

Cu-Cu₂O/GO-NH₂ 催化的芳基丙炔酸脱羧氧磷酰化反应研究

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摘要 本研究开发一种铜纳米负载的氨基石墨烯(Cu-Cu₂O/GO-NH₂)作为多相催化剂用于合成 β -羰基磷酸酯类化合物的新方法. 与传统的均相催化相比, 该方法可以实现催化剂的多次循环利用. 该多相催化反应体系不需要添加任何碱和催化剂助剂, 操作简单, 催化活性高, 底物适用范围广, 为 β -羰基磷酸酯类化合物的合成提供了可供选择的新策略.
关键词 铜纳米粒子; 石墨烯; 氧磷酰化反应; 多相催化; β -羰基磷氧

Decarboxylative Oxyphosphorylation of Alkynyl Carboxylic Acids with *H*-Phosphonates Catalyzed by Cu-Cu₂O/GO-NH₂

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Abstract A graphene based hybrid with copper nanoparticles (Cu-Cu₂O/GO-NH₂) as a heterogeneous catalyst for the preparation of β -ketophosphonates was investigated. Compared with traditional homogeneous catalysis, Cu-Cu₂O/GO-NH₂ catalyst can be recovered from the reaction system. The present methodology provides a facile and efficient approach to access a wide range of β -ketophosphonates in good yields. This reaction can be conducted under base-free conditions without any external co-catalysts, which provides an alternative strategy for the synthesis of β -ketophosphonates.

Keywords Cu nanoparticles; graphene; oxyphosphorylation; heterogeneous catalysis; β -ketophosphonates

1 Introduction

Organophosphorus compounds has been widely used in medicinal chemistry, agrochemistry and organic synthesis owing to their unique bioactivities.^[1] Among all the organophosphorus compounds, the representative β -ketophosphonates have been widely used as vital synthons in the organic chemistry and pharmaceutical synthesis.^[2] For instance, β -ketophosphonates as starting materials can produce β -aminophosphonates,^[2b] useful building blocks in

the preparation of phosphopeptides. Recently, various synthetic methodologies of β -ketophosphonates have been also reported because of their versatile utility.^[3] In 2011, Ji's group presented a simple copper/iron co-catalyzed oxidative synthesis of β -ketophosphonates by direct difunctionalization of alkenes with dioxygen and *H*-phosphonates.^[3b] After that, a series of synthetic approaches were reported for the β -ketophosphonates,^[4] mainly involving in oxyphosphorylation of alkynes or aryl acetylene acid.^[5] Herein, most of methods were suitable for the ho-

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mogeneous systems,^[6] inevitably leading to low utilization of catalyst and hard separation of products.

Recently, some heterogeneous catalysts have successfully overcome the shortcomings of homogeneous catalysis,^[7] providing more economic methodology for the synthesis of β -ketophosphonates. In 2015, Radivoy's group reported CuNPs/ZnO as a heterogeneous catalyst for the direct synthesis of β -ketophosphonates,^[7a] good reaction efficiency could be achieved. However, heterogeneous catalysis usually suffered from poor chemoselectivity and stereoselectivity. Therefore, the development of high-performance catalysts is still of great importance.

Metallic graphene-based composites as known heterogeneous catalysts have been widely used in various organic reactions,^[8] such as Suzuki-Miyaura cross-coupling, Heck reaction and Ullmann coupling. Graphene-based heterogeneous catalysts can also catalyze the formation of C—P bond.^[9] Hence, in this work, we developed an amino-graphene-supported copper catalyst (Cu-Cu₂O/GO-NH₂) to catalyze the decarboxylative oxyphosphorylation of arylpropionic acids with *H*-phosphonates in the O₂.

2 Results and discussion

2.1 Characterization of Cu-Cu₂O/GO-NH₂ catalyst

The prepared Cu-Cu₂O/GO-NH₂ catalyst was characterized by X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS) and transmission electron microscopy (TEM). The results were displayed in Figure 1. The crystal structures of Cu nanoparticles and amino-graphene (GO-NH₂) were analyzed by XRD in Figure 1a. For GO-NH₂ material, the peak at $2\theta=10.2^\circ$ was observed, corresponding to the interlayer spacing of GO. A new peak $2\theta=24.6^\circ$ presented interlayer spacing of 0.356 nm, which was mainly due to installation of the amino groups that might exist between the GO layers. For the Cu-Cu₂O/GO-NH₂ catalyst, the peaks at 2θ values of 36.9° (111), 61.7° (200), and 73.9° (311) were consistent with the standard XRD data for the Cu₂O nanoparticles, while the peaks at 43.4° (111) and 50.1° (200) could belong to Cu nanoparticles. These results showed that two kinds of Cu nanoparticles were immobilized on the GO-NH₂ sheets.

The additional qualitative evidence for the installation of GO surface bound amino groups was obtained through XPS analysis in Figure 1b. Obviously, the Cu-Cu₂O/GO-NH₂ material included C, N, O and Cu elements, indicating that amino groups were successfully grafted on the GO. Additionally, the morphology of the catalyst was observed by TEM. As seen from Figure 1c, about 10~20 nm size amorphous Cu nanoparticles were well dispersed on the GO-NH₂ surface.

