

Gold-Catalysed Direct Couplings of Indoles and Pyrroles with 1,3-Dicarbonyl Compounds

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Abstract: The gold-catalysed direct couplings of indoles **1** and pyrroles **5** with 1,3-dicarbonyls **2** is described. This new method for C–C bond formation allows high functional group tolerance, regioselectivity, and scope under relatively mild conditions. Moreover, the 3-alkenylindoles **3** can be readily available through gold-catalysed sequential cyclization/alkeny-

lation reaction of 2-alkynylanilines derivatives **4** with 1,3-dicarbonyls **2**.

Keywords: 2-alkynylanilines; C–C bond formation; 1,3-dicarbonyl compounds; gold catalysis; indoles; pyrroles

Introduction

Countless natural products and biologically active compounds incorporate indole and pyrrole heterocycles.^[1] For this reason, the functionalisation of such compounds *via* selective and eco-friendly strategies is still spurring on great research activities.^[2] Transition metal-mediated couplings are the staple reactions for intermolecular C–C bond formation between these heterocycles and other organic substrates.^[3] Typically, transition metal-catalysed oxidative carbon-carbon heterocouplings require that one or both entities are primed to react by functionalisation.^[4] In a sense, the partners are pre-programmed to seek each other and react. Pre-programming, however, incurs cost in time, materials, and resources. Thus, simple and practical methods that eliminate this prerequisite represent synthetic goals.^[5] Particular focus is devoted on developing new methods to couple indoles and pyrroles with carbonyl compounds directly, without modification of either coupling partner. Remarkably simple methods for the transition metal-catalysed coupling of the C-3 carbon of indoles and the C-2 carbon atom of pyrroles with the α -carbon of carbonyl compounds have been reported.^[6] By contrast, to the best of our knowledge there are only rare examples of coupling reaction of indoles with 1,3-dicarbonyl compounds^[7] and the direct coupling of pyrroles with

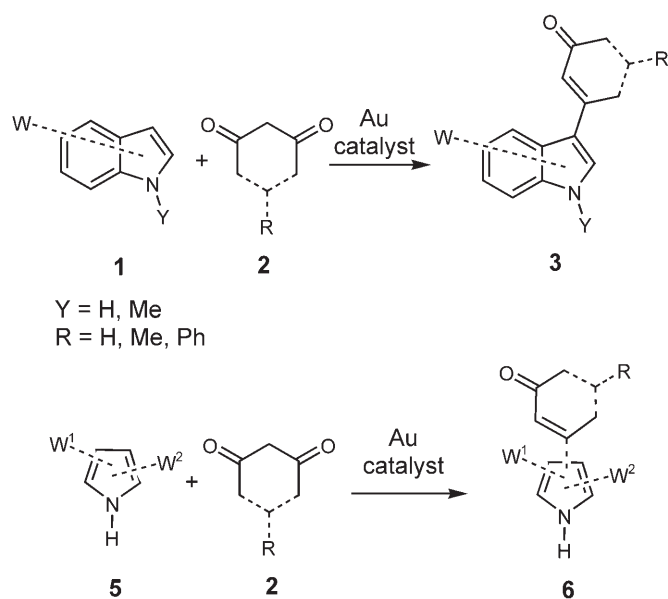
1,3-dicarbonyls has not been previously reported. Our continuing interest in the development of catalytic processes that exploit selective and controllable C–H functionalisation of aromatic heterocycles^[8] led us to develop new synthetic approaches for the direct intermolecular alkenylation^[9] of indoles and pyrroles through their gold-catalysed reactions with 1,3-dicarbonyl compounds. Gold is an excellent catalyst for the C–H functionalisation of aromatic heterocycles, thereby opening new pathways for carbon-carbon bond formation.^[10] Herein we describe the results of our investigation.

