

Cite this: *Chem. Sci.*, 2024, 15, 6012

All publication charges for this article have been paid for by the Royal Society of Chemistry

Received 28th January 2024

Accepted 11th March 2024

DOI: 10.1039/d4sc00649f

rsc.li/chemical-science

Cobalt- or rhodium-catalyzed synthesis of 1,2-dihydrophosphete oxides *via* C–H activation and formal phosphoryl migration†

Shengbo Xu,^a Ruijie Mi,^b Guangfan Zheng[✉]*^c and Xingwei Li[✉]*^{ab}

A highly stereo- and chemoselective intermolecular coupling of diverse heterocycles with dialkynylphosphine oxides has been realized *via* cobalt/rhodium-catalyzed C–H bond activation. This protocol provides an efficient synthetic entry to functionalized 1,2-dihydrophosphete oxides in excellent yields *via* the merger of C–H bond activation and formal 1,2-migration of the phosphoryl group. Compared with traditional methods of synthesis of 1,2-dihydrophosphetes that predominantly relied on stoichiometric metal reagents, this catalytic system features high efficiency, a relatively short reaction time, atom-economy, and operational simplicity. Photophysical properties of selected 1,2-dihydrophosphete oxides are also disclosed.

Introduction

Organophosphorus molecules are an important class of compounds which are not only widely utilized as ligands or organocatalysts for diverse transformations but also function as drugs and bioactive molecules.¹ The development of efficient methods for the synthesis of functionalized organophosphorus compounds has attracted continuous attention.² In particular, four-membered phosphorus compounds have found vast applications in the studies of catalysis, medicinal chemistry, and materials science (Fig. 1).³ For instance, compound **I** is known as a new organic catalyst that enables the reductive C–N cross-coupling of functionalized nitroalkanes with arylboronic acids, and compound **II** exhibits unique photophysical properties, while compound **III** is employed as a useful chiral bidentate

ligand. However, efficient methods to access four-membered phosphacycles, especially 1,2-dihydrophosphete (oxides), only remain sporadic. In 1985, Mathey and co-workers reported synthesis of metal complexes of 2-keto-1,2-dihydrophosphetes *via* CO insertion into a P–C bond of phosphirene-chromium, -molybdenum, and -tungsten pentacarbonyl complexes as a result of ring expansion.⁴ After that, they further disclosed coupling of electron-poor phospho-alkene P–W(CO)₅ complexes with electron-rich alkynes *via* [2 + 2] cycloadditions (Scheme 1a1).⁵ In 1989, Knobler reported the reaction of diphenyltitanacyclobutene with phenyldichlorophosphine, allowing the first isolation of free 1,2-dihydrophosphetes (Scheme 1a2).⁶ In 2021, Pietschnig and co-workers established a transition-metal free annulation reaction between 1,3-diynes and phosphanides (Scheme 1a3).⁷ Recently, Gates accomplished cyclization of 1-phosphabutadiene and isolated Au- and Pd-stabilized 1,2-dihydrophosphete complexes (Scheme 1a4).⁸

Rearrangement reactions provide straightforward and efficient access to complex organic frameworks *via* structural reorganizations.⁹ In 1989, Lukehart developed stoichiometric reactions of trialkynylphosphine oxide and platinum hydride that involve Pt–H addition and rearrangement reactions (Scheme 1b1).¹⁰ In 1997, Majoral reported synthesis of metal-lacycle-supported 1,2-dihydrophosphete *via* coupling of bis(alkynyl)phosphines with zirconocene-benzynes (Scheme 1b2).¹¹ Very recently, Cummins realized phosphinidene transfer to cyclopropenones for synthesis of phosphet-2-ones (Scheme 1b3).¹² Despite these strategies, the majority of systems require the employment of stoichiometric amounts of metal reagents such as zirconium, platinum, titanium, and tungsten complexes. In addition, the reaction scope is also limited due to compatibility issues. Therefore, efficient synthesis of 1,2-

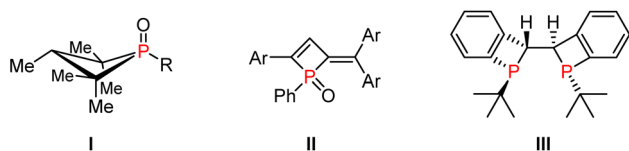


Fig. 1 Selected examples of four-membered phosphacycles.

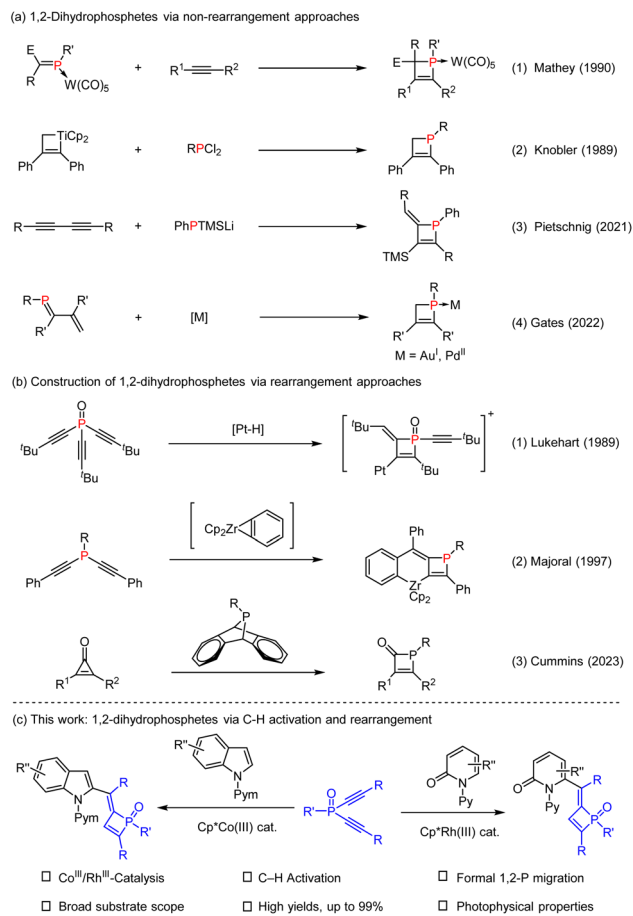
^aSchool of Chemistry and Chemical Engineering, Shaanxi Normal University (SNNU), Xi'an 710062, P. R. China. E-mail: lixw@snnu.edu.cn

^bInstitute of Molecular Science and Engineering, Institute of Frontier and Interdisciplinary Sciences, Shandong University, Qingdao 266237, P. R. China

^cDepartment of Chemistry, Northeast Normal University, Changchun 130024, P. R. China

† Electronic supplementary information (ESI) available. CCDC 2203562 and 2203561. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d4sc00649f>





Scheme 1 Synthesis of 1,2-dihydrophosphetes.

dihydrophosphetes from readily available reagents still awaits further development.

We reasoned that 1,2-dihydrophosphetes can be accessed *via* catalytic manipulation of the triple bond in dialkynylphosphine (oxides). Indeed, metal-catalyzed coupling of dialkynylphosphine oxides/sulfides delivered various powerful strategies to create complex phosphacycles.¹³ The C≡C bond in the dialkynylphosphine is expected to readily participate as a special π-bond in C-H activation reactions, and the resulting alkenyl phosphine intermediate may also undergo rearrangement to give complex structures. While significant achievements have been made in C-H bond activation catalyzed by transition metals such as Pd, Rh, Ru, Ir, Mn, and Co,¹⁴ P-containing substrates are generally less explored either as the arene or the coupling reagent.¹⁵ Consequently, catalytic construction of four-membered phosphacycles remains a formidable challenge. By taking advantage of ready availability of arenes, our objective was to synthesize 1,2-dihydrophosphetes *via* integration of C-H bond activation and migration of the P atom in the reactive intermediate. Herein, we report the development of cobalt^{III} or rhodium^{III}-catalyzed C-H activation of diverse classes of heteroarenes and coupling with dialkynylphosphine oxides, which affords a series of rare 1,2-dihydrophosphete oxides in high yields (Scheme 1c). The mechanism of this reaction has also been briefly explored.

