



Cite this: *Chem. Commun.*, 2020, 56, 8355

# CO<sub>2</sub> = CO + [O]: recent advances in carbonylation of C–H bonds with CO<sub>2</sub>

Lei Song,<sup>a</sup> Yuan-Xu Jiang,<sup>a</sup> Zhen Zhang,<sup>\*ab</sup> Yong-Yuan Gui,<sup>ac</sup> Xiao-Yu Zhou<sup>a</sup> and Da-Gang Yu<sup>id</sup> <sup>\*a</sup>

Carbon dioxide (CO<sub>2</sub>) is an ideal one-carbon source owing to its nontoxicity, abundance, availability, and recyclability. Although the thermodynamic stability and kinetic inertness of CO<sub>2</sub> bring its utilization challenges, many groups have achieved significant progress in the utilization of CO<sub>2</sub> to synthesize valuable carbonyl-containing compounds, which could be also generated *via* oxidative carbonylation of C–H bonds with CO. As CO<sub>2</sub> has a higher oxidation state than CO, it could be considered as a combination of CO and oxidant (CO<sub>2</sub> = CO + [O]), thus providing a safe, redox-neutral and economic strategy. In this Feature Article, we have summarized the recent advances in carbonylation of C–H bonds with CO<sub>2</sub> based on this concept. The plausible mechanisms of such reactions and future of this field are also discussed.

Received 20th January 2020,  
Accepted 12th March 2020

DOI: 10.1039/d0cc00547a

rsc.li/chemcomm

## 1. Introduction

CO<sub>2</sub> has been regarded as a promising C1 source for a long time as it is a nontoxic, abundant and recyclable building block providing various benefits in organic synthesis.<sup>1</sup> Although the utilization of CO<sub>2</sub> is restricted due to its thermodynamic stability and kinetic inertness, significant effort has been exerted toward the conversion of CO<sub>2</sub> into value-added chemicals.<sup>2</sup> Many kinds of organic transformations of CO<sub>2</sub> have been developed in the last

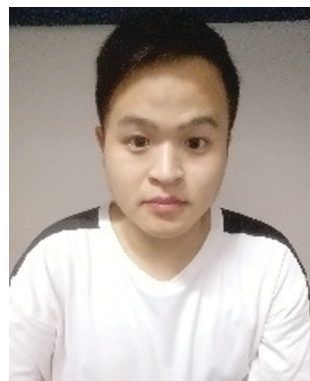
few decades to generate a variety of valuable organic molecules, including important carbonyl-containing compounds.

As it is well known, carbonylation reaction is an important and useful method to synthesize carbonyl-containing compounds, which are widely found in natural products and pharmaceutical molecules.<sup>3</sup> Traditionally, phosgene is the main carbonylation reagent due to its high reactivity.<sup>4</sup> With the development of transition metal catalysis, the feedstock gas carbon monoxide (CO) has been extensively used as a replacement of phosgene in organic synthesis. Notably, the transition-metal-mediated and/or catalyzed oxidative carbonylation with CO *via* direct C–H bond functionalization<sup>5</sup> attracts more and more attention owing to the high efficiency and economy (Scheme 1A).<sup>6</sup> However, both highly toxic CO and stoichiometric oxidants, such as high-valence metal salts or O<sub>2</sub>, are indispensable in such carbonylation reactions, which causes

<sup>a</sup> Key Laboratory of Green Chemistry & Technology of Ministry of Education, College of Chemistry, Sichuan University, Chengdu 610064, P. R. China. E-mail: dgyu@scu.edu.cn

<sup>b</sup> College of Pharmacy and Biological Engineering, Chengdu University, Chengdu 610106, P. R. China. E-mail: zhangzhen1@cdu.edu.cn

<sup>c</sup> College of Chemistry and Materials Science, Sichuan Normal University, Chengdu 610068, P. R. China



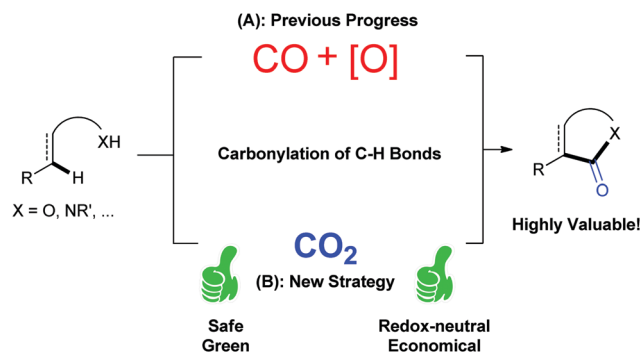
Lei Song

Lei Song was born in Hunan, China, in 1993. He received his MS degree in chemistry from Sichuan University in 2018 and has been a PhD student under the supervision of Prof. Da-Gang Yu. His current research focuses on the carboxylation/carbonylation of C–H bonds with CO<sub>2</sub>.



Yuan-Xu Jiang

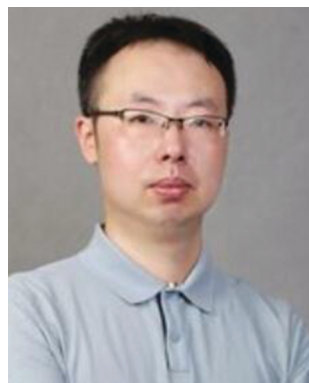
Yuan-Xu Jiang was born in Sichuan Province, China, in 1996. He received his BS degree in applied chemistry from Huaqiao University in 2018. He is currently pursuing his MS degree at Sichuan University under the guidance of Prof. Da-Gang Yu. His research projects focus on the activation and utilization of CO<sub>2</sub>.



Scheme 1  $\text{CO}_2 = \text{CO} + [\text{O}]$ : new strategy of carbonylation of C-H bonds with  $\text{CO}_2$ .

environmental impact, safety issues and high cost. Therefore, it is highly desirable to develop a novel carbonylation strategy

avoiding the use of oxidants and toxic CO. Because the carbon in  $\text{CO}_2$  shows a higher oxidation state than that in CO,  $\text{CO}_2$  might act similarly to the combination of CO and oxidant, that is,  $\text{CO}_2 = \text{CO} + [\text{O}]$  (Scheme 1B).<sup>2f</sup> Following this concept, if we use  $\text{CO}_2$  as the carbonylation source in carbonylation of C-H bonds, we could realize such transformations under redox-neutral conditions, and ideally, with “ $\text{H}_2\text{O}$ ” (or carbonate in the presence of base) as the only byproduct, thus solving the problems remaining in the oxidative carbonylation reaction of C-H bonds with CO. Although it looks simple and fantastic, there are huge challenges to formally cleave the strong C=O bond, which is highly energy-demanding. In this Feature Article, we have summarized very recent advances in carbonylation of C-H bonds with  $\text{CO}_2$ , such as lactamization and lactonization, based on this concept. The plausible mechanisms of such reactions and future of this field are discussed. Another important strategy, *in situ* reduction of  $\text{CO}_2$  to CO and the following carbonylation



Zhen Zhang

2017 and then joined Chengdu University as associate professor. His research projects focus on green chemistry and biochemistry.

Prof. Dr Zhen Zhang was born in Shanxi Province, China, in 1985. He received his bachelor's degree in 2007 from Sichuan University. In 2012, he joined Prof. Yong-Gang Zhi's group to pursue master and doctoral studies at Chengdu Institute of Organic Chemistry, Chinese Academy of Sciences. From 2015, as a visiting PhD student, he joined Prof. Da-Gang Yu's laboratory at Sichuan University. He received his PhD in organic chemistry in



Yong-Yuan Gui

Science, Sichuan Normal University. His research interests include photocatalysis, asymmetric catalysis and other sustainable chemistry.

Dr Yong-Yuan Gui was born in Henan, China, in 1987. He received his PhD degree in chemistry from Chengdu Institute of Organic Chemistry, Chinese Academy of Sciences, in 2015 (with Prof. Li-Xin Wang). He then joined the laboratory of Prof. Da-Gang Yu at Sichuan University as a postdoctoral fellow, focusing on photoredox/nickel dual catalysis and asymmetric catalysis with  $\text{CO}_2$ . In 2019, he joined the faculty of the College of Chemistry and Materials



Xiao-Yu Zhou

Xiao-Yu Zhou was born in Chongqing, China, in 1996. She received her BS degree in applied chemistry from Northwest A&F University in 2018. She is currently pursuing her MS degree at Sichuan University under the guidance of Prof. Da-Gang Yu. Her research projects focus on the activation and utilization of  $\text{CO}_2$ .



Da-Gang Yu

Young Scholars. His research interests mainly focus on novel transformations of  $\text{CO}_2$ , radical chemistry and novel transition metal-catalysis. He received the Thieme Chemistry Journal Award in 2017 and the Chinese Chemical Society Youth Award in 2018.

Prof. Dr Da-Gang Yu was born in Jiangxi province, China, in 1986. He received his PhD with Prof. Dr Zhang-Jie Shi from Peking University in 2012. Then he carried out postdoctoral research with Humboldt fellowship in the group of Prof. Dr Frank Glorius, Muenster University. Since 2015, he has been working independently in Sichuan University with support from “The Thousand Young Talents Plan” and National Natural Science Foundation of China-Outstanding

with CO<sub>2</sub><sup>6j,k</sup> is different from the concept here and will be only briefly mentioned.

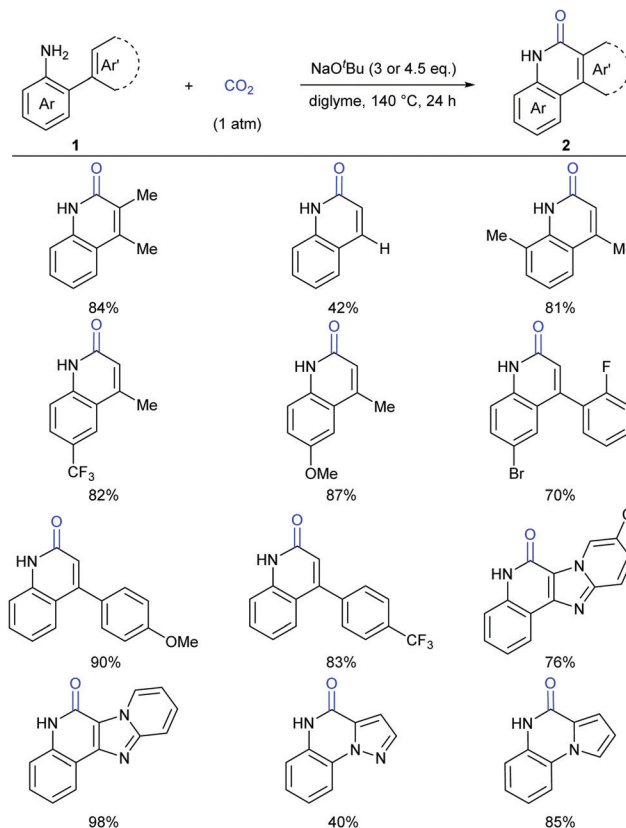
## 2. Lactamization of C–H bonds with CO<sub>2</sub>

Lactam-containing heterocyclic compounds are common motifs in drugs and bioactive natural products, as well as important intermediates in organic synthesis (Scheme 2).<sup>7</sup> Recently, many groups, such as Alper, Zhu, Chuang, and Zhang groups, have developed nice and efficient methodologies to synthesize these compounds through transition-metal-catalyzed oxidative carbonylation of C–H bonds with CO.<sup>8</sup> However, the requirement of (sub)stoichiometric metal oxidants (Ag<sup>+</sup> or Cu<sup>2+</sup> salts) represents a major limitation associated with the methods described above.

