ACS central science

http://pubs.acs.org/journal/acscii

Research Article

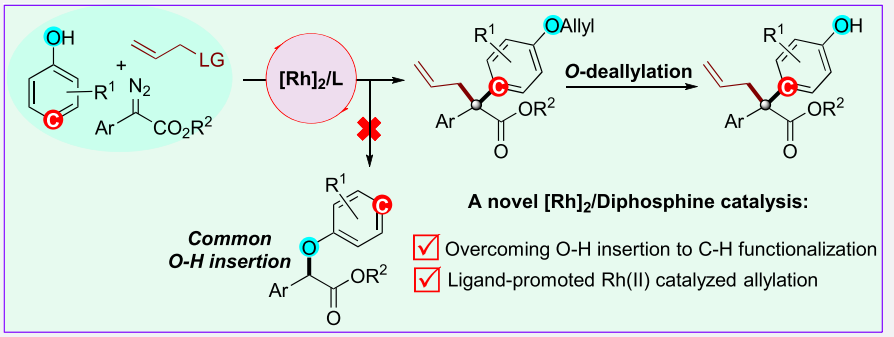
Overcoming O−H Insertion to *Para*-Selective C−H Functionalization of Free Phenols: Rh(II)/Xantphos Catalyzed Geminal Difunctionalization of Diazo Compounds

Yang Yang,[‖] Bin Lu,[‖] Guiqing Xu,* and Xiaoming Wang*

Cite This: *ACS Cent. Sci.* 2022, 8, 581−589

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information



ABSTRACT: *Para*-selective C−H functionalization of free phenols by metal carbenoids is rather challenging due to the generally more favorable competing O−H insertion. Herein, with the use of the combination of Rh(II) and a Xantphos ligand as the catalyst, a novel multicomponent reaction of free phenols, diazoesters, and allylic carbonates was successfully developed, affording a wide variety of phenol derivatives, bearing an all-carbon quaternary center and a synthetically useful allylic unit. This reaction is likely to occur through a tandem process of carbene-induced *para*-selective C−H functionalization, followed by Rh(II)/Xantphos-catalyzed allylation. The distinctive reactivity of *para*-selective C−H rather than O−H insertion for the carbenoid intermediate, combined with features of excellent functional group compatibility, high atom and step economy, and ease in further diversification of the products, might render this protocol highly attractive in facile functionalization of unprotected phenols.

I. INTRODUCTION

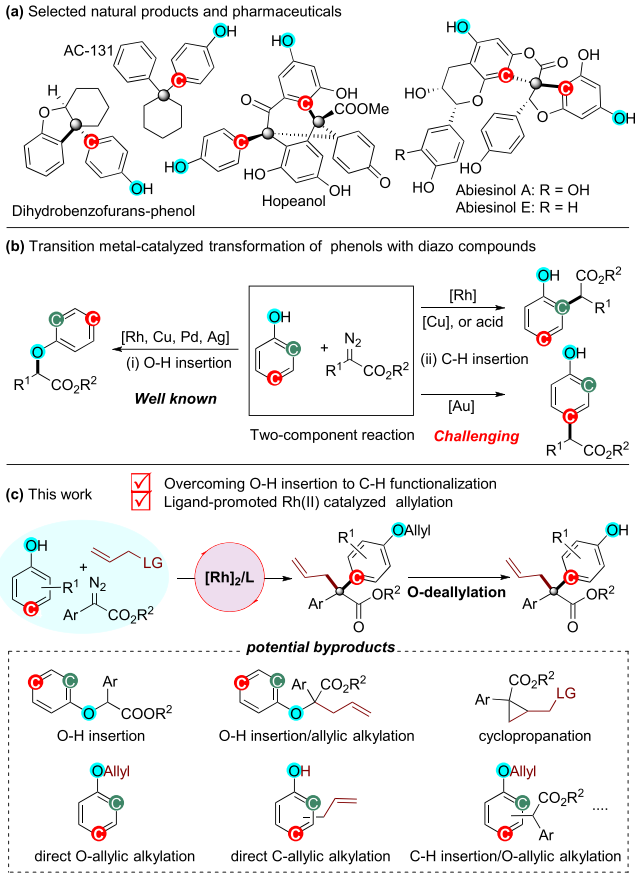
Due to the importance of phenol motifs in natural products, pharmaceuticals, and functional materials, transformations of inexpensive and abundant phenols into their structurally more complex homologues have attracted much attention for a long time.[1,2] In particular, phenol derivatives that contain a diaryl all-carbon quaternary center α to the *para*-position have shown unique biological activities (Scheme 1a).[3−6] Therefore, the development of synthetic routes for *para*-selective C(sp^2)−H functionalization of phenols is highly attractive.[7−12] Although great advances have been made in the area of metal carbenoid induced C−H functionalization of (hetero)arenes,[13−26] the direct C(sp^2)−H functionalization of free phenols in a chemo- and regioselective manner with diazo compounds is rather challenging and surprisingly rare, probably because the competitive O−H bond insertion is often found more favorable than C(sp^2)−H functionalization for carbenoids generated from a range of typical transition metals (e.g., Rh, Cu, Pd, Ag; Scheme 1b-i).[27−41] Very recently, remarkable advances have been achieved in highly *para*-selective C(sp^2)−H functionalization of free phenols with diazoesters, as reported independently by Zhang[42−44] and Shi,[45] using the specific carbophilicity of gold catalysts, wherein the chemoselectivity is largely dependent on the nature of the supporting ligands (Scheme 1b-ii).

On the other hand, dirhodium(II)-catalyzed multicomponent reactions (MCRs) involving metal carbenes offer an elegant and powerful tool to rapidly generate structural complexity and diversity by modulations of each component in an atom-economical and convergent fashion.[46,47] Remarkably, Hu and co-workers have developed dirhodium(II)-catalyzed MCRs of diazoesters, electron-rich arenes, and imines, wherein the metal carbene induced zwitterionic intermediates were trapped by electrophilic imines to enable direct C(sp^2)−H functionalization of electron-rich aromatic rings such as indole and *N*,*N*-disubstituted anilines.[48−51] Nevertheless, implementing such a methodology with free

Received: January 3, 2022
Published: April 20, 2022

https://doi.org/10.1021/acscentsci.2c00004
ACS Cent. Sci. 2022, 8, 581−589

Scheme 1. Catalytic Transformations of Free Phenols with Metal Carbene Derived from Diazo Compounds



phenols might be rather difficult, as the competitive O−H bond insertion is often the preferential process in reactions of a metal carbenoid with a phenol.[27−41,52] In addition, the introduction of allylic substrate as the electrophile in Rh(II)-catalyzed MCRs is rather challenging since activation of the allylic reactant via oxidative addition would be unfavorable for Rh(II).[53−62]

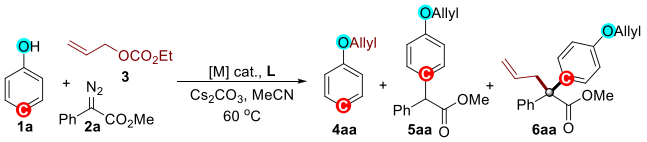
As a continuation of our interest in multicomponent reactions under a unique dirhodium(II)/diphosphine catalysis,[63−70] we envisioned a novel multicomponent reaction of unprotected phenols, diazo compounds, and allylic compounds, which may proceed via a sequence of *para*-selective C(sp^2)−H functionalization followed by an allylic alkylation (Scheme 1c). While such a strategy can provide a straightforward route to phenol derivatives bearing diaryl-substituted all-carbon quaternary centers, some uncertainties might severely impede the implementation of this strategy; e.g., (1) the catalytic reactivity of the dirhodium(II)/ligand for the proposed individual steps of the tandem process is unclear; (2) C(sp^2)−H functionalization reaction of free phenols with a Rh(II) carbenoid still remains an unknown challenge; (3) the conceivable competitive reactions of O−H insertion, cyclopropanation[71] of a metal carbene and C═C bond, and direct C/O-allylation of phenol with allylic compounds[72,73] can cause considerable difficulties in chemoselectivity or site-selectivity control.