2.2 Catalytic performance of Cu-Cu₂O/GO-NH₂ catalyst

To evaluate the catalytic performance of Cu-Cu₂O/GO-NH₂ composite in organic reaction, the aerobic decarboxylative oxyphosphorylation of alkynyl carboxylic acids

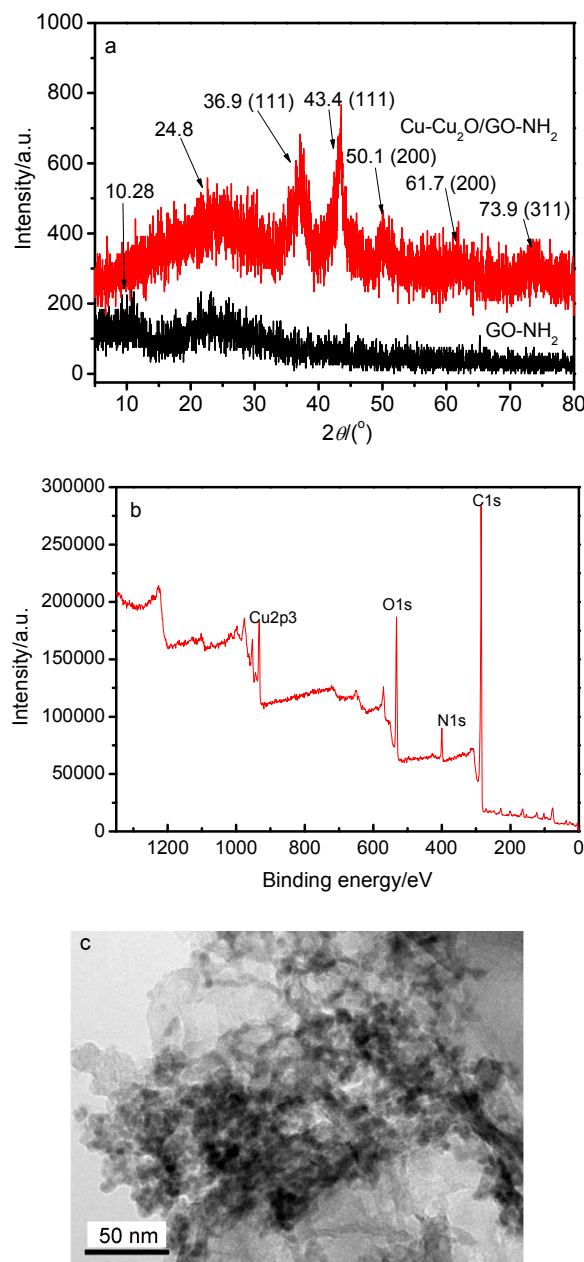


Figure 1 Characterization of catalyst
(a) XRD; (b) XPS; (c) TEM

with *H*-phosphonates was investigated. As shown in Table 1, the reaction conditions were first screened.

In our initial experiment, 3-phenylpropionic acid (**1a**, 0.5 mmol) was treated with diethyl phosphite (**2a**, 1.0 mmol) in acetonitrile at room temperature for 4 h in the presence of Cu-Cu₂O/GO-NH₂ (5 mg), only low yield of diethyl-(2-oxo-2-phenylethyl) phosphonate (**3a**) was obtained. With the increase of reaction temperature, the yield of **3a** was up to 72% at 80 °C. However, when the reaction temperature was increased to 90 °C, the yield of **3a** declined slightly. Next, the influence of various solvents was examined at 80 °C. *N,N*-Dimethylformamide (DMF) as the solvent could provide good reaction efficiency. Finally, the examination of amount of catalyst found that 10 mg of

Table 1 Optimization of the reaction conditions^a

Entry	Loading/mg	Temp./°C	Solvent	Yield ^b /%
1	5	25	CH ₃ CN	10
2	5	50	CH ₃ CN	18
3	5	60	CH ₃ CN	36
4	5	70	CH ₃ CN	65
5	5	80	CH ₃ CN	72
6	5	90	CH ₃ CN	70
7	5	100	CH ₃ CN	68
8	5	80	1,4-Dioxane	27
9	5	80	DCE	15
10	5	80	THF	46
11	5	80	DMF	86
12	5	80	DMSO	79
13	2	80	DMF	61
14	8	80	DMF	87
15	10	80	DMF	90

^a Conditions: **1a** (0.5 mmol), **2a** (1.0 mmol), catalyst: Cu-Cu₂O/GO-NH₂, solvent (4 mL), 4 h, O₂ balloon. ^b Isolated yields.

catalyst could give the optimal yields.

Next, the scope of substrates was explored with the optimal conditions in hand. As shown in Table 2, various arylpropionic acids with different substituents were suitable for this reaction, and good yields were obtained. The electronic effect of substituents had a slight effect on the yield of desired products. Generally, *para*-substituted arylpropionic acids with electron-donating substituents were more suitable than electron-withdrawing substituted acids, such as methoxy (**3d**), *tert*-butyl (**3g**), halogen (**3b**, **3c**, **3l**), nitro (**3i**). Additionally, steric effects of substituents had somewhat effect on the efficiency of the reaction. Especially, the substituted groups in the 2-position of benzene ring obviously decreased the yields of products as a result of steric hindrance (**3f**, **3h**). Additionally, 3-(2,4,5-trifluorophenyl)propionic acid and 3-(naphthalen-2-yl)propionic acid could also afford the desired products in good yields (**3m**, **3n**). However, alkyl acetylenic acids were not compatible for the reaction, such as 2-butyric acid and 2-hexynoic acid (**3o**, **3p**).

Finally, in addition to diethyl phosphite, other *H*-phosphine oxides and *H*-phosphonates could also be tolerated in the reaction to afford good yields (**3q**~**3t**).

