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Esterification of Carboxylic Acids with Aryl Halides via the Merger of Paired Electrolysis and Nickel Catalysis

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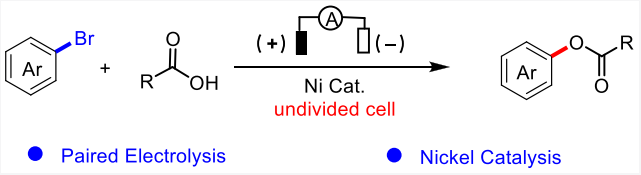
ABSTRACT: Electrochemistry has been successfully applied in metal catalysis to avoid the usage of chemical redox agents. This strategy proved to be a powerful approach to construct carbon−carbon (C−C) and carbon−heteroatom (C−X) bonds. However, most of the developed methods are based on either anodic oxidation or cathodic reduction, in which a sacrificial reaction occurs at the counter electrode. Paired electrolysis merging with metal catalysis is underdeveloped, wherein both anodic and cathodic processes are taking place simultaneously. Herein, we demonstrated that by using esterification of carboxylic acids with aryl halides via paired electrolysis using nickel as the catalyst the respective aryl esters were obtained in good to excellent yields at room temperature in an undivided electrochemical cell.



INTRODUCTION

The organic electrochemical synthesis represents an environmentally friendly method, as caustic stoichiometric chemical redox reagents which are required in the conventional methods could be reduced or prevented.[1] Additionally, electrochemical methods offer a few advantages over chemical redox agents such as tunable redox strength, innocent feature, and mechanistic investigation. In general, direct electrolysis presents higher electric potentials and undesired side reactions. Indirect electrolysis has received special attention since the reactivity and selectivity could be governed by redox mediators.[2] In particular, the use of organotransition metals as redox mediators has received tremendous attention since redox potentials can be tuned via the modification of ligand, and organotransition-metal-catalyzed reactions are well-developed. Thereby, various organotransition-metal-catalyzed anodic oxidation has been developed, including C−H functionalization,[3] and alkene functionalization,[4] despite hydrogen being generated as a byproduct in a cathodic cell (Figure 1a, left). Organotransition-metal-catalyzed cathodic reduction has been well-investigated, including reductive carboxylation of electrophiles[5] and couplings of organohalides.[6] Unfortunately, the use of a sacrificial anode is typically required (Figure 1a, right). In order to maximize the energy efficiency of the electrolysis, the merger of an organotranisiton metal with paired electrolysis is an appealing strategy, in which both cathodic reduction and anodic oxidation of the organometal species take place simultaneously to generate the desired product (Figure 1b). However, this promising strategy is underdeveloped, and only a few examples of the merger of metal catalysis with paired electrolysis are known.[7] For instance, Baran and co-workers have reported electrochemical amination of aryl halides via the merger of Ni catalysis with paired electrolysis under mild reaction conditions.[8] Recently, we have also reported C−S bond formation via paired electrolysis.[9] We have always been interested in Ni-catalyzed electrochemical reactions; we further questioned whether esterification of carboxylic acids and aryl halides could be achieved without the use of a sacrificial anode (Figure 1c). Aryl esters are commonly encountered in natural products, pharmaceuticals, and polymers.[10] Aryl esters have also attracted great interest as green and inexpensive arylating agents for the recent development of metal-catalyzed coupling reactions via C−O activation.[11] The cross-coupling between aryl halides and carboxylic acids has been achieved using expensive Pd catalysts, or/and excessive amounts of Ag salt, or phosphine-based ligand at high temperature.[12] Visible-light-driven formations of the C−O bond have been reported by several groups using kinds of photocatalysts through energy or electron transfer.[13] However, as the most controllable and environmentally benign means, electrochemistry has not been utilized in these transformations.[14] Herein, we report esterification of carboxylic acids and aryl halides via the merger of paired electrolysis and nickel catalysis (Figure 1d).

Result and Discussion. To initiate the study, we examined the electrochemical esterification of *N*-(*tert*-butoxycarbonyl)-proline (BocPro-OH) (**1a**) with 4-bromobenzoic acid methyl ester (**2a**) under various reaction conditions. To our delight, 81% isolated yield of the desired product (**3a**) could be obtained under constant-current electrolysis at 4.0 mA in the presence of 10 mol% $NiBr_2$·glyme, 20 mol% d(OMe)bpy, 2

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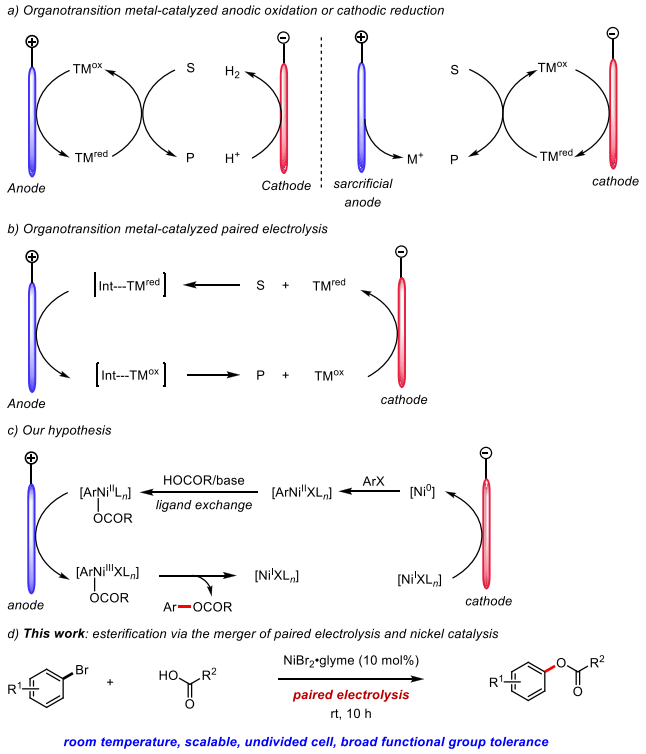
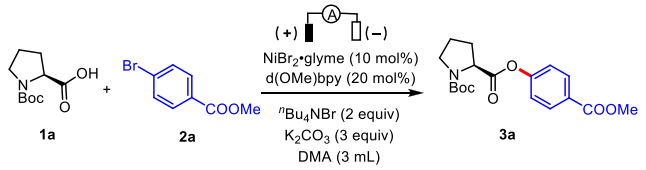


Figure 1. (a) Organotransition-metal-catalyzed anodic oxidation or cathodic reduction. (b) Organotransition-metal-catalyzed paired electrolysis. (c) Our hypothesis for esterification. (d) This work.

equiv of $^{n}Bu_4NBr$, and 3 equiv of K_2CO_3 in DMA at room temperature for 10 h (Table 1, entry 1). Variation of catalyst, ligand, and electrode led to decreased yields or no reaction

Table 1. Reaction Optimization with Substrate 1a[a]



