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Asymmetric Hydrogenation Hot Paper

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Rhodium-Catalyzed Asymmetric Hydrogenation of All-Carbon Aromatic Rings

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Abstract: Compared with heteroarenes, homogeneous asymmetric hydrogenation of all-carbon aromatic rings is a longstanding challenge in organic synthesis due to the strong aromaticity and difficult enantioselective control. Herein, we report the rhodium/diphosphine-catalyzed asymmetric hydrogenation of all-carbon aromatic rings, affording a series of axially chiral cyclic compounds with high enantioselectivity through desymmetrization or kinetic resolution. In addition, the central-chiral cyclic compounds were also obtained by asymmetric hydrogenation of phenanthrenes bearing a directing group. The key to success is the introduction of chiral diphosphine ligands with steric hindrance and strong electron-donating properties. The axially chiral monophosphine ligands could be obtained by simple conversion of the hydrogenation products bearing the phosphine atom.

Introduction

In the past few decades, considerable progress has been made in the field of homogeneous asymmetric hydrogenation (AH) of aromatic compounds, especially heteroarenes,[1–3] which provided an atom-economical, straightforward and efficient route to the construction of the corresponding chiral cyclic compounds, and laid the good foundation for its application in pharmaceutical and agrochemical synthesis.[4] Compared with heteroarenes, the development of homogeneous AH of all-carbon aromatic compounds was tardier due to the stronger aromaticity and the more difficult enantioselective control.[5–10] All the same, using the chiral *N*-heterocyclic carbene-ruthenium catalyst (Ru-NHC), the Glorius group reported the first site-selective AH of the carbocyclic ring of 6-alkyl-2,3-diphenylquinoxalines, giving the chiral 5,6,7,8-tetrahydroquinoxalines with up to 88 % ee.[6] Subsequently, Kuwano and co-workers completed the AH of carbocyclic rings of quinolines and isoquinolines with up to 82 % ee by using the Ru-PhTrap catalyst.[7b,c] In 2012, the Ru-PhTrap catalyzed AH of naphthalenes was developed by the Kuwano group, which was the first example of AH of aromatics without heteroatoms.[7a] Recently, AH of 9,10-disubstituted phenanthreneamines has been realized for the synthesis of chiral amines with two consecutive stereocenters through the efforts of our group.[8] All in all, only very limited examples of homogeneous AH of aromatic carbocyclic compounds have been reported which mainly focused on the ruthenium catalysts, and the substrate scope was limited to activated carbocyclic aromatic rings such as carbocyclic rings of heteroarenes and carbocyclic rings bearing heteroatoms (Figure 1A).

In the field of hydrogenation of arenes, the homogeneous catalysis showed higher enantioselectivity and the heterogeneous catalysis exhibited higher reactivity. Very recently, combining the advances in both fields of catalysis, an elegant cooperative homogeneous and heterogeneous catalytic AH of aromatic carbocyclic compounds has been reported (Figure 1B). Glorius and co-workers discovered the complete hydrogenation of benzofurans could be achieved by using a distinctive combination of the chiral homogeneous Ru-NHC complex and the in situ activated heterogeneous rhodium catalyst.[9] Soon afterward, a single rhodium complex, as both homogeneous and heterogeneous catalyst precursor was successfully used for AH of the vinylarenes by Andersson group.[10] In the above mentioned processes, homogeneous asymmetric hydrogenation of furans or enamides was the enantio-determining step; heterogeneous hydrogenation of carbocyclic aromatic ring was a diastereoselective process. In a word, despite the success of AH of activated carbocyclic aromatic rings, the AH of all-carbon aromatic rings has been rarely reported, especially with single homogeneous systems. Therefore, the development of efficient chiral catalytic systems and extension of substrate scope of all-carbon aromatic rings remains a longstanding challenge in asymmetric hydrogenation.

For the sake of accomplishing AH of all-carbon aromatic rings, we reviewed the properties of some familiar aromatic rings. Comparing the aromaticity of simple all-carbon aromatic rings, benzene, naphthalene, phenanthrene, and anthracene, with the increase in the number of fused carbon rings, the average delocalization energy decreased gradually. Therefore, the polycyclic aromatic hydrocarbons (PAHs)

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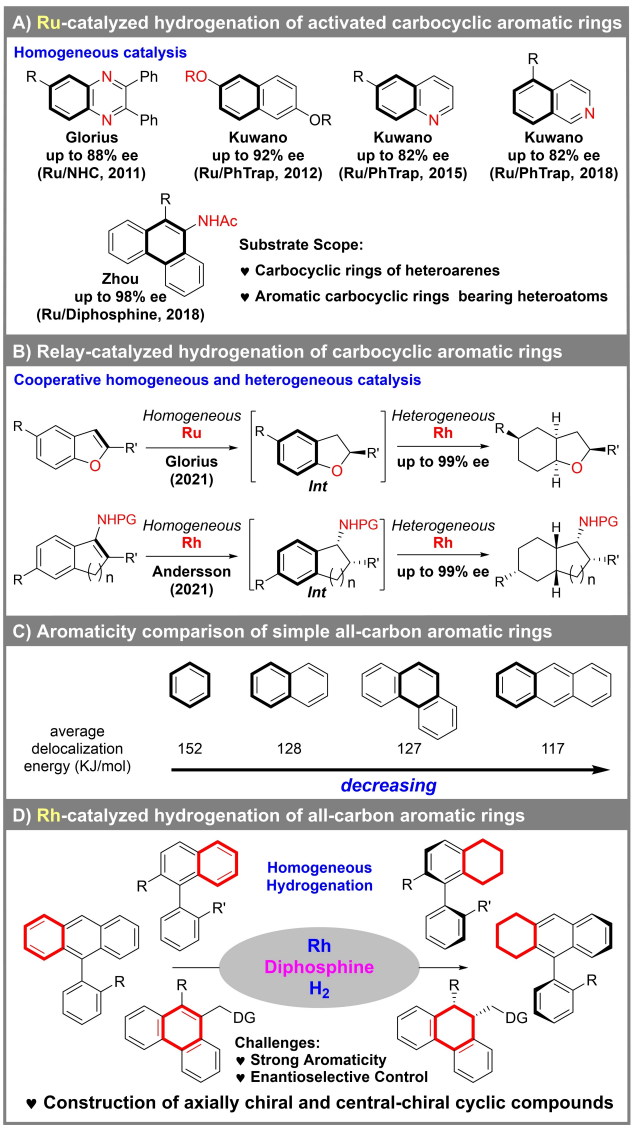

