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$Mn(OAc)_3$-Promoted Oxidative C_{sp3}-P Bond Formation through C_{sp2}-C_{sp2} and P-H Bond Cleavage: Access to *β*-Ketophosphonates.

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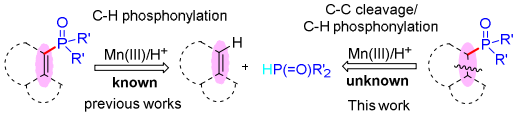
ABSTRACT: The $Mn(OAc)_3$-promoted oxidative phosphonylation of *N*,*N*-dimethylenaminones with H-phosphonates, involving a chemo- and regioselective C_{sp2}–C_{sp2} bond cleavage and C_{sp3}–P bond formation in one step, provid successfully functionalized *β*-ketophosphonates under mild reaction conditions. Oxidative C_{sp3}–H/P–H cross-coupling reactions *via* C_{sp3}–C(C=O) bond cleavage and mechanistic studies are conducted preliminarily, and a possible mechanism is proposed. This novel method proceeds in good to excellent yields, shows operational simplicity, broad substrate scope and large-scale preparation.

■ INTRODUCTION

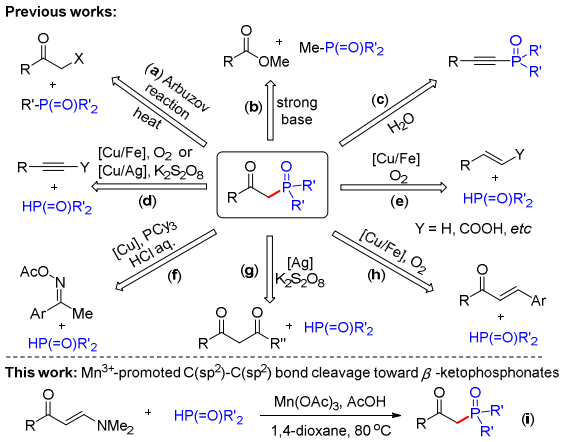
Organophosphorus compounds play a crucial role in organic chemistry,[1] medicinal chemistry[2] and material chemistry.[3] Thus, great progress has been achieved in the development of new methods for the construction of the carbon–phosphorus bond.[4] Among them, the Mn(III)-promoted radical phosphonylations of C_{sp2}–C_{sp2} compounds (alkenes,[5] heteroarenes,[6] arenes,[7] fullerene dimers,[8] *etc*.) have been developed as a powerful strategy for the formation of C_{sp2}−P bonds. However, these C_{sp2}-H phosphonylations have been limited to construct C_{sp2}−P bonds through phosphonyl radical addition and elimination process. To the best of our knowledge, no example of Mn(III)-promoted new C_{sp3}−P bond formation through selective cleavage of C_{sp2}–C_{sp2} bonds has been described (Scheme 1). Therefore, the development of a Mn(III)-promoted radical phosphonylation protocol for the formation of C_{sp3}−P bond through cleavage of C_{sp2}–C_{sp2} bond remains an unsolved challenge.



Scheme 1 Comparison of previous works with this work by Mn(III)-promoted phosphonylation.

β-Ketophosphonates, on the other hand, are a highly useful class of organophosphorus compounds, owing to their remarkable biological activities, eminent metal-complexing abilities and synthetic versatile applications in organic synthesis.[9] Thus, many efforts have been put into the development of efficient synthetic approaches for the C_{sp3}−P bond construction to construct these scaffolds.[10] Traditionally, *β*-ketophosphonates are prepared by the Arbuzov reaction (reaction with *α*-haloketones and trialkylphosphites) (Scheme 2a),[11] or the acylation of alkylphosphonates by using esters as the acylation reagent under strong-base conditions (Scheme 2b).[12] Recently, three methodologies were described in the hydration of alkynylphosphonates based on the use of Pd(II) or Au(I) or Ag(I) catalysts (Scheme 2c).[13] Very recently, various research groups (Song,[14] Zhao,[15] He,[16] Ji[17] and others[18]) independently reported elegant studies on the aerobic oxyphosphorylation of alkenes or alkynes, and the decarboxylation- or deesterification- or deamidation–oxyphosphorylation of cinnamyl/alkynyl carboxylic acids/carboxylates/amides under different bimetallic synergistically catalyzed (Cu/Fe, Cu/Ag, *etc*), which involved sequential $C_{sp/sp2}$–H/$C_{sp/sp2}$–C(C=O) bond-breaking followed by C=O and C_{sp3}−P bond-reconstruction (Scheme 2d and 2e). In addition, the Lei group developed a direct radical/radical C_{sp3}–H/P–H cross-coupling reaction of aryl

ketone *o*-acetyloximes leading to the construction of C_{sp3}−P bond with the assistance of CuCl and PCy_3 (Scheme 2f);[19] and Peng and co-workers disclosed a novel Ag(I)-catalyzed direct oxidative C_{sp3}–H/P–H cross-coupling reaction of 1,3-dicarbonyl compounds, which involved oxidative C_{sp3}−P bond formation and selective C_{sp3}–C(C=O) bond cleavage (Scheme 2g).[20] However, to the best of our knowledge, just one example of the reconstruction of C_{sp3}−P bond *via* the selective cleavage of the C_{sp2}–C_{sp2} bond was reported by the Song group, which involved the phosphorylation reaction of *α,β*-unsaturated carbonyl compounds (Scheme 2h).[21] This approach would be valuable for direct the C_{sp3}−P bond formation, but the choice of transition-metal catalyst of this aerobic phosphorylation is limited to Cu/Fe cocatalyzed system. Therefore, the development of an efficient catalytic phosphorylation system leading to the formation of C_{sp3}−P bond through C_{sp2}–C_{sp2} bond cleavage would be highly desirable. Enaminones versatile building blocks in heterocyclic synthesis,[22] which have attracted more and more attention during the past few decades owing to their excellent reactivity in various organic transformations.[23] As our ongoing interest in enaminone chemistry[24] and Mn(III)-promoted radical phosphonylation,[25] we report herein an unprecendent $Mn(OAc)_3$-promoted strategy to construct *β*-ketophosphonates from readily available *N,N*-dimethylenaminones and H-phosphonates in good yields, through selective oxidative C_{sp2}–C_{sp2} bond cleavage and C_{sp3}−P bond formation (Scheme 2i).



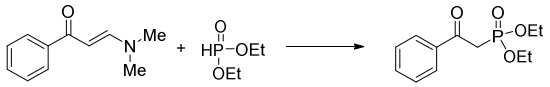
Scheme 2 Strategies for the formation of *β*-ketophosphonates.

