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PLANAR CHIRAL PHOSPHINO[2.2]PARACYCLOPHANOL-CATALYZED HIGHLY REGIO- AND STEREOSELECTIVE [3+2] ANNULATION REACTION OF MORITA–BAYLIS–HILLMAN CARBONATES WITH DICYANOMETHYLIDENEOXINDOLES

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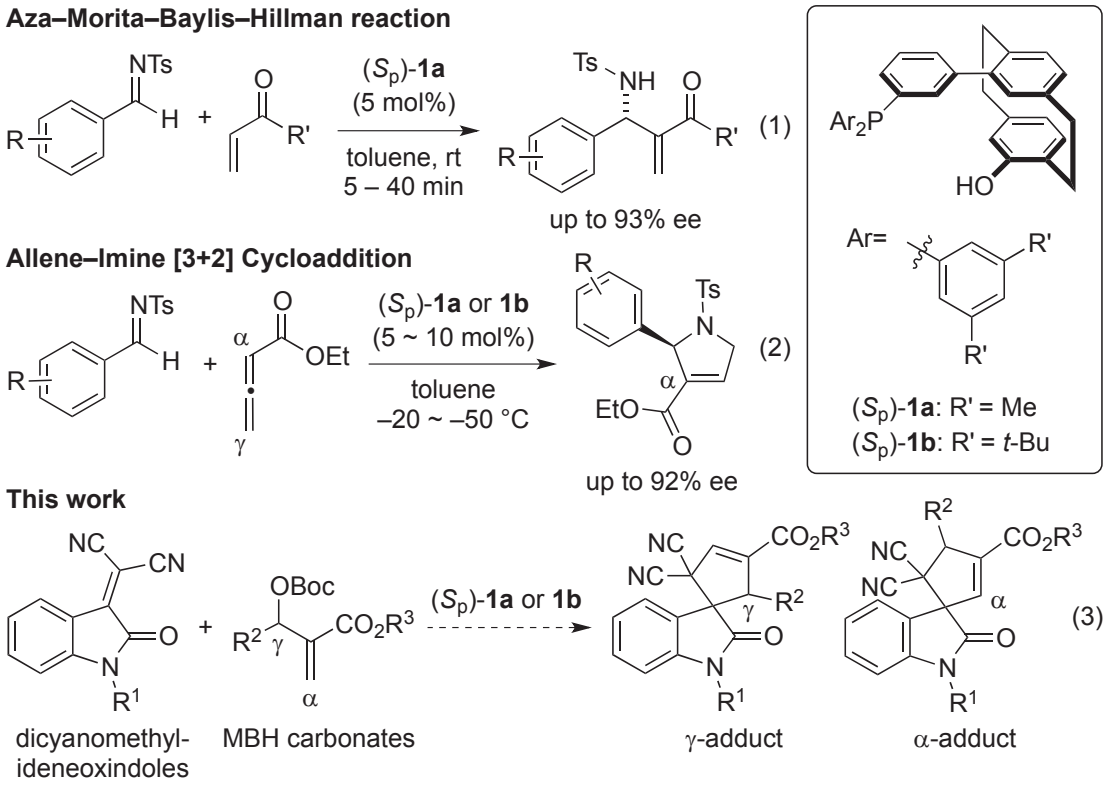
‡This paper is dedicated to Professor Dr. Kaoru Fuji on celebration of his 80th birthday.

Abstract – To demonstrate the utility of [2.2]paracyclophane as a chiral organocatalyst backbone, we examined a planar chiral pseudo-*ortho*-diarylphosphino[2.2]paracyclophanol, phosphino-PCP-ol, which has a spacer aryl group between the pseudo-*ortho*-substituted PCP-ol backbone and the diarylphosphino group. We tested this catalyst in the [3+2] annulation reaction of Morita–Baylis–Hillman carbonates, derived from aromatic aldehydes and methyl acrylate, with 3-(dicyanomethylidene)-2-oxindole. The catalyst produced the desired 3-spirocyclopentene-2-oxindoles in high yields, and high regio-, diastereo-, and enantioselectivities.

INTRODUCTION

[2.2]Paracyclophane (PCP) is recognized as a useful planar chiral backbone for ligands used in transition metal catalysts.[1] A variety of asymmetric reactions based on catalysts with planar chiral PCP-based ligands, combined with appropriate central chirality, have been reported to date.[2] However, there is little information available on the development of PCP-based organocatalysts.[3] In this context, we have developed phosphino-PCP-ol catalysts (S_p)-**1**, which have a spacer aryl group between the pseudo-*ortho*-substituted PCP-ol backbone and the diarylphosphino group (Scheme 1). The planar chiral triarylphosphine (S_p)-**1a** exhibits a high reactivity and good enantioselectivity in the aza-Morita–Baylis–Hillman (MBH) reaction of *N*-tosylaldimines with vinyl ketones (Scheme 1, eq. 1).[4] The catalysts (S_p)-**1a**

and **1b** also catalyze the [3+2] annulations of allenoates with *N*-tosylaldimines, affording 2,5-dihydropyrroles in high yields and good to high enantioselectivities (eq. 2).[5] We now report an extension of the application of the catalysts (S_p)-**1** to [3+2] annulation of MBH carbonates with 3-(dicyanomethylidene)-2-oxindoles (eq. 3).



Scheme 1. Application of Planar Chiral [2.2]Paracyclophane-based Phosphine-Phenol Catalysts

The MBH carbonates have densely functionalized structures, which enable the construction of complex molecules as valuable substrates. Various transformations of MBH carbonates have been developed, and attention has been drawn to the phosphine-catalyzed annulation reactions, such as [3+2], [3+4], [3+6], and [1+4] annulations, wherein the MBH carbonates serve as 1,3- or 1,1-dipoles.[6] However, the development of asymmetric variants of these reactions has not kept pace. One reason for this slow progress is that MBH carbonates have lower reactivity toward phosphine-catalyzed annulations than do electron-deficient allenes, which also serve as 1,3-dipoles reacting with activated alkenes or imines. We note that among the many [3+2] annulation studies reported since Lu's pioneering work,[7] the phosphino-PCP-ol catalysts (S_p)-**1** are likely to work well because among triarylphosphines, these catalysts have an exceptionally high reactivity towards aza-MBH reactions.[4] In addition, we selected 3-(dicyanomethylidene)-2-oxindole as a reaction partner alkene (Scheme 1, eq. 3) because [3+2] adducts obtained in the reaction include a 3-spirocyclopentane-2-oxindole core, which is found in many natural

products and synthetic bioactive compounds (Figure 1).[8] Shi[9] and Lu[10] independently published two excellent reports on this reaction at almost the same time. The former group developed the highly regio- and diastereoselective annulation reaction of the MBH carbonates with ethyl ester and 3-(dicyanomethylidene)-2-oxindoles catalyzed by achiral triphenylphosphine or 1,4-bis(diphenylphosphino)butane, dppb, and also reported one example of an asymmetric version using a chiral phosphine-thiourea catalyst. The latter group achieved a highly enantioselective [3+2] annulation of the MBH carbonates with *tert*-butyl ester catalyzed by amino acid-derived chiral phosphine-thioureas. However, when *o*-substituted aromatic or heteroaromatic or aliphatic aldehyde-derived MBH carbonates were used, the catalysts induced annulation in low to moderate regioselectivity (γ/α selectivity). Therefore, the development of catalysts based on a new type of scaffold would be desirable to extend the usefulness of these annulation reactions.[11]

