RSC Advances

ROYAL SOCIETY OF CHEMISTRY

PAPER

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Cite this: *RSC Adv.*, 2020, **10**, 29114

Received 7th July 2020
Accepted 27th July 2020

DOI: 10.1039/d0ra05921h

rsc.li/rsc-advances

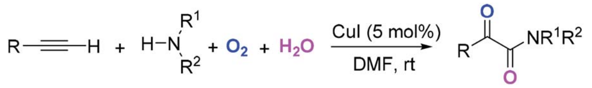
Copper-catalyzed synthesis of α-ketoamides using water and dioxygen as the oxygen source†

Yuanyuan Xiao,[a] Zijuan Yi,[b] Xianyong Yu[b] and Fang Xiao *[a]

The reaction employing H_2O and O_2 as the co-oxygen source in the catalytic synthesis of α-ketoamides is described. This copper-catalyzed reaction is carried out in a tandem manner constituted by the hydroamination of alkyne, hydration of vinyl–Cu complex and subsequent oxidation. Isotope labeling and radical capture experiments reveal that the oxygen atom of α-ketone at α-ketoamides derives from O_2 and the oxygen atom of amide group originates from H_2O.

Introduction

The introduction of oxygen atoms into organic molecules to construct oxygenated compounds is one of the most fundamental subjects in organic chemistry. From a "green and sustainable chemistry" perspective, water and dioxygen are the most environmentally benign and cost-effective oxygen-containing reagents.[1] Consequently, employing them as oxygen sources offers appealing access to oxygen-containing organic compounds.[2,3] Herein, the example of direct utilization of H_2O and O_2 as the co-oxygen source to assemble α-ketoamides is reported. Isotope labeling and radical capture experiments demonstrate that the oxygen atom of α-ketone at α-ketoamide derives from dioxygen and the oxygen atom of amide group originates from water (eqn (1)).



(1)

α-Ketoamides have attracted increasingly synthetic pursuit of chemists, as key structural motifs of many biologically active compounds and versatile building blocks.[4] Various synthetic methods for the preparation of α-ketoamides have been developed over the past decades, such as amidation of α-ketoacids,[5] oxidation of enamines,[6] ynamines,[7] arylacetamides[8] and α-cyanoamides,[9] Pd-catalyzed double carbonylative amination of aryl halides,[10] and the oxidation of acyl cyanophosphoranes followed by amidation of the resulting α,β-diketone nitriles.[11] Most of these well established approaches toward α-ketoamides often require toxic, expensive or preformed oxygen sources, such as SeO_2, $K_2Cr_2O_7$, CO, TBHP, and O_3. Thus, the development of direct incorporation oxygen atoms from clean and cheap oxygen sources into organic frameworks to construct α-ketoamides is highly desirable.[12] In 2010, Zhu reported the transformation of aldehydes with isocyanides to α-ketoamides using water as the oxygen source.[13] Recently, various metal-catalyzed or metal-free methods for the oxidative synthesis of α-ketoamides from terminal alkynes,[14] aryl acetaldehydes,[15] ketones,[16] 1-arylethanols,[17] phenethyl alcohol derivatives,[18] and ethylarenes[19] have also been developed by using dioxygen as oxygen source. In 2019, Wei and co-workers reported the transformation of α-ketoacids with isocyanides to α-ketoamides using water as the oxygen source.[20]

Multicomponent reaction has emerged as a powerful protocol to construct complex organic compounds.[21] The present multicomponent reaction of copper-catalyzed direct oxidative transformation of alkynes and secondary amines to α-ketoamides is realized at room temperature without any ligand or additive, in which H_2O and O_2 were employed as the co-oxygen source (eqn (1)). Preliminary mechanistic studies suggest that this multicomponent reaction is performed in a tandem manner constituted by the hydroamination of alkyne, hydration of vinyl–Cu complex and subsequent oxidation with dioxygen. This methodology not only provides an interesting and attractive approach to α-ketoamides, but also allows an avenue to simultaneously introduce oxygen atoms from H_2O and O_2 into organic frameworks to access multi-oxygen containing compounds.

