Palladium Catalysis

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Palladium-Catalyzed Coupling Reactions: Carbonylative Heck Reactions To Give Chalcones**

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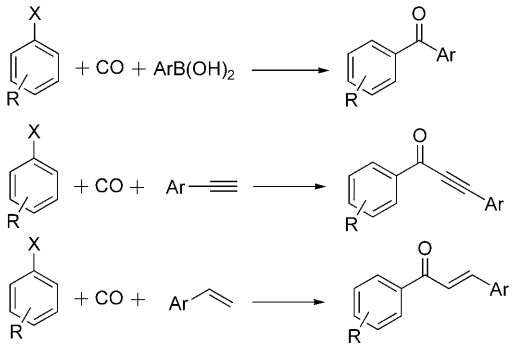
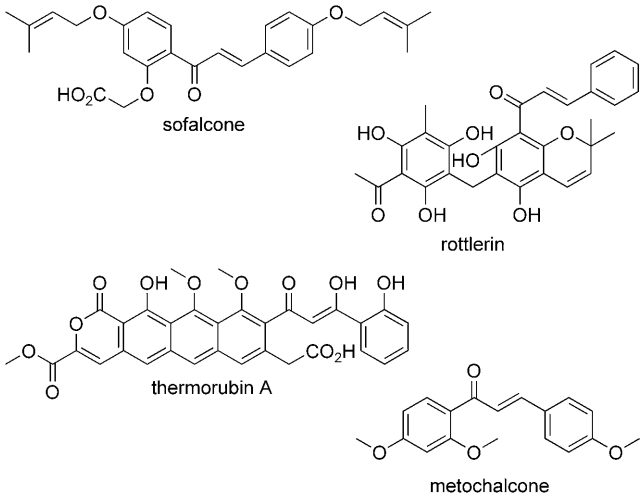
In the past decades palladium-catalyzed coupling reactions have emerged as a power tool for advanced organic synthesis.[1,2] Nowadays, the formation of C–C, C–O, and C–N bonds of aryl, heteroaryl, and vinyl–X (X = I, Br, Cl, OTf, OMs, etc.) compounds in the presence of homogeneous palladium catalysts is of significant value for the preparation of pharmaceuticals, agrochemicals, and advanced materials. Both academic as well as industrial laboratories continuously investigate and develop new applications in this area.

Among the different available coupling methods, three-component carbonylation reactions,[3,4] such as the carbonylative Suzuki process[5] and particularly the carbonylative Sonogashira reaction,[6] create interesting building blocks, which allow for a significant increase in molecular complexity (Scheme 1).



Scheme 1. Carbonylative three-component coupling reactions of aryl–X compounds.

To the best of our knowledge, to date only the related intramolecular reaction of aryl iodides, carbon monoxide, dihydrofurane, and cyclopentene have been described.[7,8] This situation is somewhat surprising because the resulting structural motif is present in numerous biologically active compounds and some currently employed pharmaceuticals.[9] Among the different (hetero)aryl vinyl ketones, 1,3-diarylpropen-1-ones (chalcones) constitute a well-known class of natural products that belong to the flavonoids.[10] These compounds display manifold biological activities including anticancer, antiinflammatory, antioxidant, antimicrobial, analgesic, antipyretic, antihepatotoxic, antimalarial, and antiallergic properties (Scheme 2).[11]



Scheme 2. Selected examples of bioactive chalcones.

Initially, the reaction of bromobenzene with an excess amount of styrene in the presence of carbon monoxide was investigated. However, the desired 1,3-diphenylpropen-1one was not obtained, instead traces of benzoic acid derivatives and stilbene were formed. Apparently, the reactivity of the benzoylpalladium(II) bromide, which is generated in situ, is too low for reaction with the olefin. We assumed that in a similar manner to palladium-catalyzed olefin/copolymerizations, a cationic palladium intermediate should be better suited for this reaction.[12] Indeed, the reaction of phenyl triflate with styrene and carbon monoxide (10 bar) in the presence of 1 mol% of $[\{(cinnamyl)PdCl\}_2]$ and 1,2-bis(diadamantyl)xylylphosphine[13] gave the desired chalcone, albeit in low yield (8%).

