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# Cobalt-Catalyzed Asymmetric Olefin Aziridination with Diphenylphosphoryl Azide

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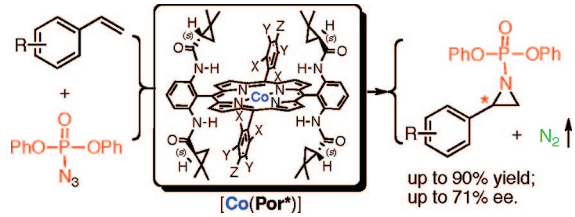


The cobalt(II) complexes of $D_2$-symmetric chiral porphyrins, such as 3,5-Di$^t$Bu-ChenPhyrin **P5**, can catalyze asymmetric olefin aziridination with diphenylphosphoryl azide (DPPA) as a nitrene source. Acceptable asymmetric inductions were observed for the [Co(**P5**)]-based catalytic system, forming the desired *N*-phosphorus-substituted aziridines in moderate to high yields and good enantioselectivities.

## Introduction

The fundamental and practical significance of aziridine derivatives in chemistry and biology have stimulated intensive research activities focused on their syntheses.[1] Among several synthetic schemes, metal-catalyzed aziridination of alkenes with nitrene sources is a method that has received the most attention because of its direct nature and the abundance of alkenes.[2] Despite their general mechanistic similarity, aziridination is a much less developed process than the analogous epoxidation and cyclopropanation reactions partly due to the lack of effective nitrene sources. In the past three decades, several types of nitrogen-containing reagents have been examined as potential nitrene sources for metal-catalyzed aziridination.[1,2] Currently, the most widely used nitrene sources are PhI=NTs and related iminoiodane derivatives,[3] including their in situ variants that have been recently implemented with notable success.[4] Driven by the desire to overcome some of the limitations associated with the use of these hypervalent iodine reagents, growing efforts have been devoted to developing alternative nitrene sources such as chloramine-T,[5] bromamine-T,[6] and tosyloxycarbamates.[7] Along the same line, azides, a broad class of compounds that are widely available or can be easily synthesized,[8] have also been pursued recently by several groups,

* To whom correspondence should be addressed at the University of South Florida. Fax: 813-974-1733.

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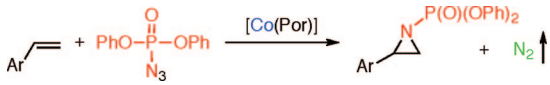
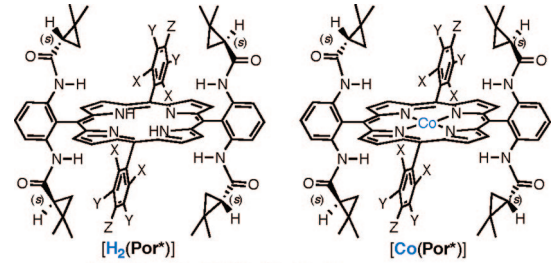
**SCHEME 1. Cobalt-Catalyzed Olefin Aziridination with DPPA**




including Cenini,[9] Katsuki,[10] Driver,[11] and us,[12] as promising nitrene sources for metal-catalyzed nitrene transfer reactions.[13] An additional advantage of using azides as nitrene sources is that environmentally benign dinitrogen is the only byproduct of the process.

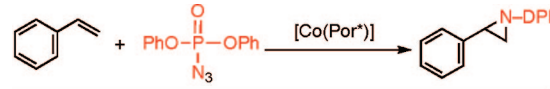
Most of the catalytic aziridination processes produce *N*-sulfonylated aziridines.[1,2] The deprotection of these *N*-sulfonyl groups typically requires harsh conditions.[14] However, commercially available diphenylphosphoryl azide (DPPA)[15] has recently been shown by us as a new nitrene source to form *N*-phosphorylated aziridines via olefin aziridination by a Co-based catalytic system (Scheme 1).[12a] *N*-Phosphorylated and the related *N*-phosphinylated aziridines are more advantageous synthetic building blocks due to the easier deprotection of the *N*-phosphoryl and *N*-phosphinyl groups.[16−18] While the Co-catalyzed aziridination with DPPA represented the first direct preparation of *N*-phosphorus-substituted aziridines from alkenes, the catalyst Co(TPP) that was initially employed suffers from the low-yielding formation of desired products.[12a] To improve its catalytic efficiency as well as to develop its asymmetric variant, we have made considerable efforts to identify chiral porphyrins to support the Co-based catalytic process with hopes of enhancing its activity and selectivity. Herein, we describe the results from our systematic studies regarding the use of $D_2$-symmetric chiral porphyrins (Figure 1) for the Co-based asymmetric olefin aziridination using DPPA. In addition to improved yields under milder conditions, acceptable asymmetric induction has been achieved. This represents the first Co(II)-catalyzed asymmetric aziridination process.