Herein, we disclose a dirhodium(II)/Xantphos catalyzed multicomponent reaction of free phenols, diazoesters, and allylic compounds, affording various phenol derivatives bearing an allylic moiety and an all-carbon quaternary center (Scheme 1c). Mechanistic studies suggested that the reaction proceeds via alkali-promoted *para*-selective C(sp^2)−H functionalization of phenols to Rh(II) carbenoid, followed by allylic alkylation of the resulting intermediate. Notably, the allyl aryl ether products can undergo facile and selective O-deallylation under mild conditions, furnishing the corresponding free phenol derivatives bearing all-carbon quaternary centers, together with an allylic unit as a valuable handle for further synthetic manipulation to diverse complex molecular structures.

II. RESULTS AND DISCUSSION

1. Reaction Development. Our studies began with the reaction of phenol (**1a**), methyl phenyldiazoacetate (**2a**), and allyl ethyl carbonate (**3**) using $Rh_2(Oct)_4$ as the catalyst and Cs_2CO_3 as a base in CH_3CN at 60 °C. All the results are summarized in Table 1. No multicomponent coupling product

Table 1. Optimization of the Reaction Conditions[a]



entry	[M] cat.	ligand (mol %)	yield (%) 4aa[b]	5aa[b]	6aa[b]
1	$Rh_2(Oct)_4$	–	74	31	0
2	$Rh_2(Oct)_4$	BINAP (1.5)	75	26	3
3	$Rh_2(Oct)_4$	Xantphos (1.5)	76	7	18
4	$Rh_2(Oct)_4$	dppb (1.5)	86	0	5
5	$Rh_2(Oct)_4$	PPh_3 (3.0)	86	8	0
6	$Rh_2(Oct)_4$	^{i}Pr-NHC[c] (3.0)	53	4	15
7	$Rh_2(TPA)_4$	Xantphos (1.5)	91	0	12
8	**$Rh_2(OPiv)_4$**	**Xantphos (1.5)**	**42**	**0**	**85**
9	CuCl	Xantphos (1.5)	27	0	0
10	$[Pd(PhCN)_2Cl_2]$	Xantphos (1.5)	99	0	0
11	$Rh(COD)_2BF_4$	Xantphos (1.5)	99	0	0
12	–	Xantphos (1.5)	0	0	0

[a]**1a** (0.375 mmol, 1.5 equiv), **2a** (0.25 mmol, 1.0 equiv), **3** (0.75 mmol, 3.0 equiv), MeCN (2.0 mL), [M] catalyst (1.0 mol %), ligand (1.5 mol %), Cs_2CO_3 (3.5 equiv), 60 °C, 6.0 h. [b]GC yields. Yields for **4aa** were calculated based on **1a** as the limiting substrate. Yields for **5aa** and **6aa** were calculated based on **2a** as the limiting substrate. [c]^{i}Pr-NHC = 1,3-bis(2,6-diisopropylphenyl)imidazolium chloride.

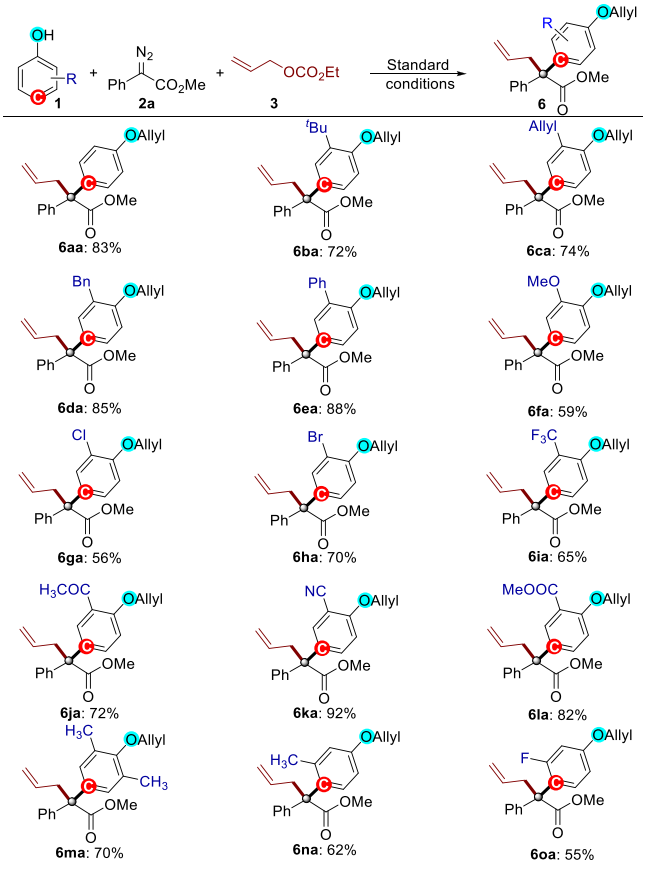
6aa was detected in the absence of a ligand, and only the direct phenol O-allylation product **4aa** and the *para* C−H functionalization product **5aa** were found in 74 and 31% yields, respectively (entry 1). On the other hand, use of BINAP as the ligand led to the formation of the target product **6aa**, albeit only in a rather low yield (3%), along with substantial amounts of **4aa** and **5aa** (entry 2). Encouraged by this result, several phosphines or NHC ligands were screened in the reaction (entries 3−6). Pleasingly, Xantphos showed better performance, furnishing the product **6aa** in a promising albeit still low yield of 18% (entry 3), thus attesting for the feasibility of the proposed protocol. However, further attempts to use a catalytic amount of dppb, PPh_3, or ^{i}PrNHC as the ligand failed to improve the yield of **6aa** (entries 4−6). Gratifyingly, $Rh_2(OPiv)_4$ was then identified as a more effective rhodium precursor for this reaction, delivering the target product **6aa** in

https://doi.org/10.1021/acscentsci.2c00004
ACS Cent. Sci. 2022, 8, 581−589

85% yield (entry 8). Other metal salts, such as CuCl and $[Pd(PhCN)_2Cl_2]$, which are commonly used in carbene transfer involving phenols and diazo compounds, were also tested in combination with Xantphos as the catalyst in the reaction, resulting the formation of **4aa** as the detectable products in these cases (entries 9 and 10). Notably, with the change from the Rh(II) carboxylate to the Rh(I) salt $[Rh(COD)_2]BF_4$ under otherwise identical conditions, the reaction gave exclusively **4aa** in 99% yield (entry 11). In addition, no **6aa** was observed in the absence of a dirhodium catalyst (entry 12), demonstrating the essential role of a $Rh(II)_2$ salt in promoting the reaction. All these results clearly indicated that this dirhodium/Xantphos catalysis displayed a unique catalytic reactivity and selectivity that is distinct from other metal catalysts in this reaction.

2. Scope and Synthetic Applications. With the optimal conditions in hand, the phenol coupling partners **1** for this protocol were evaluated first in substrate scope studies. As depicted in Scheme 2, various commercially available free

Scheme 2. Scope of Phenols 1[a]



[a]**1** (0.375 mmol, 1.5 equiv), **2a** (0.25 mmol, 1.0 equiv), **3** (0.75 mmol, 3.0 equiv), MeCN (2.0 mL), $Rh_2(OPiv)_4$ (1.0 mol %), Xantphos (1.5 mol %), Cs_2CO_3 (3.5 equiv), 60 °C, 6.0 h. Isolated yields.

