−9808

Table 1. Enantioselective Ring-Opening of Meso Cyclic Epoxides Catalyzed by 4a and 4b

entry	cat.	substrates	product[b]	T (°C)	time (h)	conv (%)	yield[a] (%)	ee (%)
1	**4a**	**5a**, **6a**	**7aa**	40	40	100	70	68
2	**4b**	**5a**, **6a**	**7aa**	40	40	100	55	66
3	**4b**	**5b**, **6b**	**7bb**	0	40	10		27
4	**4b**	**5b**, **6b**	**7bb**	25	20	50	30	63
5	**4b**	**5b**, **6b**	**7bb**	40	20	55	36	50
6	**4b**	**5b**, **6b**	**7bb**	60	20	100	62	51
7	**4b**	**5c**, **6b**	**7cb**	25	23	100	20	65

[a]Yield, reaction performed with 7 mol % of catalyst **4** and a ratio **6**/**5**: 1.2 in CH_2Cl_2 or $C_2H_4Cl_2$ according to reaction temperature. [b]Products obtained with *R* catalyst have the configuration 1*R*, 2*R* . See ref 16 for determination of the configuration.

(entries 3−6). The maximum value of 63% for the enantiomeric excess of **7bb** was recorded at 25 °C.

To determine if lithium chloride could influence the catalytic properties of compounds **4** we examined the aminolysis of epoxides using as catalyst a mixture of **4** prepared as described above (separated from LiCl) with 4 equiv of lithium or potassium chloride. This study has been achieved on the ring-opening of epoxide **5b** by *o*-anisidine **6b** since conversion is easier to measure than for the ring-opening of epoxide **5a** which is lost during the treatment of reaction mixture. The results are indicated in Table 2. Interestingly, a good enantiomeric excess

Table 2. Influence of the Presence of Salts on the Formation of Amino Alcohol 7bb Catalyzed by 4a or 4b

entry	catalyst	time (h)	conv (%)	yield[c] (%)	ee (%)
1	**4a**	20	39	35	80
2	**4a** + LiCl	20	40[a]	36	78
3	**4a** + LiCl[b]	50	95	57	76
4	**4b**	20	50	30	63
5	**4b** + LiCl	20	73[a]	40	74
6	**4b** + KCl	20	100[a]	44	64
7	**4b** + LiCl[b]	50	100	51	80

[a]Conversion for reactions performed at room temperature using 7 mol % of catalyst, 28 mol % of LiCl or KCl, epoxide **5b**, and amine **6b** with a ratio of **6b**/**5b** 1.2 in CH_2Cl_2. [b]Reaction performed using the in situ prepared catalyst without separation of lithium chloride. [c]Unoptimized yields.

of 80% was obtained at room temperature with yttrium complex **4a** (entry 1). The presence of 4 equiv of lithium or potassium chloride per samarium or yttrium led to either the same enantiomeric excess (entries 1, 2 and 4, 6) or to an increased value (entry 5 vs 4). In the presence of lithium chloride or potassium chloride the rate of the samarium-catalyzed reaction was increased (entries 4−6). These results indicate that the separation of the salts is not required for using catalysts. After successive additions of lithium trimethylsilyl methide and binaphthol on rare earth chloride the solvent was evaporated and the solid directly employed in a catalytic reaction. Under these conditions, high enantiomeric excesses of 76% and 80% have been respectively obtained with yttrium and samarium catalysts (entries 3 and 7). We have thus established a very rapid preparation of the catalysts which can be synthesized and used in a one-pot procedure. All the following results have been obtained with in situ prepared catalysts.

The following step was to check if the optimized conditions for reactions catalyzed by **4a** or **4b** without lithium chloride were also the best ones for the reactions with catalysts prepared by the new procedure (Table 3). For the aminolysis of 2,5-

Table 3. Influence of Temperature on Asymmetric Induction for the Aminolysis of Epoxides Catalyzed by 4a or 4b in the Presence of Lithium Chloride

entry	cat.	product[b]	T (°C)	time (h)	conv (%)	yield[a] (%)	ee[c] (%)
1	**4a**	**7aa**	40[d]	40	100	61	81
2	**4b**	**7aa**	40[d]	40	100	55	84
3	**4c**	**7aa**	40	92	95		50
4	**4a**	**7ba**	25	90	86	86	50
5	**4a**	**7ba**	60	48	100	34	55
6	**4a**	**7bb**	25	50	95	57	76
7	**4a**[e]	**7bb**	25	70	100	93	79
8	**4a**	**7bb**	60	27	100		64
9	**4b**	**7ba**	25	50	100		44
10	**4b**	**7ba**	60	17	100	89	60
11	**4b**	**7bb**	25	50	100	51	80
12	**4b**	**7bb**	40	24	100	55	62
13	**4b**	**7bb**	60	27	100		60
14	**4a**	**7cb**	0	60	95		28
15	**4a**	**7cb**	40	40	100		36
16	**4b**	**7ca**	25	60	100	50	33
17	**4b**	**7ca**	60	40	100		29
18	**4b**	**7cb**	−40	43	100		57
19	**4b**	**7cb**	0	43	100		67
20	**4b**	**7cb**	25	23	100	27	65
21	**4b**	**7cb**	40	16	100		60
22	**4b**	**7cb**	60	23	100	24	48
23	**4c**	**7cb**	60	48	90		56

[a]Yield, reaction performed with 7 mol % of catalyst **4** and a ratio of **6**/**5** 1.2 in CH_2Cl_2 or $C_2H_4Cl_2$ according to reaction temperature. [b]Enantiomeric excess measured by HPLC. [c]Products obtained with R catalyst have the configuration (1*R*, 2*R*). [d]Low conversions were observed after 48 h at room temperature. [e]Reaction performed with 2 mol % of catalyst **4a**.

dihydrofuran oxide **5a** by *p*-anisidine **6a**, both yttrium and samarium catalysts containing lithium chloride allowed us to prepare the *β*-amino alcohol **7aa** with total conversion in the same conditions (40 °C, 40 h) as without LiCl. To our delight, the asymmetric induction was significantly increased with ee values over 80% with both catalysts (Table 3, entries 1 and 2). For the aminolysis of epoxide **5b** by *o*- and *p*-anisidine the influence of temperature on asymmetric induction has been examined using samarium and yttrium catalysts. Only small variations of enantiomeric excesses have been observed from 25 to 60 °C for *β*-amino alcohols **7ba** and **7bb** in yttrium-catalyzed reactions (entries 4−8). When a lower catalytic ratio of **4a** (2 mol %) was used, *β*-amino alcohol **7bb** could be isolated in high yield (93%) and without decrease of enantiomeric excess (79%) at room temperature but in an increased reaction time