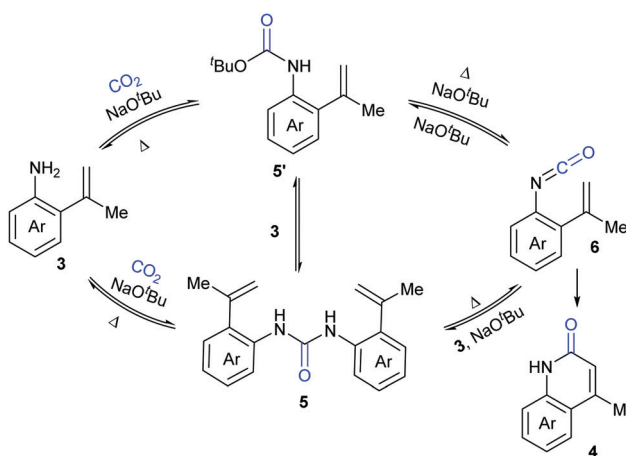
Different from previous strategies, our group reported the direct lactamization of C(sp<sup>2</sup>)–H bonds in *o*-alkenyl- or *o*-heteroaryl-anilines with CO<sub>2</sub> in the presence of base (Scheme 3).<sup>9</sup> In these reactions, CO<sub>2</sub> serves as a carbonylation reagent to avoid the use of external chemical oxidants and toxic CO. These transition metal-free and redox-neutral reactions are simple to operate and user-friendly. By heating *o*-alkenyl- and *o*-heteroaryl-anilines with NaO<sup>t</sup>Bu in diglyme under 1 atm of CO<sub>2</sub> at 140 °C for 24 hours, a series of important quinolinones and polyheterocyclic compounds were delivered in high efficiency, making it an attractive method for the pharmaceutical industry. We further showed the potential applications of this transformation toward some valuable intermediates and biologically active compounds, including an HBV inhibitor and a key intermediate to Tipifarnib.

A series of control experiments were conducted to probe the mechanism of this process. First, NaO<sup>t</sup>Bu-mediated nucleophilic attack of aniline **3** on CO<sub>2</sub> under the reaction conditions would generate intermediates **5** and **5'**, which could undergo elimination to give the key intermediate isocyanates **6**. The following cyclization reaction would efficiently afford the stable products **4** and/or the corresponding deprotonated versions, which might also be a driving force for this transformation (Scheme 4).

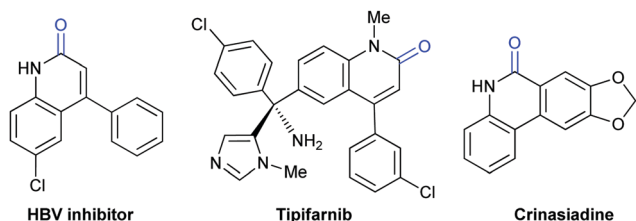
This process was further demonstrated by the Li group.<sup>10</sup> Based on the DFT calculation, they speculated that the reaction went through three stages: (i) C–N bond construction to generate the intermediate carbamate species; (ii) deoxygenation of carbamate species to generate isocyanate species **6**; (iii) intramolecular cyclization and H migration to yield the final product **4**. The deoxygenation of the carbamate species in stage (ii) was the rate-determining step for the entire reaction and the base was



Scheme 3 Transition metal-free carbonylation of C(sp<sup>2</sup>)–H bonds in *o*-alkenyl- and *o*-heteroaryl-anilines with CO<sub>2</sub> in the presence of NaO<sup>t</sup>Bu.



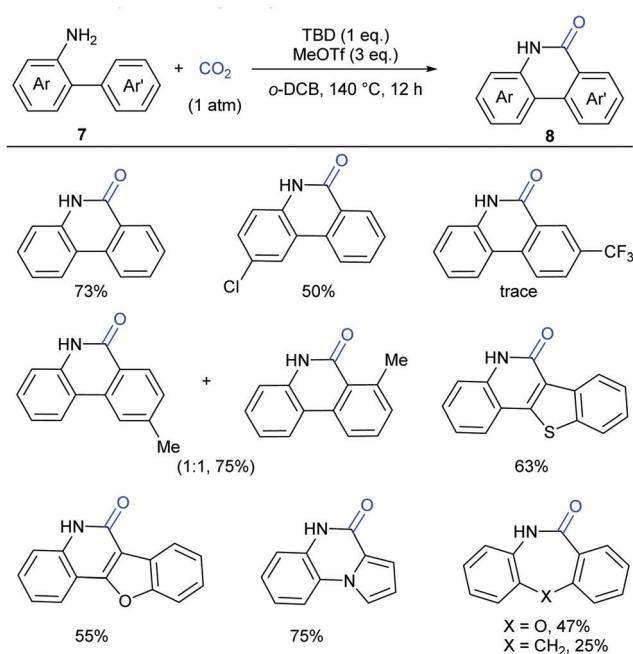
Scheme 4 Possible mechanism for the lactamization reaction.



Scheme 2 Selected biologically active lactam-containing moieties.

very important in overcoming the energetic bottleneck in stages (i) and (iii).

Although our system worked well for those anilines bearing electron-rich alkene or heteroarenes at the *ortho* position, it was not suitable for the unactivated *o*-phenylaniline derivatives, which might arise from the low electron density and nucleophilicity of the *o*-phenyl motif to attack the *in situ* generated isocyanate intermediate. Soon after the publication of our work,<sup>9</sup>

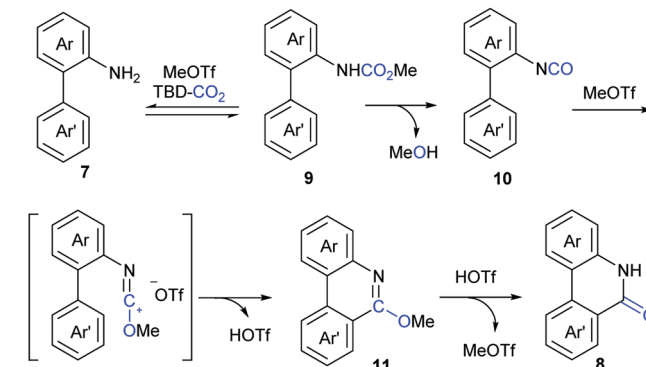


**Scheme 5** Transition metal-free carbonylation of C(sp<sup>2</sup>)-H bonds in *o*-(hetero)arylanilines with CO<sub>2</sub> in the presence of TBD and MeOTf. *o*-DCB = 1,2-dichlorobenzene.

Xi's group independently reported the carbonylation of (hetero)aryl C(sp<sup>2</sup>)-H of *o*-arylanilines with CO<sub>2</sub> by utilizing the combination of methyl triflate (MeOTf) and 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD) (Scheme 5).<sup>11</sup> Under such conditions, unactivated *o*-phenylaniline derivatives worked nicely. Importantly, high temperature and primary amines were also required for the success of this reaction. The reaction went well with electron-rich aromatic substrates to afford the desired products in high yields. In contrast, the electron-poor ones, such as a CF<sub>3</sub>-substituted *o*-phenylaniline, only gave a trace amount of the desired products. When a *meta*-substituted substrate was applied, the regioselectivity of this transformation was difficult to control, providing a mixture of two isomers in 1:1 ratio. Notably, besides phenanthridinones, seven-membered lactams could also be obtained using this method, representing a significant advance in lactamization.

In lactamization by Xi's group, they isolated the methyl carbamate **9** and also observed the formation of isocyanate **10** in the reaction system. As shown in Scheme 6, with the aid of MeOTf, the substrate reacted with the adduct of TBD and CO<sub>2</sub> to afford methyl carbamate **9**, which underwent subsequent elimination of one molecule of MeOH at high temperature and converted to aryl isocyanate **10**. Then, methylation of **10** with MeOTf afforded a highly active species, such as the carbenium ion, which was attacked by the *o*-phenyl motif to generate 6-methoxyphenanthridine **11**. Finally, the desired product **8** was obtained *via* acidification.

In the above-mentioned two cases, the lactamization of C-H bonds with CO<sub>2</sub> requires the prepared *o*-alkenyl- or *o*-(hetero)-aryl-anilines as substrates. It has also been interesting whether the lactamization reaction could be realized in cascade reactions through generating such substrates *in situ* from simple

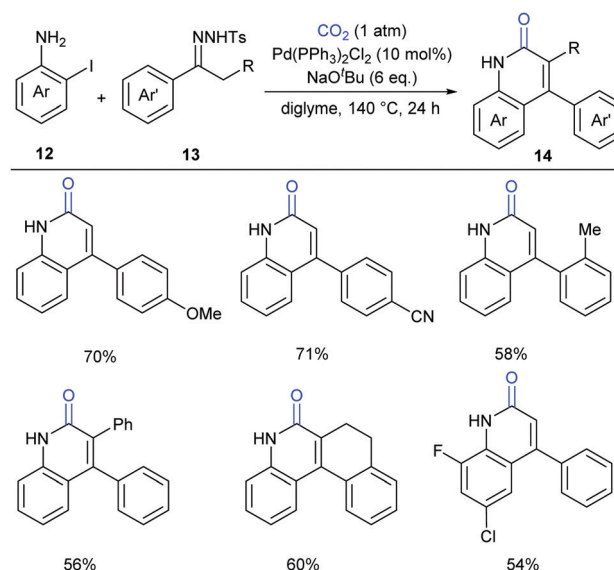


**Scheme 6** Proposed mechanism by Xi's group.

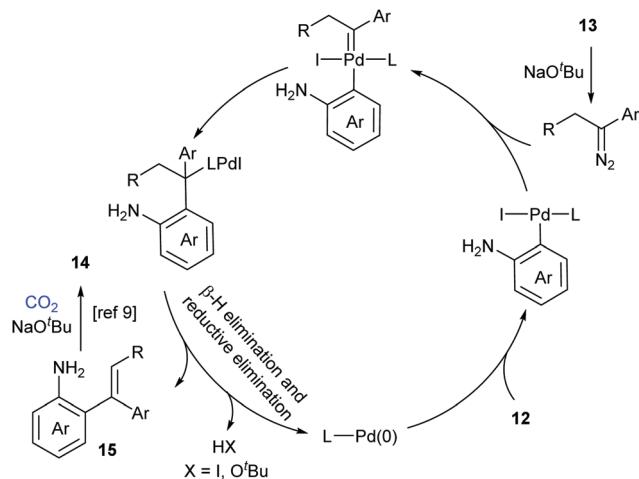
raw materials. Later in 2016, Cheng's group successfully developed a palladium-catalyzed three-component reaction with *N*-tosylhydrazones, 2-iodoanilines and atmospheric CO<sub>2</sub> to generate a series of 4-aryl-2-quinolinones (Scheme 7).<sup>12</sup> The procedure allowed the formation of four bonds in one pot synthesis, representing an efficient methodology for incorporation of CO<sub>2</sub> into heterocycles.