**P1** (ChenPhyrin): X = Y = Z = H
**P2** (2,6-DiMeO-ChenPhyrin): X = MeO; Y = Z = H
**P3** (2,4,6-TriMe-ChenPhyrin): X = Z = Me; Y = H
**P4** (3,5-DiMeO-ChenPhyrin): X = Z = H; Y = MeO
**P5** (3,5-Di$^t$Bu-ChenPhyrin): X = Z = H; Y = *t*-Bu
**P6** (4-$^t$Bu-ChenPhyrin): X = Y = H; Z = *t*-Bu

**FIGURE 1.** Structures of chiral porphyrins and Co(II) complexes.

**TABLE 1. Asymmetric Aziridination of Styrene with Diphenylphosphoryl Azide Catalyzed by Cobalt(II) Complexes of Different Chiral Porphyrins**[a]




| entry | catalyst[b] | temp (°C) | yield (%)[c] | ee (%)[d] |
|---|---|---|---|---|
| 1 | [Co(**P1**)] | 80 | 82 | 10 |
| 2 | [Co(**P2**)] | 60 | 46 | 4 |
| 3 | [Co(**P2**)] | 40 | 24 | 4 |
| 4 | [Co(**P3**)] | 60 | 70 | 11 |
| 5 | [Co(**P3**)] | 40 | 47 | 14 |
| 6 | [Co(**P4**)] | 40 | 75 | 25 |
| 7 | [Co(**P4**)] | 30 | 51 | 33 |
| 8 | [Co(**P5**)] | 40 | 88 | 37[f] |
| 9 | [Co(**P5**)] | 30 | 43 | 39 |
| 10 | [Co(**P6**)] | 40 | 90 | 17 |
| 11 | [Co(**P6**)] | 30 | 61 | 18 |
| 12[e] | Co(TPP) | 80 | 19 | n/a |
| 13[e] | Co(TPP) | 100 | 50 | n/a |

[a] Reactions were carried out for 18 h in chlorobenzene under $N_2$ in the presence of 5 Å molecular sieves using 10 mol % of [Co(Por*)]. Concentration: 0.50 mmol of styrene/1 mL of chlorobenzene. Styrene/azide = 5:1. [b] See Figure 1. [c] Isolated yields. [d] Determined by chiral HPLC. [e] Reference 12a. [f] The optical rotation was measured: $[\alpha]^{20}_D = -79.5$ ($c = 0.088$, $CHCl_3$).

## Results and Discussion

For the aziridination of styrene with DPPA (Table 1), Co(TPP) was previously shown to catalyze the aziridine formation in the highest yield of 50% at 100 °C; lowering the reaction temperature significantly reduced the yields (entries 12 and 13).[12a] A series of $D_2$-symmetric chiral porphyrins (Figure 1), which were synthesized from bromoporphyrins via Pd-mediated quadruple amidations,[19] were employed to improve

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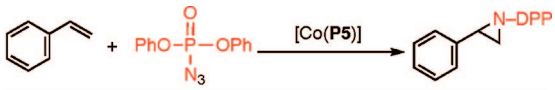
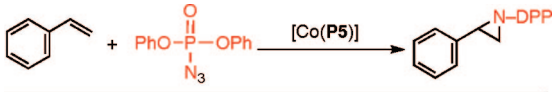
**TABLE 2. Solvent Effect in [Co(P5)]-Catalyzed Asymmetric Aziridination of Styrene with Diphenylphosphoryl Azide[a]**




| entry | solvent | mol (%)[b] | temp (°C) | yield (%)[c] | ee (%)[d] |
|---|---|---|---|---|---|
| 1 | $ClC_6H_5$ | 10 | 40 | 88 | 37 |
| 2 | $ClC_6H_5$ | 5 | 60 | 81 | 29 |
| 3 | $FC_6H_5$ | 5 | 60 | 72 | 31 |
| 4 | $Cl(CH_2)_2Cl$ | 5 | 60 | 49 | 43 |
| 5 | $CH_2Cl_2$ | 5 | 60 | 6 | 36 |
| 6 | $CH_2Cl_2$ | 10 | 40 | 37 | 47 |
| 7 | $MeC_6H_5$ | 5 | 60 | 7 | 32 |
| 8 | $C_6H_6$ | 5 | 60 | 14 | 32 |
| 9 | THF | 5 | 60 | <5 | -- |
| 10 | $CH_3CN$ | 5 | 60 | 0 | -- |

[a] Reactions were carried out for 18 h under $N_2$ in the presence of 5 Å molecular sieves. Concentration: 0.50 mmol of styrene/1 mL of solvent. Styrene/azide = 5:1. [b] Catalyst loading of [Co(**P5**)]. [c] Isolated yields. [d] Determined by chiral HPLC.

