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Intramolecular PIFA-Mediated Alkyne Amidation and Carboxylation Reaction

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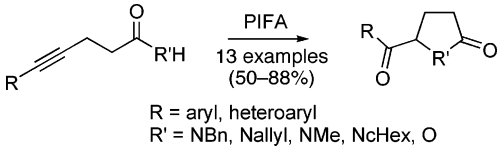
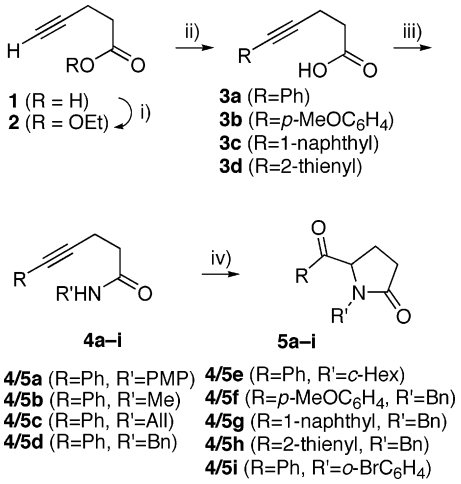


The hypervalent iodine reagent PIFA promotes the intramolecular electrophilic cyclization of easily accessible alkynylamides and alkynyl carboxylic acids, leading to the formation of pyrrolidinone and lactone skeletons, respectively, in a very efficient way. A synthetic study and a mechanistic proposal for these transformations are presented.

In a recent communication,[1] we have reported a novel approach to the synthesis of 5-aroylpyrrolidinones based on the action of the trivalent iodine reagent PIFA [phenyliodine(III)-bis(trifluoroacetate)] on properly substituted alkynyl-*N*-arylamides. The key feature of this transformation relies on the generation of an electrophilic acyl−nitrenium intermediate, stabilized by the donating properties of the aryl ring, that suffers the intramolecular attack of the alkyne moiety to afford efficiently the final heterocyclic products. As a metal-free protocol, this PIFA-mediated intramolecular addition of a nitrogen functionality across a carbon−carbon multiple bond shows superiority over other established metal-based methods in terms of economy, sustainability, stability of the I(III) reagents to air and moisture, and its tolerance to different functional groups. In this context, the employment of alkaline metals,[2] transition metal complexes,[3] lanthanides,[4] and actinides[5] as catalysts describes a representative overview of the research in this area. On the other hand, and although less exploited, the reaction of alkynylamines with electrophilic reagents toward this end has the advantage of the experimental simplicity and the possibility to get functionalized products. Additionally, these functionalities allow further manipulations toward the synthesis of more complex structures. As a result, the use of different electrophilic reagents,[6] molecular iodine and IPy_2BF_4 (Barluenga's reagent), inter alia, has been reported in the efficient syntheses of nitrogen-containing heterocycles such as isoindolinones, indoles, and isoquinolinones.[7]

SCHEME 1. Preparation and Reactivity of Alkynylamides 4a−i and Synthesis of 5-Aroylpyrrolidinones 5a−i[a]



[a] Reagents and conditions: (i) H_2SO_4 (c), EtOH, room temperature (94%); (ii) (a) RI, $Pd(PPh_3)_4$, CuI, Et_2NH, CH_2Cl_2, room temperature; (b) KOH, dioxane, room temperature (55−62% two steps); (iii) R′NH_2, HOBt, EDC·HCl, Et_3N, CH_2Cl_2, 0 °C to room temperature (63−98%); (iv) PIFA, CF_3CH_2OH, 0 °C (50−88%).

By analogy with previous observations in our group on the PIFA-mediated olefin amidation reaction,[8] it was originally assumed by us that the presence of an aryl group onto the nitrogen able to stabilize the deficient intermediate was a fundamental structural requirement for the success of the reaction.[9] Continuous research carried out by our group has proven lately that this assumption happens to be untrue, an observation that enriches the scope of the presented protocol. As a consequence, an extension of this methodology to the preparation of differently N-substituted 5-aroylpyrrolidinones, and also 5-aroylfuranones, is presented in this paper.