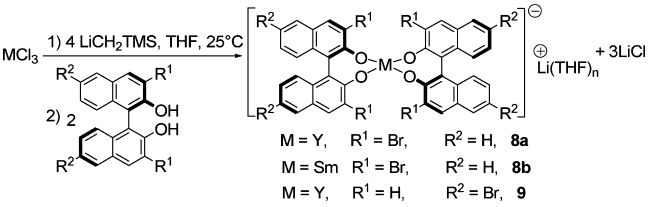
dx.doi.org/10.1021/jo2019015 | J. Org. Chem. 2011, 76, 9801−9808

(entry 7). Interestingly, with samarium catalyst **4b** total conversions have been observed at room temperature for **7bb**. The highest enantiomeric excess for **7ba** was obtained at 60 °C (entry 10) and for **7bb** at room temperature (entry 11). *o*-Anisidine furnished higher enantiomeric excesses than *p*-anisidine (compare entries 4 and 6, 10 and 11). Under the optimized conditions, yttrium and samarium compounds **4a** and **4b** led to products **7ba** and **7bb** with similar activities, while samarium was slightly more enantioselective than yttrium (compare entries 5 and 10, 6 and 11). Heterobimetallic catalysts **4** afforded higher asymmetric inductions for the aminolysis of heterocycles containing epoxides than samarium iodobinaphtholate that we previously studied. The aminolysis of cyclohexene oxide **5c** by *o*- and *p*-anisidine catalyzed by **4a** and **4b** at different temperatures led to total or nearly total conversions even at low temperatures due to the absence of supplementary heteroatom. With yttrium catalyst, low enantiomeric excesses with marginal variation with temperature were observed in reactions involving *o*-anisidine **6b** (entries 14 and 15). For samarium-catalyzed reactions low values of enantiomeric excesses were similarly obtained using *p*-anisidine **6a** at room temperature or 60 °C (entries 16 and 17). Yet *o*-anisidine **6b** furnished higher values for the enantiomeric excess with a non monotonous variation with temperature, the maximum value 67% ee being recorded at 0 °C (entries 18−22).

In order to study the influence of the structure of the catalyst and to try to improve the enantioselectivity of the aminolysis of epoxides we prepared a variety of heterobimetallic compounds by changing the rare earth metal or ligands. We first examined a scandium catalyst obtained by a one-pot addition of a solution of lithium trimethylsilylmethide in tetrahydrofuran to scandium trichloride followed by the addition of binaphthol as described above (Scheme 3). ^{1}H NMR spectra of compound **4c** showed the absence of signals corresponding to lithium trimethylsilylmethide or binaphthol and OH band was not observed in FT-IR spectrum. The catalyst was used in situ without separation of lithium chloride for aminolyzes of epoxides. The different catalysts were first compared for the aminolysis of 2,5-dihydrofuran oxide at 40 °C by *p*-anisidine (Table 3, entries 1−3). Lower values of enantiomeric excesses have been found for scandium than for yttrium and samarium catalysts. Only for the reaction of cyclohexene oxide **5c** with *o*-anisidine **6b** at 60 °C was a higher value of the enantiomeric excess of **7cb** obtained with scandium catalyst **4c** than with samarium **4b** (entries 22 and 23).

Since changing yttrium and samarium by a rare earth of smaller ionic radius like scandium did not allow us to enhance the asymmetric induction for the aminolysis of epoxides containing other heteroatoms, we turned our attention to the variation of the ligand. We selected 3,3′- or 6,6′-bromo-substituted binaphthol ligands to study the influence of electronic or steric effects on yttrium and samarium catalysts. The same procedure as for binaphthol-based heterobimetallic complexes was followed (Scheme 5). All complexes have been tested without elimination of LiCl, and the different catalysts have been used in situ for the desymmetrization of epoxide **5b** (see Table 4). Comparison of yttrium catalysts **4a** and **8a** coordinated, respectively, by binaphthol and 3,3′-bisbromobinaphthol yielded a decrease in the rate of formation of amino alcohol **7bb** and also a lower value of the enantiomeric excess with the substituted ligand (entries 1 and 2). A similar trend was observed with samarium catalysts **4b** and **8b** coordinated by binaphthol and 3,3′-bisbromobinaphthol (entries 3 and 4).

Scheme 5. Synthesis of Complexes 8 and 9



Ligand 6,6′-bisbromobinaphthol was used for preparing yttrium heterobimetallic complex **9**, which catalyzed the formation of amino alcohol **7ba** with an enantiomeric excess slighly higher than corresponding binaphthol complex **4a** but with lower conversion (entries 5 and 6). For the aminolysis of **5b** by *o*-anisidine a slight decrease of asymmetric induction was recorded with 6,6′-bisbromobinaphthol (entries 1 and 8). The presence of bromo substituents in 3,3′ or 6,6′ positions on binaphthol did not lead to improved activity or enantioselectivity of heterobimetallic yttrium or samarium catalysts for the aminolysis of an *N*-heterocyclic epoxide. However, only preliminary experiments have been achieved, and further studies varying both the structure of the ligand and the size of the metal are in progress.

Heterobimetallic lithium samarium or yttrium binaphtholate complexes are efficient catalysts for the enantioselective aminolysis of *meso*-epoxides including a heterocycle. Optimizing the preparation of catalysts and conditions for the catalytic reactions has allowed us to obtain enantiomeric excesses up to 84%. For a further improvement of the experimental procedure, catalytic reactions were performed outside the glovebox. Catalysts **4a** and **4b** were weighted in air and reactions were run with non degassed solvent and substrates at room temperature. To our delight, yttrium and samarium catalysts **4a** and **4b** afforded *β*-amino alcohol **7bb** in good yields and with 74% and 79% ee, respectively. Yttrium complex **4a** prepared without separation from LiCl was stored under argon outside the glovebox and tested as catalyst for the aminolysis leading to **7bb**. No decrease in the yield or the enantiomeric excess of **7bb** was observed after 4 weeks of storage, indicating these new catalysts can be employed in very convenient conditions. Gratifingly, preparation of catalysts and catalytic reactions are both realized following straightforward procedures.