Figure 1. A) Ru-catalyzed hydrogenation of activated carbocyclic aromatic rings. B) Relay-catalyzed hydrogenation of carbocyclic aromatic rings. C) Aromaticity comparison of all-carbon aromatic rings. D) Rh-catalyzed asymmetric hydrogenation of all-carbon aromatic rings.

usually have slightly weaker aromaticity, which provides a good point for us to solve this challenge (Figure 1C).[11] As far as PAHs were concerned, aromatic carbocycles with substituents were more difficult to hydrogenate compared with the unsubstituted ones.[5f] In addition, to facilitate the determination of the enantiopurity through chiral high-performance liquid chromatography (HPLC), we chewed over installing polar groups away from the reaction site on the substrates.

Rhodium/diphosphine systems showed excellent activity and enantioselectivity in the AH of C=C bonds, and the diversity of diphosphine ligands provided the possibility to explore new asymmetric reactions.[12] Herein, we reported the first rhodium/diphosphine catalyzed AH of all-carbon aromatic rings, anthracenes, and naphthalenes, affording the axially chiral biaryl compounds by desymmetrization or kinetic resolution.[13] Meanwhile, central-chiral cyclic compounds were also obtained by AH of phenanthrenes bearing a directing group (Figure 1D).

Results and Discussion

Rh-Catalyzed Asymmetric Hydrogenative Desymmetrization of Anthracenes

Among the simple all-carbon aromatic rings (Figure 1C), the average delocalization energy of anthracene is the lowest. Thus, the hydrogenative desymmetrization of anthracenes was attempted first. We started our investigation with *N*-(2-(anthracen-9-yl)phenyl)-4-methylbenzenesulfonamide **1a** as the model substrate to explore the optimal conditions. Diphosphine ligands played a crucial role in the reactivity and enantioselectivity. To our surprise, ligand SynPhos (**L1**) could give the desired hydrogenation product **2a** with 60 % yield and 29.9 % ee (Table 1, entry 1), which inspired us to further screen the commercially available chiral diphosphine ligands such as MeO-Biphep (**L2**), Me-DuPhos (**L3**) and C3-TunePhos (**L4**) (entries 2–4). Regrettably, the MeO-Biphep (**L2**) showed moderate ee albeit with high reactivity. Other ligands also failed to improve the enantioselectivities. Subsequently, a series of ligands with steric hindrance and strong electron-donating properties, originally developed by Tang's group,[14] was tested (entries 5–7). By increasing the steric hindrance near the phosphorus centers, the enantioselectivity increased significantly. When **L7** WingPhos with anthracenyl groups, providing a deep chiral pocket, was applied, the desired hydrogenation product **2a** was obtained in 77 % yield and 89.3 % ee (entry 7). Screening of other rhodium precursors (entries 8 and 9) showed that $Rh(COD)_2SbF_6$ provided the best result in terms of yield (95 %) and ee value (91.9 % ee).

The solvent screening showed that chlorinated solvents, particularly dichloromethane, could achieve an excellent 95.2 % of enantioselectivity, while other solvents failed to get satisfactory results (entries 10–14). To facilitate the isolation of the product, we increased the substrate scale and observed 98.1 % ee (entry 15). The observation of a higher ee might ascribe to a process of kinetic resolution as the naphthalene ring of the product could be further hydrogenated. As expected, a shorter reaction time (5 h) could avoid the formation of the over-hydrogenation side product (entry 16). Thus, the optimal conditions were determined to involve the use of substrate **1a** (0.15 mmol), H_2 (600 psi), $Rh(COD)_2SbF_6$ (5.0 mol%), WingPhos (5.5 mol%), and dichloromethane (6 mL) at 30 °C for 5 h.

