ORGANIC LETTERS

2010
Vol. 12, No. 23
5362−5365

Gold(I)-Catalyzed Cycloisomerization of β-Alkynylpropiolactones to Substituted α-Pyrones

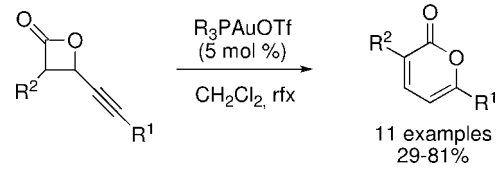
Thomas Dombray, Aurélien Blanc,* Jean-Marc Weibel, and Patrick Pale*

Laboratoire de Synthèse et Réactivité Organiques Associé au CNRS, Institut de Chimie, Université de Strasbourg, 4 rue Blaise Pascal, 67000 Strasbourg, France

ablanc@unistra.fr; ppale@unistra.fr

Received July 3, 2010

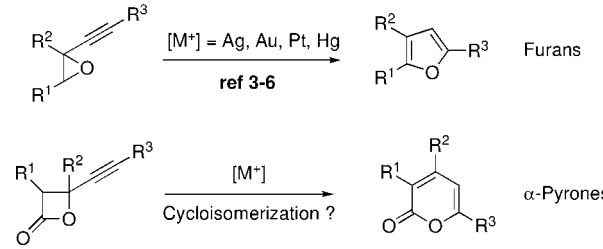
ABSTRACT



Substituted α-pyrones were straightforwardly synthesized in good to excellent yields by a new gold(I)-catalyzed rearrangement of β-alkynylpropiolactones.

Late transition metals, especially silver and gold, proved very efficient catalysts for various organic transformations over the past decade.[1,2] Among the latter, cycloisomerizations hold a special position, often offering a rapid entry to functionalized heterocycles. The cycloisomerization of alkynyloxiranes is a typical example, providing a powerful method to generate substituted furans. Silver[3] and gold,[4] but also platinum[5] and mercury,[6] have been successfully employed as catalysts for this transformation, although different mechanisms have been proposed (Scheme 1, top).

Scheme 1. Hypothesis for Transition-Metal-Catalyzed Conversion of β-Alkynylpropiolactones to α-Pyrones



On the basis of our precedents in such reactions,[3,7] we reasoned that incrementation of the epoxide ring in alkynyloxiranes, i.e., alkynyloxetanes, would lead to the corresponding homologated heterocycle, i.e., pyrans. With less strain, alkynyloxetanes would be less prone to ring opening before

(1) For recent reviews on silver chemistry, see: (a) Weibel, J.-M.; Blanc, A.; Pale, P. *Chem. Rev.* **2008**, *108*, 3149–3173. (b) Alvarez-Corral, M.; Munoz-Dorado, M.; Rodriguez-Garcia, I. *Chem. Rev.* **2008**, *108*, 3174–3198. (c) Yamamoto, Y. *Chem. Rev.* **2008**, *108*, 3199–3222. (d) Patil, N. T.; Yamamoto, Y. *Chem. Rev.* **2008**, *108*, 3395–3442. (e) Halbes-Letinois, U.; Weibel, J.-M.; Pale, P. *Chem. Soc. Rev.* **2007**, *36*, 759–769.

(2) For selected recent reviews on gold chemistry, see: (a) Li, Z.; Brouwer, C.; He, C. *Chem. Rev.* **2008**, *108*, 3239–3265. (b) Arcadi, A. *Chem. Rev.* **2008**, *108*, 3266–3325. (c) Jiménez-Nunez, E.; Echavarren, A. M. *Chem. Rev.* **2008**, *108*, 3326–3350. (d) Gorin, D. J.; Sherry, B. D.; Toste, F. D. *Chem. Rev.* **2008**, *108*, 3351–3378. (e) Hashmi, A. S. K.; Rudolph, M. *Chem. Soc. Rev.* **2008**, *37*, 1766–1775. (f) Hashmi, A. S. K. *Chem. Rev.* **2007**, *107*, 3180–3211. (g) Jiménez-Núñez, E.; Echavarren, A. M. *Chem. Commun.* **2007**, 333–346. (h) Hashmi, A. S. K.; Hutchings, G. J. *Angew. Chem., Int. Ed.* **2006**, *45*, 7896–7936.