In Table 1 selected results from the variation of solvents, bases, and ligands are shown. Although monodentate ligands did not give any appreciable amount of product, several bidentate phosphine derivatives (except dppf) converted phenyl triflate into the chalcone in 4–12% yield (Table 1, entries 1–6). Optimization of the base when the best ligand, 1,3-bis(diphenylphosphino)propane (dppp), was applied, led to a significant increase of the desired product (50–65% yield; Table 1, entries 7–10). Variation of the solvent resulted in 75% yield of the isolated chalcone (Table 1, entry 13).

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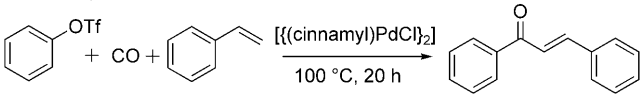
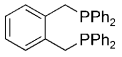
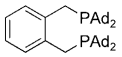
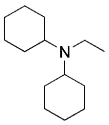
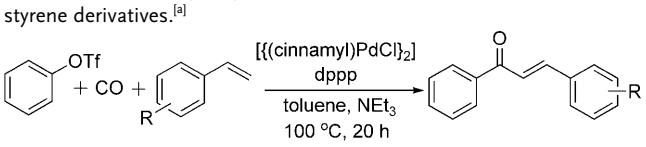
Table 1: Synthesis of chalcone: Variation of the reaction conditions.[a]

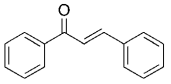
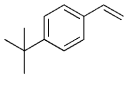
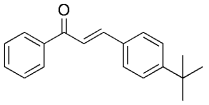
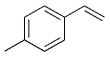
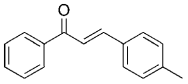
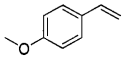
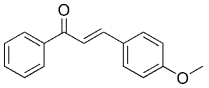
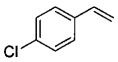
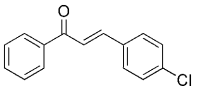
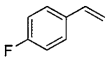
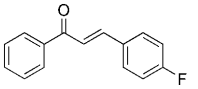


Entry	Ligand (2 mol%)	Base (2 equiv)	Solvent (0.5 mL)	Yield [%][b]
1		pyridine	DMF	4
2		pyridine	DMF	8
3	diop	pyridine	DMF	5
4	dppp	pyridine	DMF	12
5	dppf	pyridine	DMF	<1
6	dpppe	pyridine	DMF	4
7	dppp	NEt_3	DMF	65
8	dppp		DMF	63
9	dppp		DMF	54
10	dppp	DABCO (1 equiv)	DMF	50
11	dppp	DMAP (1 equiv)	DMF	2
12	dppp	NEt_3	NMP	67
13	dppp	NEt_3	toluene	75
14	dppp	NEt_3	dioxane	67
15	dppp	NEt_3	toluene	66[c]
16	dppp	NEt_3	toluene	64[d]
17	dppp	NEt_3	toluene	72[e]
18	dppp	NEt_3	toluene	59[f]
19	dppp	NEt_3	toluene	66[g]

[a] Phenyl triflate (1 mmol), styrene (6 mmol), CO (10 bar), [{(cinnamyl)PdCl}$_2$] (1 mol%), ligand (2 mol%), base (2 mmol), solvent (0.5 mL), 100°C, 20 h. [b] Yields were determined by GC analysis with hexadecane as the internal standard. [c] [{(cinnamyl)PdCl}$_2$] (0.5 mol%), dppp (1 mol%). [d] 3 equivalents of styrene. [e] 1.5 equivalents of styrene. [f] CO (5 bar). [g] CO (2 bar). DABCO = 1,4-diazabicyclo-[2.2.2]octane, diop = 4,5-bis(diphenylphosphinomethyl)-2,2-dimethyl-1,3-dioxolane, DMAP = 4-dimethylaminopyridine, DMF = *N*,*N*-dimethylformamide dppf = 1,1′-bis(diphenylphosphanyl)ferrocene, dpppe = 1,5-bis(diphenylphosphino)pentane, NMP = *N*-methyl-2-pyrrolidone.