With the optimized conditions in hand, the scope of substrates with various groups on the nitrogen or different substituents on the benzene ring was tested first. As shown in Scheme 1, a series of substrates with different sulfonyl or acyl groups on the nitrogen smoothly underwent hydrogenative desymmetrization, giving the axially chiral compounds in excellent yields and good to high ee values (**2a**–**2e**). When the substituent on the nitrogen was acetyl, the yield did not reduce, but a slight drop in the enantioselectivity was observed (**2d**). When using methyl-protected tertiary amine **1f** as the starting

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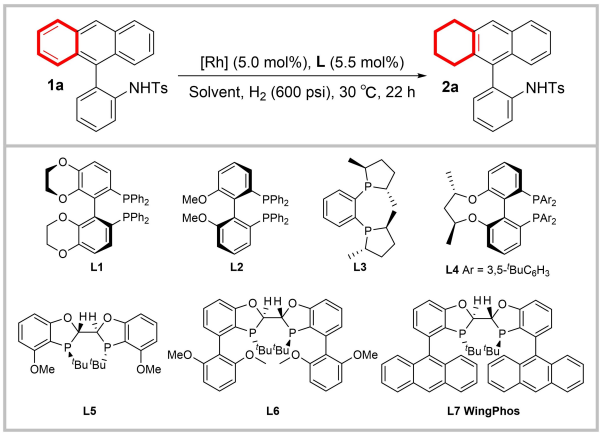
Table 1: Condition optimization for the hydrogenative desymmetrization of anthracenes.



Entry[a]	Ligand	[Rh]	Solvent	Yield %[b]	ee %[c]
1	**L1**	$Rh(COD)_2BF_4$	DCE	60	29.9
2	**L2**	$Rh(COD)_2BF_4$	DCE	94	31.4
3	**L3**	$Rh(COD)_2BF_4$	DCE	61	9.2
4	**L4**	$Rh(COD)_2BF_4$	DCE	24	31.8
5	**L5**	$Rh(COD)_2BF_4$	DCE	74	29.4
6	**L6**	$Rh(COD)_2BF_4$	DCE	81	71.6
7	**L7**	$Rh(COD)_2BF_4$	DCE	77	89.3
8	**L7**	$Rh(COD)_2SbF_6$	DCE	95	91.9
9	**L7**	$Rh(COD)_2OTf$	DCE	26	91.1
10	**L7**	$Rh(COD)_2SbF_6$	EA	<5	–
11	**L7**	$Rh(COD)_2SbF_6$	THF	10	72.5
12	**L7**	$Rh(COD)_2SbF_6$	Toluene	10	2.9
13	**L7**	$Rh(COD)_2SbF_6$	DCM	98	95.2
14	**L7**	$Rh(COD)_2SbF_6$	$CHCl_3$	40	94.7
15[d]	**L7**	$Rh(COD)_2SbF_6$	DCM	90	98.1
16[e]	**L7**	$Rh(COD)_2SbF_6$	DCM	95[f]	95.0

[a] Reactions were carried with **1a** (0.05 mmol), [Rh] (5.0 mol%), **L** (5.5 mol%), solvent (2 mL), H_2 (600 psi), 30 °C, 22 h. [b] Yield was measured by analysis of ^{1}H-NMR spectra. [c] Determined by chiral HPLC. [d] Reactions were carried with **1a** (0.15 mmol), solvent (6 mL), 22 h. [e] Reactions were carried with **1a** (0.15 mmol), solvent (6 mL), 5 h. [f] Isolated yield. DCE denotes 1,2-dichloroethane. EA denotes ethyl acetate. THF denotes tetrahydrofuran. DCM denotes dichloromethane.

material, no loss of yield and ee value was observed (**2f**). The influence of methyl at different positions of the benzene ring was investigated, and all of them gave excellent yields and ee values (**2g**–**2l**). Furthermore, the electron-withdrawing groups such as chlorine and fluorine at the 5-position of the benzene ring were well tolerated with high yields and enantioselectivities (**2m** and **2n**).

Our protocol could also be extended to 2-(anthracen-9-yl)phenol (**3a**) and its derivatives (**3b**–**3m**). It needs to be noted that most of these compounds showed loftier reactivity than 2-(anthracen-9-yl)aniline derivatives (**1a**–**1n**) and we were able to perform the hydrogenation with lower catalyst loading (2 mol%, Scheme 2). The hydrogenative desymmetrization of 2-(anthracen-9-yl)phenol (**3a**) could proceed smoothly to deliver the product with 97 % yield and 44 % ee. To further improve the enantioselectivity, we attempted multifarious groups on the oxygen atom such as tosyl, acetyl, trifluoromethanesulfonyl, benzoyl, and *t*-butyloxycarbonyl group. To our delight, these substrates could afford the respective products (**4b**–**4f**) in excellent yields and enantioselectivities. Electronically distinct substituents at the benzene ring were tolerated, attaining the desired products (**4g**–**4i**) in good results. The absolute configuration of **4c** was unambiguously assigned by X-ray analysis.[17] To further understand the factors that affect the enantioselectivity of the reaction, the sulfonyl or acyl groups were substituted by alkyl groups with different steric hindrances. As expected, the greater the steric hindrance, the higher the enantioselectivity and without loss of yield (**4j**–**4m**). Compared with these ether compounds, the products with sulfonyl or acyl groups show better enantioselectivities, which is most likely due to the coordination ability of the carbonyl or sulfonyl groups. Rejoicingly, hydrogenation products without any heteroatom at the 2-position of the benzene ring (**4n**–**4o**) were prepared in high yields and moderate enantiomeric excesses. This provided a way of AH of all-carbon aromatic rings without heteroatoms.