Results and Discussion

In the past and still today, most aromatic products are prepared on the industrial level by well-known classic transformations such as Friedel–Crafts alkylations, Friedel–Crafts acylations, nitrations, and halogenations.^[11] Although these methods work reliably with a variety of substrates, they often have major drawbacks such as drastic reaction conditions (high temperature, strong acidic conditions), low regioselectivity, and large amounts of by-products. More specifically, we are interested in the development of mild, efficient and general methodologies for constructing scaffolds that incorporate nitrogen moieties as indoles and pyrroles which cir-

cumvent the undesirable rearrangements and polymerisations that readily occur with indoles and pyrroles under the strongly acidic conditions typically utilised. Recently, new efficient Lewis acid catalysts, such as SmI_2 ,^[12] bismuth(III) derivatives,^[13] $\text{Yb}(\text{OTf})_3 \cdot 3 \text{H}_2\text{O}$,^[14] ceric ammonium nitrate (CAN)^[15] and InBr_3 ^[16] have attracted attention to avoid undesirable rearrangements and polymerisations in electrophilic substitution reactions with indoles and pyrroles. Lewis acidic metal catalysts have been employed to a lesser extent.^[17] Therefore, the development of new direct C–C coupling reactions of arenes/heteroarenes is an important topic in organometallic chemistry and catalysis.^[18] In our search for new and improved catalysts for the regioselective electrophilic substitution of indoles and pyrroles we studied their gold-catalysed alkenylation with 1,3-dicarbonyl compounds (Scheme 1). Gold is a soft transition metal showing high electrophilic affinity for alkynes, arenes, and allenes.^[19] It can also act as a Lewis acid for the activation of electrophiles.^[20] Gold catalysts are quite robust, and exclusion of water and oxygen in most cases is not necessary. The peculiar features of the high catalytic activity of gold salts, determining the need for extremely small amount of these catalysts, the high selectivity and the mild reaction conditions, are of great importance for homogeneous catalysis. Many gold(I) as well as gold(III) compounds are powerful catalysts and both oxidation states I and III have been proposed for the active species. In consequence, gold derivatives are growing in importance as efficient catalysts of several organic transformations.

Selected results of the gold-catalysed reaction of indoles **1** with 1,3-dicarbonyl compounds **2** are given in Table 1.



Scheme 1. Gold-catalysed alkenylation of indoles and pyrroles with 1,3-dicarbonyl compounds.

Usually, the reactions of indoles **1** with 1,3-dicarbonyl derivatives **2** proceed smoothly with high selectivity. In general, indoles **1** were reacted in the presence of an excess of 1,3-dicarbonyl compounds **2** (**2**:**1**=2). With regard to indoles **1**, the procedure is compatible with a variety of functional groups. The reaction of functionalised 3-unsubstituted indoles with cyclic **2** resulted in a better yield at 80 °C, while with acetylacetone (**2e**) satisfactory results have been observed even at 40 °C. Gold showed higher catalytic activity in the higher oxidation state. Generally, $\text{NaAuCl}_4 \cdot 2 \text{H}_2\text{O}$ (5 mol %) in acetonitrile afforded satisfactory results. AuCl_3 and AuBr_3 can also catalyse the reaction but they gave the products in better yield in combination with silver(I) salts. Silver salt should help generate a more electrophilic gold(III) species. AgOTf alone did not efficiently catalyse these reactions under the same conditions. It is noteworthy that, by contrast with the results obtained in the $\text{BF}_3 \cdot \text{Et}_2\text{O}$ -catalysed reaction of **1a** with **2a** which gave mainly the formation of 11-(1*H*-indol-3-yl)-2,3,4,5,10,11-hexahydrodibenzo[*b, f*]azepin-1-one,^[7c] the transition metal-catalysed reaction allows the chemoselective formation of the 3-(indol-3-yl)cyclohexen-2-en-1-one (**3a**) as the only reaction product. Moreover, the formation of the indole dimer which has been suggested as the key intermediate for the dibenzoazepinone derivative, can be ruled out by the recovering of the starting indole **1a**. C–H functionalisation by C–C bond formation points out the unique catalytic properties of gold derivatives. The catalytic activation of sp^2 hybridised aryl C–H bonds by gold has been applied to the development of a variety of syntheses of heterocycles.^[21] He and Shi reported an efficient gold(III)-catalyzed hydroarylation reaction of alkynes and alkenes^[22] as well as gold-catalysed alkylation of arenes with epoxides.^[23] Dyker, Hashmi and co-workers found that gold(III) chloride indeed nicely catalyses the addition of 2-methylfuran to α,β -enones. Au(I) complexes are effective in catalysing the regioselective hydroheteroarylation of acetylenecarboxylic acid ester by furan.^[24] The intramolecular hydroarylation of *N*-propargyl-*N*-tosylanilines catalysed by the cationic complex formed from $[\text{Au}(\text{PPh}_3)\text{Me}]$ and HBF_4 gave 1,2-dihydroquinolines.^[25] A highly efficient imino-Friedel–Crafts-type addition of heteroarenes to imines has been developed by using a combination of gold and silver catalysts.^[26] In all these reactions it is uncertain whether a C–C or a C–N multiple bond is activated by gold and then attacks the arene in an electrophilic manner or whether the electrophilic auration of arenes generates aryl-/heteroaryl-gold species which undergo an addition reaction to the multiple bond. Moreover, the combination of gold and silver salts catalysed the addition of 1,3-dicarbonyl compounds to styrene derivatives, dienes, triene, and cyclic enol ethers with high regioselectivity.^[27] We previously investigated the effectiveness of gold(III) catalysis in the reaction of 1,3-dicarbonyls with N-, O-, S-, and P-nucleophiles.^[28]