Results and discussion

We commenced our studies with optimization of reaction parameters of the coupling of 1-(pyrimidin-2-yl)-1*H*-indole **1a** and methylbis(phenylethynyl)phosphine oxide **2a** (Table 1). The reaction occurred at 100 °C in the presence of a Cp*Co(CO)I₂/AgSbF₆ catalyst in DCE for 3 h, and the desired four membered P^V=O product (**3a**) was isolated in 95% yield. It was found that Cp*Co(CO)I₂ showed superiority to other catalysts such as [Cp*RhCl₂]₂ and [Cp*Co(MeCN)₃](BF₄)₂ (Table 1, entries 1–3). The screening of solvents showed that TFE was the best choice (Table 1, entries 4–8), and a nearly quantitative yield was realized when the reaction was performed at 100 °C (entry 8). In addition, the reaction efficiency was slightly affected when the reaction temperature was lowered from 100 °C to 60 °C (entries 8–12).

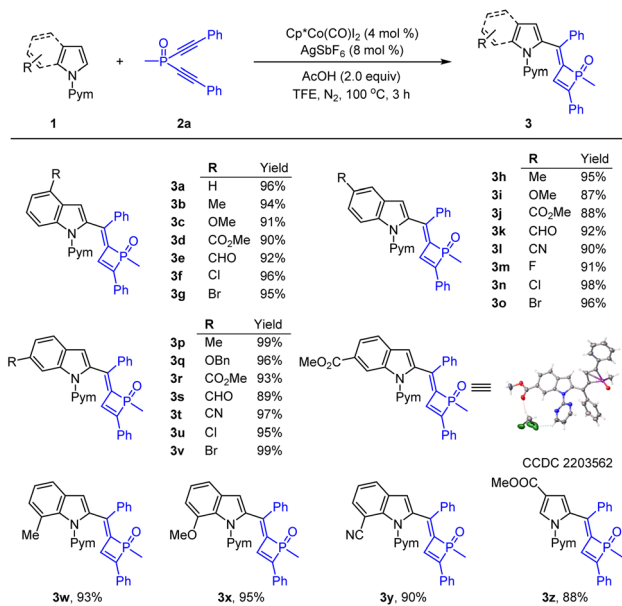
With the optimized conditions established, we next evaluated the generality of this transformation (Scheme 2). Indoles with a variety of functionalities at the 4-position such as methyl, methoxy, halogens, ester group and formyl reacted smoothly to give the corresponding products **3a–3g** in excellent yields. Besides, other functional groups such as electron-donating (Me, OBn) and -withdrawing (CO₂Me, CHO and CN) and halogen groups (F, Cl and Br) at the C-5 position of the indoles were all generally tolerated, and the corresponding products (**3h–3o**) were isolated in high yields. Indoles bearing a 6-substituent underwent rapid coupling with **2a** in good to excellent chemical yields (up to 99% yield, **3p–3v**). The structure of **3r** was confirmed by X-ray crystallographic analysis.¹⁶ 7-Substituted indoles were also viable, affording the desired coupling products in good efficiency (**3w–3y**). Moreover, a pyrrole substrate

Table 1 Optimization studies^a

Entry	Catalyst	Solvent	Temp. (°C)	Yield ^b (%)
1	[Cp*RhCl ₂] ₂ ^c	DCE	100	78
2	[Cp*Co(MeCN) ₃](BF ₄) ₂	DCE	100	93 ^d
3	Cp*Co(CO)I ₂	DCE	100	95
4	Cp*Co(CO)I ₂	MeCN	100	43
5	Cp*Co(CO)I ₂	THF	100	Trace
6	Cp*Co(CO)I ₂	EA	100	35
7	Cp*Co(CO)I ₂	Dioxane	100	40
8	Cp*Co(CO)I ₂	TFE	100	98
9	Cp*Co(CO)I ₂	TFE	90	96
10	Cp*Co(CO)I ₂	TFE	80	91
11	Cp*Co(CO)I ₂	TFE	70	90
12	Cp*Co(CO)I ₂	TFE	60	93

^a The reactions were carried out with **1a** (0.13 mmol), **2a** (0.10 mmol), M cat. (4 mol%), AgSbF₆ (8 mol%) and HOAc (2.0 equiv.) in a solvent (1.0 mL) under N₂ for 3 h. ^b Isolated yields. ^c AgSbF₆ (16 mol%) was used. ^d No AgSbF₆ was used.



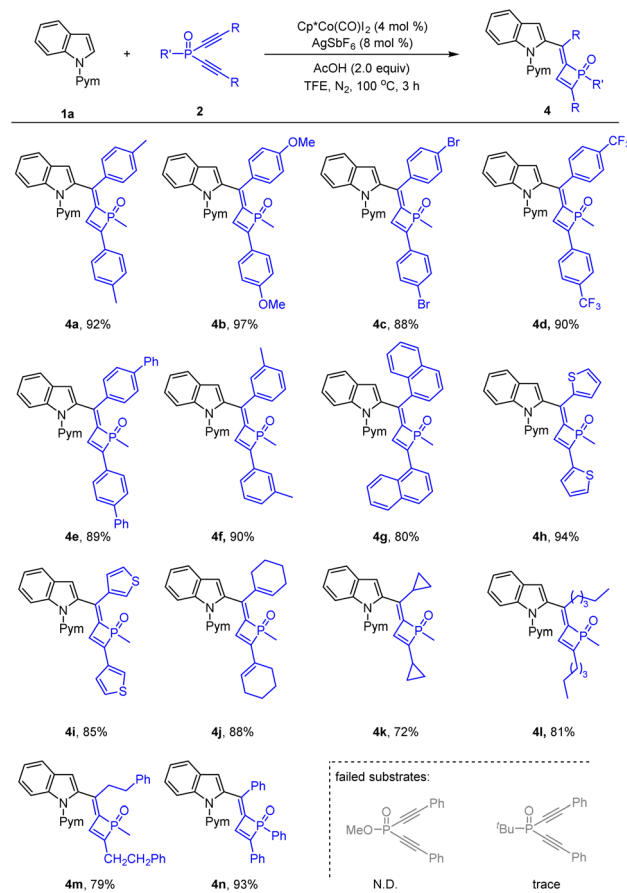


Scheme 2 Substrate scope of indoles by cobalt-catalysis. Conditions: indoles **1** (0.26 mmol), dialkynylphosphine oxide **2a** (0.20 mmol, 1.0 equiv.), Cp*Co(CO)₂ (4.0 mol%), AgSbF₆ (8 mol%), HOAc (2.0 equiv.) in 2.0 mL of TFE under N₂ at 100 °C for 3 h. Isolated yields.

was also amenable to this transformation, delivering the desired product **3z** in 88% yield.

The scope of the dialkynylphosphine oxides was next investigated (Scheme 3). Examination of the *para*- and *meta*-substituents in the benzene ring of the diyne terminus revealed that both electron-withdrawing and -donating groups were tolerated, providing products **4a–4f** in 88–97% yields. The reaction worked well when a 1-naphthyl-substituted substrate was used, delivering the product **4g** in 80% yield. Besides, dialkynylphosphine oxides containing heteroaryl groups in the alkyne unit were also applicable, and 2- and 3-thienyl groups produced the desired products **4h** and **4i** in 94% and 85% yield, respectively. Gratifyingly, alkenyl-substituted substrates afforded satisfactory results as in the isolation of product **4j** in 88% yield. Cyclic and linear alkyl substituents were all tolerated under the reaction conditions with corresponding **4k–4m** being isolated in 72–81% yields. Of note, changing the *P*-methyl group diyne to a *P*-phenyl one led to the desired product **4n** in high isolated yield. To our disappointment, replacing the methyl group on the phosphorus center with a methoxyl or *tert*-butyl group failed to deliver any desired product.

