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Palladium-Catalyzed Decarboxylative Annulation of 2-Arylbenzoic Acids with [60]Fullerene via C−H Bond Activation

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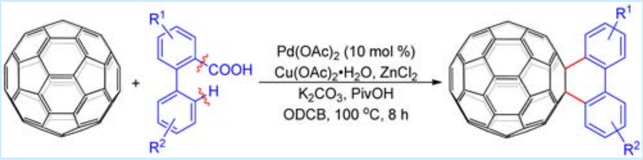
Supporting Information

ABSTRACT: A convenient and highly efficient palladium-catalyzed decarboxylative annulation of 2-arylbenzoic acids with [60]fullerene has been exploited to synthesize the novel and scarce [60]fullerene-fused dihydrophenanthrenes. The use of Lewis acid $ZnCl_2$ is crucial for the success of the present formal [4 + 2] annulation reaction. Plausible reaction pathways leading to the observed products have been proposed, and the electrochemistry of the fullerene products has also been investigated.



The synthesis of novel [60]fullerene (C_{60}) derivatives has attracted considerable attention, mainly because of their potential applications in material science and biomedicine.[1] The exploration of new derivatization protocols to tune their properties is critical to increase their utilization efficiency and expand the range of potential applications. Our group has focused on developing new protocols to functionalize fullerenes over the years. Recently, we successfully introduced the palladium-catalyzed C−H activation strategy into fullerene chemistry and synthesized a series of novel [60]fullerene derivatives.[2] However, most of these reactions require directing groups to form palladacycles and subsequent formation of C_{60}-fused heterocycles, which make the products contain at least one heteroatom attached to the fullerene skeleton. The attached heteroatoms will lower the LUMO energy levels of fullerene derivatives and, thus, are not beneficial to the improvement of open-circuit voltage (*Voc*), a key factor in evaluating the power conversion efficiency of organic photovoltaic devices.[3] Therefore, it is still a challenge to develop new methods to synthesize novel fullerene derivatives with two carbon atoms directly attached to the fullerene skeleton.[4] On the other hand, as the most common and readily available reagents, carboxylic acids have been widely used in organic synthesis. The use of arylcarboxylic acids as arylating reagents for decarboxylative cross-coupling reactions represents a major breakthrough.[5] Recently, Glorius and co-workers reported the synthesis of phenanthrenes from 2-phenylbenzoic acids with alkynes through a decarboxylation/C−H activation sequence.[6] Inspired by this pioneering work, herein we report a palladium-catalyzed decarboxylative coupling of 2-arylbenzoic acids with C_{60} to afford C_{60}-fused dihydrophenanthrenes. It is worth noting that the synthesis of this type of biaryl-fused fullerene derivatives is very rare. Recently, the Itami group reported the trifluoromethanesulfonic acid (TfOH)-catalyzed reaction of aziridino[60]fullerene with bithiophenes and arylthiophenes to give the corresponding bithienyl- and arylthienyl-fused fullerene derivatives.[7] Compared with this work, our strategy provides various novel biaryl-fused fullerene derivatives using the common 2-arylbenzoic acids in a one-step procedure.

We began our exploration with 4-methoxybiphenyl-2-carboxylic acid as the representative substrate to optimize the reaction conditions (Table 1). The initial use of $Cu(OAc)_2 \cdot H_2O$ as the oxidant and $Pd(TFA)_2$ as the catalyst in 1,2-dichlorobenzene (ODCB) at 140 °C failed to provide any desired product (Table 1, entry 1). When Lewis acid $ZnCl_2$ was added to this reaction, the desired product **2a** was successfully obtained in 19% yield (Table 1, entry 2). In order to improve the yield, K_2CO_3 and PivOH, which had been shown to be beneficial additives in palladium-catalyzed directed arylations,[8] were added to this reaction. To our delight, the yield of **2a** was substantially increased to 32% (Table 1, entry 3). It should be noted that other Lewis acids such as $ZnBr_2$, ZnI_2, $FeCl_3$, and $AlCl_3$ completely failed to promote this transformation (Table 1, entries 4−7). $ZnCl_2$ clearly stood out and facilitated the decarboxylation/C−H activation sequence. Further examination of other oxidants, including $K_2S_2O_8$, BQ, Ag_2CO_3, $Cu(TFA)_2$, and $Cu(OTf)_2$, indicated that $Cu(OAc)_2 \cdot H_2O$ was the most effective oxidant for this reaction (Table 1, entries 8−12). Replacing $Pd(TFA)_2$ with the cheaper and more common $Pd(OAc)_2$ slightly increased the yield of **2a** to 33% (Table 1, entry 13). Interestingly, lowering the temperature from 140 to 120 °C and 100 °C gave the same yield (Table 1, entries 14 and 15), but further lowering the temperature to 90 °C reduced the product yield significantly to 10% (Table 1, entry 16). Prolonging the reaction time or changing the ratio of