Our study started with the synthesis of amides **4a−i** that were differently substituted both at the terminal position of the triple bond and at the nitrogen (see Scheme 1). This could be easily accomplished by esterification of commercially available 4-pentynoic acid (**1**), followed by treatment of the resulting ethyl ester

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(2) (a) Cid, M. M.; Domínguez, D.; Castedo, L.; Vázquez-López, E. M. *Tetrahedron* **1999**, *55*, 5599−5610. (b) Tzalis, D.; Koradin, C.; Knochel, P. *Tetrahedron Lett.* **1999**, *40*, 6193−6195.
(3) Early transition metals: (a) Bystschkov, I.; Doye, S. *Eur. J. Org. Chem.* **2003**, 935−946. (b) Ackermann, L.; Bergman, R. G.; Loy, R. N. *J. Am. Chem. Soc.* **2003**, *125*, 11956−11963. (c) Tillack, A.; Garcia Castro, I.; Hartung, C. G.; Beller, M. *Angew. Chem., Int. Ed.* **2002**, *41*, 2541−2543. Palladium: (d) Yamamoto, Y.; Kadota, I.; Lutete, L. M. *J. Am. Chem. Soc.* **2004**, *126*, 1622−1623. (e) Shimada, T.; Yamamoto, Y. *J. Am. Chem. Soc.* **2002**, *124*, 12670−12671. (f) Jacobi, P. A.; Brielmann, H. L.; Hauck, S. I. *J. Org. Chem.* **1996**, *61*, 5013−5023. Ruthenium: (g) Tokunaga, M.; Eckert, M.; Wakatsuki, Y. *Angew. Chem., Int. Ed.* **1999**, *38*, 3222−3225. Rhodium: (h) Hartung, C. G.; Tillack, A.; Trauthwein, H.; Beller, M. *J. Org. Chem.* **2001**, *66*, 6339−5343. Silver: (i) Koseki, Y.; Kusano, S.; Ichi, D.; Yoshida, K.; Nagasaka, T. *Tetrahedron* **2000**, *56*, 8855−8865.
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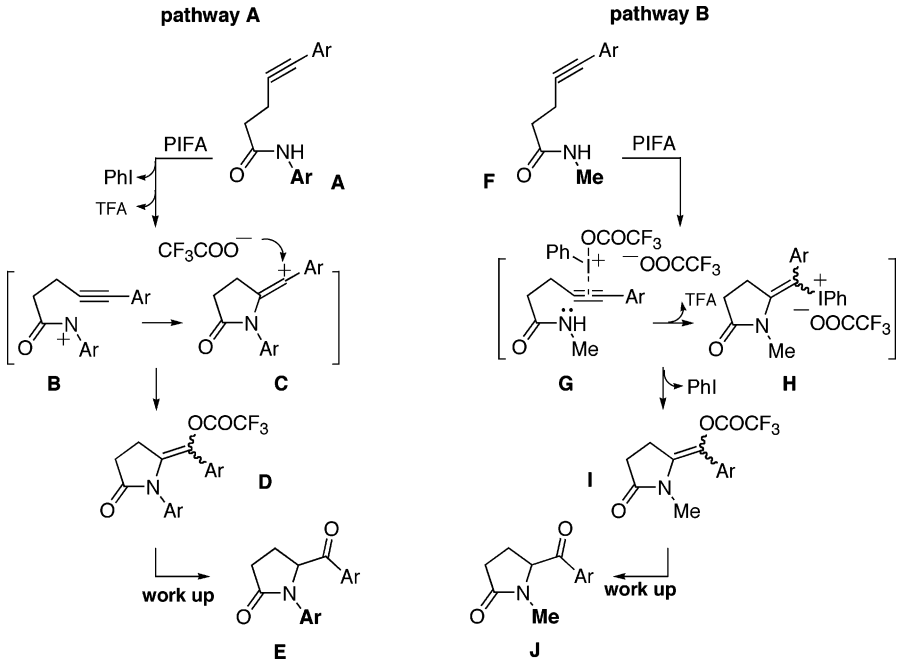
SCHEME 2. Proposed Mechanisms for the PIFA-Mediated Intramolecular Alkyne Amidation on *N*-Arylamides (pathway A) and *N*-Alkylamides (pathway B)