Table 2: Reaction of phenyl triflate with carbon monoxide and different styrene derivatives.[a]



Entry	Styrene	Chalcone	Yield [%][b]
1			71, 68[c]
2			72
3			95
4			92
5			74
6			88

[a] Phenyl triflate (1 mmol), alkene (6 mmol), CO (10 bar), [{(cinnamyl)PdCl}$_2$] (1 mol%), dppp (2 mol%), NEt_3 (2 mmol), toluene (0.5 mL), 100°C, 20 h. [b] Yield of isolated product. [c] 10 mmol scale.

Notably, when we decreased the catalyst loading to 0.5 mol% or lowered the amount of styrene to 1.5 equivalents, the yield was only slightly decreased (Table 1, entries 15–17). Advantageously, the reaction can be performed at a relatively low pressure of CO (2–5 bar) without significant decrease of the yield (Table 1, entries 18–19).

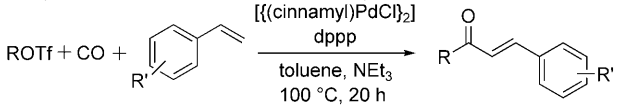
Once optimized reaction conditions were identified, we investigated the influence of different styrene derivatives in this reaction. To our delight the novel palladium-catalyzed carbonylative vinylation took place with both electron-donating and electron-accepting substituents and gave good to very good yields (71–95% yield of isolated product; Table 2, entries 1–6). Notably, reactions can be performed on a 10 mmol scale without a decrease of the yield. Next, the scope and limitations with respect to the aryl triflate were explored.[14] Different aryl triflate derivatives, including heteroaromatic compounds were coupled smoothly with styrene and carbon monoxide to give the corresponding chalcone derivatives (Table 3).

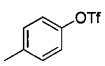
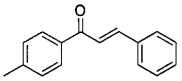
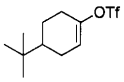
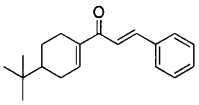
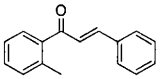
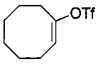
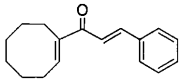
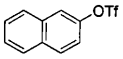
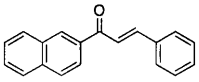
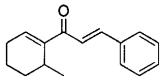
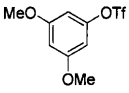
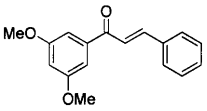
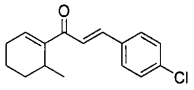
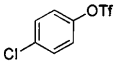
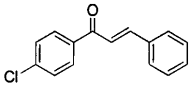
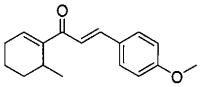
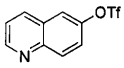
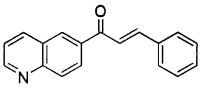
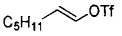
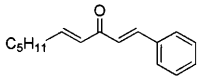
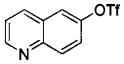
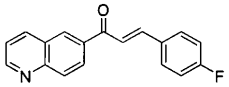
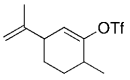
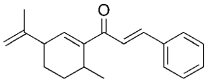
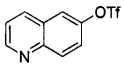
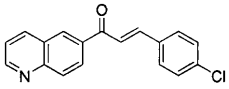
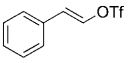
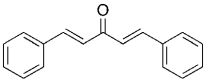
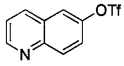
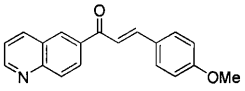
Arene compounds substituted with electron-donating or -withdrawing groups at the *para*, *meta*, or even *ortho* position gave the desired products in high yields (Table 3, entries 1–9). Notably, alkenyl triflates—both internal and teminal ones—reacted and gave moderate to good yields of the respective dienyl ketones (Table 3, entries 10–17). It is well known that such products are interesting building blocks, for example, for Nazarov cyclizations. The required alkenyl triflates are easily prepared from the corresponding ketones or aldehydes.[15] Hence, our method represents a straightforward carbonyl extension strategy.

