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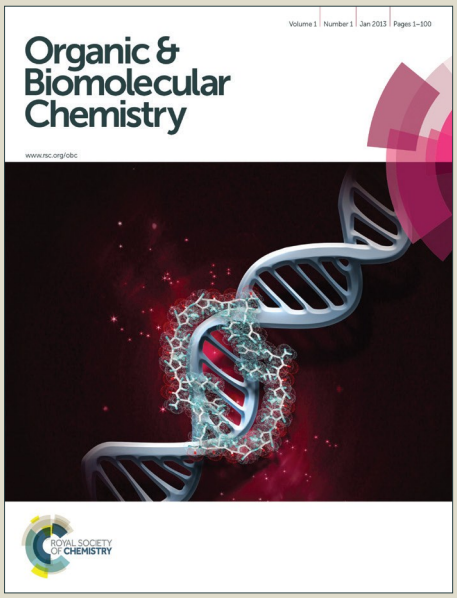

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ARTICLE TYPE

P-Stereogenic PNP Pincer-Pd Catalyzed Intramolecular Hydroamination of Amino-1,3-dienes

Zehua Yang[a], Chao Xia[a], Delong Liu[a], Yangang Liu[a], Masashi Sugiya[b], Tsuneo Imamoto[b,c,*] and Wanbin Zhang[a,d,*]

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A new P-stereogenic PNP pincer-Pd complex was readily prepared from optically pure 2,6-bis[(boranato(*tert*-butyl)methylphosphino)methyl]pyridine. It was used in the asymmetric intramolecular hydroamination of amino-1,3-dienes, with the desired products being obtained in good yields and with excellent regioselectivities and up to moderate enantioselectivities. The absolute configuration of one of the hydroamination products was determined by X-ray crystallography studies. This simple and efficient procedure can be used for the synthesis of allyl-type chiral pyrrolidine derivatives.

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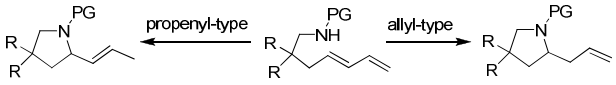
Introduction

Chiral pyrrolidine derivatives are valuable and commercially important chemicals that are prevalent in many biologically active natural products and pharmaceutical drug candidates.[1] The construction of such scaffolds has attracted a great deal of attention.[2] Significant progress has been made in pursuit of this goal using the direct intramolecular hydroamination of an amine to an unsaturated C=C bond. This tactic represents the shortest and most efficient synthetic pathway.[2c,2h,2j] Among these strategies, the hydroamination of 1,3-dienes is a promising yet challenging option - the resulting products possess a preserved C=C bond for further functionalization. However, it is difficult to control the preferential formation of one of the two possible regioisomeric products, i.e. the formation of propenyl-type and allyl-type isomers (Scheme 1).



Scheme 1. Two possible regioisomeric products

The majority of reported diene hydroamination reactions focus on the formation of propenyl-type pyrrolidine derivatives.[3] In contrast, the formation of allylic-type compounds in such reactions has seldom been explored. Marks described an organolanthanide catalyzed regioselective intramolecular hydroamination/cyclization of conjugated aminodienes to afford both propenyl-type and allylic-type products.[4] The regioselectivity of the reaction relies strongly on the structure of the corresponding 1,3-dienes. Yamamoto developed an achiral carbaboranyl-Hg catalyzed cycloisomerization of 1,3-dienes, exclusively giving racemic allylic-type azacycles and cycloalkanes from a range of sulfonamidodiene substrates.[5] Toste reported an asymmetric catalytic hydroamination using a chiral catalytic system of Au(I)/menthol. High enantioselectivity as well as good reactivity was observed with this particular catalytic system, while a regioisomeric mixture of both propenyl-type and allylic-type products was obtained in most cases.[6] As can be seen, allylic-type compounds can be exclusively obtained in the hydroamination reactions, however, to the best of our knowledge, there are no reports relating to asymmetric catalytic reactions which give allylic type heterocycles as the sole products.

Pincer-type metal complexes are structurally stable, possess a rigid skeleton, and can be used in many transformations.[7,8] We have developed a pincer-Pd complex which can be utilized in the chemoselective transfer hydrogenation of α,β-unsaturated ketones with high reactivity and selectivity, providing an attractive methodology for the preparation of saturated ketones from α-enones.[9] Following on from the success of the work, novel P-stereogenic PCP pincer-Pd complexes were designed and applied to the asymmetric addition of diarylphosphines to nitroalkenes with excellent yields and good enantioselectivities.[10] Recently, Michael and coworkers applied an achiral PNP type pincer-Pd catalyst to synthesize allylic-type nitrogen heterocyclic compounds via the intramolecular hydroamination of aminodienes in high yields.[11] We would therefore like to utilize our P-stereogenic pincer-type catalyst in such reactions for the construction of chiral nitrogen heterocycles. Herein we report a new P-stereogenic PNP-type pincer-Pd complex catalyzed intramolecular hydroamination of amino-1,3-dienes, exclusively generating enantioenriched allylic-type pyrrolidines.

Results and Discussion

[a] *School of Pharmacy, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, P. R. China*
[b] *Organic R&D Department, Nippon Chemical Industrial Co., Ltd., Kameido, Koto-ku, Tokyo 136-85 15, Japan*
[c] *Department of Chemistry, Graduate School of Science, Chiba University, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan*
[d] *School of Chemistry and Chemical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, P. R. China*
Fax: +86-21-5474-3265; Tel: +86-21-5474-3265; E-mail: wanbin@sjtu.edu.cn; imamoto@faculty.chiba-u.jp

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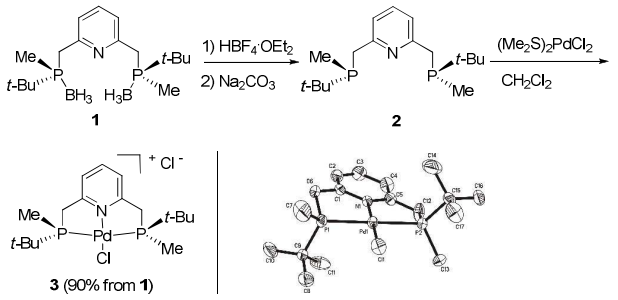
Synthesis of P-stereogenic PNP type pincer-Pd complex

Based on the synthesis of the P-stereogenic PCP pincer Pd complex,[10] we adopted the Livinghouse's deprotection method[12] to prepare the P-stereogenic PNP type pincer-Pd complex over two high-yielding steps (Scheme 2). Thus, the boranato groups were removed via the reaction of (*R*,*R*)-2,6-bis[(boranato(*tert*-butyl)methylphosphino)methyl]pyridine (**1**)[13] with tetrafluoroboric acid diethyl ether in degassed dry dichloromethane, followed by treatment with degassed 10% Na_2CO_3 solution to produce the resulting bisphosphine pyridine **2**. The ligand **2** was then reacted directly with $(Me_2S)_2PdCl_2$ in degassed dry dichloromethane to form the P-stereogenic pincer-Pd complex **3** as an orange solid. The total yield for the above two steps from **1** to **3** was 90%. The resulting solid product is stable to air and moisture and requires no special storage precautions.

Scheme 2. The synthetic route of pincer-Pd complex

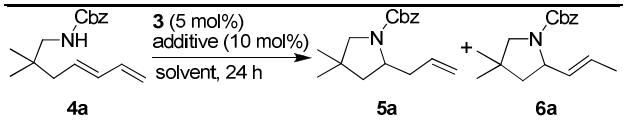


The structure of the pincer-Pd complex **3** was confirmed by single-crystal X-ray diffraction (Scheme 2).[14] The crystal structure indicates that there is a rigid and C_2-symmetric stereo environment around the Pd atom. The large difference between the small methyl group and the bulky *tert*-butyl group is expected to provide efficient stereocontrol for asymmetric catalysis.

Intramolecular Hydroamination of Amino-1,3-dienes

With complex **3** in hand, intramolecular hydroamination of Cbz-protected aminodiene **4a** was carried out in the presence of additives at 25 °C for 24 h (Table 1). When the reaction was carried out in the presence of $AgBF_4$ in dichloromethane, an allylic-type pyrrolidine derivative was obtained exclusively in quantitative yield but with a low enantioselectivity (entry 1). A low ee value was also observed when $AgBF_4$ was replaced with $AgSbF_6$ (entry 2). With AgOTf as an additive, however, both low yield and enantioselectivity were obtained (entry 3). No reaction occurred when $NaBAr_F$ was used as an additive even after 24 h (entry 4).