To highlight synthetic usefulness, this method was examined in the hydrogenative desymmetrization of phosphine oxide derivatives (**5a**–**5d**) for the synthesis of axially chiral phosphorus-containing compounds (Scheme 3). Pleasingly, with the phosphine oxide **5a**, the hydrogenation product **6a** was obtained with 96 % yield and 88 % ee. After recrystalliza-

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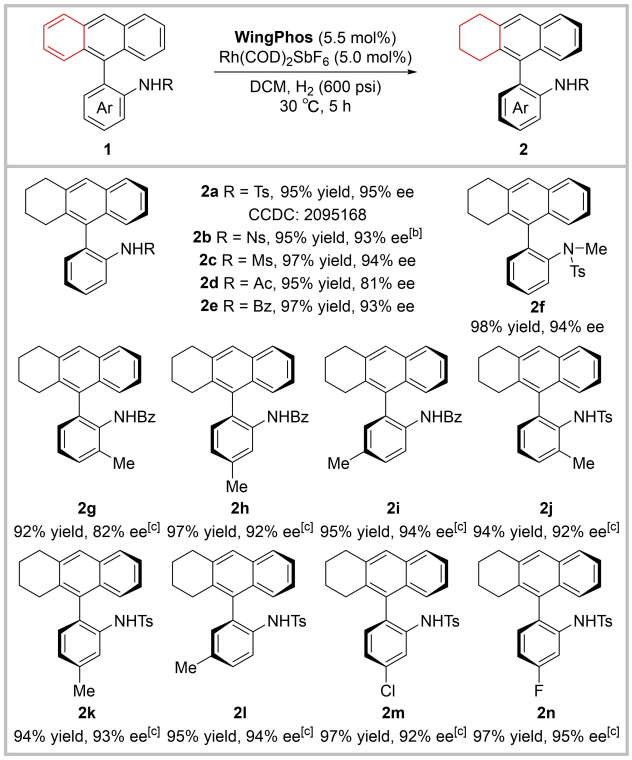
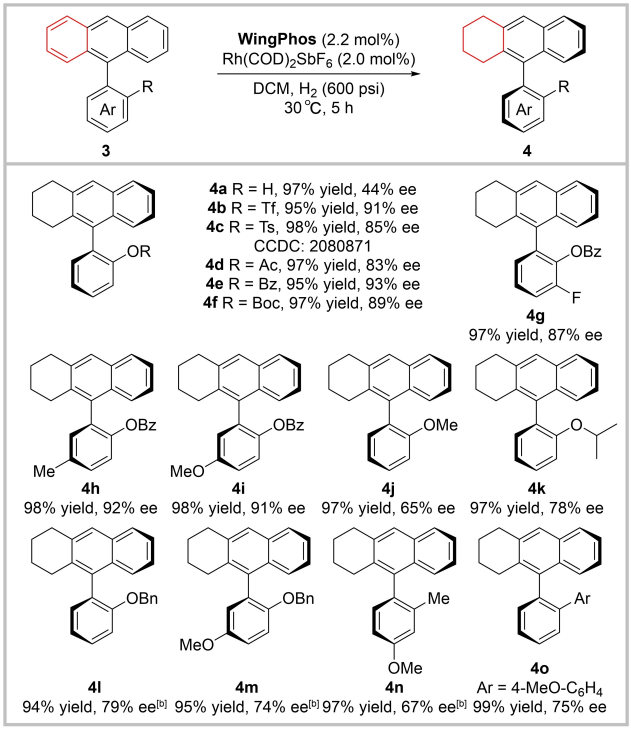
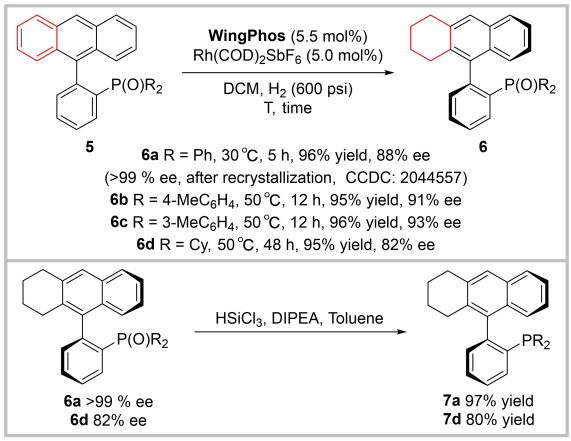


Scheme 1. Substrate scope of desymmetrization: anthracenes bearing nitrogen atom.[a]
[a] Conditions: **1** (0.15 mmol), $Rh(COD)_2SbF_6$ (5.0 mol%), **WingPhos** (5.5 mol%), DCM (6 mL), H_2 (600 psi), 30 °C, 5 h. [b] The reaction time was extended to 12 h. [c] The reaction time was reduced to 45 min.



Scheme 2. Substrate scope of desymmetrization: anthracenes bearing oxygen atom containing-, alkyl- or aryl- substituents.[a]
[a] Conditions: **3** (0.15 mmol), $Rh(COD)_2SbF_6$ (2.0 mol%), **WingPhos** (2.2 mol%), DCM (6 mL), H_2 (600 psi), 30 °C, 5 h. [b] $Rh(COD)_2SbF_6$ (5.0 mol%) and **WingPhos** (5.5 mol%) were used.

tion, **6a** was upgraded to >99% ee, then its absolute configuration was determined by X-ray diffraction analysis.[17] The reaction still yielded excellent results after the introduction of a methyl group on the benzene ring (**6b** and **6c**). When the phenyl group was replaced by the cyclohexyl group (**6d**), 82% ee could be obtained. A significant drop in the reactivity was observed because of the large steric hindrance. As a further application of the products, hydrogenation products **6a** and **6d** could be reduced with trichlorosilane to give the axially chiral monophosphine ligands **7a** and **7d** in 97% and 80% yields, respectively, which might possess potential application in asymmetric catalysis.