2.3 Recyclability of Cu-Cu₂O/GO-NH₂ catalyst

To evaluate the recyclability of this catalyst, the recycled experiment was conducted. The as-prepared Cu-Cu₂O/GO-NH₂ catalyst can be used five times without significant

Table 2 Screening of the substrate scope^a

3a , 90%	3b , 76%	3c , 82%	3d , 95%	3e , 92%
3f , 88%	3g , 91%	3h , 62%	3i , 70%	3j , 73%
3k , 78%	3l , 80%	3m , 63%	3n , 79%	3o , 0%
3p , 0%	3q , 80%	3r , 83%	3s , 79%	3t , 81%

^a Conditions: **1** (0.5 mmol), **2** (1.0 mmol), Cu-Cu₂O/GO-NH₂ (10 mg), DMF (4 mL), 80 °C, 4 h, O₂ balloon. Isolated yields.

decrease of activity (Figure 2a). The morphology of recyclable catalyst was characterized by TEM (Figure 2b). Obviously, most Cu nanoparticles was still immobilized on the GO-NH₂ surface. Compared with the fresh Cu-Cu₂O/GO-NH₂ catalyst, the size and morphology of Cu nanoparticles had an obvious difference. The analysis of XPS spectra illustrated the distinction of Cu species valence between fresh catalyst and reused catalyst (Figures 2c and 2d). The binding energy of Cu(II) species located at about 935 eV, while the peak at 932 eV was assigned to Cu(I) species. These results indicated that the Cu(I) species might be oxidized to give Cu(II) species under the atmosphere of O₂.

Additionally, copper loading in the GO-NH₂ was detected from the acid extract of the sample before and after reaction by using inductively coupled plasma-atomic emission spectroscopy (ICP-AES). For the fresh catalyst, copper loading was 23 wt%. After the catalyst was used five times, copper loading in the GO-NH₂ was decreased to 12 wt%, indicating that the leaching of the copper species occurred during reaction, which might lead to the damage of catalytic performance of Cu-Cu₂O/GO-NH₂.

Finally, the different catalytic systems were compared for the oxyphosphorylation of 3-phenylpropionic acid. As seen from Table 3, compared with homogeneous catalysis, the Cu-Cu₂O/GO-NH₂ catalyst showed higher reaction efficiency. The reaction could be conducted under base-free and additive-free condition. In the heterogeneous system, the catalyst could be recycled well, which might be benefit for the practical applications.

Table 3 Comparison of various catalysts for the oxyphosphorylation.

Entry	Catalyst	Conditions	Y/%	Ref.
1	Ag ₂ CO ₃	EtOH, Mn(OAc) ₃ •2H ₂ O, r.t.	12	[4e]
2	CuSO ₄ •5H ₂ O	TBHP, NH ₃ •H ₂ O, CH ₃ CN, 60 °C	22	[3e]
3	CuOTf+FeCl ₃	Et ₃ N, DMSO, 60 °C	78	[4f]
4	Cu-Cu ₂ O/GO-NH ₂	DMF, 80 °C	90	This work

2.4 Mechanism of the reaction

To improve our understanding of the reaction mechanism, a series of control experiments were conducted. When radical scavenger TEMPO was added in the present reaction, only a trace amount of the desired product **3a** was

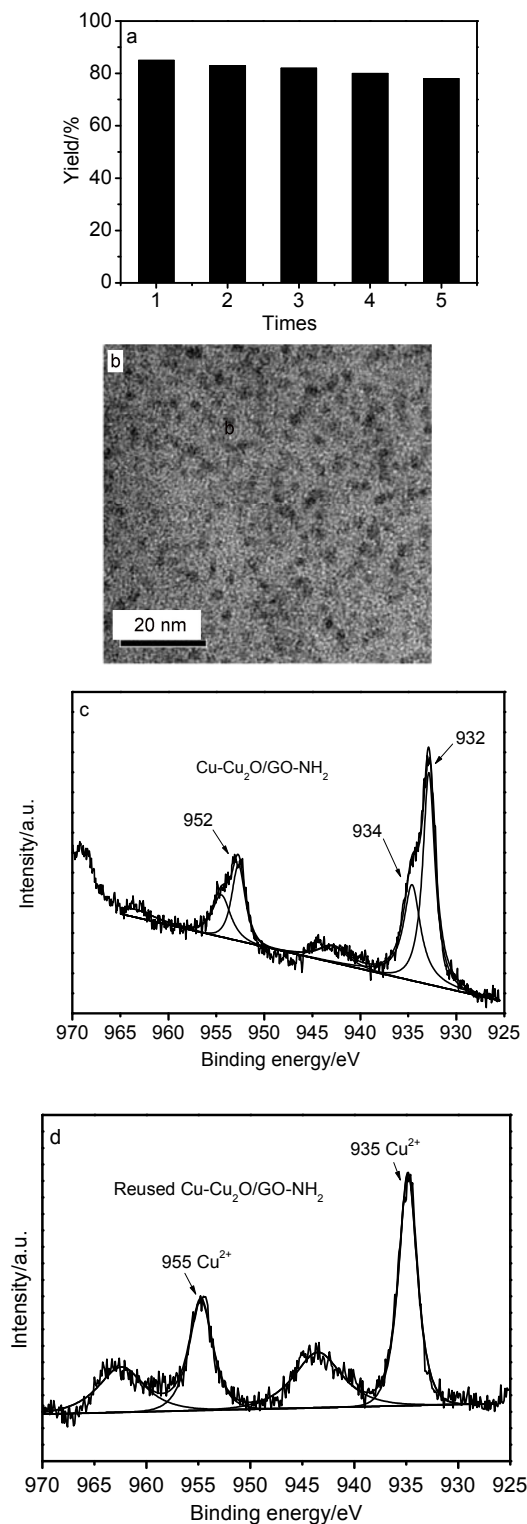
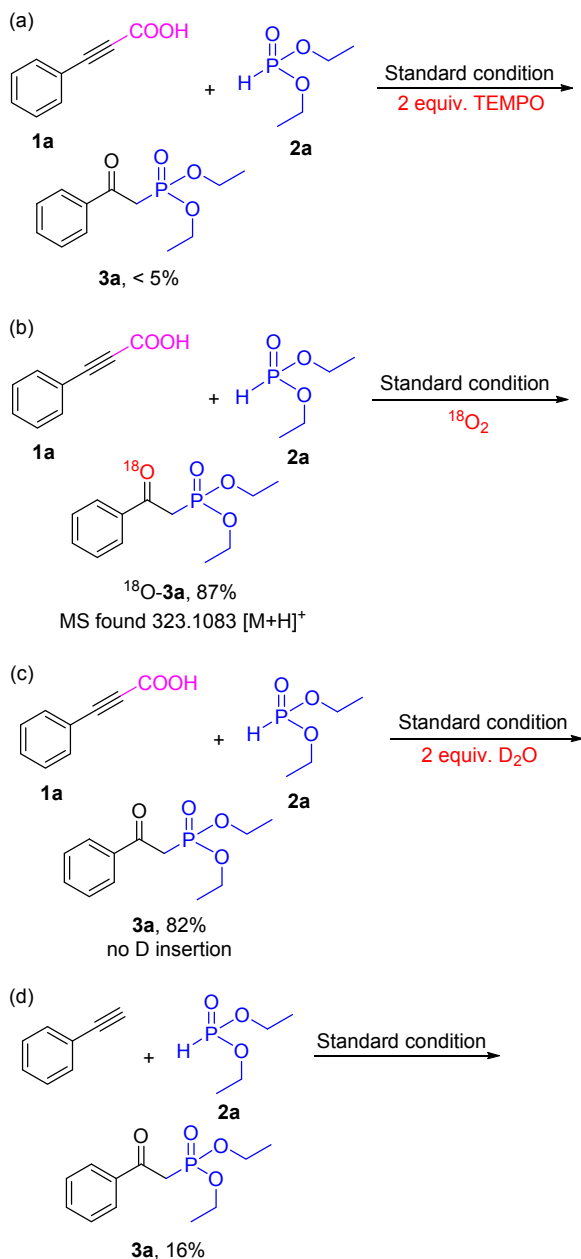