Table 1 Screening of additive and solvent[a]



4a 5a 6a

Entry	Solvent	Additive	T (°C)	**5a** / **6a**[b]	Yield (%)[c]	ee (%)[d]
1	CH_2Cl_2	$AgBF_4$	25	> 99 : 1	99	14
2	CH_2Cl_2	$AgSbF_6$	25	> 99 : 1	99	10
3	CH_2Cl_2	AgOTf	25	> 99 : 1	44	7
4	CH_2Cl_2	$NaBAr_F$	25	-	nd	-
5	$ClCH_2CH_2Cl$	$AgBF_4$	25	> 99 : 1	99	6
6	$PhCH_3$	$AgBF_4$	25	> 99 : 1	10	-15
7	EtOAc	$AgBF_4$	25	> 99 : 1	10	-10
8	acetone	$AgBF_4$	25	> 99 : 1	21	-10
9	EtOH	$AgBF_4$	25	-	trace	-
10	CH_2Cl_2	$AgBF_4$	reflux	> 99 : 1	99	5
11	CH_2Cl_2	$AgBF_4$	15	> 99 : 1	98	10
12	CH_2Cl_2	$AgBF_4$	0	> 99 : 1	95	9
13	CH_2Cl_2	$AgBF_4$	–20	> 99 : 1	79	9

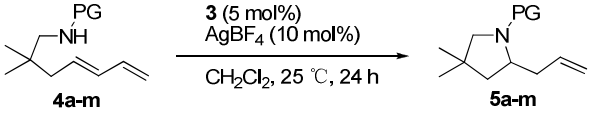
[a] Reactions of **4a** (0.1 mmol) were carried out using **3** (5 mol%) as a chiral catalyst in the presence of different additives (0.01 mmol) in a suitable solvent (3 mL) for 24 h. [b] Determined by ^{1}H NMR spectra. [c] Isolated yield. [d] Determined by chiral HPLC using Daicel ChiralPak IC-3 column. Cbz = benzyloxycarbonyl.

We next investigated the influence of solvent on the reaction. All the reactions showed excellent regioselectivities with allylic-type pyrrolidines being obtained as the sole products. The desired product was obtained in quantitative yield when the reaction was carried out in 1,2-dichloroethane but with very low enantioselectivity (entry 5). Other solvents, such as toluene, ethyl acetate and acetone, provided low reaction activities and low enantioselectivities albeit with excellent regioselectivities (entries 5-8). The protic solvent ethanol provided only trace amount of product (entry 9).

Temperature had an apparent effect on the reaction activities and enantioselectivities. Reaction under reflux conditions gave the product with quantitative yield with lower ee (entry 10). Reducing the temperature resulted in both lower yields and ees (entries 11-13).

Subsequently, different amine protecting groups were screened with the aim of improving the enantioselectivities of the pyrrolidine products (Table 2). Acyl amines were first examined using **3** as a chiral catalyst in the presence of $AgBF_4$ in dichloromethane at 25 ℃ for 24 h (entries 1-4). Substrates bearing carbamate protecting groups, such as Cbz (**4a**), Boc (**4b**) and Fmoc (**4c**), were successfully converted to their corresponding hydroamination products in quantitative yields and with excellent regioselectivities but with no more than 20% ee (entries 1-3). Hydroamination of substrate **4d** possessing an acetyl protecting group gave the target product with somewhat higher enantioselectivity but lower yield (entry 4). Under the same reaction conditions, hydroamination of sulfonamide-protected amine **4e** gave the desired product with a relatively high yield and enantiomeric excess, thus providing us with an opportunity to find a more suitable protecting group for the substrates (entry 5).

Table 2 Screening of the protecting group[a]



4a-m 5a-m

Entry	PG	**5**	Yield (%)[b]	ee (%)[c]
1	Cbz (**4a**)	**5a**	99	14 (-)
2	Boc (**4b**)	**5b**	99	10 (-)
3	Fmoc (**4c**)	**5c**	99	9 (-)
4	Ac (**4d**)	**5d**	76	22 (-)

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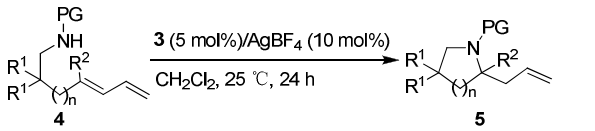
5	$PhSO_2$ (**4e**)	**5e**	95	18 (-)
6	Ns (**4f**)	**5f**	55	5 (-)
7	*o*-$MeC_6H_4SO_2$ (**4g**)	**5g**	60	29 (-)
8	*m*-$MeC_6H_4SO_2$ (**4h**)	**5h**	70	21 (-)
9	*p*-$MeC_6H_4SO_2$ (**4i**)	**5i**	72	18 (-)
10	2,4-$Me_2C_6H_4SO_2$ (**4j**)	**5j**	56	33 (-)
11	2,5-$Me_2C_6H_4SO_2$ (**4k**)	**5k**	48	29 (-)
12	2,4,6-$Me_3C_6H_4SO_2$ (**4l**)	**5l**	20	29 (-)
13	Nps (**4m**)	**5m**	20	25 (-)

[a] Reactions of **4** (0.1 mmol) were carried out using **3** (5 mol%) as a chiral catalyst in the presence of $AgBF_4$ (0.01 mmol) in CH_2Cl_2 (3 mL) at 25 ℃ for 24 h and all reactions afforded more than 99 : 1 regioselectivities. [b] Isolated yield. [c] Determined by chiral HPLC. Boc = *tert*-butoxycarbonyl, Ac = acetyl, Fmoc = 9-fluorenylmethoxycarbonyl, Ns = 4-nitrobenzenesulfonyl, Nps = 1-Naphthalenesulfonyl.

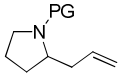
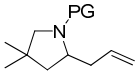
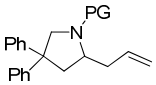
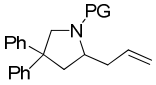
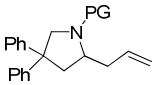
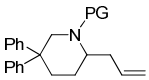
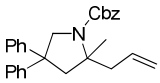
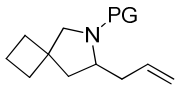
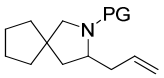
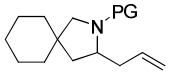
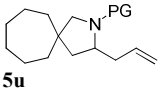
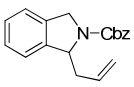
We subsequently investigated the effect of different benzenesulfonyl protecting groups on the reaction. Hydroamination of substrate **4f** possessing an electron-withdrawing group led to the desired product with decreased yield and enantioselectivity (entry 6). Therefore benzenesulfonyl protecting groups possessing electron-donating groups were examined. For the monomethyl-benzenesulfonyl aminediene, the *o*-substituted substrates provided the most promising results (entries 7-9). Further increase of the steric hindrance of the aromatic ring improved the enantioselectivity with 2,4-dimethylbenzenesulfonyl protected substrates giving better enantiomeric excess. (entries 10-11). However, when 2,4,6-trimethyl substituted benzenesulfonyl aminodiene was used, the yield and enantiomeric excess decreased (entry 12). A naphthylsulfonyl group also used as a protecting group, but the yield and enantiomeric excess remained low (entry 13). Therefore, we chose 2,4-dimethylbenzenesulfonyl as the protecting group for use in following reactions due to its relatively high enantioselectivity and yield (entry 10).

Substrates with a different substituted R^1 group were examined using the above optimal reaction conditions (Table 3). Substrates lacking an R^1 group (R^1=H) provided the desired products in low yield and enantiomeric excess (entry 1). Increasing the steric hindrance improved the reaction activity and enantioselectivity, and up to 96% yield and 43% ee were obtained when a phenyl group (**4o**) was used (entries 2, 3). We then increased the catalyst loading from 5% to 10 and 20 mol%, nevertheless up to 47% ee can be obtained (entries 4, 5). Based on this result, we attempted to construct a similar allylic-type piperidine derivative and the desired product was obtained in moderate yield but lower enantioselectivity than the corresponding pyrrolidine product (entry 6). Products possessing a quaternary carbon center at the 2-position of the pyrrolidine could also be obtained with excellent regioselectivity but poor enantioselectivity (entry 7). Substrates with cyclic R^1 groups were also utilized providing the corresponding chiral spiro compounds with promising catalytic results (entries 8-11). 2-Substituted chiral isoindoline could also be prepared using this P-stereogenic PNP pincer-Pd catalyzed intramolecular hydroamination but with a low ee value (entry 12).