(3) Blanc, A.; Tenbrink, K.; Weibel, J.-M.; Pale, P. *J. Org. Chem.* **2009**, *74*, 4360–4363.

(4) Hashmi, A. S. K.; Sinha, P. *Adv. Synth. Catal.* **2004**, *346*, 432–438.

(5) (a) Yoshida, M.; Al-Amin, M.; Matsuda, K. S. *Tetrahedron Lett.* **2008**, *49*, 5021–5023. (b) Yoshida, M.; Al-Amin, M.; Shishido, K. *Synthesis* **2009**, 2454–2466.

(6) Miller, D. *J. Chem. Soc. C* **1969**, 12–15.

(7) (a) Blanc, A.; Tenbrink, K.; Weibel, J.-M.; Pale, P. *J. Org. Chem.* **2009**, *74*, 5342–5348. (b) Blanc, A.; Alix, A.; Weibel, J.-M.; Pale, P. *Eur. J. Org. Chem.* **2010**, 1644–1647.

10.1021/ol1023739
Published on Web 11/11/2010

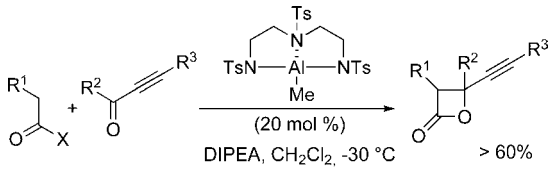
cyclization as shown for alkynyloxiranes,[7] and thus, other or new mechanisms would occur, improving our mechanistic knowledge of Au-catalyzed reactions.[8] For further synthetic purpose, we chose β-alkynylpropionolactones (4-alkynyloxetan-2-ones) as starting materials. Such compounds should give α-pyrones upon Ag- or Au-catalyzed cycloisomerization (Scheme 1, bottom).

α-Pyrones (2-pyrones or pyran-2-ones) indeed are an interesting class of compounds in organic chemistry as such structures are found in many natural products and in various pharmacologically active compounds.[9] They exhibit a wide range of biological activities. Therefore, any new synthetic method affording highly substituted α-pyrones under mild conditions would be valuable in this context, especially since the reported procedures usually required several steps with a relatively modest efficiency (overall yields often lower than 40%).[9]

We report here that gold(I) catalyzes the rearrangement of β-alkynylpropiolactones to substituted α-pyrones, providing an unprecedented route to such heterocycles[10] in a two-step and high overall yield procedure.

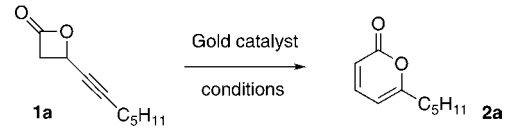
β-Lactones[11] can be conveniently prepared through the cyclocondensation of acyl halides and propargyl aldehydes using an achiral procedure derived from the reaction described by Nelson and co-workers.[12] Despite the inherent fragility of these substrates, isolated yields were routinely higher than 60% (Scheme 2).