A possible reaction mechanism to explain the tandem carbene migratory insertion/lactamization pathway is shown in Scheme 8. The reaction might start with palladium-catalyzed coupling of aryl halides **12** and *N*-tosylhydrazones **13** to generate a vital intermediate, *o*-vinyl aniline **15**, which further undergoes a similar pathway with CO<sub>2</sub> as in our work to deliver the desired product **14**.<sup>9</sup> Meanwhile, the pathway generating *o*-iodoisocyanatobenzene prior to *o*-vinyl aniline **15** formation could not be excluded.

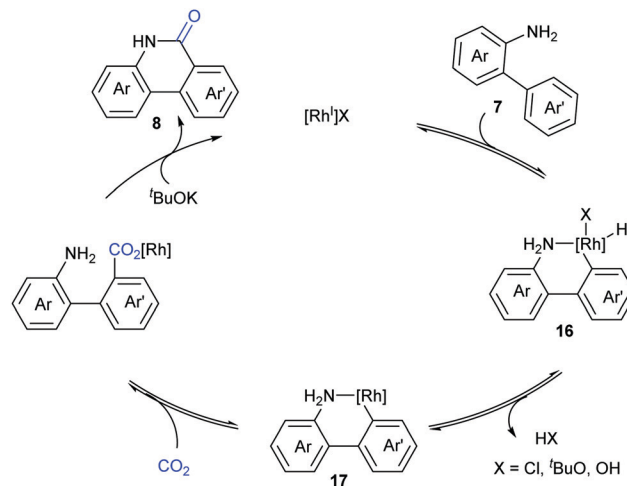
Although such transition-metal-free lactamization protocols are powerful and efficient, there are still limitations in electron-poor aryl substrates. Recently the Li group have reported a novel Rh(I)-catalyzed, amino-group-directed lactamization of aryl C(sp<sup>2</sup>)-H bonds in *o*-(hetero)arylanilines with CO<sub>2</sub> in the presence of KO<sup>t</sup>Bu (Scheme 9).<sup>13</sup> Based on the previous reports on Rh(I)-catalyzed C-H



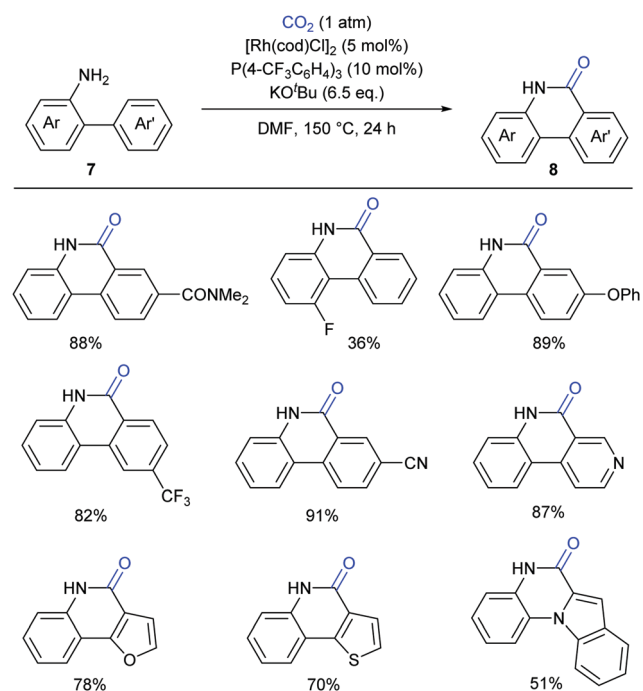
**Scheme 7** Cascade lactamization by Cheng's group.



Scheme 8 The proposed mechanism by Chen's group.



Scheme 10 The catalytic cycle of Rh(I)-catalyzed lactamization.

Scheme 9 Rh-Catalyzed C-H lactamization of *o*-arylanilines with  $\text{CO}_2$ .

activation<sup>5</sup> and facile insertion of  $\text{CO}_2$  into the rhodium-carbon bond,<sup>14</sup> the authors successfully realized such a Rh(I)-catalyzed carbonylation with generation of various functionalized phenanthridinones under redox-neutral conditions. Both electron-rich and electron-poor substrates showed good reactivity for this transformation, which showed a significant improvement compared to previous works.<sup>9,11</sup> Besides *o*-arylanilines, this reaction could be also extended to *o*-heteroarylanilines, such as pyridyl-, furanyl- and indolyl-substituted anilines, giving products with potential biological activity.

Based on the control experiments, a possible mechanism involving reversible oxidative addition of the aryl C-H bond to a Rh(I) species **16**, reductive elimination of HX, and reversible

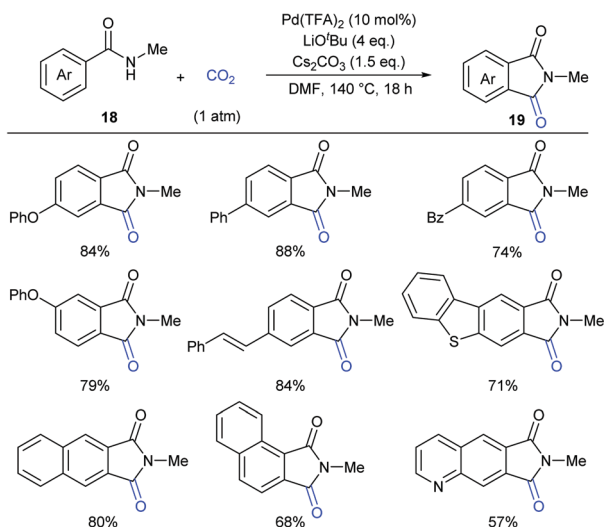
nucleophilic carboxylation with  $\text{CO}_2$ , followed by irreversible lactamization, was proposed by Li and co-workers (Scheme 10).

In addition to the construction of six-membered lactam-containing heterocyclic compounds, the core of five-membered phthalimides also attracts much attention.<sup>15</sup> Recently, this skeleton has usually been constructed through transition-metal-catalyzed carbonylation of C-H bonds with CO in the presence of oxidants or hydrogen acceptors.<sup>16</sup> In 2018, our group reported the first example of palladium-catalyzed carbonylation of unactivated aryl C-H bonds in benzamides with  $\text{CO}_2$  to afford phthalimides under redox-neutral conditions (Scheme 11a).<sup>17a</sup> Due to the influence of steric hindrance and directing ability, the substituents on the nitrogen of the benzamides were crucial, only the methyl group featuring good reactivity. Both electron-donating groups and electron-withdrawing groups could be well tolerated in the standard conditions. It is worth mentioning that carbonylation of the C-H bond selectively occurred at the less hindered *ortho* position for the substrates with *meta* substituents.

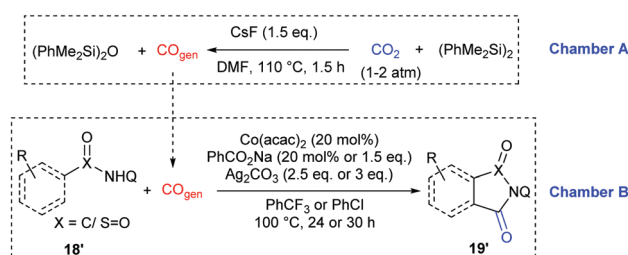
Some control experiments were further conducted to shed light on the mechanism of the transformation (Scheme 12). We first excluded the possibility of the *in situ* generation of CO as the active carbonylation reagent and confirmed that the carbonyl group comes from  $\text{CO}_2$  via  $^{13}\text{C}$ -labeling experiments. The kinetic isotope effect (KIE) value indicated that the C-H activation step might be involved in the rate-determining step. We also postulated that the palladacycle species **20** might act as a vital intermediate in the reaction, as it was detected by ESI-HRMS when nitrogen ligands were employed to increase its stability. Notably, it also showed reactivity in both stoichiometric and catalytic version of such carbonylation.

Later, another strategy, *in situ* reduction of  $\text{CO}_2$  to CO and the following carbonylation with CO, was also used to construct phthalimide skeletons by Sundararaju's group.<sup>17b</sup> A tandem reaction was realized in a two-chamber reactor for efficient fluoride-mediated generation of CO from  $\text{CO}_2$  using disilane as a deoxygenating reagent and utilization of the *in situ*-produced CO for C-H carbonylation using cobalt catalysis (Scheme 11b). In addition to the  $\text{C}(\text{sp}^2)\text{-H}$  bond, the  $\text{C}(\text{sp}^3)\text{-H}$  bond was also compatible in the system.

## a) Pd-catalyzed carbonylation



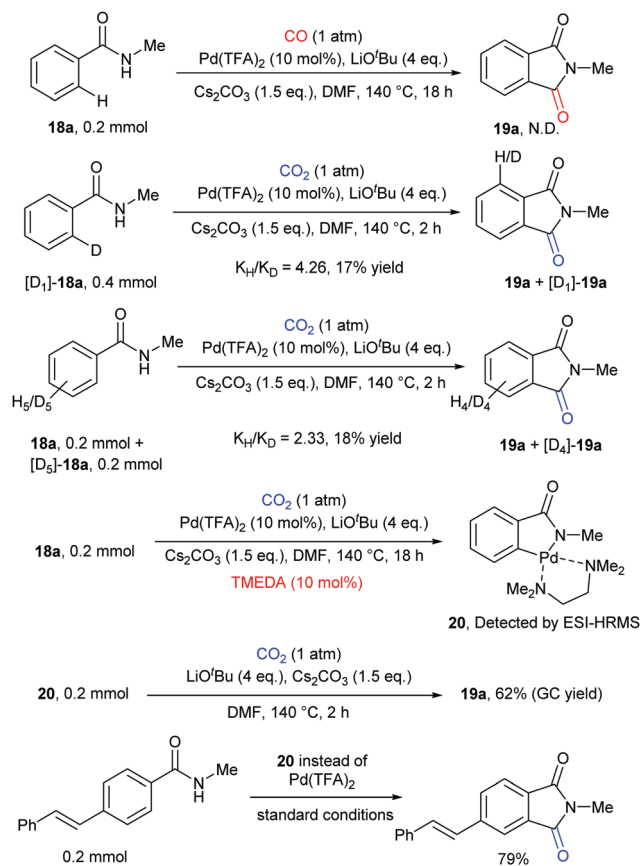
## b) Co-catalyzed carbonylation

Scheme 11 Transition-metal-catalyzed carbonylation of benzamides with  $\text{CO}_2$ .

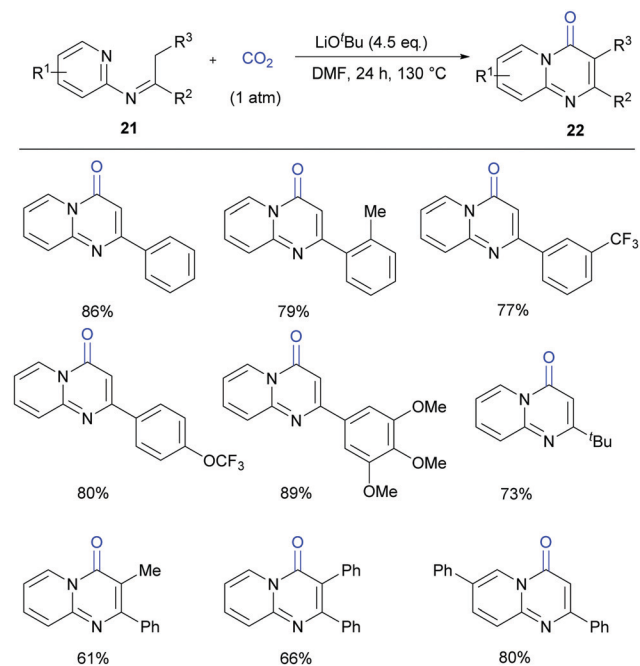
Compared to most of the research in this field which focused on the lactamization of  $\text{C}(\text{sp}^2)\text{-H}$  bonds, lactamization of  $\text{C}(\text{sp}^3)\text{-H}$  bonds with  $\text{CO}_2$  is more challenging. Very recently, our group reported the lactamization of  $\text{C}(\text{sp}^3)\text{-H}$  bonds in pyridylamines with one atmosphere of  $\text{CO}_2$  to synthesize important pyrimidinones (Scheme 13).<sup>18a</sup> Different from the previous report on Pd-catalyzed lactamization of ketoimines with CO and oxidant,<sup>18b</sup> these reactions take place under transition-metal-free and redox-neutral conditions with atmospheric  $\text{CO}_2$  as the carbonyl source. The reactions can be performed on a gram scale, and the product can undergo derivatization easily. Moreover, some bio-active compounds can be quickly prepared by this method.

