Axially chiral open-chain olefins are an underexplored class of chiral molecules, especially for trisubstituted olefins. In this work, axially chiral olefins and enantioselective hydrophosphination are integrated, and palladium-catalyzed atroposelective hydrophosphination of internal alkynes has been realized using diverse symmetrical and nonsymmetrical secondary phosphines, affording C-N axially chiral trisubstituted olefins (vinylphosphines) in excellent regioselectivity, E-selectivity, enantioselectivity, and as diastereoselectivity. The reactivity and selectivity were established via the judicious choice of a chiral bidentate ligand.
Palladium-catalyzed asymmetric hydrophosphination of internal alkynes: Atroposelective access to phosphine-functionalized olefins

Danqing Ji,1 Jierui Jing,1 Yi Wang,1 Zisong Qi,1 Fen Wang,1 Xuepeng Zhang,1 Yong Wang,3,* and Xingwei Li1,2,4,*

SUMMARY
Palladium-catalyzed underexplored atroposelective hydrophosphination of sterically hindered internal alkynes with secondary phosphines has been realized, affording C-N axially chiral trisubstituted olefins (vinylphosphines) in excellent regioselectivity, (E)-selectivity, and enantioselectivity. The axial chirality was constructed via the integration of hydrophosphination and dynamic kinetic transformation of the alkynes, with both symmetrical and nonsymmetrical secondary phosphines being applicable.

INTRODUCTION
Development of novel synthetic methods that utilize simple and abundant reagents is highly desirable toward selective construction of value-added organics. The catalytic hydrofunctionalization1–6 of alkynes is intriguing for achieving these goals in that both substrates are widely available and readily accessible, and this transformation also features high atom and step economies. While diverse mechanistic pathways have allowed the development of numerous synthetic methods of alkyne hydrofunctionalization, the functionalized products are mostly achiral since this reaction does not directly generate a chiral carbon center. In the case of asymmetric alkyne hydrofunctionalization, enantioenriched products are often afforded via desymmetrization7–9 of the prochiral alkyne or the coupling reagent, formation of chiral allylic compounds,10,11 or exhaustive hydrofunctionalization to C–C single bonds.12–14

On the other hand, axial chirality represents a large family of chiral platforms that are widely found in numerous chiral ligands or catalysts, synthetic building blocks, and pharmaceuticals.15–25 The majority of axially chiral molecules that have been extensively studied are biaryls.21–23 In contrast, axially chiral olefins24–28 have been much less explored likely due to their synthetic challenges associated with their reduced atropostability since the bonds around the open-chain C=C bond may undergo distortion to minimize the steric repulsion. The ready availability of substrates renders alkyne hydrofunctionalization an attractive strategy to address such synthetic challenges, provided that sterically internal alkynes are used and the reaction also occurs with the correct regioselectivity. However, sterically hindered alkynes generally exhibited relatively low reactivity. Consequently, atroposelective hydrofunctionalization of alkynes that affords trisubstituted chiral olefins remains a drastic challenge, especially when the products are atropomerically labile. In fact, to evade this challenge, annulative difunctionalization of alkynes has often been explored instead via well-known metal-catalyzed [2+2+2] cycloaddition,29,30 [4+2] annulation,31 or C–H bond activation,32–34 but the products are typically (hetero)aromatics.

THE BIGGER PICTURE
Asymmetric hydrofunctionalization is an important chemical reaction to install functional groups at π-bonds with defined configuration and sought due to its relative atom economy. Asymmetric hydrophosphination is a specific reaction within this broader class that enables access to useful chiral phosphines. In contrast to the well-investigated asymmetric hydrophosphination reactions that deliver central chirality, access to axially chiral phosphines by this means is underexplored.