Figure 2 Recyclability of experiment

(a) Recycled experiment; (b) TEM image of reused catalyst; (c) XPS spectrum of Cu2p for fresh catalyst; (d) XPS spectrum of Cu2p for the reused catalyst

obtained, indicating that a radical process might be involved in this transformation (Scheme 1a). Next, the isotope labeling studies was carried out. When ¹⁸O₂ or D₂O was added to the mixture under the standard condition, only isotope-labeled product ¹⁸O-**3a** was detected by

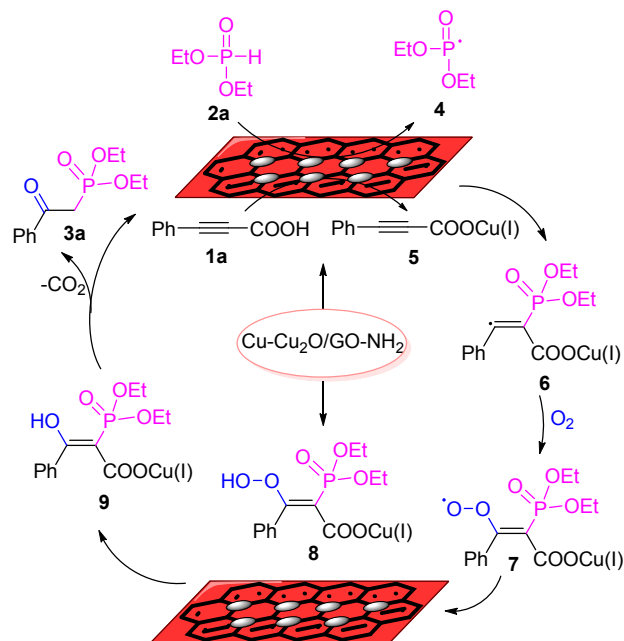
HRMS spectrum (Schemes 1b and 1c). The result showed that the oxygen atom in product **3a** (C=O) was provided by the O₂ molecular, while the hydrogen atoms of methylene in **3a** (COCH₂) might be derived from **2a** (P-H) and **1a** (COOH). Herein, phenylacetylene was used as substrate instead of alkynyl carboxylic acid leading to generate extremely low yield of **3a**, illustrating that (phenylethynyl)-copper might not be a key intermediate in this reaction (Scheme 1d).



Scheme 1 Control experiments

Although the mechanism of heterogeneous reaction is still not clear enough, based on the control experiments and previous reports,^[1d,3e,4e,10] a possible pathway in Scheme 2 is supposed. First, the Cu-Cu₂O/GO-NH₂ catalyst might motivate **2a** to generate phosphorus radical **4**. **1a** easily reacted with Cu nanoparticles to form copper salt **5**.

Next, the resulting radical **4** selectively added to copper salt **5**, leading to α -styryl radical **6**. This intermediate **6** was trapped by O₂ to generate radical **7**. Subsequently, radical **7** was converted into hydroperoxide **8** by abstracting one hydrogen atom from the surface of catalyst. Under heating condition, the intermediate **8** transformed into enol **9** by reoxidizing Cu(0) to Cu(I) nanoparticles on the GO-NH₂. Finally, the desired product **3a** was produced via a decarboxylation/isomerization of **9**.