In the mechanistic studies, we found that **22a** was generated in very low yield at  $80^\circ\text{C}$  and the carboxylative product could be detected obviously by ESI-MS. When the reaction was quenched by  $\text{CH}_3\text{I}$ , we detected the corresponding methyl ester by ESI-MS and the product **22a** in a higher yield, all of which indicated that both the carboxylate intermediate and the ester were important in cyclization reaction to generate the desired product (Scheme 14).

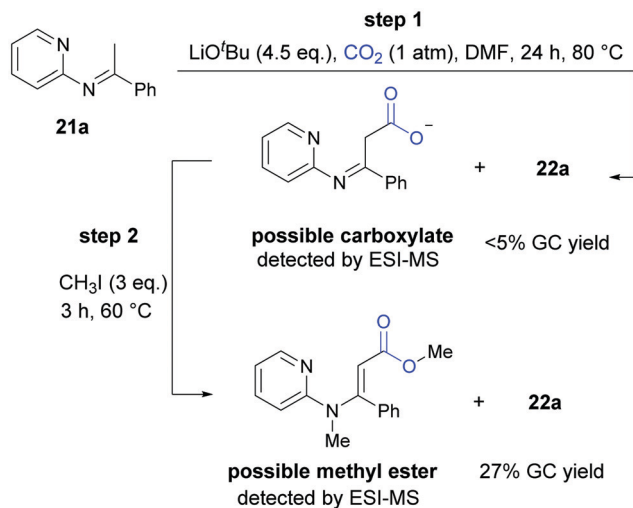
Based on the mechanistic studies and previous reports,<sup>19</sup> a possible pathway was proposed (Scheme 15). **21a-1** was formed in the presence of  $\text{LiO}^t\text{Bu}$  and further reacted with  $\text{CO}_2$  to generate carboxylate intermediates **21a-2** and **21a-3**. Then **21a-3** might react with  $\text{LiO}^t\text{Bu}$  to generate **21a-4**, which transformed



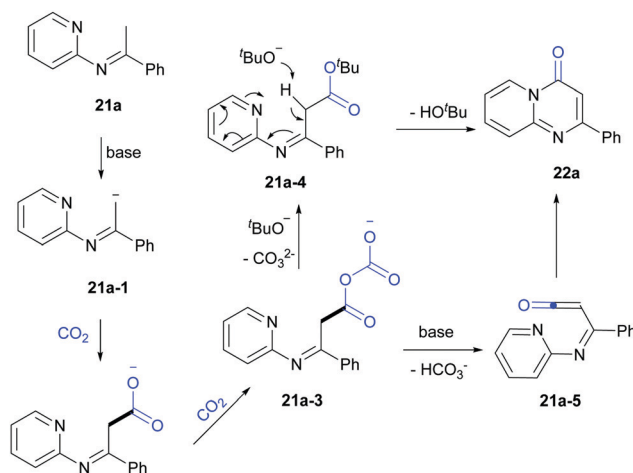
Scheme 12 Selected mechanistic studies for Pd-catalyzed carbonylation.

Scheme 13 Transition metal-free carbonylation of  $\text{C}(\text{sp}^3)\text{-H}$  bonds in pyridylamines with  $\text{CO}_2$  in the presence of  $\text{LiO}^t\text{Bu}$ .

to **22a** in the presence of base. In addition, another pathway through **21a-5** might be also possible.



Scheme 14 Mechanistic studies for carbonylation of C(sp<sup>3</sup>)-H bonds in pyridylamines with CO<sub>2</sub>.

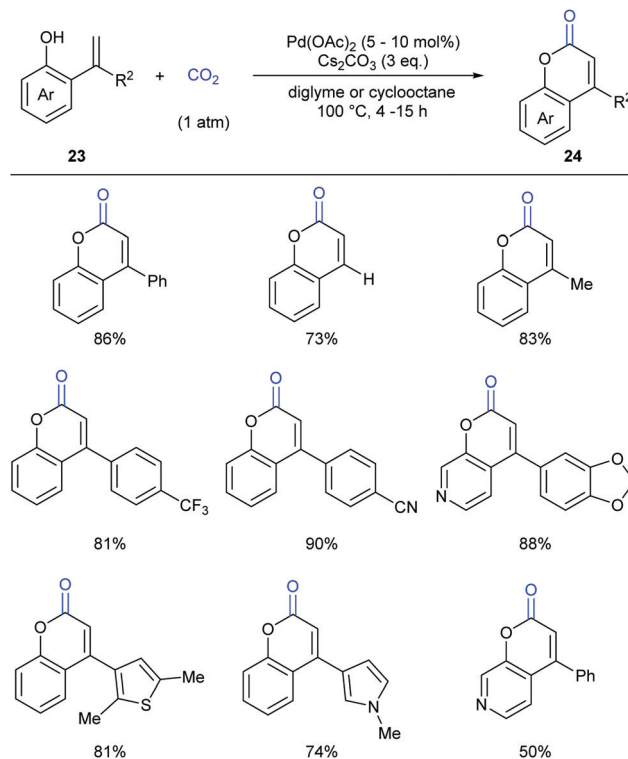


Scheme 15 Proposed mechanism for carbonylation of C(sp<sup>3</sup>)-H bonds in pyridylamines with CO<sub>2</sub>.

### 3. Lactonization of C-H bonds with CO<sub>2</sub>

As another important class of carbonyl compounds, lactone-containing compounds are also prevalent in nature and a key structural motif in many bioactive molecules.<sup>20</sup> Among the diverse ways to synthesize such structures, it is of great significance to realize carbonylation of C-H bonds. However, the carbonylation reagents are mainly restricted to highly toxic CO.<sup>3</sup> Considering the advantages of CO<sub>2</sub>, it is highly important to develop such reactions with CO<sub>2</sub> as the carbonyl source.

In 2013, the Iwasawa group pioneered in this field and developed the first palladium-catalyzed lactonization of alkenyl C-H bonds in *o*-alkenylphenols **23** with CO<sub>2</sub> to afford a variety of coumarins **24** with good yields (Scheme 16).<sup>21</sup> The use of Pd-catalyst was vital for the reaction and Cs<sub>2</sub>CO<sub>3</sub> was important for the high efficiency. Many functional groups, such as

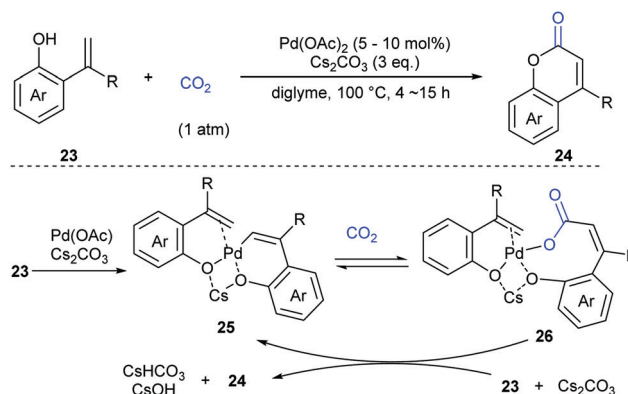


Scheme 16 Pd-Catalyzed carbonylation of cyclization of *o*-alkenylphenols with CO<sub>2</sub>.

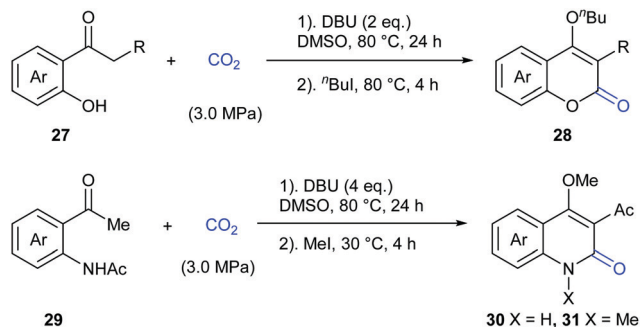
trifluoromethyl, methoxyl and cyano groups, as well as many heterocycles, such as thiophene, pyrrole and pyridine, could be well tolerated under the reaction conditions.

Extensive studies were performed to reveal the mechanism (Scheme 17). A six-membered palladacycle **25**, the key intermediate generated *via* C-H bond cleavage, was isolated and characterized by means of single-crystal X-ray diffraction. Then, the nucleophilic addition of **25** to CO<sub>2</sub> gave a palladium carboxylate intermediate, which further reacted with another molecule of *o*-alkenylphenol **23** and Cs<sub>2</sub>CO<sub>3</sub> to give the desired coumarin product **24** and regenerate the intermediate **25**.

In 2015, the Zhang and Lu group reported a novel transition metal-free carbonylation of C(sp<sup>3</sup>)-H bonds in *o*-hydroxyacetophenones and *o*-aminoacetophenones with CO<sub>2</sub> in the presence of



Scheme 17 Proposed mechanism for Pd-catalyzed carbonylation reaction.

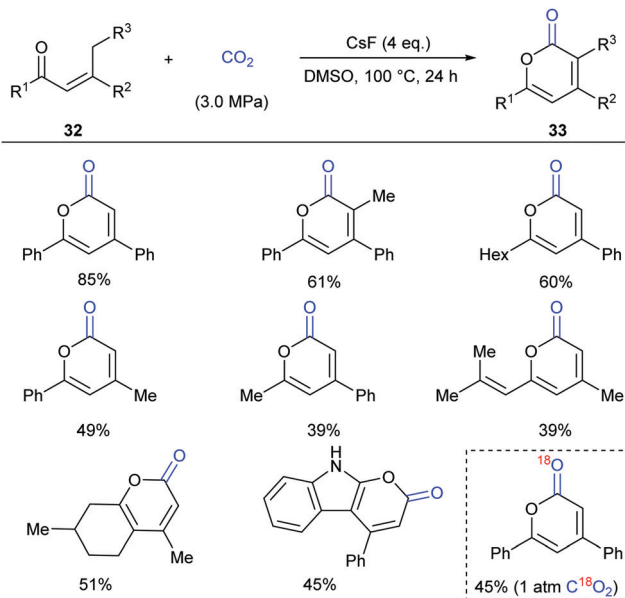


Scheme 18 DBU-mediated carbonylation reaction.