■ RESULTS AND DISCUSSION

At the outset, the coupling of *N,N*-dimethylenaminone **1a** with readily available diethyl phosphite **2a** was studied with $Mn(OAc)_3$ (3.0 equiv) as a catalyst in air. As shown in Table 1, the reaction in toluene at 80 °C for 12 h did not afford any phosphorylation product (entry 1). To our delight, the desired product **3a** was isolated in lower yield when the reaction was performed in acetic acid (AcOH) (entry 2). Gratifyingly, the yield was remarkably improved to 62% in toluene when AcOH was selected as a co-catalyst (entry 3). Comparable results were observed for reactions in tetrahydrofuran (THF), CH_3CN, and dichloroethane (DCE) (entries 4–6), and the results were significantly improved for reactions in 1,4-dioxane, as **3a** was obtained in 82% yield (entry 7). However, Subsequent catalyst and co-catalyst screening indicated that generally $Mn(OAc)_3$/AcOH was more efficient catalytic system than other catalysts and co-catalysts, including $Mn(OAc)_3$, $FeCl_3$, $CuCl_2$, $Fe(NO_3)_3$, $CuSO_4$, toluene-*p*-sulfonic acid (*p*-TSA) and benzoic acid (BA) (entry 7 *vs* entries 8–14). After further investigation of the catalyst and co-catalyst amounts, reaction temperature and times, we found that these variables were not provided the best result (entry 7 *vs* entries 15–22). The role of AcOH and O_2 have also been tested. The reaction with 3.0 equiv $Mn(OAc)_3$ in 1,4-dioxane under air at 80 °C for 12 h in absence of AcOH did not obtained the desired

product **3a** (entry 23), and the reaction without O_2 had little impact on the results (entry 24). Therefore, the best results were obtained using 3.0 equiv $Mn(OAc)_3$ and 2.0 mL AcOH in 4.0 mL of 1,4-dioxane under air at 80 °C for 12 h.

Table 1 Optimization of the reaction conditions.[a]



1a **2a** **3a**

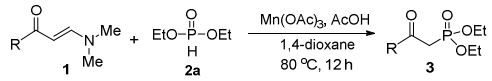
Entry	Oxidant [equiv]	Acid [mL]	Solvent	Temp [°C]	Time [h]	Yield [%][b]
1	$Mn(OAc)_3$ (3.0)	-	toluene	80 °C	12	n.d. [c]
2	$Mn(OAc)_3$ (3.0)	-	AcOH	80 °C	12	28
3	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	toluene	80 °C	12	62
4	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	THF	80 °C	12	51
5	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	CH_3CN	80 °C	12	63
6	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	DCE	80 °C	12	57
7	**$Mn(OAc)_3$ (3.0)**	**AcOH (2.0)**	**1,4-dioxane**	**80 °C**	**12**	**82**
8	$Mn(OAc)_2$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	n.d. [c]
9	$FeCl_3$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	n.d. [c]
10	$CuCl_2$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	n.d. [c]
11	$Fe(NO_3)_3$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	n.d. [c]
12	$CuSO_4$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	n.d. [c]
13	$Mn(OAc)_3$ (3.0)	*p*-TSA (2 mmol)	1,4-dioxane	80 °C	12	38
14	$Mn(OAc)_3$ (3.0)	BA (2 mmol)	1,4-dioxane	80 °C	12	33
15	$Mn(OAc)_3$ (4.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	73
16	$Mn(OAc)_3$ (2.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	53
17	$Mn(OAc)_3$ (3.0)	AcOH (1.0)	1,4-dioxane	80 °C	12	69
18	$Mn(OAc)_3$ (3.0)	AcOH (3.0)	1,4-dioxane	80 °C	12	80
19	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	1,4-dioxane	60 °C	12	71
20	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	1,4-dioxane	100 °C	12	77
21	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	10	76
22	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	14	80
23	$Mn(OAc)_3$ (3.0)	-	1,4-dioxane	80 °C	12	n.d. [c]
24	$Mn(OAc)_3$ (3.0)	AcOH (2.0)	1,4-dioxane	80 °C	12	83 [d]

[a] Reaction conditions: *N*,*N*-Dimethylenaminone **1a** (1.0 mmol, 1.0 equiv), diethyl phosphite **2a** (2.0 mmol, 2.0 equiv), oxidant and acid in air; [b] Isolated yield based on *N*,*N*-dimethylenaminone **1a**; [c] No detected; [d] N_2 atmosphere.

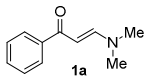
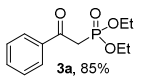
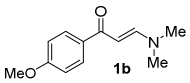
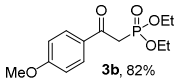
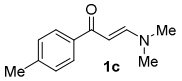
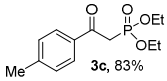
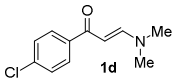
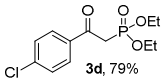
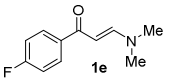
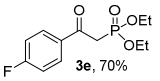
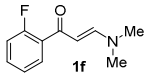
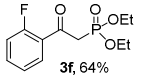
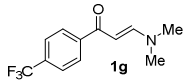
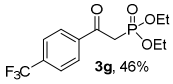
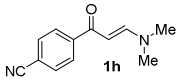
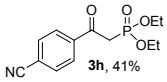
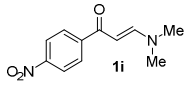
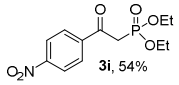
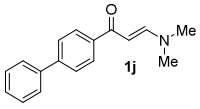
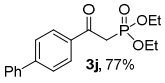
Under the optimized reaction conditions, we next examined the scope of *N*,*N*-dimethylenaminones. Representative products are summarized in Table 2. Electron-rich (4-OMe), electron-neutral (4-H, 4-Me) and halogenated (4-F, 4-Cl, 2-F) on the aromatic ring were smoothly converted to the corresponding products **3a**–**3f** in good to excellent yields (64–83%). When the substituent of aromatic ring was changed to strong electron-withdrawing groups (4-CF_3, 4-CN and 4-NO_2), low to moderate yields were obtained in certain cases (**3g**–**3i**, 41–54%). Gratifyingly, substrates bearing polycyclic aromatic (1,1'-biphenyl and naphthalene) and heterocyclic substituents (furyl and thienyl) at the α-position of the carbonyl group successfully participated in the reaction, providing access to the desired products **3j**–**3n** (57–80%), though the reactions failed for substrates containing pyridyl or pyrazinyl group, presumably due to their highly electron deficient natures (**3o**–**3p**). Interestingly, substrates containing a phenemyl moiety at the α-position of the carbonyl group proceeded smoothly and afforded the β-ketophosphonate **3q** in 63% yield, but styrylphosphonate **3r** was obtained in 76% yield when the substituent at α-position of the enaminone moiety was changed to a styryl group, which involved the selective cleavage of the C_{sp2}–C_{sp2} bond of styryl group instead of the cleavage of C_{sp2}–C_{sp2} bond of enaminone structure to the corresponding β-ketophosphonate. Moreover, aliphatic *N*,*N*-dimethylenaminone **1s** was also employed

