

A Domino Reaction of α,β -Acetylenic γ -Hydroxy Nitriles with Arenecarboxylic Acids: An Unexpected Facile Shortcut to 4-Cyano-3(2*H*)-furanones

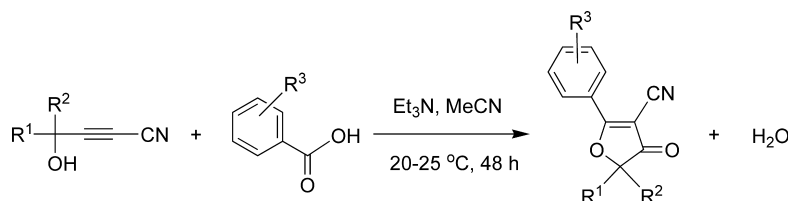
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ABSTRACT



R^1, R^2 = alkyl, cycloalkyl; R^3 = H, 3-Me, 4-Me, 3-F, 2-Cl, 3-Cl, 2-Br, 3-I

An unexpected facile domino reaction of α,β -acetylenic γ -hydroxy nitriles with arenecarboxylic acids (Et_3N , MeCN, 20–25 °C, 48 h) affords 4-cyano-3(2*H*)-furanones in 67–86% yield. The reaction is triggered by the addition of an arenecarboxylic acid to a triple bond, followed by the domino reaction sequence: intramolecular transesterification—enol formation and Claisen condensation of the ketoacetonitrile tautomer with ester functional group.

The 3(2*H*)-furanone is a key structural unit in many naturally occurring compounds such as bullatenon,¹ geiparvarin,^{1b,d,2} eremantholide A,³ jatrophone,⁴ and pseuro-

tin A.⁵ In addition, the 3(2*H*)-furanone derivatives are considered to be promising pharmaceutical candidates which

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(1) (a) Parker, W.; Raphael, R. A.; Wilkinson, D. I. *J. Chem. Soc.* **1958**, 3871. (b) Jackson, R. F. W.; Raphael, R. *Tetrahedron Lett.* **1983**, 24, 2117. (c) Felman, S. W.; Jirkovsky, I.; Memoli, K. A.; Borella, L.; Wells, C.; Russell, J.; Ward, J. *J. Med. Chem.* **1992**, 35, 1183. (d) Villemain, D.; Jaffrès, P.-A.; Hachémi, M. *Tetrahedron Lett.* **1997**, 38, 537. (e) Reiter, M.; Turner, H.; Mills-Webb, R.; Gouverneur, V. *J. Org. Chem.* **2005**, 70, 8478.

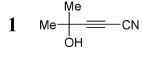
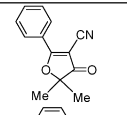
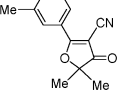
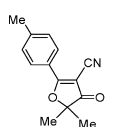
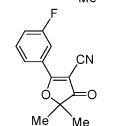
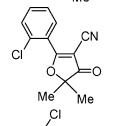
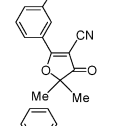
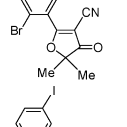
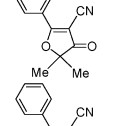
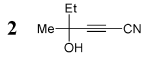
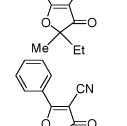
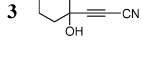
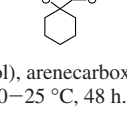
(2) (a) Jerris, P. J.; Smith, A. B., III. *J. Org. Chem.* **1981**, 46, 577. (b) Sakai, T.; Ito, H.; Yamawaki, A.; Takeda, A. *Tetrahedron Lett.* **1984**, 25, 2987. (c) Manfredini, S.; Baraldi, P. G.; Bazzanini, R.; Guarneri, M.; Simoni, D.; Balzarini, J.; De Clercq, E. *J. Med. Chem.* **1994**, 37, 2401. (d) Chimichi, S.; Boccalini, M.; Cosimelli, B.; Viola, G.; Vedaldi, D.; Dall'Acqua, F. *Tetrahedron Lett.* **2002**, 43, 7473. (e) Viola, G.; Vedaldi, D.; Dall'Acqua, F.; Basso, G.; Disarò, S.; Spinelli, M.; Cosimelli, B.; Boccalini, M.; Chimichi, S. *Chem. Biodiversity* **2004**, 4, 1265. (f) Chimichi, S.; Boccalini, M.; Cravotto, G.; Rosati, O. *Tetrahedron Lett.* **2006**, 47, 2405. (g) Crone, B.; Kirsch, S. F. *J. Org. Chem.* **2007**, 72, 5435, and references therein. (h) Chimichi, S.; Boccalini, M.; Salvador, A.; Dall'Acqua, F.; Basso, G.; Viola, G. *Chem. Med. Chem.* **2009**, 4, 769. (i) Egi, M.; Azechi, K.; Saneto, M.; Shimizu, K.; Akai, S. *J. Org. Chem.* **2010**, 75, 2123.