We now report Pd-catalyzed highly atroposelective hydrophosphination of internal alkynes in regio- and E-specificity by integration of axial chirality and hydrophosphination. Different classes of internal alkynes and symmetrical as well as nonsymmetrical secondary phosphines are applicable. In the latter case, additional P-central chirality has been constructed. This chemistry provides a new avenue to access underexplored chiral open-chain olefins and may provide new insights into underexplored atroposelective transformations of alkynes.
Nevertheless, organocatalysis plays a pivotal role in atroposelective hydrofunctionalization of alkynes (Figure 1A). In 2017, Tan elegantly realized hydroalkylation of alkynals using β-diketones toward the construction of trisubstituted acroleins via the intermediacy of reactive allene species. Yan and others developed novel organocatalyzed hydrofunctionalization of 1-alkynyl-2-naphthol analogs by taking advantage of a vinylidene ortho-quinone methide (VQM) intermediate. In this regime, Tan also extended the nucleophile to 2-naphthols for efficient hydroarylation. Recently, Chi described N-heterocyclic carbenes (NHC)-catalyzed atroposelective synthesis of axially chiral styrenes, with selective 1,4-addition of sulfinic anion to acetylenic acylazolium intermediate as the key step. In these cases, sterically hindered alkynes bearing a functional handle at the alkynyl position or in the naphthol ring have been employed. Despite the progress, the hydrofunctionalization is limited in the reaction patterns governed by the intrinsic organocatalytic modes with a handle in the sterically hindered alkyne. Thus, introduction of new heteroatoms such as phosphorus, as in hydrophosphination that deliver functional molecules, is under great demand.

The significance of chiral phosphines as ligands or catalysts has called for new asymmetric synthetic methods. Asymmetric hydrophosphination of alkynes has been developed mostly using terminal alkynes as the substrates (Figure 1B), and the products have been restricted to P-chirality. Besides alkynes, asymmetric hydrophosphination of activated olefins has been extensively studied since 2010 by Duan, Leung, Yin, Zhang, Harutyunyan and Ge, and others using Pd, Ni, Cu, and Mn catalysts. Chi recently also developed NHC-catalyzed hydrophosphination of α-bromoenals. Moreover, enantioselective addition of P(V)-H to diverse π-bonds has been accomplished by Dong and others. In addition to unsaturated substrates, carbon and hetero electrophiles also effectively coupled with P(III)-H and P(V)-H reagents under metal catalysis. In all these reports, the reactions are limited to the generation of C- or P-chiral centers. Of note, synthesis of the large family of axially chiral phosphines remains largely untouched via a hydrophosphination pathway. In atroposelective hydrophosphination of alkynes, the reactivity, regioselectivity, and enantioselectivity are major concerns. We reasoned that the reactivity and the regioselectivity may be partially addressed using an electronically activated and sterically hindered alkyne such as 1-alkynylindole. Nevertheless, the substrate inhibition should be fully addressed since in many cases, the PH substrate and the phosphine product may competitively bind to the catalyst. We rationalized that the substrate inhibition and the enantioselectivity may be collectively addressed using a proper electron-rich chiral bidentate phosphine ligand that can suppress the PH binding while rendering chiral induction (Figure 1C). We now report our proof-of-concept studies on palladium-catalyzed atroposelective hydrophosphination of different classes of internal alkynes for the generation of axial and central chirality using symmetrical and nonsymmetrical secondary phosphines.

RESULTS AND DISCUSSION

We initially designed 1-alkynyl indoles bearing a proper 2-steric group as electronically activated internal alkynes for hydrophosphination studies. Thus, the 2-sulfonylindole-functionalized alkyne 1a and Ph₂PH were selected as model substrates by palladium catalysis (Figure 2). A large set of chiral bidentate ligands were screened at 30°C. In many cases, decay of the enantioselectivity was observed as the reaction time was prolonged. Among the chiral ligands surveyed, (S, S) BDPP, QuinoxP, and selected Josiphos ligands outperformed others and offered promising enantioselectivity in general (entries 1, 2, and 12). As expected, generally higher enantioselectivity was obtained.
when an electron-rich ($R_1P$, $R_2P$)-Josiphos SL-J003-1 (L12) was used (entry 12). Screening of the palladium source indicated that Pd(acac)$_2$ was superior in terms of enantioselectivity (entries 15–17). Evaluation of solvents returned PhMe or PhCl as the more suitable ones (entries 18–20). Introduction of CsOAc further improved the enantioselectivity to 94%, and the product was isolated in excellent yield (entry 22). Other acid or base additives tended to give inferior results (entries 21, 23, and 24). The direct hydrophosphination product 3’ turned out to be moderately stable under air at ambient temperature, and it was converted to the oxide for convenience of characterization.