Since compounds **4** proved to be interesting catalysts we turned our efforts toward deeper insight on their structure. These heterobimetallic compounds could have an ate structure with dissociation of the lithium cation or a neutral structure with lithium coordinated to oxygen. The latter has been proposed for the scandium complex **1** by Vallée but was not supported by structural studies.[4] Similar binaphthyl amido rare earth complexes of ate structure have been characterized.[5] For an aluminum heterobimetallic binaphthoxide derivative, Shibasaki proposed either a neutral complex or an equilibrium in solution between the two structures.[2] A linked-BINOL ligand was employed by the same group for the preparation of different rare earth catalysts and especially a stable La-linked BINOL containing two binol units coordinated to lanthanum. This complex was successfully employed for the catalysis of asymmetric Michael reactions,[18] yet a large variety of heterobimetallic complexes REMB including three binaphthoxide ligands and three alkali metals per rare earth metal have been isolated and used for the catalysis of a wide range of

dx.doi.org/10.1021/jo2019015 | J. Org. Chem. 2011, 76, 9801−9808

Table 4. Influence of the Ligand on the Aminolysis of Epoxide 5b

entry	ligand	cat.	product	T (°C)	time (h)	conv (%)	yield[a] (%)	ee (%)
1	BINOL	**4a**	**7bb**	25	50	95	57	76
2	3,3′-Br BINOL	**8a**	**7bb**	25	72	50	40	24
3	BINOL	**4b**	**7bb**	25	50	100	51	80
4	3,3′-Br BINOL	**8b**	**7bb**	25	72	50	nd	66
5	BINOL	**4a**	**7ba**	25	90	86	30	50
6	6,6′-Br BINOL	**9**	**7ba**	25	46	33	27	56
7	6,6′-Br BINOL	**9**	**7ba**	60	48	100	31	46
8	6,6′-Br BINOL	**9**	**7bb**	25	46	90	38	64

[a]Yield, reaction performed with 7 mol % of catalyst in the presence of lithium chloride and a ratio of **6**/**5** 1.2 in CH_2Cl_2 or $C_2H_4Cl_2$ according to reaction temperature.

reactions.[19] These very stable complexes can be obtained by different routes, and aqua and anhydrous complexes showed different structures and reactivity.[20] Mechanistic studies have been performed on aza-Michael reactions catalyzed by the yttrium complex YLB to determine whether three or two binaphthol units are involved in the active catalytic species.[21] To address the question of the formation of complex YLB during the preparation of complex **4** and of YLB acting as main catalytic species we decided to prepare the YLB complex **10** (Figure 2) and to compare the NMR spectra and catalytic properties of **4a** and **10**.

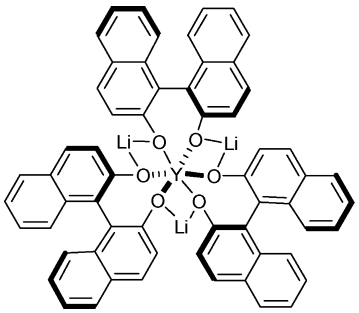


Figure 2. Structure of complex YLB **10**.

YLB was obtained following the anhydrous route described by Aspinall.[16a] The aminolysis of epoxide **5b** by *o*-anisidine at room temperature using 7 mol % complex **10** as catalyst yielded *β*-amino alcohol **7bb** with 43% yield and 18% ee. The heterobimetallic complex YLB was far less enantioselective than complex **4a** prepared without or with LiCl (80% ee and 76% ee, respectively), which indicated that it cannot be the major active catalytic species in the reaction catalyzed by **4a**. In addition, conversely to **10** which is highly soluble in CD_2Cl_2 and C_6D_6, complex **4a** has a poor solubility in these solvents. The ^1H and ^{13}C NMR spectra of **4a** in THF-d_8 are well resolved and different from the ^1H and ^{13}C NMR spectra of YLB **10** (see the Supporting Informations). It thus appears that complex **10** is not formed during the synthesis of complex **4a** in THF.[22]

Shibasaki found that the addition of LiOTf led to a dramatic increase of the reactivity and the enantioselectivity of aldol–Tischenko reactions catalyzed by LLB. This was explained by a structural change and formation of a binuclar complex $[La_2Li_4(binaphthoxide)_5]$ complex which was characterized by X-ray structure analysis.[23] For the aminolysis catalyzed by yttrium complex **4a** the presence of LiCl had no effect on the enantioselectivity of the reactions (Table 2, entries 1–3), while with **4b** increased enantiomeric excesses were observed with catalysts containing LiCl (Table 2, entries 4, 5, and 7).

Different experimental procedures were followed for the preparation of catalysts **4a** and **4b** without LiCl. Compound **4a** was obtained from isolated alkyl ate complex **3**. However, **4b** was in situ prepared from $SmCl_3$ and separated from LiCl after the addition of binaphthol. The presence of LiCl in complex **4b** could be detected on the IR spectrum (large band at 300 cm^{-1} not observed for complex **4a**). Elemental analyses for **4b** are in agreement with a structure in which two heterobimetallic samarium and lithium units are coordinated to one LiCl molecule such as $[C_{40}H_{24}LiO_4Sm(THF)_2]_2{\cdot}LiCl$. In spite of numerous attempts, crystals of **4a** or **4b** suitable for X-ray structure determinations could not be grown and the exact structure of these complexes as well as that of the other catalysts described could not be determined.[24] Yet as suggested for similar heterobimetallic complexes,[23] an equilibrium between several species depending on the solvent, the rare earth, and the presence of LiCl is possibly occurring. The non-monotonous variations of ee with temperature for **7bb** (Table 1) and **7ca** (Table 3) catalyzed by **4b** support such an equilibrium.