Table 1. Gold-catalysed alkenylation of indoles **1** with 1,3-dicarbonyl compounds **2**.

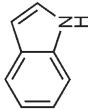
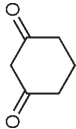
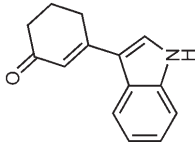
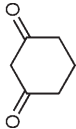
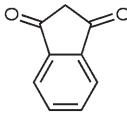
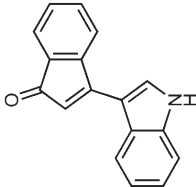
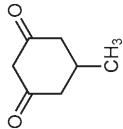
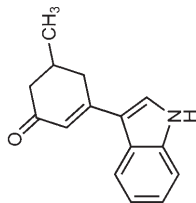
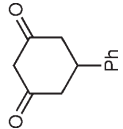
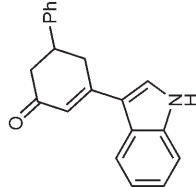
Indole 1	1,3-Dicarbonyl compound 2	Catalyst	Time [h]	Reaction conditions ^[b]	Product 3	Yield [%] ^[a]
 1a	 2a	NaAuCl ₄ ·2 H ₂ O	24	A	 3a	54 (19) ^[c]
	 2a	AuCl	24	B	3a	23 (68) ^[c]
		AuBr ₃ /AgOTf	24	C	3a	46 (18) ^[c]
1a	 2b	NaAuCl ₄ ·2 H ₂ O	2	A	 3b	60
1a	 2c	NaAuCl ₄ ·2 H ₂ O	24	A	 3c	80
1a	 2d	AuBr ₃	24	D	 3d	74 (25) ^[c]
1a	2d	AuBr ₃ /AgOTf	24	C	3d	90 (7) ^[c]

Table 1 (cont.)

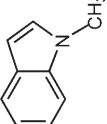

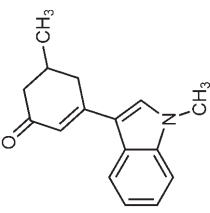
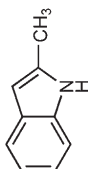

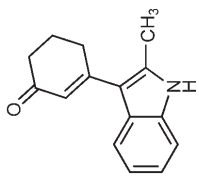
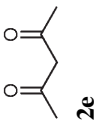
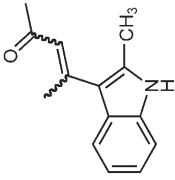
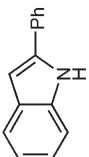
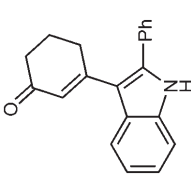
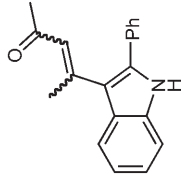
Indole 1	1,3-Dicarbonyl compound 2	Catalyst	Time [h]	Reaction conditions ^[b]	Product 3	Yield [%] ^[a]
 1b	2c 	NaAuCl ₄ ·2 H ₂ O	7	A	 3e	75 (13) ^[c]
 1c	2a 	AuBr ₃ /AgOTf	3	C	 3f	89
1c	 2e	AuBr ₃ /AgOTf	0.5	C	 3g 3g	48 (6) ^[c]
1c	2e	AuCl ₃ /AgOTf	1	C	3g 3g	62 ^[d] (14) ^[c]
 1d	2e	NaAuCl ₄ ·2 H ₂ O	24	A	 3h	76 (19) ^[c]
1d	2e	AuBr ₃ /AgOTf	24	C	 3i	44 ^[d] (43)
		AuBr ₃ /AgOTf	40	C		70 (21) ^[c]