Having established of the optimal reaction conditions, we next explored the scope and generality of this coupling system (Figure 3A). Under the standard conditions, a broad scope of 1-indolylalkynes has been defined. The 3-unsubstituted indolyl substrate also reacted efficiently with slightly reduced enantioselectivity (4, 91% ee). Variation of the 3-substituent to benzyl or ethyl group was also successful (5 and 6). Various substituents such as alkyl, halogen, and methoxy at the 3-, 4-, and 5-positions of the indole ring were compatible (7–13, 88%–94% ee). The absolute configuration of the product 12 was determined to be (S) by X-ray crystallographic analysis (CCDC 2126532). Extension of the alkyne terminus to phenyl groups bearing various electron-donating, electron-withdrawing, and halogen substituents at the meta and para positions and to a 2-naphthyl group proved successful (14–20, 86%–93% ee). A 2-fluorophenyl group was also compatible, affording the expected product 21 in 85% ee. The presence of a 2-thienyl group gave the product 22 in high yield albeit with lower enantioselectivity (81% ee). Significantly, extension of the
substituent to alkyl (23 and 25) and cyclopropyl group (24) met with no difficulty, and the products were all isolated in excellent enantiomeric selectivities, suggesting tolerance of the electronic effect of the alkyne. As expected, the coupling of a cyclohexenyl-substituted alkyne with PHPh2-afforded product 26 in high enantioselectivity. The 2-sulfonyl group in the indole functions as an activating group as well as a bulky group to ensure axial chirality. Extension of the Ts group to other arenesulfonyls was successful (27–29, 88%–93% ee). Extension of the 2-sulfonyl group to an ester met with failure under the standard reaction conditions, under which the ee of the

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Figure 2. Optimization of reaction conditions

Reaction conditions: 1a (0.1 mmol), 2a (0.2 mmol), Pd catalyst (6 mol %), chiral ligand (9 mol %), and additive (0.3 equiv) in PhMe (2 mL), 30°C, 96 h; then H2O2 at 0°C for 20 min. Isolated yield. The enantiomeric excess (ee) was determined by HPLC analysis using a chiral stationary phase.

See also Tables S1–S5.
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coupled product decayed significantly versus reaction time. Moving the chiral ligand to \((R, R)-\text{Ph-BPE} 0\)/\(C14\) afforded the product 30 in good yield and in 82% ee, and the configuration of 30 has been established by electronic circular dichroism (ECD) spectroscopy (see Figure S1). The atropostability of product 3 has been examined, from which \(\Delta G_{\text{rac}}^a \geq 33.4\) kcal/mol was estimated (essentially no decay of ee for 16 h at 100°C. In addition, a lower barrier of racemization (\(\Delta G_{\text{rac}}^a = 30.2\)) has been determined for the corresponding phosphine 3’ (80°C, PhMe) (see supplemental information [experimental section]).