With respect to the reaction mechanism, this novel carbonylative Heck reaction should proceed through oxidative addition of the aryl triflate to the Pd^0 center, migration of CO to give the acyl palladium complex, insertion of styrene and final β-hydride elimination. In most of the cases, only a small amount (<5%) of the Heck coupling product was detected. However, in the case of sterically hindered substrates the amount of this product increased (Table 3, entry 2).

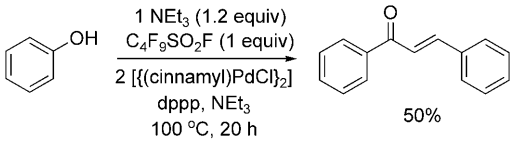
Finally, we demonstrated that activation of phenol and subsequent palladium-catalyzed coupling reaction can be conveniently performed in a "one-pot" manner. Without any optimization, phenyl nonaflate was prepared at room temperature in the presence of triethylamine, followed by addition of the palladium precatalyst, the ligand, and further triethyl-

Table 3: Reaction of different aryl and alkenyl triflate derivatives with CO and styrene derivatives.[a]



Entry	Triflate	Chalcone	Yield [%][b]	Entry	Triflate	Chalcone	Yield [%][b]
1			80	10			86
2			68	11			80
3			82	12			71
4			79	13			46
5			80	14			56
6			70	15			63
7			75	16			54
8			73	17			40
9			86				

[a] Aryl or alkenyl triflate (1 mmol), styrene (6 mmol), CO (10 bar), [{(cinnamyl)PdCl}$_2$] (1 mol%), dppp (2 mol%), NEt$_3$ (2 mmol), toluene (0.5 mL), 100°C, 20 h. [b] Yield of isolated product.



Scheme 3. "One-pot" Heck carbonylation of phenol.

amine. After heating for 20 hours, chalcone was obtained in 50% overall yield (Scheme 3).

In conclusion, we have developed the first carbonylative Heck reactions of aryl and alkenyl triflates and aromatic olefins. This method represents a "missing link" between the already established carbonylative Suzuki and carbonylative Sonogashira reactions. Starting from easily available aryl and alkenyl triflates the corresponding unsaturated ketones are obtained in generally good yields. The products obtained represent useful building blocks for the synthesis of numerous biologically active compounds.

Experimental Section

Synthesis of chalcone: The reaction was carried out in a Parr Instruments 4560 series 300 mL autoclave containing an alloy plate with wells for six 4 mL glass vials. [{(cinnamyl)PdCl}$_2$] (1 mol%, 5.2 mg), dppp (2 mol%, 8.3 mg), and a magnetic stir bar were placed in each of the vials, which were then capped with a septum equipped with an inlet needle and flushed with argon. Then, phenyl triflate (1 mmol, 0.162 mL), styrene (6 mmol, 0.69 mL), NEt$_3$ (2 mmol, 0.28 mL), and toluene (0.5 mL) were added to each vial with a syringe. The vials were placed in an alloy plate, which was then placed in the autoclave. Once sealed, the autoclave was purged several times with CO, then pressurized to 10 bar at RT and heated at 100°C for 20 h. The autoclave was then cooled to RT and vented to discharge the excess CO. Water (2 mL) was added, and the product was extracted with diethyl ether (3×3 mL). The organic layers were washed with brine, dried over Na_2SO_4, and evaporated with adsorption onto silica gel. The crude product was purified by column chromatography on silica gel (eluent: heptane/EtOAc = 40:1) to give the title compound (148 mg, 71%) as a yellow solid. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.29–7.37 (m, 3H), 7.38–7.43 (m, 1H), 7.46 (d, 1H, J = 15.89 Hz), 7.44–7.47 (m, 1H), 7.49–7.61 (m, 3H), 7.58 (d, 1H, J = 15.66 Hz), 7.91–7.98 ppm (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = 122.03,

128.42, 128.47, 128.60, 128.93, 130.52, 132.76, 134.84, 138.17, 144.82, 190.52 ppm. GC-MS (EI, 70 eV): m/z(%) 208(M^+, 75), 207(100), 179(20), 131(25), 103(15), 77(35). HRMS (EI): m/z calcd for $C_{15}H_{11}O$ (M−H): 207.0804; found: 207.07984.