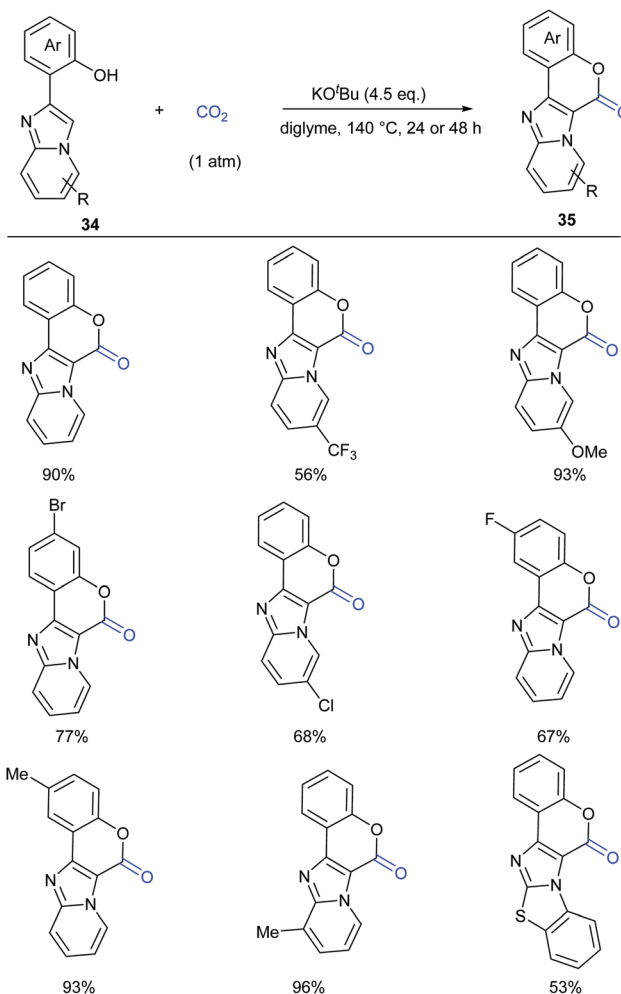
1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) as base (Scheme 18).<sup>22</sup> The driving force for this transformation mainly relied on the cyclization of the *in situ* formed  $\beta$ -ketoester with tethered oxygen and nitrogen nucleophiles to form stable heterocycles.

Inspired by the results, in 2016 the same group continuously developed a CsF-promoted carboxylative cyclization of propenyl ketones with CO<sub>2</sub> to synthesize  $\alpha$ -pyrones (Scheme 19).<sup>23</sup> A low concentration of the substrate and a high pressure of CO<sub>2</sub> are vital for high conversion and selectivity of the reaction. To exclude the possibility of a trace amount of palladium impurity in base functioning as a catalyst, Pd(OAc)<sub>2</sub> was added into the system and decreased reactivity was observed, implying a transition-metal free environment for the reaction conditions. When C<sup>18</sup>O<sub>2</sub> was utilized in this reaction, the product was obtained with only one <sup>18</sup>O atom, which clearly demonstrated that the carbonyl was from CO<sub>2</sub> in this transformation.

Considering the important biological activity of imidazo [1,2-*a*]pyridine skeleton-containing compounds, we envisioned whether a series of hybrid structures of coumarin derivatives could be obtained *via* carbonylation of C–H bonds in imidazo [1,2-*a*]pyridines with CO<sub>2</sub>. In 2017, our group successfully



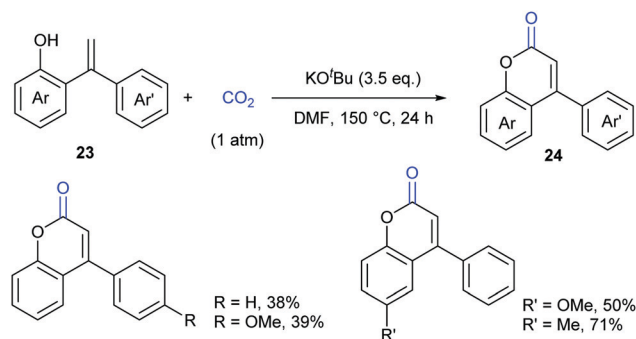
Scheme 19 CsF-mediated carbonylation reaction.

Scheme 20 Lactonization of *o*-(imidazole[1,2-*a*]pyridine-2-yl)phenols with CO<sub>2</sub>.

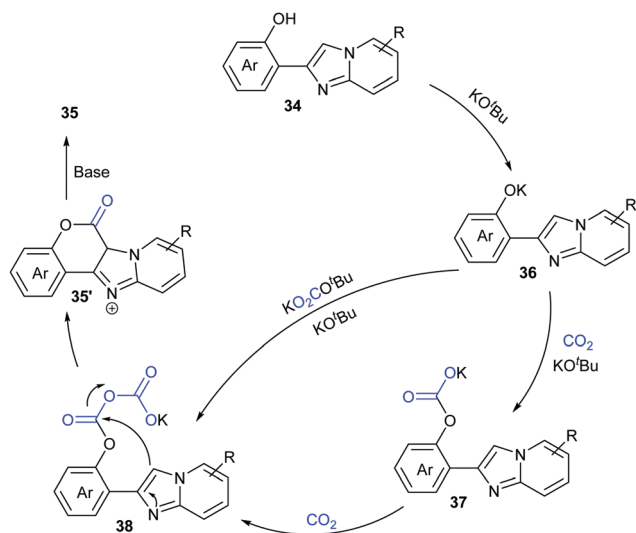
developed the KO<sup>t</sup>Bu-promoted lactonization of *o*-heteroaryl- and *o*-alkenyl phenols with CO<sub>2</sub> to generate coumarin derivatives with good to excellent yields (Scheme 20).<sup>24</sup> This transformation featured a broad substrate scope and good functional group tolerance. In addition to *o*-(imidazole[1,2-*a*]pyridine-2-yl)phenols, *o*-(benzo[*d*]imidazo[2,1-*b*]thiazol-2-yl)-phenol and *o*-alkenylphenols could also undergo a similar lactonization reaction with high efficiency (Scheme 21).

Based on the control experiments, we proposed a possible mechanism (Scheme 22). Deprotonation of compounds 34 with KO<sup>t</sup>Bu formed phenolic potassium 36, which could react with CO<sub>2</sub> or with the *in situ* generated adduct of CO<sub>2</sub> and KO<sup>t</sup>Bu (*e.g.* KOCO<sub>2</sub><sup>t</sup>Bu) to afford the carbonate intermediate 37. Then, a similar process took place further to give the intermediate 38. Intramolecular nucleophilic attack with the assistance of base afforded the desired coumarin product 35.

Different from our previous works,<sup>9,24</sup> we wondered whether the carbonylation initiated *via* the nucleophilic attack from the electron-rich carbon sites instead of heteroatom sites (such as nitrogen in aniline and oxygen in phenol) was feasible. Therefore, we turned our attention to electron-rich enamides, which should



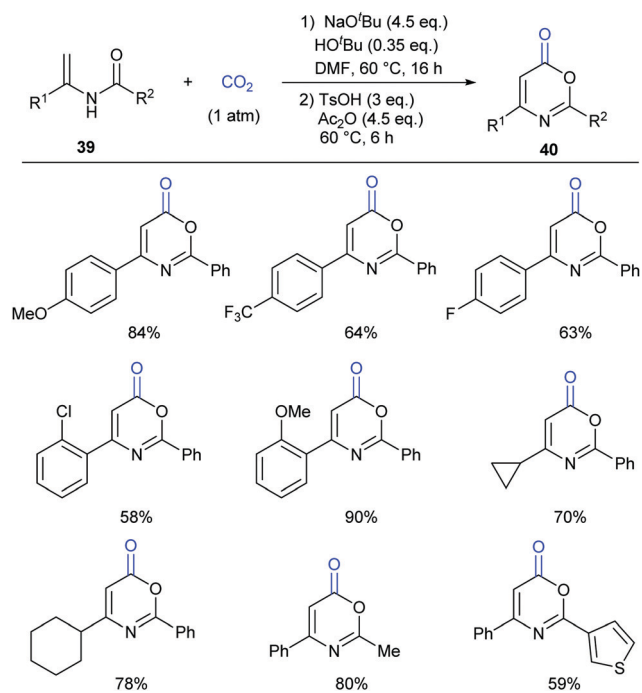
Scheme 21 KO<sup>t</sup>Bu-promoted lactonization of *o*-alkenylphenols with CO<sub>2</sub>.



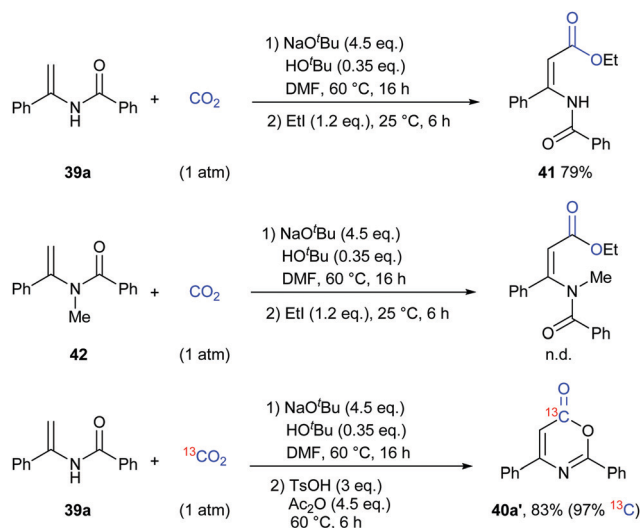
Scheme 22 The plausible mechanism for KO<sup>t</sup>Bu-promoted lactonization of *o*-(hetero)aryl/alkenyl phenols with CO<sub>2</sub>.

show higher nucleophilicity in the presence of a strong base. If the carboxylation of C(sp<sup>2</sup>)-H bonds in enamides with CO<sub>2</sub> and the following cyclization happened in sequence, we might be able to construct important oxazinone motifs.<sup>25</sup> Indeed, based on this hypothesis, we succeeded in the synthesis of 1,3-oxazin-6-ones in one pot with two steps (Scheme 23).<sup>26</sup> Although we did realize the carboxylation of C(sp<sup>2</sup>)-H bonds in enamides with CO<sub>2</sub> in the presence of NaO<sup>t</sup>Bu, the intermediates did not undergo condensation under the basic reaction conditions. Therefore, additional acid and anhydride were vital to promote the condensation to afford the desired products. Notably, such products could be transformed to important pyrimidines and pyridines through decarboxylation [4+2] cycloaddition.

To gain more insight into this transformation, some mechanistic studies were conducted (Scheme 24). First, the corresponding ester **41** could be obtained by adding iodoethane (EtI) into the system, which could confirm the process of nucleophilic attack of electron-rich carbon in enamides on CO<sub>2</sub>. Then, when the *N*-methyl substituted enamide **42** was used, this transformation could not occur, which indicated that the interconversion of



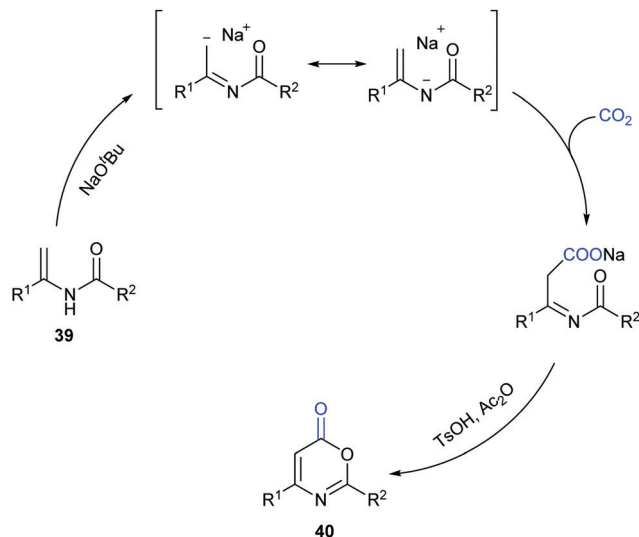
Scheme 23 NaO<sup>t</sup>Bu-promoted carboxylation cyclization of enamides with CO<sub>2</sub>.