To further expand the scope of arenes, 2-pyridones were then examined. The coupling of 2-pyridone **5a** and dialkynylphosphine oxide **2a** only gave poor efficiency when using the same Cp*Co(CO)₂ catalyst. To our delight, when catalyzed by [Cp*RhCl₂]₂/AgSbF₆ in DCE, the desired product was isolated in 92% yield (see the ESI† for details). The scope of the 2-pyridone substrate was then explored using the dialkynylphosphine oxide **2a** as a coupling partner (Scheme 4). Thus, 2-pyridones bearing a series of substituents such as methyl, methoxyl, benzyloxy, halogen, cyano and

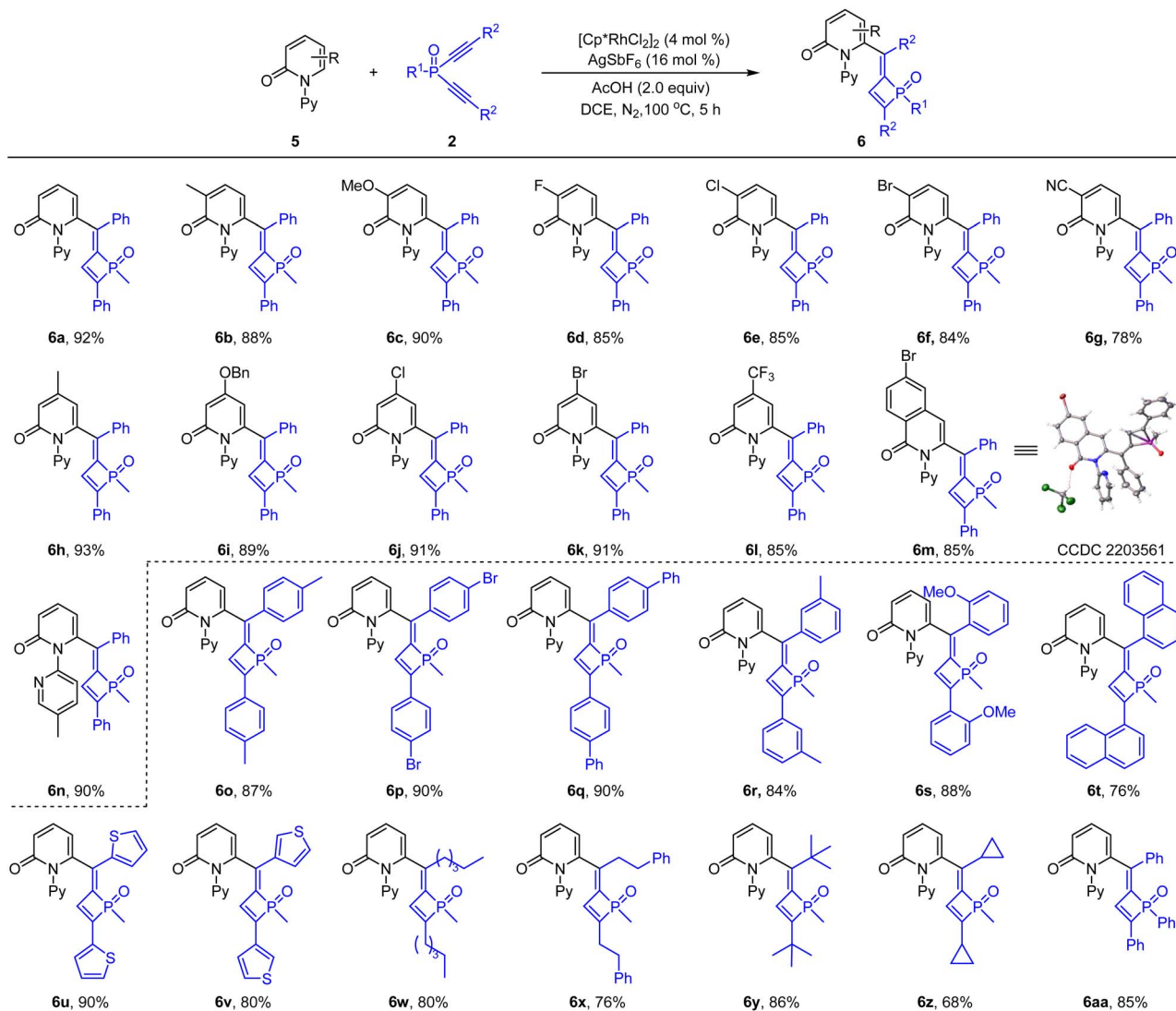


Scheme 3 Substrate scope of dialkynylphosphine oxides by cobalt catalysis. Conditions: indoles **1a** (0.26 mmol), dialkynylphosphine oxides **2** (0.20 mmol, 1.0 equiv.), Cp*Co(CO)₂ (4.0 mol%), AgSbF₆ (8 mol%), and HOAc (2.0 equiv.) in TFE (2 mL) under N₂ at 100 °C for 3 h. Isolated yields.

trifluoromethyl at the C3- or C4-positions were all compatible in this reaction, delivering the corresponding products in consistently high yields (**6b–6l**, 78–93% yield). 6-Bromo-isoquinolinone was tolerated under the reaction conditions and the coupling afforded the corresponding product **6m** in 85% yield, which was confirmed by X-ray crystallography studies.¹⁷ 2-Pyridone bearing a 5-methyl-*N*-pyridinyl group reacted smoothly to give product **6n** in 90% yield. Regarding the dialkynylphosphine oxides, our results indicated that a series of phenyl, naphthyl, heteroaryl, and alkyl groups in the alkyne were all tolerated, furnishing the corresponding 1,2-dihydrophosphete oxides in good to high yields (**6o–6z**, 68–90%). The tolerance of bulky ^tBu groups in **6y** may provide mechanistic insights (*vide infra*).

The photophysical properties of six products were briefly investigated (Fig. 2 and Table 2). Compounds **3a–4h** displayed an intense absorption band in the UV/Vis region centered at 370 nm, attributed to the π–π* transitions of the extended π-conjugated system. Besides, these derivatives exhibited blue emissions. The fluorescent emission maxima appeared in the range of 470–504 nm (Table 2). These results may indicate their potential for applications in photoelectronics.





Scheme 4 Scope of 2-pyridones and dialkynylphosphine oxides by rhodium catalysis. Conditions: 2-pyridones **5** (0.26 mmol), dialkynylphosphine oxides **2** (0.20 mmol, 1.0 equiv.), $[\text{Cp}^*\text{RhCl}_2]_2$ (4.0 mol%), AgSbF_6 (16 mol%), HOAc (2.0 equiv.) in 2.0 mL of DCE under N_2 at 100 °C for 5 h. Isolated yields.

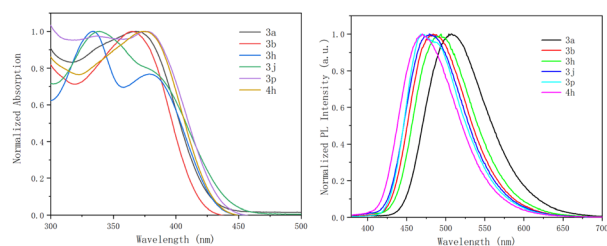


Fig. 2 Normalized absorption (left) and emission (right) spectra of **3a**, **3b**, **3h**, **3j**, **3p**, and **4h** in DCM (1×10^{-5} M).

Table 2 Photophysical properties of selected products (1×10^{-5} M in DCM)

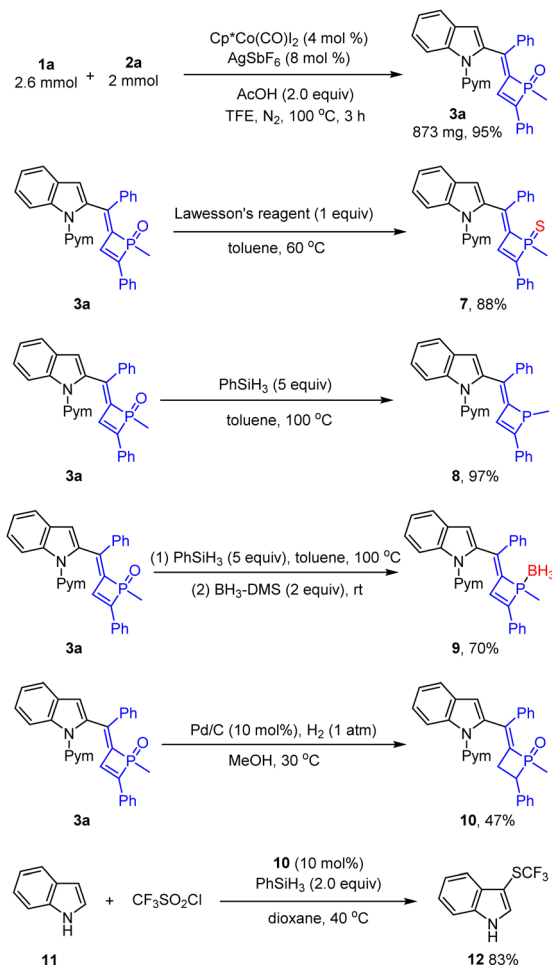
Compound	λ_{abs}^a (nm)	λ_{em}^b (nm)	Φ_{F}^c
3a	368	504	0.0383
3b	365	484	0.0478
3h	334, 379	494	0.0282
3j	339	479	0.0305
3p	346, 375	470	0.0430
4h	374	470	0.0288

^a Absorption maxima. ^b Fluorescent emission maxima. ^c Absolute quantum yields (determined with an integrating sphere system).