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[1] For selected reviews, see: a) F. Alonso, I. P. Beletskaya, M. Yus, *Tetrahedron* **2008**, *64*, 3047 – 3101; b) P. Rollet, W. Kleist, V. Dufaud, L. Djakovitch, *J. Mol. Catal. A* **2005**, *241*, 39 – 51; c) A. Zapf, M. Beller, *Chem. Commun.* **2005**, 431 – 440; d) A. Frisch, M. Beller, *Angew. Chem.* **2005**, *117*, 680 – 695; *Angew. Chem. Int. Ed.* **2005**, *44*, 674 – 688; e) E. Negishi, L. Anastasia, *Chem. Rev.* **2003**, *103*, 1979 – 2017; f) D. S. Surry, S. L. Buchwald, *Angew. Chem.* **2008**, *120*, 6438 – 6461; *Angew. Chem. Int. Ed.* **2008**, *47*, 6338 – 6361; g) H. Doucet, J.-C. Hierso, *Angew. Chem.* **2007**, *119*, 850 – 888; *Angew. Chem. Int. Ed.* **2007**, *46*, 834 – 871; h) K. C. Nicolaou, P. G. Bulger, D. Sarlah, *Angew. Chem.* **2005**, *117*, 4516 – 4563; *Angew. Chem. Int. Ed.* **2005**, *44*, 4442 – 4489; i) A. Roglans, A. Pla-Quintana, M. Moreno-Manas, *Chem. Rev.* **2006**, *106*, 4622 – 4643.

[2] For reviews on industrial applications, see: a) C. Torborg, M. Beller, *Adv. Synth. Catal.* **2009**, *351*, 3027 – 3043; b) A. Zapf, M. Beller, *Top. Catal.* **2002**, *19*, 101 – 109; c) C. E. Tucker, J. G. de Vries, *Top. Catal.* **2002**, *19*, 111 – 118.

[3] For reviews on palladium-catalyzed carbonylations, see: a) A. Brennführer, H. Neumann, M. Beller, *Angew. Chem.* **2009**, *121*, 4176 – 4196; *Angew. Chem. Int. Ed.* **2009**, *48*, 4114 – 4133; b) A. Brennführer, H. Neumann, M. Beller, *ChemCatChem* **2009**, *1*, 28 – 41; c) C. F. J. Barnard, *Organometallics* **2008**, *27*, 5402 – 5422; d) M. Beller, B. Cornils, C. D. Frohning, C. W. Kohlpaintner, *J. Mol. Catal. A* **1995**, *104*, 17 – 85.

[4] For selected examples of palladium-catalyzed carbonylations of aryl halides, see: a) A. Schoenberg, I. Bartoletti, R. F. Heck, *J. Org. Chem.* **1974**, *39*, 3318 – 3326; b) A. Schoenberg, R. F. Heck, *J. Org. Chem.* **1974**, *39*, 3327 – 3331; c) A. Schoenberg, R. F. Heck, *J. Am. Chem. Soc.* **1974**, *96*, 7761 – 7764; d) H. Neumann, A. Brennführer, P. Groß, T. Riermeier, J. Almena, M. Beller, *Adv. Synth. Catal.* **2006**, *348*, 1255 – 1261; e) S. Klaus, H. Neumann, A. Zapf, D. Strübing, S. Hübner, J. Almena, T. Riermeier, P. Groß, M. Sarich, W.-R. Krahnert, K. Rossen, M. Beller, *Angew. Chem.* **2006**, *118*, 161 – 165; *Angew. Chem. Int. Ed.* **2006**, *45*, 154 – 158; f) A. Brennführer, H. Neumann, S. Klaus, T. Riermeier, J. Almena, M. Beller, *Tetrahedron* **2007**, *63*, 6252 – 6258; g) J. McNulty, J. J. Nair, A. Robertson, *Org. Lett.* **2007**, *9*, 4575 – 4578; h) J. R. Martinelli, T. P. Clark, D. A. Watson, R. H. Munday, S. L. Buchwald, *Angew. Chem.* **2007**, *119*, 8612 – 8615; *Angew. Chem. Int. Ed.* **2007**, *46*, 8460 – 8463; i) J. Liu, X. Peng, W. Sun, Y. Zhao, C. Xia, *Org. Lett.* **2008**, *10*, 3933 – 3936; j) A. Brennführer, H. Neumann, M. Beller, *Synlett* **2007**, 2537 – 2540; k) A. G. Sergeev, A. Zapf, A. Spannenberg, M. Beller, *Organometallics* **2008**, *27*, 297 – 300; l) H. Neumann, A. Brennführer, M. Beller, *Chem. Eur. J.* **2008**, *14*, 3645 – 3652; m) A. Sergeev, A. Spannenberg, M. Beller, *J. Am. Chem. Soc.* **2008**, *130*, 15549 – 15563; n) Z. Zhang, Y. Liu, M. Gong, X. Zhao, Y. Zhang, J. Wang, *Angew. Chem.* **2010**, *122*, 1157 – 1160; *Angew. Chem. Int. Ed.* **2010**, *49*, 1139 – 1142; o) L. M. Ambrosini, T. A. Cernak. T. H. Lambert, *Synthesis* **2010**, 870 – 881.