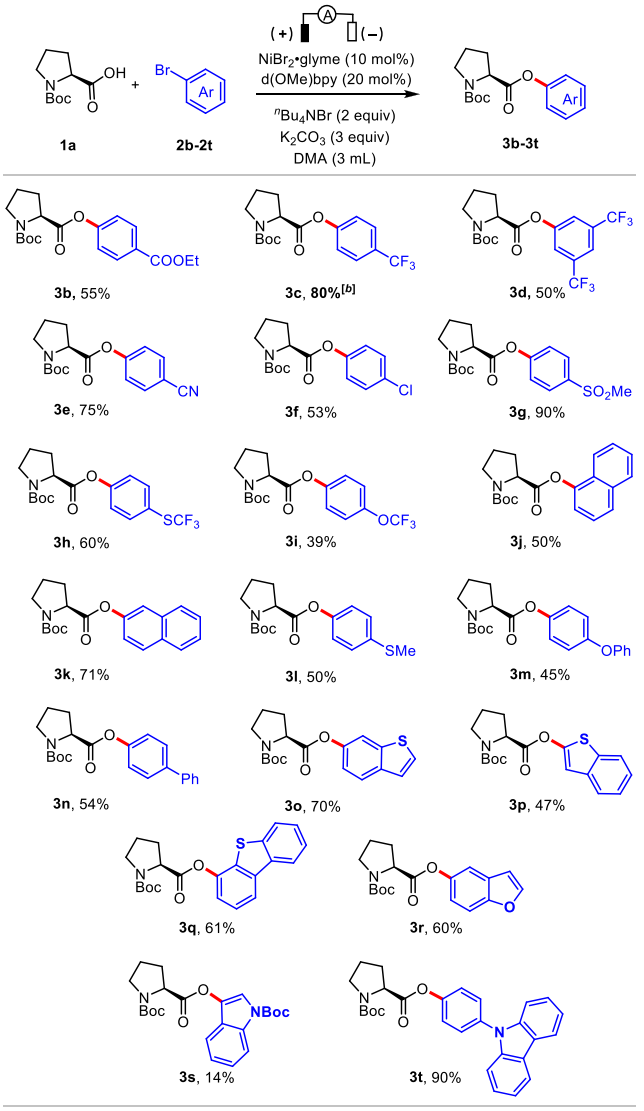
entry	variation from standard conditions	yield (%)[b]
1	none	90 (81)[c]
2	$NiBr_2$ instead of $NiBr_2$·glyme	42
3	2,2-bpy instead of d(OMe)bpy	58
4	RVC instead of Graphite	65
5	Pt−Pt instead of graphite and Ni foam	0
6	Cs_2CO_3 instead of K_2CO_3	38
7	KF instead of K_2CO_3	0
8	KO^{t}Bu instead of K_2CO_3	0
9	2,4,6-collidine instead of K_2CO_3	0
10	TMG instead of K_2CO_3	0
11	no $NiBr_2$·glyme	0
12	no electric current	0

[a]Reaction conditions: **1a** (0.3 mmol), **2a** (2.0 equiv), $NiBr_2$·glyme (10 mol%), d(OMe)bpy (20 mol%), $^{n}Bu_4NBr$ (2.0 equiv), and DMA (3 mL), in an undivided cell with a Ni-foam electrode (2.0 × 3.0 cm^2) as cathode and a graphite plate (1.0 × 2.0 cm^2) as anode, rt, 4.0 mA, 10 h. [b]Yields were determined by ^1H NMR analysis with CH_2Br_2 as an internal standard. [c]Isolated yield in parentheses. RVC = reticulated vitreous carbon. TMG = tetramethylguanidine.

(entries 2−5). The organic or inorganic bases such as collidine, TMG, KO^{t}Bu, and KF were tested. These proved inapplicable to this transformation (entries 7−10), whereas Cs_2CO_3 gave the desired product in 38% yield (entry 6). Control experiments indicate that $NiBr_2$·glyme and electrical current are necessary for this reaction (entries 11 and 12).

Next, the scope of the reaction was evaluated under the optimized reaction conditions. As shown in Scheme 1, arenes

Scheme 1. Evaluation of Aryl Bromides[a]



[a]Reaction conditions: undivided cell with a Ni-foam electrode (2.0 × 3.0 cm^2) as cathode and a graphite plate (1.0 × 2.0 cm^2) as anode, rt, 4.0 mA, 10 h. [b]Undivided cell with two platinum electrodes (1.0 × 1.0 cm^2).

substituted with a variety of functional groups such as ester, trifluoromethyl, nitrile, chloro, sulfonyl, trifluoromethylthio, and trifluoromethoxy groups were tolerated (**3b**−**3i**), affording the product in good to excellent yields. In general, aryl bromides with electron-deficient substituents reacted particularly well. In addition, various heterocycles, such as benzofuran, benzothiophene, and indole substrates, are also subjected to the electrochemical esterification protocol (**3o**−**3t**). Besides, electron-donating groups, such as methylthio and

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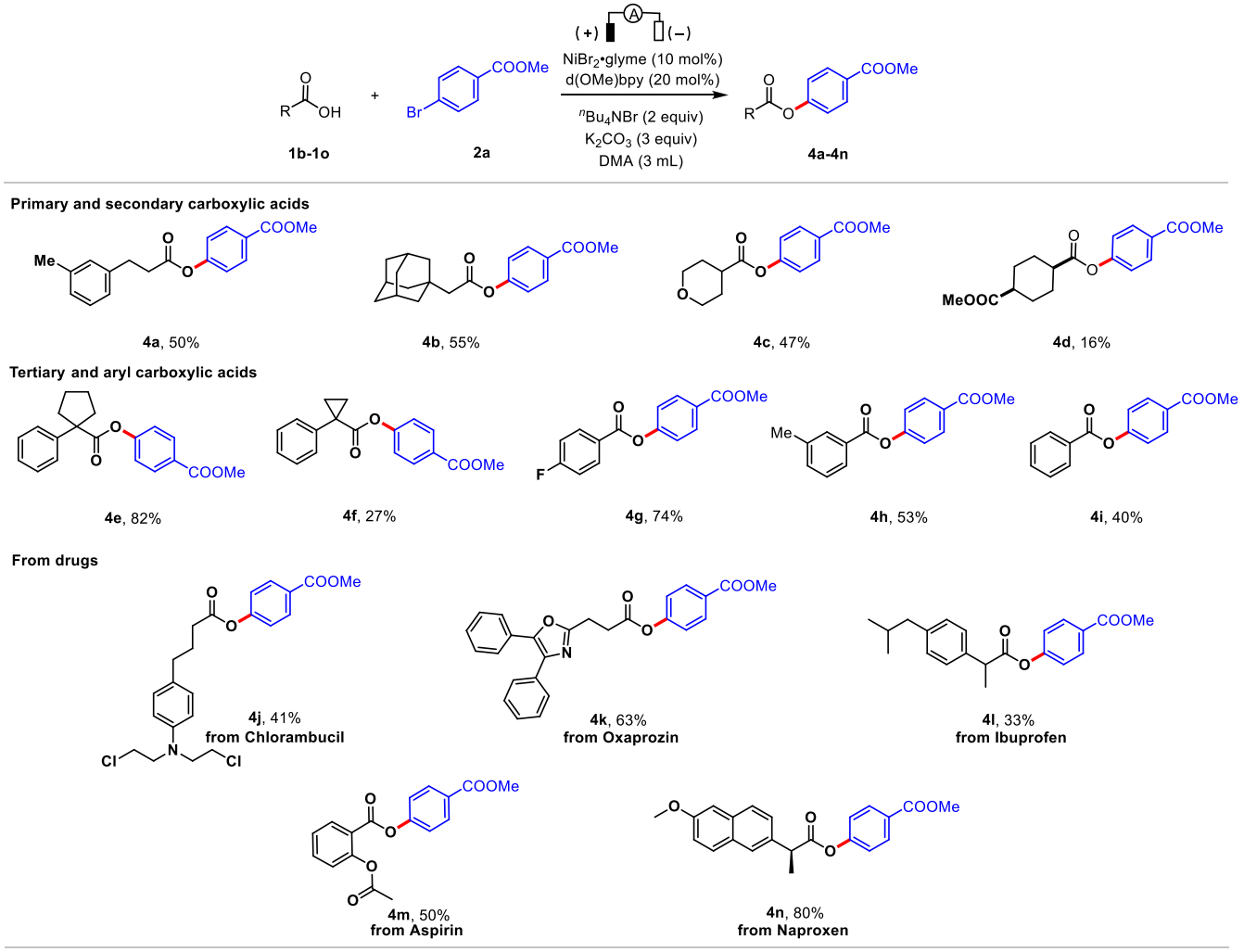
Scheme 2. Evaluation of Carboxylic Acids