Synthetic applications of a representative product have been demonstrated (Scheme 5). The reaction of **1a** and dialkynylphosphine oxide **2a** was scaled up to a mmol scale, from which product **3a** was isolated in 95% yield. Treatment of **3a** with Lawesson's reagent afforded the phosphine sulfide **7** in

high yield. The phosphine oxide **3a** was reduced by PhSiH_3 to give phosphine **8** in excellent yield. Reduction of the phosphine oxide by PhSiH_3 followed by protection by borane gave the

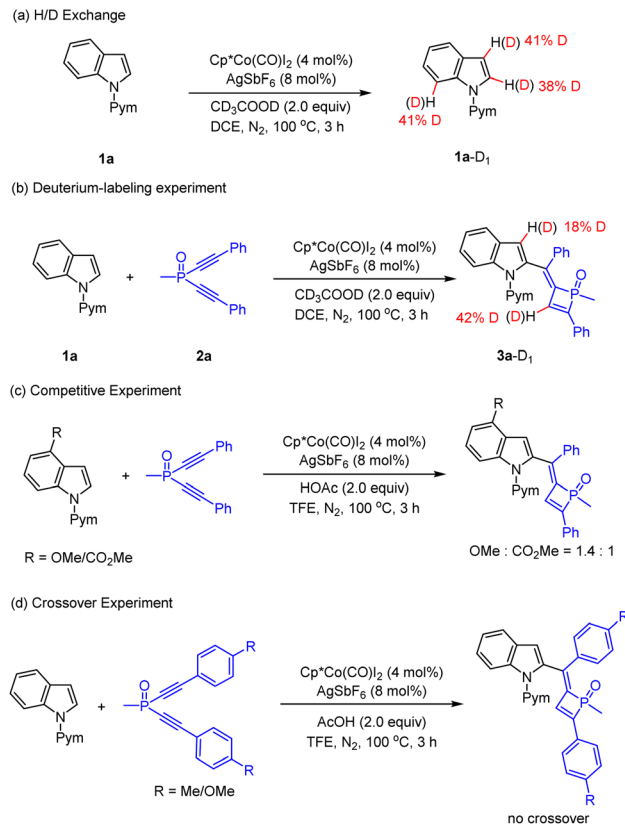




Scheme 5 Synthetic applications of a product.

adduct **9** in 70% yield. Tetrahydrophosphete oxide **10** was formed in 47% yield under a palladium/ H_2 reductive system. Meanwhile, the tetrahydrophosphete oxide **10** as an organic phosphine catalyst could catalyze deoxygenation of CF_3SO_2Cl and the reaction with indole to afford C3-trifluoromethylsulfenylation indole **12** in 83% yield.^{3f}

Preliminary mechanistic studies were conducted to gain insight into the reaction mechanism (Schemes 6 and 7). First, an H/D exchange experiment was conducted using CD_3COOD as a deuterium source, and H/D scrambling was observed at the C2, C3, and C7 of indole **1a** (Scheme 6a), supporting the reversibility of C–H activation at these positions under the reaction conditions. A deuterium labeling experiment was then performed using **1a** and **2a** in the presence of CD_3COOD (Scheme 6b), and analysis of the product by 1H NMR spectroscopy revealed that the 3-position of the indole and olefinic C–H of dihydrophosphete ring was substantially deuterated. The significant deuteration at the olefinic C–H position likely suggests protonolysis of a Co–C bond in the catalytic cycle. Parallel competitive reactions of two electronically distinguishable indoles **1b** ($R = OMe$) and **1d** ($R = CO_2Me$) have been conducted, and the more electron-rich indole tends to react with slightly higher reactivity (Scheme 6c). Next, a crossover

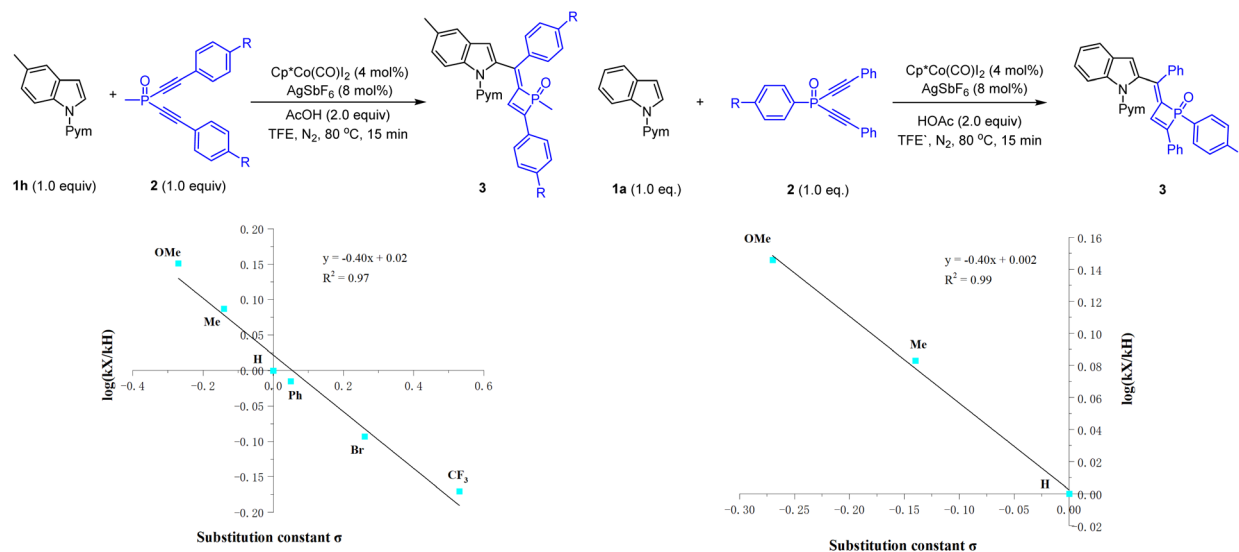


Scheme 6 Mechanistic studies.