Only a few enantioselective catalysts have been reported for the aminolysis of epoxides including *O*- or *N*-heterocycles. These epoxides exhibit low reactivity toward ring-opening reactions due to the complexation of the heteroatom to the Lewis acid catalyst. Kobayashi has found enantiomeric excesses over 80% in niobium-catalyzed reactions for both epoxides studied in this work using aniline as the sole electrophile and a substituted binaphthol ligand.[8e] Aminolysis of epoxides **5a** and **5b** by *p*- or *o*-anisidine which allows further deprotection of the nitrogen has only been described previously in our samarium iodobinaphtholate-catalyzed reactions.[13] Heterobimetallic catalysts **4a** and **4b** were revealed to be more active and enantioselective than samarium iodobinaphtholate, especially for the *N*-heterocycle-containing epoxide. To the best of our knowledge, rare earth alkaline heterobimetallic complexes have not been used for the catalysis of aminolysis of epoxides, but in various asymmetric reactions with this family of catalysts it has been shown that both metals are involved.[16b,20] For aza-Michael additions, in particular, a cooperative Lewis acid–Lewis acid mechanism was suggested.[19c] Similarly for GaLB- and Ti–Ga-salen-catalyzed desymmetrisation of *meso* epoxides by thiols or selenols it has been proposed that metals act as two different Lewis acids coordinating to the substrates.[3,19b,25] Further studies are necessary to determine if both rare earth and lithium are involved in the active species for the aminolysis of epoxides catalyzed by complexes **4**.

dx.doi.org/10.1021/jo2019015 | J. Org. Chem. 2011, 76, 9801–9808

CONCLUSIONS

We have prepared a new family of complexes which are readily obtained within short times from commercial reagents and using tetrahydrofuran in small amount as the sole solvent. The heterobimetallic complexes of lithium and yttrium or samarium are stable for months if stored under argon. Both catalysts used in situ are efficient for the formation of β-amino alcohols and samarium reveals slightly more enantioselective. β-Amino alcohols resulting from the ring-opening of 2,5-dihydrofuran oxide and of *N-tert*-butyloxycarbonyl-3-pyrroline oxide respectively with *p*- and *o*-anisidine have been isolated with enantiomeric excesses over 80%. Catalytic reactions could be realized under mild conditions using as low as 2 mol % catalyst. The study of the catalytic activity of these new complexes for various enantioselective desymmetrisation of epoxides as well as for different reactions is currently in progress.

EXPERIMENTAL SECTION

All manipulations were carried out under argon atmosphere using standard Schlenk or glovebox techniques. Tetrahydrofuran and C_6D_6 were distilled from benzophenone−sodium and degassed immediately prior to use. Toluene, hexane, dichloromethane, and dichloroethane were distilled from CaH_2 and degassed immediately prior to use. Catalysts **4a** and **4b** have been prepared from enantiopure (*R*)-1,1-binaphthol. Ligands for catalysts **8a** or **8b** and **9** were prepared according to the literature from enantiopure (*R*)-1,1-binaphthol: (*R*)-3,3′-dibromo-1,1-binaphthol[26] and (*R*)-6,6′-dibromo-1,1-binaphthol.[27] Yttrium ate complex $Y(CH_2TMS)_4Li(THF)_4$ was prepared as described in literature.[15] Yttrium heterobimetallic complex **10** was prepared according to the Aspinall procedure.[16a] Epoxide **5a** was synthesized according to the literature procedure.[28] The *tert*-butyl 6-oxa-3-azabicyclo[3.1.0]hexane-3-carboxylate **5b** was obtained by reaction of commercially available 3-pyrroline with *tert*-butyl dicarbonate followed by epoxidation.[29] Epoxides and amines were distilled and degassed or recrystallized prior to use.

^1H and ^{13}C NMR spectra were operating at 360, 300, and 250 MHz for ^1H and at 90.6, 75, and 62.5 MHz for ^{13}C in $CDCl_3$. Chemical shifts for ^1H and ^{13}C spectra were referenced internally according to the residual solvent resonances and reported in ppm. Infrared spectra were recorded as KBr disks or in Nujol using CsI cells and reported in cm^{-1}. Optical rotations were measured at room temperature in cell of 1 dm length at the sodium D line (λ = 589 nm) and were reported as follows: $[\alpha]^{20}_D$ (*c* in g per 100 mL, $CHCl_3$). HPLC analyses were performed with an UV detector and chiral stationary-phase columns (Chiralcel OD-H, Chiralpak IA). All of the crude products were purified by preparative thin-layer chromatography on silica gel 60 PF254 (heptane/ethyl acetate 50/50 for **7aa**, **7ba**, **7bb** and 90/10 for **7ca**, **7cb**). Enantiomeric excesses were determined as we previously described.[12,13]

Preparation of Catalysts. *Preparation of **4a** from Y(CH$_2$TMS)$_4$Li(THF)$_4$.* In a glovebox, yttrium ate complex **3** (1 mmol, 660 mg) was dissolved in a Schlenk tube in THF (5 mL) and a solution of 1,1′-binaphthol (2 mmol, 572 mg) in THF (1 mL) was added slowly. After 30 min of stirring, THF was evaporated under vacuum and the complex isolated as a powder and stored in the glovebox.

*Preparation of **4a** with LiCl Removal.* In a glovebox, yttrium chloride (1 mmol, 195 mg) was suspended in a Schlenk tube in THF (5 mL) and stirred at room temperature for 30 min. To this mixture was added slowly 4 equiv of $LiCH_2TMS$ (4 mmol, 376 mg) in THF (2 mL). After 30 min of stirring, THF was evaporated and toluene (5 mL) added. The white precipitate of lithium chloride was separated by centrifugation. A solution of 1,1′-binaphthol (2 mmol, 572 mg) in THF (3 mL) was added to the supernatant, and the reaction mixture was stirred at room temperature for 30 min. The solution was evaporated under vacuum and the complex isolated as a powder and stored in the glovebox.

4a: $C_{40}H_{24}LiO_4Y\cdot(THF)_2$; white powder; yield 74%; IR (CsI, Nujol)/cm^{-1} ν 1615, 1590, 1500, 1423, 1337, 1270, 1245, 1142, 1071, 1018, 994, 958, 860, 813, 743, 667, 576, 486; ^1H NMR (250 MHz, C_6D_6) δ (ppm) 1.11 (s, 8 H, 4 CH_2), 3.07 (s, 8 H, 4 CH_2), 7.96−6.60 (m, 24 H, Ar). Anal. Calcd for $C_{48}H_{40}LiO_6Y$ (808.687): C, 71.29; H, 4.99. Found: C, 70.93; H, 5.38.