Scheme 2 Possible mechanism

3 Conclusions

In summary, a new heterogeneous catalytic system was developed for the decarboxylative oxyphosphorylation of alkynyl carboxylic acids with *H*-phosphonates using Cu-Cu₂O/GO-NH₂ catalyst. Various β -ketophosphonates were synthesized in good yield. Cu-Cu₂O/GO-NH₂ catalyst showed high catalytic activity and good recyclability. Compared with homogeneous reaction, the heterogeneous catalytic system was very benefit to isolate product and recycle of catalyst, which might be of great importance for practical application.

4 Experimental section

4.1 General information

All reagents and solvents were used without further purification. Analytical thin layer chromatography (TLC) was performed on percolated silica gel 60 F254 plates. ¹H NMR and ¹³C NMR spectra were recorded in CDCl₃ with tetramethylsilane (TMS) as internal standard, and ³¹P NMR spectra were obtained in CDCl₃ with H₃PO₄ as the internal standard. Column chromatography was conducted on columns of silica gel (100~200 mesh). The graphene composites were characterized by X-ray diffraction (XRD, D/MAX Ultima IV, JAPAN). X-Ray photoelectron spec-

troscopy (XPS) was performed using an ESCALAB 250 Xi with a high-performance Al monochromatic source ($h\nu = 1486.6$ eV, 150 W). Transmission electron microscopy (TEM) characterization was carried out using a Tecnai G² 20 field emission electron microscope operated at 200 kV accelerating voltage.

4.2 Preparation of Cu-Cu₂O/GO-NH₂ catalyst

GO was purchased from commercial corporation. First, GO (50 mg) was dispersed in *N,N*-dimethylformamide (DMF, 100 mL), and then sonicated to obtain the homogeneous suspension. Subsequently, *N,N*-dimethylethane-1,2-diamine (10 mmol, 880 mg), *O*-(7-azabenzotriazol-1-yl)-*N,N,N',N'*-tetramethyluronium hexafluorophosphate (HATU, 10 mmol, 3.8 g) and *N,N*-diisopropylethylamine (DIPEA, 20 mmol, 2.6 g) were added successively into the suspension under magnetic stirring. The mixture kept warm at 30 °C for 24 h, and then isolated by vacuum filtration. The filter cake was washed with distilled water repeatedly. Finally, the obtained solid was dispersed into 100 mL of H₂O again to obtain the GO-NH₂ solution.

A 50 mL of copper(II) chloride dihydrate (0.5 mmol, 85 mg) solution (10 mmol/L) was added into GO-NH₂ suspension, and sonicated for 30 min. Next, the 95 mL NaBH₄ solution (2.0 mg·mL⁻¹) was added dropwise into the above solution for 1 h by the constant flow pump. After completion of reaction, the solid was filtrated, followed by washing with water and ethanol, respectively. Finally, the obtained catalyst (Cu-Cu₂O/GO-NH₂) was dried at 50 °C for 12 h under vacuum.

4.3 Decarboxylative oxyphosphorylation of alkynyl carboxylic acids with *H*-phosphonates

Alkynyl carboxylic acids (**1**, 0.5 mmol), *H*-phosphonates (**2**, 1 mmol), catalyst (10 mg), and solvent (4 mL) were added into a 25 mL round-bottomed flask and stirred at setting temperature for 4 h in O₂ atmosphere. After completion of reaction, the mixture was quenched with saturated sodium bicarbonate solution (20 mL), and extracted with ethyl acetate (10 mL×3). The combined organic layers were washed with saturated brine twice, and dried over anhydrous MgSO₄. After filtration, the solvent was evaporated in vacuum. The crude product was purified by silica gel chromatography (petroleum ether/ethyl acetate, *V*: *V*=10:1) to give the desired compounds.

4.4 Recycled experiment

3-Phenylpropionic acid (**1a**, 0.5 mmol), diethyl phosphite (**2a**, 1.0 mmol), catalyst (10 mg), and DMF (4 mL) were added into 25 mL round-bottomed flask and stirred at setting temperature for 4 h in O₂ atmosphere. After the completion of reaction, the mixture was centrifuged to separate the solid catalyst and organic phase. The organic phase was quenched with saturated sodium bicarbonate solution (20 mL), and extracted with ethyl acetate (10×3 mL). The combined organic layers were washed with saturated brine twice, and dried over anhydrous MgSO₄. After filtration, the solvent was evaporated in vacuum. The crude product

was purified by silica gel chromatography (petroleum ether/ethyl acetate, *V*: *V*=10:1) to give the desired compound **3a**. The collected solid catalyst was washed by water and alcohol three times, and dried for 12 h under vacuum oven. The recycled catalyst was reused in the next reaction.

Diethyl (2-oxo-2-phenylethyl)phosphonate (**3a**): Colorless oil. ¹H NMR (400 MHz, CDCl₃) δ : 8.02 (d, *J*=7.4 Hz, 2H), 7.60 (t, *J*=7.4 Hz, 1H), 7.49 (t, *J*=7.7 Hz, 2H), 4.18~4.11 (m, 4H), 3.65 (d, *J*=22.7 Hz, 2H), 1.29 (t, *J*=7.1 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 191.99 (d, *J*=6.7 Hz), 136.50 (d, *J*=2.1 Hz), 133.70, 129.05, 128.62, 62.69 (d, *J*=6.5 Hz), 38.45 (d, *J*=130.1 Hz), 16.25 (d, *J*=6.4 Hz); ³¹P NMR (162 MHz, CDCl₃) δ : 19.97. HRMS (ESI) calcd for C₁₂H₁₈O₄P [M+H]⁺ 257.0898; found 257.0895.