Table 3 Substrate scope of the hydroamination[a]



4 **5**

Entry	R^1	Product	Yield (%)[b]	ee (%)[c]
1[d]	H	 **5n**	30[e]	23 (-)
2[d]	Me	 **5j**	56	33 (-)
3[d]	Ph	 **5o**	96	43 (+)
4[d]	Ph	 **5o**	97[f]	45 (+)
5[d]	Ph	 **5o**	99[g]	47 (+)
6[h]	Ph	 **5p**	62	32 (+)
7[i]	Ph	 **5q**	92	3 (-)
8[d]	-$(CH_2)_3$-	 **5r**	52	33 (-)
9[d]	-$(CH_2)_4$-	 **5s**	73	32 (-)
10[d]	-$(CH_2)_5$-	 **5t**	96	35 (-)
11[d]	-$(CH_2)_6$-	 **5u**	92	36 (-)
12[d]	-C_4H_4-	 **5v**	74	9 (+)

[a] Reactions of **4** (0.1 mmol) were carried out using **3** (5 mol%) as a chiral catalyst in the presence of $AgBF_4$ (0.01 mmol) in CH_2Cl_2 (3 mL) at 25 ℃ for 24 h and all reactions afforded more than 99 : 1 regioselectivities. [b] Isolated yield. [c] Determined by chiral HPLC. [d] R^2 = H, n = 1. [e] Stirred for 96 h. [f] 10 mol% catalyst was used. [g] 20 mol% catalyst was used. [h] R^2 = H, n = 2. [i] R^2 = Me, n = 1. PG = 2,4-dimethylbenzenesulfonyl.

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To determine the absolute configuration of the hydroamination reaction products, an X-ray crystallography study was performed. Recrystallization of **5o** from a mixed solvent system of dichloromethane and *n*-hexane provided a crystal suitable for single crystal X-ray diffraction. Diffraction data and HPLC analysis showed that the major enantiomer of the catalytic reaction appears to be the product with the (*S*)-absolute configuration (Figure 1).[15]

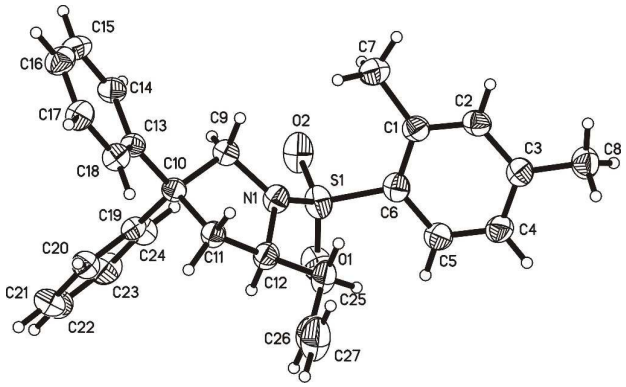
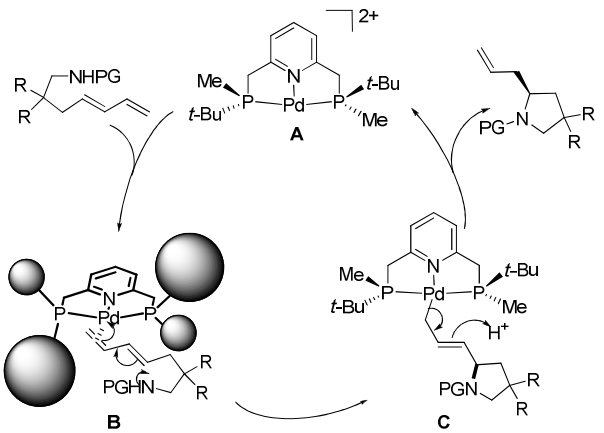


Figure 1. ORTEP diagram for complex **5o** (Thermal ellipsoids are at the 30% probability level)

A mechanism has been proposed to explain the excellent regioselectivity for the intramolecular hydroamination of amino-1,3-dienes (Scheme 3). Initially, the chiral pincer-type catalyst **3** reacts with $AgBF_4$ to give an activated catalytic molecule **A**. This cationic palladium species interacts with the terminal double bond of the amino-1,3-diene in close proximity the methyl group located on the phosphorus atom due to the strong steric hindrance of the *tert*-butyl group, affording the square planar π-complex **B**. The intermediate **B** undergoes an intramolecular C-N bond formation to produce the η^1-allyl–palladium complex **C**, which is consistent with Michael's discovery of the isolated η^1-allyl–palladium intermediate.[11] Subsequent protonation and cleavage of the Pd-C bond produces the allylic-type *S*-configuration product, regenerating the catalyst **A**. In the absence of a bulky substituent, such as a *tert*-butyl group, the internal double bond of the amino-1,3-diene can also coordinate to the Pd atom of **A**, eventually leading to the undesired propenyl-type product.[5] Because of the remote distance (four bonds) between the palladium atom and the reaction site in **B**, the moderate 43% ee obtained for the allylic-type pyrrolidine derivative presents a very promising result.



Scheme 3 Proposed reaction pathway

Conclusions

We have prepared a novel P-stereogenic PNP pincer-Pd complex from optically pure 2,6-bis[(boranato(*tert*-butyl)methylphosphino)methyl]pyridine and used it in the asymmetric intramolecular hydroamination of amino-1,3-dienes. The desired products were obtained in high yields (up to quantitative yield) and with excellent regioselectivities (> 99 : 1) and up to moderate enantioselectivities (up to 47% ee). The absolute configuration of an enantioenriched product was determined by X-ray crystallography studies. A proposed mechanism has been suggested to explain the excellent regioselectivity of the intramolecular hydroamination. The observed enantioselectivities are only moderate, but the results apparently indicate that the distinct enantioselection occurs at the reaction site separated by four bonds from the catalyst metal center.

4. Experimental

General Details

All air and moisture sensitive manipulations were carried out with standard Schlenk techniques or in a glove box under nitrogen atmosphere. Column chromatography was performed using 200-300 mesh silica gels. All solvents were refined by the standard method of solvent manual. The other reagents were purchased from Adamas-Beta Ltd., Energy Chemical Inc. or J&K Scientific Inc. and used without further purification unless otherwise specified. The NMR spectra were recorded on a Varian MERCURY plus-400 (400 MHz, ^{1}H; 101 MHz, ^{13}C; 162 MHz, ^{31}P) spectrometer with chemical shifts reported in ppm relative to the residual deuterated solvents, the internal standard tetramethylsilane or 85% phosphoric acid. Mass spectrometry analysis was carried out using an electrospray spectrometer Waters Micromass Q-TOF Premier Mass Spectrometer. Melting points were measured with SGW X-4 micro melting point apparatus. IR spectra were recorded on a Thermo Scientific Nicolet IS10 infrared spectrometer. Optical rotations were measured on a Rudolph Research Analytical Autopol VI automatic polarimeter using a 50 mm path-length cell at 589 nm. Enantiomeric excess analyses were performed on a Shimadzu LC-10Avp HPLC system and using Daicel Chiralcel IC-3, IE, OD-H, OJ-H, and OZ-H columns with *n*-hexane/*i*-propyl alcohol as a eluent. The X-ray diffraction data were collected on an Oxford Diffraction Gemini A Ultra diffractometer with graphite monochromator.

Preparation of Catalyst

(*R*,*R*)-2,6-Bis[(*tert*-butylmethylphosphino)methyl]pyridine (2). A two-necked flask (20 mL) equipped with a magnetic stirring bar and a nitrogen balloon was charged with (*R*,*R*)-2,6-bis[(boranato(*tert*-butyl)methylphosphino)methyl]pyridine (**1**) (170 mg, 0.5 mmol) and degassed dry dichloromethane (3 mL). The flask was immersed in an ice-water bath, and tetrafluoroboric acid diethyl ether adduct (HBF_4•OEt_2, 0.95 mL, 7.0 mmol) was slowly added over 10 min. The ice-water bath was removed and the mixture stirred at ambient temperature for 2 h, whereupon hydrogen gas was evolved and a white crystalline solids appeared. The flask was again immersed in an ice-water bath, and degassed *n*-hexane (5 mL) was added. To this mixture was slowly added a degassed 10% Na_2CO_3 solution (5 mL), and then the mixture was stirred

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at 40 ℃ for 30 min. The aqueous layer was removed by using a syringe, and the *n*-hexane layer was dried over anhydrous $MgSO_4$ under nitrogen. The *n*-hexane solution was transferred to another flask filled with nitrogen, and the solvent was removed under reduced pressure to give **2** as a colourless oil, which was used in the next step without further purification.