**TABLE 3. Axial Ligand Effect in [Co(P5)]-Catalyzed Asymmetric Aziridination of Styrene with Diphenylphosphoryl Azide[a]**

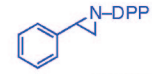
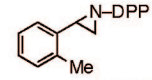
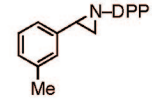
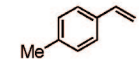
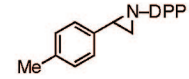
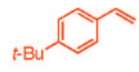
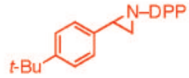
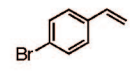
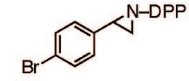
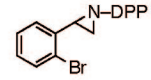
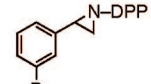
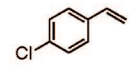
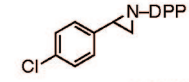
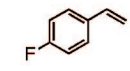
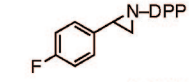
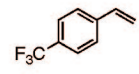
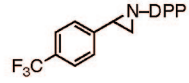
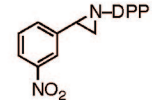



| entry | ligand (mol %)[b] | solvent | yield (%)[c] | ee (%)[d] |
|---|---|---|---|---|
| 1 | none (0) | $ClC_6H_5$ | 88 | 37 |
| 2 | THF (20) | $ClC_6H_5$ | 59 | 32 |
| 3 | *N*-MeIm (12) | $ClC_6H_5$ | 14 | 39 |
| 4 | *N*-MeIm (20) | $ClC_6H_5$ | 15 | 47 |
| 5 | *N*-MeIm (50) | $ClC_6H_5$ | 14 | 51 |
| 6 | 3,5-DiMePy (20) | $ClC_6H_5$ | 15 | 48 |
| 7 | DMAP (5) | $ClC_6H_5$ | 32 | 38 |
| 8 | DMAP (10) | $ClC_6H_5$ | 21 | 55 |
| 9 | DMAP (20) | $ClC_6H_5$ | 20 | 55 |
| 10 | DMAP (20) | $MeC_6H_5$ | 24 | 58 |
| 11 | DMAP (20) | $CH_2Cl_2$ | 20 | 71 |
| 12 | *t*-BuNC (20) | $ClC_6H_5$ | 14 | 62 |

[a] Reactions were carried out for 18 h under $N_2$ at 40 °C in the presence of 5 Å molecular sieves using 10 mol % of [Co(**P5**)]. Concentration: 0.50 mmol of styrene/1 mL of solvent. Styrene/azide = 5:1. [b] Axial ligand mol % relative to azide; *N*-MeIm, *N*-methylimidazole; 3,5-DiMePy, 3,5-dimethylpyridine; DMAP, 4-(dimethylamino)pyridine. [c] Isolated yields. [d] Determined by chiral HPLC.

the catalytic process and to control stereoselectivity. The Co(II) complexes of ChenPhyrin **P1** and its derivatives **P2**−**P6** (Figure 1) were found to be much more effective catalysts than Co(TPP), allowing for aziridination to occur at much lower temperatures (Table 1). For example, the aziridination could be catalyzed by [Co(**P1**)] at 80 °C to afford the desired product in 82% yield, but with a low degree of asymmetric induction (entry 1). The use of more sterically hindered [Co(**P2**)] and [Co(**P3**)] resulted in lower yields without improving the stereocontrol (entries 2−5). Improved enantioselectivities were observed for the reactions catalyzed by [Co(**P4**)] where the 3,5-positions of the *meso*-phenyl groups contain MeO substituents, albeit in lower yields (entries 6 and 7). Changing the 3,5-diMeO to 3,5-di$^t$Bu substituents provided the catalyst [Co(**P5**)] that led to improvements in both enantioselectivity and yield (entries 8 and 9). A further increase in aziridine yield was achieved by employing the less sterically imposing catalyst [Co(**P6**)] but with reduced enantioselectivity (entries 10 and 11).