Scheme 2. Direct Synthesis of β-Alkynylpropiolactones



To establish appropriate reaction conditions, we subjected the 3-(1-heptynyl)propiolactone **1a** to various gold catalysts expecting the formation of the 6-pentyl-2-pyrone **2a** (Table 1). It is noteworthy that pyrone **2a** is a natural product, first identified from *Trichoderma viride*,[9,13] exhibiting a characteristic coconut-like aroma as well as antibiotic and antifungal properties.[14]

Table 1. Screening of Catalysts for the Transformation of β-Alkynylpropiolactones **1a**



entry	catalyst (5 mol %)	conditions[a]	time (h)	yield (%)[b]
1	AgOTf	CH_2Cl_2, rfx	48	8
2	AgOTf/*p*TsOH	CH_2Cl_2, rfx	24/48	traces[c]
3	PPh_3AuX[d]	CH_2Cl_2/MeOH, rt	48	–[e]
4	AuCl	CH_2Cl_2, rfx	48	1[c,f]
5	$AuCl_3$	CH_2Cl_2, rfx	48	4[c,f]
6	PPh_3AuCl	CH_2Cl_2, rfx	48	traces[e]
7	PPh_3AuBF_4	CH_2Cl_2, rfx	3	53
8	PPh_3AuSbF_6	CH_2Cl_2, rfx	1	75
9	PPh_3AuOTf	CH_2Cl_2, rfx	3	**81**
10	PPh_3AuSbF_6	CH_2Cl_2, rt	5	60
11	PPh_3AuOTf	CH_2Cl_2, rt	5	54
12	PPh_3AuOTf	CH_3CN, rfx	16	–[g]
13	PPh_3AuOTf	Toluene, rfx	1	74
14	$(pCF_3Ph)_3PAuOTf$	CH_2Cl_2, rt	5	65
15	$(pCF_3Ph)_3PAuOTf$	CH_2Cl_2, rfx	3	**81**
16	$(F_5Ph)_3PAuOTf$	CH_2Cl_2, rt	2.5	71
17	$(F_5Ph)_3PAuOTf$	CH_2Cl_2, rfx	1	74

[a] Reactions run under argon, $C = 0.1$ mol/L. [b] Yields of pure isolated products, unless otherwise stated. [c] The starting material was recovered. [d] Various anions have been checked (X = Cl, SbF_6, OTf, NTf_2). [e] Degradation occurred. [f] Yields of **2a** were estimated from crude ^{1}H NMR spectra. [g] Decarboxylation occurred (see text).

Applying our best conditions for the Ag- or Au-catalyzed alkynyloxirane cycloisomerization in the presence or not of a proton source[3] or nucleophile[7] mostly returned the starting materials or led to decomposition (entries 1−3). Nevertheless, the expected pyrone **2a** could be isolated from Ag-catalyzed reactions, although in very low yield, even in refluxing dichloromethane (entry 1). Switching to simple gold chloride catalysts in pure dichloromethane did not help and led to almost no transformation despite the detection of the expected pyrone (entries 4 and 5). Although more soluble, the corresponding triphenylphosphinogold chloride was not reactive, leaving mostly untouched the starting lactone **1a**, even after prolonged heating (entry 6). In contrast, cationic gold complexes in situ prepared from the chloride complex gave the expected α-pyrones in variable yields depending on the counteranion (entries 7−9). As expected, higher temperatures sped up the reaction and often increased yields (e.g., entries 8 vs 10 and 9 vs 11). Heat could also favor the formation of side products, β-lactones usually leading to enynes resulting from retro-[2 + 2]-cycloaddition (**4** in Scheme 3).[11] However, the main side product formed in the presence of gold was the conjugated acid **3a** and surprisingly not the retro-[2 + 2]-cycloaddition enyne product **4a** (Scheme 3). The best compromise between rearrangement

(8) For the sole review on Au-catalyzed reaction mechanisms, see: Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2010**, *49*, 5232–5241.

(9) For reviews on α-pyrones, see: (a) Goel, A.; Ram, V. J. *Tetrahedron* **2009**, *65*, 7865–7913. (b) McGlacken, G. P.; Fairlamb, I. J. S. *Nat. Prod. Rep.* **2005**, *22*, 369–385.