2 under standard Sonogashira[10] cross-coupling reaction conditions to place different aryl groups at the terminal position of the triple bond.[11] The basic hydrolysis of the intermediate esters produced the desired carboxylic acids **3a**−**d** in good overall yields.[12] Finally, the synthesis of amides **4a**−**i** was effectively achieved employing HOBt and EDC·HCl as activating reagents.[13]

Next, the series of amides **4a**−**i**[14] was treated with the hypervalent iodine reagent PIFA under optimized conditions (1.5 equiv of PIFA in CF_3CH_2OH at 0 °C)[15] to find that not only the *N*-aryl-substituted amide **4a** reacted to afford the expected heterocyclic product **5a** but also *N*-methyl, *N*-allyl, *N*-benzyl, and *N*-cyclohexylamides **4b**−**i** afforded the corresponding pyrrolidinones **5b**−**i** in very good yields and short reaction times (typically less than 60 min).[16] Consequently, we must give an explanation to this pleasant but unexpected result. Originally, and on the base of previously accepted mechanisms,[9] we proposed that the presented cyclization would exclusively take place on *N*-aryl-substituted amides as the only way to stabilize the positively charged nitrenium intermediate **B** generated (see Scheme 2, pathway A). Thus, nitrenium **B** reacts intramolecularly with the alkyne residue to form a new intermediate **C**. Reaction of **C** with a free trifluoroacetate ligand delivered by PIFA results in the formation of a nonisolable ester **D**, which, after basic hydrolysis during the workup, affords the substituted pyrrolidinone skeleton **E**. Conversely (see Scheme 2, pathway B), the success on the cyclization of *N*-alkynylamides of type **F**, where a positive charge on nitrogen would not be adequately stabilized, led us to propose an alternative mechanism

(6) I_2: (a) Yao, T.; Larock, R. C. *J. Org. Chem.* **2005**, *70*, 1432−1437. $KMnO_4$: (b) Hayashi, Y.; Shoji, M.; Yamaguchi, S.; Mukaiyama, T.; Yamaguchi, J.; Kakeya, H.; Osada, H. *Org. Lett.* **2003**, *5*, 2287−2290.

(7) (a) Yue, D.; Yao, T.; Larock, R. C. *J. Org. Chem.* **2006**, *71*, 62−69. (b) Yue, D.; Larock, R. C. *Org. Lett.* **2004**, *6*, 1037−1040. (c) Cherry, K.; Thibonnet, J.; Duchêne, A.; Parrain, J.-L.; Abarbri, M. *Tetrahedron Lett.* **2004**, *45*, 2063−2066. (d) Amjad, M.; Knight, D. W. *Tetrahedron Lett.* **2004**, *45*, 539−541. (e) Barluenga, J.; Trincado, M.; Rubio, E.; González, J. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 2406−2409. (f) Huang, Q.; Hunter, J. A.; Larock, R. C. *J. Org. Chem.* **2002**, *67*, 3437−3444. (g) Kobayashi, K.; Hase, K.; Hashimoto, K.; Fujita, S.; Tanmatsu, M.; Morikawa, O.; Konishi, H. *Synthesis* **2006**, 2493−2496.

(8) (a) Tellitu, I.; Urrejola, A.; Serna, S.; Moreno, I.; Herrero, M. T.; Domínguez, E.; SanMartin, R.; Correa, A. *Eur. J. Org. Chem.* **2007**, 437−444. (b) Serna, I.; Tellitu, I.; Domínguez, E.; Moreno, I.; SanMartin, R. *Tetrahedron Lett.* **2003**, *44*, 3483−3486.

(9) *N*-Methoxyamides and *N*-phthalimidoamides are also known to generate stable acyl−nitrenium intermediates. (a) Falvey, D. E.; Kung, A. C. *J. Org. Chem.* **2005**, *70*, 3127−3132. (b) Kikugawa, Y.; Nagashima, A.; Sakamoto, T.; Miyazama, E.; Shiiya, M. *J. Org. Chem.* **2003**, *68*, 6739−6744. (c) Prata, J. V.; Clemente, D. T. S.; Prabhakar, S.; Lobo, A. M.; Mourato, I.; Branco, P. S. *J. Chem. Soc., Perkin Trans. 1* **2002**, 513−528. (d) Glover, S. A.; Goosen, A.; McCleland, C. W.; Schoonraad, J. L. *Tetrahedron* **1987**, *43*, 2577−2592.