Scheme 24 Mechanistic studies for the carbonylation of enamides with CO<sub>2</sub>.

enamides and imines was important for the reaction under the basic conditions. Moreover, we also ran this reaction with <sup>13</sup>C<sub>2</sub> and obtained the <sup>13</sup>C-labeled coumarin in high yield, demonstrating that the carbonyl was derived from CO<sub>2</sub>.

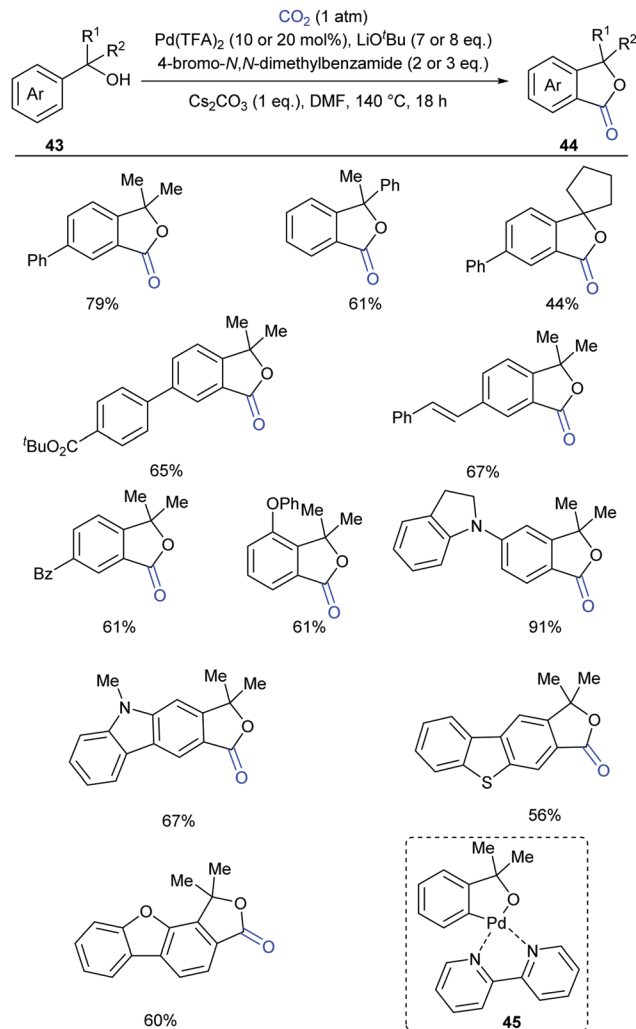
On the basis of the results, we proposed a possible pathway as shown in Scheme 25. Deprotonation of enamides by NaO<sup>t</sup>Bu occurred to generate the enamide anions, which could react with CO<sub>2</sub> to form carboxylates. Then, the desired product could be achieved by acidification and cyclization in the presence of acid and anhydride.



**Scheme 25** The plausible mechanism of the carbonylation of enamides with CO<sub>2</sub>.

Compared to the C(sp<sup>2</sup>)-H bonds in alkenes and electron-rich heteroarenes, the carbonylation of unactivated aryl C-H bonds with CO<sub>2</sub> is more difficult due to the lower reactivity and less nucleophilicity. In 2018, our group reported the first palladium-catalyzed carbonylation of the unactivated aryl C-H bond with CO<sub>2</sub> to construct phthalides (Scheme 26)<sup>27</sup> using tertiary benzylic alcohols as directing groups, which exhibit weak coordination to transition metals and might undergo several side reactions, including β-H elimination and C-C bond cleavage. We used a strong base to deprotonate the benzyl alcohol, thus enhancing the coordinative ability of oxygen. However, under such basic conditions, the palladium(II) catalyst was prone to be reduced to inactive palladium black. After an extensive survey of mild oxidants, aryl bromides stood out for maintaining palladium(II) catalyst activity without interfering with the reaction. The selectivity issue arising from the side reactions of tertiary benzylic alcohols was suppressed by lactonization to form the desired products, although the primary and secondary alcohols mainly underwent oxidation *via* Pd-catalyzed β-H elimination. This reaction was not hampered by *ortho* substitution and C-H lactonization selectively occurred at the less hindered *ortho* position for *meta* substituted substrates. Heterocycles were also tolerated. When <sup>13</sup>C-labeled CO<sub>2</sub> and an <sup>18</sup>O-labeled substrate were used, we could confirm that the carbonyl group was from CO<sub>2</sub> and the alcohol oxygen atom was fully incorporated into the product. Based on the mechanistic experiments, we postulated that the five-membered palladacycle species **45** was a plausible intermediate, which could be detected by ESI-HRMS using bipyridine as the ligand.

Based on the density functional theoretical (DFT) calculations and the experimental results, we proposed a possible mechanism (Scheme 27). The active catalytic complex **46** could be generated *in situ* from Pd(TFA)<sub>2</sub> in the presence of LiO<sup>t</sup>Bu and CO<sub>2</sub>, followed by a counter anion exchange with lithium alcoholate intermediate **47** to afford alcoholate-Pd intermediate **48**. Subsequent C-H bond cleavage generated the five-membered

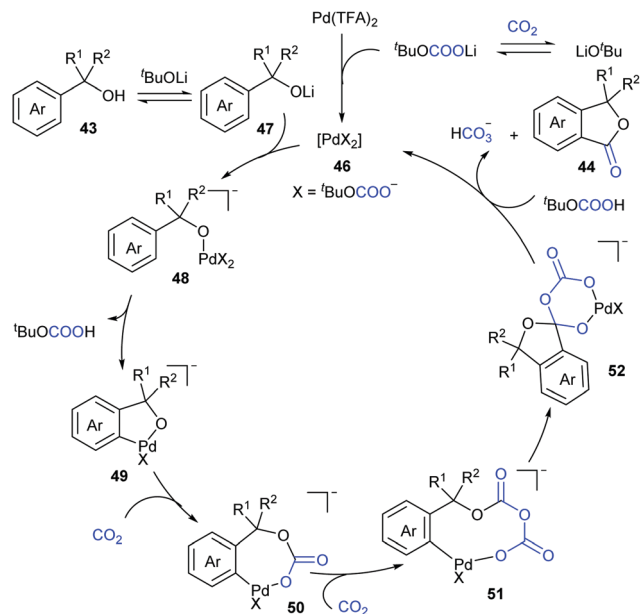


**Scheme 26** Pd-Catalyzed carbonylation of tertiary benzylic alcohols with CO<sub>2</sub>.

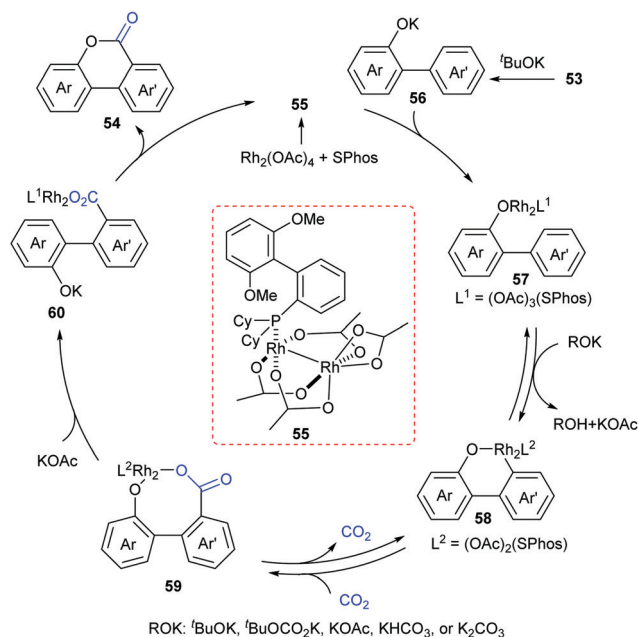
palladacycle intermediate **49**, followed by two sequential nucleophilic attack on CO<sub>2</sub> to afford intermediate **51**. Intramolecular attack then leads to complex **52**, which further underwent decarboxylation and ligand exchange to deliver the desired product **44** and regenerate the catalyst **46**. In this catalytic cycle, CO<sub>2</sub> has been proven to promote this reaction by decreasing the ring strain in the intramolecular nucleophilic addition and enhancing the leaving ability and provide a novel pathway *via* decarboxylation for C-O bond cleavage.

At the same time, the Li group independently displayed an elegant Rh-catalyzed lactonization of *o*-(hetero)arylphenols with CO<sub>2</sub> (Scheme 28).<sup>14d</sup> The utilization of an electron-rich phosphine ligand, 2-dicyclohexylphosphino-2',6'-dimethoxybiphenyl (SPhos), greatly enhanced the reactivity and avoided the undesired Kolbe-Schmitt type reaction. KO<sup>t</sup>Bu could trap CO<sub>2</sub> and increase the concentration of CO<sub>2</sub> in the solution. Steric hindrance was tolerated in the phenolic part but not in the phenyl part. This transformation occurred at the less hindered *ortho* position for *meta*-substituted substrates with unique selectivity.

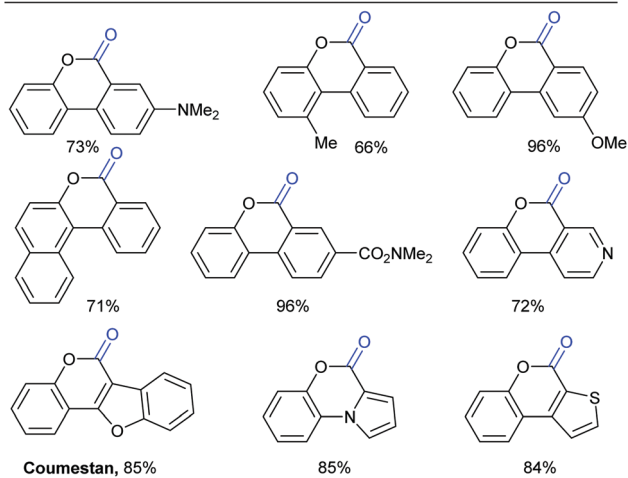
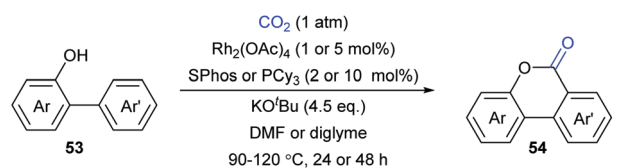
A plausible reaction mechanism was proposed as shown in Scheme 29. The intermediate **55** was formed *in situ* by coordination