Scheme 3. Substrate scope of desymmetrization: anthracenes bearing phosphine atom and synthesis of chiral monophosphine ligands.

Rh-Catalyzed Hydrogenation of Naphthalenes through Kinetic Resolution

In the process of the hydrogenative desymmetrization of anthracenes, the emergence of over-hydrogenation products provided an opportunity to explore AH of naphthalenes, which had a stronger aromaticity and a higher delocalization energy. Inspired by our group's previous work on the kinetic resolution of axially chiral 5- or 8-substituted quinolines,[15] we tried to explore the kinetic resolution of 1,2-disubstituted naphthalenes through hydrogenation to construct axially chiral cyclic compounds.

To validate the feasibility of the proposed process, we selected 2-(2-methylnaphthalen-1-yl)phenyl benzoate (*rac*)-**8a** with the benzoyl group as the model substrate for the optimization of reaction conditions (Table 2). We commenced our studies by assessing AH using $Rh(COD)_2SbF_6$/WingPhos (**L7**) as the catalyst in tetrahydrofuran (THF) at 30 °C for 5 h. Disappointedly, (*rac*)-**8a** converted entirely (Table 2, entry 1). Then, we examined the effect of solvents such as toluene, ethyl acetate (EA), 1,2-dichloroethane (DCE), and dichloromethane

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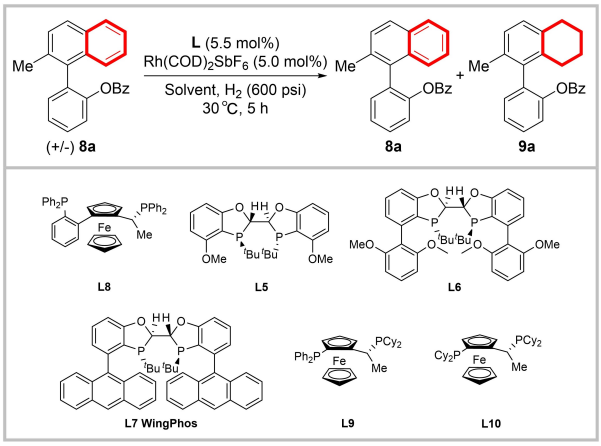
Table 2: Optimization of the reaction conditions for the kinetic resolution of naphthalenes.



Entry[a]	Solvent	Ligand	Conv. %[b]	**8a** ee %[c]	**9a** ee %[c]	s[e]
1	THF	**L7**	>95	–	–	–
2	Toluene	**L7**	<5	–	–	–
3	EA	**L7**	<5	–	–	–
4	DCE	**L7**	<5	–	–	–
5	DCM	**L7**	31[d]	39.6	88.3	24
6	DCM	**L5**	<5	–	–	–
7	DCM	**L6**	62[d]	64.3	38.9	4
8	DCM	**L8**	>95	–	–	–
9	DCM	**L9**	35[d]	15.3	27.8	2
10	DCM	**L10**	>95	–	–	–
11[f]	DCM	**L7**	18[d]	20.2	89.3	22

[a] Reactions were carried with **8a** (0.10 mmol), $Rh(COD)_2SbF_6$ (5.0 mol%), **L** (5.5 mol%), solvent (2 mL), H_2 (600 psi), 30 °C, 5 h. [b] Determined by ^{1}H-NMR. [c] Determined by chiral HPLC. [d] Calculated conversion: Conv. = $ee_{8a}/(ee_{8a}+ee_{9a})$. [e] Calculated selectivity factors: $s = \ln[(1-C)(1-ee_{8a})]/\ln[(1-C)(1+ee_{8a})]$. [f] $Rh(COD)_2BF_4$ (5.0 mol%) was used. DCE denotes 1,2-dichloroethane. EA denotes ethyl acetate. THF denotes tetrahydrofuran. DCM denotes dichloromethane.

(DCM) (entries 2–5). To our delight, the reaction proceeded successfully in dichloromethane and afforded the desired product **9a** in 88.3 % ee, albeit with only moderate ee (39.6 %) of the recovered starting material **8a** (entry 5). After calculation, a selectivity factor[16] of 24 was obtained. Encouraged by this, an exhaustive optimization study was done subsequently with different electron-rich bisphosphine ligands (entries 6–10). It was upset to find that the kinetic resolution did not proceed with **L5** as the ligand (entry 6), and was out of control with **L8** and **L10** which was most likely due to the electron-rich property with the skeleton of ferrocene (entries 8 and 10). Other ligands **L6** and **L9** also failed to achieve better results (entries 7 and 9). $Rh(COD)_2BF_4$ as the precursor instead of the $Rh(COD)_2SbF_6$ could get the similar result ($s = 22$) (entry 11). To sum up the above results, the optimal conditions were determined as: $Rh(COD)_2SbF_6$ (5.0 mol%), WingPhos (5.5 mol%), H_2 (600 psi) and DCM (2 mL) at 30 °C for 5 h.

The generality of the hydrogenative kinetic resolution of 1,2-disubstituted naphthalenes was then surveyed (Table 3). When the reaction time was extended to 10 hours, the optical purity of starting material **8a** could reach 91 % ee with the same *s* factor (entry 1). Then, a variety of substituents on the benzoyl groups were investigated. Both electron-donating and electron-withdrawing substituents gave excellent selectivities ($s = 23$–26) (entries 2–4). More interestingly, *s* factor increased slightly when the benzoyl group was replaced by the tosyl group (entry 5). Tosyl group was fixed as the optimal substituent on the benzene ring, and the substituents on the naphthalene were examined. When the methyl was replaced by the methoxy, only moderate selectivity could be achieved ($s = 11$) (entry 6). The kinetic resolution of substrate **8g**, substituent-free at the 2-position of the naphthalene, gave moderate selectivity ($s = 16$), and the recovered starting material **8g** was isolated with 37 % yield and 97 % ee (entry 7).