(10) (a) Tykwinski, R. R. *Angew. Chem., Int. Ed.* **2003**, *42*, 1566−1568. (b) Sonogashira, K. *J. Organomet. Chem.* **2002**, *653*, 46−49.

(11) It is known that terminal triple bonds react with PIFA to render α-hydroxyketones. Therefore, in our case, that position must be blocked for a successful transformation. Tamura, Y.; Yakura, T.; Haruta, J.-I.; Kita, Y. *Tetrahedron Lett.* **1985**, *26*, 3837−3840.

(12) (a) Amides **4e** and **4i** were directly prepared from the ethyl ester of acid **3a** by treatment with Me_3Al and the corresponding amine. (b) For the preparation of carboxylic acid **3b**, see: Arcadi, A.; Cacchi, S.; Delmastro, M.; Marinella, F. *Synlett* **1991**, 409−411.

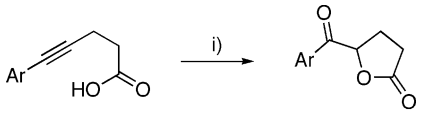
(13) For a recent review on amide bond formation, see: Montalbetti, C. A. G. N.; Falque, V. *Tetrahedron* **2005**, *61*, 10827−10852.

(14) The preparation and cyclization of amide **4a** to afford pyrrolidinone **5a** has already been performed (see ref 1). It is included here for comparative purposes.

(15) The employment of a highly polar non-nucleophilic solvent, such as CF_3CH_2OH, was crucial for the success of the reaction. For a revision about the chemical properties and synthetic uses of trifluoroethanol and other related solvents, see: Bégué, J.-P.; Bonnet-Delpon, D.; Crousse, B. *Synlett* **2004**, 18−29.

(16) (a) It is noteworthy that the present access to 5-aroylpyrrolidines of type **5** offers many advantages over other alternatives described in the literature that involve multistep syntheses (chlorination *plus* Friedel−Craft acylation) starting from pyroglutamic acid or related derivatives, a process that lacks of regioselectivity when substituted arenes are employed. Rigo, B.; El Ghammarti, S.; Gautret, P.; Couturier, D. *Synth. Commun.* **1994**, *24*, 2597−2607. (b) It was additionally verified that the formation of a related pyrrolidine derivative by application of the cyclization conditions to *N*-methyl-4-pentenamide was not possible. Instead, a 5-hydroxymethyl-4,5-dihydrofuranone was the only identified product. Examples of this type of transformation can be found in: Takahata, H.; Suzuki, T.; Maruyama, M.; Moriyama, K.; Mozumi, M.; Takamatsu, T.; Yamazaki, T. *Tetrahedron* **1988**, *44*, 4777−4786.

SCHEME 3. Preparation of Furanones 6a−d[a]



3a–d **6a–d**

6a, Ar=Ph (55% from **3a**)
6b, Ar=*p*MeOC$_6$H$_4$ (65% from **3b**)
6c, Ar=1-naphthyl (61% from **3c**)
6d, Ar=2-thienyl (58% from **3d**)

[a] Reagents and conditions: (i) PIFA, CF_3CH_2OH, 0 °C.

that includes activation of the triple bond by PIFA (instead of nitrogen oxidation)[17] to give an electrophilic intermediate that reacts intramolecularly with the nucleophilic amide. Analogous steps would render the final *N*-alkylpyrrolidinones of type **J**.

Therefore, in order to get more information to support the second mechanistic alternative (pathway B in Scheme 2), we envisaged that the behavior of carboxylic acids, as the nucleophilic component of this PIFA-mediated cyclization, might be coherent with the obtained results on the cyclization of *N*-alkylamides. To carry out this study, carboxylic acids **3a−d** were also submitted to the action of PIFA (1.5 equiv of PIFA and CF_3CH_2OH as solvent at 0 °C), and in all cases, we verified the formation of the expected furanones **6a−d** in moderate to good yields (see Scheme 3).[18] Consequently, these results not only increase the synthetic applicability of the described methodology but they also support the previously proposed alternative mechanism shown in Scheme 2.