**TABLE 4. [Co(P5)]-Catalyzed Asymmetric Aziridination of Aromatic Olefins with Diphenylphosphoryl Azide[a]**

| entry | olefin | aziridine | yield (%)[b] | ee (%)[c] |
|---|---|---|---|---|
| 1 |  |  | 88 | 37 |
| 2 |  |  | 35<br>70[d] | 46<br>33[d] |
| 3 |  |  | 52<br>78[d] | 44<br>32[d] |
| 4 |  |  | 58<br>55[d] | 37<br>21[d] |
| 5 |  |  | 77 | 53 |
| 6 |  |  | 65 | 28 |
| 7 |  |  | 68 | 7 |
| 8 |  |  | 58 | 45 |
| 9 |  |  | 64 | 6 |
| 10 |  |  | 39<br>72[d] | 10<br>17[d] |
| 11 |  |  | 64 | 44 |
| 12 |  |  | 58 | 46 |

[a] Reactions were carried out for 18 h in chlorobenzene at 40 °C under $N_2$ in the presence of 5 Å molecular sieves using 10 mol % of [Co(**P5**)]. Concentration: 0.50 mmol of olefin/1 mL of chlorobenzene. Olefin/azide = 5:1. [b] Isolated yields. [c] Determined by chiral HPLC. [d] Carried at 60 °C.

A dramatic solvent effect was observed for the Co-catalyzed asymmetric aziridination, as shown with the [Co(**P5**)]-catalyzed styrene reaction (Table 2). In general, halogenated solvents (entries 1−6) gave better results than the nonhalogenated ones (entries 7 and 8). Potentially coordinating solvents, such as tetrahydrofuran and acetonitrile, were detrimental to the catalytic process (entries 9 and 10). Among various solvents employed, chlorobenzene gave the best yields (entries 1 and 2). Dichloromethane as solvent provided the highest enantioselectivity but lower yields (entries 5 and 6).

A wide range of potentially coordinating reagents were evaluated for a possible axial ligand effect for [Co(**P5**)]-catalyzed aziridination of styrene (Table 3). In accord with its inferiority as a solvent, the addition of a substoichiometric amount of tetrahydrofuran lowered the product yield without significantly influencing the enantioselectivity (entries 1 and 2). A more negative axial ligand effect on yield was observed for the nitrogen-based reagents, such as imidazole and pyridine derivatives, presumably due to their stronger coordinating ability (entries 3−11). Conversely, a considerably positive effect on enantioselectivity was recognized, albeit with lower product yields, through the addition of a substoichiometric amount of DMAP in dichloromethane, which resulted in the near doubling of the enantiomeric excess from 37% to 71% (entries 1 and 11). It is interesting to note a similar effect with *tert*-butyl isocyanide (entry 12).[20]

In addition to styrene, the [Co(**P5**)]-based catalytic system could be applied to a wide range of aromatic olefins (Table 4). For example, styrene derivatives bearing electron-neutral substituents, such as methyl and *tert*-butyl groups, at different positions could be equally aziridinated with DPPA in similar yields and enantioselectivities (entries 1−5). The reactions of styrenes substituted with halogen atoms afforded the *N*-phosphorylated aziridines in good yields but with varied enantioselectivities, depending on the nature of the halogen atom and the position of substitution (entries 6−10). For example, the aziridination of styrenes substituted with an *o*-, *m*-, or *p*-bromo atom provided the corresponding products with 7%, 45%, and 28% ee, respectively (entries 6−8). The catalytic system seemed equally suitable to styrene derivatives containing strongly electron-withdrawing groups, as demonstrated with 4-trifluoromethylstyrene and 3-nitrostyrene, which are often more challenging substrates (entries 11 and 12). However, results indicted that the [Co(**P5**)]/DPPA catalytic system was ineffective for multisubstituted aromatic olefins and aliphatic olefins as well.

## Conclusions

In summary, we have established the first Co-catalyzed asymmetric olefin aziridination system that can employ the commercially available DPPA as a convenient nitrene source. The cobalt(II) complex of 3,5-Di*t*Bu-ChenPhyrin [Co(**P5**)] has been demonstrated to be an effective catalyst for catalyzing the aziridination of a range of aromatic olefins with DPPA under mild conditions, affording the synthetically valuable *N*-phosphorylated aziridines in moderate to good yields with acceptable degree of asymmetric induction. Continued efforts are underway to develop a new generation of chiral porphyrins to improve the Co-based catalytic aziridination system.

## Experimental Section

**General Considerations.** All catalytic reactions were carried out under a nitrogen atmosphere in an oven-dried Schlenk tube. Diphenylphosphoryl azide and all olefins were purchased commerically and used without further purification. Chlorobenzene and dichloromethane were dried with calcium hydride in reflux. Toluene and tetrahydrofuran was distilled under nitrogen from sodium benzophenone ketyl. All other solvents were purchased as anhydrous forms. All chiral metalloporphyrins were synthesized using literature methods.[19] Proton, carbon, fluorine, and phosphorus nuclear magnetic resonance spectra ($^1$H NMR, $^{13}$C NMR, $^{19}$F NMR, and $^{31}$P NMR) were recorded on a Varian Mercury 300 MHz spectrometer or a Varian Inova 400 MHz spectrometer and referenced with respect to residual solvent. Infrared spectra were measured with a Nicolet Avatar 320 spectrometer with a Smart Miracle accessory. HRMS data were measured on an Agilent 1100 LC/MS ESI/TOF mass spectrometer. Enantiomeric excess determination was measured on a Shimadzu LC-20AT HPLC with a SPD-M20A diode array detector using a Pirkle Covalent WHELK-O1 or a Chiralcel AD-H chiral column. Thin-layer chromatography was carried out on E. Merck silica gel 60 F-254 TLC plates.