**Scheme 27** Possible reaction mechanism for carbonylation of tertiary benzylic alcohols with CO<sub>2</sub>.

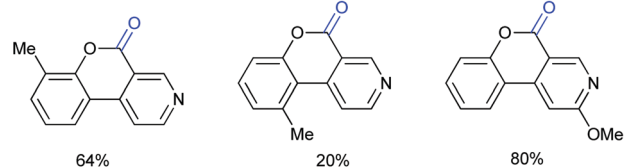
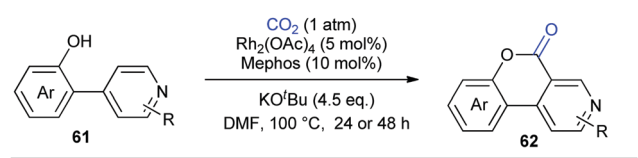


**Scheme 29** The catalytic cycle of Rh-catalyzed lactonization reaction.

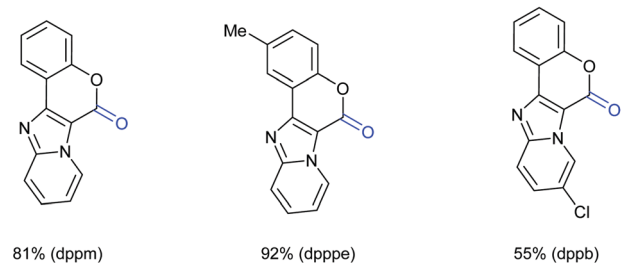
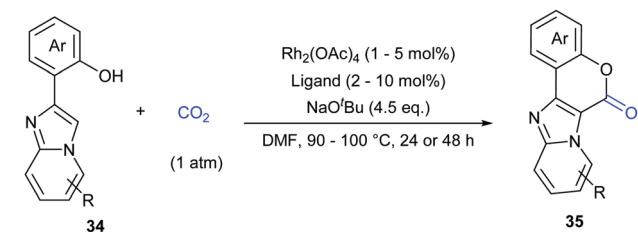


**Scheme 28** Rh-Catalyzed lactonization of *o*-(hetero)arylphenols with CO<sub>2</sub>.

of the Rh-catalyst. Then, it coordinated with **56** generated from deprotonation of **53** by KO<sup>t</sup>Bu to afford intermediate **57**. With the assistance of an external base, the rhodacycle **58** was generated through the reversible aryl C–H bond activation of **57** *via* a proton abstraction process, followed by nucleophilic attack on CO<sub>2</sub> to achieve the eight-membered complex **59**. Subsequently, ligand exchange and rapid lactonization delivered the desired product **54** and regenerated the complex **55**. It was noteworthy that the shift of the carboxylation–decarboxylation equilibrium to the



**Scheme 30** Rh-Catalyzed C–H carbonylation of 2-pyridylphenols with CO<sub>2</sub>. Mephos = 2-(dicyclohexylphosphino)-2'-methylbiphenyl.



**Scheme 31** Rh-Catalyzed carbonylation of *o*-(imidazo[1,2-*a*]pyridine-2-yl)phenols with CO<sub>2</sub>. dppm = bis(diphenylphosphino)methane, dpppe = 1,5-bis(diphenylphosphino)pentane, dppb = 1,4-bis(diphenylphosphino)butane.

carboxylation intermediate **59** could be determined by the ligand exchange and lactonization process. This process should be fast and irreversible under the reaction conditions.

Although the Li group have developed an efficient Rh-catalyzed lactonization method, there is only an isolated example of *o*-pyridylphenol in this work.<sup>14d</sup> To extend this strategy, this group further reported Rh-catalyzed C–H carboxylation cyclization of more challenging electron-deficient 2-pyridylphenols with CO<sub>2</sub> by tuning ligands (Scheme 30).<sup>14e</sup> A class of pyrido-coumarin derivatives has been synthesized. Apart from this, the group continuously expanded the catalytic system to *o*-(imidazo[1,2-*a*]pyridine-2-yl)phenols through ligand changes, and provided an access to coumarin derivatives based on the structure of imidazo[1,2-*a*]pyridine (Scheme 31).<sup>14f</sup>

## 4. Conclusions

Carbonylation of C–H bonds with CO<sub>2</sub> has emerged as an alternative to the traditional oxidative carbonylation in constructing carbonyl-containing heterocycles under redox-neutral conditions. As a carbonylation reagent, CO<sub>2</sub> has displayed great superiority over CO used in oxidative carbonylation, which usually poses safety, cost, and environmental issues. The main pathway for the redox-neutral carbonylation with CO<sub>2</sub> refers to the successive nucleophilic attack on CO<sub>2</sub> with the substrate possessing two nucleophilic sites. In many cases, a carbonate might be generated as a byproduct in the presence of base, facilitating the challenging C=O bond cleavage. Although promising, there are still many important challenges in the carbonylation with CO<sub>2</sub>. For example, high temperature and high loading of a strong base are always required in the process. It would be more favorable to realize CO<sub>2</sub> transformation under milder and more environmentally benign conditions. Then, the current catalytic system is mainly focused on noble metal catalysis, and the turnover number/efficiency is still unsatisfactory. It is urgent to develop more efficient and inexpensive transition metal catalytic systems. Moreover, the type of C–H activation is essentially confined to C(sp<sup>2</sup>)-H bonds and the relatively acidic C(sp<sup>3</sup>)-H bonds; the more inert C(sp<sup>3</sup>)-H bonds are less explored. Furthermore, the asymmetric C–H carbonylation should be further developed with suitable chiral ligands for highly enantioselective control. Last but not least, the application of this concept in the generation of ketones *via* double C–H carbonylation will be also highly attractive in organic synthesis. Taken together, we believe that the concept of CO<sub>2</sub> as the combination of CO and oxidant (CO<sub>2</sub> = CO + [O]) will continue to show its special advantages and invoke more and more attention in both laboratory and industry.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

We are grateful to the financial support from the National Natural Science Foundation of China (21822108, 21801025, 21502124),

the “973” Project from the MOST of China (2015CB856600) and the Fundamental Research Funds for the Central Universities.

## Notes and references

- (a) *Carbon Dioxide as Chemical Feedstock*, ed. M. Aresta, Wiley-VCH, Weinheim, Germany, 2010; (b) *Green Carbon Dioxide: Advances in CO<sub>2</sub> Utilization*, ed. G. Centi and S. Perathoner, Wiley-VCH, Weinheim, Germany, 2014.
- (a) T. Sakakura, J.-C. Choi and H. Yasuda, *Chem. Rev.*, 2007, **107**, 2365; (b) L. Ackermann, *Angew. Chem., Int. Ed.*, 2011, **50**, 3842; (c) K. Huang, C.-L. Sun and Z.-J. Shi, *Chem. Soc. Rev.*, 2011, **40**, 2435; (d) R. Martin and A. W. Kleij, *ChemSusChem*, 2011, **4**, 1259; (e) Y. Tsuji and T. Fujihara, *Chem. Commun.*, 2012, **48**, 9956; (f) W. Zhang and X.-B. Lu, *Chin. J. Catal.*, 2012, **33**, 745; (g) M. He, Y. Sun and B. Han, *Angew. Chem., Int. Ed.*, 2013, **52**, 9620; (h) L. Zhang and Z. Hou, *Chem. Sci.*, 2013, **4**, 3395; (i) M. Aresta, A. Dibenedetto and A. Angelini, *Chem. Rev.*, 2014, **114**, 1709; (j) C. Maeda, Y. Miyazaki and T. Ema, *Catal. Sci. Technol.*, 2014, **4**, 1482; (k) Q. Liu, L. Wu, R. Jackstell and M. Beller, *Nat. Commun.*, 2015, **6**, 5933; (l) D. Yu, S. P. Teong and Y. Zhang, *Coord. Chem. Rev.*, 2015, **293–294**, 279; (m) C. Martin, G. Fiorani and A. W. Kleij, *ACS Catal.*, 2015, **5**, 1353; (n) S. Wang, G. Du and C. Xi, *Org. Biomol. Chem.*, 2016, **14**, 3666; (o) W. Zhang, N. Zhang, C. Guo and X. Lu, *Chin. J. Org. Chem.*, 2017, **37**, 1309; (p) Y.-Y. Gui, W.-J. Zhou, J.-H. Ye and D.-G. Yu, *ChemSusChem*, 2017, **10**, 1337; (q) X.-F. Wu and F. Zheng, *Top. Curr. Chem.*, 2017, **375**, 4; (r) Q.-W. Song, Z.-H. Zhou and L.-N. He, *Green Chem.*, 2017, **19**, 3707; (s) J. Luo and I. Larrosa, *ChemSusChem*, 2017, **10**, 3317; (t) Z. Zhang, T. Ju, J.-H. Ye and D.-G. Yu, *Synlett*, 2017, 741; (u) A. Tortajada, F. Juliá-Hernández, M. Börjesson, T. Moragas and R. Martin, *Angew. Chem., Int. Ed.*, 2018, **57**, 15948; (v) S.-S. Yan, Q. Fu, L.-L. Liao, G.-Q. Sun, J.-H. Ye, L. Gong, Y.-Z. Bo-Xue and D.-G. Yu, *Coord. Chem. Rev.*, 2018, **374**, 439; (w) Y. Cao, X. He, N. Wang, H.-R. Li and L.-N. He, *Chin. J. Chem.*, 2018, **36**, 644; (x) J. Hou, J.-S. Li and J. Wu, *Asian J. Org. Chem.*, 2018, **7**, 1439; (y) J. Hu, H. Liu and B. Han, *Sci. China: Chem.*, 2018, **61**, 1486; (z) S. Wang and C. Xi, *Chem. Soc. Rev.*, 2019, **48**, 382; (aa) J. Hong, M. Li, J. Zhang, B. Sun and F. Mo, *ChemSusChem*, 2019, **12**, 6; (ab) L. Cheng and J. Xie, *Chin. J. Org. Chem.*, 2020, **40**, 247.
- (a) *Modern Carbonylation Methods*, ed. L. Kollár, Wiley-VCH, Weinheim, 2008; (b) A. Brennfürher, H. Neumann and M. Beller, *Angew. Chem., Int. Ed.*, 2009, **48**, 4114; (c) L. Wu, X. Fang, Q. Liu, R. Jackstell, M. Beller and X.-F. Wu, *ACS Catal.*, 2014, **4**, 2977.
- H. Babad and A. G. Zeiler, *Chem. Rev.*, 1973, **73**, 75.
- (a) C.-L. Sun, B.-J. Li and Z.-J. Shi, *Chem. Rev.*, 2011, **111**, 1293; (b) S. R. Neufeldt and M. S. Sanford, *Acc. Chem. Res.*, 2012, **45**, 936; (c) C. S. Yeung and V. M. Dong, *Chem. Rev.*, 2011, **111**, 1215; (d) D. A. Colby, A. S. Tsai, R. G. Bergman and J. A. Ellman, *Acc. Chem. Res.*, 2012, **45**, 814; (e) Z. Chen, B. Wang, J. Zhang, W. Yu, Z. Liu and Y. Zhang, *Org. Chem. Front.*, 2015, **2**, 1107; (f) Z. Huang, H. N. Lim, F. Mo, M. C. Young and G. Dong, *Chem. Soc. Rev.*, 2015, **44**, 7764; (g) O. Daugulis, J. Roane and L. D. Tran, *Acc. Chem. Res.*, 2015, **48**, 1053; (h) J. F. Hartwig and M. A. Larsen, *ACS Cent. Sci.*, 2016, **2**, 281; (i) J. He, M. Wasa, K. S. L. Chan, Q. Shao and J.-Q. Yu, *Chem. Rev.*, 2017, **117**, 8754; (j) Y. Park, Y. Kim and S. Chang, *Chem. Rev.*, 2017, **117**, 9247; (k) T. Gensch, M. James, T. Dalton and F. Glorius, *Angew. Chem., Int. Ed.*, 2018, **57**, 2296; (l) J. Huang, Q. Gu and S. You, *Chin. J. Org. Chem.*, 2018, **38**, 51; (m) Q.-L. Yang, P. Fang and T.-S. Mei, *Chin. J. Chem.*, 2018, **36**, 338; (n) Y. Liu, H. Yi and A. Lei, *Chin. J. Chem.*, 2018, **36**, 692; (o) Z.-T. Jiang, B.-Q. Wang and Z.-J. Shi, *Chin. J. Chem.*, 2018, **36**, 950; (p) S. Rej and N. Chatani, *Angew. Chem., Int. Ed.*, 2019, **58**, 8304; (q) Q. Zhang and B.-F. Shi, *Chin. J. Chem.*, 2019, **37**, 647.
- (a) T. W. Lyons and M. S. Sanford, *Chem. Rev.*, 2010, **110**, 1147; (b) Q. Liu, H. Zhang and A. Lei, *Angew. Chem., Int. Ed.*, 2011, **50**, 10788; (c) X.-F. Wu, H. Neumann and M. Beller, *Chem. Rev.*, 2013, **113**, 1; (d) X.-F. Wu, H. Neumann and M. Beller, *ChemSusChem*, 2013, **6**, 229; (e) X.-F. Wu, X. Fang, L. Wu, R. Jackstell, H. Neumann and M. Beller, *Acc. Chem. Res.*, 2014, **47**, 1041; (f) B. Liu, F. Hu and B.-F. Shi, *ACS Catal.*, 2015, **5**, 1863; (g) Y. Yi, M. Chen and Z. Guan, *Chin. Sci. Bull.*, 2015, **60**, 2927; (h) Y. Li, Y. Hu and X. Wu, *Chem. Soc. Rev.*, 2018, **47**, 172; (i) N. Rajesh, N. Barsu and B. Sundararaju, *Tetrahedron Lett.*, 2018, **59**, 862; (j) X. He, Y. Cao,