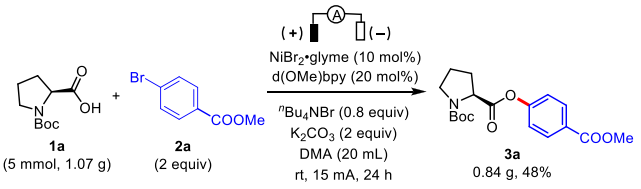
phenoxy, are also accommodated with medium yield (**3l** and **3m**).

Next, the reactivity of a series of carboxylic acids was investigated. As shown in Scheme 2, a variety of functional groups were well-tolerated in the reaction. This protocal is amenable to a wide range of primary, secondary, tertiary, and aryl acids (**4a**−**4i**). To further showcase the utility of this protocol, we subjected several drug molecules to the optimized conditions. Remarkably, chlorambucil containing alkyl chloride also succeeded in this transformation with the chlorine atoms intact (**4j**). With nitrogen and oxygen-containing heterocycles, oxaprozin (**4k**) afforded the desired product in good yield. Carboxylic acids at activated positions, including ibuprofen and naproxen (**4l** and **4n**), were all converted to their corresponding esterification analogs.

Furthermore, the preparative utility of this electrochemical esterification reaction was demonstrated by using a reaction containing 5 mmol of substrate **2a**, which furnished desired product **3a** in 48% yield (Scheme 3).

A series of cyclic voltammetric analyses were conducted to gain insight into the mechanism of this electrochemical esterification reaction (Figures 2 and S2−S6). Compared to the substrates, the nickel catalyst is more easily reduced to a lower valency (see Figure S2). In the present of 2 equiv of d(OMe)bpy, the nickel complex exhibits two quasi-reversible

Scheme 3. Gram-Scale Experiment



reductive peaks at −1.61 and −1.89 V versus $Ag/AgNO_3$ in DMA (red line, Figure 2), and they were all attributed to the reductive potential of Ni(II)/Ni(I) because of loose coordination between the ligand and nickel catalyst.[15] With the addition of **1a**, the reductive peak increased significantly. Consequently, we monitored the potentials of the cathode during electrolysis with a $Ag/AgNO_3$ reference electrode; the cathode potential stabilized at the range of −1.79 V to −1.92 V (see Figure S6). Ni(II) could be reduced to Ni(I) facilely under standard conditions.

CONCLUSION

In conclusion, we have developed Ni-catalyzed electrochemical esterification of aryl bromides in an undivided cell at room temperature. These findings provide a new avenue for transition-metal-catalyzed cross-coupling reactions. Further

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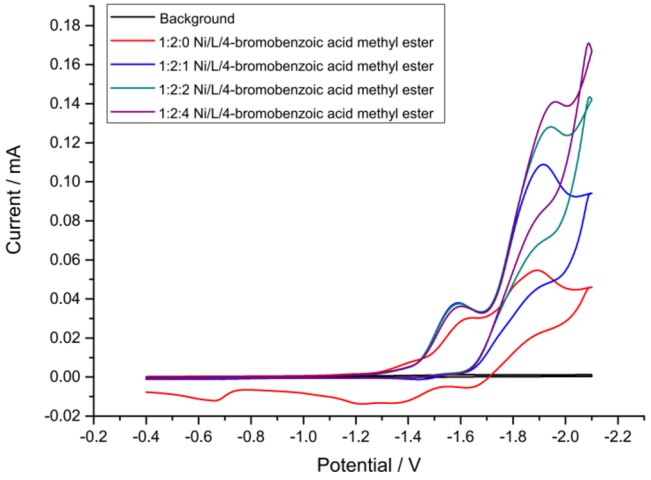

Figure 2. Cyclic voltammograms recorded on a glassy carbon electrode at 100 mVs^{-1}. All potentials are referenced against the Ag/$AgNO_3$ redox couple. (a) DMA containing 0.1 M $^nBu_4NPF_6$ (black line). (b) Solution (a) with 10 mM $NiBr_2$·glyme and 20 mM d(OMe)bpy added (red line). (c) Solution (b) with 10 mM **1a** added (blue line). (d) Solution (c) with 10 mM **1a** added (green line). (e) Solution (d) with 20 mM **1a** added (purple line).

efforts to understand the reaction mechanism are currently underway in our laboratory.

EXPERIMENTAL SECTION

General Experimental Section. Commercially available materials were used without further purification. Column chromatography was performed using either 100−200 mesh or 300−400 mesh silica gel. Visualization of spots on the TLC plate was accomplished with UV light (254 nm) and staining over an I_2 chamber. All commercial reagents of the highest purity grade were purchased from TCI, Alfa-aesar, Adamas-beta, J&K, Bide chemistry, and Energy Chemical. They were used without further purification unless specified. Nickel(II) bromide ethylene and glycol dimethyl ether were purchased from Strem chemicals and used as received. DMA (99.8%, SuperDry) was purchased from J&K and was used without further purification. ^1H NMR and ^{13}C NMR spectra were recorded on Agilent AV 400, Bruker 400, and Varian Inova 400 (400 and 100 MHz, respectively). ^{19}F NMR spectra were recorded on Agilent AV 400 and Varian Inova 400 (376 MHz) instrument. The peaks were internally referenced to TMS (0.00 ppm) or residual undeuterated solvent signal. The following abbreviations were used to explain multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, and br = broad. Infrared spectra were obtained on a Bio-Rad FTS-185 instrument. High-resolution mass spectra (HRMS) were recorded at the Center for Mass Spectrometry, Shanghai Institute of Organic Chemistry. Analytical and spectral data of all those known compounds exactly match the reported values.

General Procedure for Electrochemical Esterification. In a nitrogen-filled glovebox, to an oven-dried 10 mL hydrogenation tube charged with a stir bar were added aryl bromide **1a−1t** (0.6 mmol), carboxylic acids **2a−2n** (64.5 mg, 0.3 mmol), $NiBr_2$·glyme (9.3 mg, 0.03 mmol), d(OMe)bpy (13 mg, 0.06 mmol), $^nBu_4NBr$ (193.5 mg, 0.6 mmol), and K_2CO_3 (126 mg, 0.9 mmol) to the electrochemical cell. The tube was installed with a Ni foam (2.0 × 3.0 cm^2) as the cathode and graphite flake (1.0 × 2.0 cm^2) as an anode. The reaction mixture was vigorously stirred and electrolyzed under a constant current of 4 mA until the complete consumption of the starting materials as judged by TLC (about 10 h). After the reaction, the aqueous layer was extracted with EtOAc (3 × 10 mL), and the combined organics were washed with saturated brine (3 × 20 mL), dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The crude product was purified by column chromatography to furnish the desired product.