exhibit antitumor,^{1b,d,2g,i,3e,6} antiulcer,^{1c} antiallergic,⁷ selective COX-2 inhibition,^{2g,8} selective MAO-B inhibition activities,^{2f,g,i,9} and ligands for nuclear hormone receptors.¹⁰ These features have spurred growing efforts to develop more efficient syntheses of 3(2*H*)-furanones. Traditional routes to substituted 3(2*H*)-furanones utilize a cyclization/dehydration reaction of 1-hydroxy-2,4-diketones under the action of acids^{2a,4b,11} or K₂CO₃.^{5a} Among the alternative methods are the hydrogenolyses and subsequent acidic hydrolyses of isoxazoles,^{2c,6b,12} the aldol reaction of 3-silyloxyfuranes,¹³ the base-catalyzed cyclizations of 1-halo-2,4-diketones,¹⁴ and the Knoevenagel-type condensation of α -acyloxycarbonyl compounds.^{1d,15} Recently, Au(III)-, Ag(I)-, Cu(I)-, Hg(II)-, Pd(II)-, or Pt(II)-catalyzed cyclizations of propargylic ketols,^{2g,16} α -hydroxy ynones,¹⁷ and 2-oxo-3-butynoic esters or disubstituted 1,2-diones¹⁸ to 3(2*H*)-furanones have attracted attention. More recently, the combination of (*p*-CF₃C₆H₄)₃PAuCl and AgOTf has been shown to actively catalyze the cyclizations of γ -hydroxyalkynones to 3(2*H*)-furanones.²¹ Still, the further development of more efficient and atom-economical routes to functionalized 3(2*H*)-furanones remains a focus of modern organic synthesis.

Herein, we report the hitherto unknown and extremely facile domino reaction between α,β -acetylenic γ -hydroxy nitriles **1–3** and arenecarboxylic acids **4–11** to deliver a novel family of functionalized 3(2*H*)-furanones, namely 5-aryl-4-cyano-2,2-dialkyl-3(2*H*)-furanones **12–21** in 67–86% yield. The reaction proceeds smoothly under transition-metal-

free conditions at 20–25 °C in the presence of Et₃N in MeCN (Table 1).

Table 1. Synthesis of 4-Cyano-3(2*H*)-furanones^a

1–3		4–11		12–21	
acetylene		arenecarboxylic acid		3(2 <i>H</i>)-furanone	yield (%) ^b
1 	4 	12 		86	
1	5 	13 		77	
1	6 	14 		80	
1	7 	15 		73	
1	8 	16 		68	
1	9 	17 		74	
1	10 	18 		67	
1	11 	19 		80	
2 	4	20 		74	
3 	4	21 		79	

^a Reaction conditions: acetylenes **1–3** (1 mmol), arenecarboxylic acids **4–11** (1 mmol), Et₃N (1 mmol), MeCN (6 mL), 20–25 °C, 48 h. ^b Isolated yield after recrystallization or preparative TLC.