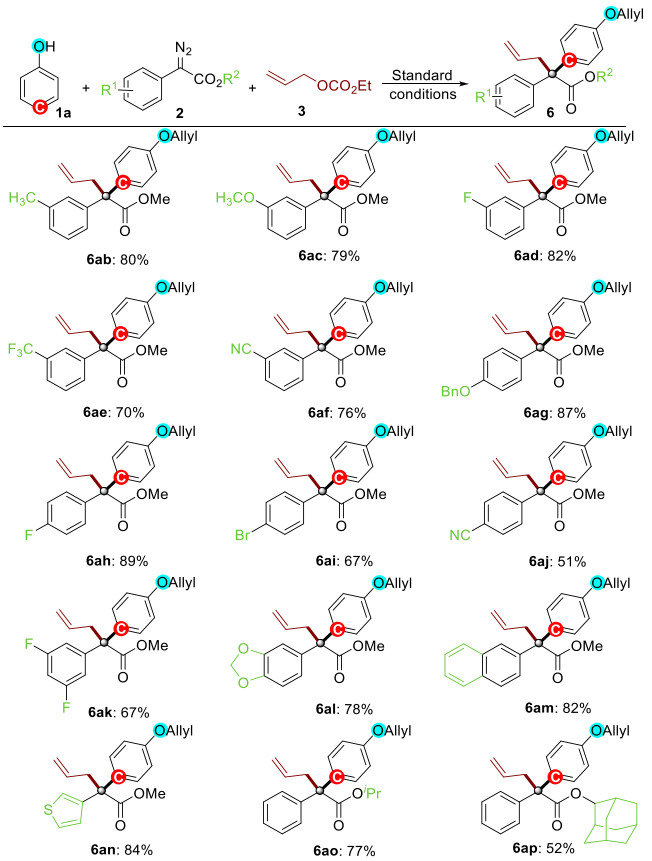
phenols smoothly participated in these MCRs with **2a** and **3**, furnishing site-specific and chemo-specific *para* C−H functionalization/allylation products **6aa**−**6oa** in moderate to high yields (55−92%). Phenols with either electron-donating (**1b**−**1f**) or electron-withdrawing substituent(s) (**1g**−**1l**) on the *ortho*-position of the phenyl ring were effective coupling partners, affording the corresponding products **6ba**−**6la** in 56−92% yields. It is noteworthy that the reaction of the phenol (**1c**) bearing an *ortho* allylic group still gave the corresponding product **6ca** in 74% yield without formation of any cyclopropanation product, indicating that the *para* C−H bond functionalization is more favorable than the potential cyclopropanation of a C═C bond in this dirhodium catalysis. Importantly, halogen substituents such as chloride (**1g**) and bromide (**1h**) on the phenol substrates are well tolerated in the reactions, delivering the corresponding products that can be used as good platform molecules for downstream transformations by cross coupling. In addition, other functional groups, including ketone (**1j**), cyano (**1k**), and ester (**1l**), could be readily introduced in the reaction, offering a useful handle for further potential synthetic manipulations. Interestingly, 2,6-dimethyl substituted phenol **1m** was also found as a competent substrate in the reaction, providing the multisubstituted product **6ma** in 70% yield. Notably, the reactions of *m*-Me substituted phenol **1n** or *m*-F substituted **1o** containing sterically hindered *para* C−H bonds still gave the corresponding *para* C−H functionalization products **6na** and **6oa**, respectively, in 62 and 55% yields, suggesting that the *para* C−H functionalization is a more preferential process compared with O−H insertion for this catalyst system. With the use of *p*-methylphenol **1p** as the substrate under standard conditions, the reaction failed to give the desired *ortho* C−H functionalization product **6pa** (for details, see the Supporting Information).

Subsequently, the scope of diazo esters **2** was investigated in reactions with **1a** and **3** under otherwise identical conditions. As shown in Scheme 3, various diazo esters with different groups on the *meta*-position of the benzene ring, including −Me, −OMe, −F, $-CF_3$, and −CN, all performed well in the reactions, delivering the corresponding phenol derivatives **6ab**−**6af** in moderate to good yields (70−82%). When diazo esters possessing either electron-donating (−OBn) or electron-withdrawing (−F, −Br, −CN) substituents on the *para*-position of the phenyl moiety were employed, the corresponding products **6ag**−**6aj** were isolated in 51−89% yields. Additionally, 3,5-difluorine substituted phenyl and [1,3]-dioxonyl diazo substrates **2k** and **2l** also reacted smoothly as competent coupling partners in this reaction, giving the corresponding multisubstituted products **6ak** and **6al** in good yields (67 and 78%, respectively). Interestingly, the diazo substrates containing heteroaryl rings, such as 2-naphthyl (**2m**) and 3-thienyl motif (**2n**), were also suitable substrates for this reaction, affording the corresponding products (**6am** and **6an**) in good yields (82 and 84%). Moreover, with changing the methyl ester of the diazo reactant to isopropyl (**2o**) or adamantan-2-yl ester (**2p**), the reactions also worked smoothly, leading to the corresponding products (**6ao** and **6ap**) in 77 and 52% yields, respectively. It is worth mentioning that all these reactions afforded the corresponding phenol derivatives **6** bearing all-carbon quaternary centers without detection of any byproducts via O−H insertion or cyclopropanation. Subsequently, we turned our attention to the development of the asymmetric version of this transformation. However, preliminary attempts showed that no appreciable stereoselectivity was achieved currently either by employing chiral disphosphine ligands with $Rh_2(OPiv)_4$ or by using chiral Rh(II) precursors with Xantphos (for details, see the Supporting Information).

To show the synthetic utility of the methodology, the transformations using drug molecules, natural products, and

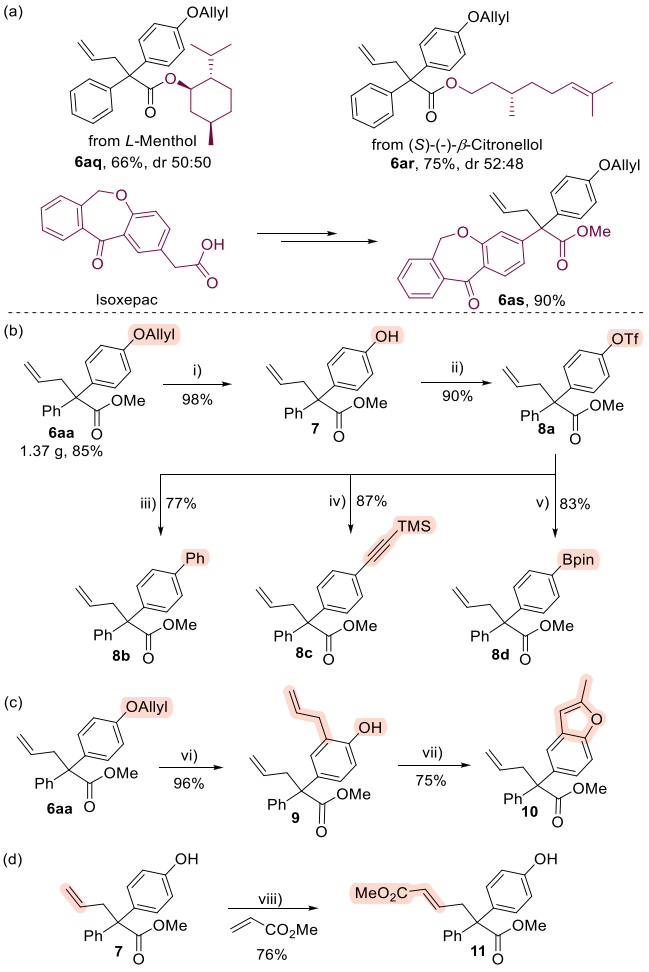
https://doi.org/10.1021/acscentsci.2c00004
ACS Cent. Sci. 2022, 8, 581−589

Scheme 3. Scope of Diazo Esters 2[a]



[a]**1a** (0.375 mmol, 1.5 equiv), **2** (0.25 mmol, 1.0 equiv), **3** (0.75 mmol, 3.0 equiv), MeCN (2.0 mL), $Rh_2(OPiv)_4$ (1.0 mol %), Xantphos (1.5 mol %), Cs_2CO_3 (3.5 equiv), 60 °C, 6.0 h. Isolated yields.