(*S*,*S*)-2,6-Bis[(*tert*-butylmethylphosphino)methyl]pyridine-palladium(II) dichloride (3). A dichloromethane solution (5 mL) of compound **2** (the entire product obtained by the procedure described above, ca. 0.5 mmol) was added to a dichloromethane solution (5 mL) of $(Me_2S)_2PdCl_2$ (150.8 mg, 0.5 mmol), and the mixture was stirred for 1 h. The solvent was removed and the residue was washed with ethyl acetate (3 × 5 mL) and dried under vacuum to give complex **3** as a yellow solid (220 mg, 90% from compound **1**). Crystals suitable for X-ray analysis were obtained by diffusion of a concentrated dichloromethane solution of **3** with ethyl ether. m.p. 247.0 – 248.3 ℃; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.97 (brs, 3H), 4.28 (dt, J = 18.3, 4.1 Hz, 2H), 4.07 (dt, J = 18.3, 4.6 Hz, 2H), 1.74 (vt, J = 3.1 Hz, 6H), 1.26 (vt, J = 8.3 Hz, 18H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 163.7 (vt, J = 4.0 Hz), 141.6 (s), 123.9 (vt, J = 5.7 Hz), 39.6 (vt, J = 10.7 Hz), 32.6 (vt, J = 13.1 Hz), 26.4 (s), 6.1 (vt, J = 12.7 Hz); ^{31}P NMR (162 MHz, $CDCl_3$): δ 46.58; HRMS (ESI): calcd. for $C_{17}H_{31}ClNP_2Pd$ $[M-Cl]^+$ 452.0655, found 452.0667; IR (KBr disc) ν/cm^{-1}: 3385, 2958, 1600, 1465, 1369, 1293, 902, 883, 744; $[\alpha]_D^{25}$ = +97.8 (*c* 0.8, $CHCl_3$).

General procedure for the intramolecular hydroamination

Complex **3** (2.44 mg, 0.005 mmol) and $AgBF_4$ (1.95 mg, 0.01 mmol) were added to a dry 10 mL Schlenk tube under N_2 atmosphere. CH_2Cl_2 (2 mL) was added by syringe and the reaction mixture was stirred for 1 h at given temperature. A solution of the substrate (0.1 mmol) in CH_2Cl_2 (1 mL) was added by syringe to the stirring mixture. Stirring was continued for a predetermined length of time, and the reaction mixture was filtered through a plug of celite. Purification by column chromatography (ethyl acetate/petroleum ether) on silica gel afforded the pure product.

(–)-Benzyl 2-allyl-4,4-dimethylpyrrolidine-1-carboxylate (5a).[10] Colourless oil (27.1 mg, 99%). ^{1}H NMR (400 MHz, $CDCl_3$, observed as a mixture of rotamers): δ 7.40 – 7.27 (m, 10H, both), 5.82 – 5.59 (m, 2H, both), 5.26 – 4.95 (m, 8H, both), 3.94 (m, 2H, both), 3.48 (d, J = 10.6 Hz, 1H, minor), 3.39 (d, J = 10.3 Hz, 1H, major), 2.98 (d, J = 10.6 Hz, 2H, both), 2.73 (brs, 1H, major), 2.54 (brs, 1H, minor), 2.32 – 2.23 (m, 2H, both), 1.78 (ddd, J = 12.7, 7.4, 1.7 Hz, 2H, both), 1.07 (s, 6H, both), 0.97 (s, 6H, both); ^{13}C NMR (101 MHz, $CDCl_3$): δ 155.6, 155.3, 137.4, 137.2, 134.6, 134.3, 128.7, 128.1, 128.0, 127.9, 117.8, 117.7, 67.0, 66.7, 59.9, 59.7, 57.2, 56.6, 45.7, 44.9, 39.5, 38.4, 37.6, 37.3, 26.7, 26.2; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 98/2, 210 nm, 1 mL/min, t_{R1} = 13.3 min (minor), t_{R2} = 14.0 min (major), ee = 14%; $[\alpha]_D^{25}$ = –4.0 (*c* 0.3, $CHCl_3$).

(–)-*tert*-Butyl 2-allyl-4,4-dimethylpyrrolidine-1-carboxylate (5b). Colorless oil (23.7 mg, 99%). ^{1}H NMR (400 MHz, $CDCl_3$, observed as a mixture of rotamers): δ 5.75 – 5.65 (m, 2H, both), 5.08 – 5.04 (m, 4H, both), 3.88 (d, J = 5.4 Hz, 1H, minor), 3.79 (d, J = 7.0 Hz, 1H, major), 3.41 (d, J = 10.2 Hz, 1H, minor), 3.27 (d, J = 10.1 Hz, 1H, major), 2.89 (d, J = 10.8 Hz, 2H, both), 2.67 (brs, 1H, minor), 2.52 (brs, 1H, major), 2.30 – 2.20 (m, 2H, both), 1.75 (ddd, J = 12.6, 7.4, 1.7 Hz, 2H, both), 1.47 (s, 18H, both), 1.06 (s, 6H, both), 0.96 (s, 6H, both); ^{13}C NMR (101 MHz, $CDCl_3$): δ 155.2, 134.8, 117.5, 60.1, 59.2, 56.6, 45.8, 45.0, 39.7, 38.6, 28.8, 26.6, 26.3; HRMS (ESI): calcd. for $C_{14}H_{26}NO_2$ $[M+H]^+$ 240.1964, found 240.1980; IR (KBr disc) ν/cm^{-1}: 3361, 2964, 1705, 1511, 1366, 1248, 1171, 1004, 897, 779; HPLC Daicel ChiralPak OJ-H, *n*-hexane, 210 nm, 1 mL/min, t_{R1} = 4.4 min (minor), t_{R2} = 5.1 min (major), ee = 10%; $[\alpha]_D^{25}$ = –5.1 (*c* 0.3, $CHCl_3$).

(–)-(9*H*-Fluoren-9-yl)methyl 2-allyl-4,4-dimethylpyrrolidine-1-carboxylate (5c). Chartreuse oil (35.8 mg, 99%). ^{1}H NMR (400 MHz, $CDCl_3$, observed as a mixture of rotamers): δ 7.76 (d, J = 7.4 Hz, 4H, both), 7.60 (d, J = 7.1 Hz, 4H, both), 7.39 (t, J = 6.9 Hz, 4H, both), 7.31 (t, J = 7.4 Hz, 4H, both), 5.77 – 5.67 (m, 1H, major), 5.55 – 5.44 (m, 1H, minor), 5.16 – 4.84 (m, 3H, both), 4.69 – 4.50 (m, 1H, major), 4.51 – 4.34 (m, 2H, minor), 4.27 – 4.25 (d, J = 5.6 Hz, 1H, minor), 3.94 (brs, 1H, major), 3.60 (brs, 1H, minor), 3.42 (d, J = 10.6 Hz, 1H, minor), 3.34 (d, J = 10.4 Hz, 1H, minor), 2.99 (d, J = 10.4 Hz, 1H, major), 2.90 (d, J = 10.9 Hz, 1H, minor), 2.72 (brs, 1H, major), 2.39 – 2.16 (m, 2H, both), 2.07 – 1.87 (m, 1H, minor), 1.86 – 1.65 (m, 2H, both), 1.53 – 1.35 (m, 2H, both), 1.08 (d, J = 20.6 Hz, 6H, both), 0.93 (d, J = 29.3 Hz, 6H, both); ^{13}C NMR (101 MHz, $CDCl_3$): δ 155.4, 155.0, 144.2, 144.1, 141.4, 141.3, 134.3, 127.6, 127.0, 125.1, 125.0, 124.7, 124.6, 119.9, 117.5, 117.3, 66.6, 66.3, 59.4, 56.9, 56.2, 47.6, 47.4, 45.5, 44.6, 39.0, 38.1, 37.4, 36.9, 26.5, 26.3, 26.0, 25.9; HRMS (ESI): calcd. for $C_{24}H_{28}NO_2$ $[M+H]^+$ 362.2120, found 362.2122; IR (KBr disc) ν/cm^{-1}: 3064, 2952, 2784, 1698, 1449, 780, 758, 733; HPLC Daicel ChiralPak OJ-H, *n*-hexane/*i*-PrOH = 90/10, 230 nm, 1 mL/min, t_{R1} = 9.4 min (major), t_{R2} = 10.1 min (minor), ee = 9%; $[\alpha]_D^{25}$ = –5.0 (*c* 0.4, $CHCl_3$).