Results and discussion

During the course of investigation on transition-metal-catalyzed oxidative transformation of alkynes and secondary amines to α-ketoamides, we found CuBr can catalyze the reaction of phenylacetylene **1a** with piperidine **2a** to give the product **3aa** in presence of H_2O (2 equiv.) under O_2 without ligand or additive (Table 1, entry 1). Preliminary exploration showed that no **3aa** was detected when the reaction was performed in the absence of

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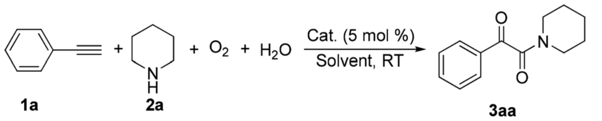
† Electronic supplementary information (ESI) available. See DOI: 10.1039/d0ra05921h

Table 1 Optimization of reaction conditions[a]



Entry	Catalyst (mol%)	Solvent	**3aa**[b] (%)
1	CuBr	THF	21
2	CuBr	THF	0[c]
3	CuBr	THF	0[d]
4	$CuBr_2$	THF	18
5	$CuCl_2$	THF	15
6	CuCl	THF	14
7	$Cu(OTf)_2$	THF	16
8	$(CH_3CN)_4CuPF_6$	THF	21
9	CuI	THF	43
10	AgOTf	THF	0
11	$RhCl_3$,	THF	0
12	$InCl_3$,	THF	0
13	AlF_3	THF	0
14	$AuBr_3$	THF	Trace
15	—	THF	0
16	CuI	1,4-Dioxane	25
17	CuI	MeOH	0
18	CuI	EtOH	0
19	CuI	DME	45
20	CuI	DCE	32
21	CuI	Toluene	23
22	CuI	DMSO	34
23	CuI	DMF	71
24	CuI	DMF	46[e]

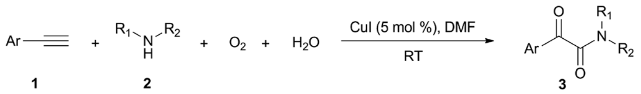
[a] Reaction conditions: **1a** (2 mmol), **2a** (0.5 mmol), catalyst (5 mol%), H_2O (2 equiv.), O_2 (balloon), solvent (0.5 mL), at room temperature, 12 h. [b] Isolated yields based on **2a**. [c] Under N_2. [d] Dry THF was used and 4 Å molecular sieve was added. [e] Under air.

O_2 or H_2O (Table 1, entries 2 and 3). These results suggested that H_2O might be served as the oxygen source of **3aa** and O_2 as the oxidant or both of them were used as the co-oxygen source. This interesting phenomenon prompted us to optimize the reaction conditions and disclose the accurate origination of the oxygen atoms of α-ketoamides.

Initially, the reaction of phenylacetylene **1a** with piperidine **2a** was performed to examine the catalytic activity of various transition metal complexes including Au, Ag, Cu, Rh, Ni, Pd, Al, Bi, and In salts in the presence of H_2O (2 equiv.) under the oxygen atmosphere. As shown in Table 1, among those metal catalysts examined (entries 4–14), CuI was found to be the best catalyst to catalyze the formation of α-ketoamide **3aa**. No conversion was observed in the absence of catalyst (entry 15). The screening of solvents indicated that DMF was the optimal reaction medium (entries 16–23). This reaction could also proceed smoothly under the air atmosphere (entry 24).

With the optimized conditions in hand, the scope of this new reaction was investigated (Table 2). Generally, the reaction tolerated electron-donating (*para*-, *meta*-, and *ortho*-substituted) and electron-withdrawing groups at the aromatic ring of alkynes (Table 2, entries 1–5). It was found that the reaction

Table 2 Copper-catalyzed synthesis of α-ketoamides[a]



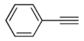
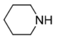
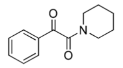
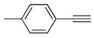
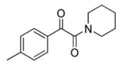
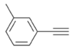
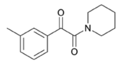
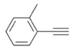
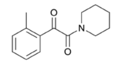
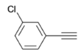
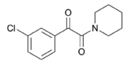
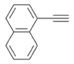
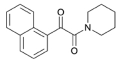
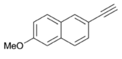
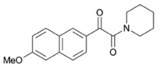
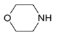
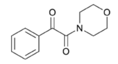
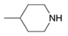
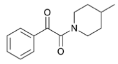
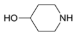
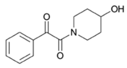
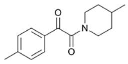
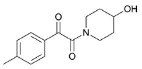
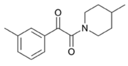
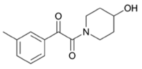
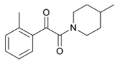
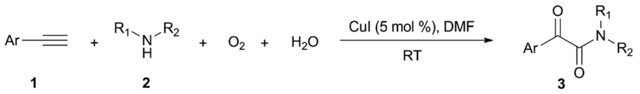
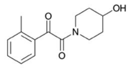
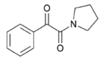
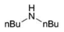
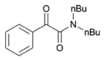
Entry	Alkyne (**1**)	Amine (**2**)	Product (**3**)	Yield[b] (%)
1	 **1a**	 **2a**	 **3aa**	71
2	 **1b**	**2a**	 **3ba**	72
3	 **1c**	**2a**	 **3ca**	61
4	 **1d**	**2a**	 **3da**	60
5	 **1e**	**2a**	 **3ea**	56
6	 **1f**	**2a**	 **3fa**	64
7	 **1g**	**2a**	 **3ga**	57
8	**1a**	 **2b**	 **3ab**	65
9	**1a**	 **2c**	 **3ac**	56
10	**1a**	 **2d**	 **3ad**	64
11	**1b**	**2c**	 **3bc**	65
12	**1b**	**2d**	 **3bd**	62
13	**1c**	**2c**	 **3cc**	63
14	**1c**	**2d**	 **3cd**	60
15	**1d**	**2c**	 **3dc**	61