Diethyl (2-(4-fluorophenyl)-2-oxoethyl)phosphonate (**3b**): Colorless oil. ¹H NMR (400 MHz, CDCl₃) δ : 8.05 (dd, *J*=8.5, 5.5 Hz, 2H), 7.14 (t, *J*=8.5 Hz, 2H), 4.26~4.03 (m, 4H), 3.60 (d, *J*=22.8 Hz, 2H), 1.28 (t, *J*=7.1 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 190.34 (d, *J*=6.5 Hz), 166.08 (d, *J*=256.0 Hz), 132.91 (dd, *J*=2.6, 1.9 Hz), 131.86 (d, *J*=9.5 Hz), 115.74 (d, *J*=22.0 Hz), 62.73 (d, *J*=6.5 Hz), 38.58 (d, *J*=129.5 Hz), 16.24 (d, *J*=6.3 Hz); ³¹P NMR (162 MHz, CDCl₃) δ : 19.63. HRMS (ESI) calcd for C₁₂H₁₇FO₄P [M+H]⁺ 275.0804; found 275.0801.

Diethyl (2-(4-bromophenyl)-2-oxoethyl)phosphonate (**3c**): Colorless oil. ¹H NMR (400 MHz, CDCl₃) δ : 7.89 (d, *J*=8.5 Hz, 2H), 7.63 (d, *J*=8.5 Hz, 2H), 4.23~4.07 (m, 4H), 3.60 (d, *J*=22.8 Hz, 2H), 1.29 (t, *J*=7.1 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 190.96 (d, *J*=6.6 Hz), 135.19 (d, *J*=1.6 Hz), 131.94, 130.59, 129.09, 62.79 (d, *J*=6.5 Hz), 38.60 (d, *J*=129.4 Hz), 16.27 (d, *J*=6.3 Hz); ³¹P NMR (162 MHz, CDCl₃) δ : 19.44. HRMS (ESI) calcd for C₁₂H₁₆BrNaO₄P [M+Na]⁺ 356.9862; found 356.9858.

Diethyl (2-(4-methoxyphenyl)-2-oxoethyl)phosphonate (**3d**): Colorless oil. ¹H NMR (400 MHz, CDCl₃) δ : 8.00 (d, *J*=8.9 Hz, 2H), 6.94 (d, *J*=8.9 Hz, 2H), 4.13 (p, *J*=7.3 Hz, 4H), 3.87 (s, 3H), 3.58 (d, *J*=22.7 Hz, 2H), 1.28 (t, *J*=7.1 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 190.27 (d, *J*=6.4 Hz), 163.99, 131.50, 129.60 (d, *J*=1.9 Hz), 113.76, 62.63 (d, *J*=6.5 Hz), 55.52, 38.89, 37.60, 16.26 (d, *J*=6.3 Hz); ³¹P NMR (162 MHz, CDCl₃) δ : 20.45. HRMS (ESI) calcd for C₁₃H₂₀O₅P [M+H]⁺ 287.1004; found 287.1009.

Diethyl (2-(3-methoxyphenyl)-2-oxoethyl)phosphonate (**3e**): Colorless oil. ¹H NMR (400 MHz, CDCl₃) δ : 7.60 (d, *J*=7.7 Hz, 1H), 7.55~7.52 (m, 1H), 7.39 (t, *J*=8.0 Hz, 1H), 7.14 (dd, *J*=8.2, 2.5 Hz, 1H), 4.19~4.10 (m, 4H), 3.86 (s, 3H), 3.63 (d, *J*=22.7 Hz, 2H), 1.29 (t, *J*=7.1 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 191.78 (d, *J*=6.6 Hz), 159.80, 137.85 (d, *J*=2.1 Hz), 129.59, 121.90, 120.43, 112.79, 62.68 (d, *J*=6.5 Hz), 55.47, 38.58 (d, *J*=130.3 Hz), 16.26 (d, *J*=6.3 Hz); ³¹P NMR (162 MHz, CDCl₃) δ : 19.96. HRMS (ESI) calcd for C₁₃H₂₀O₅P [M+H]⁺ 287.1004; found 287.1006.

Diethyl (2-(2-methoxyphenyl)-2-oxoethyl)phosphonate (**3f**): Colorless oil. ¹H NMR (400 MHz, CDCl₃) δ : 7.71

(dd, $J=7.7, 1.7$ Hz, 1H), 7.53~7.43 (m, 1H), 7.05~6.93 (m, 2H), 4.16~4.03 (m, 4H), 3.93 (s, 3H), 3.82 (d, $J=21.9$ Hz, 2H), 1.24 (t, $J=7.1$ Hz, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 193.43 (d, $J=7.2$ Hz), 158.63, 134.23, 130.91, 127.70, 120.76, 111.52, 62.23 (d, $J=6.4$ Hz), 55.60, 43.15, 41.86, 16.24 (d, $J=6.4$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 21.23. HRMS (ESI) calcd for $\text{C}_{13}\text{H}_{20}\text{O}_5\text{P}$ $[\text{M}+\text{H}]^+$ 287.1004; found 287.0998.