The scope of the symmetric diarylphosphines was next explored in the coupling with alkyne 1a (Figure 3B). Diarylacetylenes bearing diverse electron-donating and electron-withdrawing groups at the para position all reacted smoothly under the standard conditions (31–39, 91%–96% ee). Phosphines bearing different meta-substituted and 1,3-disubstituted phenyls also reacted in excellent enantioselectivity (40–43, 88%–93% ee). Sluggish reaction was found for ortho-substituted diarylphosphines due to the steric effect. Nevertheless, ortho-methoxy-substituted diphenylphosphine coupled in acceptable yield with high enantioselectivity (44, 89% ee). The secondary phosphine substrate is not limited to diarylsubstitution, and dibenzylphosphine reacted smoothly under the standard conditions A to give the product 45 in high yield and excellent enantioselectivity. Unfortunately, other dialkylphosphines such as Cy2PH and tBu2PH were completely inactive after extensive attempts.

Having established the scope of symmetrical phosphines, we next moved to coupling using nonsymmetrical secondary phosphines, which will generate both axial and P-chirality (Figure 4). The HPPhMes bearing two sterically biased groups was evaluated, and its coupling with alkyne 1a was extensively screened. Our previous catalyst system turned out to be inapplicable. After various studies, a bidentate \((S, S)-\text{Bophoz} (L8)\) was identified as a superior ligand at 0°C. Thus, the coupling with 1a afforded the product 46 in good dr (9:1) and in excellent enantioselectivity (90% ee). The scope of the alkyne was also briefly explored. It turned out that indolylalkyne bearing different substituents at the 2- and 4-positions or bearing a different sulfonyl substituent generally underwent smooth coupling in 6.5 to 9.0:1 dr and in 82%–92% ee for the major product (47–53), and similar enantioselectivity was consistently observed for both the major and minor diastereomeric products. The major product of 48 was determined to be \((S, S)\) configuration by X-ray crystallography (CCDC 2126528), and the rest products were assigned by analogy. A comparable diastereoselectivity was observed when the indole ring is 3-unsubstituted (54, 88% ee). All the above initially hydrophosphinated products are reasonably air stable, but the diastereomeric products cannot be chromatographically separated unless they were oxidized. Extension of the sterically biased phosphine to phenyl-tert-butylphosphine was also successful, affording the product 55 in 10:1 dr and 85% ee.

To better define the scope of the alkyne, we explored another class of N-alkynyl indoles (Figure 5). Thus, indoles bearing a 2-phosphonyl group coupled effectively with HPPh2 in excellent enantioselectivity under the modified conditions with Fe(OAc)2 being an additive and with the bidentate L1 as the chiral ligand, yielding a relatively air-stable phosphine-phosphine oxide (56’, CCDC 2190722) that is potentially a diphosphine precursor. The scope of this class of alkyne also turned
to be broad, and both electron-donating and electron-withdrawing could be introduced to the phosphonyl group (57–59, 87%–94% ee). The alkyne terminus has also been successfully extended to several alkyl and heteroaryl groups (61–63). A decent scope of diarylphosphines has also been established with different substituents at the meta and para positions of the phenyl ring (65–69). Moreover, dibenzylphosphine also worked well under the same conditions (70, 80% ee). In all cases, the hydrophosphination products were isolated in 84%–97% ee. The bulky group in the alkyne has also been extended to a naphthyl ring. Thus, the coupling of a 1-alkynyl-2-sulfonyloxylnaphthalene with PHPh2 proceeded in high enantioselectivity although the efficiency was only low or moderate due to the lack of substrate activation (71 and 72, 91% ee minor: 93% ee). Slightly lower enantioselectivity was also obtained for 2-OBn-substituted substrate (73 and 74, 76%–82% ee). The atropostability of the phosphine-phosphine oxide 56’ has been measured. To our great surprise, a rather low activation barrier of 27.7 kcal/mol was obtained experimentally despite the larger steric effect the P(O)Ph2 group compared with the Ts group. Our density functional theory (DFT) assessment of the structures of 56’ and 3’ revealed ground-state stabilization of the latter, and strong π-π stacking was detected between the Ts group and the alkenyl-phenyl ring in the product 3’, and this tethering effect serves to increase its atropostability.26 In addition, the C(indole)–P versus C(indole)–S bond lengths also differs (see supplemental information [experimental section and ECD spectrum of (S)-30, (R)-71, (R)-73 and DFT calculations]). This indicates that the electronic effect of the atropoisomer may contribute significantly toward the racemization barrier. In contrast, a high (>34.9 kcal/mol) racemization barrier was estimated for the diphosphine dioxide 56. Accordingly, the high temperature required for the reduction of phosphine oxide in 56’ precluded it from being as a suitable chiral