[5] a) H. Neumann, A. Brennführer, M. Beller, *Adv. Synth. Catal.* **2008**, *350*, 2437 – 2442; b) T. Ishiyama, H. Kizaki, T. Hayashi, A. Suzuki, N. Miyaura, *J. Org. Chem.* **1998**, *63*, 4726 – 4731; c) S. Zheng, L. Xu, C. Xia, *Appl. Organomet. Chem.* **2007**, *21*, 772 – 776; d) J.-J. Brunet, R. Chauvin, *Chem. Soc. Rev.* **1995**, *24*, 89 – 95.

[6] a) A. S. Karpov, E. Merkul, F. Rominger, T. J. J. Müller, *Angew. Chem.* **2005**, *117*, 7112 – 7117; *Angew. Chem. Int. Ed.* **2005**, *44*, 6951 – 6956; b) B. Liang, M. Huang, Z. You, Z. Xiong, K. Lu, R. Fathi, J. Chen, Z. Yang, *J. Org. Chem.* **2005**, *70*, 6097 – 6100; c) M. S. Mohamed Ahmed, A. Mori, *Org. Lett.* **2003**, *5*, 3057 – 3060; d) M. T. Rahman, T. Fukuyama, N. Kamata, M. Sato, I. Ryu, *Chem. Commun.* **2006**, 2236 – 2238; e) J. Liu, J. Chen, C. Xia, *J. Catal.* **2008**, *253*, 50 – 56.

[7] This novel reaction should not be confused with the so-called Heck carbonylation, a term which is sometimes used for palladium-catalyzed alkoxycarbonylations of aryl halides, for example see references [4a–c].

[8] For an intermolecular carbonylation of aryl iodides, CO and dihydrofurane or cyclopentene, see: a) T. Satoh, T. Itaya, K. Okuro, M. Miura, M. Nomura, *J. Org. Chem.* **1996**, *60*, 7267 – 7271; for intramolecular carbonylations, see: b) X. Wu, P. Nilsson, M. Larhed, *J. Org. Chem.* **2005**, *70*, 346 – 349; c) E. Negishi, S. Ma, J. Amanfu, C. Copéret, J. A. Miller, J. M. Tour, *J. Am. Chem. Soc.* **1996**, *118*, 5919 – 5931; d) T. Hayashi, J. Tang, K. Kato, *Org. Lett.* **1999**, *1*, 1487 – 1489; for a related addition of acylmolybdenum complexes to alkenes, see: e) K. Sangu, T. Watanabe, J. Takaya, N. Iwasawa, *Synlett* **2007**, 929 – 933.