In summary, the fact that *N*-alkyl (and not only *N*-aryl)-substituted alkynylamides can be transformed into the corresponding pyrrolidinones by the action of PIFA led us to propose that this hypervalent iodine reagent can also activate alkyne moieties toward the intramolecular nucleophilic attack of the amide functional group. This suggestion is reinforced by the verification that the treatment of a series of alkynylcarboxylic acids with PIFA leads to the formation of the corresponding furanones under the same reaction conditions in moderate to good yields.

Experimental Section

Typical Procedure for the PIFA-Mediated Alkyne Amidation. Synthesis of 5-Benzoyl-1-methylpyrrolidin-2-one (5b). A solution of amide **4b** (100 mg, 0.53 mmol) in CF_3CH_2OH (5 mL) was cooled to 0 °C, and a solution of PIFA (142 mg, 0.78 mmol) in CF_3CH_2OH (6 mL) was added dropwise. The reaction mixture was stirred at 0 °C until completion was observed by TLC (1 h). Aqueous Na_2CO_3 10% (5 mL) was added and extracted with CH_2Cl_2 (3 × 10 mL). The combined organic extracts were washed with brine, dried over Na_2SO_4, and the solvent evaporated. Purification of the crude by flash chromatography (EtOAc/MeOH, 96:4), followed by crystallization from hexanes, afforded pyrrolidinone **5b** as a white solid (84 mg, 78%): mp 97−98 °C (hexanes); ^{1}H NMR ($CDCl_3$) δ 1.93−2.08 (m, 1H), 2.36−2.57 (m, 3H), 2.83 (s, 3H), 5.05−5.10 (m, 1H), 7.49 (dd, J = 8.3, 7.3 Hz, 2H), 7.61 (t, J = 7.3 Hz, 1H), 7.94 (d, J = 8.3 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 22.9, 28.9, 29.1, 63.9, 128.2, 128.9, 130.0, 133.9, 175.3, 196.3; IR (KBr) ν 1690; MS (EI) *m*/*z* (%) 203 (M^+, 1), 98 (100); HRMS calcd for $C_{12}H_{13}NO_2$ 203.0946, found 203.0952.

1-Allyl-5-benzoylpyrrolidin-2-one (5c). According to the typical procedure, pyrrolidinone **5c** was obtained from amide **4c** in 81% yield as a colorless oil after purification by flash chromatography (EtOAc): ^{1}H NMR ($CDCl_3$) δ 1.96−2.01 (m, 1H), 2.39−2.42 (m, 3H), 3.39 (dd, J = 15.0, 7.9 Hz, 1H), 4.45−4.51 (m, 1H), 5.02−5.15 (m, 3H), 5.55−5.78 (m, 1H), 7.45−7.63 (m, 3H), 7.91 (d, J = 7.1 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 23.0, 29.4, 44.2, 60.6, 118.6, 128.2, 128.9, 132.3, 133.9, 134.0, 175.0, 196.8; IR (film) ν 1694; MS (EI) *m*/*z* (%) 229 (M^+, 1), 124 (100), 105 (23); HRMS calcd for $C_{14}H_{15}NO_2$ 229.1103, found 229.1111.

5-Benzoyl-1-benzylpyrrolidin-2-one (5d). According to the typical procedure, pyrrolidinone **5d** was obtained from amide **4d** in 71% yield as colorless oil after purification by flash chromatography (EtOAc). All spectroscopic data were in agreement with those reported in the literature.[19]

5-Benzoyl-1-cyclohexylpyrrolidin-2-one (5e). According to the typical procedure, pyrrolidinone **5e** was obtained from amide **4e** in 50% yield as a white solid after purification by flash chromatography (hexanes/EtOAc, 4:6) followed by triturating in hexanes: mp 102−103 °C (hexanes); ^{1}H NMR ($CDCl_3$) δ 0.82−1.00 (m, 2H), 1.10−1.41 (m, 3H), 1.52−1.78 (m, 5H), 1.86−2.00 (m, 1H), 2.24−2.56 (m, 3H), 3.87−3.97 (m, 1H), 5.18−5.21 (m, 1H), 7.48−7.52 (m, 2H), 7.58−7.63 (m, 1H), 7.93−7.97 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 24.6, 25.4, 25.5, 25.6, 29.9, 30.8, 31.4, 52.0, 58.9, 128.1, 129.0, 133.8, 134.0, 175.3, 198.0; IR (KBr) ν 1681; MS (EI) *m*/*z* (%) 272 (M^+ + 1, 5), 271 (M^+, 1), 167 (41), 166 (93), 105 (100), 84 (91), 77 (99), 69 (44), 55 (82), 51 (94); HRMS calcd for $C_{17}H_{21}NO_2$ 271.1572, found 271.1569.