*1-(tert-Butyl)-2-(4-(methoxycarbonyl)phenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3a**).*[13c] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (85.0 mg, 81%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.06 (m, 2H), 7.18 (m, 2H), 4.53−4.43(m, 1H), 3.90 (m, 3H), 3.64−3.41 (m, 2H), 2.43−1.91 (m, 4H), 1.46 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.1) 171.0, (166.3) 166.1, (154.4) 154.1, 153.6, 131.2 (131.0), 127.8, (121.5) 121.1, 80.3, 59.1 (59.0), 52.2 (52.1), (46.6) 46.4, (31.0) 29.9, 28.3, (24.5) 23.7.

*1-(tert-Butyl)-2-(4-(ethoxycarbonyl)phenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3b**)^{new}.* Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (60.4 mg, 55%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.05 (m, 2H), 7.16 (m, 2H), 4.52−4.42 (m, 1H), 4.38−4.32 (m, 2H), 3.69−3.36 (m, 2H), 2.48−1.80 (m, 4H), 1.44 (m, 9H), 1.36 (t, J = 7.2, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.1, 165.7, (154.4) 154.1, 153.6, 131.2 (131.1), 128.2, (121.5) 121.1, (80.3) 80.1, 61.1 (61.0), 59.2 (59.1), (46.6) 46.5, 31.0 (30.0), 28.4, (24.5) 23.7, 14.3. IR (neat): 2978, 1668, 1412, 1366, 1272, 1159, 888, 772 cm^{-1}. HRMS (ESI): calcd for $C_{19}H_{25}NO_6Na$ $[M + Na]^+$: 386.1574. Found: 386.1578.

*1-(tert-Butyl)-2-(4-(trifluoromethyl)phenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3c**).*[13c] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (86.2 mg, 80%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.72−7.53 (m, 2H), 7.23 (m, 3H), 4.48 (m, 1H), 3.74−3.36 (m, 2H), 2.52−2.24 (m, 1H), 2.21−1.81 (m, 3H), 1.45 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.2) 171.1, (154.4) 153.6, (153.2) 153.0, 128.2 (128.0) (q, C−F, $^2J_{C-F}$ = 33.4 Hz), 126.8 (126.6) (q, C−F, $^3J_{C-F}$ = 3.8 Hz), (123.8) 123.7 (q, C−F, $^1J_{C-F}$ = 272.9 Hz), (122.0) 121.6, 80.3 (80.1), 59.1 (59.0), (46.6) 46.4, 30.9 (29.9), 28.3, (24.5) 23.64. ^{19}F NMR (376 MHz, $CDCl_3$) δ −62.30, −62.35.

*2-(3,5-Bis(trifluoromethyl)phenyl)-1-(tert-butyl)(S)-pyrrolidine-1,2-dicarboxylate (**3d**)^{new}.* Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (64.1 mg, 50%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, J = 12.8 Hz, 1H), 7.60 (d, J = 17.2 Hz, 2H), 4.50 (m, 1H), 3.54 (m, 2H), 2.32 (m, 1H), 2.07 (m, 3H), 1.45 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.0 (170.9), 154.5 (153.5), 151.3 (151.1), (133.1) 132.8 (q, C−F, $^2J_{C-F}$ = 34.0 Hz), 122.7 (122.6) (q, C−F, $^1J_{C-F}$ = 271.0 Hz), 122.5 (122.0), 119.6 (m), (80.5) 80.4, 59.0, 46.6 (46.5), (30.9) 29.8, 28.3, 24.6 (23.7). ^{19}F NMR (376 MHz, $CDCl_3$) δ −63.13, −63.22. IR (neat): 2982, 1721, 1664, 1420, 1276, 1165, 1124, 1000, 876, 702, 681 cm^{-1}. HRMS (ESI): calcd for $C_{18}H_{19}NO_4F_6Na$ $[M + Na]^+$: 450.1110. Found: 450.1106.

*1-(tert-Butyl)-2-(4-cyanophenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3e**).*[13c] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (71.7 mg, 75%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.69 (m, 2H), 7.27 (m, 2H, contains residual solvent signal of $CDCl_3$), 4.53−4.45 (m, 1H), 3.65−3.44 (m, 2H), 2.46−2.32 (m, 1H), 2.24−1.91 (m, 3H), 1.46 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (170.9) 170.8, (154.5) 154.1, (153.8) 153.5, (133.7) 133.6, (122.6) 122.2, (118.2) 118.1, (109.9) 109.7, (80.4) 80.2, (59.1) 59.0, (46.6) 46.4, 31.0 (29.9), 28.4, (24.6) 23.6.

*1-(tert-Butyl)-2-(4-chlorophenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3f**).*[13c] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (51.6 mg, 53%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.51−7.31 (m, 2H), 7.07−6.97 (m, 2H), 4.51−4.42 (m, 1H), 3.64−3.41 (m, 2H), 2.43−2.28 (m, 1H), 2.19−1.89 (m, 2H), 1.47−1.45 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.5) 171.4, (154.5) 153.7, (149.2) 149.1, (132.6) 132.4, (131.3) 131.2, (129.6) 129.4, 123.3, (122.9) 122.5, 80.3, (59.2) 59.1, (46.6) 46.5, 31.0 (30.0), 28.4, (24.6), 23.7.

*1-(tert-Butyl)-2-(4-(methylsulfonyl)phenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3g**)^{new}.* Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (99.6 mg, 90%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.01−7.95 (m, 2H), 7.36−7.31 (m, 2H), 4.54−4.46 (m, 1H), 3.66−3.45 (m, 2H), 3.07−3.06 (m, 3H), 2.47−2.33 (m, 1H), 2.22−1.94 (m, 3H), 1.48−1.46 (m, 9H).

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$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.1) 171.0, (154.9) 154.6, (154.5) 153.6, (138.0) 137.8, (129.3) 129.2, (122.7) 122.3, (80.4) 80.3, (59.1) 59.1, 46.7 (46.5), 44.6, 31.0 (30.0), 28.4, (24.6) 23.7. IR (neat): 2973, 1697, 1587, 1398, 1291, 1120, 963, 763, 537, 519 cm^{-1}. HRMS (ESI): calcd for $C_{17}H_{23}NO_6NaS$ $[M + Na]^+$: 392.1138. Found: 392.1137.