**Figure 4. Scope of nonsymmetric secondary phosphines in enantioselective hydrophosphination**

*Reactions conditions C: alkyne (0.1 mmol), nonsymmetric phosphine (0.2 mmol), Pd(OAc)2 (6 mol %), and L8 (9 mol %) in dioxane (1 mL)/EtOAc (1 mL) at 0°C, 96 h. The diastereomeric ratio (d.r.) was determined by chiral HPLC analysis.*
diphosphine ligand, and only a racemic product was obtained from the standard reduction of 56 or 56′. In line with these observations, the hydrophosphination of a 2-phosphonylindole-functionalized alkyne devoid of the 3-methyl substituent
Figure 6. Synthetic applications
(A) 1 mmol scale synthesis of 3.
(B) Protect the initial hydrosphosphination product 3'.
(C) The synthesis of 79 from the product 3.

\[ \text{iTMSC} \text{H, Pd(PPh}_3\text{)}_2\text{Cl}_2 (2 \text{ mol } \%), \text{CuI, PPh}_3, \text{Et}_3\text{N} \rightarrow \text{TsPh} \]

76 91% (93% ee)

3' 92% ee

75 95% (92% ee)

3 (92% ee)

77 74% (92% ee)

78 83% (92% ee)

79 73% (92% ee)

Please cite this article in press as: Ji et al., Palladium-catalyzed asymmetric hydrophosphination of internal alkynes: Atroposelective access to phosphine-functionalized olefins, Chem (2022), https://doi.org/10.1016/j.chempr.2022.08.019
only reacted with poor enantioselectivity (31% ee), possibly due to the poor stereochemical stability of the product.

Synthetic applications of representative products were next performed. The reaction of 1a and 2a was easily scaled up, affording product 3 in excellent yield with only slightly lower enantioselectivity (Figure 6A). In addition to the protection in the oxide form, the initial hydrophosphination product 3' could also be protected upon treatment with S8 (75) or BH3-DMS (76, Figure 6B). The olefin unit in product 3 is somewhat electronically activated. Treatment of 3 with Br2 led to electrophilic bromination at the olefinic site, and tetrasubstituted olefin 77 was obtained in 92% ee. Alkynylation followed by dysilylation, click reaction, and standard reduction afforded a triazole-functionalized phosphine 79 that is a potential bidentate ligand (92% ee, Figure 6C). Phosphine 3' was then designated as a chiral ligand in palladium-catalyzed asymmetric allylic alkylation of an allyl acetate, affording products 80 in high enantioselectivity (Figure 6D). In addition to palladium catalysis, ligand 3' also worked well as a chiral ligand in Ru(II)-catalyzed asymmetric C–C coupling between a ketone and phenylboronic acid to yield the alcohol 81 in high enantioselectivity (Figure 6E). Although the enantio-enriched diphosphine failed to be obtainable from the reduction of 56, the monophosphine 56' may serve well as a P–O bidentate ligand. Thus, by using 56' as a chiral bidentate ligand, an interesting Pd-catalyzed atroposelective C–C coupling has been attempted for the coupling of an alkyne-tether aryl iodide and an o-alkynylaniline.89 This unprecedented double cyclization-C–C coupling reaction proceeded well in 91:9 enantiomeric ratio (e.r.) to give the desired axially chiral olefin product 82 under mild conditions (Figure 6F). In addition, treatment of PdCl2(MeCN)2 with 56' afforded the P–O bidentate Pd(II) complex (83) in high yield, which could be a potentially useful chiral catalyst (Figure 6G and see supplemental information [experimental section] for the details).