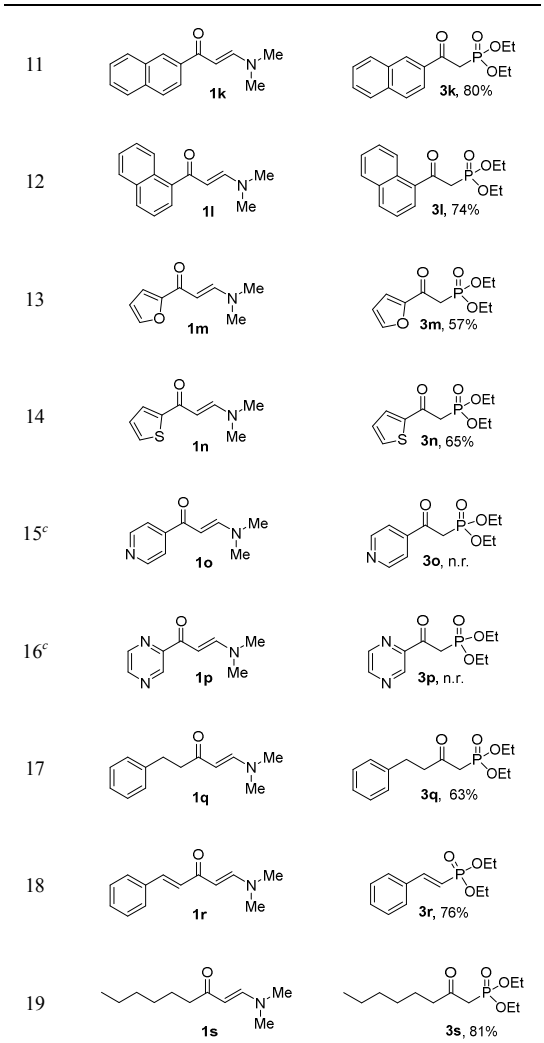
successfully and the desired phosphonylation product **3s** was generated in excellent yield (81%). Furthermore, reaction of 2-hydroxyphenyl moiety *N*,*N*-dimethylenaminone **1t** with diethyl phosphite **2a** afforded phosphinative cyclization product **4a** (20%) and chromone **5** (52%), and could not to cleave the C_{sp2}–C_{sp2} bond of enaminone structure to *β*-ketophosphonate products (Scheme 3a). Consequently, in order to identify the first process of the phosphinative cyclization concerning phosphorylation and cyclization, chromone **5** was treated with diethyl phosphite **2a** under the optimal reaction conditions and failed to give phosphinative cyclization product **4a** (Scheme 3b). The result indirectly indicated that the phosphinative cyclization could occur firstly phosphorylation and intermediate **6** was formed, follow by cyclization to **4a** in one-step process.

Table 2 Scope of various *N*,*N*-dimethylenaminones by changing the substituents on the aromatic ring[a,b]

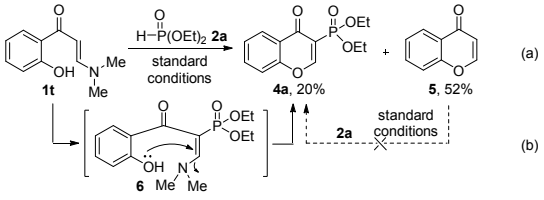


1 **2a** **3**

Entry	*N*,*N*-Dimethylenaminones **1**	yiled[b]
1	 **1a**	 **3a**, 85%
2	 **1b**	 **3b**, 82%
3	 **1c**	 **3c**, 83%
4	 **1d**	 **3d**, 79%
5	 **1e**	 **3e**, 70%
6	 **1f**	 **3f**, 64%
7	 **1g**	 **3g**, 46%
8	 **1h**	 **3h**, 41%
9	 **1i**	 **3i**, 54%
10	 **1j**	 **3j**, 77%



[a] Reaction conditions: *N*,*N*-Dimethylenaminones **1** (1.0 mmol, 1.0 equiv) and diethyl phosphite **2a** (2.0 mmol, 2.0 equiv) and $Mn(OAc)_3$ (3.0 mmol, 3.0 equiv) and AcOH (2.0 mL) in air; [b] Isolated yield based on *N*,*N*-dimethylenaminones **1**; [c] No reaction.

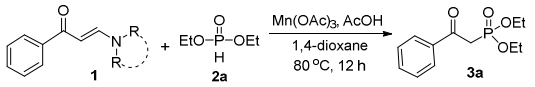


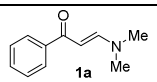
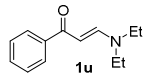
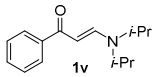
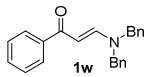
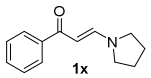
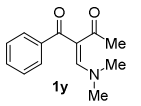
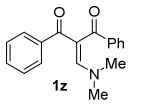
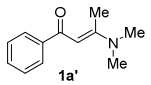
Scheme 3 $Mn(OAc)_3$-promoted phosphonation of 2-hydroxyphenyl moiety *N*,*N*-dimethylenaminone **1s**.

To elaborate further the scope of this reaction, we tested the behavior of a linker of enaminones (Table 3). Surprisingly, the unusual *N*,*N*-disubstituent was also viable, including *N*,*N*-diethyl, *N*,*N*-diisopropyl, *N*,*N*-dibenzyl and *N*-tetrahydropyrrolyl. Reaction of these enaminones (**1a**, **1u**-**1x**) formed **3a** under the standard conditions, respectively. Notably, when the α- or β-position of enaminone had an acetyl or formyl or methyl group (**1y**, **1z** and **1a'**), the radical phosphonylation also could be achieved and β-ketophosphonate **3a** was obtained in moderate to good yields (51%, 53% and 75%), involving the chemoselective cleavage of the C_{sp2}–C_{sp2} bond and C_{sp2}–C(C=O)

bond access to C_{sp3}−P bond-reconstruction.

Table 3 Scope of various *N*,*N*-dimethylenaminones by changing the *N*,*N*-substituents[a,b]

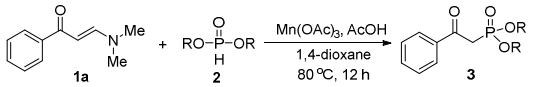


Entry	*N*,*N*-Dimethylenaminone **1**	yiled[b]
1	 **1a**	85%
2	 **1u**	73%
3	 **1v**	71%
4	 **1w**	65%
5	 **1x**	68%
6	 **1y**	51%
7	 **1z**	53%
8	 **1a'**	75%

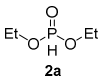
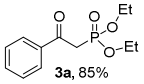
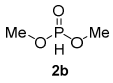
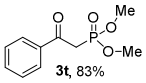
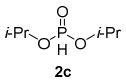
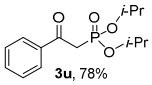
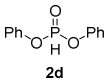
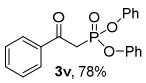
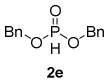
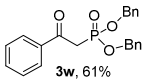
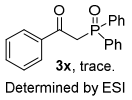
[a] Reaction conditions: *N*,*N*-Dimethylenaminones **1** (1.0 mmol, 1.0 equiv) and diethyl phosphite **2a** (2.0 mmol, 2.0 equiv) and $Mn(OAc)_3$ (3.0 mmol, 3.0 equiv) and AcOH (2.0 mL) in air; [b] Isolated yield based on *N*,*N*-dimethylenaminones **1**.

We subsequently investigated the scope of H-phosphonates **2** to test the compatibility of this transformation, as shown in Table 4. A wide range of H-phosphonates with ether groups (such as MeO, EtO, *i*-PrO, PhO and BnO) underwent the desired reactions with *N*,*N*-dimethylenaminones **1a** to afford phosphonylation products in moderate to high yields (**3a** and **3t**–**3w**, 61–85%). However, no desired product **3x** was obtained from diphenylphosphine oxide **2f**, which might demonstrate that phosphonates were desirable donors and phosphine oxide could not suitable for this transformation.

Table 4 H-Phosphonates scope[a,b]

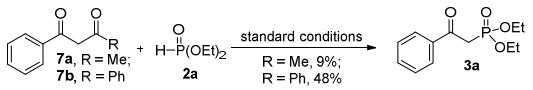


Entry	Phosphite ester **2**	yiled[b]

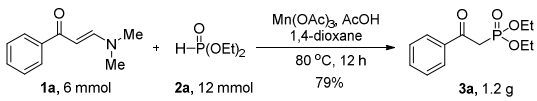
1	 **2a**	 **3a**, 85%
2	 **2b**	 **3t**, 83%
3	 **2c**	 **3u**, 78%
4	 **2d**	 **3v**, 78%
5	 **2e**	 **3w**, 61%
6	 **2f**	 **3x**, trace. Determined by ESI

[a] Reaction conditions: *N*,*N*-Dimethylenaminone **1a** (1.0 mmol, 1.0 equiv) and H-diethyl phosphonate **2** (2.0 mmol, 2.0 equiv) and $Mn(OAc)_3$ (3.0 mmol, 3.0 equiv) and AcOH (2.0 mL) in air; [b] Isolated yield based on *N*,*N*-dimethylenaminone **1a**.