*1-(tert-Butyl)-2-(4-((trifluoromethyl)thio)phenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3h**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (70.6 mg, 60%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.70−7.65 (m, 2H), 7.22−7.17 (m, 2H), 4.53−4.44 (m, 1H), 3.65−3.43 (m, 2H), 2.44−2.30 (m, 1H), 2.20−1.92 (m, 3H), 1.47 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.2) 171.1, (154.5) 153.6, (153.0) 152.8, 137.8 (137.7), 129.4 (q, C−F, $^1J_{C-F}$ = 308.4 Hz), (122.7) 122.4, 121.6 (121.3), 80.3 (80.2), 59.2 (59.1), (46.6) 46.5, 31.0 (30.0), 28.4, (24.6) 23.7. ^{19}F NMR (376 MHz, $CDCl_3$) δ −42.92, −42.99. IR (neat): 2980, 1720, 1664, 1601, 1416, 1154, 1113, 834, 521 cm^{-1}. HRMS (ESI): calcd for $C_{17}H_{20}NO_4F_3NaS$ $[M + Na]^+$: 414.0957. Found: 414.0948.

*1-(tert-Butyl)-2-(4-(trifluoromethoxy)phenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3i**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (43.6 mg, 39%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.25−7.19 (m, 2H), 7.16−7.11 (m, 2H), 4.52−4.43 (m, 1H), 3.64−3.42 (m, 2H), 2.43−2.29 (m, 1H), 2.20−1.91 (m, 3H), 1.46 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.5) 171.4, (154.5) 153.7, (149.0) 148.8, 146.6, (122.8) 122.5, 122.2 (122.1), 120.4 (q, C−F, $^1J_{C-F}$ = 258.5 Hz), 80.3 (80.1), 59.1 (59.0), (46.6) 46.5, 31.0 (30.0), 28.4, (24.5) 23.7. ^{19}F NMR (376 MHz, $CDCl_3$) δ −58.18. IR (neat): 2980, 1721, 1667, 1510, 1416, 1366, 1154, 888, 592 cm^{-1}. HRMS (ESI): calcd for $C_{17}H_{20}NO_5F_3Na$ $[M + Na]^+$: 398.1186. Found: 398.1182.

*1-(tert-Butyl)-2-(naphthalen-1-yl)(S)-pyrrolidine-1,2-dicarboxylate (**3j**).*[16] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (50.5 mg, 50%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.06−7.84 (m, 2H), 7.76−7.72 (m, 1H), 7.52−7.43 (m, 3H), 7.28−7.25 (m, 1H, contains residual solvent signal of $CDCl_3$), 4.73−4.65 (m, 1H), 3.72−3.48 (m, 2H), 2.55−2.28 (m, 2H), 2.21−1.97 (m, 2H), 1.52−1.51 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.8) 171.5, (154.6) 153.9, (146.8) 146.4, 134.7 (134.6), 128.1 (127.8), 127.0 (126.7), 126.6 (126.5),126.4, 126.1 (126.1), 125.4 (125.3), 121.7, 121.1, (117.9) 117.6, 80.5 (80.1), 59.3 (59.3), (46.7) 46.5, 31.4 (30.3), 28.5, (24.7) 23.8. HRMS (ESI): calcd for $C_{20}H_{23}NO_4Na$ $[M + Na]^+$: 364.1519. Found: 364.1512.

*1-(tert-Butyl)-2-(naphthalen-2-yl)(S)-pyrrolidine-1,2-dicarboxylate (**3k**).*[17] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (72.2 mg, 71%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.87−7.78 (m, 3H), 7.59−7.56 (m, 1H), 7.51−7.41 (m, 2H), 7.28−7.21 (m, 1H, contains residual solvent signal of $CDCl_3$), 4.60−4.49 (m, 1H), 3.69−3.43 (m, 2H), 2.46−2.31 (m, 1H), 2.27−2.17 (m, 1H), 2.12−2.03 (m, 1H), 2.00−1.90 (m, 1H), 1.49 (s, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.8, (154.5) 153.8, (148.5) 148.3, 133.7, 131.5, 129.5 (129.4), 127.8 (127.8), 127.7 (127.6), 126.7 (126.5), 125.8 (125.7), (121.1) 120.7, (118.5) 118.1, 80.3 (80.0), 59.3 (59.2), (46.7) 46.5, 31.1 (30.1), 28.5, (24.6) 23.8. HRMS (ESI): calcd for $C_{20}H_{23}NO_4Na$ $[M + Na]^+$: 364.1519. Found: 364.1519.

*1-(tert-Butyl)-2-(4-(methylthio)phenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3l**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (50.0 mg, 50%). M.p.: 76.3−77.4 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 7.29−7.24 (m, 2H, contains residual solvent signal of $CDCl_3$), 7.06−7.01 (m, 2H), 4.52−4.42 (m, 1H), 3.65−3.41 (m, 2H), 2.48−2.46 (m, 3H), 2.42−2.28 (m, 1H), 2.20−1.89 (m, 3H), 1.48−1.46 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.6, (154.5) 153.7, (148.6) 148.3, 135.9 (135.6), 128.0, (122.0) 121.6, 80.2 (80.0), 59.2 (59.1), (46.6) 46.5, 31.1 (30.0), 28.4, (24.5) 23.7, (16.6) 16.5. IR (neat): 2970, 2920, 1766, 1704, 1487, 1392, 1202, 1167, 938, 860, 810 cm^{-1}. HRMS (ESI): calcd for $C_{17}H_{23}NO_4NaS$ $[M + Na]^+$: 360.1240. Found: 360.1234.

*1-(tert-Butyl)-2-(4-phenoxyphenyl)(S)-pyrrolidine-1,2-dicarboxylate (**3m**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (51.1 mg, 45%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.36−7.30 (m, 2H), 7.13−6.98 (m, 7H), 4.53−4.43 (m, 1H), 3.66−3.42 (m, 2H), 2.43−2.29 (m, 1H), 2.20−1.89 (m, 1H), 1.48−1.47 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.8, (157.3) 157.1, 154.9 (154.7), (154.5) 153.7, (146.3) 146.0, 129.8 (129.8), 123.5 (123.3), (122.6) 122.3, (119.6) 119.6, 118.9 (118.7), 80.2 (80.0), 59.2 (59.1), (46.7) 46.5, 31.1 (30.0), 28.5, (24.5) 23.7. IR (neat): 2977, 1666, 1486, 1414, 1216, 1119, 845, 750, 691 cm^{-1}. HRMS (ESI): calcd for $C_{22}H_{25}NO_5Na$ $[M + Na]^+$: 406.1613. Found: 406.1625.

*2-([1,1′-Biphenyl]-4-yl)-1-(tert-butyl)(S)-pyrrolidine-1,2-dicarboxylate (**3n**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (59.5 mg, 54%). M.p.: 137.9−139.9 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 7.64−7.53 (m, 1H), 7.47−7.40 (m, 2H), 7.38−7.32 (m, 1H), 7.22−7.15 (m, 2H), 4.59−4.43 (m, 1H), 3.70−3.41 (m, 2H), 2.46−2.29 (m, 1H), 2.25−1.91 (m, 3H), 1.49 (s, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.7, (154.4) 153.7, (150.2) 149.9, (140.4) 140.2, 139.1 (138.9), 128.8 (128.7), 128.2 (128.1), 127.4 (127.2), (121.7) 121.4, 80.2 (80.0), 59.2 (59.0), (46.6) 46.4, 31.0 (30.0), 28.4, (24.5) 23.7. IR (neat): 2958, 2922, 1769, 1704, 1394, 1166, 1118, 923, 865, 759, 688 cm^{-1}. HRMS (ESI): calcd for $C_{22}H_{25}NO_4Na$ $[M + Na]^+$: 390.1676. Found: 390.1685.