The 3(2*H*)-furanones **12–21** are crystalline compounds with sharp melting points and good solubility in most organic solvents (examples: acetone, acetonitrile, benzene, chloroform, diethyl ether, dimethyl sulfoxide, ethanol, methanol) and poor solubility in water. In addition, the structure of

(3) (a) Raffauf, R. F.; Huang, P.-K. C.; Le Quesne, P. W.; Levery, S. B.; Brennan, T. F. *J. Am. Chem. Soc.* **1975**, *97*, 6884. (b) Le Quesne, P. W.; Levery, S. B.; Menachery, M. D.; Brennan, T. F.; Raffauf, R. F. *J. Chem. Soc., Perkin Trans. 1* **1978**, 1572. (c) Takao, K.; Ochiai, H.; Hashizuka, T.; Koshimura, H.; Tadano, K.; Ogawa, S. *Tetrahedron Lett.* **1995**, *36*, 1487. (d) Takao, K.; Ochiai, H.; Yoshida, K.; Hashizuka, T.; Koshimura, H.; Tadano, K.; Ogawa, S. *J. Org. Chem.* **1995**, *60*, 8179. (e) Li, Y.; Hale, K. J. *Org. Lett.* **2007**, *9*, 1267.

(4) (a) Kupchan, S. M.; Sigel, C. W.; Matz, M. J.; Gilmore, C. J.; Bryan, R. F. *J. Am. Chem. Soc.* **1976**, *98*, 2295. (b) Smith, A. B., III.; Guaciario, M. A.; Schow, S. R.; Wovkulich, P. M.; Toder, B. H.; Hall, T. W. *J. Am. Chem. Soc.* **1981**, *103*, 219. (c) Smith, A. B., III.; Malamas, M. S. *J. Org. Chem.* **1982**, *47*, 3442. (d) Taylor, M. D.; Smith, A. B., III.; Furst, G. T.; Gunasekara, S. P.; Bevelle, C. A.; Cordell, G. A.; Farmworth, N. R.; Kupchan, S. M.; Uchida, H.; Branfman, A. R.; Dailey, R. G., Jr.; Sneden, A. T. *J. Am. Chem. Soc.* **1983**, *105*, 3177. (e) Schmeda-Hirschmann, G.; Razmilic, I.; Sauvain, M.; Moretti, C.; Muñoz, V.; Ruiz, E.; Balanza, E.; Fournet, A. *Phytother. Res.* **1996**, *10*, 375. (f)ertino, M.; Schmeda-Hirschmann, G.; Santos, L. S.; Rodríguez, J. A.; Theoduloz, C. Z. *Naturforsch.* **2007**, *62b*, 275.

(5) (a) Shao, X.; Tamm, C. *Tetrahedron Lett.* **1991**, *32*, 2891. (b) Ishikawa, M.; Ninomiya, T. *J. Antibiot.* **2008**, *61*, 692. (c) Ishikawa, M.; Ninomiya, T.; Akabane, H.; Kushida, N.; Tsujiuchi, G.; Ohya, M.; Gomi, S.; Shito, K.; Murata, T. *Bioorg. Med. Chem.* **2009**, 1457.

(6) (a) Ishida, Y.; Tsuruta, H.; Tsuneta, S. T.; Uno, T.; Watanabe, K.; Aizono, Y. *Biosci. Biotechnol. Biochem.* **1998**, *62*, 2146. (b) Chimichi, S.; Boccalini, M.; Cosimelli, B.; Dall'Acqua, F.; Viola, G. *Tetrahedron* **2003**, *59*, 5215. (c) Rappai, J. P.; Raman, V.; Unnikrishnan, P. A.; Prathapan, S.; Thomas, S. K.; Paulose, C. S. *Bioorg. Med. Chem. Lett.* **2009**, *19*, 764.

(7) Mack, R. A.; Zazulak, W. I.; Radov, L. A.; Baer, J. E.; Stewart, J. D.; Elzer, P. H.; Kinsolving, C. R.; Georgiev, V. S. *J. Med. Chem.* **1988**, *31*, 1910.

(8) (a) Silverstein, F. E.; Faich, G.; Goldstein, J. L.; Simon, L. S.; Pincus, T.; Whelton, A.; Makuch, R.; Eisen, G.; Agrawal, N. M.; Stenson, W. F.; Burr, A. M.; Zhao, W. W.; Kent, J. D.; Lefkowitz, J. B.; Verbarg, K. M.; Geis, G. S. *JAMA, J. Am. Med. Assoc.* **2000**, *284*, 1247. (b) Shin, S. S.; Byun, Y.; Lim, K. M.; Choi, J. K.; Lee, K.-W.; Moh, J. H.; Kim, J. K.; Jeong, Y. S.; Kim, J. Y.; Choi, Y. H.; Koh, H.-J.; Park, Y.-H.; Oh, Y. I.; Noh, M.-S.; Chung, S. J. *J. Med. Chem.* **2004**, *47*, 792. (c) Shamshina, J. L.; Snowden, T. S. *Tetrahedron Lett.* **2007**, *48*, 3767.