Scheme 4. Late-Stage Functionalization of Complex Architectures and Synthetic Transformation[a]



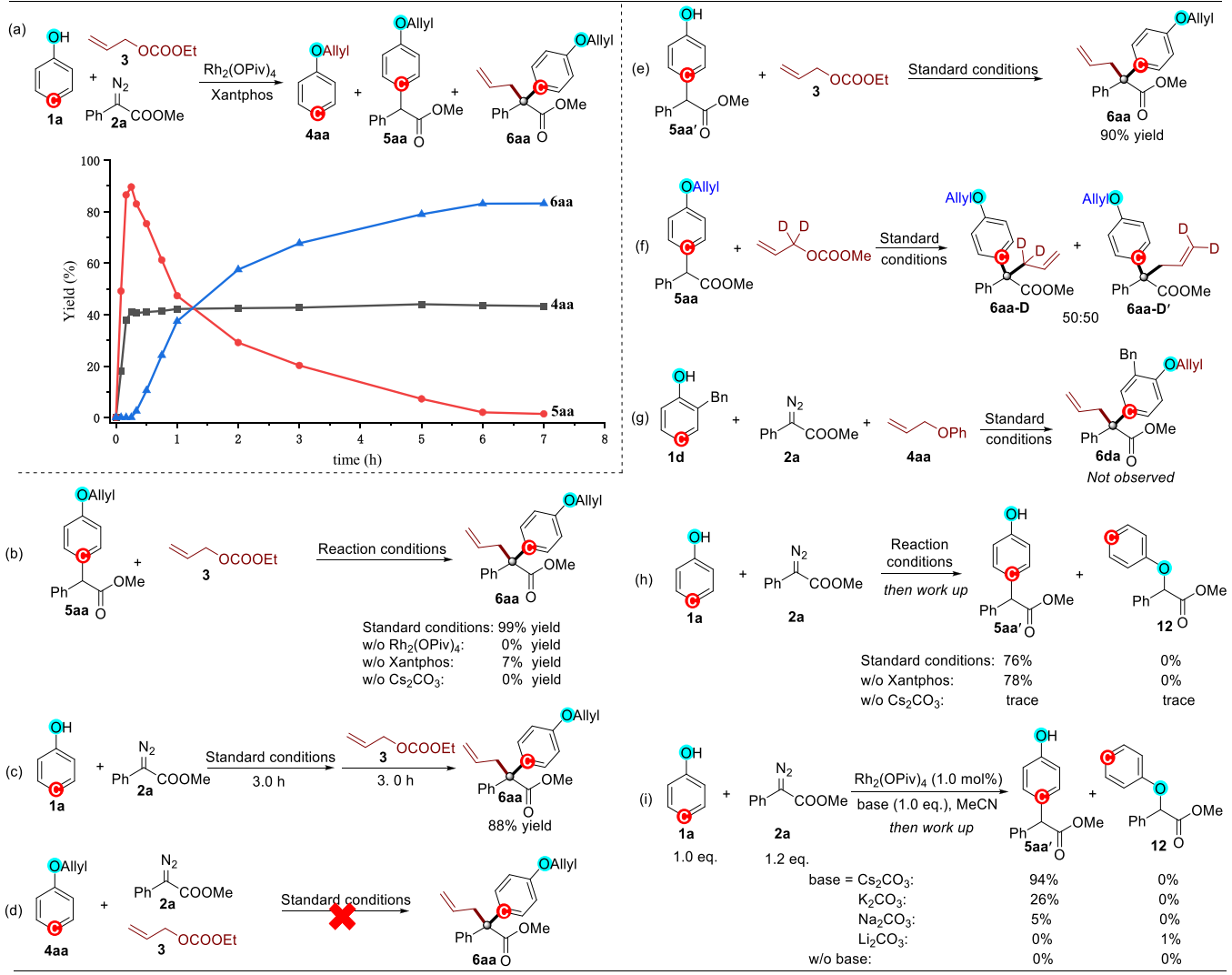
[a](i) $Pd(PPh_3)_4$, K_2CO_3, MeOH, rt. (ii) Tf_2O, DMAP, Et_3N, DCM, 0 °C to rt. (iii) $PhB(OH)_2$, $Pd(PPh_3)_4$, K_3PO_4, 1,4-dioxane, 110 °C. (iv) Ethynyltrimethylsilane, $Pd(PPh_3)_2Cl_2$, CuI, Et_3N, DMF, 90 °C. (v) B_2Pin_2, $Pd(dppf)Cl_2$, AcOK, 1,4-dioxane, 120 °C. (vi) Et_2AlCl, hexane, 80 °C. (vii) $PdCl_2$, $Cu(OAc)_2$, DMF, 100 °C. (viii) Second-generation Grubbs catalyst (5 mol %), DCM (0.2 M), 40 °C.

their derivatives as the reaction partners were conducted. As depicted in Scheme 4a, the α-diazo esters that were easily derived from L-menthol and (*S*)-(−)-β-citronellol worked well in the reactions with **1a** and **3**, giving **6aq** and **6ar** in 66 and 75% yields, respectively. Additionally, α-diazo ester prepared from isoxepac was also found to react smoothly in MCRs with **1a** and **3**, successfully incorporating synthetically useful allylic group and phenol unit into the α-site of the acid derivative (**6as**, 90%). Moreover, a gram-scale (5.0 mmol) reaction of **1a**, **2a**, and **3** proceeded smoothly under standard conditions, affording the product **6aa** in 85% yield (1.37 g), highlighting the practicality of the approach (Scheme 4b). Notably, Pd-catalyzed selective O-deallylation of **6aa** can be readily achieved under mild conditions, providing the corresponding product **7** bearing a free hydroxyl group in very high yield. Importantly, the hydroxyl group can be used as a versatile synthetic handle for further transformation. For example, triflate **8a** was easily prepared in 90% yield, which can then serve as versatile synthons in Pd-catalyzed coupling reactions, giving products bearing diphenyl (**8b**, 77%), synthetically important alkynyl (**8c**, 87%), or boron groups (**8d**, 83%). Furthermore, treatment of compound **6aa** with Et_2AlCl offered product **9** efficiently in 96% yield through *ortho* Claisen rearrangement, which underwent a Pd(II)-catalyzed intramolecular oxidative cyclization of alkene with hydroxyl group to furnish the product **10** with a 2-substituted benzofuran unit (75% yield, Scheme 4c), which is a core structure of some bioactive molecules.[74] Finally, the cross-metathesis reaction of compound **7** with methyl acrylate was realized in the presence of second-generation Grubbs catalyst, giving the corresponding product **11** in 76% yield (Scheme 4d).

3. Mechanistic Studies. To gain insight into the mechanism for the MCR, several experiments were conducted. First, the kinetic profiles for the reaction of **1a**, **2a**, and **3** under standard conditions were obtained through GC analysis of aliquots taken at specified periods. As depicted in Scheme 5a, the yield of compound **4aa** showed a rapid increase in the first 5 min, and after that time remained almost constant during the whole reaction course. On the other hand, in the initial period (ca. 5 min) a rapid accumulation of **5aa** was also observed, followed by a gradual decay in the rest of the reaction. This was accompanied by a slower but steady growth in the amount of the multicomponent coupling product **6aa**, suggesting a tandem process, wherein **5aa** might act as a nucleophile in the further reaction with **3**. To confirm this hypothesis, the reaction of isolated compound **5aa** with allylic partner **3** was performed under standard conditions. Indeed, the target

https://doi.org/10.1021/acscentsci.2c00004
ACS Cent. Sci. 2022, 8, 581−589

Scheme 5. Reaction Profiles of the MCR (a) and Controlled Experiments (b–i)