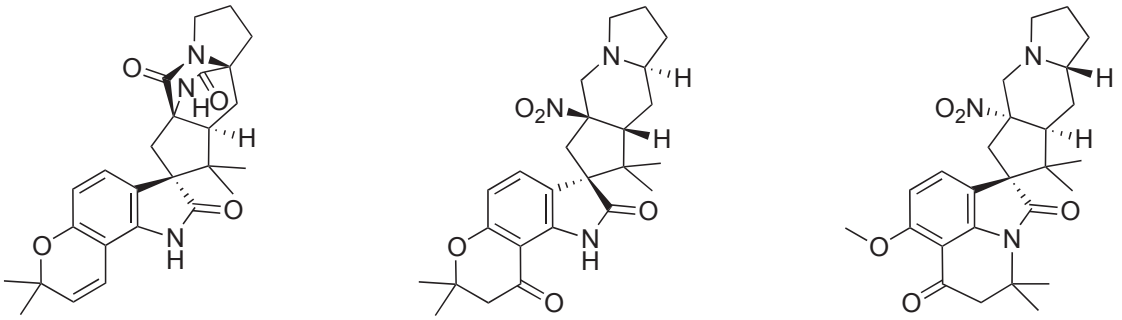


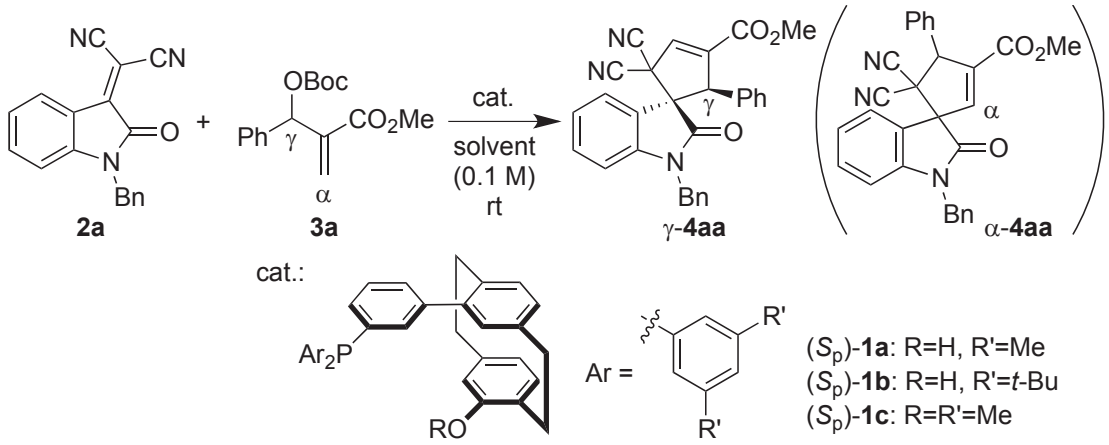
Figure 1. Natural Products Bearing Spirocyclopentaneoxindole Structure

RESULTS AND DISCUSSION

We started by evaluating the phosphino-PCP-ol catalyst (S_p)-**1a** with the xylyl group in the reaction of *N*-benzyl-3-(dicyanomethylidene)-2-oxindole (**2a**) and MBH carbonate **3a**, derived from benzaldehyde and methyl acrylate (Table 1). A reaction with 5 mol% of (S_p)-**1a** in toluene at room temperature completed within 30 min to provide the γ-adduct γ-**4aa** in quantitative yield with 56% ee (entry 2). Neither the diastereomer nor α-adduct were detected in the reaction mixture. The use of a more polar solvent, such as THF and acetonitrile, slowed the reaction rate and decreased both the diastereo- and enantioselectivity (entries 5 and 6). Among the solvents examined, dichloromethane (DCM) was most effective in terms of enantioselectivity albeit with a slightly prolonged reaction time and decreased diastereoselectivity (entries 1–9). The hydroxy group-masked catalyst (S_p)-**1c** resulted in markedly lower reactivity and diastereo- and enantioselectivity, which suggested that the hydroxy group is an important feature of the catalyst (S_p)-**1a** (entry 10). The catalyst (S_p)-**1b** with two bulky *tert*-butyl groups also slowed the reaction, although the diastereoselectivity improved, and the ee of the major product was

almost unchanged (entry 9 vs 11). The use of molecular sieves slightly improved the stereoselectivities but prolonged the reaction time (entry 12).

Table 1. Optimization of Reaction Conditions



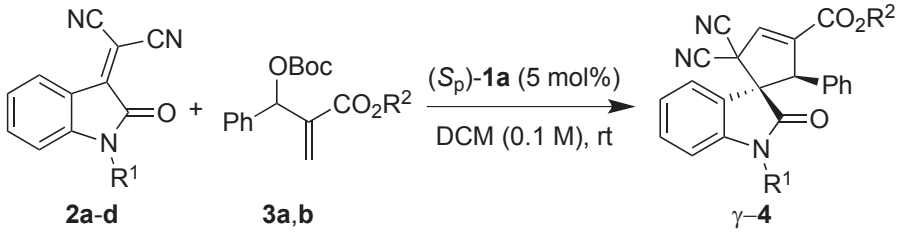
entry	cat. (mol%)	solvent	time	yield (%)[a]	dr[b]	% ee of major[c]
1	(S_p)-**1a** (10)	toluene	15 min	>99	>19:1	55
2	(S_p)-**1a** (5)	toluene	30 min	97	>19:1	56
3	(S_p)-**1a** (10)	C_6H_5Cl	15 min	>99	>19:1	50
4[d]	(S_p)-**1a** (10)	$C_6H_5CF_3$	1 h	>99	16:1	51
5	(S_p)-**1a** (5)	THF	22 h	>99	12:1	43
6	(S_p)-**1a** (5)	MeCN	2 h	>99	1.1:1	45
7	(S_p)-**1a** (10)	DCE	1 h	>99	6.1:1	56
8	(S_p)-**1a** (5)	$CHCl_3$	1 h	>99	19:1	58
9	(S_p)-**1a** (5)	DCM	50 min	>99	8.1:1	64
10	(S_p)-**1c** (5)	DCM	22 h	>99	1.5:1	–17
11	(S_p)-**1b** (5)	DCM	48 h	>99	>19:1	61
12[e]	(S_p)-**1a** (5)	DCM	80 min	>99	9:1	67

[a] Isolated yield of a mixture of diastereoisomers. [b] Determined by ^{1}H NMR analysis of the crude products. [c] Determined by HPLC analysis of the purified product. [d] The reaction was performed at the substrate concentration of 0.05 M. [e] MS 4Å (30 mg) was added. DCE: 1,2-dichloroethane.

To improve the enantioselectivity, we performed simple protecting group manipulations of the dicyanomethylideneoxindole **2** and MBH carbonate **3** using 5 mol% of (S_p)-**1a** in DCM at room temperature. However, replacement of the benzyl group in **2a** with PMB (*p*-methoxybenzyl) gave similar results in terms of yield and selectivities. When we used the *N*-methyl-protected **2**, diastereoselectivity markedly decreased, and the *N*-acetyl substrate also had decreased reactivity (Table 2, entries 1–4). The MBH adduct **3b** with *tert*-butyl ester was not a suitable substrate for the catalyst (S_p)-**1a**, in contrast to Lu's amino acid-derived catalysts.[10] The structure of the minor product in the reaction of **2b** and **3b** was determined by NMR analysis, including HMBC measurements, to be the diastereoisomer of the known

major product γ-**4bb**[10] rather than the regioisomer. In addition, the absolute configuration of γ-**4bb** was (1*S*,5*S*) based on a comparison of the optical rotation with literature data.[10] We assigned the other products by analogy.

Table 2. Effects of Protecting Groups



2a-**d** **3a**,**b** γ–**4**

entry	R^1 (**2**)	R^2 (**3**)	time	product (**4**)	yield (%)[a]	dr[b]	% ee of major[c]
1	Bn (**2a**)	Me (**3a**)	50 min	**4aa**	>99	8.1:1	64
2	PMB (**2b**)	Me (**3a**)	60 min	**4ba**	>99	8.1:1	63
3[d]	Me (**2c**)	Me (**3a**)	20 min	**4ca**	80	2.4:1	63
4[d,e]	Ac (**2d**)	Me (**3a**)	24 h	**4da**	20	>19:1	50
5	Bn (**2a**)	*t*Bu (**3b**)	23 h	**4ab**	72	1.2:1	42
6	PMB (**2b**)	*t*Bu (**3b**)	48 h	**4bb**	40	1.2:1	43

[a] Isolated yield of a mixture of diastereoisomers. [b] Determined by ^{1}H NMR analysis of the crude products. [c] Determined by HPLC analysis of the purified product. [d] MS 4Å (30 mg) was added. [e] Reaction was performed at reflux.