(10) A synthesis of α-pyrones has recently been reported, based on gold-catalyzed [3 + 3]-sigmatropic rearrangement and cyclization. See: (a) Luo, T.; Schreiber, S. L. *Angew. Chem., Int. Ed.* **2007**, *46*, 8250–8253. (b) Luo, T.; Schreiber, S. L. *J. Am. Chem. Soc.* **2009**, *131*, 5667–5674.

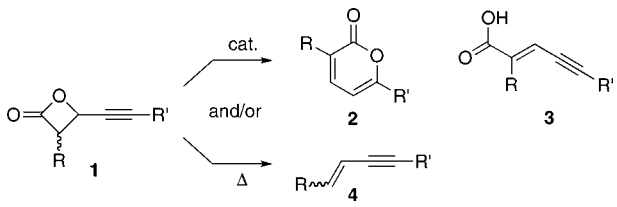
(11) For reviews on β-lactones, see: (a) Pommier, A.; Pons, J.-M. *Synthesis* **1993**, 441–459. (b) Yang, H. W.; Romo, D. *Tetrahedron* **1999**, *55*, 6403–6434. (c) Schneider, C. *Angew. Chem., Int. Ed.* **2002**, *42*, 744–746.

(12) See Supporting Information: (a) Nelson, S. G.; Peelen, T. J.; Wan, Z. *J. Am. Chem. Soc.* **1999**, *121*, 9742–9743. (b) Nelson, S. G.; Wan, Z. *Org. Lett.* **2000**, *2*, 1883–1886.

(13) Collins, R. P.; Halim, A. F. *J. Agric. Food Chem.* **1972**, *20*, 437–438.

(14) (a) Simon, A.; Dunlop, R. W.; Ghisalberti, E. L.; Sivasithamparam, K. *Soil Biol. Chem.* **1988**, *20*, 263–264. (b) Scarselletti, R.; Faull, J. L. *Mycol. Res.* **1994**, *98*, 1207–1209.

Scheme 3. Competitive Reactions Sometimes Observed during the β-Alkynylpropiolactone to Pyrone Rearrangement



efficiency and byproduct formation was achieved with triphenylphosphinogold triflate in refluxing dichloromethane (entry 9). With this catalyst, more coordinating solvents proved deleterious, inhibiting the reaction (entry 12), while in apolar noncoordinating solvent, the reaction went faster but some decarboxylation also occurred probably due to the higher temperature (entry 13). It is worth noting that decarboxylation was the only process in refluxing acetonitrile (entry 12).

More electrophilic complexes gave the same trends. With the tris(4-trifluoromethylphenyl)phosphine as the gold ligand, results almost identical to those achieved with triphenylphosphinogold triflate were obtained (entries 15 vs 9) but only in refluxing dichloromethane (entries 14 vs 15). The more electron-withdrawing tris(pentafluorophenyl)phosphine rendered the catalyst more reactive and thus induced a faster reaction (entries 16 and 17). As before, heat slightly improved the reaction efficiency, but again side reactions became competitive (entries 17 vs 16).

Control experiments showed the stability of the 2-pyrone **2a** under the conditions used, confirming that the side products, formed under certain conditions, originated from the starting β-lactone **1a**.

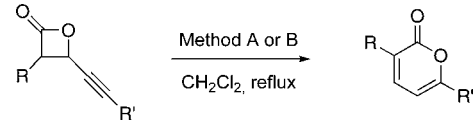
Since two sets of conditions emerged from this screening (entries 9 and 14), we submitted various alkynyl-β-lactone derivatives to both conditions, to examine the scope of this new Au-catalyzed rearrangement (Table 2).