Table 2 *(Contd.)*



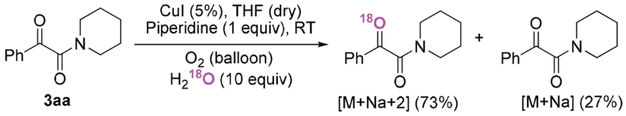
Entry	Alkyne (**1**)	Amine (**2**)	Product (**3**)	Yield^b (%)
16	**1d**	**2d**	 **3dd**	60
17	**1a**	 **2e**	 **3ae**	52
18	**1a**	 **2f**	 **3af**	63

^{a} Reaction conditions: **1** (2 mmol), **2** (0.5 mmol), CuI (5 mol%), H_2O (2 equiv.), O_2 (balloon), DMF (0.5 mL), rt, 12–48 h. ^{b} Isolated yields.

efficiency was affected by the steric effect. The more sterically demanding substrates such as *ortho*-methyl or chloro substituted arylalkynes demonstrated slightly lower activities (Table 2, entries 1–5). The present method can also apply to alkynes connected with naphthalene rings (Table 2, entries 6 and 7). The scope of amines was also examined, and both cyclic amines and linear amines were suitable substrates for this process. Cyclic amines such as piperidine, morpholine, 4-substituted piperidines, and pyrrolidine reacted with phenylacetylene or substituted phenylacetylenes to generate the corresponding products in moderate to good yields (Table 2, entries 1 and 8–17). The reaction of di-*n*-butylamine with **1a** afforded α-ketoamide in moderate yield (Table 2, entry 18).

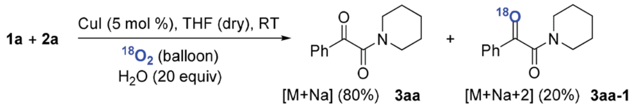
Isotope labeling and radical capture experiments were performed to elucidate the origination of the oxygen atoms of α-ketoamide. Results of these experiments demonstrate the oxygen atom of amide group originates from H_2O and the oxygen atom of α-ketone at α-ketoamide derives from dioxygen.

Firstly, the α-ketone group at α-ketoamide is more electrophilic than a ketone due to the electron-withdrawing effect of the amide group, thus it is possible for oxygen atom exchange with water *via* a hemiketal intermediate, while the amide group of α-ketoamide is stable. Indeed, as illustrated in eqn (2), when **3aa** was stirred with CuI, piperidine, and $H_2^{18}O$ (10 equiv.) under oxygen atmosphere in THF,[22] 73% singly ^{18}O-labeled, 27% unlabeled product were obtained and no doubly ^{18}O-labeled α-ketoamide was detected (see HRMS in ESI†).

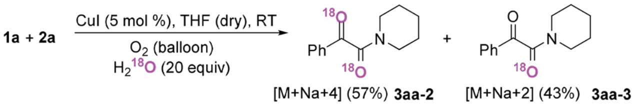


(2)

Subsequently, when the reaction of **1a** and **2a** was conducted in the presence of H_2O (20 equiv.) under $^{18}O_2$, 80% unlabeled (**3aa**, eqn (3)) and 20% singly ^{18}O-labeled product (**3aa-1**, eqn (3)) were detected (see HRMS in ESI†). If the oxygen atom of amide group originates from $^{18}O_2$, unlabeled product would not be observed *via* oxygen exchange with H_2O. The existence of 80% unlabeled product (**3aa**, eqn (3)) demonstrated that the oxygen atom of amide group originated from H_2O. Further control experiment showed that 57% doubly ^{18}O-labeled (**3aa-2**, eqn (4)) and 43% singly ^{18}O-labeled product (**3aa-3**, eqn (4)) were detected when the reaction of **1a** and **2a** was performed in the presence of $H_2^{18}O$ (20 equiv.) under O_2 (see HRMS in ESI†). This result also revealed the oxygen atom of amide group derived from H_2O (eqn (4)).