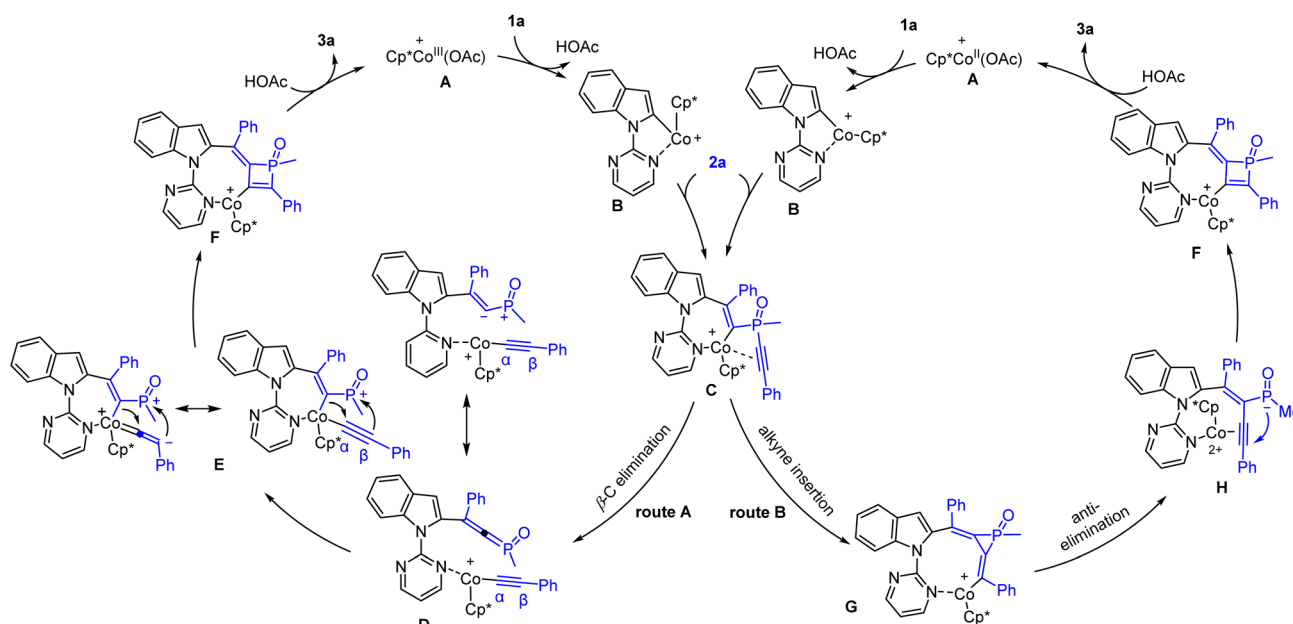
experiment using a mixture of **2a** ($R = Me$) and **2b** ($R = OMe$) was then performed, and HRMS analysis of the product mixture indicated that no crossover product was present, revealing an intramolecular P=O migration process (Scheme 6d). Moreover, Hammett studies were also performed for a series of indoles with various substituents at the C5-position (see the ESI† for details) and for a series of dialkynylphosphine oxides bearing different para substituents (Scheme 7). A linear correlation was observed for each series through the Hammett plot. A negative ρ value (-0.40 for the dialkynylphosphine oxide series) and (-1.18 for the indole series (see the ESI† for details)) was observed for each plot, and this outcome suggests positive charge accumulation in the transition state, which is stabilized by an electron-donating substituent.

On the basis of these results and related literature reports of C–H activation-coupling with alkynes, a plausible mechanism for the Co(III)-catalyzed system is proposed in Scheme 8. Starting from a Co(III) carboxylate species, C–H activation occurs at the C(2) position to give the intermediate **B** via cyclometalation. Subsequently, the resulting Co–C(2) bond undergoes migratory insertion into an alkyne unit of the incoming diyne **2a**, forming an alkenylcobalt intermediate **C**. At this stage, two pathways are possible. In route A (Scheme 8, left), β -C(alkynyl) elimination is proposed to give a cobalt alkynyl intermediate with a pendant phosphonium ylide (**D**). Coordination of the carbanion leads to an alkenyl intermediate **E**, and the subsequent α insertion of the Co–alkenyl bond into the vinylidene-like C(α) triggers





Scheme 7 Hammett studies for the cobalt-catalyzed systems.



Scheme 8 Proposed possible reaction pathways.

a nucleophilic addition of the C(β) to the phosphonium center. The resulting intermediate **F** undergoes protonolysis to release the final product and completes the catalytic cycle. Alternatively in route B (Scheme 8, right), the intermediate **C** is proposed to undergo the 2nd migratory insertion into the alkyne to generate a three-membered phosphacycle (**G**). Anti-elimination¹⁸ of the phosphinate anion gives an enyne intermediate **H**, where the alkyne unit is activated toward 4-*endo*-dig cyclization to form the same intermediate **F**. While it is challenging to unequivocally distinguish between these two pathways by experimental methods, we tend to prefer the route A based on the kinetic studies. Hammett plots (Scheme 7) of both series of Co-

catalyzed reactions supported the intermediacy of key cationic species that is stabilized by EDGs. Accordingly, the route A is more likely. On the other hand, the isolation of product **6y** in good yields under the Rh-catalyzed conditions starting from the diyne with *tert*-butyl termini also argues against the route B. This is because the formation of the corresponding rhodium congener of intermediate **G** will cause strong steric repulsions between the metal center and proximal *t*Bu group.

Conclusions

In summary, a series of 1,2-dihydrophosphetes were efficiently synthesized through a cobalt/rhodium-catalyzed C-H



alkenylation/P=O migration sequence *via* the coupling of indoles/2-pyridone with dialkynylphosphine oxides. A large array of functional groups were tolerated in this catalytic system. The photophysical properties of selected products indicate the potentiality of 1,2-dihydrophosphetes as electro-luminescent materials. Mechanistic studies have been performed and Hammett studies suggest build-up of positive charges in the catalytic cycle, and the *P*-alkynyl group likely undergoes beta-elimination and migratory insertion. Asymmetric reactions of the related chemistry of diynes are underway in our laboratory.

Data availability

Further details of the experimental procedure, ^1H and ^{13}C NMR, and X-ray crystallographic data for products **3r** and **6m** are available in the ESI.†

Author contributions

X. L. conceived the idea and initiated the project. G. Z. performed the initial studies and analyzed the data. S. X. and R. M. performed the experiments. X. L. and S. X. wrote the manuscript.

Conflicts of interest

The authors declare no competing financial interests.

Acknowledgements

Financial support from the NSFC (No. 22371175), research grant from the Central Universities of China (GK202306002), and research fund from the SNNU are gratefully acknowledged.

Notes and references

- (a) J. Grembecka, A. Mucha, T. Cierpicki and P. Kafarski, The Most Potent Organophosphorus Inhibitors of Leucine Aminopeptidase. Structure-Based Design, Chemistry, and Activity, *J. Med. Chem.*, 2003, **46**, 2641–2655; (b) Y. Wei and M. Shi, Multifunctional Chiral Phosphine Organocatalysts in Catalytic Asymmetric Morita–Baylis–Hillman and Related Reactions, *Acc. Chem. Res.*, 2010, **43**, 1005–1018; (c) T. Wang, X. Han, F. Zhong, W. Yao and Y. Lu, Amino Acid-Derived Bifunctional Phosphines for Enantioselective Transformations, *Acc. Chem. Res.*, 2016, **49**, 1369–1378; (d) W. Huang, S. Liu, D. Zou, M. Thomas, Y. Wang, T. Zhou, J. Romero, A. Kohlmann, F. Li, J. Qi, L. Cai, T. Dwight, Y. Xu, R. Xu, R. Dodd, A. Toms, L. Parillon, X. Lu, R. Anjum, S. Zhang, F. Wang, J. Keats, S. Wardwell, Y. Ning, Q. Xu, L. Moran, Q. Mohemmad, H. Jang, T. Clackson, N. Narasimhan, V. Rivera, X. Zhu, D. Dalgarno and W. Shakespeare, Discovery of Brigatinib (AP26113), a Phosphine Oxide-Containing, Potent, Orally Active Inhibitor of Anaplastic Lymphoma Kinase, *J. Med. Chem.*, 2016, **59**, 4948–4964; (e) P. Thornton, H. Kadri, A. Miccoli