Table 1 (cont.)

Indole 1	1,3-Dicarbonyl compound 2	Catalyst	Time [h]	Reaction conditions ^[b]	Product 3	Yield [%] ^[a]

^[a] Yields refer to single non-optimised runs, and are given for pure isolated products.

^[b] Reactions were carried out by using the following molar ratios and at 80 °C: A = **1**:2:NaAuCl₄·2 H₂O = 1:2:0.05 in CH₃CN; B = **1**:2:0.05 in CH₃CN; C = **1**:2:0.05:AgOTf = 1:2:0.05:0.10 in ClCH₂CH₂Cl.

^[c] Figures in parentheses refer to the recovered starting indole **1**.

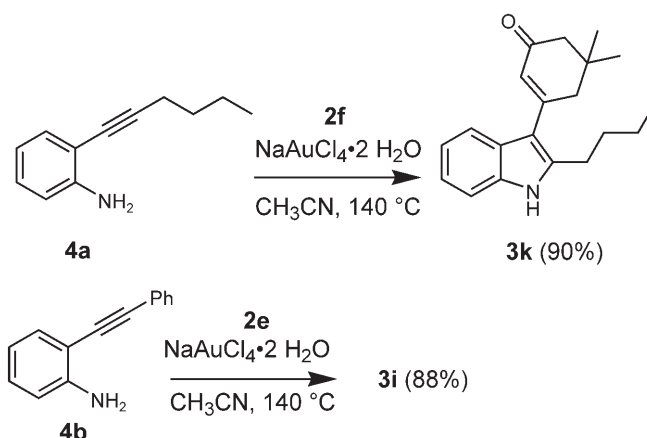
^[d] Reaction temperature 40 °C.

No matter what the exact mechanism of the reaction of **1** with **2** is, this gold-catalysed alkenylation reaction seems to be a synthetically useful reaction.

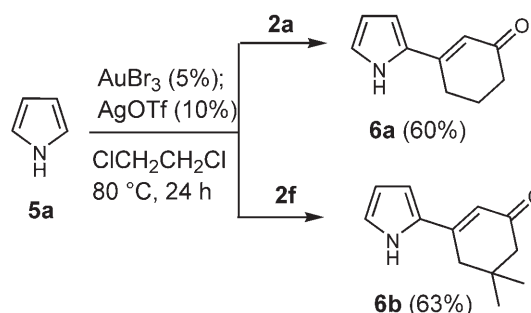
Interestingly the gold-catalysed domino reaction of 2-alkynylanilines^[29] **4a, b** with **2e, f** accomplished the formation of the corresponding products **3k, l** in 90 and 88% yields, respectively (Scheme 2).

The nitrogen of 2-alkynylanilines **4a, b** did not require prior protection to avoid the gold-catalysed competitive formation of the β -enaminone derivative. The sequential cyclization/alkenylation reaction of **4** leading to 3-alkenylindoles **3** can be directed by increasing the reaction temperature. As the 2-alkynylanilines **4** are easily available by established synthetic procedures,^[30] the methods for the syntheses of **3** with these compounds as the starting materials are much more versatile.