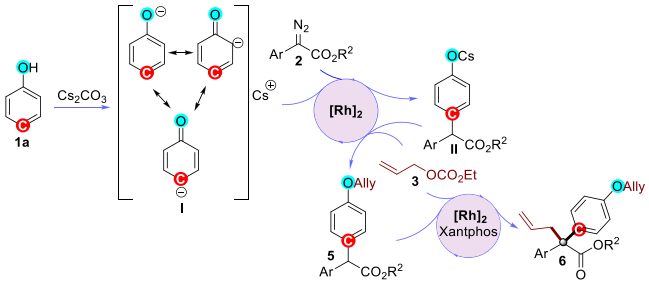
product **6aa** was isolated in 99% yield in this case (Scheme 5b). In contrast, almost no **6aa** was detected in the absence of $Rh_2(OPiv)_4$, Xantphos, or Cs_2CO_3 (99% versus 0–7%). Next, when the reaction of **1a** with **2a** and **3** was conducted in a stepwise addition sequence of the reagents, **6aa** was generated in 88% yield (Scheme 5c), further suggesting that this MCR reaction is a tandem process. Additionally, no formation of **6aa** and no conversion of **4aa** were observed in the reaction of **4aa** and **2a** with **3** under standard conditions (Scheme 5d). These results suggested that compound **5aa** rather than **4aa** should be involved as a plausible intermediate. It worth mentioning that neither the C–H functionalization nor cyclopropanation reaction took place in this multicomponent system (Scheme 5d), and the same was true for the two-component reaction of **4aa** and **2a** (for details, see the Supporting Information). Moreover, when compound **5aa′** prepared from phenol **1a** with **2a** was subjected to react with allylic compound **3**, the target product **6aa** was afforded in 90% yield (Scheme 5e). This result, together with the reactions in Scheme 5d, imply that C–H functionalization proceeds prior to O-allylation in the reaction steps for the formation of **5aa**. On the basis of previous reports[63−70] and these experimental results, we propose that the reaction is most likely to proceed through a tandem process of Rh(II) carbenoid induced C–H functionalization and $[Rh_2]$/Xantphos-catalyzed allylic alkylation, which is distinctive from the well-known $[Rh(II)_2]$-catalyzed MCRs, wherein an active ylide/zwitterionic intermediate generated *in situ* was directly trapped by an electrophile.[46,47] The necessity of the Xantphos ligand in this catalysis may be owing to the coordination modification of the active center of dirhodium, leading to a novel catalytic activity for allylic alkylation.[63−70] Nonetheless, the possibility of the formation of monorhodium species cannot be completely ruled out at the present stage. To gain some further insights into the allylic substitution process, compound **5aa** was treated with deuterated allyl methyl carbonate under standard conditions, and two products, **6a-D** and **6a-D′**, were obtained in 50:50 ratio (Scheme 5f). The result showed that *O*-allyl remained unchanged and *C*-allyl of **6aa-D** (**6aa-D′**) was completely from deuterated allyl substrate. In other words, the migration of the *O*-allyl to *C*-allyl might be unlikely involved in this reaction (for details, see the Supporting Information). Moreover, when allyl phenyl ether **4aa** was introduced to the mixture of 2-benzylphenol **1d** with **2a** under standard conditions, no multicomponent coupling product **6da** was detected by GC–MS (Scheme 5g), further indicating that the allyl phenyl ether could not serve as an allyl source in this multicomponent transformation.

https://doi.org/10.1021/acscentsci.2c00004
ACS Cent. Sci. 2022, 8, 581−589

To understand the *para* C−H functionalization selectivity of phenol with diazo compound in the current dirhodium catalysis, several two component reactions of **1a** with **2a** were conducted. As depicted in Scheme 5h, compound **5aa′** generated by the *para* C−H functionalization was delivered as the main product (76 and 78% isolated yields, respectively), and no O−H insertion product **12** was detectable under standard conditions and conditions without Xantphos ligand. In contrast, without Cs_2CO_3, only a trace amount of **5aa′** was generated under standard conditions, indicating the essential role of Cs_2CO_3. Accordingly, it was speculated that a facile formation of phenate intermediate from the free hydroxyl group and Cs_2CO_3 might promote the *para*-selective C−H functionalization in this dirhodium catalysis. Published data show that, due to the electropositive character of the Cs^+ and the electron delocalization from the negatively charged oxygen to the aromatic ring, the electron density of the C4-carbon atom of phenolate is obviously increased as compared with **1a** bearing the neutral OH group, thus enhancing the nucleophilic ability of the aromatic ring.[75−79] To further evaluate this hypothesis, several commercially available alkali metal carbonates were tested as additives in the reaction of **1a** and **2a** (Scheme 5i). It was found that product **5aa′** was formed in 5−94% yields in the presence of Cs_2CO_3, K_2CO_3, or Na_2CO_3. No **5aa′** was detected when Li_2CO_3 was used or in the absence of any base. It is worth mentioning that the yields of **5aa′** by using different alkali metal carbonates in the reactions are consistent with their electron density ranking from ^{13}C NMR of the phenolic models in the literature,[75,76] which can be attributed to the different Coulombic interactions between the alkali metal cation and phenolate anion. These results demonstrated that the base additive plays a critical role in improving the reactivity and selectivity for *para* C−H functionalization of phenol with diazo compound in this dirhodium catalysis.

Based on these results, a possible reaction pathway is proposed in Scheme 6. In the presence of the base Cs_2CO_3,

Scheme 6. Possible Reaction Pathway



phenolate salt **I** with different resonance forms is generated first, which then undergoes $[Rh]_2$-catalyzed *para*-selective C−H functionalization with **2** to afford the intermediate **II** due to the higher electron density of the C4-carbon atom of the phenolate. Subsequently, O-allylation of **II** with allylic substrate **3** takes place under $[Rh]_2$ or $[Rh]_2$/Xantphos catalysis, delivering the intermediate **5**. Finally, product **6** is produced by $[Rh]_2$/Xantphos catalyzed allylic alkylation of **5** with allylic substrate **3**.

III. SUMMARY AND CONCLUSIONS

In conclusion, an unprecedented multicomponent reaction of free phenols, diazoesters, and allylic compounds has been developed, providing versatile phenol derivatives bearing acyclic all-carbon quaternary centers with synthetic useful allyl units. Mechanistic studies suggest that the reaction is likely to proceed via a tandem process of carbene-induced C−H functionalization and sequential Rh(II)/Xantphos-catalyzed allylation. Moreover, it is found that the base additives play an essential role in the *para*-selective C−H functionalization of free phenol with diazo compound in this dirhodium catalysis, which would broaden the application of dirhodium complex in carbene transfer reactions. The salient features of this protocol, including easily available starting materials, mild reaction conditions, good substrate scope, and versatile synthetic transformations of the products, would render the protocol highly appealing for late-stage modification of pharmaceuticals.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acscentsci.2c00004.

Experimental procedures, complete characterization data, and copies of ^1H, ^{13}C, and ^{19}F NMR spectra (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Guiqing Xu − *Henan Engineering Research Center of Chiral Hydroxyl Pharmaceutical, Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China*; Email: guiqingxu@163.com

Xiaoming Wang − *State Key Laboratory of Organometallic Chemistry, Center for Excellence in Molecular Synthesis, Shanghai Institute of Organic Chemistry, University of Chinese Academy of Sciences, Chinese Academy of Sciences, Shanghai 200032, China; School of Chemistry and Materials Science, Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China*; orcid.org/0000-0001-7981-3757; Email: xiaoming@sioc.ac.cn

Authors

Yang Yang − *Henan Engineering Research Center of Chiral Hydroxyl Pharmaceutical, Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China; State Key Laboratory of Organometallic Chemistry, Center for Excellence in Molecular Synthesis, Shanghai Institute of Organic Chemistry, University of Chinese Academy of Sciences, Chinese Academy of Sciences, Shanghai 200032, China*

Bin Lu − *State Key Laboratory of Organometallic Chemistry, Center for Excellence in Molecular Synthesis, Shanghai Institute of Organic Chemistry, University of Chinese Academy of Sciences, Chinese Academy of Sciences, Shanghai 200032, China*

https://doi.org/10.1021/acscentsci.2c00004
ACS Cent. Sci. 2022, 8, 581−589

Complete contact information is available at:
https://pubs.acs.org/10.1021/acscentsci.2c00004

Author Contributions

[‖]Y.Y. and B.L. contributed equally to this work.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was generously supported by the National Natural Science Foundation of China (21821002).