*Preparation of **4b** with LiCl Removal.* In a glovebox, samarium chloride (1 mmol, 256 mg) was suspended in a Schlenk tube in THF (5 mL) and stirred at room temperature for 30 min. To this mixture was added slowly a solution of $LiCH_2TMS$ (4 mmol, 376 mg) in THF (2 mL). After 30 min of stirring, a solution of 1,1′-binaphthol (2 mmol, 572 mg) in THF (3 mL) was slowly added. After 30 min of stirring, THF was evaporated and toluene (5 mL) added. The white precipitate of lithium chloride was separated by centrifugation. Toluene was evaporated under vacuum, and the catalyst was isolated as a powder and stored in the glovebox.

4b: $[C_{40}H_{24}LiO_4Sm(THF)_2]_2\cdot LiCl$; yellow powder; yield 54%; IR (CsI, Nujol)/cm^{-1} ν 1615, 1590, 1500, 1424, 1338, 1272, 1242, 1143, 1071, 1042, 990, 956, 859, 818, 743, 666, 632, 575, 523, 483, 389, 300; ^1H NMR (250 MHz, C_6D_6) δ (ppm) 1.13 (s, 8 H, 4 CH_2), 3.38 (s, 8 H, 4 CH_2), 8.66−6.13 (m, 24 H, Ar). Anal. Calcd for $C_{96}H_{80}ClLi_3O_{12}Sm_2$(1782.677): C, 64.68; H, 4.52; Cl, 1.99; Li, 1.17. Found: C, 62.55; H, 4.68; Cl, 1.92; Li, 1.21.

Preparation of Catalysts without LiCl Removal. In the glovebox, rare earth (III) chloride (1 mmol) was suspended in a Schlenk tube in THF (5 mL) and stirred at room temperature for 30 min before the slow addition of a solution of $LiCH_2TMS$ (4 mmol, 376 mg) in THF (2 mL). After 30 min of stirring, a solution of the ligand (2 mmol) in THF (3 mL) was slowly added and the reaction mixture stirred for 30 min. THF was evaporated under vacuum, and the catalyst was isolated as a powder and stored in the glovebox.

*[**4a** + 3LiCl]·(THF)$_6$:* white powder; yield 92%; ^1H NMR (300 MHz, $CDCl_3$) δ (ppm) 1.25 (s, 24 H, 12 CH_2), 3.32 (s, 24 H, 12 CH_2,), 5.78−7.75 (m, 24 H, Ar); ^1H NMR (250 MHz, C_6D_6) δ (ppm) 1.32 (s, 24 H, 12 CH_2), 3.43 (s, 24 H, 12 CH_2), 6.37−8.57 (m, 24 H, Ar); ^1H NMR (300 MHz, THF-d_8) δ (ppm) 6.87−7.04 (m, 12 H, Ar), 7.32−7.35 (m, 4 H, Ar), 7.66−7.73 (m, 8 H, Ar); ^{13}C NMR (360 MHz, THF-d_8) δ (ppm) 119.3, 119.9, 123.7, 125.8, 126.1, 126. 8, 127.3, 128.0, 135.2, 160.5.

*[**4b** + 3LiCl]·(THF)$_6$:* yellow powder; yield: 78%; ^1H NMR (250 MHz, $CDCl_3$) δ (ppm) 1.26 (s, 24 H, 12 CH_2), 3.41 (s, 24 H, 12 CH_2), 6.72−7.74 (m, 24 H, Ar); ^1H NMR (250 MHz, C_6D_6) δ (ppm) 1.35 (s, 24 H, 12 CH_2), 3.53 (s, 24 H, 12 CH_2), 5.83−8.91 (m, 24 H, Ar); ^1H NMR (300 MHz, THF-d_8) δ (ppm) 6.85 (s br, 4 H, Ar), 7.16−7.36 (m, 12 H, Ar), 7.70 (d, 7.9 Hz, 4 H, Ar), 8.17 (d, 7.9 Hz, 4 H, Ar); ^{13}C NMR (360 MHz, THF-d_8) δ (ppm) 119.7, 124.2, 125.9, 126.8, 127.6, 128.1, 137.2, 169.3.

*[**4c** + 3LiCl]·(THF)$_4$:* white powder; yield 85%; ^1H NMR (300 MHz, $CDCl_3$) δ (ppm) 1.56 (s,16 H, 8 CH_2), 3.26 (s, 16 H, 8 CH_2), 6.71−7.93 (m, 24 H, Ar); ^1H NMR (250 MHz, C_6D_6) δ (ppm) 1.19 (s, 16 H, 8 CH_2), 3.19 (s, 16 H, 8 CH_2,), 6.44−7.97 (m, 24 H, Ar); ^1H NMR (300 MHz, THF-d_8) δ (ppm) 6.28−6.46 (m, 1 H, Ar), 6.77−7.27 (m, 15 H, Ar), 7.43−7.56 (m, 3H, Ar), 7.64−7.85 (m, 5 H, Ar); ^{13}C NMR (360 MHz, THF-d_8) δ (ppm) 113.8, 118.5, 120.1, 122.4, 123.9, 124.2, 125.7, 125.8, 125.9, 127.6, 128.0, 129.4, 134.8, 153.8, 162.2.

Typical Procedure for the Aminolysis of Epoxides. In a glovebox, catalyst **4** (0.035 mmol) and molecular sieves 4 Å (100 mg) were weighed in a Schlenk tube and dichloromethane (5 mL) was added. *o*-Anisidine **6b** (74 mg, 0.6 mmol) was added to the solution, which was stirred at room temperature for 15 min. Outside the glovebox, the reaction was heated to the desired temperature, and a solution of *tert*-butyl 6-oxa-3-azabicyclo[3.1.0]hexane-3-carboxylate **5b** (92.5 mg, 0.5 mmol) in dichloromethane (1 mL) was then added by syringe. After being stirred for the specified time, the reaction mixture was hydrolyzed with HCl 0.1 M, diluted with CH_2Cl_2, and neutralized with NaOH 0.1 M. The aqueous layer was extracted with CH_2Cl_2. After concentration, the product was purified by thin-layer chromatography with hexane/ethyl acetate mixtures. The crude product was purified by preparative thin-layer chromatography on silica gel (heptane/EtOAc 50/50). The enantiomeric excesses of β-

dx.doi.org/10.1021/jo2019015 | J. Org. Chem. 2011, 76, 9801−9808

amino alcohols were determined by HPLC analysis as described below.