- and Y. Mehellou, Nucleoside Phosphate and Phosphonate Prodrug Clinical Candidates, *J. Med. Chem.*, 2016, **59**, 10400–10410; (f) T. Imamoto, Searching for Practically Useful P-Chirogenic Phosphine Ligands, *Chem. Rev.*, 2016, **16**, 2659–2673; (g) E. Peris and R. Crabtree, Key factors in pincer ligand design, *Chem. Soc. Rev.*, 2018, **47**, 1959–1968; (h) H. Guo, Y. Fan, Z. Sun, Y. Wu and O. Kwon, Phosphine Organocatalysis, *Chem. Rev.*, 2018, **118**, 10049–10293; (i) H. Ni, W. Chan and Y. Lu, Phosphine-Catalyzed Asymmetric Organic Reactions, *Chem. Rev.*, 2018, **118**, 9344–9411; (j) E. Regulska, P. Hindenberg and C. Romero-Nieto, From Phospha-phenalenes to Diphosphahexaarenes: An Overview of Linearly Fused Six-Membered Phosphorus Heterocycles, *Eur. J. Inorg. Chem.*, 2019, **2019**, 1519–1528; (k) P. van Leeuwen, P. Kamer, J. Reek and P. Dierkes, Ligand Bite Angle Effects in Metal-catalyzed C–C Bond Formation, *Chem. Rev.*, 2000, **100**, 2741–2770; (l) A. Mucha, P. Kafarski and Ł. Berlicki, Remarkable Potential of the α -Aminophosphonate/Phosphinate Structural Motif in Medicinal Chemistry, *J. Med. Chem.*, 2011, **54**, 5955–5980.
- (a) T. Lei, G. Liang, Y.-Y. Cheng, B. Chen, C.-H. Tung and L.-Z. Wu, Cobaloxime Catalysis for Enamine Phosphorylation with Hydrogen Evolution, *Org. Lett.*, 2020, **22**, 5385–5389; (b) H. Hou, B. Zhou, J. Wang, D. Zhao, D. Sun, X. Chen, Y. Han, C. Yan, Y. Shi and S. Zhu, Stereo- and Regioselective *cis*-Hydrophosphorylation of 1,3-Enynes Enabled by the Visible-Light Irradiation of $\text{NiCl}_2(\text{PPh}_3)_2$, *Org. Lett.*, 2021, **23**, 2981–2987; (c) J. Gbubele and T. Olszewski, Asymmetric synthesis of organophosphorus compounds using H–P reagents derived from chiral alcohols, *Org. Biomol. Chem.*, 2021, **19**, 2823–2846; (d) D.-L. Zhu, S. Jiang, Q. Wu, H. Wang, L.-L. Chai, H.-Y. Li and H.-X. Li, Visible-Light-Induced Nickel-Catalyzed P(O)–C(sp²) Coupling Using Thioxanthen-9-one as a Photoredox Catalysis, *Org. Lett.*, 2021, **23**, 160–165; (e) D. Ji, J. Jing, Y. Wang, Z. Qi, F. Wang, X. Zhang, Y. Wang and X. Li, Palladium-catalyzed asymmetric hydrophosphination of internal alkynes: atroposelective access to phosphine-functionalized olefins, *Chem*, 2022, **8**, 3346–3362; (f) P.-C. Cui, Z.-C. Yin and G.-W. Wang, Visible-Light-Promoted C4-Selective Phosphorylation of Pyridine and Quinoline Derivatives, *Org. Lett.*, 2023, **25**, 2663–2668; (g) V. Roy and S. Raha Roy, Light-Induced Activation of C–X Bond via Carbonate-Assisted Anion– π Interactions: Applications to C–P and C–B Bond Formation, *Org. Lett.*, 2023, **25**(6), 923–927; (h) D. Ji, Z. Qi and X. Li, Palladium-Catalyzed Regio- and Enantioselective Hydrophosphination of *gem*-Difluoroallenes, *Org. Lett.*, 2023, **25**, 5957–5962; (i) R. Cui, Y. Wang, L. Yuwen, L. Gao, Z. Huang, W.-H. Wang and Q.-W. Zhang, Ni-Catalyzed Asymmetric C–P Cross-Coupling Reaction for the Synthesis of Chiral Heterocyclic Phosphine Oxides, *Org. Lett.*, 2023, **25**, 6139–6142; (j) S. Zhang, N. Jiang, J.-Z. Xiao, G.-Q. Lin and L. Yin, Copper(I)-Catalyzed Asymmetric Hydrophosphination of 3,3-Disubstituted Cyclopropenes, *Angew. Chem., Int. Ed.*, 2023, **62**, e20221879; (k) W. Luo, F. Xu, Z. Wang, J. Pang, Z. Wang, Z. Sun, A. Peng, X. Cao and L. Li,



- Chemodivergent Staudinger Reactions of Secondary Phosphine Oxides and Application to the Total Synthesis of LL-D05139 β Potassium Salt, *Angew. Chem., Int. Ed.*, 2023, **62**, e20231011; (l) Y. Masuda, D. Ikeshita, K. Higashida, M. Yoshida, N. Ishida, M. Murakami and M. Sawamura, Photocatalytic 1,2-Phosphorus-Migrative [3 + 2] Cycloaddition of Tri(*t*-butyl)phosphine with Terminal Alkynes, *J. Am. Chem. Soc.*, 2023, **145**, 19060–19066.
- 3 (a) G. Li, Y. Kanda, S. Hong and A. Radosevich, Enabling Reductive C–N Cross-Coupling of Nitroalkanes and Boronic Acids by Steric Design of P(III)/P(V)=O Catalysts, *J. Am. Chem. Soc.*, 2022, **144**, 8242–8248; (b) J. Tönjes, L. Longwitz and T. Werner, Poly(methylhydrosiloxane) as a reductant in the catalytic base-free Wittig reaction, *Green Chem.*, 2021, **23**, 4852–4857; (c) L. Longwitz and P.-D. Thomas Werner, Reduction of Activated Alkenes by P^{III}/P^V Redox Cycling Catalysis, *Angew. Chem., Int. Ed.*, 2020, **59**, 2760–2763; (d) J. Lin, Y. Zhu, W. Cai and Y. Huang, Phosphine-Mediated Sequential [2+4]/[2+3] Annulation to Construct Pyrroloquinolines, *Org. Lett.*, 2022, **24**, 1593–1597; (e) S. Hong and A. Radosevich, Chemoselective Primary Amination of Aryl Boronic Acids by P^{III}/P^V=O-Catalysis: Synthetic Capture of the Transient Nef Intermediate HNO, *J. Am. Chem. Soc.*, 2022, **144**, 8902–8907; (f) J. Buonomo, M. Cole, C. Eiden and C. Aldrich, 1,3-Diphenyldisiloxane Enables Additive-Free Redox Recycling Reactions and Catalysis with Triphenylphosphine, *Synthesis*, 2020, **52**, 3583–3594; (g) P. Finkbeiner, J. Hehn and C. Gnam, Phosphine Oxides from a Medicinal Chemist's Perspective: Physicochemical and in Vitro Parameters Relevant for Drug Discovery, *J. Med. Chem.*, 2020, **63**, 7081–7107; (h) T. Nykaza, G. Li, J. Yang, M. Luzung and A. Radosevich, P^{III}/P^V=O Catalyzed Cascade Synthesis of N-Functionalized Azaheterocycles, *Angew. Chem., Int. Ed.*, 2020, **59**, 4505–4510; (i) L. Longwitz, A. Spannenberg and T. Werner, Phosphetane Oxides as Redox Cycling Catalysts in the Catalytic Wittig Reaction at Room Temperature, *ACS Catal.*, 2019, **9**, 9237–9244; (j) A. Ghosh, M. Lecomte, S.-H. Kim-Lee and A. Radosevich, Organophosphorus-Catalyzed Deoxygenation of Sulfonyl Chlorides: Electrophilic (Fluoroalkyl)sulfonylation by P^{III}/P^V=O Redox Cycling, *Angew. Chem., Int. Ed.*, 2019, **58**, 2864–2869; (k) T. Nykaza, J. Cooper, G. Li, N. Mahieu, A. Ramirez, M. Luzung and A. Radosevich, Intermolecular Reductive C–N Cross Coupling of Nitroarenes and Boronic Acids by P^{III}/P^V=O Catalysis, *J. Am. Chem. Soc.*, 2018, **140**, 15200–15205; (l) T. Nykaza, A. Ramirez, T. Harrison, M. Luzung and A. Radosevich, Biphilic Organophosphorus-Catalyzed Intramolecular C_{sp2}–H Amination: Evidence for a Nitrenoid in Catalytic Cadogan Cyclizations, *J. Am. Chem. Soc.*, 2018, **140**, 3103–3113; (m) H. Chen, S. Pascal, Z. Wang, P.-A. Bouit, Z. Wang, Y. Zhang, D. Tondelier, B. Geffroy, R. Réau, F. Mathey, Z. Duan and M. Hissler, 1,2-Dihydrophosphete: A Platform for the Molecular Engineering of Electroluminescent Phosphorus Materials for Light-Emitting Devices, *Chem.–Eur. J.*, 2014, **20**, 9784–9793; (n) T. Imamoto, K. Crépy and K. Katagiri, Optically active 1,1'-di-*tert*-butyl-2,2'-dibenzophosphetenyl: a highly strained P-stereogenic diphosphine ligand, *Tetrahedron: Asymmetry*, 2004, **15**, 2213–2218.
- 4 A. Marinetti, J. Fischer and F. Mathey, Carbonylation of a strained phosphorus-carbon bond, conversion of phosphirene into 2-keto-1,2-dihydrophosphete complexes: an entry into the chemistry of the phosphorus analogs of unsaturated. β -Lactams, *J. Am. Chem. Soc.*, 1985, **107**, 5001–5002.
- 5 A. Marinetti and F. Mathey, [2 + 2] Cycloadditions between electron-poor phospho-alkene complexes and electron-rich alkenes or alkynes, a new route to phosphetane and 1,2-dihydrophosphete rings, *J. Chem. Soc., Chem. Commun.*, 1990, 153–154.
- 6 K. Doxsee, G. Shen and C. Knobler, Uses of metallacyclobutenes in heterocyclic synthesis. Synthesis and structural characterization of 1,2-dihydrophosphete, *J. Am. Chem. Soc.*, 1989, **111**, 9129–9130.
- 7 F. Roesler, M. Kovács, C. Bruhn, Z. Kelemen and R. Pietschnig, Phosphetes via Transition Metal Free Ring Closure – Taking the Proper Turn at a Thermodynamic Crossing, *Chem.–Eur. J.*, 2021, **27**, 9782–9790.
- 8 (a) N. Huy, L. Ricard and F. Mathey, Synthesis of the phosphorus-carbon double bond by reaction between pentacarbonylchromium or -tungsten complexes of phosphinidenes and carbenes. Application to the synthesis of the 1,2-dihydrophosphete ring, *Organometallics*, 1988, **7**, 1791–1795; (b) J. Slootweg, S. Krill, F. Kanter, M. Schakel, A. Ehlers, M. Lutz, A. Spek and K. Lammertsma, Valence Isomerization of 2-Phosphabicyclo-[1.1.0]butanes, *Angew. Chem., Int. Ed.*, 2005, **44**, 6579–6582; (c) H. Walsgrove, B. Patrick and D. Gates, Transition Metal-Induced Cyclization of 1-Phosphabutadienes: Selective Formation of 1-Phosphet-2-ene or P=C-Substituted Phosphacyclohexene Ligands, *Organometallics*, 2022, **41**, 3399–3410.
- 9 (a) W. Li, W. Xu, J. Xie, S. Yu and C. Zhu, Distal radical migration strategy: an emerging synthetic means, *Chem. Soc. Rev.*, 2018, **47**, 654–667; (b) M. Korb and H. Lang, The anionic Fries rearrangement: a convenient route to ortho-functionalized aromatics, *Chem. Soc. Rev.*, 2019, **48**, 2829–2882; (c) X. Wu and C. Zhu, Radical-Mediated Remote Functional Group Migration, *Acc. Chem. Res.*, 2020, **53**, 1620–1636; (d) X. Wu, Z. Ma, T. Feng and C. Zhu, Radical-mediated rearrangements: past, present, and future, *Chem. Soc. Rev.*, 2021, **50**, 11577–11613; (e) S. Dong, X. Liu and X. Feng, Asymmetric Catalytic Rearrangements with α -Diazocarbonyl Compounds, *Acc. Chem. Res.*, 2022, **55**, 415–428.
- 10 C. Lukehart, A. McPhail, D. McPhail, J. Myers Jr and H. Soni, Transformation of a trialkynylphosphine oxide to a 2-alkylidene-1,2-dihydro-3-phosphete P-oxide ligand by Pt-H addition and rearrangement reactions. Activation of molecular hydro-gen by a platinum(II) complex, *Organometallics*, 1989, **8**, 1007–1014.
- 11 (a) L. Dupuis, N. Pirio, P. Meunier, A. Igau, B. Donnadiu and J. Majoral, Zirconocen–Benzyme-Mediated Intramolecular Coupling of Bis(alkynyl)phosphane: A Way