In addition, the effect of the position of substituents on the benzene ring was tested. For the methyl, irrespective of the *ortho*, *meta*, or *para* position of the tosyl group, high selectivity factors were obtained (entries 8–10). When methyl was at the *ortho* position of the tosyl group, increasing the steric hindrance, *s* factor was the highest ($s = 39$). Moreover, *para*-substituted **8k** and **8l** and *ortho*-substituted **8m** and **8n** gave good selectivities regardless of electron-donating or electron-withdrawing substituents (entries 11–14). Excitedly, the starting material **8o** containing chlorine was recovered in 45 % yield with 99 % ee, and the hydrogenation product **9o** was isolated in 55 % yield with 82 % ee; for this substrate, $s = 52$. Finally, substrate **8p** bearing tosyl group on the nitrogen could be accessed with high enantiopurity (95 % ee, 40 % yield, $s = 17$). Its corresponding hydrogenation product **9p** was obtained with 66 % ee in 59 % yield (entry 16). The crystals of the **8m** and

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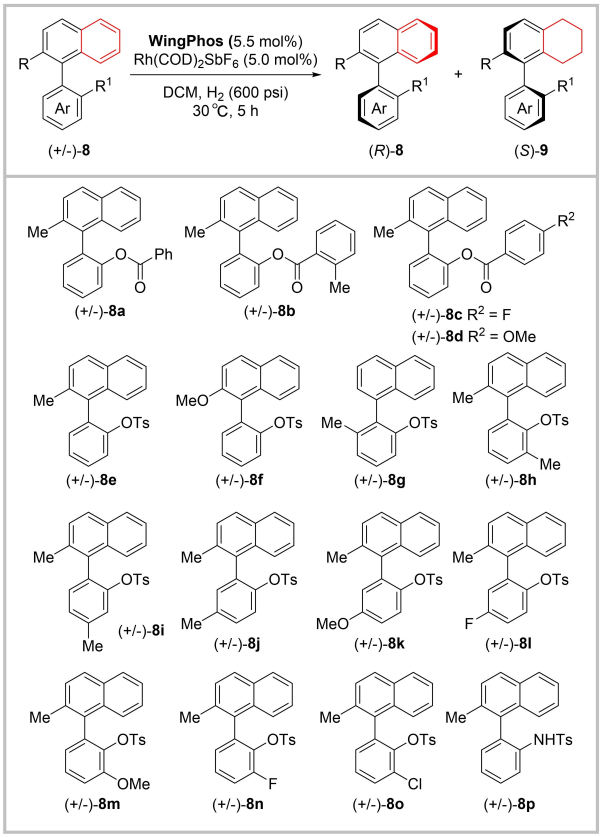
Table 3: Substrate scope of kinetic resolution: naphthalenes.



Entry[a]	(±)-8	9	8 ee %[b]	8 Yield %[c]	9 ee %[b]	9 Yield %[c]	s[d]
1[e]	**8a**	**9a**	91	46	77	52	24
2	**8b**	**9b**	82	48	80	50	23
3[e]	**8c**	**9c**	97	42	71	58	24
4[e]	**8d**	**9d**	96	43	74	55	26
5	**8e**	**9e**	95	44	77	55	28
6[e]	**8f**	**9f**	84	43	63	56	11
7	**8g**	**9g**	97	37	60	62	16
8	**8h**	**9h**	96	46	82	53	39
9	**8i**	**9i**	74	52	81	47	21
10	**8j**	**9j**	92	46	80	53	29
11[e]	**8k**	**9k**	99	37	60	62	19
12	**8l**	**9l**	96	43	73	57	24
13	**8m**	**9m**	99	40	69	59	27
14	**8n**	**9n**	97	45	80	55	37
15	**8o**	**9o**	99	45	82	55	52
16	**8p**	**9p**	95	40	66	59	17

[a] Reactions were carried with **8** (0.20 mmol), $Rh(COD)_2SbF_6$ (5.0 mol%), **L** (5.5 mol%), DCM (2 mL), H_2 (600 psi), 30 °C, 5 h. [b] Determined by chiral HPLC. [c] Isolated yield. [d] Calculated conversion and selectivity factors: conv. $= ee_8/(ee_8+ee_9)$ $s = \ln[(1-C)(1-ee_8)]/\ln[(1-C)(1+ee_8)]$. [e] The reaction time was extended to 10 h.