(1R,2R)-4-Oxa-2-(4-methoxyphenylamino)cyclopentanol ***7aa:*** mp 130−132 °C; $[\alpha]^{20}_{D}$ = +8.1 (*c* 1.0, $CHCl_3$) for 66% ee; HRMS (EI) calcd for $C_{11}H_{15}O_3N$ (M) 209.1046, found 209.1054; IR (CaF_2, $CHCl_3$) (cm^{-1}) ν 3684, 3622, 3021, 2977, 2930, 1364, 1216, 1046; ^1H NMR (360 MHz, $CDCl_3$) δ 3.67 (1H, dd, *J* = 9.6 Hz, *J* = 2.5 Hz), 3.76 (3H, s), 3.73−3.79 (1H, m), 3.82−3.86 (1H, m), 4.04 (1H, dd, *J* = 11.3 Hz, *J* = 4.3 Hz), 4.24−4.29 (2H, m), 6.64 (2H, d, *J* = 9.0 Hz), 6.81 (2H, d, *J* = 8.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 56.0, 62.9, 72.8, 74.8, 76.3, 114.9, 115.3, 140.8, 152.9; HPLC (Chiralpak ADH column, flow rate: 0.7 mL·min^{-1}, hexane/ethanol 85/15, λ 254 nm, t_R(minor) = 26.3 min, t_R(major) = 30.8 min).

(3R,4R)-tert-Butyl 3-hydroxy-4-(4-methoxyphenylamino)-pyrrolidine-1-carboxylate ***7ba:*** mp 103−106 °C; $[\alpha]^{20}_{D}$ = +8.5 (*c* 0.96, $CHCl_3$) for 55% ee; IR (KBr) (cm^{-1}) ν 3385, 3338, 2975, 2923, 1685, 1662, 1515, 1424, 1246, 1122; ^1H NMR (300 MHz, $CDCl_3$) δ 1.47 (9H, s), 3.21−3.42 (2H, m), 3.62−3.65 (1H, m), 3.75 (3H, s), 3.74−3.97 (2H, m), 4.24 (1H, bs), 6.61 (2H, d, *J* = 8.7 Hz), 6.79 (2H, d, *J* = 8.7 Hz); ^{13}C NMR (75 MHz, $CDCl_3$, rotamers) δ 28.4, 50.1, 50.5, 51.7, 52.0, 55.7, 59.7, 60.2, 73.2, 73.9, 79.8, 114.6, 114.9, 140.5, 152.6, 154.8; MS (ESI) *m/z* 331.1 (MNa^+, 100); HPLC (Chiralpak IA column, flow rate: 0.5 mL·min^{-1}, hexane/2-propanol: 95/5, λ 254 nm, $t_{R(minor)}$ = 44.7 min, $t_{R(major)}$ = 47.6 min).

(3R,4R)-tert-Butyl 3-hydroxy-4-(2-methoxyphenylamino pyrrolidine-1-carboxylate ***7bb:*** mp 123−126 °C; $[\alpha]^{20}_{D}$ = +22 (*c* 1.0, $CHCl_3$) for 76% ee; HRMS calcd for $C_{16}H_{24}O_4N_2$ (M) 308.1731, found 308.1725; IR (KBr)/cm^{-1} ν 3478, 2945, 1682, 1601, 1513, 1413, 1233, 1161, 1120, 1024, 742; ^1H NMR (300 MHz, $CDCl_3$) δ 1.44 (9H, s), 3.26−3.41 (2H, m), 3.58−3.62 (1H, m), 3.73−3.88 (2H, m), 3.79 (3H, s), 4.16−4.33 (1H, m), 6.63−6.84 (4H, m); ^{13}C NMR (62.5 MHz, $CDCl_3$, rotamers) δ 28.6, 50.4, 50.8, 51.9, 52.2, 55.5, 58.9, 59.2, 73.2, 74.0, 80.0, 109.7, 110.4, 117.4, 121.4, 136.5, 146.9, 155.2. HPLC (Chiralpak IA column, flow rate: 0.5 mL·min^{-1}, hexane/2-propanol: 85/15, λ 254 nm, t_R(minor) = 12.2 min, t_R(major) = 13.6 min).

(1R,2R)-2-(4-Methoxyphenylamino)cyclohexanol ***7ca:*** oil; HRMS calcd for $C_{13}H_{20}NO_2$ (M + H^+) 222.1489, found 222.1495; IR (KBr) (cm^{-1}) ν 3677, 3529, 3366, 3021, 3013, 2938, 2861, 2836, 1612, 1512, 1465, 1450, 1401, 1296, 1239, 1221, 1180, 1136, 1067, 1038; ^1H NMR (250 MHz, $CDCl_3$) δ (ppm) 0.85 −1.10 (m, 1H), 1.12−1.40 (m, 3H), 1.60−1.80 (m, 2H), 2.0−2.18 (m, 2H), 2.60 (bs, 1H), 2.92−3.04 (m, 1H), 3.24−3.55 (m, 1H), 3.73 (s, 3H), 6.66 (d, 2H, *J* = 8.8 Hz), 6.76 (d, 2H, *J* = 8.8 Hz); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ (ppm) 24.2, 25.0, 31.5, 33.0, 55.7, 61.6, 74.3, 114.8, 116.3, 141.5, 152.8; HPLC (Chiralcel OD-H column, flow rate: 1 mL·min, hexane/2-propanol: 85/15, λ 254 nm, t_R(minor) = 7.9 min, t_R(major) = 11.2 min.