4-cyano-2,2-dimethyl-5-phenyl-3(2*H*)-furanone **12** was confirmed by single-crystal X-ray analysis (Figure 1).

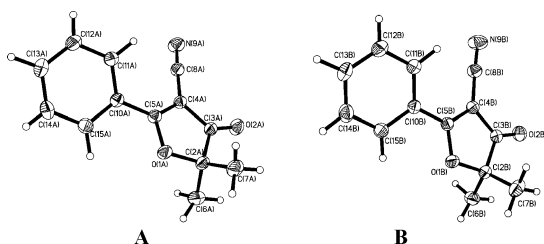
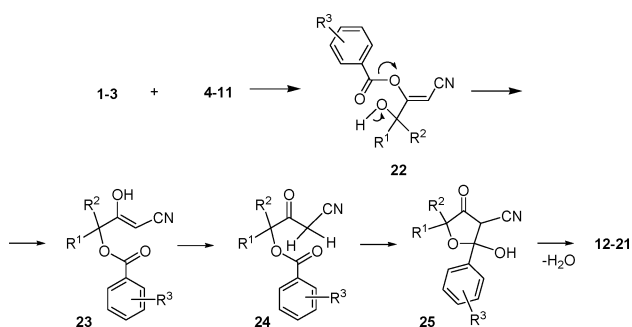


Figure 1. X-ray crystal structures of **A** and **B** molecules of **12**.

The reaction conditions and resulting products in Table 1 indicate a domino sequence that is triggered by the nucleophilic addition of arenecarboxylic acids **4–11** across the triple bonds of acetylenes **1–3** to afford the enol esters **22** (Scheme 1). The enol esters are transformed via intramo-

Scheme 1. Plausible Scheme of Domino Sequence Leading to 3(2*H*)-Furanones **12–21**



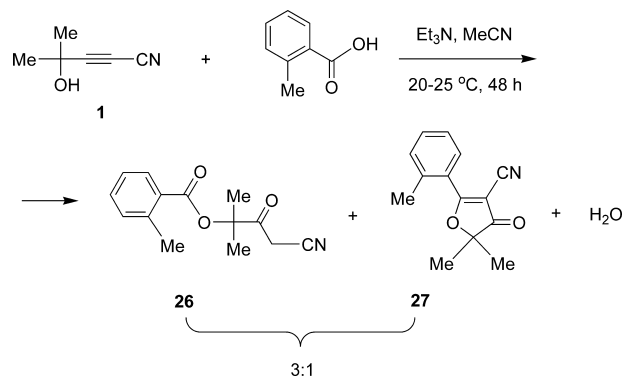
lecular transesterification to the enols **23**, subsequently tautomerizing to the keto esters **24**. The latter undergo a ring closure via intramolecular Claisen condensation with participation of the active CH_2 group of the β -ketonitrile and the carbonyl function of the ester residue to give hemiketals **25**. After dehydration to form a $\text{C}_{\text{sp}^2}\text{--C}_{\text{sp}^2}$ bond, the 3(2*H*)-furanones **12–21** are produced.

The reaction can be stopped at the stage of the intermediate keto esters **24**. For example, the keto ester **24** ($\text{R}^1 = \text{R}^2 = \text{Me}$, $\text{R}^3 = \text{H}$) was isolated from the reaction mixture in 31% yield, after acetylene **1** and benzenecarboxylic acid **4** were allowed to react in the presence of 10 mol % of K_2CO_3 at 20–25 °C for 48 h (the water was not specially added to the reaction mixture). When ketone **24** had been kept in acetonitrile in the presence of Et_3N at 20–25 °C (i.e., under

the Table 1 reaction conditions), the expected 3(2*H*)-furanone **12** was detected (^1H NMR) in the reaction mixture (30% conversion after 3 h).