(–)-1-(2-Allyl-4,4-dimethylpyrrolidin-1-yl)ethanone (5d). Colourless oil (13.8 mg, 76%). ^{1}H NMR (400 MHz, $CDCl_3$, observed as a mixture of rotamers): δ 5.77 – 5.58 (m, 2H, both), 5.18 – 4.93 (m, 4H, both), 4.13 – 4.06 (m, 2H, both), 3.98 – 3.84 (m, 1H, minor), 3.76 (d, J = 11.5 Hz, 1H, minor), 3.18 – 3.08 (m, 4H, both), 2.84 (d, J = 11.5 Hz, 1H, major), 2.76 – 2.61 (m, 2H, both), 2.53 – 2.36 (m, 1H, minor), 2.36 – 2.20 (m, 2H, both), 2.09 (s, 3H, minor), 2.01 (s, 3H, major), 1.92 – 1.87 (m, 1H, minor), 1.82 – 1.73 (m, 2H, major), 1.56 (dd, J = 12.9, 7.7 Hz, 1H, minor), 1.46 (dd, J = 12.8, 9.0 Hz, 2H, major), 1.09 (d, J = 1.9 Hz, 6H, both), 0.97 (s, 3H, major), 0.94 (s, 1H, minor); ^{13}C NMR (101 MHz, $CDCl_3$): δ 169.4, 134.6, 133.3, 118.7, 117.7, 61.4, 58.3, 57.4, 56.3, 46.1, 44.5, 40.6, 37.9, 26.9, 26.6, 26.4, 26.2, 23.6; HRMS (ESI): calcd. for $C_{11}H_{20}NO$ $[M+H]^+$ 182.1545, found 182.1543; IR (KBr disc) ν/cm^{-1}: 2959, 2924, 2855, 1655, 1417, 1260, 1097; HPLC Daicel ChiralPak OD-H, *n*-hexane/*i*-PrOH = 98/2, 210 nm, 1 mL/min, t_{R1} = 10.1 min (major), t_{R2} = 12.1 min (minor)], ee = 22%; $[\alpha]_D^{25}$ = –4.5 (*c* 0.4, $CHCl_3$).

(–)-2-Allyl-4,4-dimethyl-1-(phenylsulfonyl)pyrrolidine (5e). Colourless oil (26.5 mg, 95%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88 – 7.83 (m, 2H), 7.61 – 7.48 (m, 3H), 5.73 (ddt, J = 17.3, 10.2, 7.1 Hz, 1H), 5.18 – 4.99 (m, 2H), 3.75 – 3.61 (m, 1H), 3.22 – 3.06 (m, 2H), 2.87 – 2.72 (m, 1H), 2.50 – 2.36 (m, 1H), 1.64 (ddd, J = 12.7, 7.2, 1.1 Hz, 1H), 1.51 (dd, J = 12.7, 8.9 Hz, 1H), 1.01 (s, 3H), 0.47 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 138.5, 134.4, 132.7, 129.2, 127.6, 118.1, 61.7, 59.8, 45.7, 40.8, 37.5, 26.5, 25.9; HRMS (ESI): calcd. for $C_{15}H_{22}NO_2S$ $[M+H]^+$ 280.1371, found 280.1368; IR (KBr disc) ν/cm^{-1}: 2951, 2855, 1464, 1355, 1260, 1165, 1094, 1051, 801, 718, 692, 601, 569; HPLC Daicel ChiralPak IE, *n*-hexane/*i*-PrOH = 90/10, 230 nm, 1 mL/min, t_{R1} = 15.6 min

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(major), t_{R2} = 18.3 min (minor), ee = 18%; $[\alpha]_D^{25}$ = –7.6 (*c* 0.5, $CHCl_3$).

(–)-2-Allyl-4,4-dimethyl-1-(4-nitrophenylsulfonyl) pyrrolidine (5f). Colourless oil (17.8 mg, 55%).^{1}H NMR (400 MHz, $CDCl_3$): δ 8.37 (d, *J* = 7.9 Hz, 2H), 8.03 (d, *J* = 7.9 Hz, 2H), 5.76 – 5.61 (m, 1H), 5.17 – 5.02 (m, 2H), 3.81 – 3.74 (m, 1H), 3.16 (dd, *J* = 35.6, 10.5 Hz, 2H), 2.80 – 2.68 (m, 1H), 2.46 – 2.32 (m, 1H), 1.72 (dd, *J* = 12.8, 7.3 Hz, 1H), 1.61 – 1.49 (m, 1H), 1.05 (s, 3H), 0.60 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 149.9, 144.7, 133.4, 128.3, 124.2, 118.3, 61.5, 59.9, 45.4, 40.2, 37.6, 25.9, 25.8; HRMS (ESI): calcd. for $C_{15}H_{21}N_2O_4S$ $[M+H]^+$ 325.1222, found 325.1229; IR (KBr disc) ν/cm^{-1}: 2960, 1529, 1350, 1162, 1091, 918, 855, 735, 688, 615, 574; HPLC Daicel ChiralPak OD-H, *n*-hexane/*i*-PrOH = 95/5, 200 nm, 1 mL/min, t_{R1} = 13.7 min (major), t_{R2} = 15.6 min (minor), ee = 5%; $[\alpha]_D^{25}$ = –3.7 (*c* 0.4, $CHCl_3$).

(–)-2-Allyl-4,4-dimethyl-1-(*o*-tolylsulfonyl)pyrrolidine (5g). Colourless oil (17.6 mg, 60%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.96 (d, *J* = 7.0 Hz, 1H), 7.43 (t, *J* = 7.5 Hz, 1H), 7.30 (t, *J* = 7.0 Hz, 2H), 5.59 (ddt, *J* = 17.3, 10.3, 7.1 Hz, 1H), 4.99 – 4.92 (m, 2H), 4.01 (ddd, *J* = 16.3, 8.9, 3.5 Hz, 1H), 3.41 (dd, *J* = 10.3, 1.4 Hz, 1H), 2.98 (d, *J* = 10.3 Hz, 1H), 2.67 (s, 3H), 2.55 – 2.44 (m, 1H), 2.19 – 2.06 (m, 1H), 1.82 (ddd, *J* = 12.6, 7.4, 1.4 Hz, 1H), 1.53 (dd, *J* = 12.7, 8.8 Hz, 1H), 1.07 (s, 3H), 0.95 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 138.9, 137.6, 133.9, 132.5, 132.4, 129.3, 126.0, 117.6, 61.3, 59.2, 45.9, 39.8, 37.6, 26.1, 25.8, 20.6; HRMS (ESI): calcd. for $C_{16}H_{24}NO_2S$ $[M+H]^+$ 294.1528, found 294.1520; IR (KBr disc) ν/cm^{-1}: 3065, 2961, 2871, 1641, 1470, 1318, 1156, 1069, 1019, 920, 808, 760, 697, 606, 581, 544; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 90/10, 230 nm, 1 mL/min, t_{R1} = 13.1 min (major), t_{R2} =14.2 min (minor), ee = 29%; $[\alpha]_D^{25}$ = –5.3 (c 0.4, $CHCl_3$).

(–)-2-Allyl-4,4-dimethyl-1-(*m*-tolylsulfonyl)pyrrolidine (5h). Yellowish solid (20.5 mg, 70%). m.p. 56.0 – 57.7 ℃; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.69 – 7.61 (m, 2H), 7.44 – 7.34 (m, 2H), 5.74 (ddt, *J* = 17.3, 10.2, 7.1 Hz, 1H), 5.14 – 5.02 (m, 2H), 3.71 – 3.64 (m, 1H), 3.17 – 3.09 (m, 2H), 2.85 – 2.73 (m, 1H), 2.43 (s, 3H), 2.45 – 2.38 (m, 1H), 1.65 (ddd, *J* = 12.7, 7.2, 1.1 Hz, 1H), 1.51 (dd, *J* = 12.7, 8.9 Hz, 1H), 1.02 (s, 3H), 0.50 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 139.0, 138.2, 134.2, 133.2, 128.8, 127.7, 124.5, 117.7, 61.5, 59.5, 45.5, 40.5, 37.3, 26.3, 25.7, 21.4; HRMS (ESI): calcd. for $C_{16}H_{24}NO_2S$ $[M+H]^+$ 294.1528, found 294.1518; IR (KBr disc) ν/cm^{-1}: 3076, 2959, 2926, 2873, 1641, 1600, 1467, 1348, 1217, 1155, 1097, 1050, 919, 789, 735, 698, 607, 583; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 90/10, 230 nm, 1 mL/min, t_{R1} = 19.6 min (major), t_{R2} = 20.6 min (minor), ee = 21%; $[\alpha]_D^{25}$ = –22.0 (*c* 0.1, $CHCl_3$).