Diethyl (2-(4-(*tert*-butyl)phenyl)-2-oxoethyl)phosphonate (**3g**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 7.96 (d, $J=8.5$ Hz, 2H), 7.49 (d, $J=8.5$ Hz, 2H), 4.14 (p, $J=7.2$ Hz, 4H), 3.62 (d, $J=22.7$ Hz, 2H), 1.34 (s, 9H), 1.29 (t, $J=7.1$ Hz, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 191.52 (d, $J=6.5$ Hz), 157.52, 133.98 (d, $J=2.1$ Hz), 129.04, 125.57, 62.64 (d, $J=6.5$ Hz), 39.02, 37.73, 35.17, 31.03, 16.25 (d, $J=6.4$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 20.25. HRMS (ESI) calcd for $\text{C}_{16}\text{H}_{26}\text{O}_4\text{P}$ $[\text{M}+\text{H}]^+$ 313.1524; found 313.1528.

Diethyl (2-(2-nitrophenyl)-2-oxoethyl)phosphonate (**3h**): Yellow oil. ^1H NMR (400 MHz, CDCl_3) δ : 8.16~8.09 (m, 1H), 7.78~7.71 (m, 1H), 7.67~7.58 (m, 2H), 4.18~4.05 (m, 4H), 3.58~3.47 (m, 2H), 1.32~1.25 (m, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 193.82 (d, $J=5.9$ Hz), 145.35, 137.14 (d, $J=1.2$ Hz), 134.46, 131.00, 128.78, 124.14, 62.80 (d, $J=6.4$ Hz), 42.36 (d, $J=128.4$ Hz), 16.25 (d, $J=6.3$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 18.76. HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{17}\text{NO}_6\text{P}$ $[\text{M}+\text{H}]^+$ 302.0749; found 302.0744.

Diethyl (2-(4-nitrophenyl)-2-oxoethyl)phosphonate (**3i**): Yellow oil. ^1H NMR (400 MHz, CDCl_3) δ : 8.38~8.31 (m, 2H), 8.25~8.19 (m, 2H), 4.24~4.09 (m, 4H), 3.69 (d, $J=23.0$ Hz, 2H), 1.31 (t, $J=7.1$ Hz, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 190.61 (d, $J=6.8$ Hz), 150.55, 140.78 (d, $J=1.4$ Hz), 130.16, 123.80, 62.96 (d, $J=6.5$ Hz), 39.27 (d, $J=128.6$ Hz), 16.28 (d, $J=6.3$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 18.44. HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{17}\text{NO}_6\text{P}$ $[\text{M}+\text{H}]^+$ 302.0749; found 302.0752.

Diethyl (2-(2-chlorophenyl)-2-oxoethyl)phosphonate (**3j**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 7.58~7.52 (m, 1H), 7.41~7.35 (m, 2H), 7.35~7.29 (m, 1H), 4.20~3.98 (m, 4H), 3.77~3.61 (m, 2H), 1.29~1.15 (m, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 194.32 (d, $J=6.9$ Hz), 138.55, 132.31, 131.04, 130.47, 129.95, 126.95, 62.64 (d, $J=6.4$ Hz), 42.05 (d, $J=128.7$ Hz), 16.19 (d, $J=6.4$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 19.17. HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{17}\text{ClO}_4\text{P}$ $[\text{M}+\text{H}]^+$ 292.0445; found 292.0449.

Diethyl (2-(3-chlorophenyl)-2-oxoethyl)phosphonate (**3k**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 8.00~7.94 (m, 1H), 7.92~7.85 (m, 1H), 7.59~7.51 (m, 1H), 7.47~7.36 (m, 1H), 4.25~3.99 (m, 4H), 3.60 (d, $J=22.8$ Hz, 2H), 1.36~1.20 (m, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 190.73 (d, $J=6.7$ Hz), 137.94 (d, $J=1.7$ Hz), 134.90, 133.54, 129.93, 129.00, 127.24, 62.76 (d, $J=6.5$ Hz), 38.67 (d, $J=129.5$ Hz), 16.22 (d, $J=6.4$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 19.20. HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{17}\text{ClO}_4\text{P}$ $[\text{M}+\text{H}]^+$ 292.0445; found 292.0440.

Diethyl (2-(4-chlorophenyl)-2-oxoethyl)phosphonate (**3l**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 8.02~7.88 (m, 2H), 7.53~7.36 (m, 2H), 4.22~4.03 (m, 4H), 3.61 (d, $J=22.8$ Hz, 2H), 1.29 (t, $J=7.1$ Hz, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 190.74 (d, $J=6.6$ Hz), 140.27, 134.79 (d, $J=1.7$ Hz), 130.51, 128.93, 62.77 (d, $J=6.5$ Hz), 38.62 (d, $J=129.4$ Hz), 16.26 (d, $J=6.3$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 19.46. HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{17}\text{ClO}_4\text{P}$ $[\text{M}+\text{H}]^+$ 292.0445; found 292.0447.

Diethyl (2-oxo-2-(2,4,5-trifluorophenyl)ethyl)phosphonate (**3m**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 7.87~7.67 (m, 1H), 7.14~6.93 (m, 1H), 4.26~4.02 (m, 4H), 3.80~3.52 (m, 2H), 1.29 (t, $J=7.1$ Hz, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 187.36 (dd, $J=7.3, 3.8$ Hz), 157.59 (ddd, $J=254.7, 10.1, 2.5$ Hz), 153.63 (ddd, $J=261.0, 14.8, 12.9$ Hz), 147.12 (ddd, $J=248.2, 12.6, 3.2$ Hz), 121.77 (ddd, $J=13.9, 3.7, 2.1$ Hz), 118.94 (ddd, $J=20.3, 3.4, 2.5$ Hz), 106.75 (dd, $J=30.4, 21.2$ Hz), 62.69 (d, $J=6.4$ Hz), 42.30 (dd, $J=129.8, 8.5$ Hz), 16.23 (d, $J=6.3$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 19.06. HRMS (ESI) calcd for $\text{C}_{12}\text{H}_{15}\text{F}_3\text{O}_4\text{P}$ $[\text{M}+\text{H}]^+$ 311.0615; found 311.0611.