*2-(Benzo[b]thiophen-6-yl)-1-(tert-butyl)(S)-pyrrolidine-1,2-dicarboxylate (**3o**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (72.0 mg, 70%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.80−7.75 (m, 1H), 7.65−7.61 (m, 1H), 7.42−7.37 (m, 1H), 7.30−7.27 (m, 1H), 7.14−7.08 (m, 1H), 4.56−4.46 (m, 1H), 3.66−3.41 (m, 2H), 2.43−2.29 (m, 1H), 2.23−2.13 (m, 1H), 2.09−1.90 (m, 2H), 1.49−1.48 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.8, (154.5) 153.8, (147.9) 147.7, 140.3 (140.2), 137.6 (137.5), 126.9 (126.7), 124.1 (124.0), 123.5 (123.4), (118.8) 118.4, (115.0) 114.7, 80.2 (80.0), 59.2 (59.1), (46.7) 46.5, 31.1 (30.1), 28.5, (24.5) 23.7. IR (neat): 2974, 2879, 1765, 1692, 1461, 1392, 1134, 1084 cm^{-1}. HRMS (ESI): calcd for $C_{18}H_{21}NO_4NaS$ $[M + Na]^+$: 370.1083. Found: 370.1080.

*2-(Benzo[b]thiophen-2-yl)-1-(tert-butyl)(S)-pyrrolidine-1,2-dicarboxylate (**3p**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (48.7 mg, 47%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.82−7.67 (m, 2H), 7.48 (s, 0.5H), 7.40−7.34 (m, 2.5H), 4.66−4.53 (m, 1H), 3.73−3.46 (m, 2H), 2.48−2.34 (m, 1H), 2.27−2.20 (m, 1H), 2.13−1.95 (m, 2H), 1.49 (s, 4H), 1.40 (s, 5H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (170.6) 170.5, (154.5) 153.7, (140.7) 140.3, (136.9) 136.7, (132.1) 131.9, 125.3 (125.1), 124.4 (124.3), 122.9 (122.8), (120.8) 120.4, (112.0) 111.4, 80.5 (80.2), 59.4 (59.1), (46.7) 46.5, 31.2 (30.2), 28.5, 28.3, (24.6) 23.8. IR (neat): 2976, 1696, 1651, 1394, 1366, 1158, 1126, 734 cm^{-1}. HRMS (ESI): calcd for $C_{18}H_{21}NO_4NaS$ $[M + Na]^+$: 370.1083. Found: 370.1084.

*1-(tert-Butyl)-2-(dibenzo[b,d]thiophen-4-yl)(S)-pyrrolidine-1,2-dicarboxylate (**3q**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (72.6 mg, 61%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.06−8.04 (m, 1H), 7.95−7.91 (m, 1H), 7.76−7.73 (m, 1H), 7.42−7.36 (m, 3H), 7.27−7.17 (m, 1H, contains residual solvent signal of $CDCl_3$), 4.61−4.50 (m, 1H), 3.65−3.38 (m, 2H), 2.45−2.25 (m, 2H), 2.14−1.92 (m, 2H), 1.43 (s, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 170.6, (154.5) 153.8, (145.6) 145.5, (139.3) 139.1, 138.2 (138.0), (135.6) 135.5, (131.7) 131.5, 127.3 (127.1), 125.5, 124.8 (124.6), 122.9, 122.0 (121.9), (119.6) 119.1, (119.0) 118.9, 80.4 (80.1), 59.3 (59.2), (46.7) 46.5, 31.3 (30.3), 28.5, (24.6) 23.8. IR (neat): 2975, 1717, 1571, 1413, 1158, 1129, 749 cm^{-1}. HRMS (ESI): calcd for $C_{22}H_{23}NO_4NaS$ $[M + Na]^+$: 420.1240. Found: 420.1236.

*2-(Benzofuran-5-yl)-1-(tert-butyl)(S)-pyrrolidine-1,2-dicarboxylate (**3r**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (59.6 mg, 60%). ^1H NMR (400 MHz, $CDCl_3$) δ 7.64−7.61 (m, 1H), 7.48−7.43 (m, 1H), 7.34−7.30 (m, 1H), 7.03−6.97 (m, 1H), 6.74−6.71 (m,

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1H), 4.55−4.45 (m, 1H), 3.66−3.41 (m, 2H), 2.41−2.28 (m, 1H), 2.22−2.13 (m, 1H), 2.09−1.88 (m, 2H), 1.48−1.46 (m, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (172.1) 172.0, (154.5) 153.8, 152.6, 146.4 (146.4), (146.2) 146.2, 128.1 (128.0), (118.0) 117.6, (113.6) 113.3, 111.9 (111.7), 106.9, 80.2 (80.0), 59.2 (59.1), (46.7) 46.5, 31.1 (30.1), 28.5, (24.5) 23.7. IR (neat): 2977, 2881, 1749, 1667, 1394, 1366, 1156, 1127, 762, 732 cm^{-1}. HRMS (ESI): calcd for $C_{18}H_{21}NO_5Na$ $[M + Na]^+$: 354.1312. Found: 354.1312.

*2-(1-(tert-Butoxycarbonyl)-1H-indol-3-yl)-1-(tert-butyl)(S)-pyrrolidine-1,2-dicarboxylate (**3s**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (18.1 mg, 14%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.16 (bra, 1H), 7.83−7.72 (m, 1H), 7.55−7.47 (m, 1H), 7.34 (q, J = 8.4 Hz, 1H), 7.27−7.21 (m, 1H, contains residual solvent signal of $CDCl_3$), 4.66−4.49 (m, 1H), 3.71−3.44 (m, 2H), 2.47−2.31 (m, 1H), 2.24−1.92 (m, 3H), 1.69−1.61 (m, 9H), 1.48 (s, 4H), 1.39 (s, 5H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (170.4) 170.3, (154.5) 153.8, 149.7, (133.3) 133.2, (132.9) 132.7, 125.4 (125.2), (123.6) 123.3, 122.8 (122.7), (117.8) 117.5, 115.3 (115.2), (114.4) 113.9, 84.0 (83.8), 80.4 (80.2), 59.3 (59.0), (46.7) 46.5, 31.2 (30.2), 28.5, 28.3, 28.2, (24.5) 23.8. IR (neat): 2957, 2924, 1695, 1587, 1524, 1367, 1249, 1151, 755 cm^{-1}. HRMS (ESI): calcd for $C_{23}H_{30}N_2O_6Na$ $[M + Na]^+$: 453.1996. Found: 453.2003.

*2-(4-(9H-Carbazol-9-yl)phenyl)-1-(tert-butyl)(S)-pyrrolidine-1,2-dicarboxylate (**3t**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (121.0 mg, 90%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.17−8.15 (m, 2H), 7.61−7.56 (m, 2H), 7.45−7.28 (m, 8H), 4.62−4.52 (m, 1H), 3.73−3.48 (m, 2H), 2.50−2.36 (m, 1H), 2.28−2.19 (m, 1H), 2.15−1.98 (m, 2H), 1.54 (s, 9H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ (171.7) 171.6, (154.6) 153.8, (149.7) 149.5, (140.9) 140.9, 135.4 (135.2), 128.3 (128.1), 126.1 (126.0), 123.4 (123.4), (123.0) 122.7, 120.4 (120.3), 120.1 (120.0), (109.7) 109.7, 80.4 (80.2), 59.3 (59.2), (46.7) 46.5, 31.2 (30.1), 28.5, (24.6) 23.8. IR (neat): 2976, 1665, 1515, 1452, 1414, 1366, 1229, 1159, 910, 834, 749, 724 cm^{-1}. HRMS (ESI): calcd for $C_{28}H_{28}N_2O_4Na$ $[M + Na]^+$: 479.1941. Found: 479.1939.