(–)-2-Allyl-4,4-dimethyl-1-tosylpyrrolidine (5i).[6] Colourless oil (21.2 mg, 72%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.73 (d, *J* = 7.6 Hz, 2H), 7.30 (d, *J* = 8.0 Hz, 2H), 5.79 – 5.68 (m, 1H), 5.14 – 5.01 (m, 2H), 3.69 – 3.62 (m, 1H), 3.19 – 3.06 (m, 2H), 2.81 – 2.76 (m, 1H), 2.42 (s, 3H), 2.44 – 2.35 (m, 1H), 1.64 (dd, *J* = 12.7, 7.3 Hz, 1H), 1.51 (dd, *J* = 12.7, 8.7 Hz, 1H), 1.02 (s, 3H), 0.53 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 143.2, 135.4, 134.3, 129.5, 127.4, 117.7, 61.5, 59.5, 45.5, 40.5, 37.2, 26.3, 25.8, 21.5; HPLC Daicel ChiralPak OD-H, *n*-hexane/*i*-PrOH = 99/1, 200 nm, 1 mL/min, t_{R1} = 10.5 min (major), t_{R2} = 11.6 min (minor), ee = 18%; $[\alpha]_D^{25}$ = –9.4 (*c* 0.5, $CHCl_3$).

(–)-2-Allyl-1-(2,4-dimethylphenylsulfonyl)-4,4-dimethylp yrrolidine (5j). Colourless oil (17.2 mg, 56%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.84 (d, *J* = 8.7 Hz, 1H), 7.09 – 7.08 (m, 2H), 5.60 (ddt, *J* = 17.2, 10.3, 7.1 Hz, 1H), 5.02 – 4.90 (m, 2H), 4.03 – 3.93 (m, 1H), 3.37 (dd, *J* = 10.3, 1.5 Hz, 1H), 2.95 (d, *J* = 10.3 Hz, 1H), 2.62 (s, 3H), 2.54 – 2.48 (m, 1H), 2.36 (s, 3H), 2.18 – 2.06 (m, 1H), 1.81 (dd, *J* = 11.9, 6.6 Hz, 1H), 1.52 (dd, *J* = 12.7, 8.7 Hz, 1H), 1.06 (s, 3H), 0.95 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 143.0, 137.5, 135.9, 134.1, 133.2, 129.6, 126.6, 117.5, 61.3, 59.0, 45.9, 39.8, 37.6, 26.2, 25.9, 21.2, 20.5; HRMS (ESI): calcd. for $C_{17}H_{26}NO_2S$ $[M+H]^+$ 308.1684, found 308.1681; IR (KBr disc) ν/cm^{-1}: 3076, 2959, 2925, 2870, 1604, 1456, 1318, 1155, 1138, 1062, 923, 618, 590, 549; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 95/5, 230 nm, 1 mL/min, t_{R1} = 24.9 min (major), t_{R2} = 26.5 min (minor), ee = 33%; $[\alpha]_D^{25}$ = –3.0 (*c* 0.4, $CHCl_3$).

(–)-2-Allyl-1-(2,5-dimethylphenylsulfonyl)-4,4-dimethylp yrrolidine (5k). Colourless oil (14.8 mg, 48%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.78 (s, 1H), 7.23 (d, *J* = 7.8 Hz, 1H), 7.17 (d, *J* = 7.7 Hz, 1H), 5.61 (ddt, *J* = 17.2, 10.3, 7.1 Hz, 1H), 5.06 – 4.89 (m, 2H), 4.07 – 3.94 (m, 1H), 3.38 (dd, *J* = 10.3, 1.5 Hz, 1H), 2.96 (d, *J* = 10.3 Hz, 1H), 2.61 (s, 3H), 2.57 – 2.46 (m, 1H), 2.37 (s, 3H), 2.20 – 2.07 (m, 1H), 1.81 (ddd, *J* = 12.6, 7.4, 1.4 Hz, 1H), 1.53 (dd, *J* = 12.7, 8.7 Hz, 1H), 1.07 (s, 3H), 0.94 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 138.3, 135.8, 134.5, 134.1, 133.2, 132.5, 129.8, 117.6, 61.3, 59.1, 45.9, 39.8, 37.6, 26.2, 25.9, 20.8, 20.1; HRMS (ESI): calcd. for $C_{17}H_{26}NO_2S$ $[M+H]^+$ 308.1684, found 308.1676; IR (KBr disc) ν/cm^{-1}: 2963, 2905, 2871, 2380, 1590, 1573, 1453, 1369, 1067, 1019, 819; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 95/5, 230 nm, 1 mL/min, t_{R1} = 12.4 min (major), t_{R2} = 13.9 min (minor), ee = 29%; $[\alpha]_D^{25}$ = –9.0 (*c* 0.2, $CHCl_3$).

(–)-2-Allyl-1-(mesitylsulfonyl)-4,4-dimethylpyrrolidine (5l). Colourless oil (6.4 mg, 20%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.93 (s, 2H), 5.55 (ddt, *J* = 17.2, 10.4, 7.1 Hz, 1H), 4.96 (d, *J* = 10.2 Hz, 1H), 4.90 (d, *J* = 17.1 Hz, 1H), 4.03 (ddd, *J* = 11.7, 8.6, 3.6 Hz, 1H), 3.42 (d, *J* = 10.3 Hz, 1H), 2.88 (d, *J* = 10.3 Hz, 1H), 2.65 (s, 6H), 2.37 – 2.31 (m, 1H), 2.29 (s, 3H), 2.02 – 1.91 (m, 1H), 1.87 (dd, *J* = 12.6, 7.6 Hz, 1H), 1.53 (dd, *J* = 12.6, 8.4 Hz, 1H), 1.07 (s, 6H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 142.2, 139.6, 134.5, 134.2, 131.8, 117.5, 61.1, 58.7, 46.1, 39.5, 37.5, 29.7, 26.3, 26.2, 22.9; HRMS (ESI): calcd. for $C_{18}H_{28}NO_2S$ $[M+H]^+$ 322.1841, found 322.1836; IR (KBr disc) ν/cm^{-1}: 2957, 2925, 2855, 1604, 1457, 1319, 1151, 1059, 918, 851, 800, 672, 593; HPLC Daicel ChiralPak OD-H, *n*-hexane/*i*-PrOH = 99/1, 230 nm, 1 mL/min, t_{R1} = 8.5 min (major), t_{R2} = 10.1 min (minor), ee = 29%; $[\alpha]_D^{25}$ = –3.6 (*c* 0.4, $CHCl_3$).

(–)-2-Allyl-4,4-dimethyl-1-(naphthalen-1-ylsulfonyl)pyrro lidine (5m). Yellowish oil (6.6 mg, 20%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.88 (d, *J* = 8.6 Hz, 1H), 8.28 (dd, *J* = 7.4, 1.1 Hz, 1H), 8.07 (d, *J* = 8.2 Hz, 1H), 7.94 (d, *J* = 7.9 Hz, 1H), 7.71 – 7.65 (m, 1H), 7.61 (t, *J* = 7.0 Hz, 1H), 7.58 – 7.53 (m, 1H), 5.66 – 5.53 (m, 1H), 5.05 – 4.92 (m, 2H), 4.05 (ddd, *J* = 16.3, 8.9, 3.4 Hz, 1H), 3.44 (dd, *J* = 10.3, 1.3 Hz, 1H), 3.08 (d, *J* = 10.3 Hz, 1H), 2.66 – 2.62 (m, 1H), 2.32 – 2.18 (m, 1H), 1.75 (ddd, *J* = 12.6, 7.2, 1.3 Hz, 1H), 1.52 (dd, *J* = 12.7, 8.9 Hz, 1H), 1.04 (s, 3H), 0.70 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 135.4, 134.3, 134.0, 133.9, 129.4, 129.0, 128.9, 127.9, 126.7, 125.2, 124.1, 117.7, 61.3, 59.2, 45.8, 39.9, 29.7, 26.0, 25.7; HRMS (ESI): calcd. for $C_{19}H_{24}NO_2S$ $[M+H]^+$ 330.1528, found 330.1533; IR (KBr disc) ν/cm^{-1}: 3061, 2960, 2853, 1507, 1371, 1417, 1319, 1262, 1200, 1132, 919, 803, 679, 636, 600, 577, 524; HPLC Daicel ChiralPak OD-H, *n*-hexane/*i*-PrOH = 99/1, 230 nm, 1 mL/min, t_{R1} = 17.8 min (minor), t_{R2} = 21.3 min

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(major), ee = 25%; $[\alpha]_D^{25}$ = –1.9 (*c* 0.5, $CHCl_3$).