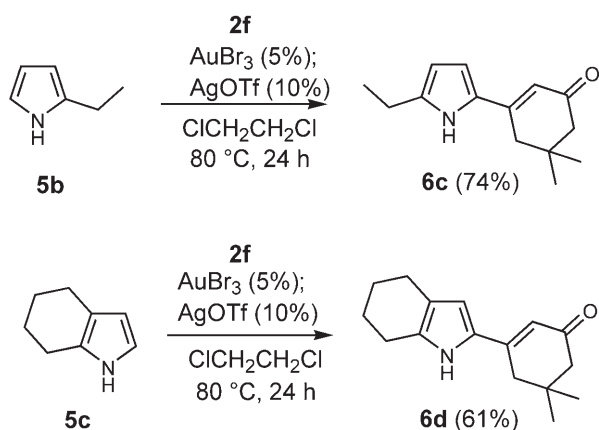
We imagined that the results of the reaction of indoles with 1,3-dicarbonyl compounds could be extended to an analogous coupling of pyrroles. Whereas the locus of nucleophilicity of indole is at C-3, it resides at C-2 for the pyrrole nucleus,^[31] and it was expected that direct coupling would link pyrroles to 1,3-dicarbonyl derivatives at that site. Indeed by using the same reactions conditions as for indoles, this proved to be the case as shown in Scheme 3.



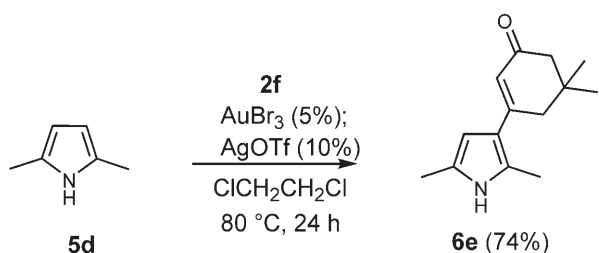
Scheme 2. Sequential gold-catalysed cyclisation/alkenylation reaction of 2-alkynylanilines with 1,3-dicarbonyl compounds.



Scheme 3. Gold-catalysed alkenylation reaction of pyrrole.



Scheme 4. Gold-catalysed alkenylation reaction of substituted pyrroles.



Scheme 5. Gold-catalysed β -alkenylation reaction of α, α' -disubstituted pyrroles.

The reactions proceeded smoothly with high selectivity. Pyrrole (**5a**) underwent electrophilic substitution exclusively at its α -position. The reactions were clean and the formation of any side polymerisation products that are normally observed under the influence of strong acids has not been observed. For a comparison, the reactions of **5a** with **2a** in 1,2-dichloroethane at 80 °C in the presence of a catalytic amount of *p*-toluenesulphonic acid (*p*-toluenesulphonic acid/**5a** ratio = 0.15) led mainly to polymerisation derivatives and **6a** was isolated in only 26% yield. Substitution patterns are tolerated on the pyrrole subunit (Scheme 4).

The formation of the β -alkenyl-substituted pyrrole derivatives could be observed when the α, α' positions of the free N–H pyrroles were substituted (Scheme 5).

Conclusion

This investigation shows that gold(III) derivatives are efficient catalysts for the direct selective alkenylation reaction of indoles and pyrroles with 1,3-dicarbonyl compounds. This new method for C–C bond formation allows high functional group tolerance, regioselectivity, and scope under relatively mild conditions. Moreover, the 3-alkenylindoles can be readily available through gold-catalysed sequential cyclisation/alkenylation reaction of 2-alkynylanilines with 1,3-dicarbonyl compounds. Current efforts are aimed at elucidating the

mechanism and exploring further scope of these transformations.

Experimental Section

General Procedure A

To a solution of the indole derivative **1** (1 mmol) in CH_3CN (2 mL) were added the 1,3-dicarbonyl compound **2** and $\text{NaAuCl}_4 \cdot 2 \text{H}_2\text{O}$ (0.05 mmol). The mixture was stirred at 80 °C for the appropriate time and monitored by TLC or GC-MS. After completion, the solvent was removed by evaporation. The residue was purified by chromatography on silica gel (230–400 mesh) eluting with *n*-hexane/ethyl acetate mixtures to afford the pure derivative **3**.