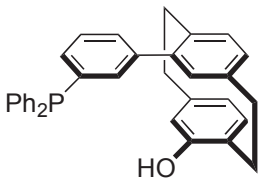
Finally, the effects of reaction temperature were examined in the reactions of **2a** and **3a** under the influence of the catalyst (S_p)-**1a** (10 mol%). Both the diastereomer ratio (>19:1) and ee value (84%) improved in a reaction at –30 °C (Table 3, entry 1). We next explored the substrate generality with respect to MBH carbonates with the optimal reaction conditions. The reaction of MBH carbonates **3c**-**e** and **3g** bearing an electron-withdrawing group at the *para* or *meta* positions on the benzene ring of R proceeded at –50 °C to afford the desired cycloadducts with good to high yields (76%–>99%), high diastereoselectivity (>19:1), and high enantioselectivity (89%–93% ee) (Table 3, entries 2–4, 6). Substrates **3f** and **3h** bearing electron-donating group at the *para* or *meta* position also provided the desired products in good to high yields (72%–>99%) and high selectivities (>19:1, 82%–87% ee) at –30 °C (entries 5 and 7). The use of *o*-fluoro-substituted **3i** maintained the product yield and ee value (86%), although with lower diastereoselectivity (8.1:1) (entry 8). Furthermore, the reaction of the substrate **3j** bearing a bulkier bromo group did not complete even at room temperature, and both the diastereo- and enantioselectivity decreased (entry 9). The use of a less sterically hindered catalyst (S_p)-**1d**[4] improved the enantioselectivity of the major product; however, the reaction did not complete at room

temperature (entry 10). Thienyl derivative **3k** also showed lower reactivity and selectivity than that of the phenyl derivative (entry 11). Unfortunately, aliphatic substrates **3l** and **3m** were unsuitable for this reaction system, and the reaction of **3m** was not complete (entries 12 and 13).

Table 3. Substitution Scope

entry	R (**3**)	temp.	time	product (**4**)	yield (%)[a]	dr[b]	% ee of major[c]
1	Ph (**3a**)	–30 °C	2 d	**4aa**	>99	>19:1	84
2	*p*-$NO_2C_6H_4$ (**3c**)	–50 °C	29 h	**4ac**	76	>19:1	93
3	*p*-CNC_6H_4 (**3d**)	–50 °C	4 d	**4ad**	97	>19:1	93
4	*p*-ClC_6H_4 (**3e**)	–50 °C	4 d	**4ae**	>99	>19:1	92
5	*p*-$MeOC_6H_4$ (**3f**)	–30 °C	7 d	**4af**	72	>19:1	87
6	*m*-BrC_6H_4 (**3g**)	–50 °C	8 d	**4ag**	>99	>19:1	89
7	*m*-MeC_6H_4 (**3h**)	–30 °C	7 d	**4ah**	>99	>19:1	82
8	*o*-FC_6H_4 (**3i**)	–30 °C	8 d	**4ai**	>99	8.1:1	86
9	*o*-BrC_6H_4 (**3j**)	–20 °C to rt	4 d	**4aj**	54	1.8:1	67
10[d]	*o*-BrC_6H_4 (**3j**)	–20 °C to rt	3 d	**4aj**	20	4.3:1	80
11	2-thienyl (**3k**)	–30 °C	7 d	**4ak**	19	1.5:1	68
12	(*E*)-PhCH=CH (**3l**)	rt	5 d	**4al**	80	>19:1	12
13[e]	$PhCH_2CH_2$ (**3m**)	rt	5 d	**4am**	37	3:1	39

[a] Isolated yield of a mixture of diastereoisomers. [b] Determined by ^{1}H NMR analysis of the crude products. [c] Determined by HPLC analysis of the purified product. [d] Catalyst (S_p)-**1d** (10 mol%) was used. [e] Catalyst (S_p)-**1a** (5 mol%) was used.

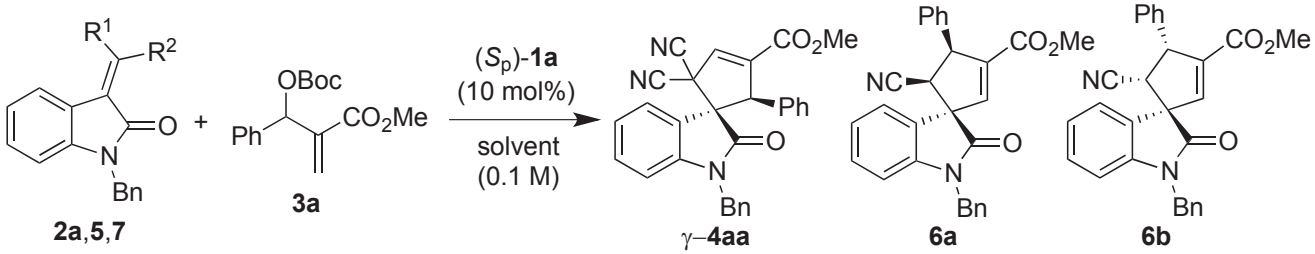


(S_p)-**1d**

The necessity for dicyano substituents in methylideneoxindole was confirmed as follows (Table 4). The (*Z*)-monocyanoalkene (*Z*)-**5** did not undergo (S_p)-**1a**-catalyzed [3+2] annulation with **3a** in DCM at room temperature, and only isomerization to (*E*)-**5** was observed under the conditions (entry 1). The reaction of (*E*)-**5** did not proceed under the same conditions but proceeded in toluene at 50 °C to provide a 1.1:1 mixture of **6a** and **6b** in 74% yield with 25% ee and 3% ee, respectively (entries 2 and 3). Under the same conditions as those for entry 3, dicyanoalkene **2a** afforded γ-**4aa** in 93% yield together with >19:1 dr and 51% ee (entry 4), suggesting that dicyano groups were essential for this highly selective reaction. When

bis(ethoxycarbonyl)alkene **7**[9] was used as the substrate, no reaction occurred even refluxing in toluene, likely because of steric effects (entry 6).