Preliminary experimental studies have been conducted to explore the reaction mechanism (Figure 7). The coupling of 1a with DPPH2 afforded the product 3-Dn with H/D exchange (~50% D) at the olefinic position (Figure 7A). This observation is consistent with a reaction pathway that involves protonolysis or sigma-bond metathesis of a palladium alkenyl intermediate. In a competitive experiment, two electronically distinguishable indolylalkynes bearing different groups at the 5-position were allowed to competitively couple with HPPh2. NMR analysis indicated that the 5-methyl substrate completely overrode its 5-Cl analog, affording the product 9 in excellent yield (Figure 7B). This may suggest that a more electron-rich indole ring facilitated the coupling with more pronounced substrate activation or with stronger alkyne coordination. To explore possible phosphine inhibition, control experiments have been conducted. The employment of alkyne 1a as a substrate toward coupling with different amounts of HPPh2 afforded the product with negligible variations of the enantioselectivity with up to 10 equiv of PHPh2 (48 h, Figure 7C). In contrast, appreciable decrease of the enantioselectivity was detected for the 3-unsubstituted alkyne 1a' only in the presence of a large amount (10 equiv) of PHPh2. In both cases, the reaction was significantly inhibited by 10 equiv of PHPh2, suggesting substrate inhibition but probably with dechelation of...
Figure 7. Mechanistic studies

(A) H/D exchange experiment.
(B) Competitive reactions.
(C) Exploring possible phosphine inhibition.
(D) Control experiments to investigate the role of the base.
the chiral ligand only in the case of 1a’, which is less sterically hindered and less electron rich and consequently more prone to ligand substitution-dechelation (see Figure 1C). These results highlighted the subtle steric and electronic differences of these alkynes and the importance of proper choice of a chiral bidentate ligand. The role of the base additive was then examined. It was found that the enantioselectivity of the coupling of alkyne 1a’ slightly decayed as the reaction proceeded in the absence of any base additive. Control experiments indicated that the decay was not caused by post-coupling interaction of the product with the catalyst. Introduction of CsOAc afforded a constant ee although the reaction was slightly retarded (Figure 7D). The presence of this base additive probably facilitated the formation of more coordinating PPh2 ligand and fine-tuned the enantioselectivity. To further explore the possible product inhibition, the coupling of 1a was conducted in the presence of an enantioenriched or a racemic phosphine product 10’ at the beginning (Figure 7E). Neither the coupling efficiency nor the enantioselectivity was essentially affected in either case, indicative of negligible phosphine product inhibition. We also attempted to apply 10’ as the sole chiral ligand for the coupling of 1a and PHPh2, but only starting materials were recovered under various conditions (Figure 7F). These observations verified the irrelevance of autocatalysis in this coupling system, and the chiral phosphine product cannot outcompete the PHPh2 substrate (see supplemental information [experimental section]).