■ REFERENCES

(1) Rappoport, Z. *The Chemistry of Phenols*; Wiley-VCH: Weinheim, 2003.
(2) Quideau, S.; Deffieux, D.; Douat-Casassus, C.; Pouysegu, L. Plant polyphenols: chemical properties, biological activities, and synthesis. *Angew. Chem. Int. Ed.* **2011**, *50*, 586−621.
(3) Snyder, S. A.; Thomas, S. B.; Mayer, A. C.; Breazzano, S. P. Total syntheses of hopeanol and hopeahainol A empowered by a chiral Bronsted acid induced pinacol rearrangement. *Angew. Chem. Int. Ed.* **2012**, *51*, 4080−4084.
(4) Sunden, H.; Ma, J. N.; Hansen, L. K.; Gustavsson, A. L.; Burstein, E. S.; Olsson, R. Design of a highly selective and potent class of non-planar estrogen receptor β agonists. *ChemMedChem.* **2013**, *8*, 1283−1294.
(5) Wu, H.; Wang, Q.; Zhu, J. Catalytic Enantioselective Pinacol and Meinwald Rearrangements for the Construction of Quaternary Stereocenters. *J. Am. Chem. Soc.* **2019**, *141*, 11372−11377.
(6) Wang, Y.; Zhang, W. Y.; Xie, J. H.; Yu, Z. L.; Tan, J. H.; Zheng, C.; Hou, X. L.; You, S. L. Enantioselective Desymmetrization of Bisphenol Derivatives via Ir-Catalyzed Allylic Dearomatization. *J. Am. Chem. Soc.* **2020**, *142*, 19354−19359.
(7) Xu, X.; Luo, J. Transition Metal-Catalyzed Directing-Group-Assisted C-H Activation of Phenols. *ChemSusChem* **2019**, *12*, 4601−4616.
(8) Al Mamari, H. H.; Štefane, B.; Žugelj, H. B. Metal-catalyzed C-H bond functionalization of phenol derivatives. *Tetrahedron* **2020**, *76*, 130925.
(9) Huang, Z.; Lumb, J.-P. Phenol-Directed C−H Functionalization. *ACS Catal.* **2019**, *9*, 521−555.
(10) For template-assisted *para* C−H functionalization of phenols, see: Patra, T.; Bag, S.; Kancherla, R.; Mondal, A.; Dey, A.; Pimparkar, S.; Agasti, S.; Modak, A.; Maiti, D. Palladium-Catalyzed Directed *para* C-H Functionalization of Phenols. *Angew. Chem. Int. Ed.* **2016**, *55*, 7751−7755.
(11) Ciana, C. L.; Phipps, R. J.; Brandt, J. R.; Meyer, F. M.; Gaunt, M. J. A highly *para*-selective copper(II)-catalyzed direct arylation of aniline and phenol derivatives. *Angew. Chem. Int. Ed.* **2011**, *50*, 458−462.
(12) Sagadevan, A.; Charpe, V. P.; Ragupathi, A.; Hwang, K. C. Visible Light Copper Photoredox-Catalyzed Aerobic Oxidative Coupling of Phenols and Terminal Alkynes: Regioselective Synthesis of Functionalized Ketones via C≡C Triple Bond Cleavage. *J. Am. Chem. Soc.* **2017**, *139*, 2896−2899.
(13) Ye, T.; McKervey, M. A. Organic Synthesis with α-Diazo Carbonyl Compounds. *Chem. Rev.* **1994**, *94*, 1091−1160.
(14) Padwa, A. Domino reactions of rhodium(II) carbenoids for alkaloid synthesis. *Chem. Soc. Rev.* **2009**, *38*, 3072−3081.
(15) Doyle, M. P.; Duffy, R.; Ratnikov, M.; Zhou, L. Catalytic Carbene Insertion into C-H Bonds. *Chem. Rev.* **2010**, *110*, 704−724.
(16) Davies, H. M. L.; Morton, D. Guiding principles for site selective and stereoselective intermolecular C-H functionalization by donor/acceptor rhodium carbenes. *Chem. Soc. Rev.* **2011**, *40*, 1857−1869.
(17) Zhu, S.-F.; Zhou, Q.-L. Transition-Metal-Catalyzed Enantioselective Heteroatom−Hydrogen Bond Insertion Reactions. *Acc. Chem. Res.* **2012**, *45*, 1365−1377.
(18) Gillingham, D.; Fei, N. Catalytic X−H insertion reactions based on carbenoids. *Chem. Soc. Rev.* **2013**, *42*, 4918−4931.
(19) Ford, A.; Miel, H.; Ring, A.; Slattery, C. N.; Maguire, A. R.; McKervey, M. A. Modern Organic Synthesis with α-Diazocarbonyl Compounds. *Chem. Rev.* **2015**, *115*, 9981−10080.
(20) Hu, F.; Xia, Y.; Ma, C.; Zhang, Y.; Wang, J. C-H bond functionalization based on metal carbene migratory insertion. *Chem. Commun.* **2015**, *51*, 7986−7995.
(21) Li, Y.-P.; Li, Z.-Q.; Zhu, S.-F. Recent advances in transition-metal-catalyzed asymmetric reactions of diazo compounds with electron-rich (hetero-) arenes. *Tetrahedron Lett.* **2018**, *59*, 2307−2316.
(22) Zhao, X.; Wu, G.; Zhang, Y.; Wang, J. Copper-catalyzed direct benzylation or allylation of 1,3-azoles with *N*-tosylhydrazones. *J. Am. Chem. Soc.* **2011**, *133*, 3296−3299.
(23) Xu, B.; Li, M. L.; Zuo, X. D.; Zhu, S. F.; Zhou, Q. L. Catalytic Asymmetric Arylation of α-Aryl-α-diazoacetates with Aniline Derivatives. *J. Am. Chem. Soc.* **2015**, *137*, 8700−8703.
(24) Li, Z.; Chen, Y.; Wang, C.; Xu, G.; Shao, Y.; Zhang, X.; Tang, S.; Sun, J. Construction of C-C Axial Chirality via Asymmetric Carbene Insertion into Arene C-H Bonds. *Angew. Chem. Int. Ed.* **2021**, *60*, 25714−25718.
(25) Zhu, D. X.; Liu, J. G.; Xu, M. H. Stereodivergent Synthesis of Enantioenriched 2,3-Disubstituted Dihydrobenzofurans via a One-Pot C-H Functionalization/Oxa-Michael Addition Cascade. *J. Am. Chem. Soc.* **2021**, *143*, 8583−8589.
(26) Zhu, D. X.; Xia, H.; Liu, J. G.; Chung, L. W.; Xu, M. H. Regiospecific and Enantioselective Arylvinylcarbene Insertion of a C-H Bond of Aniline Derivatives Enabled by a Rh(I)-Diene Catalyst. *J. Am. Chem. Soc.* **2021**, *143*, 2608−2619.
(27) Song, X. G.; Zhu, S. F.; Xie, X. L.; Zhou, Q. L. Enantioselective copper-catalyzed intramolecular phenolic O-H bond insertion: synthesis of chiral 2-carboxy dihydrobenzofurans, dihydrobenzopyrans, and tetrahydrobenzooxepines. *Angew. Chem. Int. Ed.* **2013**, *52*, 2555−2558.
(28) Maier, T. C.; Fu, G. C. Catalytic enantioselective O-H insertion reactions. *J. Am. Chem. Soc.* **2006**, *128*, 4594−4595.
(29) Chen, C.; Zhu, S. F.; Liu, B.; Wang, L. X.; Zhou, Q. L. Highly enantioselective insertion of carbenoids into O-H bonds of phenols: An efficient approach to chiral α-aryloxycarboxylic esters. *J. Am. Chem. Soc.* **2007**, *129*, 12616−12617.
(30) Liang, X. S.; Li, R. D.; Wang, X. C. Copper-Catalyzed Asymmetric Annulation Reactions of Carbenes with 2-Iminyl- or 2-Acyl-Substituted Phenols: Convenient Access to Enantioenriched 2,3-Dihydrobenzofurans. *Angew. Chem. Int. Ed.* **2019**, *58*, 13885−13889.
(31) Harada, S.; Tanikawa, K.; Homma, H.; Sakai, C.; Ito, T.; Nemoto, T. Silver-Catalyzed Asymmetric Insertion into Phenolic O-H Bonds using Aryl Diazoacetates and Theoretical Mechanistic Studies. *Chem. Eur. J.* **2019**, *25*, 12058−12062.
(32) Xie, X. L.; Zhu, S. F.; Guo, J. X.; Cai, Y.; Zhou, Q. L. Enantioselective palladium-catalyzed insertion of α-aryl-α-diazoacetates into the O-H bonds of phenols. *Angew. Chem. Int. Ed.* **2014**, *53*, 2978−2981.
(33) Shen, H.-Q.; Xie, H.-P.; Sun, L.; Zhou, Y.-G. Enantioselective Carbene Insertion into O−H of Phenols with Chiral Palladium/2,2′-Biimidazole Complexes. *Organometallics* **2019**, *38*, 3902−3905.
(34) Zhang, Y.; Yao, Y.; He, L.; Liu, Y.; Shi, L. Rhodium(II)/Chiral Phosphoric Acid-Cocatalyzed Enantioselective O-H Bond Insertion of α-Diazo Esters. *Adv. Synth. Catal.* **2017**, *359*, 2754−2761.
(35) Nakayama, H.; Harada, S.; Kono, M.; Nemoto, T. Chemoselective Asymmetric Intramolecular Dearomatization of Phenols with α-Diazoacetamides Catalyzed by Silver Phosphate. *J. Am. Chem. Soc.* **2017**, *139*, 10188−10191.
(36) Yu, Z.; Li, Y.; Shi, J.; Ma, B.; Liu, L.; Zhang, J. $(C_6F_5)_3B$ Catalyzed Chemoselective and ortho-Selective Substitution of