(–)-2-Allyl-1-(2,4-dimethylphenylsulfonyl)pyrrolidine (5n). Colourless oil (8.4 mg, 30%). ^{1}H NMR (400 MHz, $CDCl_3$, observed as a mixture of rotamers): δ 7.82 (d, *J* = 8.5 Hz, 1H, major), 7.78 (d, *J* = 8.0 Hz, 1H, minor), 7.10 (brs, 2H, major), 7.08 (d, *J* = 6.7 Hz, 2H, minor), 5.74 – 5.59 (m, 1H, major), 5.40 – 5.35 (m, 1H, minor), 5.02 – 4.97 (m, 4H, both), 4.24 – 4.17 (m, 1H, minor), 3.93 – 3.89 (m, 1H, major), 3.36 – 3.32 (m, 2H, both), 3.25 – 3.21 (m, 2H, both), 2.61 (s, 3H, major), 2.57 (s, 3H, minor), 2.45 – 2.38 (m, 1H, major), 2.36 (s, 3H, major), 2.35 (s, 3H, minor), 2.17 – 2.11 (m, 1H, major), 1.90 – 1.82 (m, 2H, both), 1.81 – 1.70 (m, 2H, both); ^{13}C NMR (101 MHz, $CDCl_3$): δ 143.2, 137.9, 134.7, 134.5 133.3, 132.9, 130.9, 130.2, 129.8, 126.9, 126.6, 126.3, 117.5, 61.4, 59.0, 48.5, 47.9, 40.0, 33.3, 30.4, 29.7, 24.2, 21.2, 20.5; HRMS (ESI): calcd. for $C_{15}H_{22}NO_2S$ $[M+H]^+$ 280.1371, found 280.1378; IR (KBr disc) ν/cm^{-1}: 2074, 2963, 2925, 2855, 1640, 1604, 1448, 1261, 1062, 1026, 918, 873, 818, 662, 590, 552, 405; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 90/10, 230 nm, 1 mL/min, t_{R1} = 29.8 min (major), t_{R2} = 31.0 min (minor), ee = 23%; $[\alpha]_D^{25}$ = –14.4 (*c* 0.1, $CHCl_3$).

(+)-2-Allyl-1-(2,4-dimethylphenylsulfonyl)-4,4-diphenylpyrrolidine (5o). White solid (41.4 mg, 96%). m.p. 114.1 – 115.7 ℃; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.84 (d, *J* = 8.7 Hz, 1H), 7.33 – 7.16 (m, 10H), 7.09 (d, *J* = 7.2 Hz, 2H), 5.68 – 5.53 (m, 1H), 5.01 (d, *J* = 10.1 Hz, 1H), 4.89 (d, *J* = 17.1 Hz, 1H), 4.31 (d, *J* = 10.4 Hz, 1H), 4.02 – 3.96 (m, 1H), 3.96 (d, *J* = 10.4 Hz, 1H), 2.84 (ddd, *J* = 12.6, 7.2, 0.9 Hz, 1H), 2.56 (s, 3H), 2.55 – 2.49 (m, 2H), 2.39 (s, 3H), 1.99 – 1.86 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 145.4, 144.6, 143.2, 137.6, 135.7, 134.1, 133.4, 129.6, 128.6, 128.5, 126.7, 126.6, 126.58, 126.52, 118.0, 58.7, 58.0, 52.6, 42.8, 39.1, 21.3, 20.5; HRMS (ESI): calcd. for $C_{27}H_{30}NO_2S$ $[M+H]^+$ 432.1997, found 432.1991; IR (KBr disc) ν/cm^{-1}: 3060, 3025, 2974, 2925, 1602, 1496, 1447, 1322, 1156, 1059, 1030, 919, 820, 751, 701, 665, 585, 552; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 90/10, 240 nm, 1 mL/min, t_{R1} = 21.1 min (major), t_{R2} = 24.2 min (minor), ee = 43%; $[\alpha]_D^{25}$ = +11.2 (*c* 0.1, $CHCl_3$).

(+)-2-Allyl-1-(2,4-dimethylphenylsulfonyl)-5,5-diphenylpiperidine (5p). Colourless oil (27.6 mg, 62%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.91 (d, *J* = 8.0 Hz, 1H), 7.21 (t, *J* = 7.5 Hz, 2H), 7.13 (d, *J* = 7.4 Hz, 2H), 7.09 – 7.03 (m, 3H), 6.97 (dd, *J* = 14.1, 6.2 Hz, 3H), 6.81 (d, *J* = 7.2 Hz, 2H), 5.781 – 5.70 (m, 1H), 5.15 – 5.07 (m, 2H), 4.07 – 4.05 (m, 1H), 4.01 (dd, *J* = 13.4, 2.2 Hz, 1H), 3.47 (d, *J* = 13.3 Hz, 1H), 2.82 – 2.69 (m, 1H), 2.55 – 2.44 (m, 2H), 2.41 (s, 3H), 2.32 – 2.20 (m, 1H), 2.13 (s, 3H), 1.82 – 1.77 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 147.5, 143.5, 143.0, 138.8, 134.7, 133.8, 133.6, 130.8, 128.4, 128.1, 127.1, 126.4, 126.3, 126.1, 125.6, 117.6, 51.7, 48.6, 45.7, 33.7, 28.7, 22.7, 21.3, 19.6; HRMS (ESI): calcd. for $C_{28}H_{32}NO_2S$ $[M+H]^+$ 446.2154, found 446.2148; IR (KBr disc) ν/cm^{-1}: 3076, 2958, 2871, 1730, 1641, 1490, 1464, 1391, 1371, 1318, 1210, 1154, 1069, 957, 818, 700, 614, 535, 465; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 90/10, 240 nm, 1 mL/min, t_{R1} = 20.4 min (minor), t_{R2} = 24.0 min (major), ee = 32%; $[\alpha]_D^{25}$ = +14.7 (*c* 0.2, $CHCl_3$).

(–)-Benzyl 2-allyl-2-methyl-4,4-diphenylpyrrolidine-1-carboxylate (5q).[10] Colourless oil (37.9 mg, 92%). ^{1}H NMR (400 MHz, $CDCl_3$, observed as a mixture of rotamers): δ 7.47 – 7.12 (m, 30H, both), 5.74 – 5.59 (m, 2H, both), 5.21 (s, 4H, both), 5.03 (d, *J* = 10.2 Hz, 2H, both), 4.96 (d, *J* = 17.0 Hz, 1H, major), 4.90 (d, *J* = 17.0 Hz, 1H, minor), 4.67 (d, *J* = 11.9 Hz, 1H, minor), 4.54 (d, *J* = 11.7 Hz, 1H, major), 3.87 – 3.82 (m, 2H, both), 2.98 – 2.92 (m, 2H, both), 2.63 – 2.28 (m, 6H, both), 1.62 (s, 2H, both), 1.12 (s, 3H, major), 1.02 (s, 3H, minor); ^{13}C NMR (101 MHz, $CDCl_3$): δ 154.8, 153.3, 146.2, 146.1, 146.0, 145.9, 137.3, 136.6, 134.1, 133.8, 128.5, 128.5, 128.47, 128.45, 128.44, 128.0, 127.9, 127.8, 127.7, 126.8, 126.7, 126.6, 126.5, 126.3, 126.2, 126.1, 118.8, 118.7, 67.1, 66.3, 63.3, 62.6, 56.8, 56.2, 50.9, 50.4, 50.1, 48.9, 44.5, 43.2, 26.2, 24.9; HPLC Daicel ChiralPak OZ-H, hexane/*i*-PrOH = 99/1, 210 nm, 1 mL/min, t_{R1} = 5.7 min (major), t_{R2} = 9.2 min (minor), ee = 3%; $[\alpha]_D^{25}$ = –10.3 (*c* 0.6, $CHCl_3$).