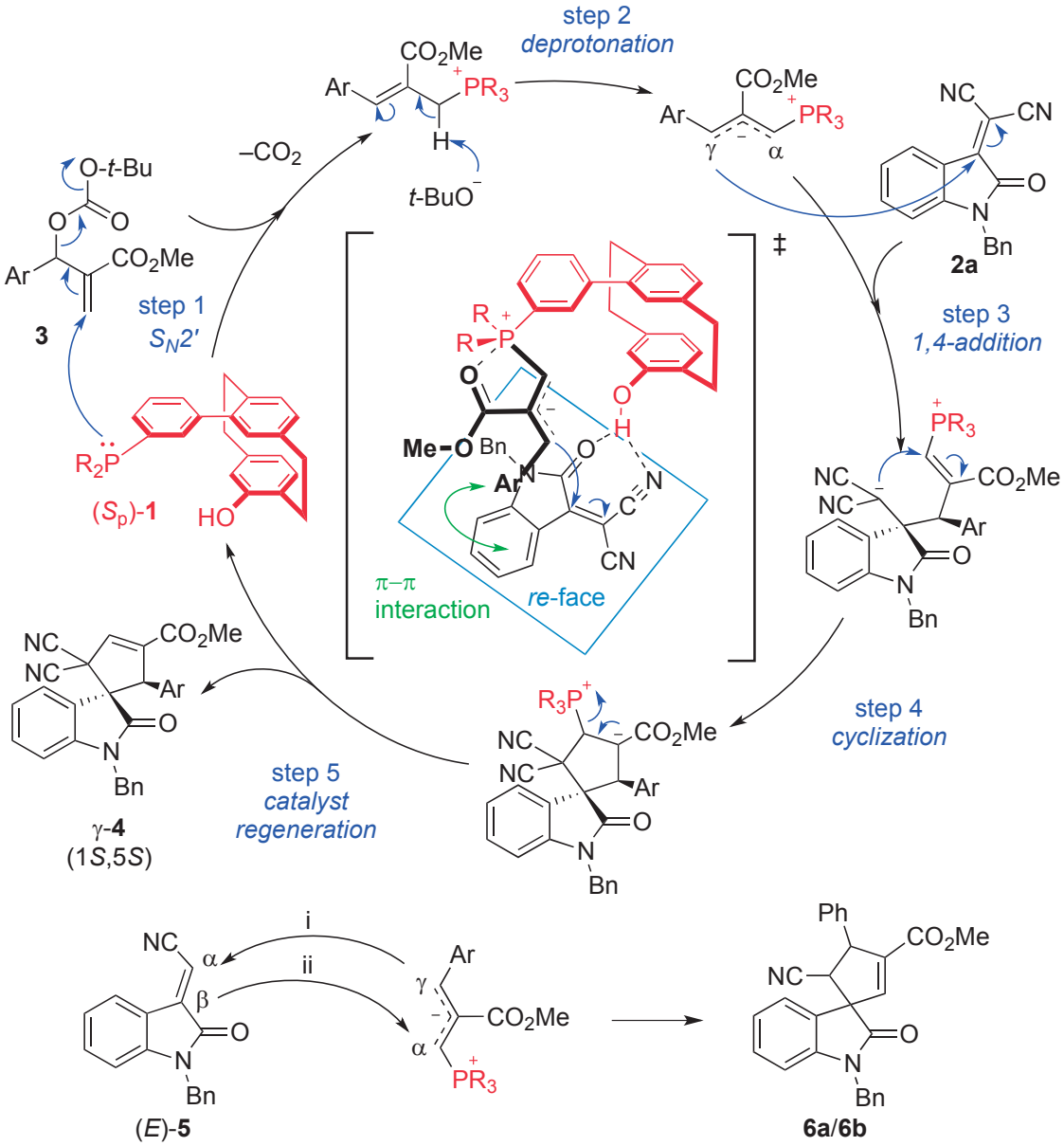
Table 4. Effects of Dicyano Groups



entry	alkene	R^1	R^2	solvent	temp.	time	product	yield (%)[a]	dr[b]	% ee[c]
1	(*Z*)-**5**	H	CN	DCM	rt	2 d	-	NR	-	-
2	(*E*)-**5**	CN	H	DCM	rt	2 d	-	NR	-	-
3	(*E*)-**5**	CN	H	toluene	50 °C	7 h	**6a**/**6b**[d]	74	1.1:1	25/3
4[e]	**2a**	CN	CN	toluene	50 °C	15 min	γ-**4aa**	93	>19:1	51
5	**7**	CO_2Et	CO_2Et	DCM	rt	4 d	-	NR	-	-
6	**7**	CO_2Et	CO_2Et	toluene	110 °C	1 d	-	NR	-	-

[a] Isolated yield of a mixture of diastereoisomers. [b] Determined by ^{1}H NMR analysis of the crude products. [c] Determined by HPLC analysis of the purified product. [d] The structures of **6a** and **6b** were confirmed by HMBC, COSY, and NOESY. Absolute configulation of the products was not determined. [e] Catalyst (5 mol%) was used. NR: no reaction.

The catalytic cycle proposed by Shi[9] and Lu[10] (Scheme 2) consists of five steps. Assuming that the 1,4-addition of the allylic phosphorus ylide, obtained from the phosphine (S_p)-**1a** and MBH carbonate **3**, to dicyanomethylideneoxindole **2** (step 3) is the enantio-differentiation step, the transition state, shown in the middle of the catalytic cycle in Scheme 2, has been proposed to account for the observed stereochemistry. The oxindole **2** might be activated by the phenolic hydroxy group in (S_p)-**1a** through hydrogen-bonding interactions and oriented by π–π interactions with the aryl group of the MBH substrate. Nucleophilic attack from the γ-position of the allylic ylide occurs mainly at the *re*-face of the oxindole C3 position, and subsequent cyclization and catalyst elimination give the (1*S*,5*S*) product γ-**4**. The dicyano substituents in methylideneoxindole **2** ensured the regio- and stereoselective addition of the allylic ylides at the β-position of cyano group in **2**, the monocyano group of **5** might allow the addition of ylides at the α-position of the cyano group due to its steric and electronic properties, causing the reaction to occur in a completely different asymmetric environment from that of **2**.



Scheme 2. Mechanistic Proposal

In summary, we found that the phosphino-PCP-ol catalyst (S_p)-**1a** catalyzed the [3+2] annulation of MBH carbonates and 3-methylidene-2-oxindoles to produce optically active 3-spirocyclopentene-2-oxindoles. The catalyst works particularly well in the reaction of aryl aldehyde-derived MBH carbonates **3** and dicyanomethylidene derivatives **2**, showing high reactivity and selectivity. Although catalyst (S_p)-**1a** was ineffective for MBH carbonates **3** with alkyl or alkenyl groups, the results based on **3** with an aryl group are comparable with those of Lu et al.[10] in terms of the product yield and total selectivities, including regio-, diastereo-, and enantioselectivity. Although *tert*-butyl ester MBH carbonates often give higher selectivity in these reactions, these substrates are not easily prepared. However, the performance of our

catalysts was maintained even for more easily prepared MBH carbonates with a methyl ester group. Further applications of the catalysts (S_p)-**1** in other asymmetric reactions are currently underway.

EXPERIMENTAL

General Information: Melting point (mp) was measured by Yanaco melting point apparatus MP-500D and uncorrected. Optical rotations were measured on a JASCO P-2200. IR spectra were measured with a JASCO FT/IR-4100 spectrometer for samples in $CHCl_3$. ^1H NMR and ^{13}C NMR spectra were recorded by a Bruker Avance III 600 spectrometer operating at 600 MHz (150 MHz for ^{13}C NMR) at 25 °C with tetramethylsilane (δ = 0.0 ppm) as an internal standard. The data are reported as follows: chemical shift in ppm (δ), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet), integration, and coupling constant (Hz). High resolution mass spectra were measured with a Thermo Scientific Exactive Plus Orbitrap. Analytical thin-layer chromatography (TLC) was performed on MERCK silica gel, grade 60 F_{254}. The spots and bands were detected by UV light of irradiation (254 nm) and/or by staining with 5% phosphomolybdic acid followed by heating. Column chromatography for isolation of the products was carried out on KANTO Sillica Gel 60 (230-400 mesh). HPLC analyses were performed using Interigent UV/VIS Detector JASCO UV-2075 Plus and UV-4075. The chiral columns included CHIRALPAK AD-H, AS-H and IA-3 (Daicel Chemical Industries, Ltd., 0.46 Φ × 25 cm).

All the 3-(dicyanomethylidene)-2-oxindoles (**2a-d)** and compounds **5** and **7** were prepared from the corresponding isatins following the literature procedures.[12] The MBH carbonates were synthesized following the literature method.[13]

General procedure for the [3+2] annulation of 2a and 3a in Table 1

Methyl 1'-benzyl-2,2-dicyano-2'-oxo-5-phenylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4aa): The following reaction was carried out under Ar. To a stirred solution of **2a** (14.3 mg, 5.00×10^{-2} mmol) in dry solvent (0.5 mL or 1.0 mL) were added **3a** (21.7 mg, 7.42×10^{-2} mmol) and catalyst (5 or 10 mol%). After being stirred at rt for 0.25-48 h, the mixture was concentrated under reduced pressure. The residue was purified by flash column chromatography (EtOAc/hexane, 1:4) to provide γ-**4aa** as yellow solids. mp 163-166 °C; IR ($CHCl_3$): 1613, 1721, 2360, 3032 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 3.76 (s, 3H), 4.37 (d, 1H, J = 16.2 Hz), 4.883 (d, 1H, J = 16.2 Hz), 4.884 (d, 1H, J = 3.0 Hz), 6.47 (d, 2H, J = 7.8 Hz), 6.51 (dd, 1H, J = 0.6, 7.8 Hz), 6.84 (d, 2H, J = 7.2 Hz), 6.95 (d, 1H, J = 3.0 Hz), 7.09 (t, 2H, J = 7.8 Hz), 7.14-7.18 (m, 3H), 7.23-7.31 (m, 3H), 7.91 (dd, 1H, J = 0.6, 7.2 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 43.8, 45.8, 52.6, 58.0, 65.3, 110.1, 111.5, 111.8, 122.2, 123.6, 125.1, 126.5 (2C), 127.5, 128.37, 128.40 (2C), 128.6 (2C), 128.7 (2C), 131.2, 132.6, 132.8, 134.1, 143.5, 143.9, 162.6, 171.0; HPLC analysis: AD-H column; λ = 230 nm; 2-propanol/hexane = 20/80; flow rate 1.0 mL/min; t_R (min) = 27.7 for minor,

t_R (min) = 32.0 for major. Compound γ-**4aa** was determined to be 84% ee (show the best data of γ-**4aa** in Table 3, entry 1); HRMS (DART) calcd for $C_{29}H_{22}N_3O_3$ [*M*+H]$^+$: 460.1656, found: 460.1654.