1-Benzyl-5-(4-methoxybenzoyl)pyrrolidin-2-one (5f). According to the typical procedure, pyrrolidinone **5f** was obtained from amide **4f** in 88% yield as a white solid after purification by flash chromatography (EtOAc). All spectroscopic data were in agreement with those reported in the literature.[20]

1-Benzyl-5-(1-naphthoyl)pyrrolidin-2-one (5g). According to the typical procedure, pyrrolidinone **5g** was obtained from amide **4g** in 78% yield as colorless oil after purification by flash chromatography (EtOAc): ^{1}H NMR ($CDCl_3$) δ 1.86−1.98 (m, 1H), 2.12−2.28 (m, 1H), 2.40−2.66 (m, 2H), 3.96 (d, J = 15.0 Hz, 1H), 4.91 (dd, J = 9.5, 3.9 Hz, 1H), 5.29 (d, J = 15.0 Hz, 1H), 7.20−7.61 (m, 9H), 7.84−8.00 (m, 2H), 8.45 (d, J = 8.7 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 22.5, 29.4, 45.5, 62.6, 124.1, 125.0, 126.7, 127.5, 127.8, 128.3, 128.4, 128.5, 128.7, 130.3, 132.8, 133.4, 133.7, 135.9, 175.3, 200.5; IR (film) ν 1685; MS (EI) *m*/*z* (%) 329 (M^+, 1), 174 (100), 127 (15), 91 (95); HRMS calcd for $C_{22}H_{19}NO_2$ 329.1416, found 329.1413.

1-Benzyl-5-(thiophene-2-carbonyl)pyrrolidin-2-one (5h). According to the typical procedure, pyrrolidinone **5h** was obtained from amide **4h** in 82% yield as a colorless oil after purification by flash chromatography (EtOAc): ^{1}H NMR ($CDCl_3$) δ 1.95−2.07 (m, 1H), 2.12−2.65 (m, 3H), 3.75 (d, J = 15.0 Hz, 1H), 4.66−4.72 (m, 1H), 5.17 (d, J = 15.0 Hz, 1H), 7.08−7.24 (m, 6H), 7.54 (d, J = 3.6 Hz, 1H), 7.69 (d, J = 4.7 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 23.4, 29.4, 45.2, 62.2, 127.6, 128.3, 128.4, 128.6, 132.4, 134.9, 135.7, 140.8, 175.1, 190.3; IR (film) ν 1685; MS (EI) *m*/*z* (%) 285 (M^+, 1), 174 (68), 91 (100); HRMS calcd for $C_{16}H_{15}NO_2S$ 285.0824, found 285.0825.

5-Benzoyl-1-(2-bromophenyl)pyrrolidin-2-one (5i). According to the typical procedure, pyrrolidinone **5i** was obtained from amide **4i** in 54% yield as a white solid after purification by flash chromatography (hexanes/EtOAc, 7:3): mp 124−126 °C (hexanes); ^{1}H NMR ($CDCl_3$) δ 2.18−2.26 (m, 1H), 2.56−2.83 (m, 3H), 5.75

(17) *N*-Alkylnitrenium ions would not be stable enough to exist.

(18) Some selected examples of alkyne electrophilic cyclization employing oxygenated nucleophiles: (a) Arcadi, A.; Cacchi, S.; Di Giuseppe, S.; Fabrizi, G.; Marinelli, F. *Org. Lett.* **2002**, *4*, 2409−2412. (b) Gulias, M.; Rodríguez, J. R.; Castedo, L.; Mascareñas, J. L. *Org. Lett.* **2003**, *5*, 1975−1977. (c) Liu, Y.; Zhou, S. *Org. Lett.* **2005**, *7*, 4609−4611. (d) Yue, D.; Della Cá, N.; Larock, R. C. *J. Org. Chem.* **2006**, *71*, 3381−3388.