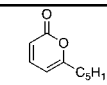
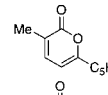
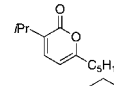
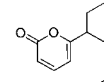
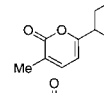
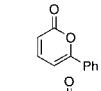
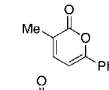
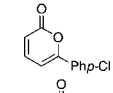
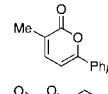
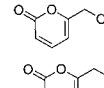
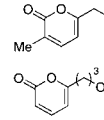
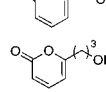
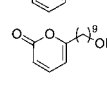
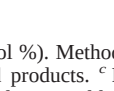
Simple alkyl chains and cycloalkyl derivatives **1a**−**e** gave the expected 6-substituted 2-pyrones in good to high yields (entries 1−10). With a substituent adjacent to the β-lactone carbonyl group, the pyrone formation was surprisingly slow (entries 3, 4 vs 1, 2 and 9, 10 vs 7, 8), and the larger the group, the larger this slowing effect (entries 5, 6 vs 3, 4).

Aryl groups tended to destabilize the starting β-lactones as well as the corresponding 2-pyrones, and thus these reactions led to more side products, lowering yields (entries 11−18 vs 1−10), even at room temperature or at 0 °C (entries 11−14). Both the corresponding enynes and the conjugated acids (**4** and **3** in Scheme 3) could be isolated or detected (respectively, 1−8% and 2−10%) depending on the conditions and the substrate.

The β-phenylethynyl-β-lactone **1f** gave the expected 6-phenyl-2-pyrone **2f** (entries 11 and 12) together with 1-phenylbut-3-en-1-yne **4f** and the conjugated acid **3f**. With $Ph_3PAuOTf$ as catalysts, the latter could be isolated in, respectively, 8 and 10% yield, while only as traces for **4f** and 8% for **3f** with $(p CF_3Ph)_3PAuOTf$ as the catalyst. With a methyl adjacent to the carbonyl group, the reactions were again slower, and heat improved yield when $(p CF_3Ph)_3$-PAuOTf was used as catalyst (entries 14 vs 13). Interestingly, adding an electron-withdrawing group on the phenyl ring stabilized the β-lactone and restored its reactivity toward gold (entries 15−16 vs 11−12). However, if this group was strongly electron-withdrawing, no evolution occurred (e.g., *p*-nitrophenyl; not mentioned in Table 2). Such behavior is reminiscent from the electronic effects observed in decarboxylation of β-lactones.[15]

Table 2. Scope of Gold(I)-Catalyzed α-Pyrone Formation



entry (cat.)[a]	β-lactones		2-pyrones		time (h)	yields (%)[b]
1 (A) 2 (B)	R = H R' = C_5H_{11}	**1a**		**2a**	2.5 3.5	81 81
3 (A) 4 (B)	R = Me R' = C_5H_{11}	**1b**		**2b**	22 7	45 71
5 (A) 6 (B)	R = *i*Pr R' = C_5H_{11}	**1c**		**2c**	30 32	33 15
7 (A) 8 (B)	R = H R' = cyclohexyl	**1d**		**2d**	2 6	80 69
9 (A) 10 (B)	R = Me R' = cyclohexyl	**1e**		**2e**	5 5	65 65
11 (A) 12 (B)	R = H R' = Ph	**1f**		**2f**	2[c] 3[c]	35 65
13 (A) 14 (B)	R= Me R'= Ph	**1g**		**2g**	4.5[c] 0.5	52 50[d]
15 (A) 16 (B)	R = H R' = *p*-ClPh	**1h**		**2h**	2 2.5	50 52
17 (A) 18 (B)	R = Me R' = *p*-ClPh	**1i**		**2i**	4 3.5	36 29
19 (A) 20 (B)	R = H R' = -CH_2OBn	**1j**		**2j**	27 24	65 48
21 (A) 22 (B)	R = Me R' = -CH_2OBn	**1k**		**2k**	48 48	-[e] -[e]
23 (A) 24 (B)	R = H R' = -$(CH_2)_3$OBn	**1l**		**2l**	20 24	37 29
25 (A) 26 (B)	R= H R'= -$(CH_2)_3$OPiv	**1m**		**2m**	4 3.5	65 68
27 (A) 28 (B)	R= H R'= -$(CH_2)_9$OBn	**1n**		**2n**	3 3.5	58 65

[a] Method A: $Ph_3PAuOTf$ (5 mol %). Method B: $(p CF_3Ph)_3PAuOTf$ (5 mol %). [b] Yields of pure isolated products. [c] Performed at 0 °C. [d] The reaction performed at 0 °C gave a lower yield (46%). [e] No conversion.