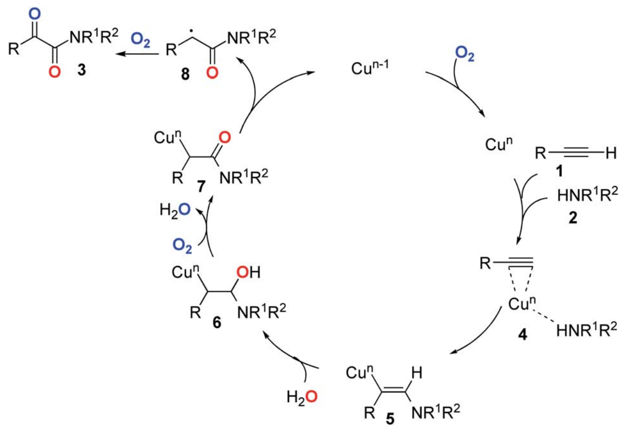


(3)



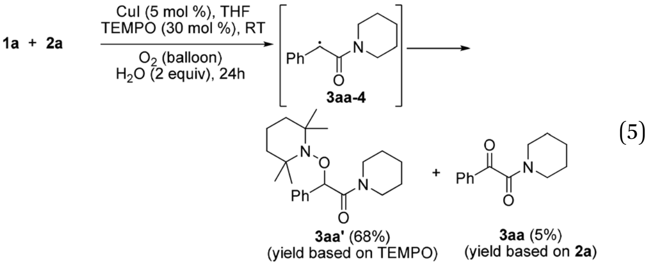
(4)

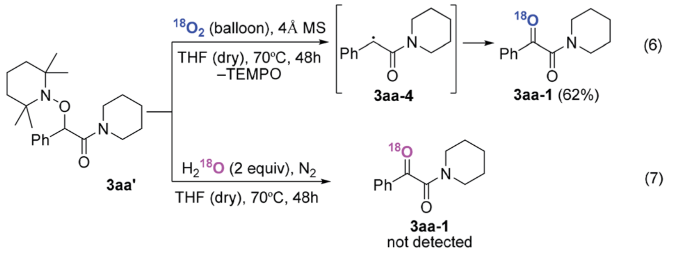
Radical capture experiments revealed that the oxygen atom of α-ketone at α-ketoamides derived from O_2, which also indicated the possible mechanism of this transformation. As shown in eqn (5), TEMPO, a well known radical-capturing species, can remarkably suppress the formation of α-ketoamide **3aa**.[23] When TEMPO (30 mol%) was added to the reaction system of **1a** and **2a**, 69% TEMPO-trapped compound **3aa′** (isolated yield based on TEMPO) was obtained and only 4% of **3aa** (isolated yield based on **2a**) was detected. Furthermore, owing to the thermal instability of the covalent bond between TEMPO and the carbon free radical intermediate **3aa-4** that was easily oxidized by dioxygen to form carbonyl compounds,[24,25] the transformation



Scheme 1 Plausible reaction pathway.

of **3aa′** to singly ^{18}O-labeled α-ketoamide and TEMPO was observed in the presence of $^{18}O_2$ at 70 °C (**3aa-1**, eqn (6)). Meanwhile, no conversion of **3aa′** to **3aa-1** was detected in the presence of $H_2{}^{18}O$ under N_2 (eqn (7)). These results suggested that the carbonyl oxygen atom of α-ketone at α-ketoamide **3aa** derived from molecular oxygen *via* a radical oxidation process.





Based on the above experiments and previous reports,[26–28] we proposed a postulated reaction pathway for this transformation as outlined in Scheme 1. Firstly, the complex **4** was formed by the reaction of the Cu species with alkyne **1** and amine **2**. Then, the migration of amine to the triple bond led to the formation of the vinyl–Cu intermediate **5**. Next, **5** underwent hydration to give **6**. Subsequently, **7** was formed through the oxidation of **6** with dioxygen. Finally, the reductive elimination of the copper species of **7**[27] followed by double oxidation with dioxygen would deliver the desired product **3**.[2,28]

Conclusions

In summary, we have successfully developed a tandem copper catalyzed approach to α-ketoamides from terminal alkynes, secondary amines, dioxygen, and water at room temperature without ligand or additive, in which O_2 and H_2O were used as the co-oxygen source of α-ketoamides. The present method opens a new window to construct complicated oxygen-containing compounds. Further studies of the detailed mechanism of this process and its application are underway in our laboratory.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the Scientific Research Fund of Hunan Provincial Education Department (18A192).

Notes and references

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