(1R, 2R)-2-(2-Methoxyphenylamino)cyclohexanol ***7cb:*** oil; HRMS calcd for $C_{13}H_{20}NO_2$ (M + H^+) 222.1489, found 222.1496; IR (KBr) (cm^{-1}) ν 3616, 3429, 3067, 2964, 1602, 1511, 1456, 1430, 1341, 1247, 1180, 1121, 1050, 1030, 977, 945; ^1H NMR (250 MHz, $CDCl_3$) δ (ppm) 0.98−1.13 (m, 1H), 1.20−1.50 (m, 3H), 1.62−1.81 (m, 2H), 2.02−2.13 (m, 2H), 2.79 (bs, 1H), 3.08−3.18 (m, 1H), 3.35−3.45 (m, 1H), 3.83 (s, 3H), 6.64−6.82 (m, 4H); ^{13}C NMR (62.5 MHz, $CDCl_3$) δ (ppm) 24.3, 25.1, 31.6, 33.1, 55.4, 59.6, 74.6, 109.8, 111.4, 117.3, 121.3, 137.6, 147.5; HPLC (Chiralcel OD-H column, flow rate: 1 mL·min, hexane/2-propanol: 85/15, λ 254 nm, t_R(minor) = 7.3 min, t_R(major) = 16.8 min).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

NMR spectra of complexes **4a** + **LiCl** (THF-d_8), **4b** + LiCl (THF-d_8), **4a** + LiCl (THF-d_8), **4b**, and **4c** and comparison NMR between complex **10** and complex **4a** + LiCl (THF-d_8). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: (J.C.) jacqueline.collin@u-psud.fr; (S.B-L.) sophie.bezzenine@u-psud.fr.

■ ACKNOWLEDGMENTS

We thank CNRS for financial support and MENERS for Ph.D. grants for M.M. and J.Y.

■ REFERENCES

(1) (a) Shibasaki, M.; Sasai, H. *Pure Appl. Chem.* **1996**, *68*, 523−530. (b) Shibasaki, M.; Sasai, H.; Arai, T. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1236−1256. (c) Shibasaki, M.; Yoshikawa, N. *Chem. Rev.* **2002**, *102*, 2187−2209.

(2) (a) Arai, T.; Sasai, H.; Aoe, K.; Okamura, K.; Date, T.; Shibasaki, M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 104−106. (b) Arai, T.; Yamada, Y. M. A.; Yamamoto, N.; Sasai, H.; Shibasaki, M. *Chem.—Eur. J.* **1996**, *2*, 1368−1372.

(3) Iida, T.; Yamamoto, N.; Sasai, H.; Shibasaki, M. *J. Am. Chem. Soc.* **1997**, *119*, 4783−4784.

(4) Chavarot, M.; Byrne, J. J.; Chavant, P. Y.; Vallée, Y. *Tetrahedron: Asymmetry* **2001**, *12*, 1147−1150.

(5) (a) Collin, J.; Daran, J. C.; Olivier, J.; Schulz, E.; Trifonov, A. *Chem.—Eur. J.* **2005**, *11*, 3455−3462. (b) Riegert, D.; Collin, J.; Daran, J. C.; Fillebeen, T.; Schulz, E.; Lyubov, D.; Fukin, G.; Trifonov, A. *Eur. J. Inorg. Chem.* **2007**, 1159−1168. (c) Aillaud, I.; Collin, J.; Duhayon, C.; Guillot, R.; Lyubov, D.; Schulz, E.; Trifonov, A. *Chem.—Eur. J.* **2008**, *14*, 2189−2200. (d) Hannedouche, J.; Collin, J.; Trifonov, A.; Schulz, E. *J. Organomet. Chem.* **2011**, *696*, 255−262.

(6) For various routes to amino alcohols, see: (a) O'Brien, P. *Angew. Chem. Ed. Engl.* **1999**, *38*, 326−329. (b) Bergmeier, S. C. *Tetrahedron* **2000**, *56*, 2561−2576. (c) Ohkuma, T.; Ishii, D.; Takeno, H.; Noyori, R. *J. Am. Chem. Soc.* **2000**, *122*, 6510−6511. (d) Adderley, N. J.; Buchanan, D. J.; Dixon, D. J; Lainé, D. I. *Angew Chem., Int. Ed.* **2003**, *42*, 4241−4244.

(7) (a) Schneider, C. *Synthesis* **2006**, *11*, 3919−3944. (b) Pineshi, M. *Eur. J. Org. Chem.* **2006**, 4979−4988.

(8) For binol/titanium catalysts, see: (a) Kureshy, R. I.; Singh, S.; Khan, N. H.; Abdi, S. H. R.; Suresh, E.; Jasra, R. V. *Eur. J. Chem* **2006**, 1303−1309. (b) Kureshy, R. I.; Singh, S.; Khan, N. H.; Abdi, S. H. R.; Agrawal, S.; Jasra, R. V. *Tetrahedron Lett.* **2006**, *47*, 5277−5279. (c) Hongly, B.; Zhou, J.; Zheng, W.; Yinlong, G.; Tianpa, Y.; Kuiing, D. *J. Am. Chem. Soc.* **2008**, *130*, 10116−10127. For binol/niobium catalysts, see: (d) Arai, K.; Salter, M. M.; Yamashita, Y.; Kobayashi, S. *Angew. Chem., Int. Ed.* **2007**, *46*, 955−957. (e) Arai, K.; Lucarini, S.; Salter, M. M.; Yamashita, Y.; Kobayashi, S. *J. Am. Chem. Soc.* **2007**, *129*, 8103−8111.

(9) For bipyridine/indium catalyst, see: (a) Mai, E.; Schneider, C. *Chem.—Eur. J.* **2007**, 2729−2741. (b) Mai, E.; Schneider, C. *Synlett* **2007**, 2136−2138. (c) Mai, E.; Schneider, C. *ARKIVOC* **2008**, *16*, 216−222. (d) For bipyridine/copper and scandium catalysts, see: Masaya, K.; Takeshi, N.; Kobayashi, S. *Chem. Lett.* **2009**, *38*, 904−905.

(10) For salen/cobalt catalyst, see: Kureshy, R. I.; Prathap, K. J.; Agrawal, S.; Kumar, M.; Khan, N. U.; Abdi, S. R.; Bajaj, H. C. *Eur. J. Org. Chem.* **2009**, 2863−2871.

(11) For a titanium/binolate/water catalyst promoted the enantioselective reaction of 4,4-dimethyl-3,5,8-trioxabicyclo[5.1.0] octane with aliphatic amines, see ref 8c.