Typical procedure for the asymmetric [3+2] annulation of 2b and 3a (Table 2, entry 2)

Methyl 2,2-dicyano-1'-(4-methoxybenzyl)-2'-oxo-5-phenylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ba): The following reaction was carried out under Ar. To a stirred solution of **2b** (15.5 mg, 4.92×10^{-2} mmol) in CH_2Cl_2 (0.5 mL) were added **3a** (21.6 mg, 7.39×10^{-2} mmol) and catalyst (S_p)-**1a** (1.35 mg, 2.50×10^{-3} mmol). After being stirred at rt for 1 h, the mixture was concentrated under reduced pressure. The residue was purified by flash column chromatography (EtOAc/hexane, 1:3) to provide γ-**4ba (**25.6 mg, >99%) as yellow solids. mp 91-94 °C; IR ($CHCl_3$): 1613, 1721, 2360, 3030 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.74 (s, 3H), 3.75 (s, 3H), 4.33 (d, 1H, *J* = 15.6 Hz), 4.78 (d, 1H, *J* = 15.6 Hz), 4.87 (d, 1H, *J* = 3.0 Hz), 6.44 (d, 2H, *J* = 8.4 Hz), 6.54 (dd, 1H, *J* = 0.6, 7.8 Hz), 6.63 (d, 2H, *J* = 8.4 Hz), 6.83 (d, 2H, *J* = 7.8 Hz), 6.95 (d, 1H, *J* = 3.0 Hz), 7.15 (t, 2H, *J* = 8.4 Hz), 7.21-7.32 (m, 3H), 7.89 (dd, 1H, *J* = 0.6, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 43.3, 45.8, 52.6, 55.2, 58.0, 65.2, 110.2, 111.5, 111.8, 114.1 (2C), 122.2, 123.6, 125.1, 126.2, 128.0 (2C), 128.3, 128.4 (2C), 128.6 (2C), 131.1, 132.6, 132.8, 143.5, 143.9, 158.9, 162.6, 171.0; HPLC analysis: AD-H column; λ = 230 nm; 2-propanol/hexane = 20/80; flow rate 1.0 mL/min; t_R (min) = 34.9 for minor, t_R (min) = 43.2 for major. Compound γ-**4ba** was determined to be 63% ee; HRMS (DART) calcd for $C_{30}H_{24}N_3O_4$ [*M*+H]$^+$: 490.1761, found: 490.1764.

Methyl 2,2-dicyano-1'-methyl-2'-oxo-5-phenylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ca): A yellow solid (15.4 mg, 80%); mp 82-85 °C; IR ($CHCl_3$): 1613, 1722, 2360, 3031 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.80 (s, 3H), 3.75 (s, 3H), 4.78 (d, 1H, *J* = 2.4 Hz), 6.72 (d, 2H, *J* = 8.4 Hz), 6.74 (d, 1H, *J* = 7.2 Hz), 6.93 (d, 1H, *J* = 2.4 Hz), 7.10 (t, 2H, *J* = 7.8 Hz), 7.18 (td, 1H, *J* = 1.2, 7.8 Hz), 7.28 (td, 1H, *J* = 1.2, 7.8 Hz), 7.44 (td, 1H, *J* = 1.2, 7.8 Hz), 7.89 (dd, 1H, *J* = 1.2, 7.2 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 26.1, 45.1, 52.6, 58.6, 65.2, 108.8, 111.5, 111.7, 122.5, 123.6, 124.9, 128.0 (2C), 128.1 (2C), 128.3, 131.2, 132.6, 132.9, 143.5, 144.3, 162.6, 170.7; HPLC analysis: AD-H column; λ = 230 nm; 2-propanol/hexane = 30/70; flow rate 0.5 mL/min; t_R (min) = 22.0 for major, t_R (min) = 32.4 for minor. Compound γ-**4ca** was determined to be 63% ee; HRMS (DART) calcd for $C_{23}H_{18}N_3O_3$ [*M*+H]$^+$: 384.1343, found: 384.1342.

Methyl 1'-acetyl-2,2-dicyano-2'-oxo-5-phenylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4da): A yellow solid (4.1 mg, 20%); mp 71-74 °C; IR ($CHCl_3$): 1605, 1732, 1755, 2360, 3031 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.26 (s, 3H), 3.77 (s, 3H), 4.82 (d, 1H, *J* = 3.0 Hz), 6.69 (d, 2H, *J* = 7.2 Hz), 6.96 (d, 1H, *J* = 3.0 Hz), 7.15 (t, 2H, *J* = 7.8 Hz), 7.23 (t, 1H, *J* = 7.8 Hz), 7.45 (td, 1H, *J* = 1.2, 7.8 Hz), 7.52 (td, 1H, *J* = 1.2, 7.8 Hz), 7.96 (dd, 1H, *J* = 0.6, 7.8 Hz), 8.12 (dd, 1H, *J* = 0.6, 7.8 Hz); ^{13}C NMR

(150 MHz, $CDCl_3$): δ 26.1, 45.9, 52.8, 60.1, 65.6, 111.1, 111.5, 116.8, 121.8, 124.5, 126.2, 128.0 (2C), 128.5 (2C), 128.9, 131.6, 132.0, 132.7, 140.8, 143.1, 162.3, 169.6, 172.3; HPLC analysis: AD-H column; λ = 230 nm; 2-propanol/hexane = 30/70; flow rate 1.0 mL/min; t_R (min) = 6.3 for major, t_R (min) = 7.6 for minor. Compound γ-**4da** was determined to be 50% ee; HRMS (DART) calcd for $C_{24}H_{18}N_3O_4$ $[M+H]^+$: 412.1292, found: 412.1292.

***tert*-Butyl 1'-benzyl-2,2-dicyano-2'-oxo-5-phenylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ab):** A yellow solid (18.2 mg, 72%); mp 93-96 °C; IR ($CHCl_3$): 1613, 1719, 2360, 3032 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 1.32 (s, 9H), 4.35 (d, 1H, *J* = 16.2 Hz), 4.81 (d, 1H, *J* = 2.7 Hz), 4.92 (d, 1H, *J* = 16.2 Hz), 6.45 (d, 2H, *J* = 7.2 Hz), 6.51 (dd, 1H, *J* = 1.2, 7.2 Hz), 6.85 (d, 1H, *J* = 2.7 Hz), 6.86 (d, 2H, *J* = 7.2 Hz), 7.09 (t, 2H, *J* = 7.8 Hz), 7.12-7.18 (m, 3H), 7.22-7.30 (m, 3H), 7.92 (dd, 1H, *J* = 1.2, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 27.7 (3C), 43.8, 45.7, 58.3, 65.4, 83.1, 110.1, 111.8, 112.0, 122.4, 123.6, 125.2, 126.5 (2C), 127.4, 128.2, 128.3 (2C), 128.7 (2C), 128.8 (2C), 131.0, 131.4, 133.4, 134.2, 143.4, 145.8, 161.2, 171.2; HPLC analysis: AS-H column; λ = 230 nm; 2-propanol/hexane = 20/80; flow rate 1.0 mL/min; t_R (min) = 12.6 for minor, t_R (min) = 15.3 for major. Compound γ-**4ab** was determined to be 42% ee; HRMS (DART) calcd for $C_{32}H_{28}N_3O_3$ $[M+H]^+$: 502.2125, found: 502.2123.

***tert*-Butyl 2,2-dicyano-1'-(4-methoxybenzyl)-2'-oxo-5-phenylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4bb):** A yellow solids (5.3 mg, 20%); $[\alpha]^{26}_D$ –68.1 (*c* 0.20 in $CHCl_3$); {ref. 10 (1*S*,5*S*)-γ-**4bb**; $[\alpha]^{25}_D$ –164.1 (*c* 1.00 in $CHCl_3$) for 96% *ee*}; ^1H NMR (600 MHz, $CDCl_3$): δ 1.32 (s, 9H), 3.74 (s, 3H), 4.33 (d, 1H, *J* = 16.2 Hz), 4.80 (d, 1H, *J* = 2.4 Hz), 4.81 (d, 1H, *J* = 16.2 Hz), 6.42 (d, 2H, *J* = 9.0 Hz), 6.53 (dd, 1H, *J* = 0.6, 7.8 Hz), 6.62 (dt, 2H, *J* = 2.4, 9.0 Hz), 6.82-6.88 (m, 3H), 7.15 (t, 2H, *J* = 7.8 Hz), 7.21-7.31 (m, 3H), 7.90 (dd, 1H, *J* = 0.6, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 27.7 (3C), 43.3, 45.7, 55.2, 58.3, 65.4, 83.1, 110.1, 111.8, 112.1, 114.1 (2C), 122.4, 123.5, 125.1, 126.2, 127.9 (2C), 128.1, 128.2 (2C), 128.8 (2C), 131.0, 131.4, 133.4, 143.5, 145.8, 158.8, 161.2, 171.1; HPLC analysis: AD-H column; λ = 254 nm; 2-propanol/hexane = 15/85; flow rate 1.0 mL/min; t_R (min) = 20.7 for minor, t_R (min) = 23.3 for major. Compound γ-**4bb** was determined to be 43% ee.