General Procedure B

To a solution of the indole derivative **1** (1 mmol) in CH_3CN (2 mL) were added the 1,3-dicarbonyl compound **2** and AuCl (0.05 mmol). The mixture was stirred at 80 °C for the appropriate time and monitored by TLC or GC-MS. After completion, the solvent was removed by evaporation. The residue was purified by chromatography on silica gel (230–400 mesh) eluting with *n*-hexane/ethyl acetate mixtures to afford the pure derivative **3**.

General Procedure C

To a solution of the indole derivative **1** or pyrrole **5** (1 mmol) in $\text{ClCH}_2\text{CH}_2\text{Cl}$ (2 mL) were added the 1, 3-dicarbonyl compound **2**, AuX_3 (0.05 mmol) and AgOTf (0.10 mmol). The mixture was stirred at 80 °C for the appropriate time and monitored by TLC or GC-MS. After completion, the solvent was removed by evaporation. The residue was purified by chromatography on silica gel (230–400 mesh) eluting with *n*-hexane/ethyl acetate mixtures to afford the pure derivative **3** or **6**.

General Procedure D

To a solution of the indole derivative **1** (1 mmol) in $\text{ClCH}_2\text{CH}_2\text{Cl}$ (2 mL) were added the 1,3-dicarbonyl compound **2** and AuBr_3 (0.05 mmol). The mixture was stirred at 80 °C for the appropriate time and monitored by TLC or GC-MS. After completion, the solvent was removed by evaporation. The residue was purified by chromatography on silica gel (230–400 mesh) eluting with *n*-hexane/ethyl acetate mixtures to afford the pure derivative **3**.

General Experimental Procedure for the Gold-Catalysed Sequential Cyclisation/Alkenylation Reaction of 2-Alkynylphenylamines **4** with 1, 3-Dicarbonyl Compounds **2**

To a solution of 2-alkynylphenylamine **4** (1 mmol) and 1,3-dicarbonyl compound **2** (3 mmol) in acetonitrile (2 mL) was added $\text{NaAuCl}_4 \cdot 2 \text{H}_2\text{O}$ (0.028 g, 0.07 mmol). The resulting mix-

ture was allowed to react under stirring at 140 °C for the appropriate time and the reaction was monitored by TLC or GC-MS. After completion, the solvent was removed by evaporation. The residue was purified by chromatography on silica gel (230–400 mesh) eluting with *n*-hexane/ethyl acetate mixtures to afford the pure derivative **3**.

Characterization data for products **3** and **6** can be found in the Supporting Information file.