(12) Carrée, F.; Gil, R.; Collin, J. *Org. Lett.* **2005**, *7*, 1023−1026.

(13) (a) Martin, M.; Bezzenine-Lafollée, S.; Gil, R.; Collin, J. *Tetrahedron: Asymmetry* **2007**, *18*, 2598−2605. (b) Martin, M.; Bezzenine-Lafollée, S.; Collin, J. *Tetrahedron: Asymmetry* **2010**, *21*, 1722−1729.

(14) For recent examples, see: (a) Estler, F.; Eickerling, G.; Herdtweck, E.; Anwander, R. *Organometallics* **2003**, *22*, 1212−1222. (b) Gribkov, D. V.; Hultzsch, K. C.; Hampel, F. *J. Am. Chem. Soc.* **2006**, *128*, 3748−3759. (c) Ge, S.; Meetsma, A.; Hessen, B.

Organometallics **2008**, *27*, 5339−5346. (d) Stanlake, L. J. E.; Schafer, L. L. *Organometallics* **2009**, *28*, 3990−3998. (e) Lu, E.; Gan, W.; Chen, Y. *Organometallics* **2009**, *28*, 2318−2324.

(15) Wang, B.; Wang, D.; Cui, D.; Gao, W.; Tang, T.; Chen, X.; Jing, X. *Organometallics* **2007**, *26*, 3167−3172.

(16) (a) Aspinall, H. C.; Dwyer, J. L. M.; Greeves, N.; Steiner, A. *Organometallics* **1999**, *18*, 1366−1368. (b) Di Bari, L.; Lelli, M.; Salvadori, P. *Chem.—Eur. J.* **2004**, *10*, 4594−4598. (c) Yamagiwa, N.; Qin, H.; Matsunaga, S.; Shibasaki, M. *J. Am. Chem. Soc.* **2005**, *127*, 13419−13427. (d) Wooten, A. J.; Carroll, P. J.; Walsh, P. J. *J. Am. Chem. Soc.* **2008**, *130*, 7407−7419.

(17) A neutral structure with lithium coordinated to oxygen as found by Shibasaki for an aluminum complex (see ref 2) could be alternatively envisaged.

(18) (a) Kim, Y. S.; Matsunaga, S.; Das, J.; Sekine, A.; Oshima, T.; Shibasaki, M. *J. Am. Chem. Soc.* **2000**, *122*, 6506−6507. (b) Shibasaki, M.; Matsunaga, S. *J. Organomet. Chem.* **2006**, *691*, 2089−2100.

(19) (a) Shibasaki, M.; Kanai, M.; Matsunaga, S.; Kumagai, N. *Acc. Chem. Res.* **2009**, *42*, 1117−1127. For epoxide ring opening by phenolic oxygen nucleophile: (b) Matsunaga, S.; Das, J.; Roels, J.; Vogl, E. M.; Yamamoto, N.; Iida, T.; Yamaguchi, K.; Shibasaki, M. *J. Am. Chem. Soc.* **2000**, *122*, 2252−2260. (c) Iida, T.; Yamamoto, N.; Matsunaga, S.; Woo, H. G.; Shibasaki, M. *Angew. Chem. Int. Ed* **1998**, *16*, 2223−2226. For nitroaldol reaction: (d) Sone, T.; Yamagushi, A.; Matsunaga, S.; Shibasaki, M. *Tetrahedron Lett.* **2008**, *49*, 272−276. For epoxidation: (e) Sone, T.; Yamaguchi, A.; Matsunaga, S.; Shibasaki, M. *J. Am. Chem. Soc.* **2008**, *130*, 10078−10079.

(20) (a) Aspinall, H. C. *Chem. Rev.* **2002**, *102*, 1807−1850. (b) Aspinall, H. C.; Bickley, J. F.; Dwyer, J. L. M.; Greeves, N.; Kelley, R. V.; Steiner, A. *Organometallics* **2000**, *19*, 5416−5423.

(21) Yamagiwa, N.; Matsunaga, S.; Shibasaki, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 4493−4497.

(22) To check that the ratio of yttrium/binaphthol in **4a** is 1:2 rather than 1:3, we compared the ^{13}C NMR spectra of **4** alone and after addition of 1 or 3 equiv of bis-lithium binaphtholate. A signal characteristic of this lithium salt (137 ppm) was observed only when 3 equiv of bis-lithium binaphtholate was added. This supports the structure proposed for **4a**. Conversely, Shibasaki in a similar experiment observed the signal characteristic of the lithium salt after the addition of 1 equiv of bis-lithium binaphtholate to YLB.

(23) Horiuchi, Y.; Gnanadesikan, V.; Oshima, T.; Masu, H.; Katagiri, K.; Sei, Y.; Yamaguchi, K.; Shibasaki, M. *Chem.—Eur. J.* **2005**, *11*, 5195−5204.

(24) The ^1H spectra of **4a** and **4b** in $CDCl_3$ or C_6D_6 showed nonresolved signals which might be indicative of dimeric or polymeric structures.

(25) (a) Sun, J.; Yuan, F.; Yang, M.; Pan, Y.; Zhu, C. *Tetrahedron Lett.* **2009**, *50*, 548−551. (b) Sun, J.; Yang, M.; Yuan, F.; Jia, X.; Pan, Y.; Zhu, C. *Adv. Synth. Catal.* **2009**, *351*, 920−930. (c) Yang, M.; Zhu, C.; Yuan, F.; Huang, Y.; Pan, Y. *Org. Lett.* **2005**, *7*, 1927−1930.

(26) Liu, H.; Liu, Y.; Liu, M.; Chen, C.; Xi, F. *Tetrahedron Lett.* **2001**, *42*, 7083−7086.

(27) Zimmer, R.; Schefzig, L.; Peritz, A.; Dekaris, V.; Reissig, H. -U. *Synthesis* **2004**, *9*, 1439−1445.

(28) Barili, P. L.; Berti, G.; Mastrorilli, E. *Tetrahedron* **1993**, *49*, 6263−6276.

(29) Ji, H.; Stanton, B. Z.; Igarashi, J.; Li, H.; Martásek, P.; Roman, L. J.; Poulos, T. L.; Silverman, R. B. *J. Am. Chem. Soc.* **2008**, *130*, 3900−3914.