The pathway of this coupling reaction likely involves the initial deprotonation-ligand substitution between HPPh2 and L*PdX2 to give a Pd(II)PPh2 species (Figure 8). The alkyne coordination is then followed by an enantio-determining migratory insertion of the PPh2 group into the alkyne. This insertion is also regioselective as dictated by both the electronic and steric effects of the 1-indolyl group, which functioned in the same direction. Indeed, the metal tends to end up at the vinyl site that is distal to the bulky aryl group on the basis of our previous studies.32–34 Protonolysis of the C–Pd bond eventually furnishes the coupled product. In the enantio-determining migratory insertion, the more hindered indole moiety of the alkyne tends to be placed downward, and two orientations (E and E’ shown in Figure 8) of the alkyne versus the PPh2 group can be visioned. In the intermediate E, minimal repulsion between the alkyne-attached phenyl group and the alkylphosphino group is experienced. Meanwhile, the Ts side-chain of the alkyne was oriented on top of the bulky alkylphosphino group, which exerts steric effect toward ligation of the alkyne unit. While in intermediate E, one of the phenyl rings of the PPh2 group formed a T-shape orientation with the phenyl of the alkyne, and this
caused the other phenyl group in the PPh₂ to lie between the phenyl and indole rings to avoid steric interactions, which kept the Ts side-chain away from the bulky alkylphosphino group. These different phenyl-phenyl orientations (the π-π stacking versus the T-shape) along with the different orientation of the Ts side-chain affected the coordination of the alkyne carbons (in ≈2.33 Å, Pd–C₁: 2.331 Å, Pd–C₂: 2.369 Å). Of note, the hydropalladation pathway⁷⁰,⁹⁰,⁹¹ that has been suggested in alkyne hydrophosphorylation using P(O)H(OMe)₂ or HP(O)Ph₂ is unlikely because the opposite regioselectivity is
expected (Figure 8, bottom). Indeed, our DFT studies verified that the opposite (unobserved) regioselectivity of insertion is more kinetically favorable by at least 13 kcal/mol (see Tables S13 and S14). This is caused by the weaker interaction between the Pd and the C(Indolyl) akynyl carbon (Pd–C(ind): ~2.8 angstrom) than that between the Pd–C(Ph) (Pd–C: ~2.3 angstrom) in the staring palladium hydride intermediate, which is consistent with the higher nucleophilicity/coordinating ability of the C(Ph) alkylnyl site. This different binding preference causes drastically different shapes of the corresponding transition states during hydride insertion. For hydride insertion into the C(Ph) site, a triangle shape of the H-C-C-Pd moiety with large tension is observed in the transition state, while for hydride addition to the C(Indolyl), a favorable, regular quadrangle-like Pd-C-C-H transition state was identified (see supplemental information [ECD spectrum of (S)-30, (R)-71, (R)-73 and DFT calculations]).

Conclusion
In summary, we have realized palladium-catalyzed atroposelective hydrophosphination of different classes of sterically hindered internal alkynes using diverse secondary phosphines. The coupling system overcomes the low reactivity of internal alkynes via substrate activation using a sterically bulky but electron-rich 1-indolyl group with different substituents at the 2-position, affording C-N axially chiral trisubstituted olefins (vinylphosphines) in excellent regioselectivity, E-selectivity, and enantioselectivity under mild reaction conditions. The axial chirality was established via the integration of hydrophosphination and dynamic kinetic transformation of the alkynes, with both symmetrical and nonsymmetrical secondary phosphines, including a dibenzylphophine, being applicable. In the case of nonsymmetrical secondary phosphines, additional P-central chirality has been constructed in good diastereoselectivity as well as high enantioselectivity. The observed enantioselectivity has been rationalized by DFT studies. The hydrophosphinated products showed promising potential as chiral ligands in asymmetric catalysis. This hydrophosphination reaction offers a new approach to access underexplored chiral open-chain olefins and may provide new insight into direct atroposelective functionalization of alkynes.

EXPERIMENTAL PROCEDURES
Resource availability
Lead contact
Further information and requests for resources should be directed to and will be fulfilled by the lead contact Xingwei Li (lixw@snnu.edu.cn).

Materials availability
All materials generated in this study are available from the lead contact without restriction.

Data and code availability
The date of the X-ray crystallographic structures of 12, 48, and 56 have been deposited in the Cambridge Crystallographic Data Center under accession numbers CCDC: 2126532, 2126528, and 2190722, respectively.

Methods
Full experimental procedures are provided in the supplemental information.

SUPPLEMENTAL INFORMATION
Supplemental information can be found online at https://doi.org/10.1016/j.chempr.2022.08.019.
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AUTHOR CONTRIBUTIONS

X.L. conceived the concept and directed the project. D.J., J.J., Y.W., Z.Q., and F.W. conducted the experiments and data analysis. X.Z. and Y.W. conducted the DFT studies. X.L. and Z.Q. wrote the paper with feedback from all other authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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