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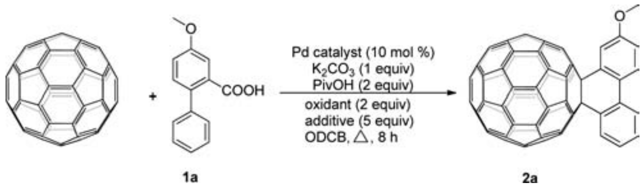
Table 1. Optimizing the Reaction Conditions for the Pd-Catalyzed Reaction of C_{60} with 1a[a]



entry	catalyst	oxidant	additive	temp (°C)	yield (%)[b]
1[c]	$Pd(TFA)_2$	$Cu(OAc)_2 \cdot H_2O$	–	140	0
2[c]	$Pd(TFA)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	140	19 (60)
3	$Pd(TFA)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	140	32 (55)
4	$Pd(TFA)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnBr_2$	140	0
5	$Pd(TFA)_2$	$Cu(OAc)_2 \cdot H_2O$	ZnI_2	140	0
6	$Pd(TFA)_2$	$Cu(OAc)_2 \cdot H_2O$	$FeCl_3$	140	0
7	$Pd(TFA)_2$	$Cu(OAc)_2 \cdot H_2O$	$AlCl_3$	140	0
8	$Pd(TFA)_2$	$K_2S_2O_8$	$ZnCl_2$	140	20 (63)
9	$Pd(TFA)_2$	BQ	$ZnCl_2$	140	trace
10	$Pd(TFA)_2$	Ag_2CO_3	$ZnCl_2$	140	6 (43)
11	$Pd(TFA)_2$	$Cu(TFA)_2$	$ZnCl_2$	140	24 (48)
12	$Pd(TFA)_2$	$Cu(OTf)_2$	$ZnCl_2$	140	20 (48)
13	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	140	33 (57)
14	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	120	33 (58)
15	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	100	33 (55)
16	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	90	10 (40)
17[d]	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	100	33 (51)
18[e]	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	100	29 (49)
19[f]	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	100	3
20[g]	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	100	19 (46)
21[h]	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	100	24 (47)
22[i]	$Pd(OAc)_2$	$Cu(OAc)_2 \cdot H_2O$	$ZnCl_2$	100	3

[a] All the reaction were performed with 0.05 mmol of C_{60}, 0.15 mmol of **1a**, 0.10 mmol of oxidant, 0.005 mmol of Pd-catalyst, 0.25 mmol of additive, 0.05 mmol of K_2CO_3, and 0.10 mmol of PivOH in 7 mL of 1,2-dichlorobenzene at preset temperature for 8 h. [b] Isolated yield. Values in parentheses were based on consumed C_{60}. [c] No addition of K_2CO_3 and PivOH. [d] The reaction time was 12 h. [e] **1a** was 0.10 mmol. [f] The amount of K_2CO_3 was increased to 2 equiv. [g] The amount of K_2CO_3 was reduced to 0.5 equiv. [h] The amount of PivOH was reduced to 1 equiv. [i] The amount of $ZnCl_2$ was reduced to 3 equiv.

K_2CO_3 and PivOH could not provide a higher yield (Table 1, entries 17–21). A very poor yield was obtained when the amount of $ZnCl_2$ was reduced to 3 equiv (Table 1, entry 22).

With the optimized reaction conditions in hand, the substrate scope was investigated by employing a wide array of 2-arylbenzoic acids. As shown in Table 2, 4-methoxy biphenyl-2-carboxylic acid with an electron-donating methyl group at the 4′-position exhibited good reactivity to afford the corresponding product in 42% yield (Table 2, entry 2). However, only a 22% yield was obtained with an electron-withdrawing chloro group at the 4′-position, even though the reaction temperature was increased to 140 °C (Table 2, entry 3). Similarly, when different substituent groups were situated at the 3′-position, the electronic effect was also very obvious. The methyl group performed far better than the methoxy group (Table 2, entry 4 vs 5). Good regioselectivity could be obtained due to steric factors. Furthermore, 4′-methyl-biphenyl-2-carboxylic acids with both electron-donating and -withdrawing substituents at the 4-position could be smoothly transformed into the desired products (Table 2, entries 6 and 7). 4,5,4′-Trimethyl-biphenyl-2-carboxylic acid, a multisubstituted substrate, performed the best to provide product **2h** in 46% yield (Table 2, entry 8). 4,5-Dimethoxy-4′-methyl-biphenyl-2-carboxylic acid reacted similarly to give product **2i** in 28% yield (Table 2, entry 9). Finally, the simplest 2-phenylbenzoic acid could also be employed to generate product **2j** in 33% yield (Table 2, entry 10). It should be noted that very small amounts of byproducts with higher polarity, most likely bisadducts, were also formed in these decarboxylative annulations of 2-arylbenzoic acids.