Diethyl (2-(naphthalen-2-yl)-2-oxoethyl)phosphonate (**3n**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 8.57 (s, 1H), 8.07 (dd, $J=8.7, 1.8$ Hz, 1H), 8.00 (d, $J=8.0$ Hz, 1H), 7.90 (t, $J=8.4$ Hz, 2H), 7.66~7.61 (m, 1H), 7.60~7.55 (m, 1H), 4.30~4.05 (m, 4H), 3.78 (d, $J=22.7$ Hz, 2H), 1.29 (t, $J=7.1$ Hz, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 191.83 (d, $J=6.7$ Hz), 135.79, 133.85 (d, $J=1.9$ Hz), 132.38, 131.49, 129.80, 128.90, 128.50, 127.77, 126.92, 124.16, 62.71 (d, $J=6.5$ Hz), 38.59 (d, $J=129.9$ Hz), 16.29 (d, $J=6.4$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 20.08. HRMS (ESI) calcd for $\text{C}_{16}\text{H}_{20}\text{O}_4\text{P}$ $[\text{M}+\text{H}]^+$ 307.1055; found 307.1059.

Dimethyl (2-oxo-2-phenylethyl)phosphonate (**3q**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 7.98 (dd, $J=8.3, 1.0$ Hz, 2H), 7.62~7.53 (m, 1H), 7.47 (t, $J=7.7$ Hz, 2H), 3.76 (d, $J=11.2$ Hz, 6H), 3.63 (d, $J=22.6$ Hz, 2H); ^{13}C NMR (101 MHz, CDCl_3) δ : 191.77 (d, $J=6.6$ Hz), 136.33 (d, $J=2.5$ Hz), 133.81, 128.95, 128.70, 53.16 (d, $J=6.5$ Hz), 37.42 (d, $J=131.5$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 22.84. HRMS (ESI) calcd for $\text{C}_{10}\text{H}_{14}\text{O}_4\text{P}$ $[\text{M}+\text{H}]^+$ 229.0585; found 229.0581.

Dibutyl (2-oxo-2-phenylethyl)phosphonate (**3r**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 8.07~7.95 (m, 2H), 7.65~7.54 (m, 1H), 7.54~7.42 (m, 2H), 4.18~3.94 (m, 4H), 3.73~3.55 (m, 2H), 1.68~1.54 (m, 4H), 1.40~1.26 (m, 4H), 0.93~0.82 (m, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 191.92 (d, $J=6.8$ Hz), 136.52, 133.63, 129.05, 128.58, 66.32 (d, $J=6.7$ Hz), 38.32 (d, $J=129.5$ Hz), 32.36 (d, $J=6.4$ Hz), 18.61, 13.56; ^{31}P NMR (162 MHz, CDCl_3) δ : 19.88. HRMS (ESI) calcd for $\text{C}_{16}\text{H}_{26}\text{O}_4\text{P}$ $[\text{M}+\text{H}]^+$ 313.1524; found 313.1528.

Ethyl (2-oxo-2-phenylethyl)(phenyl)phosphinate (**3s**): Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ : 7.99~7.86 (m, 2H), 7.83~7.67 (m, 2H), 7.58~7.33 (m, 6H), 4.16~4.00 (m, 1H), 3.99~3.83 (m, 1H), 3.83~3.71 (m, 2H),

1.26~1.16 (m, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 192.14 (d, $J=5.5$ Hz), 136.74, 133.51, 132.71 (d, $J=2.7$ Hz), 131.79 (d, $J=10.2$ Hz), 130.03 (d, $J=132.8$ Hz), 129.03, 128.60 (d, $J=13.3$ Hz), 128.49, 61.44 (d, $J=6.2$ Hz), 42.91 (d, $J=86.5$ Hz), 16.29 (d, $J=6.6$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 34.45. HRMS (ESI) calcd for $\text{C}_{16}\text{H}_{18}\text{O}_3\text{P} [\text{M}+\text{H}]^+$ 289.0949; found 289.0945.

2-(Diphenylphosphoryl)-1-phenylethan-1-one (**3t**): White solid. m.p. 140~140.5 $^{\circ}\text{C}$; ^1H NMR (400 MHz, CDCl_3) δ : 7.98 (d, $J=7.5$ Hz, 2H), 7.89~7.73 (m, 4H), 7.58~7.35 (m, 9H), 4.15 (d, $J=15.3$ Hz, 2H); ^{13}C NMR (101 MHz, CDCl_3) δ : 192.83 (d, $J=5.6$ Hz), 136.95, 133.62, 132.18 (d, $J=2.8$ Hz), 131.95 (d, $J=103.4$ Hz), 131.11 (d, $J=9.8$ Hz), 129.24, 128.65 (d, $J=12.3$ Hz), 128.54, 43.25 (d, $J=58.1$ Hz); ^{31}P NMR (162 MHz, CDCl_3) δ : 26.97. HRMS (ESI) calcd for $\text{C}_{20}\text{H}_{18}\text{O}_2\text{P} [\text{M}+\text{H}]^+$ 321.1000; found 321.0999.

Supporting Information The spectroscopic characterization of the products **3a**~**3t**. The Supporting Information is available free of charge via the Internet at <http://sioc-journal.cn>.

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