**General Procedure for Aziridination of Alkenes.** An oven-dried Schlenk tube equipped with a stirring bar was degassed on a vacuum line and purged with nitrogen. The tube was charged with metalloporphyrin (10 mol %) and activated 5 Å molecular sieves (200 mg). The tube was capped with a Teflon screw cap and then evacuated on a vacuum line for 30−45 min. The tube was backfilled with nitrogen, the Teflon screw cap was replaced with a rubber septum, and then 1 mL of solvent, diphenylphosphoryl azide (0.2 mmol), and substrate (1.0 mmol) were added successively, followed by the remaining solvent, giving 2 mL total. The tube was purged with nitrogen for 1−2 min, and the septum was replaced with the Teflon screw cap. The contents were stirred and heated at 40 or 60 °C overnight. After completion of the reaction, the mixture was cooled to room temperature and purified by flash chromatography (silica gel, ethyl acetate/hexanes (v/v) = 3:7) to afford the pure product.

**(2-Phenylaziridin-1-yl)phosphonic acid diphenyl ester.** (Table 4, entry 1)[12a] was synthesized from the reaction of styrene with DPPA at 40 °C and obtained as a yellow oil (61.5 mg, 88% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.27−7.00 (m, 15H), 3.63 (ddd, $J_{P-H}$ = 16.5 Hz, $J_{H-H}$ = 6.3, 3.6 Hz, 1H), 2.82 (ddd, $J_{P-H}$ = 19.5 Hz, $J_{H-H}$ = 6.3, 1.2 Hz, 1H), 2.24 (ddd, $J_{P-H}$ = 15.6 Hz, $J_{H-H}$ = 3.6, 1.2 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.7, 136.3, 129.6, 128.5, 128.1, 126.2, 125.2, 120.4, 38.9, 35.1. $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 6.11 (s). FT-IR (film, cm$^{-1}$): 1590, 1191, 941, 669. HRMS-EI ([M]$^+$) for $C_{20}H_{18}NO_3P$, calcd 351.1024, found 351.1022. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 2 mL/min, 2-propanol/hexanes (v/v) = 2:98 ($t_{minor}$ = 50.4 min, $t_{major}$ = 54.4 min).

**(2-*o*-Tolylaziridin-1-yl)phosphonic acid diphenyl ester.** (Table 4, entry 2) was synthesized from the reaction of *o*-methylstyrene with DPPA at 60 °C and obtained as a yellow oil (51.1 mg, 70% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.32−7.08 (m, 14H), 3.79 (ddd, $J_{P-H}$ = 16.6 Hz, $J_{H-H}$ = 6.0, 3.6 Hz, 1H), 2.90 (ddd, $J_{P-H}$ = 19.1 Hz, $J_{H-H}$ = 6.2, 1.4 Hz, 1H), 2.36 (s, 3H), 2.20 (ddd, $J_{P-H}$ = 15.3 Hz, $J_{H-H}$ = 3.5, 1.4 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 151.0, 136.7, 134.7, 130.0, 129.9, 128.0, 126.3, 125.7, 125.5, 120.6, 37.5, 34.3, 19.2. $^{31}$P NMR (161 MHz, $CDCl_3$): $\delta$ 6.71 (s). FT-IR (solid, cm$^{-1}$): 1591, 1489, 1275, 1190, 941, 755. HRMS-ESI ([M + H]$^+$) for $C_{21}H_{20}NO_3P$ calcd 366.1254, found 366.1260. Enantiomeric excess was determined via HPLC using a Chiralcel AD-H chiral column and a flow rate of 1 mL/min, 2-propanol/hexanes (v/v) = 4:96 ($t_{minor}$ = 64.5 min, $t_{major}$ = 68.5 min).