- to Mono- and Tricyclic 1,2-Dihydrophosphetes, *Angew. Chem. Int. Ed. Engl.*, 1997, **36**, 987–989; (b) N. Pirio, S. Bredeau, L. Dupuis, P. Schutz, B. Donnadiou, A. Igau, J. Majoral, J. Guillemin and P. Meunier, Intramolecular coupling of acetylenic groups of bis(alkynyl)phosphanes and silanes mediated by benzynezirconocene: a route to new mono- and tricyclic heterocycles, *Tetrahedron*, 2004, **60**, 1317–1327.
- 12 T. Xin and C. Cummins, Synthesis of Phosphet-2-one Derivatives via Phosphinidene Transfer to Cyclopropenones, *J. Am. Chem. Soc.*, 2023, **145**, 25989–25994.
- 13 (a) G. Nishida, K. Noguchi, M. Hirano and K. Tanaka, Enantioselective Synthesis of P-Stereogenic Alkynylphosphine Oxides by Rh-Catalyzed [2+2+2] Cycloaddition, *Angew. Chem., Int. Ed.*, 2008, **47**, 3410–3413; (b) N. Fukawa, T. Osaka, K. Noguchi and K. Tanaka, Asymmetric Synthesis and Photophysical Properties of Benzopyrano- or Naphthopyrano-Fused Helical Phosphafluorenes, *Org. Lett.*, 2010, **12**, 1324–1327; (c) A. Kondoh, H. Yorimitsu and K. Oshima, Synthesis of Bulky Phosphines by Rhodium-Catalyzed Formal [2 + 2 + 2] Cycloaddition Reactions of Tethered Dienes with 1-Alkynylphosphine Sulfides, *J. Am. Chem. Soc.*, 2007, **129**, 6996–6997; (d) X. Li, G. Hu, P. Luo, G. Tang, Y. Gao, P. Xu and Y. Zhao, Palladium(II)-Catalyzed Hydration of Alkynylphosphonates to β -Ketophosphonates, *Adv. Synth. Catal.*, 2012, **354**, 2427–2432; (e) Y. Zheng, L. Guo and W. Zi, Enantioselective and Regioselective Hydroetherification of Alkynes by Gold-Catalyzed Desymmetrization of Prochiral Phenols with P-Stereogenic Centers, *Org. Lett.*, 2018, **20**, 7039–7043; (f) S. Zhang, H. Cheng, S. Mo, S. Yin, Z. Zhang and T. Wang, Gold(I)-Catalyzed Synthesis of Six-Membered P,O-Heterocycles via Hydration/Intramolecular Cyclization Cascade Reaction, *Adv. Synth. Catal.*, 2019, **361**, 4227–4231; (g) Y. Zhang, F. Zhang, L. Chen, J. Xu, X. Liu and X. Feng, Asymmetric Synthesis of P-Stereogenic Compounds via Thulium(III)-Catalyzed Desymmetrization of Dialkynylphosphine Oxides, *ACS Catal.*, 2019, **9**, 4834–4840; (h) A. Gupta and B. Flynn, Electrophilic Activation of P-Alkynes in the Synthesis of P-Substituted and P-Centered Heterocycles, *J. Org. Chem.*, 2016, **81**, 4012–4019; (i) S. Doherty, J. Knight, D. Perry, N. Ward, D. Bittner, W. McFarlane, C. Wills and M. Probert, Triaryl-Like MONO-, BIS-, and TRISKITPHOS Phosphines: Synthesis, Solution NMR Studies, and a Comparison in Gold-Catalyzed Carbon–Heteroatom Bond Forming 5-*exo*-dig and 6-*endo*-dig Cyclizations, *Organometallics*, 2016, **35**, 1265–1278; (j) A. Klose, G. Kehr, C. Daniliuc and G. Erker, Phosphole formation by 1,1-carboboration – reactions of bis-alkynyl phosphanes with a frustrated P/B Lewis pair, *Dalton Trans.*, 2016, **45**, 2023–2030; (k) J. Mçbus, G. Kehr, C. Daniliuc, C. Mück-Lichtenfeld and G. Erker, Observation of a Thermally Induced Bora-Nazarov Cyclization at a Phosphole Framework, *Angew. Chem., Int. Ed.*, 2015, **54**, 12366–12369.
- 14 (a) G. Liao, T. Zhang, Z.-K. Lin and B.-F. Shi, Transition Metal-Catalyzed Enantioselective C–H Functionalization via Chiral Transient Directing Group Strategies, *Angew. Chem., Int. Ed.*, 2020, **59**, 19773–19786; (b) B. Li, A. Ali and H. Ge, Recent Advances in Using Transition-Metal-Catalyzed C–H Functionalization to Build Fluorescent Materials, *Chem*, 2020, **6**, 2591–2657; (c) S. Hong, Y. Hwang, M. Lee and S. Chang, Mechanism-Guided Development of Transition-Metal-Catalyzed C–N Bond-Forming Reactions Using Dioxazolones as the Versatile Amidating Source, *Acc. Chem. Res.*, 2021, **54**, 2683–2700; (d) B. Liu, A. Romine, C. Rubel, K. Engle and B. Shi, Transition-Metal-Catalyzed, Coordination-Assisted Functionalization of Nonactivated C(sp³)-H Bonds, *Chem. Rev.*, 2021, **121**, 14957–15074; (e) R. Mandal, B. Garai and B. Sundararaju, Weak-Coordination in C–H Bond Functionalizations Catalyzed by 3d Metals, *ACS Catal.*, 2022, **12**, 3452–3506; (f) Y. He, Z. Huang, K. Wu, J. Ma, Y.-G. Zhou and Z. Yu, Recent advances in transition-metal-catalyzed carbene insertion to C–H bonds, *Chem. Soc. Rev.*, 2022, **51**, 2759–2852; (g) Y. Pan, X. Qin, C. Yuan and Y. Lu, Application of Ligands in Cp*Rh(III)-Catalyzed C–H Bond Functionalization Reaction, *Chin. J. Org. Chem.*, 2023, **43**, 924–948; (h) H. Cao, Q. Cheng and A. Studer, meta-Selective C–H Functionalization of Pyridines, *Angew. Chem., Int. Ed.*, 2023, **62**, e202302941; (i) Z. Zeng, H. Gao, Z. Zhou and W. Yi, Intermolecular Redox-Neutral Carboamination of C–C Multiple Bonds Initiated by Transition-Metal-Catalyzed C–H Activation, *ACS Catal.*, 2022, **12**, 14754–14772; (j) P.-S. Wang and L.-Z. Gong, Palladium-Catalyzed Asymmetric Allylic C–H Functionalization: Mechanism, Stereo- and Regioselectivities, and Synthetic Applications, *Acc. Chem. Res.*, 2020, **53**, 2841–2854; (k) B.-B. Zhan, M.-X. Jiang and B.-F. Shi, Late-stage functionalization of peptides via a palladium-catalyzed C(sp³)-H activation strategy, *Chem. Commun.*, 2020, **56**, 13950–13958; (l) Y. Qiu, C. Zhu, M. Stangier, J. Struwe and L. Ackermann, Rhodaelectro-Catalyzed C–H and C–C Activation, *CCS Chem.*, 2020, **2**, 1529–1552; (m) R. Manoharan and M. Jeganmohan, Recent Advancements in Allylic C(sp³)-H Functionalization of Olefins Catalyzed by Rh(III) or Ir(III) Complexes, *Eur. J. Org. Chem.*, 2020, **2020**, 7304–7319; (n) S. Pandit, S. Maiti and D. Maiti, Noncovalent interactions in Ir-catalyzed remote C–H borylation: a recent update, *Org. Chem. Front.*, 2021, **8**, 4349–4358; (o) H. Wen, G. Liu and Z. Huang, Recent Advances in Tridentate Iron and Cobalt Complexes for Alkene and Alkyne Hydrofunctionalizations, *Coord. Chem. Rev.*, 2019, **386**, 138–153; (p) W. Ai, R. Zhong, X. Liu and Q. Liu, Hydride Transfer Reactions Catalyzed by Cobalt Complexes, *Chem. Rev.*, 2019, **119**, 2876–2953; (q) L. Lukasevics, A. Cizikovs and L. Grigorjeva, C–H Functionalization by High-Valent Cobalt Catalysis: Current Progress, Challenges and Future Perspectives, *Chem. Commun.*, 2021, **57**, 10827–10841; (r) S. Jana, V. Mayerhofer and C. Teskey, Photo- and Electrochemical Cobalt Catalyzed Hydrogen Atom Transfer for the Hydrofunctionalisation of Alkenes, *Angew. Chem., Int. Ed.*, 2023, **62**, e202304882.
- 15 (a) H. Zhang, M. Sun, Y. Ma, Q. Tian and S. Yang, Nickel-catalyzed C–P cross-coupling of diphenylphosphine oxide