Phenols with α-Aryl α-Diazoesters. *Angew. Chem. Int. Ed.* **2016**, *55*, 14807−14811.
(37) Zhang, Q.; Zhang, X. F.; Li, M.; Li, C.; Liu, J. Q.; Jiang, Y. Y.; Ji, X.; Liu, L.; Wu, Y. C. Mechanistic Insights into the Chemo- and Regio-Selective $B(C_6F_5)_3$ Catalyzed C-H Functionalization of Phenols with Diazoesters. *J. Org. Chem.* **2019**, *84*, 14508−14519.
(38) Ma, B.; Tang, Z.; Zhang, J.; Liu, L. Copper-catalysed *ortho*-selective C-H bond functionalization of phenols and naphthols with α-aryl-α-diazoesters. *Chem. Commun.* **2020**, *56*, 9485−9488.
(39) Hu, S.; Lu, Z.; Liu, M.; Xu, H.; Wu, J.; Chen, F. TfOH-Catalyzed Cascade C-H Activation/Lactonization of Phenols with α-Aryl-α-diazoesters: Rapid Access to α-Aryl Benzofuranones. *J. Org. Chem.* **2020**, *85*, 14916−14925.
(40) Guo, R. T.; Zhang, Y. L.; Tian, J. J.; Zhu, K. Y.; Wang, X. C. Rhodium-Catalyzed *ortho*-Selective Carbene C-H Insertion of Unprotected Phenols Directed by a Transient Oxonium Ylide Intermediate. *Org. Lett.* **2020**, *22*, 908−913.
(41) For a $In(OTf)_3$-catalyzed C−H allylation reaction of free phenols with vinyldiazoacetates, see: Zhao, D.; Luo, J.; Liu, L.; Liu, Y. Regiospecific and site-selective C−H allylation of phenols with vinyldiazo compounds catalyzed by In(III). *Org. Chem. Front.* **2021**, *8*, 6252−6258.
(42) Yu, Z.; Ma, B.; Chen, M.; Wu, H. H.; Liu, L.; Zhang, J. Highly site-selective direct C-H bond functionalization of phenols with α-aryl-α-diazoacetates and diazooxindoles via gold catalysis. *J. Am. Chem. Soc.* **2014**, *136*, 6904−6907.
(43) Liu, Y.; Yu, Z.; Zhang, J. Z.; Liu, L.; Xia, F.; Zhang, J. Origins of unique gold-catalysed chemo- and site-selective C-H functionalization of phenols with diazo compounds. *Chem. Sci.* **2016**, *7*, 1988−1995.
(44) Yu, Z.; Li, Y.; Zhang, P.; Liu, L.; Zhang, J. Ligand and counteranion enabled regiodivergent C-H bond functionalization of naphthols with α-aryl-α-diazoesters. *Chem. Sci.* **2019**, *10*, 6553−6559.
(45) Xi, Y.; Su, Y.; Yu, Z.; Dong, B.; McClain, E. J.; Lan, Y.; Shi, X. Chemoselective carbophilic addition of α-diazoesters through ligand-controlled gold catalysis. *Angew. Chem. Int. Ed.* **2014**, *53*, 9817−9821.
(46) Guo, X.; Hu, W. Novel multicomponent reactions via trapping of protic onium ylides with electrophiles. *Acc. Chem. Res.* **2013**, *46*, 2427−2440.
(47) Zhang, D.; Hu, W. Asymmetric Multicomponent Reactions Based on Trapping of Active Intermediates. *Chem. Rec* **2017**, *17*, 739−753.
(48) Qiu, H.; Li, M.; Jiang, L. Q.; Lv, F. P.; Zan, L.; Zhai, C. W.; Doyle, M. P.; Hu, W. H. Highly enantioselective trapping of zwitterionic intermediates by imines. *Nat. Chem.* **2012**, *4*, 733−738.
(49) Jia, S.; Xing, D.; Zhang, D.; Hu, W. Catalytic asymmetric functionalization of aromatic C-H bonds by electrophilic trapping of metal-carbene-induced zwitterionic intermediates. *Angew. Chem. Int. Ed.* **2014**, *53*, 13098−13101.
(50) Kang, Z.; Zhang, D.; Xu, X.; Hu, W. Privilege-Structure-Oriented Three-Component Asymmetric Aminomethylation: Assembly of Chiral 3-Aminomethyl Indolones. *Org. Lett.* **2019**, *21*, 9878−9883.
(51) Yu, S.; Hua, R.; Fu, X.; Liu, G.; Zhang, D.; Jia, S.; Qiu, H.; Hu, W. Asymmetric Multicomponent Reactions for Efficient Construction of Homopropargyl Amine Carboxylic Esters. *Org. Lett.* **2019**, *21*, 5737−5741.
(52) For an elegant Au-catalyzed three-component reaction of phenols and diazoesters with allenamides through O−H insertion, see: Yu, S.; Chen, J.; Liu, G.; Lei, J.; Hu, W.; Qiu, H. A gold(I)-catalysed chemoselective three-component reaction between phenols, α-diazocarbonyl compounds and allenamides. *Chem. Commun.* **2020**, *56*, 1649−1652.
(53) Tsuji, J.; Minami, I.; Shimizu, I. Allyation of carbonucleophiles with allylic carbonates under neutral conditions catalyzed by rhodium complexes. *Tetrahedron Lett.* **1984**, *25*, 5157−5160.
(54) Turnbull, B. W. H.; Evans, P. A. Asymmetric Rhodium-Catalyzed Allylic Substitution Reactions: Discovery, Development and Applications to Target-Directed Synthesis. *J. Org. Chem.* **2018**, *83*, 11463−11479.
(55) Thoke, M. B.; Kang, Q. Rhodium-Catalyzed Allylation Reactions. *Synthesis* **2019**, *51*, 2585−2631.
(56) Chen, Z.-S.; Huang, X.-Y.; Gao, J.-M.; Ji, K. Relay Rh(II)/Pd(0) Dual Catalysis: Selective Construction of Cyclic All-Quaternary Carbon Centers. *Org. Lett.* **2016**, *18*, 5876−5879.
(57) Chen, Z.-S.; Huang, X.-Y.; Chen, L.-H.; Gao, J.-M.; Ji, K. Rh(II)/Pd(0) Dual Catalysis: Regiodivergent Transformations of Alkylic Oxonium Ylides. *ACS Catal.* **2017**, *7*, 7902−7907.
(58) Huang, L.-Z.; Xuan, Z.; Jeon, H. J.; Du, Z.-T.; Kim, J. H.; Lee, S.-g. Asymmetric Rh(II)/Pd(0) Relay Catalysis: Synthesis of α-Quaternary Chiral β-Lactams through Enantioselective C−H Insertion/Diastereoselective Allylation of Diazoamides. *ACS Catal.* **2018**, *8*, 7340−7345.
(59) Chen, L.-H.; Ma, Y.-T.; Yang, F.; Huang, X.-Y.; Chen, S.-W.; Ji, K.; Chen, Z.-S. Chemo-selective Rh(II)/Pd(0) Dual Catalysis: Synthesis of All-Carbon C3-Quaternary Allylic Oxindoles from *N*-Aryl-α-Diazo-β-Keto-Amides with Functionalized Allyl Carbonates. *Adv. Synth. Catal.* **2019**, *361*, 1307−1312.
(60) Wang, X. X.; Huang, X. Y.; Lei, S. H.; Yang, F.; Gao, J. M.; Ji, K.; Chen, Z. S. Relay Rh(II)/Pd(0) dual catalysis: synthesis of α-quaternary β-keto-esters via a [1,2]-sigmatropic rearrangement/allylic alkylation cascade of α-diazo tertiary alcohols. *Chem. Commun.* **2020**, *56*, 782−785.
(61) Kang, Z.; Chang, W.; Tian, X.; Fu, X.; Zhao, W.; Xu, X.; Liang, Y.; Hu, W. Ternary Catalysis Enabled Three-Component Asymmetric Allylic Alkylation as a Concise Track to Chiral α,α-Disubstituted Ketones. *J. Am. Chem. Soc.* **2021**, *143*, 20818−20827.
(62) For an elegant example of Ru(II)/Pd(0) dual catalyzed two-component reactions of diazo compounds with allylic compounds, see: Yamamoto, K.; Qureshi, Z.; Tsoung, J.; Pisella, G.; Lautens, M. Combining Ru-Catalyzed C-H Functionalization with Pd-Catalyzed Asymmetric Allylic Alkylation: Synthesis of 3-Allyl-3-aryl Oxindole Derivatives from Aryl α-Diazoamides. *Org. Lett.* **2016**, *18*, 4954−4957.
(63) Lu, B.; Liang, X.; Zhang, J.; Wang, Z.; Peng, Q.; Wang, X. Dirhodium(II)/Xantphos-Catalyzed Relay Carbene Insertion and Allylic Alkylation Process: Reaction Development and Mechanistic Insights. *J. Am. Chem. Soc.* **2021**, *143*, 11799−11810.
(64) Trindade, A. F.; Coelho, J. A. S.; Afonso, C. A. M.; Veiros, L. F.; Gois, P. M. P. Fine Tuning of Dirhodium(II) Complexes: Exploring the Axial Modification. *ACS Catal.* **2012**, *2*, 370−383.
(65) Hong, B.; Shi, L.; Li, L.; Zhan, S.; Gu, Z. Paddlewheel dirhodium(II) complexes with *N*-heterocyclic carbene or phosphine ligand: New reactivity and selectivity. *Green Synth. Catal.* **2022**, DOI: 10.1016/j.gresc.2022.03.001.
(66) Wang, D.; Zhao, Y.; Yuan, C.; Wen, J.; Zhao, Y.; Shi, Z. Rhodium(II)-Catalyzed Dehydrogenative Silylation of Biaryl-Type Monophosphines with Hydrosilanes. *Angew. Chem. Int. Ed.* **2019**, *58*, 12529−12533.
(67) Fu, L.; Li, S.; Cai, Z.; Ding, Y.; Guo, X.-Q.; Zhou, L.-P.; Yuan, D.; Sun, Q.-F.; Li, G. Ligand-Enabled Site-Selectivity in a Versatile Rhodium(II)-Catalysed Aryl C−H Carboxylation with CO_2. *Nat. Catal.* **2018**, *1*, 469−478.
(68) Vora, H. U.; Silvestri, A. P.; Engelin, C. J.; Yu, J. Q. Rhodium(II)-Catalyzed Nondirected Oxidative Alkenylation of Arenes: Arene Loading at One Equivalent. *Angew, Chem. Int. Ed.* **2014**, *53*, 2683−2686.
(69) Kwak, J.; Kim, M.; Chang, S. Rh(NHC)-Catalyzed Direct and Selective Arylation of Quinolines at the 8-Position. *J. Am. Chem. Soc.* **2011**, *133*, 3780−3783.
(70) Gois, P. M. P.; Trindade, A. F.; Veiros, L. F.; André, V.; Duarte, M. T.; Afonso, C. A. M.; Caddick, S.; Cloke, F. G. N. Tuning the Reactivity of Dirhodium(II) Complexes with Axial N-heterocyclic Carbene Ligands: the Arylation of Aldehydes. *Angew. Chem. Int. Ed.* **2007**, *46*, 5750−5753.
(71) Lebel, H.; Marcoux, J. F.; Molinaro, C.; Charette, A. B. Stereoselective cyclopropanation reactions. *Chem. Rev.* **2003**, *103*, 977−1050.