The structures of C_{60}-fused dihydrophenanthrenes **2a–j** were unambiguously characterized by MALDI-TOF MS, ^{1}H NMR, ^{13}C NMR, FT-IR, and UV–vis spectra. All of the mass spectra of these products gave the correct molecular ion peaks. The ^{13}C NMR spectra of **2a–c**, **2e**, and **2g–i** clearly exhibited no more than 27 peaks in the range of 133–157 ppm for the sp^{2}-carbons of the C_{60} cage and two peaks in the 64–65 ppm range for the two sp^{3}-carbons of the C_{60} skeleton, consistent with the C_s symmetry of their molecular structures. In the ^{13}C NMR spectrum of **2f**, there were 15 peaks including an overlapping one in the 134–157 ppm region for the 58 sp^{2}-carbons of the C_{60} cage and a line at 64.58 ppm for the two sp^{3}-carbons of the C_{60} skeleton, consistent with its C_{2v} symmetry. It should be pointed out that the very low solubility of **2d** and **2j** prevented us from obtaining their ^{13}C NMR spectra with a good signal/noise ratio. The UV–vis spectra of **2a–j** displayed characteristic peaks at around 430 nm, which is a diagnostic absorption for 1,2-adducts of C_{60} with two carbon atoms attached to the C_{60} cage.

On the basis of the observed experimental results and previous reports,[6,9,10] the plausible reaction pathways for the formation of **2a–j** are outlined in Scheme 1. Initially, the metalated palladium species **A** is produced by the Pd-catalyzed decarboxylation. Carbopalladation of C_{60} by species **A** generates intermediate **B** (*path a*), which undergoes intramolecular C–H bond activation to afford palladacycle **C**. Meanwhile, the intramolecular C–H bond activation of species **A** may form the five-membered ring palladacycle **D** (*path b*), followed by insertion of C_{60} to generate palladacycle **C** or isomeric **G**. Subsequent reductive elimination of **C** or **G** produces C_{60}-fused dihydrophenanthrenes and Pd(0). Alternatively, the reaction may involve a Pd-catalyzed carboxylate-directed C–H bond activation process, which results in the formation of the seven-membered ring palladacycle **E**. Palladacycle **E** could undergo either decarboxylation to form the five-membered ring palladacycle **D** (*path c*) or insertion of C_{60} to generate **F** (*path d*). Decarboxylation of **F** also generates **G**. The Pd(0) species is reoxidized to Pd(II) by $Cu(OAc)_2$ to complete the catalytic cycle. Although the exact role of $ZnCl_2$ remains to be determined in this procedure, we speculate that $ZnCl_2$ may facilitate the process of decarboxylation.[11]

The electrochemical properties of **2a–j** along with C_{60} and PCBM have been investigated by cyclic voltammetry (CV), and their half-wave reduction potentials are summarized in Table 3. All of their electrochemical properties are quite similar and show three reversible redox processes. Due to the two carbon atoms attached to the fullerene cage, the first reduction potentials of **2a–j** are more negative than that of C_{60} and are close to that of PCBM. Particularly, the first reduction potential (−1.171 V) of **2f** is even more cathodically shifted relative to PCBM (−1.160 V). It means that these C_{60}-fused dihydrophenanthrenes possess higher LUMO energy levels than that of PCBM and may have potential application as acceptors in organic photovoltaic devices.[12]