with aryl chlorides, *Org. Biomol. Chem.*, 2012, **10**, 9627–9633; (b) J. Yang, T. Chen and L. Han, C–P bond-forming reactions via C–O/P–H cross-coupling catalyzed by nickel, *J. Am. Chem. Soc.*, 2015, **137**, 1782–1785; (c) W. Fu, C. So and F. Kwong, Palladium-Catalyzed Phosphorylation of Aryl Mesylates and Tosylates, *Org. Lett.*, 2015, **17**, 5906–5909; (d) Y. He, H. Wu and F. Toste, A dual catalytic strategy for carbon-phosphorus cross-coupling via gold and photoredox catalysis, *Chem. Sci.*, 2015, **6**, 1194–1198; (e) Y.-Y. Gui, L. Sun, Z.-P. Lu and D.-G. Yu, Photoredox sheds new light on nickel catalysis: from carbon–carbon to carbon–heteroatom bond formation, *Org. Chem. Front.*, 2016, **3**, 522–526; (f) S. Ung, V. Mechrouk and C.-J. Li, Shining Light on the Light-Bearing Element: A Brief Review of Photomediated C–H Phosphorylation Reactions, *Synthesis*, 2021, **53**, 1003–1022; (g) Y. Zhu, W. Zu, Q. Tian, Z. Cao, Y. Wei and L. Xu, A nickel/organoboron catalyzed metal-photoredox platform for C(sp²)-P and C(sp²)-S bond construction, *Org. Chem. Front.*, 2022, **9**, 1070–1076; (h) Y. Li, X. Jin, P. Liu, H. Zhang, X. Yu, Y. Liu, B. Liu and W. Yang, Copper-Catalyzed Dynamic Kinetic C–P Cross-

Coupling/Cyclization for the Concise Asymmetric Synthesis of Six-, Seven- and Eight-Membered P-Stereogenic Phosphorus Heterocycles, *Angew. Chem., Int. Ed.*, 2022, **61**, e202117093; (i) S.-F. Wu, G.-K. Zhang, X. Wang, Z.-J. He, Y.-C. Zhang and F. Shi, Organocatalytic Diastereoselective (4 + 1) Cycloaddition of *o*-Hydroxyphenyl-Substituted Secondary Phosphine Oxides, *J. Org. Chem.*, 2023, **88**, 16497–16510; (j) J.-H. Wu, S. Fang, X. Zheng, J. He, Y. Ma, Z. Su and T. Wang, Organocatalytic Dynamic Kinetic Resolution Enabled Asymmetric Synthesis of Phosphorus-Containing Chiral Helicenes, *Angew. Chem., Int. Ed.*, 2023, **62**, e202309515.

- 16 Deposition number 2203562 (for **3r**) contains the supplementary crystallographic data for this paper.
 17 Deposition number 2203561 (for **6m**) contains the supplementary crystallographic data for this paper.
 18 F. Della-Felice, M. Zanini, X. Jie, E. Tan and A. Echavarren, Rhodium(III)-Catalyzed Synthesis of Skipped Enynes via C(sp³)-H Alkynylation of Terminal Alkenes, *Angew. Chem., Int. Ed.*, 2021, **60**, 5693–5698.