In addition, the keto ester **26** ($\text{R}^1 = \text{R}^2 = \text{Me}$, $\text{R}^3 = 2\text{-Me}$) was obtained as a mixture with 3(2*H*)-furanone **27** in a ratio of 3:1, respectively (Scheme 2).

Scheme 2. Reaction of Acetylene **1** with 2-Methylbenzenecarboxylic Acid



Keto esters similar to **26** were formed as adducts between 3- and 4-aminobenzenecarboxylic acids and α,β -acetylenic γ -hydroxy nitriles **1–3**.¹⁹

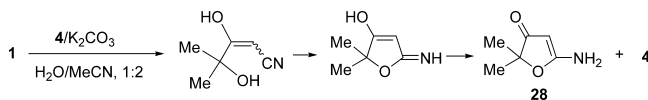
- (11) Smith, A. B., III.; Levenberg, P. A.; Jerris, P. J.; Scarborough, R. M., Jr.; Wovkulich, P. M. *J. Am. Chem. Soc.* **1981**, *103*, 1501.
- (12) Saxena, R.; Singh, V.; Batra, S. *Tetrahedron* **2004**, *60*, 10311.
- (13) Winkler, J. D.; Oh, K.; Asselin, S. M. *Org. Lett.* **2005**, *7*, 387.
- (14) (a) Langer, P.; Krummel, T. *Chem. Commun.* **2000**, 967. (b) Langer, P.; Krummel, T. *Chem.-Eur. J.* **2001**, *7*, 1720.
- (15) (a) Kato, K.; Nouchi, H.; Ishikura, K.; Takaishi, S.; Motodate, S.; Tanaka, H.; Okudaira, K.; Mochida, T.; Nishigaki, R.; Shigenobu, K.; Akita, H. *Tetrahedron* **2006**, *62*, 2545. (b) Gogoi, S.; Argade, N. P. *Tetrahedron* **2006**, *62*, 2999.
- (16) (a) Kirsch, S. F.; Binder, J. T.; Liebert, C.; Menz, H. *Angew. Chem., Int. Ed.* **2006**, *45*, 5878. (b) Binder, T. J.; Crone, B.; Kirsch, S. F.; Liebert, C.; Menz, H. *Eur. J. Org. Chem.* **2007**, 1636. (c) Bunnelle, E. M.; Smith, C. R.; Lee, S. K.; Singaram, S. W.; Rhodes, A. J.; Sarpong, R. *Tetrahedron* **2008**, *64*, 7008.
- (17) (a) Silva, F.; Reiter, M.; Mills-Webb, R.; Sawicki, M.; Klar, D.; Bensch, N.; Wagner, A.; Gouverneur, V. *J. Org. Chem.* **2006**, *71*, 8390. (b) Marson, C. M.; Edean, E.; Morrell, J. M.; Coles, S. J.; Hursthouse, M. B.; Davies, D. T. *Chem. Commun.* **2007**, 2494.
- (18) Liu, Y.; Liu, M.; Guo, S.; Tu, H.; Zhou, Y.; Gao, H. *Org. Lett.* **2006**, *8*, 3445.
- (19) Trofimov, B. A.; Mal'kina, A. G.; Shemyakina, O. A.; Nosyreva, V. V.; Borisova, A. P.; Albanov, A. I.; Kazheva, O. N.; Alexandrov, G. G.; Chekhlov, A. N.; Dyachenko, O. A. *Tetrahedron* **2009**, *65*, 2472.
- (20) (a) Trofimov, B. A.; Mal'kina, A. G.; Shemyakina, O. A.; Borisova, A. P.; Nosyreva, V. V.; Dyachenko, O. A.; Kazheva, O. N.; Alexandrov, G. G. *Synthesis* **2007**, 2641. (b) Trofimov, B. A.; Mal'kina, A. G.; Nosyreva, V. V.; Shemyakina, O. A.; Borisova, A. P.; Larina, L. I.; Kazheva, O. N.; Alexandrov, G. G.; Dyachenko, O. A. *Tetrahedron* **2010**, *66*, 1699.
- (21) (a) Mitsudo, T.; Hori, Y.; Yamakawa, Y.; Watanabe, Y. *J. Org. Chem.* **1987**, *52*, 2230. (b) Devanne, D.; Rupp, C.; Dixneuf, P. H. *J. Org. Chem.* **1988**, *53*, 925. (c) Dixneuf, P. H. *Pure Appl. Chem.* **1989**, *61*, 1763. (d) Menashe, N.; Reshef, D.; Shvo, Y. *J. Org. Chem.* **1991**, *56*, 2912. (e) Menashe, N.; Shvo, Y. *J. Org. Chem.* **1993**, *58*, 7434. (f) Doucet, H.; Derrien, N.; Kabouche, Z.; Bruneau, C.; Dixneuf, P. H. *J. Organomet. Chem.* **1997**, *551*, 151. (g) Bruneau, C.; Dixneuf, P. H. *Chem. Commun.* **1997**, 507. (h) Darcel, C.; Bruneau, C.; Dixneuf, P. H.; Roberts, S. M. *Tetrahedron* **1997**, *53*, 9241. (i) Dixneuf, P. H.; Bruneau, C. *Pure Appl. Chem.* **1998**, *70*, 1065. (j) Bruneau, C.; Dixneuf, P. H. *Acc. Chem. Rev.* **1999**, *32*, 311. (k) Den Reijer, C. J.; Drago, D.; Pregosin, P. S. *Organometallics* **2001**, *20*, 2982.