Diastereoisomer of γ-4bb: A yellow solids (5.4 mg, 21%); mp 164-166 °C; IR ($CHCl_3$): 1612, 1719, 2360, 2929 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 1.23 (s, 9H), 3.78 (s, 3H), 4.74 (d, 1H, *J* = 15.6 Hz), 5.11 (d, 1H, *J* = 15.6 Hz), 5.59 (d, 1H, *J* = 2.7 Hz), 6.55 (d, 1H, *J* = 2.7 Hz), 6.85-6.90 (m, 3H), 7.18 (t, 1H, *J* = 7.8 Hz), 7.34 (d, 2H, *J* = 8.4 Hz), 7.36 (td, 1H, *J* = 0.6, 7.8 Hz), 7.40-7.48 (m, 5H), 7.69 (d, 1H, *J* = 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 27.6 (3C), 44.4, 52.1, 55.3, 58.7, 64.3, 82.7, 110.3, 111.9, 113.1, 114.4 (2C), 123.5, 123.8, 126.4, 127.1, 128.8 (2C), 128.9 (2C), 129.1 (2C), 129.2, 131.3, 134.5, 139.7, 143.1, 143.3, 159.5, 161.6, 171.5; HRMS (DART) calcd for $C_{33}H_{30}N_3O_4$ $[M+H]^+$: 532.2231, found: 532.2231.

Typical procedure for the asymmetric [3+2] annulation of 2a and 3c (Table 3, entry 2)

Methyl 1'-benzyl-2,2-dicyano-5-(4-nitrophenyl)-2'-oxospiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ac): The following reaction was carried out under Ar. To a cooled (–50 °C) stirred solution of **2a** (14.0 mg, 4.91×10^{-2} mmol) in dry CH_2Cl_2 (0.5 mL) were added **3c** (26.7 mg, 7.92×10^{-2} mmol) and catalyst (S_p)-**1a** (2.7 mg, 10 mol%). After being stirred at –50 °C for 29 h, the mixture was concentrated under reduced pressure. The residue was purified by PTLC (acetone/hexane, 1:3) to provide γ-**4ac** (18.8 mg, 76%) as yellow solids. The dr value was determined by the ^{1}H NMR spectroscopic data of the crude product (>19:1). mp 185-188 °C; IR ($CHCl_3$): 1612, 1730, 2360, 3030 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (s, 3H), 4.43 (d, 1H, *J* = 15.6 Hz), 4.80 (d, 1H, *J* = 15.6 Hz), 4.92 (d, 1H, *J* = 2.7 Hz), 6.64 (d, 2H, *J* = 7.8 Hz), 6.71 (d, 1H, *J* = 7.8 Hz), 6.95 (d, 2H, *J* = 7.8 Hz), 7.03 (d, 1H, *J* = 2.7 Hz), 7.06 (t, 2H, *J* = 7.8 Hz), 7.14 (t, 1H, *J* = 7.8 Hz), 7.30 (td, 1H, *J* = 1.2, 7.8 Hz), 7.39 (td, 1H, *J* = 1.2, 7.8 Hz), 7.90-7.95 (m, 3H); ^{13}C NMR (150 MHz, $CDCl_3$): δ 44.0, 45.9, 52.9, 57.4, 64.9, 110.2, 111.1, 111.4, 121.5, 123.3 (2C), 124.1, 125.2, 126.9 (2C), 128.0, 128.6 (2C), 129.5 (2C), 131.7, 133.9, 134.0, 140.0, 142.5, 143.4, 147.8, 162.1, 170.6; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 30/70; flow rate 1.0 mL/min; t_R (min) = 18.2 for major, t_R (min) = 24.7 for minor. Compound γ-**4ac** was determined to be 93% ee; HRMS (DART) calcd for $C_{29}H_{21}N_4O_5$ [*M*+H]$^+$: 505.1506, found: 505.1508.

Methyl 1'-benzyl-2,2-dicyano-5-(4-cyanophenyl)-2'-oxospiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ad): A yellow solid (23.2 mg, 97%); mp 214-216 °C; IR ($CHCl_3$): 1613, 1731, 2329, 2360, 3029 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (s, 3H), 4.41 (d, 1H, *J* = 15.6 Hz), 4.83 (d, 1H, *J* = 15.6 Hz), 4.88 (d, 1H, *J* = 2.7 Hz), 6.60 (d, 2H, *J* = 7.8 Hz), 6.66 (d, 1H, *J* = 7.8 Hz), 6.92 (d, 2H, *J* = 7.8 Hz), 7.02 (d, 1H, *J* = 2.7 Hz), 7.18 (t, 2H, *J* = 7.8 Hz), 7.25 (t, 1H, *J* = 7.8 Hz), 7.28 (t, 1H, *J* = 7.8 Hz), 7.37 (td, 1H, *J* = 0.6, 7.8 Hz), 7.39 (d, 2H, *J* = 7.8 Hz), 7.90 (d, 1H, *J* = 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 44.0, 45.9, 52.8, 57.6, 65.0, 110.3, 111.1, 111.4, 112.5, 118.2, 121.5, 124.0, 125.2, 126.7 (2C), 128.1, 128.8 (2C), 129.4 (2C), 131.7, 132.0 (2C), 133.8, 134.0, 138.1, 142.5, 143.4, 162.1, 170.6; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 30/70; flow rate 1.0 mL/min; t_R (min) = 20.0 for major, t_R (min) = 26.3 for minor. Compound γ-**4ad** was determined to be 93% ee; HRMS (DART) calcd for $C_{30}H_{21}N_4O_3$ [*M*+H]$^+$: 485.1608, found: 485.1608.

Methyl 1'-benzyl-5-(4-chlorophenyl)-2,2-dicyano-2'-oxospiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ae): A yellow solid (24.8 mg, >99%); IR ($CHCl_3$): 1613, 1720, 1731, 2360, 3030 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.77 (s, 3H), 4.37 (d, 1H, *J* = 15.9 Hz), 4.84 (d, 1H, *J* = 3.0 Hz), 4.96 (d, 1H, *J* = 15.9 Hz), 6.52 (dd, 2H, *J* = 1.2, 7.8 Hz), 6.57 (d, 1H, *J* = 7.8 Hz), 6.77 (d, 2H, *J* = 8.7 Hz), 6.96 (d, 1H, *J* = 3.0 Hz), 7.12 (d, 2H, *J* = 8.7 Hz), 7.16-7.22 (m, 3H), 7.25 (td, 1H, *J* = 1.2, 7.8 Hz), 7.31 (td, 1H, *J* = 1.2, 7.8 Hz), 7.89 (dd, 1H, *J* = 1.2, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 43.9, 45.8, 52.7, 57.2, 65.2,

110.2, 111.3, 111.7, 121.8, 123.8, 125.1, 126.5 (2C), 127.7, 128.7 (2C), 128.8 (2C), 130.0 (2C), 131.35, 131.42, 133.1, 134.0, 134.5, 143.3, 143.5, 162.4, 170.9; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 25/75, flow rate 1.0 mL/min; t_R (min) = 18.6 for major, t_R (min) = 21.3 for minor. Compound γ-**4ae** was determined to be 92% ee; HRMS (DART) calcd for $C_{29}H_{21}ClN_3O_3$ [*M*+H]$^+$: 494.1266, found: 494.1265.

Methyl 1'-benzyl-2,2-dicyano-5-(4-methoxyphenyl)-2'-oxospiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4af): A yellow solid (17.5 mg, 72%); mp 121-124 °C; IR ($CHCl_3$): 1613, 1719, 1731, 2360, 3031 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.74 (s, 3H), 3.76 (s, 3H), 4.36 (d, 1H, *J* = 15.9 Hz), 4.85 (d, 1H, *J* = 3.0 Hz), 4.97 (d, 1H, *J* = 15.9 Hz), 6.48 (d, 2H, *J* = 7.2 Hz), 6.53 (d, 1H, *J* = 7.8 Hz), 6.67 (d, 2H, *J* = 8.7 Hz), 6.76 (d, 2H, *J* = 8.7 Hz), 6.92 (d, 1H, *J* = 3.0 Hz), 7.10 (t, 2H, *J* = 7.2 Hz), 7.16 (t, 1H, *J* = 7.2 Hz), 7.24 (td, 1H, *J* = 1.2, 7.8 Hz), 7.29 (td, 1H, *J* = 1.2, 7.8 Hz), 7.89 (dd, 1H, *J* = 1.2, 7.2 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 43.8, 45.6, 52.6, 55.0, 57.4, 65.3, 110.1, 111.6, 111.9, 113.8 (2C), 122.3, 123.6, 124.7, 125.1, 126.5 (2C), 127.5, 128.6 (2C), 129.8 (2C), 131.1, 132.3, 134.1, 143.5, 144.0, 159.6, 162.7, 171.2; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 30/70, flow rate 1.0 mL/min; t_R (min) = 11.3 for major, t_R (min) = 16.9 for minor. Compound γ-**4af** was determined to be 87% ee; HRMS (DART) calcd for $C_{30}H_{24}N_3O_4$ [*M*+H]$^+$: 490.1761, found: 490.1761.