(19) Deskus, J.; Fan, D.; Smith, M. B. *Synth. Commun.* **1998**, *28*, 1649−1659.

(20) Yaguang, L. U.S. Patent US6486169, 2002; *Chem. Abstr.* **2002**, *137*, 363098.

(dd, $J = 9.4$, 2.3 Hz, 1H), 7.14−7.19 (m, 1H), 7.32−7.37 (m, 2H), 7.48 (t, $J = 7.6$ Hz, 2H), 7.58−7.66 (m, 3H), 7.92 (d, $J = 7.7$ Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 24.0, 29.2, 63.4, 121.9, 128.2, 128.3, 128.9, 129.6, 132.3, 133.8, 133.9, 136.3, 175.3, 196.3; IR (film) ν 1708; MS (EI) *m*/*z* (%) 241 (10), 238 (84), 184 (68), 159 (83), 130 (83), 105 (98), 77 (100), 51 (94); HRMS calcd for $C_{17}H_{14}NO_2Br$ 343.0208, found 343.0208.

5-Benzoyl-4,5-dihydrofuran-2(3*H*)-one (6a). According to the typical procedure, furanone **6a** was obtained from carboxylic acid **3a** in 55% yield as a white solid after purification by flash chromatography (hexanes/EtOAc, 7:3). All spectroscopic data were in agreement with those reported in the literature.[21]

5-(4-Methoxybenzoyl)-4,5-dihydrofuran-2(3*H*)-one (6b). According to the typical procedure, furanone **6b** was obtained from carboxylic acid **3b** in 65% yield as a white solid after purification by flash chromatography (hexanes/EtOAc, 9:1). All spectroscopic data were in agreement with those reported in the literature.[22]

5-(1-Naphthoyl)-4,5-dihydrofuran-2(3*H*)-one (6c). According to the typical procedure, furanone **6c** was obtained from carboxylic acid **3c** in 61% yield as a white solid after purification by flash chromatography (hexanes/EtOAc, 9:1) followed by crystallization from *n*-pentane: mp 72−74 °C (*n*-pentane); ^{1}H NMR ($CDCl_3$) δ 2.34−2.75 (m, 4H), 5.82−5.87 (m, 1H), 7.50−7.65 (m, 3H), 7.88−7.94 (m, 2H), 8.06 (d, $J = 8.3$ Hz, 1H), 8.62 (d, $J = 8.3$ Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 25.2, 26.8, 79.4, 124.2, 125.2, 126.8, 128.6, 128.9, 130.5, 131.3, 133.9, 134.1, 176.4, 197.9; IR (KBr) ν 1781, 1685; MS (EI) *m*/*z* (%) 240 (M^+, 5), 155 (100), 127 (46); HRMS calcd for $C_{15}H_{12}O_3$ 240.0786, found 240.0787.

5-(Thiophene-2-carbonyl)-4,5-dihydrofuran-2(3*H*)-one (6d). According to the typical procedure, furanone **6d** was obtained from carboxylic acid **3d** in 58% yield as a white solid after purification by flash chromatography (hexanes/EtOAc, 9:1) followed by crystallization from *n*-pentane: mp 79−80 °C (*n*-pentane); ^{1}H NMR ($CDCl_3$) δ 2.41−2.68 (m, 4H), 5.53−5.59 (m, 1H), 7.15−7.19 (m, 1H), 7.75 (d, $J = 5.1$ Hz, 1H), 7.93 (d, $J = 3.6$ Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 25.4, 26.8, 79.1, 128.6, 133.9, 135.6, 140.0, 176.1, 187.9; IR (KBr) ν 1781, 1667; MS (EI) *m*/*z* (%) 196 (M^+, 8), 110 (100), 85 (20); HRMS calcd for $C_9H_8O_3S$ 196.0194, found 196.0191.

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Supporting Information Available: Experimental details and ^{1}H and ^{13}C NMR spectra of all new compounds are included. This material is available free of charge via the Internet at http://pubs.acs.org.

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