(9) Carotti, A.; Carrieri, A.; Chimichi, S.; Boccalini, M.; Cosimelli, B.; Gnerre, C.; Carotti, A.; Carrupt, P.-A.; Testa, B. *Bioorg. Med. Chem. Lett.* **2002**, *12*, 3551.

(10) Togashi, M.; Ozawa, S.; Abe, S.; Nishimura, T.; Tsuruga, M.; Ando, K.; Tamura, G.; Kuwahara, S.; Ubukata, M.; Magae, J. *J. Med. Chem.* **2003**, *46*, 4113.

It is noteworthy that an equimolar amount of aqueous K_2CO_3 did not catalyze the addition of benzenecarboxylic acid **4** to acetylene **1** to afford 3(2*H*)-furanone **12** (water–MeCN, 1:2; 20–25 °C, 48 h). Instead, hydration of acetylene **1** to 5-amino-2,2-dimethyl-3(2*H*)-furanone **28** in a yield of 76% occurred (Scheme 3).^{19,20}

Scheme 3. Synthesis of 5-Amino-2,2-dimethyl-3(2*H*)-furanone **28**

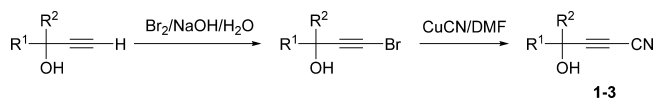


Commonly, carboxylic acids are known to add to various acetylenes²¹ (terminal alkynes,^{21a,c,d,f,g,i–k} propargyl alcohols and their derivatives,^{21a,b,f,h,i} dimethyl acetylenedicarboxylate^{21e}) under heating (60–110 °C) for 4–96 h²¹ exclusively in the presence of ruthenium catalysts, mostly complexes of complicated structure. Of industrial importance remains the classic vinylation of carboxylic acids with acetylenes by the action of $HgSO_4$, $Zn(OAc)_2/C$, H_3PO_4/C , Zn/Cd , and $Zn/Cd/Hg$ catalytic systems.²² Also known are attempts to vinylate carboxylic acids with acetylenes over palladium.²³

Thus, the first stage of the Scheme 1 domino reaction represents a unique example of transition-metal-free additions of carboxylic acids to carbon–carbon triple bonds. Taking into account that the starting acetylenic hydroxy nitriles **1–3** are readily available from acetylenic alcohols and copper cyanide through the intermediary acetylenic bromides (Scheme 4),²⁴ the domino assembly presented here may be considered as one of the most concise and expedient approaches so far known to functionalized 3(2*H*)-furanones.