8p could be used to determine the absolute configuration of the recovered starting materials to be *R*. Thus, the absolute configuration of the corresponding hydrogenation products **9m** and **9p** could be assigned as *S*.[17]

Rh-Catalyzed Asymmetric Hydrogenation of Phenanthrenes

After we completed Rh-catalyzed desymmetrization of anthracenes and the kinetic resolution of naphthalenes to construct axially chiral compounds, further expanding the substrate range of this system became the next goal. From the previous analysis, we noticed that naphthalene and phenanthrene have similar average delocalization energy. Considering that the introduction of a directing group in all-carbon aromatic rings

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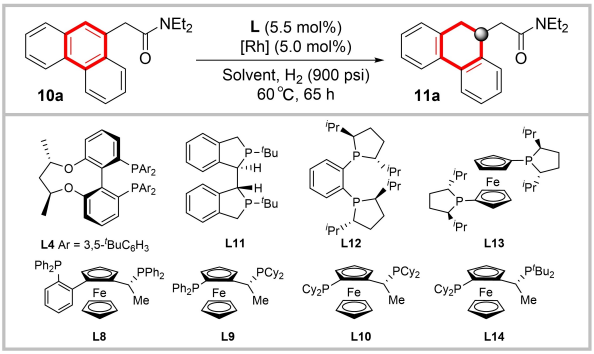
should improve the coordination ability (an increase of both reactivity and enantioselectivity), the rhodium-catalyzed AH of phenanthrenes bearing a directing group might be realized for the construction of central-chiral cyclic compounds.

Our studies began by investigating the hydrogenation of *N*,*N*-diethyl-2-(phenanthren-9-yl)acetamide **10a** with JosiPhos **L10** and bis(1,5-cyclooctadiene)rhodium hexafluoroantimonate as the catalyst in the presence of different solvents (Table 4). Regretfully, methanol, and chloroform gave no conversion (entries 1 and 2). Using toluene as solvent, good enantioselectivity (89.0 % ee) was observed albeit with poor conversion (21 % conversion) (entry 3). With further optimization of the solvents, we found that tetrahydrofuran and ethyl acetate provided both high activities and enantioselectivities (88.4 % ee, 88 % conversion, and 90.7 % ee, 97 % conversion) (entries 4 and 5). Due to the slightly better results, ethyl acetate was chosen as the optimal solvent. Subsequently, changing reaction conditions by varying ligands did not improve activities and enantioselectivities markedly (entries 6–8). Other electron-rich diphosphine ligands based on the ferrocene skeleton were further investigated. Although the desired product **11a** was obtained with high conversion by using **L13** and **L8** (97 % and 93 % conversion), the enantioselectivities decreased (entries 9 and 10). Compared with ligand **L10**, when dicyclohexyl was replaced by diphenyl, the activity and enantioselectivity dropped simultaneously, due to the decrease of steric hindrance and electron-donating ability of the ligand (48 % conversion, 77.7 % ee) (entry 11). Inspired by this, we tried to use *tert*-butyl with greater steric hindrance instead of cyclohexane to improve the enantioselectivity and maintain the activity. However, the increase in enantioselectivity was accompanied by a decrease in conversion (50 % conversion, 94.9 % ee) (entry 12). Changing the catalyst precursor failed to achieve better results (27 % conversion, 69.4 % ee) (entry 13). Thus, we chose entry 5 as our optimized conditions to study the substrate scope.

The optimized reaction conditions were applied to test the reactivity of various 9-substituted phenanthrenes **10**, as summarized in Scheme 4. Methyl, ethyl, and allyl, as substituents on amides, worked well to furnish **11a–11c** with excellent yields and enantioselectivities. It was worth mentioning that the double bonds of allyl group were also reduced. For the scope of the cyclic amides, we tested five- and six-membered cyclic amides, and the hydrogenation proceeded smoothly to give products **11d** and **11e** with satisfactory results (96 % yield, 91 % ee, and 98 % yield, 86 % ee, respectively). Replacing one of the ethyls with a phenyl led to product **11f** in 97 % yield and 90 % ee with longer time and higher temperature than **11a–c** and **11e**. We speculated that the introduction of phenyl passivated the directing group, resulting in the decrease of reactivity.

Additionally, the influence of the position of methyl on the aromatic ring was also screened. There was a marginal effect on the yields of hydrogenation products **11g–11j**. Some fluctuations in enantioselectivity appeared when the methyl

Table 4: Optimization of the reaction conditions for the hydrogenation of phenanthrene.



Entry[a]	Solvent	Ligand	[Rh]	Conv. %[b]	ee %[c]
1	MeOH	**L10**	$Rh(COD)_2SbF_6$	<5	–
2	$CHCl_3$	**L10**	$Rh(COD)_2SbF_6$	<5	–
3	Toluene	**L10**	$Rh(COD)_2SbF_6$	21	89.0
4	THF	**L10**	$Rh(COD)_2SbF_6$	88	88.4
5	EA	**L10**	$Rh(COD)_2SbF_6$	97	90.7
6	EA	**L4**	$Rh(COD)_2SbF_6$	<5	-
7	EA	**L11**	$Rh(COD)_2SbF_6$	17	87.0
8	EA	**L12**	$Rh(COD)_2SbF_6$	>95	83.3
9	EA	**L13**	$Rh(COD)_2SbF_6$	97	59.6
10	EA	**L8**	$Rh(COD)_2SbF_6$	93	65.6
11	EA	**L9**	$Rh(COD)_2SbF_6$	48	77.7
12	EA	**L14**	$Rh(COD)_2SbF_6$	50	94.9
13	EA	**L10**	$Rh(COD)_2BF_4$	27	69.4

[a] Reactions were carried with **10a** (0.10 mmol), [Rh] (5.0 mol %), **L** (5.5 mol %), solvent (2 mL), H_2 (900 psi), 60 °C, 65 h. [b] Determined by analysis of ^{1}H-NMR spectra. [c] Determined by chiral HPLC. THF denotes tetrahydrofuran. EA denotes ethyl acetate.