**(2-*m*-Tolylaziridin-1-yl)phosphonic acid diphenyl ester.** (Table 4, entry 3)[12a] was synthesized from the reaction of *m*-methylstyrene with DPPA at 60 °C and obtained as a yellow oil (57.3 mg, 78% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.28−6.95 (m, 14H), 3.61 (ddd, $J_{P-H}$ = 16.5 Hz, $J_{H-H}$ = 6.0, 3.3 Hz, 1H), 2.80 (dd, $J_{P-H}$ = 19.2 Hz, $J_{H-H}$ = 6.0 Hz, 1H), 2.22 (m, 4H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.7, 138.2, 136.2, 129.6, 128.8, 128.3, 126.8, 125.2, 123.4, 120.4, 38.9, 34.9, 21.3. $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 6.19 (s). FT-IR (film, cm$^{-1}$): 1711, 1585, 1482, 1190, 1010, 932, 762. HRMS-EI ([M]$^+$) for $C_{21}H_{20}NO_3P$ calcd 365.1181, found 365.1174. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 2 mL/min, 2-propanol/hexanes (v/v) = 2:98 ($t_{minor}$ = 50.1 min, $t_{major}$ = 57.3 min).

(20) No effect on yield and enantioselectivity was observed when sodium methylthiolate was employed as potential axial ligand under the same conditions.

**(2-*p*-Tolylaziridin-1-yl)phosphonic acid diphenyl ester.** (Table 4, entry 4) was synthesized from the reaction of *p*-methylstyrene with DPPA at 40 °C and obtained as a yellow oil (42.2 mg, 58% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.33−7.12 (m, 14H), 3.67 (ddd, $J_{P-H}$ = 16.6 Hz, $J_{H-H}$ = 6.1, 3.5 Hz, 1H), 2.88 (ddd, $J_{P-H}$ = 19.4 Hz, $J_{H-H}$ = 6.2, 1.0 Hz, 1H), 2.33 (s, 3H), 2.28 (ddd, $J_{P-H}$ = 15.7 Hz, $J_{H-H}$ = 3.5, 1.1 Hz 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 151.0, 138.1, 133.5, 129.9, 129.4, 126.4, 125.4, 120.7, 39.1, 35.1, 21.4. $^{31}$P NMR (161 MHz, $CDCl_3$): $\delta$ 6.20 (s). FT-IR (solid, cm$^{-1}$): 1588, 1487, 1188, 948, 930, 770. HRMS-ESI ([M + H]$^+$) for $C_{21}H_{20}NO_3P$, calc'd. 366.1254, found 366.1259. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 2 mL/min, 2-propanol/hexanes (v/v) = 2:98 ($t_{minor}$ = 53.1 min, $t_{major}$ = 58.4 min).

**[2-(*p*-*tert*-Butylphenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 5)[12a] was synthesized from the reaction of *p*-*tert*-butylstyrene with DPPA at 40 °C and obtained as a yellow oil (63.0 mg, 77% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.36−7.13 (m,14H), 3.70 (ddd, $J_{P-H}$ = 16.5 Hz, $J_{H-H}$ = 6.0, 3.6 Hz, 1H), 2.89 (ddd, $J_{P-H}$ = 19.8 Hz, $J_{H-H}$ = 6.6, 1.2 Hz, 1H), 2.33 (ddd, $J_{P-H}$ = 15.3 Hz, $J_{H-H}$ = 3.6, 1.2 Hz, 1H), 1.32 (s, 9H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 151.2, 133.3, 130.9, 129.6, 126.0, 125.4, 125.2, 120.4, 38.9, 34.8, 34.6, 31.3. $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 6.24 (s). FT-IR (film, cm$^{-1}$): 1592, 1490, 1193, 943, 773, 689. HRMS-EI ([M]$^+$) for $C_{24}H_{26}NO_3P$ calcd 407.1650, found 407.1658. Enantiomeric excess was determined via HPLC using a Chiralcel AD-H chiral column with a flow rate of 1 mL/min, 2-propanol/hexanes (v/v) = 4:96 ($t_{major}$ = 36.3 min, $t_{minor}$ = 46.9 min).

**[2-(*p*-Bromophenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 6)[12a] was synthesized from the reaction of *p*-bromostyrene with DPPA at 40 °C and obtained as a yellow oil (56.1 mg, 65% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.43 (d, $J$ = 8.4 Hz, 2H), 7.35−7.09 (m, 10H), 7.01 (d, $J$ = 8.4 Hz, 2H), 3.64 (ddd, $J_{P-H}$ = 16.2 Hz, $J_{H-H}$ = 6.0, 3.3 Hz, 1H), 2.88 (ddd, $J_{P-H}$ = 18.9 Hz, $J_{H-H}$ = 6.0, 1.2 Hz, 1H), 2.26 (ddd, $J_{P-H}$ = 15.3 Hz, $J_{H-H}$ = 3.3, 1.2 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.6, 135.4, 131.6, 129.7, 127.9, 125.3, 122.0, 120.4, 38.3, 35.0. $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 5.76 (s). FT-IR (film, cm$^{-1}$): 1591, 1489, 1283, 1192, 1163, 1072, 1006, 945, 827, 774. HRMS-EI ([M]$^+$) for $C_{20}H_{17}NO_3PBr$ calcd 429.0129, found 429.0127. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 2 mL/min, 2-propanol/hexanes (v/v) = 1:99 ($t_{minor}$ = 98.3 min, $t_{major}$ = 105.9 min).