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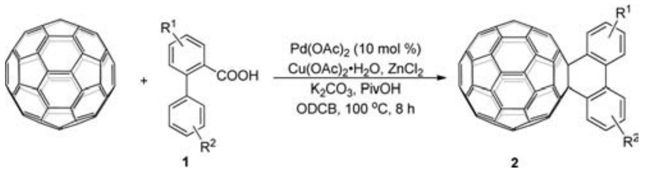
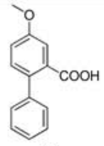
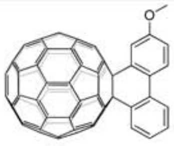
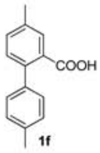
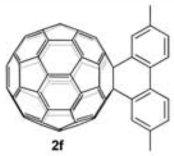
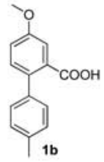
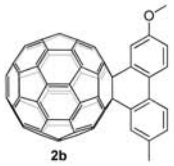
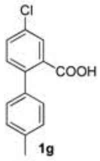
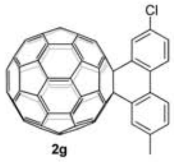
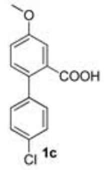
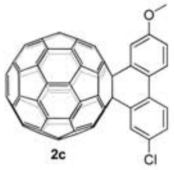
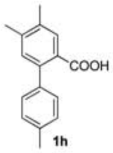
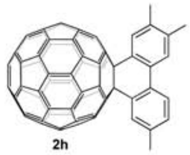
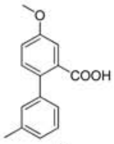
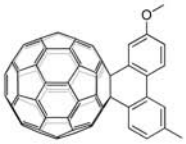
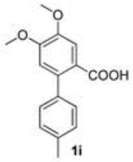
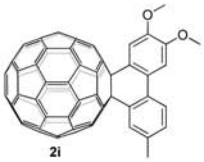
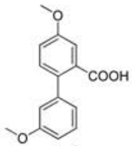
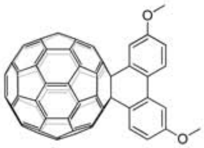
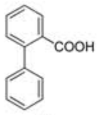
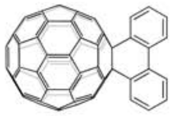
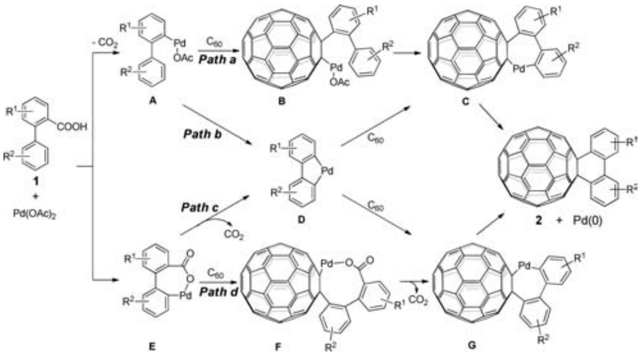
Table 2. Results for the Pd-Catalyzed Reaction of C_{60} with 2-Arylbenzoic Acids 1a–j[a]



entry	2-arylbenzoic acid **1**	product **2**	yield (%)[b]	entry	2-arylbenzoic acid **1**	product **2**	yield (%)[b]
1	 **1a**	 **2a**	33 (55)	6	 **1f**	 **2f**	37 (63)
2	 **1b**	 **2b**	42 (62)	7	 **1g**	 **2g**	25 (37)
3[c]	 **1c**	 **2c**	22 (37)	8	 **1h**	 **2h**	46 (61)
4	 **1d**	 **2d**	41 (63)	9	 **1i**	 **2i**	28 (64)
5[c]	 **1e**	 **2e**	19 (53)	10	 **1j**	 **2j**	33 (48)

[a] Unless otherwise specified, all the reactions were performed with 0.05 mmol of C_{60}, 0.15 mmol of **1**, 0.005 mmol of $Pd(OAc)_2$, 0.1 mmol of $Cu(OAc)_2 \cdot H_2O$, 0.25 mmol of $ZnCl_2$, 0.05 mmol of K_2CO_3, and 0.10 mmol of PivOH in 1,2-dichlorobenzene (7 mL) at 100 °C for 8 h. [b] Isolated yield. Values in parentheses were based on consumed C_{60}. [c] The reaction was performed at 140 °C.

Scheme 1. Proposed Reaction Mechanism



In summary, we have achieved the synthesis of C_{60}-fused dihydrophenanthrenes via the palladium-catalyzed decarboxylative annulation of 2-arylbenzoic acids with [60]fullerene. The addition of Lewis acid $ZnCl_2$ may facilitate the process of decarboxylation and is vital for the success of this formal [4 + 2] annulation reaction.

Table 3. Half-Wave Reduction Potentials (V) of C_{60}, PCBM, and C_{60}-Fused Dihydrophenanthrenes 2a–j[a]

compd	E_1	E_2	E_3
C_{60}	−1.076	−1.460	−1.925
PCBM	−1.160	−1.538	−2.050
2a	−1.154	−1.522	−2.024
2b	−1.155	−1.526	−2.033
2c	−1.136	−1.504	−2.001
2d	−1.156	−1.522	−2.027
2e	−1.156	−1.525	−2.031
2f	−1.171	−1.543	−2.048
2g	−1.139	−1.503	−1.995
2h	−1.165	−1.536	−2.036
2i	−1.160	−1.535	−2.040
2j[b]	−1.152	−1.515	−2.008

[a] Versus ferrocene/ferrocenium. Experimental conditions: 1 mM of compound and 0.1 M of $n\text{-}Bu_4NClO_4$ in anhydrous *o*-dichlorobenzene; reference electrode: SCE; working electrode: Pt; auxiliary electrode: Pt wire; scanning rate: 20 mV s^{-1}. [b] Saturated solution.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Detailed experimental procedures and characterization data, the ^{1}H NMR, ^{13}C NMR spectra, CVs, and DPVs of **2a–j**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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