- X.-D. Lang, N. Wang and L.-N. He, *ChemSusChem*, 2018, **11**, 3382; (k) L. Wang, W. Sun and C. Liu, *Chin. J. Chem.*, 2018, **36**, 353; (l) F. Xu and W. Han, *Chin. J. Org. Chem.*, 2018, **38**, 2519.
- 7 (a) P. Cheng, Q. Zhang, Y.-B. Ma, Z.-Y. Jiang, X.-M. Zhang, F.-X. Zhang and J.-J. Chen, *Bioorg. Med. Chem. Lett.*, 2008, **18**, 3787; (b) P. R. Angibaud, M. G. Venet, W. Filliers, R. Broeckx, Y. A. Ligny, P. Muller, V. S. Poncelet and D. W. End, *Eur. J. Org. Chem.*, 2004, 479; (c) J. Miyashiro, K. W. Woods, C. H. Park, X. Liu, Y. Shi, E. F. Johnson, J. J. Bouska, A. M. Olsona, Y. Luo, E. H. Fry, V. L. Giranda and T. D. Penning, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 4050.
- 8 (a) J. Ferguson, F. Zeng, N. Alwis and H. Alper, *Org. Lett.*, 2013, **15**, 1998; (b) D. Liang, Z. Hu, J. Peng, J. Huang and Q. Zhu, *Chem. Commun.*, 2013, **49**, 173; (c) V. Rajeshkumar, T.-H. Lee and S.-C. Chuang, *Org. Lett.*, 2013, **15**, 1468; (d) Z. Liang, J. Zhang, Z. Liu, K. Wang and Y. Zhang, *Tetrahedron*, 2013, **69**, 6519.
- 9 Z. Zhang, L.-L. Liao, S.-S. Yan, L. Wang, Y.-Q. He, J.-H. Ye, J. Li, Y.-G. Zhi and D.-G. Yu, *Angew. Chem., Int. Ed.*, 2016, **55**, 7068.
- 10 W. Li, C. Li and Y. Lyu, *Org. Chem. Front.*, 2018, **5**, 2189.
- 11 S. Wang, P. Shao, G. Du and C. Xi, *J. Org. Chem.*, 2016, **81**, 6672.
- 12 S. Sun, W.-M. Hu, N. Gu and J. Cheng, *Chem. – Eur. J.*, 2016, **22**, 18729.
- 13 Y. Gao, Z. Cai, S. Li and G. Li, *Org. Lett.*, 2019, **21**, 3663.
- 14 (a) H. Mizuno, J. Takaya and N. Iwasawa, *J. Am. Chem. Soc.*, 2011, **133**, 1251; (b) T. Suga, H. Mizuno, J. Takaya and N. Iwasawa, *Chem. Commun.*, 2014, **50**, 14360; (c) T. Suga, T. Saitou, J. Takaya and N. Iwasawa, *Chem. Sci.*, 2017, **8**, 1454; (d) L. Fu, S. Li, Z. Cai, Y. Ding, X. Guo, L. Zhou, D. Yuan, Q. Sun and G. Li, *Nat. Catal.*, 2018, **1**, 469; (e) Z. Cai, S. Li, Y. Gao and G. Li, *Adv. Synth. Catal.*, 2018, **360**, 4005; (f) R. Huang, S. Li, L. Fu and G. Li, *Asian J. Org. Chem.*, 2018, **7**, 1376.
- 15 (a) A. L. Machado, L. M. Lima, J. X. Araujo, J. C. M. Fraga, V. L. Koatz and E. J. Barreiro, *Bioorg. Med. Chem. Lett.*, 2005, **15**, 1169; (b) S. Gobec, I. Plantan, J. Mravljak, U. Svajger, G. S. Wilson, S. L. Besra, R. Soares, D. Appelberg and R. A. Kikelj, *Eur. J. Med. Chem.*, 2007, **42**, 54; (c) V. J. Ragavendran, D. Sriram, K. S. Patel, I. V. Reddy, N. Bharathwajan, J. Stables and P. Yogeeswari, *Eur. J. Med. Chem.*, 2007, **42**, 146.
- 16 (a) S. Inoue, H. Shita, Y. Fukumoto and N. Chatani, *J. Am. Chem. Soc.*, 2009, **131**, 6898; (b) E. J. Yoo, M. Wasa and J.-Q. Yu, *J. Am. Chem. Soc.*, 2010, **132**, 17378; (c) Y. Du, T. K. Hyster and T. Rovis, *Chem. Commun.*, 2011, **47**, 12074; (d) B. Ma, Y. Wang, J. Peng and Q. Zhu, *J. Org. Chem.*, 2011, **76**, 6362; (e) V. Rajeshkumar, T.-H. Lee and S.-C. Chuang, *Org. Lett.*, 2013, **15**, 1468; (f) L. Grigorjeva and O. Daugulis, *Org. Lett.*, 2014, **16**, 4688; (g) W. Li, C. Liu, H. Zhang, K. Ye, G. Zhang, W. Zhang, Z. Duan, S. You and A. Lei, *Angew. Chem., Int. Ed.*, 2014, **53**, 2443; (h) C. Wang, L. Zhang, C. Chen, J. Han, Y. Yao and Y. Zhao, *Chem. Sci.*, 2015, **6**, 4610; (i) F. Ji, J. Li, X. Li, W. Guo, W. Wu and H. Jiang, *J. Org. Chem.*, 2018, **83**, 104.
- 17 (a) L. Song, G. Cao, W. Zhou, J. Ye, Z. Zhang, X. Tian, J. Li and D.-G. Yu, *Org. Chem. Front.*, 2018, **5**, 2086; (b) N. Barsu, D. Kalsi and B. Sundararaju, *Catal. Sci. Technol.*, 2018, **8**, 5963.
- 18 (a) Z. Zhang, X.-Y. Zhou, J.-G. Wu, L. Song and D.-G. Yu, *Green Chem.*, 2020, **22**, 28; (b) Y. Xie, T. Chen, S. Fu, H. Jiang and W. Zeng, *Chem. Commun.*, 2015, **51**, 9377.
- 19 (a) Z. Chen, Y. Wen, H. Ding, G. Luo, M. Ye, L. Liu and J. Xue, *Tetrahedron Lett.*, 2017, **58**, 13; (b) X. Zhang, B. Yang, G. Li, X. Shu, D. C. Mungra and J. Zhu, *Synlett*, 2012, 622; (c) A. Fiksdahl, C. Plüg and C. Wentrup, Mesoions and Ketene Valence Isomers, *J. Chem. Soc., Perkin Trans.*, 2, 2000, 1841.
- 20 (a) E. Melliou, P. Magiatis, S. Mitaku, A.-L. Skaltsounis, E. Chinou and I. Chinou, *J. Nat. Prod.*, 2005, **68**, 78; (b) T. Symeonidis, M. Chamilos, D. J. Hadjipavlou-Litina, M. Kallitsakis and K. E. Litinas, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 1139; (c) H. Zhao, A. C. Donnelly, B. R. Kusuma, G. E. L. Brandt, D. Brown, R. A. Rajewski, G. Vielhauer, J. Holzbeierlein, M. S. Cohen and B. S. J. Blagg, *J. Med. Chem.*, 2011, **54**, 3839; (d) Y. Chen, S. Wang, X. Xu, X. Liu, M. Yu, S. Zhao, S. Liu, Y. Qiu, T. Zhang, B.-F. Liu and G. Zhang, *J. Med. Chem.*, 2013, **56**, 4671; (e) T. Narumi, H. Takano, N. Ohashi, A. Suzuki, T. Furuta and H. Tamamura, *Org. Lett.*, 2014, **16**, 1184; (f) B. Zhang, C. Ge, J. Yao, Y. Liu, H. Xie and J. Fang, *J. Am. Chem. Soc.*, 2015, **137**, 757.
- 21 K. Sasano, J. Takaya and N. Iwasawa, *J. Am. Chem. Soc.*, 2013, **135**, 10954.
- 22 W. Z. Zhang, S. Liu and X. B. Lu, *Beilstein J. Org. Chem.*, 2015, **11**, 906.
- 23 W.-Z. Zhang, M.-W. Yang and X.-B. Lu, *Green Chem.*, 2016, **18**, 4181.
- 24 Z. Zhang, T. Ju, M. Miao, J.-L. Han, Y.-H. Zhang, X.-Y. Zhu, J.-H. Ye, D.-G. Yu and Y.-G. Zhi, *Org. Lett.*, 2017, **19**, 396.
- 25 (a) M. C. Kim, J. H. Lee, B. Shin, L. Subedi, J. W. Cha, J.-S. Park, D.-C. Oh, S. Y. Kim and H. C. Kwon, *Org. Lett.*, 2015, **17**, 5024; (b) P. Fu, S. La and J. B. MacMillan, *J. Nat. Prod.*, 2016, **79**, 455.
- 26 Z. Zhang, C.-J. Zhu, M. Miao, J.-L. Han, T. Ju, L. Song, J.-H. Ye, J. Li and D.-G. Yu, *Chin. J. Chem.*, 2018, **36**, 430.
- 27 L. Song, L. Zhu, Z. Zhang, J.-H. Ye, S. Yan, J. Han, Z. Yin, Y. Lan and D.-G. Yu, *Org. Lett.*, 2018, **20**, 3776.