Additionally, inspired by the very recent development of synthetic routes towards *β*-ketophosphonate *via* Ag(I)-catalyzed direct oxidative C_{sp3}–H/P–H cross-coupling reaction with 1,3-dicarbonyl compounds,[20] we pursued this Mn(III)-promoted radical phosphonylation that could be used to produce these compounds from the same substrate through C_{sp3}–H/P–H cross-coupling reaction, involving the direct selective oxidative C_{sp3}–C(C=O) bond cleavage and C_{sp3}−P bond formation. Remarkably, the treatment of diethyl phosphite **2a** with 1,3-dicarbonyl compounds **7a** and **7b** under the standard conditions afforded *β*-ketophosphonate **3a** in 9% and 48%, respectively (Scheme 4). Meanwhile, we further demonstrated the utility of this transformation in the possibility of industrialized synthesis. The present $Mn(OAc)_3$-promoted tandem transformation-type reaction could be conducted on gram scale; **3a** was obtained in 79% yield (1.2 g, 6 mmol scale, Scheme 5). These extension and scalability significantly broaden the applicability of Mn(III)-promoted radical phosphonylation reaction.



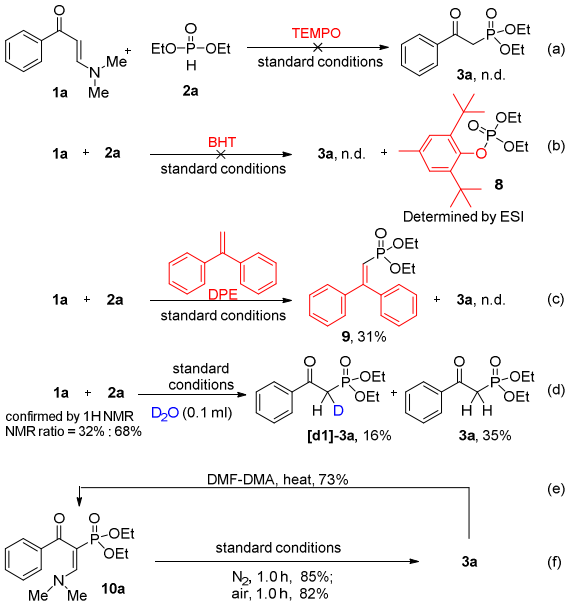
Scheme 4 $Mn(OAc)_3$-promoted phosphonation of 1,3-dicarbonyl compounds.



Scheme 5 Large-scale synthesis of **3a**.

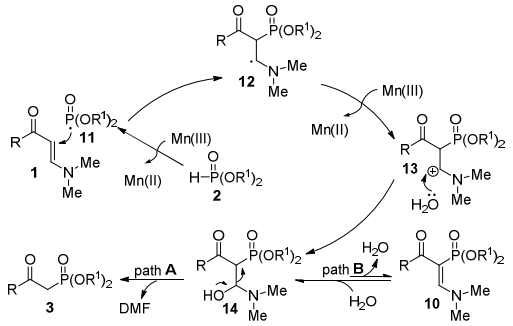
To gain preliminary mechanistic insight into this transformation, a series of control experiments were performed (Scheme 6). Frist, the reaction of *N*,*N*-dimethylenaminones **1a** and diethyl phosphite **2a** with the addition of 3.0 eqivalents radical-trapping reagent under the standard conditions was performed, such as

2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO), butylated hydroxytoluene (BHT) and 1,1-diphenylethylene (DPE) (Scheme 6a, 6b and 6c). The formation of desired product **3a** was suppressed, and only the BHT adduct **8** was detected by ESI (Fig. S1) and diethyl (2,2-diphenylvinyl)phosphonate **9** was isolated in 31% yield, indicating that a phosphonate radical is involved in this transformation. These experiments demonstrate that the phosphonylation transformation may proceed by a radical mechanism. Subsequently, the reaction was conducted in the presence of D_2O under the standard conditions, and deuterium-incorporated *β*-ketophosphonate product **[d$_1$]-3a** was isolated in 16% yield, whereas the deuterium-incorporated product **[d$_1$]-3a** was observed in tetradeuteroacetic acid, indicating that the hydrogen in the methene group came from D_2O (Scheme 6d and Fig. S2). Remarkably, 2-diethyl phosphate *N*,*N*-dimethylenaminone **10a** was synthetized by the condensation of *β*-ketophosphonate **3a** with DMF-DMA in 73% yield (Scheme 6e), and the pure **10a**, which is unstable and only be stored for two days, was also easily converted into **3a** at room temperature. Meanwhile, **10a** can be transformed quickly into **3a** under the standard conditions, and under an atmosphere of N_2 had little impact on the results (Scheme 6f). These results illustrated that **10a** could be formed during the cross-coupling transformation, and O_2 was not essential for the reaction to proceed which was different from the previous reports on aerobic phosphorylation.[14-16,21]



Scheme 6 Control experiments.

Based on the preliminary mechanistic studies and previous reports,[14-16,21] a tentative reaction mechanism for the tandem radical phosphonylation is proposed in Scheme 7. H-Phosphonates **2** was oxidized by the Mn(III) to generate the corresponding P-centered radical **11** and Mn(II). The radical addition of intermediate **11** to the *α*-position of *N*,*N*-dimethylenaminones **1** gave carbon radical **12**, which was reoxidized to carbocation intermediate **13** by the Mn(III), followed by the nucleophilic attack of H_2O to give intermediate **14**. Then, there were two group-leaving pathways for subsequent elimination of intermediate **13**: path **A** generated the desired products **3** by loss of a molecule of N,N-dimethylformamide (DMF); path **B** formed products **10** through losing a molecule of H_2O, which also retransformed to **14** *via* the nucleophilic attack of H_2O and explained the results in Scheme 6f.



Scheme 7. Proposed mechanisms for the formation of *β*-ketophosphonates **3**.

■ CONCLUSION

In conclusion, we have reported a simple and highly efficient $Mn(OAc)_3$-promoted radical phosphonylation of readily available *N*,*N*-dimethylenaminones with H-phosphonates to afford functionalized *β*-ketophosphonates in good to excellent yields. Importantly, this transformation offered the first Mn(III)-promoted protocol for C_{sp3}–P bond formation by oxidative C_{sp2}–C_{sp2} bond cleavage in one step. Notably, this powerful strategy also preliminarily promoted to other oxidative C_{sp3}–H/P–H cross-coupling reactions of simple 1,3-dicarbonyl compounds, involving the selective oxidative C_{sp3}–C(C=O) bond cleavage and C_{sp3}−P bond formation. A putative mechanism was proposed on the basis of mechanistic studies and isotope-labeling studies. This method proceeds under mild reaction conditions, shows good functionalgroup compatibility and can be effectively scaled up. Further mechanistic details and synthetic applications are underway in our laboratory.

