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A silver-initiated free-radical intermolecular hydrophosphinylation of unactivated alkenes†

Zejiang Li, Fenghua Fan, Zengyan Zhang, Yingxia Xiao, Dong Liu
and Zhong-Quan Liu*

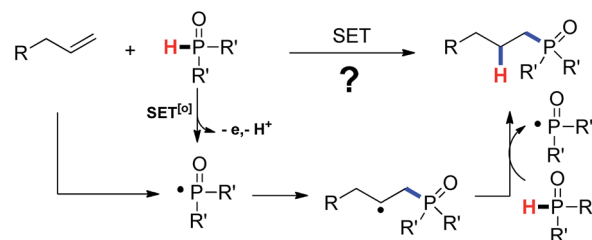
A scalable, operationally easy intermolecular hydrophosphinylation of various unactivated alkenes with H–P(O) compounds *via* an Ag(I)-initiated free radical process was developed. Mechanistic studies including electron-spin-resonance (ESR) and radical clock experiments suggest that atom transfer processes were involved in this system.

As a large class of important and valuable building blocks, organophosphorus compounds are widely applied in the synthesis of pharmaceuticals, agrochemicals and materials.¹ In the past few decades, considerable advances have been made to construct C–P bonds.² Among them, one of the most atom-economical and attractive strategies is the direct hydrophosphinylation of alkenes.³ The free-radical strategies for the addition of a P–H or (O)P–H bond to alkenes represent one of the most important methods to form a C–P bond.⁴ Although this radical addition using peroxide,⁵ AIBN,⁶ Et₃B,⁷ air/nitrogen,⁸ and organic dye/photirradiation⁹ *etc.* as the radical initiators has been achieved, more efficient and practical strategies are still highly desirable.

As our continuous investigations on the C–C bond formation *via* free-radical processes,¹⁰ we began to question whether a C–P bond could be formed *via* a single-electron-transfer (SET) process. As demonstrated in Scheme 1, single-electron oxidation of the secondary phosphine oxide followed by a deprotonation would generate a P-centered free radical. Addition of the phosphinyl radical to an olefin followed by hydrogen abstract from the phosphine oxide would lead to the product by hydrophosphinylation of alkene and regenerate the phosphinyl radical. Fortunately, we successfully accomplished an Ag(I)-initiated intermolecular hydrophosphinylation of a wide range of unactivated alkenes with phosphites (Scheme 1).

Initially, a series of experiments were carried out to test the hypothesis for hydrophosphinylation of unactivated alkenes with phosphites through a one-electron transfer process. It can be seen from Table 1 that the desired product was isolated in nearly quantitative yield by using catalytic amount of AgF (20 mol%), which was more efficient than other silver salts such as Ag₂CO₃, AgNO₃, and AgOAc *etc.* (Table 1, entries 1–7). Further optimization of the typical reaction conditions indicated that the solvent, concentration as well as the temperature also affected the reaction efficiency (entries 8–12). Furthermore, addition of persulfates such as K₂S₂O₈ and (NH₄)₂S₂O₈ could slightly raise the yield of the product (entries 13 and 14).

The substrate scope and functional group tolerance were demonstrated in Scheme 2. A wide range of terminal and internal unactivated alkenes are compatible to this system (entries 1–25). Various functional groups such as ester, halogen, ether, hydroxyl, amide and ketone *etc.* can all be well-survived. It is noteworthy that the free radical addition didn't happen at the internal C=C double bond but the terminal one when 7-(but-3-en-1-yloxy)-2H-chromen-2-one was used as the substrate (entry 13). (*E*)-Oct-2-ene afforded a regio-isomers with the ratio of 1.7/1 (entry 19). 2-Vinylpyridine also gave the corresponding product 25 in high yield. However, styrene and its derivatives are not effective in this system. Notably, *H*-phosphinates and *H*-phosphonates are proven to be effective substrates (entries 26–28). For example, ethyl phenylphosphinate afforded the desired product in 95% yield (entry 26). Addition of the dimethyl



Scheme 1 Free radical hydrophosphinylation of alkene *via* SET.

State Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou, Gansu, 730000, P. R. China. E-mail: liuzhq@lzu.edu.cn; Fax: +86 931 8915557; Tel: +86 931 8912500

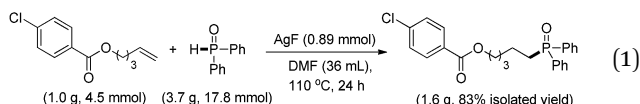
† Electronic supplementary information (ESI) available. See DOI: 10.1039/c5ra04136h

Table 1 Modification of the typical reaction conditions^a

|  | | | | |
|---|--------------------------------------|------------------------|------------|------------------------|
| Entry | Radical initiator (mol%) | Solvent (mL) | T (°C) | Yield ^b (%) |
| 1 | — | DMF (2) | 110 | — |
| 2 | Ag ₂ CO ₃ (20) | DMF (2) | 110 | 63 |
| 3 | AgNO ₃ (20) | DMF (2) | 110 | 26 |
| 4 | AgOAc (20) | DMF (2) | 110 | 50 |
| 5 | AgF (20) | DMF (2) | 110 | 96 |
| 6 | AgF (5) | DMF (2) | 110 | 46 |
| 7 | AgF (10) | DMF (2) | 110 | 70 |
| 8 | AgF (20) | DMSO (2) | 110 | 16 |
| 9 | AgF (20) | CH ₃ CN (2) | 110 | 95 |
| 10 | AgF (20) | DMF (1) | 110 | 60 |
| 11 | AgF (20) | DMF (3) | 110 | 81 |
| 12 | AgF (20) | DMF (2) | 80 | 20 |
| 13 ^c | AgF (20) | DMF (2) | 110 | 97 |
| 14 ^d | AgF (20) | DMF (2) | 110 | 98 |

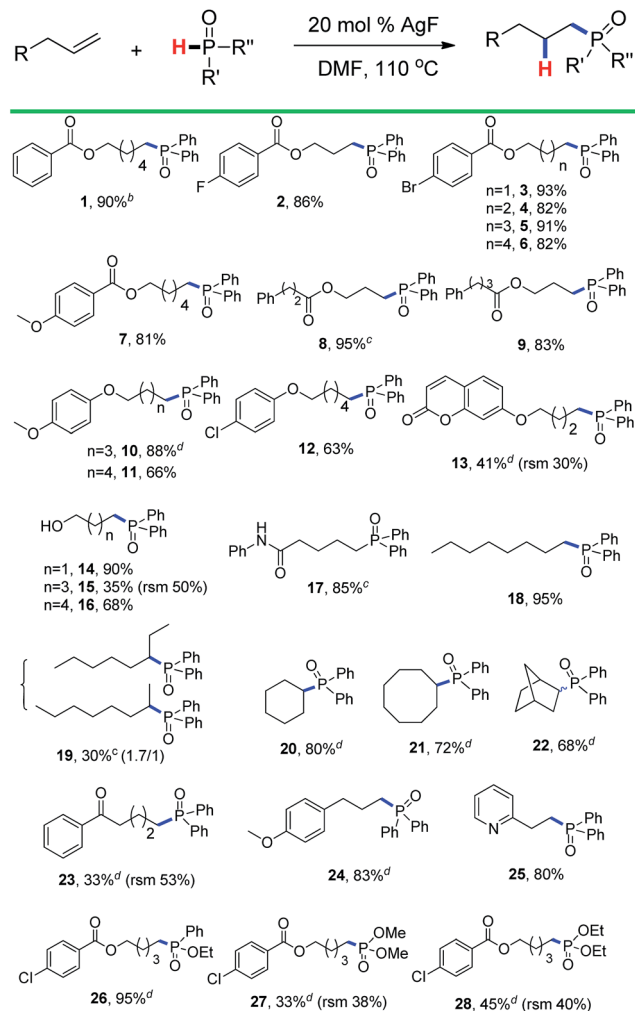
^a Reaction conditions: pent-4-en-1-yl 4-chlorobenzoate (1 equiv., 0.25 mmol), diphenylphosphine oxide (4 equiv., 1.0 mmol), 24 h, unless otherwise noted. ^b Isolated yields. ^c K₂S₂O₈ (3 equiv., 0.75 mmol) was added. ^d (NH₄)₂S₂O₈ (3 equiv., 0.75 mmol) was added.

phosphonate and diethyl phosphonate to pent-4-en-1-yl 4-chlorobenzoate gave the corresponding products in 33% and 45% yields, respectively (entries 27 and 28). Obviously, *H*-phosphonates afford relatively low yields of the desired products, which might be due to the stability of the P-centered radicals. Finally, this reaction can be easily scaled up to gram level, which suggests that it can be potentially applied in chemical industry (eqn (1)).