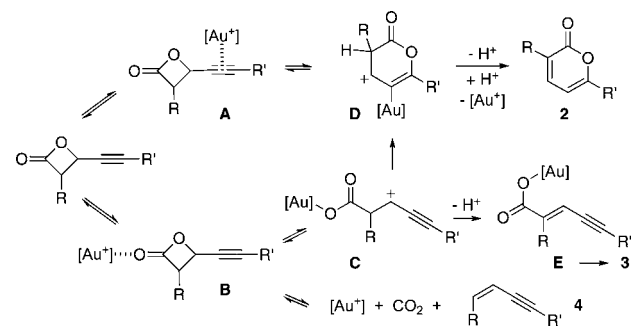
Ether substituents at the propargylic position dramatically slowed the reaction (entries 19−20 vs 1−2) and favored the side formation of the unsaturated acid **3** (28% of **3j**). The concomitant presence of a substituent α to the *β*-lactone carbonyl group slowed even more the reaction, so that almost no evolution occurred (entries 21−22 vs 19−20). Unexpectedly, a decrease in reaction time was also observed if the same ether substituent was remote from the propargylic position (entries 23−24 vs 19−20 vs 1−4). When this benzyl ether was replaced by a pivaloyl ester, the normal behavior was restored, and the corresponding pyrone was obtained in high yield within a few hours (entries 25−26 vs 23−24). The same normal behavior was also observed when this benzyl ether was far remote from the alkyne moiety (entries 27−28). These results revealed a special role of the benzyl ether unit when placed relatively close from the Au-coordinating sites, reminiscent of Au-catalyzed Friedel−Crafts reactions,[16] or from the benzyloxy fragmentation recently reported.[17,18]

It is worth noting that most derivatives with a substituent adjacent to the *β*-lactone carbonyl group proved far less reactive with a concomitant increase in reaction time (entries 3−4 vs 1−2, 5−6 vs 1−2, 9−10 vs 7−8, 13−14 vs 11−12, 17−18 vs 15−16, and 21−22 vs 19−20). Moreover, large groups reduced the reactivity more strongly than small groups (entries 5−6 vs 3−4 vs 1−2). These series of disubstituted *β*-lactones were produced as an approximate 3:1 mixture of diastereoisomers, but no significant difference was observed in their evolution, whatever the catalyst used. The results obtained with this series suggested some hindrance at some stage of the rearrangement, most probably at the coordination step (vide infra).

From a mechanistic point of view, it is not possible to naively extend the mechanism we proposed for alkynyl epoxide rearrangement after our detailed investigations.[7a] In the latter, a nucleophile, either introduced in purpose or adventitiously present, opened the epoxide, and the resulting alkoxide then cyclized in a gold-catalyzed process. In the present case, running the alkynyl-*β*-lactone to α-pyrone rearrangement in the presence of a nucleophile proved deleterious, while without it, the reaction proceeded well (see Table 1). Nucleophilic opening of alkynyl-*β*-lactone and Au-catalyzed cyclization is thus not the major pathway.