Methyl 1'-benzyl-5-(3-bromophenyl)-2,2-dicyano-2'-oxospiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ag): A yellow solid (29.4 mg, >99%); mp 152-154 °C; IR ($CHCl_3$): 1613, 1721, 2360, 3030 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (s, 3H), 4.41 (d, 1H, *J* = 15.9 Hz), 4.81 (d, 1H, *J* = 3.0 Hz), 4.89 (d, 1H, *J* = 15.9 Hz), 6.58-6.62 (m, 3H), 6.81 (d, 1H, *J* = 7.8 Hz), 6.92 (s, 1H), 6.97 (d, 1H, *J* = 3.0 Hz), 7.01 (t, 1H, *J* = 7.8 Hz), 7.14-7.21 (m, 3H), 7.26 (td, 1H, *J* = 1.2, 7.8 Hz), 7.33 (td, 1H, *J* = 1.2, 7.8 Hz), 7.38 (d, 1H, *J* = 7.8 Hz), 7.88 (dd, 1H, *J* = 1.2, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 43.9, 45.8, 52.7, 57.5, 65.1, 110.2, 111.3, 111.6, 121.9, 122.2, 123.9, 125.0, 126.6 (2C), 127.3, 127.7, 128.8 (2C), 129.9, 131.4, 131.5, 131.6, 133.2, 134.1, 135.1, 143.2, 143.4, 162.3, 170.8; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 15/85; flow rate 1.0 mL/min; t_R (min) = 52.8 for minor, t_R (min) = 63.4 for major. Compound γ-**4ag** was determined to be 89% ee; HRMS (DART) calcd for $C_{29}H_{21}BrN_3O_3$ [*M*+H]$^+$: 538.0761, found: 538.0763.

Methyl 1'-benzyl-2,2-dicyano-2'-oxo-5-(*m*-tolyl)spiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ah): A yellow solid (25.0 mg, >99%); mp 177-180 °C; IR ($CHCl_3$): 1613, 1721, 2360, 3030 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 2.13 (s, 3H), 3.76 (s, 3H), 4.34 (d, 1H, *J* = 16.2 Hz), 4.84 (d, 1H, *J* = 2.7 Hz), 4.93 (d, 1H, *J* = 16.2 Hz), 6.46 (d, 2H, *J* = 7.8 Hz), 6.51 (dd, 1H, *J* = 1.2, 7.8 Hz), 6.60 (s, 1H), 6.65 (d, 1H, *J* = 7.8 Hz), 6.93 (d, 1H, *J* = 2.7 Hz), 7.04 (t, 1H, *J* = 7.8 Hz), 7.06-7.12 (m, 3H), 7.16 (t, 1H, *J* = 7.8 Hz), 7.24 (td, 1H, *J* = 1.2, 7.8 Hz), 7.28 (td, 1H, *J* = 1.2, 7.8 Hz), 7.89 (dd, 1H, *J* = 1.2, 7.8 Hz); ^{13}C NMR

(150 MHz, $CDCl_3$): δ 21.3, 43.8, 45.8, 52.6, 58.1, 65.3, 110.0, 111.6, 111.9, 122.4, 123.6, 125.1, 125.7, 126.5 (2C), 127.5, 128.3, 128.7 (2C), 129.1, 129.2, 131.1, 132.4, 132.7, 134.2, 138.0, 143.5, 144.0, 162.7, 171.0; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 18/82; flow rate 1.0 mL/min; t_R (min) = 29.7 for minor, t_R (min) = 34.9 for major. Compound γ-**4ah** was determined to be 82% ee; HRMS (DART) calcd for $C_{30}H_{24}N_3O_3$ $[M+H]^+$: 474.1812, found: 474.1814.

Methyl 1'-benzyl-2,2-dicyano-5-(2-fluorophenyl)-2'-oxospiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ai): A yellow solid (26.3 mg, >99%); mp 85-88 °C; IR ($CHCl_3$): 1614, 1730, 2360, 3030 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 3.76 (s, 3H), 4.45 (d, 1H, *J* = 15.6 Hz), 4.95 (d, 1H, *J* = 15.6 Hz), 5.24 (brs, 1H), 6.58 (d, 1H, *J* = 7.8 Hz), 6.63 (d, 2H, *J* = 7.2 Hz), 6.87 (t, 1H, *J* = 9.0 Hz), 6.98 (d, 1H, *J* = 2.4 Hz), 7.02 (brs, 1H), 7.12 (t, 2H, *J* = 7.2 Hz), 7.17 (t, 1H, *J* = 7.2 Hz), 7.22 (td, 1H, *J* = 1.2, 7.8 Hz), 7.24-7.28 (m, 2H), 7.30 (td, 1H, *J* = 1.2, 7.8 Hz), 7.85 (d, 1H, *J* = 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 43.9, 46.2, 52.6 (2C), 64.5, 110.0, 111.4, 111.5, 115.5, 120.5 (d, *J* = 13.5 Hz), 122.4, 123.6, 124.2 (d, *J* = 3.0 Hz), 125.5, 126.7 (2C), 127.6, 128.7 (2C), 130.1 (d, *J* = 7.5 Hz), 130.7, 131.2, 132.8, 134.3, 143.0, 143.5, 160.6 (d, *J* = 247.5 Hz), 162.3, 170.9; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 20/80; flow rate 1.0 mL/min; t_R (min) = 25.4 for minor, t_R (min) = 36.4 for major. Compound γ-**4ai** was determined to be 86% ee; HRMS (DART) calcd for $C_{29}H_{21}FN_3O_3$ $[M+H]^+$: 478.1561, found: 478.1561.

Methyl 1'-benzyl-5-(2-bromophenyl)-2,2-dicyano-2'-oxospiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4aj): A yellow solid (14.2 mg, 54%); mp 123-126 °C; IR ($CHCl_3$): 1613, 1731, 2360, 3030 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 3.73 (s, 3H), 4.61 (d, 1H, *J* = 15.6 Hz), 4.88 (d, 1H, *J* = 15.6 Hz), 5.47 (d, 1H, *J* = 2.4 Hz), 6.65 (d, 1H, *J* = 7.8 Hz), 6.80 (d, 2H, *J* = 7.8 Hz), 7.04 (d, 1H, *J* = 2.4 Hz), 7.13-7.22 (m, 5H), 7.25 (td, 1H, *J* = 1.2, 7.8 Hz), 7.28-7.34 (m, 2H), 7.44 (dd, 1H, *J* = 1.2, 7.8 Hz), 7.80 (dd, 1H, *J* = 1.2, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 44.1, 46.9, 52.7, 56.6, 63.6, 110.0, 111.2, 111.4, 123.4, 123.7, 125.0, 125.9, 126.9 (2C), 127.6, 127.7, 128.8 (2C), 130.0, 130.7, 131.1, 132.96, 133.03, 133.1, 134.4, 142.9, 144.6, 162.0, 170.3; HPLC analysis: AS-H column; λ = 230 nm; 2-propanol/hexane = 3/97; flow rate 1.0 mL/min; t_R (min) = 34.5 for minor, t_R (min) = 43.8 for major. Compound γ-**4aj** was determined to be 67% ee; HRMS (DART) calcd for $C_{29}H_{21}BrN_3O_3$ $[M+H]^+$: 538.0761, found: 538.0764.