Acknowledgements

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References and Notes

- [1] a) J. W. Huffman, L. W. Padgett, *Curr. Med. Chem.* **2005**, *12*, 1395–1411; b) J. M. Padron, D. Tejedor, A. Santos-Exposito, F. Garcia-Tellado, V. S. Martin, J. Villar, *Biorg. & Med. Chem. Lett.* **2005**, *15*, 2487–249; c) J. A. Joule, in: *Science of Synthesis*, (Ed.: E. J. Thomas), Thieme Verlag, Stuttgart, **2000**, Vol. 10, p 261.
- [2] a) T. Dohi, K. Morimoto, Y. Kiyono, H. Tohma, Y. Kita, *Org. Lett.* **2005**, *7*, 537–540; b) Z. H. Zhang, *Synlett* **2005**, 711–712; c) B. M. Banik, M. Fernandez, C. Alvarez, *Tetrahedron Lett.* **2005**, *46*, 2479–2482; d) T. Hudlicky, U. Rinner, K. J. Finn, I. Ghiviriga, *J. Org. Chem.* **2005**, *70*, 3490–3499; e) D. G. Gu, S. J. Ji, Z. Q. Jiang, M.-F. Zhou, T.-P. Loh, *Synlett* **2005**, 959–962; f) P. Jaisankar, P. C. Srinivasan, *Synth. Commun.* **2005**, *35*, 923–927; g) G. Abbiati, A. Arcadi, A. Bellinazzi, E. Beccalli, E. Rossi, S. Zangola, *J. Org. Chem.* **2005**, *70*, 4088–4095.
- [3] a) For a review of metal-mediated couplings of this type, see: M. Miura, M. Nomura, *Top. Curr. Chem.* **2002**, *219*, 211–241; b) for recent advances in this area, see: B. Sezen, D. Sames, *J. Am. Chem. Soc.* **2003**, *125*, 10580–10585, and references cited therein.
- [4] a) B. Witulski, J. R. Azcon, C. Alayrac, A. Arnautu, V. Collot, S. Rault, *Synthesis* **2005**, 771–780; b) X. Wang, B. S. Lane, D. Sames, *J. Am. Chem. Soc.* **2005**, *127*, 4996–4997; c) B. S. Lane, D. Sames, *Org. Lett.* **2004**, *6*, 2897–2900; d) R. D. Rieth, N. P. Mankad, E. Calimano, J. P. Sadighi, *Org. Lett.* **2004**, *6*, 3981–3983; e) M. Bandini, A. Melloni, A. Umani-Ronchi, *Org. Lett.* **2004**, *6*, 3199–3202.
- [5] a) N. P. Grimster, C. Gauntlett, C. R. A. Godfrey, M. J. Gaunt, *Angew. Chem. Int. Ed.* **2005**, *44*, 3125–3129; b) E. Capito, J. M. Brown, A. Ricci, *Chem. Commun.* **2005**, 1854–1856; c) G. Cravotto, F. Demartin, G. Palmisano, A. Penoni, T. Radice, S. Tollari, *J. Organomet. Chem.* **2005**, *690*, 2017–2026.
- [6] a) P. S. Baran, J. M. Richter, D. W. Lin, *Angew. Chem. Int. Ed.* **2005**, *44*, 609–612; b) P. S. Baran, C. A. Guerrero, N. B. Ambhaikar, B. D. Hafensteiner, *Angew. Chem. Int. Ed.* **2005**, *44*, 606–609; c) P. S. Baran, J. M. Richter, *J. Am. Chem. Soc.* **2004**, *126*, 7450–7451.
- [7] a) K. P. Dhara, M. Saha, R. Das, S. Kanrar, H. Budzikiewicz, A. Neuman, T. Prange, *Indian J. Chem. Section B – Organic Chem. Including Med. Chem.* **2005**, *33*, 949–952; b) J. Baberji, A. Chatterjee, M. Saha, Mukherjee, S. Kanrar, *Indian J. Chem. Section B – Organic Chem. Including Med. Chem.* **2003**, *42*, 2573–2576; c) J. Baberji, M. Saha, R. Chakrabarti, S. Kanrar, A. Chatterjee, H. Budzikiewicz, T. Prange, A. Neuman, *J. Chem. Res.* **1993**, 320–321; d) W. E. Noland, D. N. Robinson, *J. Org. Chem.* **1957**, *22*, 1134–1135.
- [8] A. Arcadi, G. Bianchi, M. Chiarini, G. D’Anniballe, F. Marinelli, *Synlett* **2004**, 944–950.
- [9] C. Nevado, A. M. Echavarren, *Synthesis* **2005**, 167–187.
- [10] a) A. S. K. Hashmi, *Angew. Chem. Int. Ed.* **2005**, *44*, 6990–6993; b) D. E. De Vos, B. F. Sels, *Angew. Chem. Int. Ed.* **2005**, *44*, 30–32; c) A. S. K. Hashmi, L. Grundl, *Tetrahedron* **2005**, *61*, 6231–6236; d) C. Nevado, A. Echavarren, *Chem. Eur. J.* **2005**, *11*, 3155–3164; e) A. Hoffmann-Röder, N. Krause, *Org. Biol. Chem.* **2005**, *3*, 387–392; f) A. Arcadi, S. Di Giuseppe S. *Curr. Org. Chem.* **2004**, *8*, 795–812; g) A. S. K. Hashmi *Gold Bull.* **2004**, *37*, 51–65; h) G. Dyker, in: *Organic Synthesis Highlights*, (Eds.: H. G. Schmalz, T. Wirth), Wiley-VCH, Weinheim, **2003**, pp 48–55.
- [11] K. von Weissmermel, H.-J. Arpe, *Industrielle Organische Chemie*, VCH, Weinheim, **1988**.
- [12] Z.-P. Zhan, R. F. Yang, K. L., *Tetrahedron Lett.* **2005**, *46*, 3859–3862.
- [13] S. Leitch, J. Addison-Jones, A. McCluskey, *Tetrahedron Lett.* **2005**, *46*, 2915–2918.
- [14] A. Janczuk, W. Zhang, W. Xie, S. Lou, J. Cheng, P. G. Wang, *Tetrahedron Lett.* **2002**, *43*, 4271–4274.
- [15] a) S.-J. Li, S.-Y. Wang, *Synlett* **2003**, 2074–2076.
- [16] M. Bandini, P. G. Cozzi, M. Giacobini, P. Melchiorre, S. Selva, A. Umani-Ronchi, *J. Org. Chem.* **2002**, *67*, 3700–3704.
- [17] C. Palomo, M. Oiarbide, B. G. Kardak, J. M. Garcia, A. Linden, *J. Am. Chem. Soc.* **2005**, *127*, 4154–4155 and references cited therein.
- [18] K. Mertins, I. Iovel, J. Kischel, A. Zapf, M. Beller, *Angew. Chem. Int. Ed.* **2005**, *44*, 238–242.
- [19] a) L. Zhang, S. A. Kozmin, *J. Am. Chem. Soc.* **2005**, *127*, 6962–6963; b) S. Antonioti, E. Genin, J.-P. Genêt, *J. Am. Chem. Soc.* **2005**, *127*, 9976–9977; c) D. J. Gorin, N. R. Davis, F. D. Toste, *J. Am. Chem. Soc.* **2005**, *127*, 11260–11261; d) M. H. Suhre, M. Reif, S. F. Kirsch, *Org. Lett.* **2005**, *7*, 3925–3927; e) A. W. Sromek, M. Rubina, V. Gevorgyan, *J. Am. Chem. Soc.* **2005**, *127*, 10500–10501.
- [20] A. Arcadi, M. Chiarini, S. Di Giuseppe, F. Marinelli, *Synlett* **2003**, 203–206.
- [21] A. Arcadi, G. Bianchi, in: *Targets in Heterocyclic Systems*, (Eds.: O. A. Attanasi, D. Spinelli), Italian Society of Chemistry, Rome, **2004**, pp 82–119.
- [22] Z. Shi, C. He, *J. Org. Chem.* **2004**, *69*, 3669–3671.
- [23] Z. Shi, C. He, *J. Am. Chem. Soc.* **2004**, *126*, 13596–13597.