**[2-(*o*-Bromophenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 7) was synthesized from the reaction of *o*-bromostyrene with DPPA at 40 °C and obtained as a yellow oil (58.7 mg, 68% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.53 (d, $J$ = 7.9 Hz, 1H), 7.36−7.13 (m, 13H), 4.00 (ddd, $J_{P-H}$ = 16.3 Hz, $J_{H-H}$ = 6.1, 3.5 Hz, 1H), 2.96 (ddd, $J_{P-H}$ = 18.6 Hz, $J_{H-H}$ = 6.2, 1.2 Hz, 1H), 2.21 (ddd, $J_{P-H}$ = 15.2 Hz, $J_{H-H}$ = 3.3, 1.2 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.6, 135.8, 132.3, 129.7, 129.3, 127.5, 127.5, 125.3, 123.3, 120.3, 39.2, 34.6. $^{31}$P NMR (161 MHz, $CDCl_3$): $\delta$ 5.68 (s). FT-IR (solid, cm$^{-1}$): 1590, 1488, 1289, 1189, 940, 752. HRMS-ESI ([M + H]$^+$) for $C_{20}H_{17}NO_3PBr$ calcc 430.0202, found 430.0208. Enantiomeric excess was determined via HPLC using a Chiralcel AD-H chiral column with a flow rate of 1 mL/min, 2-propanol/hexanes (v/v) = 4:96 ($t_{minor}$ = 83.2 min, $t_{major}$ = 96.0 min).

**[2-(*m*-Bromophenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 8) was synthesized from the reaction of *m*-bromostyrene with DPPA at 40 °C and obtained as a yellow oil (49.5 mg, 58% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.40 (m, 1H), 7.34−7.12 (m, 13H), 3.64 (ddd, $J_{P-H}$ = 16.4 Hz, $J_{H-H}$ = 6.0, 3.4 Hz, 1H), 2.87 (ddd, $J_{P-H}$ = 19.0 Hz, $J_{H-H}$ = 6.1, 0.7 Hz, 1H), 2.26 (ddd, $J_{P-H}$ = 15.5 Hz, $J_{H-H}$ = 3.2, 0.8 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.6, 138.6, 131.2, 130.0, 129.7, 129.1, 125.3, 125.0, 122.6, 120.3, 38.1, 34.9. $^{31}$P NMR (161 MHz, $CDCl_3$): $\delta$ 5.73 (s). FT-IR (solid, cm$^{-1}$): 1590, 1488, 1281, 1188, 935, 773, 751, 687. HRMS-ESI ([M + H]$^+$) for $C_{20}H_{17}NO_3PBr$ calcd 430.0202, found 430.0202. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 2 mL/min, 2-propanol/hexanes (v/v) = 2:98 ($t_{minor}$ = 48.5 min, $t_{major}$ = 55.6 min).

**[2-(*p*-Chlorophenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 9)[12a] was synthesized from the reaction of *p*-chlorostyrene with DPPA at 40 °C and obtained as a yellow oil (49.4 mg, 64% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.35−7.14 (m, 14H), 3.66 (ddd, $J_{P-H}$ = 16.2 Hz, $J_{H-H}$ = 6.0, 3.3 Hz, 1H), 2.89 (ddd, $J_{P-H}$ = 19.2 Hz, $J_{H-H}$ = 6.0, 1.2 Hz, 1H), 2.27 (ddd, $J_{P-H}$ = 15.3 Hz, $J_{H-H}$ = 3.3, 1.2 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.6, 134.9, 133.9, 129.7, 128.7, 127.5, 125.3, 120.3, 38.2, 35.0. $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 5.79 (s). FT-IR (film, cm$^{-1}$): 1592, 1490, 1193, 943, 773, 689. HRMS-EI ([M]$^+$) for $C_{20}H_{17}NO_3PCl$ calcd 385.0635, found 385.0629. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 2 mL/min, 2-propanol/hexanes (v/v) = 1:99 ($t_{minor}$ = 89.7 min, $t_{major}$ = 97.1 min).