■ EXPERIMENTAL SECTION

General Information. All compounds were fully characterized by spectroscopic data. The NMR spectra were recorded on a Bruker Avance 400 (^{1}H: 400 MHz, ^{13}C: 100 MHz), Bruker DRX500 (^{1}H: 500 MHz, ^{13}C: 125 MHz) and Bruker DRX500 (^{1}H: 600 MHz, ^{13}C: 150 MHz), chemical shifts (δ) are expressed in ppm, and *J* values are given in Hz, and deuterated $CDCl_3$, Acetone-d_6 and DMSO-d_6 were used as solvent. IR spectra were recorded on a FT-IR Thermo Nicolet Avatar 360 using KBr pellet. The reactions were monitored by thin layer chromatography (TLC) using silica gel GF_{254}. The melting points were determined on XT-4A melting point apparatus and are uncorrected. HRMs were performed on an Agilent LC/MS TOF instrument.

All chemicals and solvents were used as received without further purification unless otherwise stated. Column chromatography was performed on silica gel (200–300 mesh).

Compounds **1** were prepared according to the literature[26]. The materials **2a**–**e** were purchased from Adamas-beta® and Aldrich Corporation Limited.

General Procedure for the Synthesis of *β*-ketophosphonates 3. *N*,*N*-Dimethylenaminones **1** (1 mmol, 1.0 equiv), H-phosphonates **2** (2.0 mmol, 2.0 equiv) , $Mn(OAc)_3$ (3 mmol, 3.0 equiv), AcOH (2 mL) 1,4-dioxane (4 mL) were charged into a 15 mL ace glass pressure tub, and the mixture was stirred at 80 ^{o}C for 12 h until *N*,*N*-dimethylenaminones **1** were completely consumed. The mixture was cooled to room temperature, neutralized with a saturated solution of $NaHCO_3$ to pH 8–9, and then EtOAc (30 mL × 2) were added. The organic phase was washed with water (20 mL), dried over Na_2SO_4, concentrated and purified by flash column chromatography to afford *β*-ketophosphonates **3**.

The products were further identified by FT-IR, NMR and HRMS, being in good agreement with the assigned structures. (see ESI†).

*Diethyl (2-oxo-2-phenylethyl)phosphonate (**3a**)*. Yield: 85% (217 mg); Yellow liquid; IR (KBr): 1681, 1598,

1449, 1394, 1252, 1163, 1026, 786, 690, 585, 509 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ = 1.27–1.29 (m, 6H, C–CH_3), 3.65 (d, J = 22.7 Hz, 2H, P–CH_2–C), 4.13–4.17 (m, 4H, P–CH_2–C), 7.47–7.50 (m, 2H, ArH), 7.59 (m, 1H, ArH), 8.02 (d, J =7.4Hz, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.3, 38.5 (d, J = 129 Hz, P–CH_2–C), 62.6, 62.7, 128.6, 128.6, 129.0, 129.0, 133.7, 136.5, 191.5 (d, J = 6.5 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{12}H_{18}O_4P^+$ [$(M+H)^+$], 257.0937; found, 257.0936.

*Diethyl (2-(4-methoxyphenyl)-2-oxoethyl)phosphonate (**3b**).* Yield: 82% (235 mg); Yellow liquid; IR (KBr): 1670, 1601, 1513, 1422, 1259, 1176, 1026, 824, 578, 522 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ = 1.28–1.30 (m, 6H, C–CH_3), 3.59 (d, J = 22.7 Hz, 2H, P–CH_2–C), 3.88 (s, 3H, $ArOCH_3$), 4.13–4.15 (m, 4H, O–CH_2–C), 6.95 (d, J = 8.9 Hz, 2H, ArH), 8.01 (m, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.3, 38.3 (d, J = 129 Hz, P–CH_2–C), 55.5, 62.6, 62.6, 113.8, 113.8, 129.6, 131.5, 131.5, 164.0, 190.3 (d, J = 6.0 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{13}H_{20}O_5P^+$ [$(M+H)^+$], 287.1043; found, 287.1043.

*Diethyl (2-oxo-2-(p-tolyl)ethyl)phosphonate (**3c**).* Yield: 83% (224 mg); Yellow liquid; IR (KBr): IR (KBr): 1681, 1603, 1449, 1394, 1254, 1025, 970, 786, 690, 585, 511 cm^{-1}; cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 1.26–1.30 (m, 6H, C–CH_3), 2.42 (s, 3H, $ArCH_3$), 3.59–3.64 (d, J = 22.5 Hz, 2H, P–CH_2–C), 4.11–4.17 (m, 4H, O–CH_2–C), 7.27 (d, J = 8.0 Hz, 2H, ArH), 7.91 (d, J = 8.0 Hz, 2H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 16.2, 16.3, 21.7, 38.3 (d, J = 130 Hz, P–CH_2–C), 62.6, 62.7, 129.2, 129.2, 129.3, 129.3, 134.1, 144.7, 191.5 (d, J = 6.25 Hz); HRMS (TOF ES^+): *m/z* calcd for $C13H_{20}O_4P^+$ [$(M+H)^+$], 271.1094; found, 271.1094.

*Diethyl (2-(4-chlorophenyl)-2-oxoethyl)phosphonate (**3d**).* Yield: 79% (229 mg); Yellow liquid; IR (KBr): 1681, 1589, 1489, 1399, 1252, 1026, 815, 605, 523 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ = 1.20–1.22 (m, 6H, C–CH_3), 3.54 (d, J = 22.8 Hz, 2H, P–CH_2–C), 4.04–4.09 (m, 4H, O–CH_2–C), 7.38 (d, J = 8.5 Hz, 2H, ArH), 7.89 (d, J = 8.5 Hz, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.3, 38.2 (d, J = 128 Hz, P–CH_2–C), 62.7, 62.8, 128.9, 128.9, 130.5, 130.5, 134.8, 140.2, 190.7 (d, J = 6 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{12}H_{17}ClO_4P^+$ [$(M+H)^+$], 291.0547; found, 291.0547.

*Diethyl (2-(4-fluorophenyl)-2-oxoethyl)phosphonate (**3e**).* Yield: 70% (192 mg); Yellow liquid; IR (KBr): 1680, 1599, 1509, 1413, 1242, 1160, 970, 823, 570 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ = 1.19–1.22 (m, 6H, C–CH_3), 3.54 (d, J = 22.9 Hz, 2H, P–CH_2–C), 4.04–4.09 (m, 4H, O–CH_2–C), 7.05–7.08 (m, 2H, ArH), 7.97–7.99 (m, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.2, 38.5 (d, J = 129 Hz, P–CH_2–C), 62.6, 62.7, 115.7 (d, J = 22.5 Hz), 115.7 (d, J = 22.5 Hz), 131.8 (d, J = 9.0 Hz), 131.8 (d, J = 9.0 Hz), 132.9, 166.0 (d, J = 255 Hz), 190.3 (d, J = 7.5 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{12}H_{17}FO_4P^+$ [$(M+H)^+$], 275.0843; found, 275.0843.

*Diethyl (2-(2-fluorophenyl)-2-oxoethyl)phosphonate (**3f**).* Yield: 64% (175 mg); Yellow liquid; IR (KBr): 1685, 1610, 1482, 1453, 1395, 1256, 1026, 970, 876, 830, 773, 590, 500 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 1.18–1.20 (m, 6H, C–CH_3), 3.64 (d, J = 22.0 Hz, 2H, P–CH_2–C), 4.03–4.09 (m, 4H, O–CH_2–C), 7.05–7.09 (m, 1H, ArH), 7.15–7.18 (m, 1H, ArH), 7.47–7.48 (m, 1H, ArH), 7.77–7.81 (m, 1H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 16.2, 16.2, 42.4 (d, J = 129 Hz, P–CH_2–C), 62.5, 62.5, 116.6 (d, J = 23.8 Hz) , 124.5 (d, J = 3.8 Hz), 125.5 (d, J = 12.5 Hz), 131.1 (d, J = 2.5 Hz), 135.2 (d, J = 10.0 Hz), 161.8 (d, J = 252.5 Hz), 190.0; HRMS (TOF ES^+): *m/z* calcd for $C_{12}H_{17}FO_4P^+$ [$(M+H)^+$], 275.0843; found, 275.0843.