*Methyl-4-((3-(m-tolyl)propanoyl)oxy)benzoate (**4a**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (44.7 mg, 50%). M.p.: 72.8−74.6 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 8.06 (d, J = 8.8 Hz, 2H), 7.22 (t, J = 7.6 Hz, 1H), 7.12−7.03 (m, 5H), 3.91 (s, 3H), 3.05 (t, J = 7.6 Hz, 2H), 2.89 (t, J = 8.0 Hz, 2H), 2.35 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 170.9, 166.3, 154.3, 139.9, 138.3, 131.2, 129.2, 128.6, 127.7, 127.3, 125.4, 121.6, 52.2, 36.1, 30.8, 21.4. IR (neat): 2952, 2918, 2849, 1746, 1719, 1602, 1437, 1376, 1273, 1220, 1145, 1105 cm^{-1}. HRMS (ESI): calcd for $C_{18}H_{18}O_4Na$ $[M + Na]^+$: 321.1097. Found: 321.1097.

*Methyl-4-(2-((3r,5r,7r)-adamantan-1-yl)acetoxy)benzoate (**4b**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (53.7 mg, 55%). M.p.: 100.5−101.2 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 8.06 (d, J = 8.8 Hz, 2H), 7.16 (d, J = 8.8 Hz, 2H), 3.91 (s, 3H), 2.32 (s, 2H), 2.09−1.97 (m, 3H), 1.76−1.65 (m, 12H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 169.6, 166.4, 154.4, 131.1, 127.6, 121.8, 52.2, 48.7, 42.5, 36.7, 33.3, 28.6. IR (neat): 2897, 2846, 1751, 1721, 1599, 1273, 1185, 1156, 1094 cm^{-1}. HRMS (ESI): calcd for $C_{20}H_{25}O_4$ $[M + H]^+$: 329.1747. Found: 329.1743.

*4-(Methoxycarbonyl)phenyl-tetrahydro-2H-pyran-4-carboxylate (**4c**)*.[13a] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (37.0 mg, 47%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.07 (d, J = 8.8 Hz, 2H), 7.16 (d, J = 8.8 Hz, 2H), 4.03 (dt, J = 11.6, 3.6 Hz, 2H), 3.91 (s, 3H), 3.56−3.45 (td, J = 11.2, 2.8 Hz, 2H), 2.82 (tt, J = 10.8, 4.4 Hz, 1H), 2.06−1.85 (m, 4H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 172.4, 166.3, 154.3, 131.2, 127.8, 121.5, 67.0, 52.2, 40.3, 28.5.

*1-(4-(Methoxycarbonyl)phenyl)-4-methyl-(1s,4s)-cyclohexane-1,4-dicarboxylate (**4d**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (15.4 mg, 16%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.04 (d, J = 8.8 Hz, 2H), 7.12 (d, J = 8.8 Hz, 2H), 3.88 (s, 3H), 3.67 (s, 3H), 2.77−2.69 (m, 1H), 2.57−2.42 (m, 1H), 2.06−1.92 (m, 4H), 1.85−1.69 (m, 4H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 175.2, 172.9, 166.2, 154.4, 131.0, 127.5, 121.5, 52.1, 51.6, 42.4, 42.2, 40.7, 40.4, 27.8, 25.8. IR (neat): 2951, 2919, 2849, 1752, 1723, 1270, 1203, 1128, 1107, 1023, 750 cm^{-1}. HRMS (ESI): calcd for $C_{17}H_{20}O_6Na$ $[M + Na]^+$: 343.1152. Found: 343.1154.

*Methyl-4-((1-phenylcyclopentane-1-carbonyl)oxy)benzoate (**4e**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (79.4 mg, 82%). M.p.: 85.2−86.6 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 7.99 (d, J = 8.8 Hz, 2H), 7.47 (d, J = 7.6 Hz, 2H), 7.36 (m, 2H), 7.32−7.23 (m, 1H, contains residual solvent signal of $CDCl_3$), 6.97 (d, J = 8.8 Hz, 2H), 3.88 (s, 3H), 2.79 (m, 2H), 2.06 (m, 2H), 1.83 (m, 4H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 174.0, 166.3, 154.8, 142.3, 131.0, 128.5, 127.5, 127.1, 126.8, 121.3, 59.4, 52.1, 36.0, 23.6. IR (neat): 2954, 2924, 1747, 1720, 1275, 1196, 1096, 694 cm^{-1}. HRMS (ESI): calcd for $C_{20}H_{21}O_4$ $[M + H]^+$: 325.1434. Found: 325.1433.

*Methyl-4-((1-phenylcyclopropane-1-carbonyl)oxy)benzoate (**4f**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (23.5 mg, 27%). M.p.: 99.1−101.6 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 8.01 (d, J = 8.8 Hz, 2H), 7.49−7.42 (m, 2H), 7.39−7.32 (m, 2H), 7.32−7.27 (m, 1H), 7.10 (d, J = 8.8 Hz, 2H), 3.89 (s, 4H), 1.79 (m, 2H), 1.38 (m, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 172.8, 166.3, 154.7, 138.7, 131.0, 130.6, 128.4, 127.6, 127.5, 121.5, 52.2, 29.3, 17.5. IR (neat): 2919, 2849, 1716, 1275, 1198, 1164, 1138, 1110, 1087 cm^{-1}. HRMS (ESI): calcd for $C_{18}H_{17}O_4$ $[M + H]^+$: 297.1121. Found: 297.1126.

*4-(Methoxycarbonyl)phenyl-4-fluorobenzoate (**4g**)*.[13a] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (60.7 mg, 74%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.22 (m, 2H), 8.12 (d, J = 8.8 Hz, 2H), 7.30 (d, J = 8.8 Hz, 2H), 7.19 (m, 2H), 3.93 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 166.3 (d, C−F, $^1J_{C-F}$ = 256.5 Hz), 166.3, 163.6, 154.4, 132.9 (d, C−F, $^3J_{C-F}$ = 9.5 Hz), 131.2, 127.9, 125.3 (d, C−F, $^4J_{C-F}$ = 2.9 Hz), 121.7, 115.9 (d, C−F, $^2J_{C-F}$ = 22.1 Hz), 52.2. ^{19}F NMR (376 MHz, $CDCl_3$) δ −103.77.

*4-(Methoxycarbonyl)phenyl-3-methylbenzoate (**4h**)*.[18] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (43.3 mg, 53%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.13 (d, J = 8.4 Hz, 2H), 8.00 (m, 2H), 7.49−7.37 (m, 2H), 7.30 (d, J = 8.8 Hz, 2H), 3.93 (s, 3H), 2.45 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 166.3, 164.8, 154.7, 138.5, 134.6, 131.2, 130.7, 129.0, 128.5, 127.7, 127.4, 121.8, 52.2, 21.3. HRMS (ESI): calcd for $C_{16}H_{15}O_4$ $[M + H]^+$: 271.0965. Found: 271.0965.