(–)-7-Allyl-6-(2,4-dimethylphenylsulfonyl)-6-azaspiro[3.4]octane (5r). Colourless oil (16.6 mg, 52%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83 (d, *J* = 8.6 Hz, 1H), 7.10 – 7.08 (m, 2H), 5.70 – 5.56 (m, 1H), 5.04 – 4.94 (m, 2H), 3.93 – 3.84 (m, 1H), 3.43 (d, *J* = 9.9 Hz, 1H), 3.20 (d, *J* = 10.1 Hz, 1H), 2.62 (s, 3H), 2.55 – 2.44 (m, 1H), 2.36 (s, 3H), 2.17 – 2.06 (m, 1H), 2.02 – 1.93 (m, 3H), 1.89 – 1.79 (m, 4H), 1.75 (dd, *J* = 12.7, 6.1 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 143.5, 142.7, 138.0, 134.7, 133.5, 130.1, 126.9, 117.8, 59.8, 59.1, 44.6, 43.5, 40.2, 32.1, 31.6, 21.5, 20.8, 16.4; HRMS (ESI): calcd. for $C_{18}H_{26}NO_2S$ $[M+H]^+$ 320.1684, found 320.1675; IR (KBr disc) ν/cm^{-1}: 3075, 2927, 2855, 1641, 1604, 1447, 1317, 1138, 1060, 1024, 968, 919, 819, 662, 590, 554; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 90/10, 230 nm, 1 mL/min, t_{R1} = 19.1 min (major), t_{R2} = 20.9 min (minor), ee = 33%; $[\alpha]_D^{25}$ = –12.6 (*c* 0.2, $CHCl_3$).

(–)-3-Allyl-2-(2,4-dimethylphenylsulfonyl)-2-azaspiro[4.4]nonane (5s). Colourless oil (24.3 mg, 73%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83 (d, *J* = 8.7 Hz, 1H), 7.10 – 7.08 (m, 2H), 5.68 – 5.55 (m, 1H), 5.04 – 4.92 (m, 2H), 3.96 – 3.89 (m, 1H), 3.37 (d, *J* = 10.1, 1H), 3.03 (d, *J* = 10.1 Hz, 1H), 2.62 (s, 3H), 2.58 – 2.50 (m, 1H), 2.36 (s, 3H), 2.19 – 2.09 (m, 1H), 1.91 (ddd, *J* = 12.5, 7.4, 1.2 Hz, 1H), 1.65 (dd, *J* = 12.6, 7.8 Hz, 1H), 1.63 – 1.50 (m, 8H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 143.4, 137.8, 135.8, 134.6, 133.5, 129.9, 126.8, 117.7, 60.0, 59.5, 49.0, 44.2, 40.1, 37.2, 36.6, 25.0, 24.8, 21.5, 20.8; HRMS (ESI): calcd. for $C_{19}H_{28}NO_2S$ $[M+H]^+$ 334.1841, found 334.1831; IR (KBr disc) ν/cm^{-1}: 3075, 2950, 2864, 1641, 1604, 1570, 1448, 1312, 1138, 1062, 994, 918, 820, 662, 589, 553; HPLC Daicel ChiralPak IE, *n*-hexane/*i*-PrOH = 95/5, 230 nm, 1 mL/min, t_{R1} = 24.6 min (major), t_{R2} = 26.7 min (minor), ee = 32%; $[\alpha]_D^{25}$ = –12.0 (*c* 0.3, $CHCl_3$).

(–)-3-Allyl-2-(2,4-dimethylphenylsulfonyl)-2-azaspiro[4.5]decane (5t). Colourless oil (33.4 mg, 96%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83 (d, *J* = 8.6 Hz, 1H), 7.09 – 7.07 (m, 2H), 5.66 – 5.55 (m, 1H), 5.02 – 4.91 (m, 2H), 3.95 – 3.88 (m, 1H), 3.52 (d, *J* = 10.6 Hz, 1H), 2.92 (d, *J* = 10.6 Hz, 1H), 2.61 (s, 3H), 2.54 – 2.45 (m, 1H), 2.35 (s, 3H), 2.16 – 2.06 (m, 1H), 1.89 (dd, *J* = 12.8, 7.5 Hz, 1H), 1.45 (dd, *J* = 12.8, 8.4 Hz, 1H), 1.44 – 1.26 (m, 10H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 143.3, 137.8, 136.9, 134.4, 133.5, 129.8, 126.8, 117.8, 59.0, 58.5, 43.8, 41.8, 40.2, 36.6, 34.5, 26.2, 24.0, 23.0, 21.5, 20.8; HRMS (ESI): calcd. for $C_{20}H_{30}NO_2S$ $[M+H]^+$ 348.1997, found 348.1991; IR (KBr disc) ν/cm^{-1}: 3075, 2923, 2855, 1640, 1604, 1452, 1317, 955, 917, 891, 819, 737, 666, 591, 552; HPLC Daicel ChiralPak IE, *n*-hexane/*i*-PrOH = 95/5, 230 nm, 1 mL/min, t_{R1} = 25.0 min (major), t_{R2} = 27.2 min (minor), ee = 35%; $[\alpha]_D^{25}$ = –9.2 (*c* 0.3, $CHCl_3$).

(–)-3-Allyl-2-(2,4-dimethylphenylsulfonyl)-2-azaspiro[4.6]undecane (5u). Colourless oil (33.3 mg, 92%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.82 (d, *J* = 8.6 Hz, 1H), 7.09 – 7.07 (m, 2H), 5.64 – 5.54 (m, 1H), 4.99 – 4.92 (m, 2H), 3.95 – 3.88 (m, 1H),

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3.48 (d, J = 10.3 Hz, 1H), 2.91 (d, J = 10.3 Hz, 1H), 2.61 (s, 3H), 2.52 – 2.46 (m, 1H), 2.35 (s, 3H), 2.15 – 2.04 (m, 1H), 1.92 (dd, J = 12.6, 7.3 Hz, 1H), 1.60 – 1.41 (m, 12H); ^{13}C NMR (101 MHz, $CDCl_3$): δ 143.2, 137.7, 136.3, 134.4, 133.5, 129.7, 126.8, 117.8, 60.8, 59.1, 45.7, 44.8, 40.1, 39.1, 37.4, 29.7, 29.6, 24.3, 23.5, 21.5, 20.8; HRMS (ESI): calcd. for $C_{21}H_{32}NO_2S$ $[M+H]^+$ 362.2154, found 362.2150; IR (KBr disc) ν/cm^{-1}: 3075, 2923, 2855, 1640, 1604, 1460, 1318 1235, 1139, 1060, 1020, 917, 819, 672, 591, 552; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 95/5, 230 nm, 1 mL/min, t_{R1} = 29.4 min (major), t_{R2} = 31.3 min (minor), ee = 36%; $[\alpha]_D^{25}$ = –10.9 (*c* 0.6, $CHCl_3$).

(+)-Benzyl 1-vinylisoindoline-2-carboxylate (5v).[10] Colourless oil (21.7 mg, 74%). ^{1}H NMR (400 MHz, $CDCl_3$, observed as a 1:1 mixture of rotamers): δ 7.43 – 7.32 (m, 8H, both), 7.29 – 7.16 (m, 10H, both), 5.60 – 5.44 (m, 2H, both), 5.31 – 5.14 (m, 4H, both), 5.04 – 4.85 (m, 4H, both), 4.84 – 4.73 (m, 2H, both), 4.60 (d, J = 14.8 Hz, 2H, both), 2.95 – 2.86 (m, 1H, rotamer A), 2.82 – 2.71 (m, 1H, rotamer B), 2.71 – 2.62 (m, 1H, rotamer A), 2.62 – 2.53 (m, 1H, rotamer B); ^{13}C NMR (101 MHz, $CDCl_3$): δ 154.8, 154.5, 140.3, 140.0, 136.9, 136.7, 136.6, 136.4, 132.9, 132.7, 128.5, 128.4, 128.1, 128.0, 127.9, 127.8, 127.6, 127.5, 127.3, 127.2, 122.8, 122.6, 122.5, 122.3, 118.6, 118.5, 67.1, 66.7, 63.2, 62.6, 52.7, 52.3, 39.6, 38.3; HPLC Daicel ChiralPak IC-3, *n*-hexane/*i*-PrOH = 98/2, 210 nm, 1 mL/min, t_{R1} = 19.2 min (major), t_{R2} = 21.1 min (minor), ee = 9%; $[\alpha]_D^{25}$ = +0.7 (*c* 0.3, $CHCl_3$).

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P-Stereogenic PNP Pincer-Pd Catalyzed Intramolecular Hydroamination of Amino-1,3-dienes

Zehua Yang[a], Chao Xia[a], Delong Liu[a], Yangang Liu[a], Masashi Sugiya[b], Tsuneo Imamoto[b,c,*] and Wanbin Zhang[a,d,*]

A new P-stereogenic PNP pincer-Pd complex was readily prepared and was used in the asymmetric intramolecular hydroamination of amino-1,3-dienes, with the desired products being obtained in good yields and with excellent regioselectivities and up to moderate enantioselectivities.