*Diethyl (2-oxo-2-(4-(trifluoromethyl)phenyl)ethyl)phosphonate (**3g**).* Yield: 46% (149 mg); Yellow liquid; IR (KBr): 1679, 1424, 1365, 1269, 1143, 1078, 970, 814, 730, 598 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ = 1.20–1.23 (m, 6H, C–CH_3), 3.59 (d, J = 22.9 Hz, 2H, P–CH_2–C), 4.06–4.09 (m, 4H, O–CH_2–C), 7.67 (d, J = 8.3 Hz, 2H, ArH), 8.07 (d, J = 8.2 Hz, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.2, 38.9 (d, J = 129 Hz, P–CH_2–C), 62.8, 62.8, 123.5 (d, J = 271.5 Hz), 125.5, 125.5, 129.4, 129.4, 134.7 (dd, J = 69 Hz), 139.1, 191.1 (d, J = 6.0 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{13}H_{17}F_3O_4P^+$ [$(M+H)^+$], 325.0811; found, 325.0814.

*Diethyl (2-(4-cyanophenyl)-2-oxoethyl)phosphonate (**3h**).* Yield: 41% (115 mg); Yellow liquid; IR (KBr): 2072, 1743, 1638, 1402, 1268, 1244, 1024, 823, 618, 570 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ = 1.21–1.23 (m, 6H,

C–CH_3), 3.58 (d, J = 22.9 Hz, 2H, P–CH_2–C), 4.05–4.10 (m, 4H, O–CH_2–C), 7.72 (d, J = 9.4 Hz, 2H, ArH), 8.06 (d, J = 8.3 Hz, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.3, 39.0 (d, J = 129 Hz, P–CH_2–C), 62.9, 63.0, 116.9, 117.8, 129.5, 129.5, 132.5, 132.5, 139.3, 190.8 (d, J = 7.5 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{13}H_{17}NO_4P^+$ [(M+H)$^+$], 282.0890; found, 282.0889.

Diethyl (2-(4-nitrophenyl)-2-oxoethyl)phosphonate ***(3i)***. Yield: 54% (162 mg); Yellow liquid; IR (KBr): 1673, 1603, 1454, 1397, 1250, 1170, 1026, 815, 609, 521 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.29–1.31 (m, 6H, C–CH_3), 3.68 (d, J = 23.0 Hz, 2H, P–CH_2–C), 4.14–4.18 (m, 4H, O–CH_2–C), 8.21 (d, J = 8.8 Hz, 2H, ArH), 8.33 (d, J = 8.8 Hz, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.3, 39.3 (d, J = 128 Hz, P–CH_2–C), 62.9, 63.0, 123.8, 123.8, 130.2, 130.2, 140.8, 150.6, 190.6 (d, J = 7.5 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{12}H_{17}NO_6P^+$ [(M+H)$^+$], 302.0788; found, 302.0789.

Diethyl (2-([1,1'-biphenyl]-4-yl)-2-oxoethyl)phosphonate ***(3j)***. Yield: 77% (256 mg); Yellow liquid; IR (KBr): 1674, 1470, 1392, 1252, 1025, 970, 819, 478 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.19–1.21 (m, 6H, C–CH_3), 3.57 (d, J = 22.7 Hz, 2H, P–CH_2–C), 4.04–4.09 (m, 4H, O–CH_2–C), 7.31 (d, J = 7.4 Hz, 1H, ArH), 7.35–7.38 (m, 2H, ArH), 7.53 (d, J = 7.3 Hz, 2H, ArH), 7.60 (d, J = 8.3 Hz, 2H, ArH), 7.99 (d, J = 8.4 Hz, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.3, 16.3, 38.5 (d, J = 129 Hz, P–CH_2–C), 62.7, 62.7, 127.7, 127.2, 127.3, 127.3, 128.4, 129.0, 129.0, 129.7, 129.7, 135.2, 139.6, 146.3, 191.5 (d, J = 6.0 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{18}H_{22}O_4P^+$ [(M+H)$^+$], 333.1250; found, 333.1259.

Diethyl (2-(naphthalen-2-yl)-2-oxoethyl)phosphonate ***(3k)***. Yield: 80% (245 mg); Yellow liquid; IR (KBr): 1677, 1604, 1560, 1486, 1448, 1409, 1253, 1025, 823, 767, 698, 658, 589, 510 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.18–1.21 (m, 6H, C–CH_3), 3.69 (d, J = 22.7 Hz, 2H, P–CH_2–C), 4.06–4.10 (m, 4H, O–CH_2–C), 7.48 (d, J = 7.5 Hz, 1H, ArH), 7.52–7.54 (m, 1H, ArH), 7.78–7.82 (m, 2H, ArH), 7.90 (d, J = 8.1 Hz, 1H, ArH), 7.97–7.98 (m, 1H, ArH), 8.47 (s, 1H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.3, 16.3, 38.6 (d, J = 129 Hz, P–CH_2–C), 62.7, 62.7, 124.2, 126.9, 127.8, 128.5, 128.9, 129.8, 131.5, 132.4, 133.9, 135.8, 191.8 (d, J = 6.0 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{16}H_{20}O_4P^+$ [(M+H)$^+$], 307.1094; found, 307.1097.

Diethyl (2-(naphthalen-1-yl)-2-oxoethyl)phosphonate ***(3l)***. Yield: 74% (226 mg); Yellow liquid; IR (KBr): 1680, 1508, 1442, 1393, 1247, 1025, 972, 804, 589, 484 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.13–1.16 (m, 6H, C–CH_3), 3.68 (d, J = 22.6 Hz, 2H, P–CH_2–C), 4.01–4.06 (m, 4H, O–CH_2–C), 7.43–7.47 (m, 2H, ArH), 7.51–7.53 (m, 1H, ArH), 7.79 (d, J = 8.0 Hz, 1H, ArH), 7.92–7.96 (m, 2H, ArH), 8.59 (d, J = 8.6 Hz, 1H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.3, 41.8 (d, J = 128 Hz, P–CH_2–C), 62.6, 62.7, 124.3, 125.8, 126.6, 128.3, 128.4, 129.3 130.3, 133.6, 133.9, 135.1, 195.1 (d, J = 7.5 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{16}H_{20}O_4P^+$ [(M+H)$^+$], 307.1094; found, 307.1093.

Diethyl (2-(furan-2-yl)-2-oxoethyl)phosphonate ***(3m)***. Yield: 57% (140 mg); Yellow liquid; IR (KBr): 1672, 1568, 1467, 1392, 1305, 1253, 1164, 1026, 972, 884, 777, 594, 510 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.18–1.24 (m, 6H, C–CH_3), 3.44 (d, J = 22.5 Hz, 2H, P–CH_2–C), 4.07–4.09 (s, 4H, O–CH_2–C), 6.51 (s, 1H, ArH), 7.25 (s, 1H, ArH), 7.57 (s, 1H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 16.2, 16.3, 38.2 (d, J = 129.0 Hz, P–CH_2–C), 62.7, 62.7, 112.8, 119.0, 147.2, 152.3, 180.0 (d, J = 7.5 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{10}H_{16}O_5P^+$ [(M+H)$^+$], 247.0730; found, 247.0726.