(72) Trost, B. M.; Toste, F. D. Asymmetric O- and C-alkylation of phenols. *J. Am. Chem. Soc.* **1998**, *120*, 815−816.
(73) Evans, P. A.; Leahy, D. K. Regioselective and enantiospecific rhodium-catalyzed intermolecular allylic etherification with *ortho*-substituted phenols. *J. Am. Chem. Soc.* **2000**, *122*, 5012−5013.
(74) Choi, M.; Jo, H.; Park, H. J.; Sateesh Kumar, A.; Lee, J.; Yun, J.; Kim, Y.; Han, S. B.; Jung, J. K.; Cho, J.; Lee, K.; Kwak, J. H.; Lee, H. Design, synthesis, and biological evaluation of benzofuran- and 2,3-dihydrobenzofuran-2-carboxylic acid N-(substituted)phenylamide derivatives as anticancer agents and inhibitors of NF-κB. *Bioorg. Med. Chem. Lett.* **2015**, *25*, 2545−2549.
(75) Haupt, R. A.; Renneckar, S. Chemical shifts of phenolic monomers in solution and implications for addition and self-condensation. *Magn. Reson. Chem.* **2013**, *51*, 95−101.
(76) Kremer, T.; Schleyer, P. V. R. Charge-localizing effect in alkali-metal enolates and phenolates. Structure and aromaticity of the phenolate anion. *Organometallics* **1997**, *16*, 737−746.
(77) Davies, A. G. Metals as surrogates for hydrogen in organic chemistry: anything hydrogen can do, a metal can do better. *J. Chem. Soc., Perkin Trans.* **2000**, *1*, 1997−2010.
(78) Conner, A. H.; Lorenz, L. F.; Hirth, K. C. Accelerated cure of phenol-formaldehyde resins: Studies with model compounds. *J. Appl. Polym. Sci.* **2002**, *86*, 3256−3263.
(79) Kinart, W. J.; Kinart, C. M. Studies on the catalysis of the reaction of organotin phenoxides with diethyl azodicarboxylate by lithium perchlorate. *J. Organomet. Chem.* **2003**, *665*, 233−236.

https://doi.org/10.1021/acscentsci.2c00004
ACS Cent. Sci. 2022, 8, 581−589