*Methyl-4-(benzoyloxy)benzoate (**4i**)*.[13c] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (30.7 mg, 40%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.21 (d, J = 7.2 Hz, 2H), 8.13 (d, J = 8.8 Hz, 2H), 7.66 (m, 1H), 7.57−7.50 (m, 2H), 7.31 (d, J = 8.8 Hz, 2H), 3.93 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 166.3, 164.6, 154.6, 133.9, 131.2, 130.2, 129.1, 128.6, 127.7, 121.7, 52.2.

*Methyl-4-((4-(4-(bis(2-chloroethyl)amino)phenyl)butanoyl)oxy)-benzoate (**4j**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (54.0 mg, 41%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.07 (d, J = 8.8 Hz, 2H), 7.13 (m, 4H), 6.65 (d, J = 8.8 Hz, 2H), 3.92 (s, 4H), 3.67 (m, 8H), 2.62 (m, 4H), 2.05 (m, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 171.4, 166.3, 154.3, 144.4, 131.1, 130.1, 129.7, 127.6, 121.5, 112.2, 53.5, 52.2, 40.5, 33.9, 33.6, 26.5. IR (neat): 2951, 1756, 1719, 1604, 1517, 1275, 1199, 1160, 1101 cm^{-1}. HRMS (ESI): calcd for $C_{22}H_{26}NO_4Cl_2$ $[M + H]^+$: 438.1233. Found: 438.1231.

*Methyl-4-((3-(4,5-diphenyloxazol-2-yl)propanoyl)oxy)benzoate (**4k**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (81.0 mg, 63%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.06 (d, J = 8.8 Hz, 2H), 7.65 (m, 2H), 7.59 (m, 2H), 7.36 (m, 6H), 7.20 (d, J = 8.8 Hz, 2H), 3.91 (s, 3H), 3.31 (m, 2H), 3.19 (m, 2H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 169.1, 165.3, 160.2, 153.2, 144.6, 134.2, 131.3, 130.1, 127.9, 127.7, 127.6, 127.5, 127.1, 126.8, 126.7, 125.5, 120.5, 51.2, 30.2, 22.4. IR (neat):

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2949, 1716, 1605, 1435, 1274, 1162, 1110, 762, 694 cm^{-1}. HRMS (ESI): calcd for $C_{26}H_{22}NO_5$ $[M + H]^+$: 428.1493. Found: 428.1499.

*Methyl-4-((2-(4-isobutylphenyl)propanoyl)oxy)benzoate (**4l**).*[13c] Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as colorless oil (33.7 mg, 33%). ^1H NMR (400 MHz, $CDCl_3$) δ 8.03 (d, J = 8.8 Hz, 2H), 7.30 (d, J = 8.0 Hz, 2H), 7.15 (d, J = 8.0 Hz, 2H), 7.08 (d, J = 8.8 Hz, 2H), 3.95 (q, J = 7.2 Hz, 1H), 3.90 (s, 3H), 2.48 (d, J = 7.2 Hz, 2H), 1.94−1.80 (m, 1H), 1.61 (d, J = 7.2 Hz, 3H), 0.92 (d, J = 6.8 Hz, 6H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 172.7, 166.3, 154.5, 141.0, 136.9, 131.0, 129.6, 127.6, 127.2, 121.4, 52.1, 45.3, 45.0, 30.2, 22.4, 18.4.

*4-(Methoxycarbonyl)phenyl-2-acetoxybenzoate (**4m**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (46.2 mg, 50%). M.p.: 114.4−117.8 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 8.22 (d, J = 8.0 Hz, 1H), 8.12 (d, J = 8.8 Hz, 2H), 7.66 (t, J = 8.0 Hz, 1H), 7.40 (t, J = 7.6 Hz, 1H), 7.26 (d, J = 8.0 Hz, 2H), 7.19 (d, J = 8.0 Hz, 1H), 3.93 (s, 3H), 2.31 (s, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 169.7, 166.2, 162.3, 154.1, 151.3, 134.9, 132.2, 131.3, 128.0, 126.2, 124.1, 122.1, 121.7, 52.2, 21.0. IR (neat): 2956, 2920, 1739, 1279, 1244, 1175, 1110, 1038, 1010, 751 cm^{-1}. HRMS (ESI): calcd for $C_{17}H_{14}O_6Na$ $[M + Na]^+$: 337.0683. Found: 337.0679.

*Methyl-(S)-4-((2-(6-methoxynaphthalen-2-yl)propanoyl)oxy)-benzoate (**4n**)*[new]. Purified by column chromatography on silica gel (petroleum ether/ethyl acetate = 10:1) as a white solid (87.2 mg, 80%). M.p.: 165.8−166.7 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 8.01 (d, J = 8.8 Hz, 2H), 7.75 (m, 3H), 7.53−7.46 (m, 1H), 7.21−7.12 (m, 2H), 7.07 (d, J = 8.8 Hz, 2H), 4.11 (q, J = 7.2 Hz, 1H), 3.93 (s, 3H), 3.89 (s, 3H), 1.70 (d, J = 7.2 Hz, 3H). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 172.6, 166.2, 157.8, 154.4, 134.7, 133.8, 131.0, 129.2, 128.9, 127.6, 127.4, 126.1, 125.9, 121.4, 119.1, 105.5, 55.2, 52.1, 45.5, 18.4. IR (neat): 2956, 2917, 1749, 1719, 1604, 1433, 1278, 1260, 1163, 1065, 1015, 798 cm^{-1}. HRMS (ESI): calcd for $C_{22}H_{21}O_5$ $[M + H]^+$: 365.1384. Found: 365.1387.

Gram-Scale Synthesis. In a nitrogen-filled glovebox, to a dried 100 mL hydrogenation tube equipped with a stir bar, the following were added to the electrochemical cell: aryl bromide **1a** (2.15 g, 10.0 mmol), *N*-Boc-D-proline **2a** (1.07 g, 5.0 mmol), $NiBr_2$·glyme (154 mg, 0.5 mmol), d(OMe)bpy (216 mg, 1 mol), $^nBu_4NBr$ (1.3 g, 4 mmol), K_2CO_3 (1.38 g, 10 mmol), and DMA (20 mL). The tube was installed a Ni foam (4.0 × 8.0 cm^2) as the cathode and graphite flake (2.0 × 2.0 cm^2) as the anode. Then the reaction mixture was electrolyzed under a constant current of 15 mA for 24 h. After the reaction, the aqueous layer was extracted with EtOAc (3 × 50 mL), and the combined organics were washed with saturated brine (3 × 100 mL), dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The resulting residue was purified by silica gel flash chromatography to give product **3a** as white solid with 48% yield.

Electrochemical Procedure for Cyclic Voltammetry. Cyclic voltammograms were recorded with a CHI660E potentiostat at room temperature in DMA. $^nBu_4NPF_6$ (0.1 M) was used as the supporting electrolyte, and a glass carbon electrode was used as the working electrode. The auxiliary electrode was a Pt sheet. All potentials were referenced against the $Ag/AgNO_3$ redox couple. The scan rate was 100 mV s^{-1}.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.joc.1c00204.

Experimental procedures and compound characterization data (PDF)

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Notes

The authors declare no competing financial interest.

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