Diethyl (2-oxo-2-(thiophen-2-yl)ethyl)phosphonate ***(3n)***. Yield: 65% (170 mg); Yellow liquid; IR (KBr): 1657, 1520, 1416, 1356, 1251, 1244, 1025, 973, 860, 827, 735, 589, 509 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.29–1.31 (m, 6H, C–CH_3), 3.56 (d, J = 22.6 Hz, 2H, P–CH_2–C), 4.13–4.18 (m, 4H, O–CH_2–C), 7.15–7.17 (m, 1H, ArH), 7.71 (d, J = 4.9 Hz, 1H, ArH), 7.71 (d, J = 3.6 Hz, 1H, ArH) ; ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.2, 16.3, 39.4 (d, J = 129 Hz, P–CH_2–C), 62.8, 62.8, 128.3, 134.2, 135.1, 143.9, 184.2 (d, J = 6.0 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{10}H_{16}O_4PS^+$ [(M+H)$^+$], 263.0501; found, 263.0500.

Diethyl (2-oxo-4-phenylbutyl)phosphonate ***(3q)***. Yield: 63% (179 mg); Yellow liquid; IR (KBr): 1715, 1604,

1497, 1454, 1395, 1253, 1025, 970, 809, 750, 701, 538, 494 cm^{-1}; ^1H NMR (600 MHz, $CDCl_3$): δ = 1.21–1.24 (m, 6H, C–CH_3), 2.80–2.83 (m, 2H, CH_2), 2.86–2.89 (m, 2H, CH_2) 3.00 (d, J = 22.8 Hz, 2H, P–CH_2–C), 4.00–4.05 (m, 4H, O–CH_2–C), 7.10 (m, 3H, ArH), 7.17–7.19 (m, 2H, ArH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.3, 16.3, 29.4, 42.4 (d, J = 126 Hz, P–CH_2–C), 45.4, 62.6, 62.6, 126.1, 128.4, 128.4, 128.4, 128.4, 140.6, 201.1 (d, J = 6.0 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{14}H_{22}O_4P^+$ [$(M+H)^+$], 285.1250; found, 285.1253.

*Diethyl-styrylphosphonate (**3r**).* Yield: 76% (182 mg); Yellow liquid; IR (KBr): 1617, 1449, 1394, 1247, 1026, 967, 858, 745, 692, 521 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 1.27–1.30 (m, 6H, C–CH_3), 4.03–4.10 (m, 4H, O–CH_2–C), 6.15–6.22 (m, 1H, C=CH), 7.31–7.33 (m, 3H, ArH), 7.40–7.48 (m, 3H, C=CH+ArH), ^{13}C NMR (125 MHz, $CDCl_3$): δ = 16.4, 16.4, 61.9, 61.9, 114.0 (d, J = 190.0 Hz), 127.7, 127.7, 128.9, 128.9, 130.2, 134.9 (d, J = 22.5 Hz), 148.8 (d, J = 6.3 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{12}H_{18}O_3P^+$ [$(M+H)^+$], 241.0988; found, 241.0989.

*Diethyl (2-oxooctyl)phosphonate (**3s**).* Yield: 81% (232 mg); Yellow liquid; IR (KBr): 1714, 1633, 1454, 1396, 1252, 1163, 1028, 967, 799, 622, 547 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 0.79–0.82 (m, 3H, CH_3), 1.21–1.22 (m, 6H, C-CH_3), 1.23–1.28 (m, 6H, CH_2), 1.49–1.52 (m, 2H, CH_2), 2.53–2.56 (m, 2H, CH_2), 3.01 (d, J = 25.0 Hz, 2H, CH_2), 4.04–4.11 (m, 4H, O–CH_2–C); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 13.9, 16.2, 16.2, 22.4, 23.3, 28.6, 31.5, 42.3 (d, J = 126.3 Hz, P–CH_2–C), 44.0, 62.5, 62.5, 203.1; HRMS (TOF ES^+): *m/z* calcd for $C_{12}H_{25}NaO_4P$+ [$(M+Na)^+$], 287.1383; found, 287.1387.

*Dimethyl (2-oxo-2-phenylethyl)phosphonate (**3t**).* Yield: 83% (189 mg); Yellow liquid; IR (KBr): 1680, 1598, 1449, 1254, 1032, 877, 812, 690, 585, 505 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 3.58 (d, J = 22.5 Hz, 2H, P–CH_2–C), 3.70 (s, 3H, O–CH_3), 3.72 (s, 3H, O–CH_3), 7.40–7.43 (m, 2H, ArH), 7.52 (d, J = 7.0 Hz, 1H, ArH), 7.92–7.94 (m, 2H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 37.5 (d, J = 131.3 Hz, P–CH_2–C), 53.1, 53.2, 128.7, 128.7, 129.0, 129.0, 133.8, 136.4, 191.8 (d, J = 7.5 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{10}H_{14}O_4P^+$ [$(M+H)^+$], 229.0624; found, 229.0622.

*Diisopropyl (2-oxo-2-phenylethyl)phosphonate (**3u**).* Yield: 78% (221 mg); Yellow liquid; IR (KBr): 1681, 1599, 1449, 1386, 1251, 1106, 992, 889, 777, 690, 585, 525 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 1.19–1.21 (m, 12H, C–CH_3), 3.52 (d, J = 23.0 Hz, 2H, P–CH_2–C), 4.63–4.67 (m, 2H, O–CH–C), 7.38–7.41 (m, 2H, ArH), 7.49 (d, J = 7.0 Hz, 1H, ArH), 7.93–7.95 (m, 2H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 23.7, 23.7, 23.9, 23.9, 39.7 (d, J = 130.0 Hz, P–CH_2–C), 71.4, 71.5, 128.5, 128.5, 129.5, 129.5, 133.5, 136.7, 192.1 (d, J = 7.5 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{14}H_{22}O_4P^+$ [$(M+H)^+$], 285.1250; found, 285.1247.

*Diphenyl (2-oxo-2-phenylethyl)phosphonate (**3v**).* Yield: 78% (274 mg); Yellow liquid; IR (KBr): 1682, 1594, 1490, 1449, 1401, 1277, 1187, 1008, 939, 765, 689, 589, 496 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 3.84 (d, J = 23.0 Hz, 2H, P–CH_2–C), 7.04–7.07 (m, 6H, ArH), 7.16–7.21 (m, 4H, ArH), 7.36–7.39 (m, 2H, ArH), 7.48–7.51 (d, J = 7.0 Hz, 1H, ArH), 7.93–7.93 (m, 2H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 37.8 (d, J = 133 Hz, P–CH_2–C), 120.6, 120.6, 120.7, 120.7, 125.5, 125.5, 128.8, 128.8, 129.1, 129.1, 129.9, 129.9, 129.9, 129.9, 134.0, 136.4, 150.0, 150.1, 190.8 (d, J = 7.5 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{20}H_{18}O_4P^+$ [$(M+H)^+$], 353.0937; found, 353.0940.