Methyl 1'-benzyl-2,2-dicyano-2'-oxo-5-(thiophen-2-yl)spiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4ak): A yellow solid (4.2 mg, 19%); mp 177-180 °C; IR ($CHCl_3$): 1614, 1723, 2360, 3030 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 3.79 (s, 3H), 4.52 (d, 1H, *J* = 15.6 Hz), 4.92 (d, 1H, *J* = 15.6 Hz), 5.11 (d, 1H, *J* = 3.0 Hz), 6.60 (d, 1H, *J* = 7.8 Hz), 6.73 (dd, 2H, *J* = 1.2, 7.8 Hz), 6.75 (d, 1H, *J* = 3.6 Hz), 6.88 (dd, 1H, *J* = 3.6, 4.8 Hz), 6.91 (d, 1H, *J* = 3.0 Hz), 7.13 (dd, 1H, *J* = 1.2, 4.8 Hz), 7.15-7.21 (m, 3H), 7.24 (td, 1H, *J* = 1.2, 7.8 Hz), 7.32 (td, 1H, *J* = 1.2, 7.8 Hz), 7.83 (d, 1H, *J* = 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 44.0, 45.5, 52.7, 53.3, 65.0, 110.2, 111.3, 111.7, 122.1, 123.7, 125.0, 125.6, 126.8 (2C),

127.1, 127.6, 127.8, 128.8 (2C), 131.3, 132.1, 134.1, 134.2, 143.5, 143.7, 162.3, 171.1; HPLC analysis: IA-3 column; λ = 254 nm; $CHCl_3$/hexane = 25/75; flow rate 1.0 mL/min; t_R (min) = 24.3 for minor, t_R (min) = 26.9 for major. Compound γ-**4ak** was determined to be 68% ee; HRMS (DART) calcd for $C_{27}H_{20}N_3O_3S$ [*M*+H]$^+$: 466.1220, found: 466.1223.

Methyl (*E*)-1'-benzyl-2,2-dicyano-2'-oxo-5-styrylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4al): A yellow solid (19.5 mg, 80%); mp 105-108 °C; IR ($CHCl_3$): 1613, 1729, 2360, 3030 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 3.78 (s, 3H), 4.80 (d, 1H, *J* = 15.6 Hz), 5.13 (d, 1H, *J* = 15.6 Hz), 5.15 (m, 1H), 6.40 (dd, 1H, *J* = 9.6, 15.6 Hz), 6.59 (d, 1H, *J* = 2.4 Hz), 6.85 (d, 1H, *J* = 7.8 Hz), 6.92 (d, 1H, *J* = 15.6 Hz), 7.19 (td. 1H, *J* = 0.6, 7.8 Hz), 7.28-7.40 (m, 9H), 7.50 (d, 2H, *J* = 7.8 Hz), 7.68 (d, 1H, *J* = 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 44.9, 51.0, 52.4, 56.1, 63.8, 110.3, 111.9, 112.8, 122.0, 123.2, 123.9, 126.8, 127.2 (2C), 127.6 (2C), 128.2, 128.65, 128.69 (2C), 129.0 (2C), 131.4, 134.3, 135.7, 137.8, 140.6, 140.7, 143.3, 162.6, 171.1; HPLC analysis: AD-H column; λ = 230 nm; 2-propanol/hexane = 10/90; flow rate 1.0 mL/min; t_R (min) = 36.8 for minor, t_R (min) = 39.9 for major. Compound γ-**4al** was determined to be 12% ee; HRMS (DART) calcd for $C_{31}H_{24}N_3O_3$ [*M*+H]$^+$: 486.1812, found: 486.1811.

Methyl 1'-benzyl-2,2-dicyano-2'-oxo-5-phenethylspiro[cyclopent[3]ene-1,3'-indoline]-4-carboxylate (γ-4am): A yellow solid (8.9 mg, 37%); mp 125-128 °C; IR ($CHCl_3$): 1613, 1720, 2369, 3031 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ 1.86 (m, 1H), 2.17-2.25 (m, 2H), 2.48 (m, 1H), 3.60 (m, 1H), 3.86 (s, 3H), 4.96 (d, 1H, *J* = 15.6 Hz), 5.01 (d, 1H, *J* = 15.6 Hz), 6.72 (d, 1H, *J* = 3.0 Hz), 6.77 (d, 2H, *J* = 7.8 Hz), 6.89 (d, 1H, *J* = 7.8 Hz), 7.10-7.17 (m, 4H), 7.27-7.31 (m, 3H), 7.34-7.40 (m, 3H), 7.43 (dd, 1H, *J* = 0.6, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 29.3, 33.5, 44.6, 46.4, 50.8, 52.6, 63.2, 110.1, 111.4, 111.8, 123.8, 124.0, 125.2, 126.1, 127.8 (2C), 128.1, 128.2 (2C), 128.3 (2C), 129.0 (2C), 130.9, 131.0, 134.7, 140.1, 142.9, 145.6, 162.7, 171.8; HPLC analysis: AD-H column; λ = 230 nm; 2-propanol/hexane = 20/80; flow rate 1.0 mL/min; t_R (min) = 21.7 for major, t_R (min) = 35.6 for minor. Compound γ-**4am** was determined to be 39% ee; HRMS (DART) calcd for $C_{31}H_{26}N_3O_3$ [*M*+H]$^+$: 488.1969, found: 488.1969.

Typical procedure for the asymmetric [3+2] annulation of (*E*)-5 and 3a (Table 4, entry 3)

Methyl 1'-benzyl-5-cyano-2'-oxo-4-phenylspiro[cyclopent[2]ene-1,3'-indoline]-3-carboxylate (6a and 6b): The following reaction was carried out under Ar. To a stirred solution of **5** (13.0 mg, 4.99×10^{-2} mmol) in toluene (0.5 mL) were added **3a** (23.7 mg, 8.11×10^{-2} mmol) and catalyst (S_p)-**1a** (2.7 mg, 10 mol%). After being stirred at 50 °C for 7 h, the mixture was concentrated under reduced pressure. The residue was separated by PTLC (CH_2Cl_2/hexane, 1:3) to provide pure **6b** (7.7 mg, 36%) as yellow solids and **6a** containing impurities. The mixture was purified again by PTLC (EtOAc/hexane, 4:1) to provid **6a** (8.2 mg, 38%) as yellow solids.

6a: mp 80-83 °C; IR ($CHCl_3$): 1613, 1718, 2350, 3032 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 3.73 (s, 3H), 4.49 (dd, 1H, *J* = 2.1, 10.2 Hz), 4.60 (d, 1H, *J* = 10.2 Hz), 4.81 (d, 1H, *J* = 15.6 Hz), 5.03 (d, 1H, *J* = 15.6 Hz), 6.50 (d, 1H, *J* = 7.2 Hz), 6.90 (t, 1H, *J* = 7.2 Hz), 6.94 (d, 1H, *J* = 7.2 Hz), 7.00 (d, 2H, *J* = 7.2 Hz), 7.02-7.12 (m, 6H), 7.16 (d, 1H, *J* = 2.1 Hz), 7.22-7.26 (m, 3H); ^{13}C NMR (150 MHz, $CDCl_3$): δ 44.2, 52.8, 53.7, 56.5, 66.2, 109.8, 113.3, 118.9, 122.6, 124.9, 125.3, 127.1 (2C), 127.6, 127.8, 128.1 (2C), 128.2 (2C), 128.7 (2C), 129.7, 134.4, 134.8, 142.5, 148.1, 169.9, 175.0; HPLC analysis: AD-H column; λ = 230 nm; 2-propanol/hexane = 20/80; flow rate 1.0 mL/min; t_R (min) = 22.5 for major, t_R (min) = 41.5 for minor. Compound **6a** was determined to be 25% ee; HRMS (DART) calcd for $C_{28}H_{23}N_2O_3$ $[M+H]^+$: 435.1703, found: 435.1703.

6b: A yellow solid; mp 81-84 °C; IR ($CHCl_3$): 1612, 1721, 2360, 3030 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ 3.63 (s, 3H), 3.87 (d, 1H, *J* = 8.4 Hz), 4.79 (dd, 1H, *J* = 1.8, 8.4 Hz), 4.92 (d, 1H, *J* = 15.9 Hz), 5.02 (d, 1H, *J* = 15.9 Hz), 6.58 (d, 1H, *J* = 1.8 Hz), 6.83 (d, 1H, *J* = 7.8 Hz), 7.15 (td, 1H, *J* = 0.6, 7.8 Hz), 7.29-7.35 (m, 8H), 7.39-7.43 (m, 4H); ^{13}C NMR (150 MHz, $CDCl_3$): δ 44.5, 46.5, 52.0, 56.0, 62.0, 110.1, 117.3, 123.7, 124.9, 126.1, 127.1 (2C), 127.3 (2C), 128.0, 128.2, 129.0 (2C), 129.2 (2C), 130.3, 134.9, 139.5, 139.9, 141.3, 142.3, 163.1, 175.1; HPLC analysis: AS-H column; λ = 230 nm; 2-propanol/hexane = 15/85; flow rate 1.0 mL/min; t_R (min) = 19.9 for minor, t_R (min) = 24.3 for major. Compound **6b** was determined to be 3% ee; HRMS (DART) calcd for $C_{28}H_{23}N_2O_3$ $[M+H]^+$: 435.1703, found: 435.1704.

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