Of special synthetic significance of this synthesis is that it allows the cyano group (which may be easily converted to amino,²⁵ amido,²⁶ or carboxylic^{26a–c} functions) to be

Scheme 4. Synthesis of α,β Acetylenic γ -Hydroxy Nitriles **1–3**



introduced into the cyclopentanone moiety. Evidently, the reaction should be of general character and be valid for various carboxylic acids and α,β -acetylenic γ -hydroxy nitriles with tertiary alcohol moieties. Certainly, the scope and limitation of the reaction is still to be further scrutinized. α,β -Acetylenic γ -hydroxy nitriles with primary and secondary alcohol moieties are poorly understood (among them only 4-hydroxy-2-butyne nitrile is known²⁷). Amino analogues of hydroxyacetylenes **1–3** are almost inaccessible: just 4-amino-2-butyne nitrile has been so far described as hydrochloride.^{27b} In the case of aliphatic carboxylic acids, under the conditions studied, a mixture of products containing the expected 3(2*H*)-furanones and intermediate keto esters (in ratio 1–2:1) is formed; hence, the reaction promises to be successfully optimized.

In summary, a new synthetic concept for the design of functionalized 3(2*H*)-furanones in a one-step, extremely facile domino reaction of available α,β -acetylenic γ -hydroxy nitriles and arenecarboxylic acids has been put forward and experimentally proved. The concept may find a widespread application and propagation in the synthesis of pharmaceutically important functionalized 3(2*H*)-furanones.

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Supporting Information Available: Experimental procedures and full spectroscopic data for all new compounds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(22) *Acetylene. Its Properties, Manufacture and Uses*; Miller, S. A., Ed.; Ernest Benn Ltd.: London, 1966; Vol. 2, p 246.

(23) (a) Hori, Y.; Mitsudo, T.-A.; Watanabe, Y. *J. Organomet. Chem.* **1987**, 321, 397. (b) Temkin, O. N.; Shestakov, G. K.; Treger, Yu. A. *Acetylene: Chemistry, Reaction Mechanisms and Technology*; Khimiya: Moscow, 1991 (in Russian).

(24) (a) Landor, S. R.; Demetriou, B.; Grzeskowiak, R.; Pavey, D. *J. Organomet. Chem.* **1975**, 93, 129. (b) Hopf, H.; Witulski, B. Functionalized Acetylenes in Organic Synthesis - The Case of the 1-Cyano- and 1-Halogenoacetylenes. In *Modern Acetylene Chemistry*; Stang, P. J., Diederich, F., Eds.; VCH: Weinheim, 1995; pp 33–67. (c) Trofimov, B. A.; Mal'kina, A. G. *Heterocycles* **1999**, 51, 2485. (d) Trofimov, B. A.; Andriyankova, L. V.; Shaikhudinova, S. I.; Kazantseva, T. I.; Mal'kina, A. G.; Zhivet'ev, S. A.; Afonin, A. V. *Synthesis* **2002**, 853.

(25) (a) Wu, B.; Zhang, J.; Yang, M.; Yue, Y.; Ma, L.-J.; Yu, X.-Q. *ARKIVOC* **2008**, xii, 95. (b) Haddenham, D.; Pasumansky, L.; DeSoto, J.; Eagon, S.; Singaram, B. *J. Org. Chem.* **2009**, 74, 1964.

(26) (a) Wilgus, C. P.; Downing, S.; Molitor, E.; Bains, S.; Pagni, R. M.; Kabalka, G. W. *Tetrahedron Lett.* **1995**, 36, 3469. (b) Kukushkin, V. Yu.; Pombeiro, A. J. L. *Chem. Rev.* **2002**, 102, 1771. (c) Baelen, G. V.; Maes, B. U. W. *Tetrahedron* **2008**, 64, 5604. (d) Lee, J.; Kim, M.; Chang, S.; Lee, H.-Y. *Org. Lett.* **2009**, 11, 5598. (e) Ramón, R. S.; Marion, N.; Nolan, Steven P. *Chem.-Eur. J.* **2009**, 15, 8695.

(27) (a) Fleming, F. F.; Gudipati, V.; Steward, O. M. *Tetrahedron* **2003**, 59, 5585. (b) Jeon, H.-B.; Sayre, L. M. *Biochem. Biophys. Res. Commun.* **2003**, 304, 788.