*Dibenzyl (2-oxo-2-phenylethyl)phosphonate (**3w**).* Yield: 61% (232 mg); Yellow liquid; IR (KBr): 1681, 1598, 1498, 1450, 1380, 1256, 1130, 995, 886, 734, 696, 591, 462 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ = 3.57 (d, J = 22.5 Hz, 2H, P–CH_2–C), 4.91–5.01 (m, 4H, O–CH_2–C), 7.17–7.25 (m, 10H, ArH), 7.32–7.35 (m, 2H, ArH), 7.46–7.49 (m, 1H, ArH), 7.85–7.87 (m, 2H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 38.7 (d, J = 131 Hz, P–CH_2–C), 68.0, 68.1, 128.1, 128.1, 128.1, 128.1, 128.5, 128.5, 128.6, 128.6, 128.6, 128.6, 128.7, 128.7, 129.0, 129.0, 133.7, 135.9, 135.9, 136.5, 191.7 (d, J = 7.5 Hz); HRMS (TOF ES^+): *m/z* calcd for $C_{22}H_{22}O_4P^+$ [$(M+H)^+$], 381.1250; found, 381.1251.

*Diethyl (4-oxo-4H-chromen-3-yl)phosphonate (**4a**).* Yield: 20% (56 mg); Yellow liquid; IR (KBr): 1655, 1611, 1556, 1460, 1381, 1343, 1307, 1258, 1056, 1026, 969, 806, 752, 692, 591, 535; ^1H NMR (600 MHz, $CDCl_3$): δ =

1.29–1.31 (m, 6H, C–CH_3), 4.15–4.23 (m, 4H, O–CH_2–C), 7.38–7.40 (m, 1H, ArH), 7.43 (d, J = 8.3 Hz, 1H, ArH), 7.64–7.66 (m, 1H, ArH), 8.14–8.16 (m, 1H, ArH), 8.45 (d, J = 9.5 Hz, 1H, C=CH); ^{13}C NMR (150 MHz, $CDCl_3$): δ = 16.3, 16.4, 63.0, 63.1, 114.0 (d, J = 157.5 Hz, P–C–C), 118.3, 124.4 (d, J = 7.5 Hz), 126.2, 126.2, 134.5, 156.2, 163.4 (d, J = 19.5 Hz), 175.3; HRMS (TOF ES$^+$): *m/z* calcd for $C_{13}H_{16}O_5P$+ [(M+H)$^+$], 283.0730; found, 283.0729.

*4H-Chromen-4-one (**5**).* Yield: 52% (76 mg); Yellow liquid; IR (KBr): 1653, 1462, 1401, 1338, 1243, 1185, 1123, 1006, 962, 836, 756, 678, 527, 465 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 6.25 (d, J = 6.0 Hz, 1H, C=CH), 7.30–7.33 (m, 1H, ArH), 7.36 (d, J = 8.5 Hz, 1H, ArH), 7.56–7.60 (m, 1H, ArH), 7.77 (d, J = 10.0 Hz, 1H, C=CH), 8.11 (d, J = 9.5 Hz, 1H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 113.0, 118.2, 124.9, 125.2, 125.8, 133.8, 155.3, 156.5, 177.6; HRMS (TOF ES$^+$): *m/z* calcd for $C_9H_7O_2$+ [(M+H)$^+$], 147.0441; found, 147.0443.

*Diethyl (2,2-diphenylvinyl)phosphonate (**9**).* Yield: 31% (98 mg); Yellow liquid; IR (KBr): 1600, 1487, 1445, 1394, 1242, 1161, 1038, 962, 840, 767, 701, 526 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.04–1.07 (m, 6H, C–CH_3), 3.72–3.77 (m, 2H, O–CH_2–C), 3.82–3.87 (m, 2H, O–CH_2–C), 6.11 (d, J = 15.5 Hz, 1H, C–CH–P), 7.19–7.27 (m, 5H, ArH), 7.29–7.31 (m, 5H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 15.1, 15.1, 60.5, 60.6, 113.7 (d, J = 192.5 Hz, P–CH–C), 126.8, 127.2, 127.2, 127.3, 127.3, 127.6, 127.6, 128.4, 128.7, 137.9 (d, J = 7.5 Hz), ,140.5 (d, J = 22.5 Hz), 159.1 (d, J = 5 Hz); HRMS (TOF ES$^+$): *m/z* calcd for $C_{18}H_{22}O_3P^+$ [(M+H)$^+$], 317.1301; found, 317.1305.

General Procedure for the Large-scale synthesis of *β*-ketophosphonate 3a. *N*,*N*-Dimethylenaminone **1a** (6 mmol, 1.0 equiv), diethyl phosphite **2a** (12.0 mmol, 2.0 equiv) , $Mn(OAc)_3$ (18 mmol, 3.0 equiv), AcOH (12 mL) 1,4-dioxane (24 mL) were charged into a 100 mL round-bottom flask, and the mixture was stirred at 80 ^{o}C for 12 h until *N*,*N*-dimethylenaminone **1a** were completely consumed. The mixture was cooled to room temperature, neutralized with a saturated solution of $NaHCO_3$ to pH 8–9, and then EtOAc (30 mL × 2) were added. The organic phase was washed with water (120 mL), dried over Na_2SO_4, concentrated and purified by flash column chromatography to afford *β*-ketophosphonate **3a** (79%, 1.2g).

General Procedure for the Synthesis of intermediate *bis*-enaminones 10a. To a solution of *β*-ketophosphonates **3a** (1.00 mmol, 1.0 equiv) in DMF-DMA (1.0 mL) at 80 °C (oil bath) was added L-proline (0.10 mmol, 0.1 equiv), and the mixture was stirred for 2 h, the full conversion of *β*-ketophosphonates **3a** monitored by TLC. To the resulting mixture was added 25 mL of brine and extracted with ethyl acetate (10 mL × 3). The combined organic layers were washed with brine and dried over anhydrous Na_2SO_4, filtered and concentrated under reduced pressure. Purification by flash chromatography on silica gel afforded the intermediate compound **10a**.

*Diethyl (E)-(1-(dimethylamino)-3-oxo-3-phenylprop-1-en-2-yl)phosphonate (**10a**).* Yield: 73% (227 mg); Yellow liquid; IR (KBr): 1627, 1603, 1383, 1257, 1027, 963, 794, 614 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.10–1.18 (m, 6H, C–CH_3), 2.77–2.80 (m, 6H, N–CH_3), 3.88–3.95 (m, 4H, O–CH_2–C), 7.31–7.34 (m, 2H, ArH), 7.40–7.43 (m, 1H, ArH), 7.59 (d, J = 16.0 Hz, 1H, C=CH), 7.73 (d, J = 8.0 Hz, 2H, ArH); ^{13}C NMR (125 MHz, $CDCl_3$): δ = 16.0, 16.1, 44.7, 44.7, 61.7, 61.8, 128.1, 128.1, 128.9, 128.9, 132.0, 140.8, 158.4, 173.7, 193.3; HRMS (TOF ES$^+$): *m/z* calcd for $C_{15}H_{23}NO_4P^+$ [(M+H)$^+$], 312.1359; found, 312.1366.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: xx.xxxx/acs.joc.xxxxxxx.

Copies of ^{1}H NMR and ^{13}C NMR spectra for compounds **3a**–**3w**, **4a**, **5**, **8** and **9a** (PDF)

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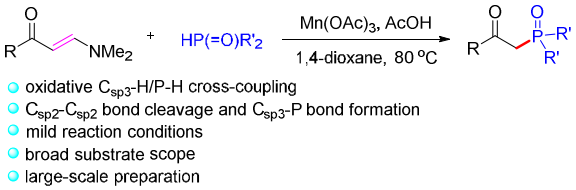
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R
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+
HP(=O)R'2
Mn(OAc)3, AcOH
1,4-dioxane, 80 °C
O
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oxidative Csp3-H/P-H cross-coupling
Csp2-Csp2 bond cleavage and Csp3-P bond formation
mild reaction conditions
broad substrate scope
large-scale preparation