The general trend observed with an extra group close to the *β*-lactone carbonyl group on one hand and the role of some alkynyl substituent on the other hand suggested changes in coordination ability and thus supported equilibrium between *σ*- and *π*-Au complexes (Scheme 4, **A** and **B**).[19]

Scheme 4. Proposed Mechanism for the Au(I)-Catalyzed Rearrangement of *β*-Alkynylpropiolactones to α-Pyrones



The formation of side products, especially the acid **3** (see Scheme 3), also supported *σ*-coordination at the *β*-lactone carbonyl. The resulting *σ*-Au *β*-lactone complexes **B** could be more prone to decarboxylation, especially when fully conjugated enynes—e.g., **4f**,**g** (R′ = Ph)—could be obtained (Table 2, entries 11−18). Such *σ*-Au complexes **B** could also evolve to an open cationic gold carboxylate **C**, a precursor of the enynoic acids **3** (Scheme 4). It is worth mentioning that such cationic intermediates have been postulated to rationalize the stereochemical outcome of *β*-lactone decarboxylation[20] and must be involved in the Lewis acid promoted ring expansion of *β*-lactones.[21] Both *σ*- and *π*-Au complexes **A** and **B** would lead to cationic pyrone gold intermediate **D**, possibly through either a 1,3-oxygen shift or Hashmi-type cyclization[4] from **A** and through cyclization of **C** from **B**. The intermediate **D** would then give the corresponding pyrones **2** upon proton elimination and subsequent protodeauration (Scheme 4).[22]

In conclusion, we have reported a novel synthesis of α-pyrones through Au-catalyzed cycloisomerization of *β*-alkynylpropiolactones. Since the latter can be obtained by condensing acyl chlorides to aldehydes, this synthesis is particularly appealing, providing in two steps with good to high yields a wide diversity of α-pyrones starting from very simple compounds.

Acknowledgment. The authors thank the CNRS and the French Ministry of Research for financial support. T.D. thanks the French Ministry of Research for a PhD fellowship.

Supporting Information Available: Selected experimental procedures and spectral data. This material is available free of charge via the Internet at http://pubs.acs.org.

OL1023739

(15) Krabbenhoft, H. O. *J. Org. Chem.* **1978**, *43*, 1305–1307.

(16) For some recent examples, see: (a) Bandini, M.; Eichholzer, A. *Angew. Chem., Int. Ed.* **2009**, *48*, 9533–9537. (b) Lu, Y.; Du, X.; Jia, X.; Liu, Y. *Adv. Synth. Catal.* **2009**, *351*, 1517–1522. (c) Zhang, Z.; Shi, M. *Chem.—Eur. J.* **2010**, *16*, 7725–7729.

(17) Bolte, B.; Odabachian, Y.; Gagosz, F. *J. Am. Chem. Soc.* **2010**, *132*, 7294–7296.

(18) It is worth noting that no benzaldehyde[17] could be detected in the crude mixture by NMR, but modified aromatic compounds were detected (≤10%).[16]

(19) (a) Yamamoto, Y. *J. Org. Chem.* **2007**, *72*, 7817–7831. (b) Pérez, A. G.; López, C. S.; Marco-Contelles, J.; Faza, O. N.; Soriano, E.; de Lera, A. R. *J. Org. Chem.* **2009**, *74*, 2982–2991.

(20) (a) Mulzer, J.; Zippel, M.; Brüntrup, G. *Angew. Chem., Int. Ed.* **1980**, *19*, 465–467. (b) Moyano, A.; Pericas, M. A.; Valenti, E. *J. Org. Chem.* **1989**, *54*, 573–581. (c) Asencio, G.; Miranda, M. A.; Perez-Prieto, J.; Sabater, M. J.; Simon-Fuentes, A. *Angew. Chem., Int. Ed.* **1990**, *29*, 1146–1148.

(21) (a) Mulzer, J.; Brüntrup, G. *Angew. Chem., Int. Ed.* **1979**, *18*, 793–795. (b) Black, T. H.; Hall, J. A.; Sheu, R. G. *J. Org. Chem.* **1988**, *53*, 2371–2378.

(22) Krauter, C. M.; Hashmi, A. S. K.; Pernpointner, M. *Chem. Catal. Chem.* **2010**, *2*, 1226–1230.