**[2-(*p*-Fluorophenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 10)[12a] was synthesized from the reaction of *p*-fluorostyrene with DPPA at 60 °C and obtained as a yellow oil (53.0 mg, 72% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.35−7.13 (m, 12H), 7.00 (t, $J$ = 8.7 Hz, 2H), 3.68 (ddd, $J_{P-H}$ = 16.5 Hz, $J_{H-H}$ = 6.0, 3.6 Hz, 1H), 2.89 (ddd, $J_{P-H}$ = 19.5 Hz, $J_{H-H}$ = 6.3, 0.7 Hz, 1H), 2.28 (ddd, $J_{P-H}$ = 15.0 Hz, $J_{H-H}$ = 3.3, 0.7 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.6, 140.5, 129.7, 126.5, 125.4, 120.3, 38.2, 35.1. Two peaks were not observed. $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 5.96 (s). $^{19}$F NMR (376 MHz, $CDCl_3$): $\delta$ −114.37 (s). FT-IR (film, cm$^{-1}$): 1592, 1490, 1224, 1192, 932, 835, 689. HRMS-EI ([M]$^+$) for $C_{20}H_{17}NO_3FP$ calcd 369.0930, found 369.0946. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 2 mL/min, 2-propanol: hexanes (V:V) = 1:99 ($t_{minor}$ = 87.8 min, $t_{major}$ = 94.8 min).

**[2-(*p*-Trifluoromethylphenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 11)[12a] was synthesized from the reaction of *p*-trifluoromethylstyrene with DPPA at 40 °C and obtained as a yellow oil (53.5 mg, 64% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 7.56 (d, $J$ = 7.80 Hz, 2H), 7.36−7.16 (m, 12H), 3.75 (ddd, $J_{P-H}$ = 16.2 Hz, $J_{H-H}$ = 6.0, 3.6 Hz, 1H), 2.93 (dd, $J_{P-H}$ = 19.2 Hz, $J_{H-H}$ = 6.3 Hz, 1H), 2.30 (dd, $J_{P-H}$ = 15.3 Hz, $J_{H-H}$ = 3.3 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 150.6, 140.5, 129.8, 126.5, 125.4, 120.3, 38.2, 35.1. (Three peaks were not observed). $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 5.63 (s). $^{19}$F NMR (376 MHz, $CDCl_3$): $\delta$ −63.00 (s). FT-IR (film, cm$^{-1}$): 1621, 1592, 1490, 1326, 1193, 1165, 1068, 1005, 947, 904, 774, 689. HRMS-EI ([M]$^+$) for $C_{21}H_{17}NO_3$ $F_3P$ calcd 419.0898, found 419.0894. Enantiomeric excess was determined via HPLC using a Pirkle Covalent WHELK-O1 chiral column with a flow rate of 1 mL/min, 2-propanol/hexanes (v/v) = 1:99 ($t_{minor}$ = 211.7 min, $t_{major}$ = 224.8 min).

**[2-(*m*-Nitrophenyl)aziridin-1-yl]phosphonic acid diphenyl ester.** (Table 4, entry 12)[12a] was synthesized from the reaction of *m*-nitrostyrene with DPPA at 40 °C and obtained as a yellow oil (45.6 mg, 58% yield). $^1$H NMR (400 MHz, $CDCl_3$): $\delta$ 8.12 (dd, $J$ = 8.1, 0.9 Hz, 1H), 8.05 (s, 1H), 7.55 (d, $J$ = 7.7 Hz, 1H,), 7.47 (t, $J$ = 8.0 Hz, 1H), 7.35−7.12 (m, 10H), 3.76 (ddd, $J_{P-H}$ = 16.2 Hz, $J_{H-H}$ = 6.0, 3.3 Hz, 1H), 2.95 (dd, $J_{P-H}$ = 18.6 Hz, $J_{H-H}$ = 6.0 Hz, 1H), 2.33 (dd, $J_{P-H}$ = 15.3 Hz, $J_{H-H}$ = 3.3 Hz, 1H). $^{13}$C NMR (100 MHz, $CDCl_3$): $\delta$ 148.4, 138.7, 132.3, 129.8, 129.8, 129.5, 125.5, 123.0, 121.1, 120.3, 37.9, 35.1. $^{31}$P NMR (121 MHz, $CDCl_3$): $\delta$ 5.27 (s). FT-IR (film, cm$^{-1}$): 1591, 1531, 1488, 1350, 1190, 950. HRMS-EI ([M − H]$^+$) for $C_{20}H_{17}N_2O_5P$ calcd 395.0797, found 395.0789. Enantiomeric excess was determined via HPLC using a WHELK-O1 chiral column and a flow rate of 2 mL/min, 2-propanol/hexanes (v/v) = 2:98 ($t_{minor}$ = 103.5 min, $t_{major}$ = 116.8 min).

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**Supporting Information Available:** $^{1}$H NMR, $^{13}$C NMR, $^{31}$P NMR, and $^{19}$F NMR spectra and HPLC traces for all products. This material is available free of charge via the Internet at http://pubs.acs.org.

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