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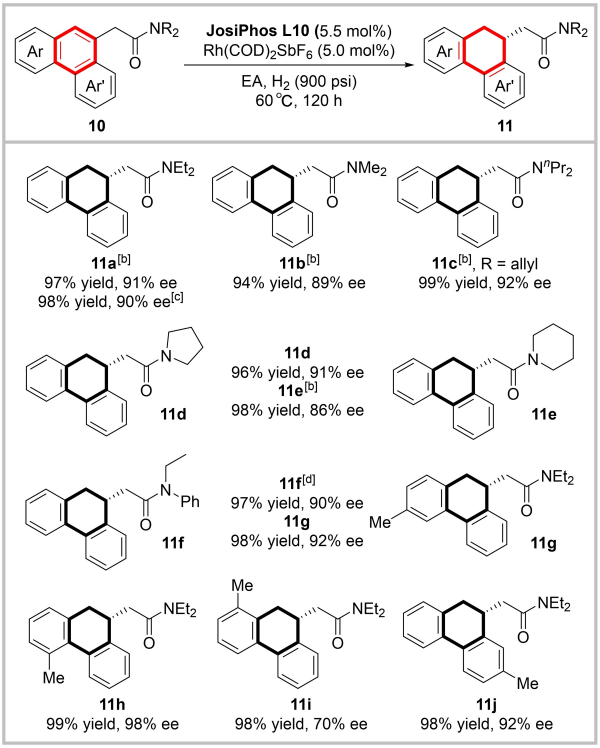
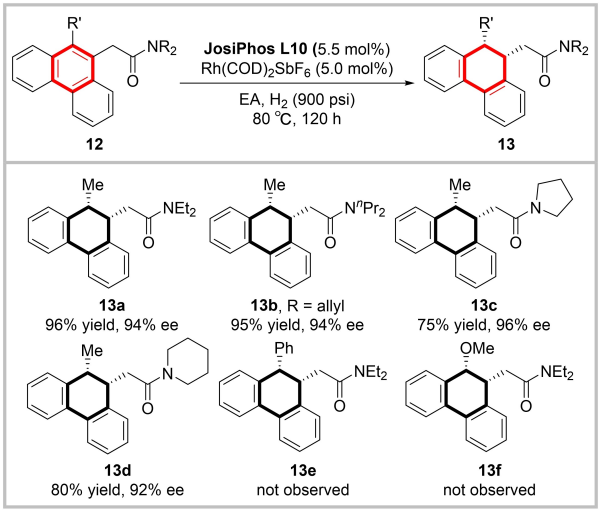


Scheme 4. Substrate scope: 9-substituted phenanthrenes.[a] [a] Conditions: **10** (0.20 mmol), $Rh(COD)_2SbF_6$ (5.0 mol%), **L10** (5.5 mol%), EA (2 mL), H_2 (900 psi), 60 °C, 120 h. [b] The reaction time was reduced to 65 h. [c] **10a** (2.0 mmol) was used. [d] The temperature was raised to 80 °C.

group was on the aromatic ring far away from the directing group. When methyl was installed at the 4-position of phenanthrene, the enantioselectivity increased remarkably (**11h**, 98 % ee). The enantioselectivity decreased (**11i**, 70 % ee) when methyl was installed at the 1-position of phenanthrene. The AH of **10a** could be performed on the 2.0 mmol scale to afford **11a** in 98 % yield and 90 % ee without loss of reactivity and enantioselectivity, showing the scalability of this methodology.

The next step of scope studies focused on the more challenging asymmetric hydrogenation of 9,10-disubstituted phenanthrenes (Scheme 5). Gratifyingly, when *N*,*N*-diethyl-2-(10-methylphenanthren-9-yl)acetamide **12a** was used as the model substrate, the desired product **13a** could be obtained with high enantioselectivity under the standard conditions, although the starting material was not fully converted. Then the temperature was raised to 80 °C, and the desired product **13a** was obtained with 96 % yield and 94 % ee. After adjusting the optimal conditions, the influence of the substituents on the amides was investigated. As before, when the substituent was allyl, the hydrogenation proceeded on an even keel with double bonds of allyl hydrogenation product **13b** in 95 % yield and 94 % ee. In the case of cyclic amides **13c** and **13d**, a slight decrease in the yields was observed, while the enantioselectivity was not affected. Unfortunately, the desired products were not observed when methyl was replaced by phenyl or methoxy.



Scheme 5. Substrate scope: 9,10-disubstituted phenanthrenes.[a] [a] Conditions: **12** (0.20 mmol), $Rh(COD)_2SbF_6$ (5.0 mol%), **L10** (5.5 mol%), EA (2 mL), H_2 (900 psi), 80 °C, 120 h.

Conclusion

In conclusion, we have reported the first rhodium/diphosphine catalyzed asymmetric hydrogenation of all-carbon aromatic rings, affording a series of axially chiral cyclic compounds with high enantioselectivity through desymmetrization or kinetic resolution. Meanwhile, the central-chiral cyclic compounds were also obtained by asymmetric hydrogenation of 9-substituted and 9,10-disubstituted phenanthrenes bearing a directing group. The key to success is the introduction of chiral diphosphine ligands with steric hindrance and strong electron-donating properties. The synthetic utility was demonstrated by the synthesis of axially chiral monophosphine ligands by simple conversion of the hydrogenation products bearing the phosphine atom. Further studies on the more challenging asymmetric hydrogenation of naphthalenes and benzenes are ongoing.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information of this article.

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Keywords: All-Carbon Aromatic Rings · Asymmetric Hydrogenation · Desymmetrization · Kinetic Resolution · Rhodium

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