Mechanistic studies including radical clock and ESR were carried out to confirm the previously proposed free radical process. As depicted in Scheme 3, ((4-methyl-1-tosylpyrrolidin-3-yl)methyl)diphenylphosphine oxide was obtained in 40% yield, which might proceed a radical addition/cyclization cascade process (Scheme 3a). In addition, ethyl 2-cyclopropylacrylate led to a ring opening product 30 in 42% yield (Scheme 3b). Furthermore, a series of experiments were designed to get evidences of key radical intermediates through spin trapping technology and ESR. As a result, the ESR signal of a P-centered radical species ($g = 2.0060$, $a_N = 1.411$ mT; $a_H = 1.888$ mT; $a_P = 3.475$ mT) was observed by using 5,5-dimethyl-1-pyrroline *N*-oxide (DMPO) as a radical spin trap (Scheme 4). Overall, the proposed free radical addition mechanism is supported by these studies.

In summary, a silver(I)-triggered free radical intermolecular C–P bond formation has been developed. A variety of

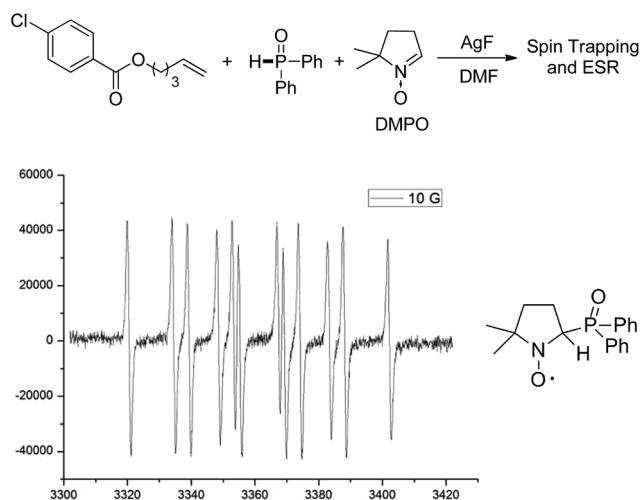


Scheme 2 AgF-promoted hydrophosphinylation of alkenes with H–P(O). ^aReaction conditions: alkene (1 equiv., 0.25 mmol), organophosphorus compounds (4 equiv., 1.0 mmol), AgF (20 mol%, 0.05 mmol), DMF (2 mL), 110 °C, 24 h, unless otherwise noted. ^bIsolated yields. ^cK₂S₂O₈ (3 equiv., 0.75 mmol) was added. ^d(NH₄)₂S₂O₈ (3 equiv., 0.75 mmol) was added.

alkyldiphenylphosphine oxides, alkyl phosphinates as well as alkyl phosphonates can be facilely prepared *via* addition of H–P(O) compounds with unactivated alkenes by using this strategy. The features of wide substrate scope, completely anti-



Scheme 3 Radical clock experiments.



Scheme 4 ESR studies. ESR spectrum of a solution of pent-4-en-1-yl 4-chlorobenzoate ($5.0 \times 10^{-2} \text{ mol L}^{-1}$), diphenylphosphine oxide (0.2 mol L^{-1}), AgF ($1.0 \times 10^{-2} \text{ mol L}^{-1}$), and DMPO ($6.0 \times 10^{-2} \text{ mol L}^{-1}$) in DMF (2 mL), 110°C for 2.5 h.

Markovnikov addition and scalability make this methodology attractive to organophosphorus synthetic chemistry. Radical clock and ESR studies support the free-radical addition pathway.

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