- [24] M. T. Reetz, K. Sommer, *Eur. J. Org. Chem.* **2003**, 3485–3496.
- [25] C. Nieto-Oberhuber, M. P. Muñoz, E. Buñuel, C. Nevado, D. J. Cárdenas, A. M. Echavarren, *Angew. Chem. Int. Ed.* **2004**, 43, 2402–2406.
- [26] Y. Luo, C.-J. Li, *Chem. Commun.* **2004**, 1930–1931.
- [27] a) R.-V. Nguyen, X.-Q. Yao, D. S. Bohle, C.-J. Li, *Org. Lett.* **2005**, 7, 673–675; b) X.-Q. Yao, C.-J. Li, *J. Am. Chem. Soc.* **2004**, 126, 6884–6885.
- [28] A. Arcadi, G. Bianchi, S. Di Giuseppe, F. Marinelli, *Green Chem.* **2003**, 5, 64–67.
- [29] M. Alfonsi, A. Arcadi, M. Aschi, G. Bianchi, F. Marinelli, *J. Org. Chem.* **2005**, 70, 2665–2673.
- [30] a) J. Ezquerro, C. Pedregal, C. Lamas, J. Barluenga, M. Pérez, M. A. García-Martín, J. M. González, *J. Org. Chem.* **1996**, 61, 5804–5812; b) Y. Kondo, S. Kojima, T. Sakamoto, *Heterocycles* **1996**, 43, 2741–2746; c) D. E. Rudisill, J. K. Stille, *J. Org. Chem.* **1989**, 54, 5856; d) A. Arcadi, S. Cacchi, F. Marinelli, *Tetrahedron Lett.* **1989**, 30, 2581–2584.
- [31] J. S. Yadav, S. Abraham, B. V. Reddy, G. Sabitha, *Tetrahedron Lett.* **2001**, 42, 8063–8065.