[9] a) B. J. Venhuis, D. Dijkstra, D. J. Wustrow, L. T. Meltzer, L. D. Wise, S. J. Johnson, T. G. Heffner, H. V. Wikström, *J. Med. Chem.* **2003**, *46*, 584 – 590; b) P. D. Bailey, I. D. Collier, S. P. Hollininshead, M. H. Moore, K. M. Morgan, D. I. Smith, J. M. Vernon, *J. Chem. Soc. Perkin Trans. 1* **1997**, 1209 – 1214; c) D. S. Larsen, M. D. A. O'Shea, *Tetrahedron Lett.* **1993**, *34*, 1373 – 1376; d) H. Yuan, S. Sarre, G. Ebinger, Y. Michotte, *Brain Res.* **2004**, *1026*, 95 – 107; e) D. Liu, H. V. Wikström, D. Dijkstra, J. B. de Vries, B. J. Venhuis, *J. Med. Chem.* **2006**, *49*, 1494 – 1498.

[10] For selected synthesis of chalcones, see: a) B. M. Trost, C. Jonasson, M. Wuchrer, *J. Am. Chem. Soc.* **2001**, *123*, 12736 – 12737; b) J. S. Yadav, B. V. S. Reddy, P. Vishnumurthy, *Tetrahedron Lett.* **2005**, *46*, 1311 – 1313; c) T. J. J. Mueller, *Eur. J. Org. Chem.* **2005**, 1834 – 1848; d) M. Lakshmi Kantam, B. Veda Prakash, C. Venkat Reddy, *Synth. Commun.* **2005**, *35*, 1971 – 1978; e) P. O. Miranda, M. A. Ramirez, J. I. Padron, V. S. Martin, *Tetrahedron Lett.* **2006**, *47*, 283 – 286; f) O. G. Schramm (née Dediu), T. J. J. Müller, *Adv. Synth. Catal.* **2006**, *348*, 2565 – 2571; g) N. Marion, P. Carlqvist, R. Gealageas, P. de Fremont, F. Maseras, S. P. Nolan, *Chem. Eur. J.* **2007**, *13*, 6437 – 7451; h) M. Yu, G. Li, S. Wang, L. Zhang, *Adv. Synth. Catal.* **2007**, *349*, 871 – 875; i) E. Bustelo, P. H. Dixneuf, *Adv. Synth. Catal.* **2007**, *349*, 933 – 942; j) J. S. Yadav, B. V. S. Reddy, R. Vishnumurthy, *Tetrahedron Lett.* **2008**, *49*, 4498 – 4450; k) D. N. Liu, S. K. Tian, *Chem. Eur. J.* **2009**, *15*, 4538 – 4542; l) L. Artok, M. Kus, O. Aksin-Artok, F. N. Dege, F. Y. Ozkihnc, *Tetrahedron* **2009**, *65*, 9125 – 9133.

[11] a) D. N. Dhar, *The Chemistry of Chalcones and Related Compounds*, Wiley, New York, **1981**, 213; b) R. J. Anto, K. Sukumaran, G. Kuttan, M. N. A. Rao, V. Subbaraju, R. Kuttan, *Cancer Lett.* **1995**, *97*, 33 – 37; c) W. M. Weber, L. A. Hunsaker, S. F. Abcouwer, L. M. Deck, D. L. V. Jagt, *Bioorg. Med. Chem.* **2005**, *13*, 3811 – 3820; d) W. M. Weber, L. A. Hunsaker, C. N. Roybal, E. V. Bobrovnikova-Marjon, S. F. Abcouwer, R. E. Royer, L. M. Deck, D. L. V. Jagt, *Bioorg. Med. Chem.* **2006**, *14*, 2450 – 2461; e) A. Modzelewska, C. Pettit, G. Achanta, N. E. Davidson, P. Huang, S. R. Khan, *Bioorg. Med. Chem.* **2006**, *14*, 3491 – 3495; f) Z. Nowakowska, *Eur. J. Med. Chem.* **2007**, *42*, 125 – 137; g) B. P. Bandgar, S. S. Gawande, R. G. Bodade, J. V. Totre, C. N. Khobragade, *Bioorg. Med. Chem.* **2010**, *18*, 1364 – 1370.

[12] a) E. Drent, J. A. M. van Broekhoven, M. J. Doyle, *J. Organomet. Chem.* **1991**, *417*, 235 – 251; b) K. Nozaki, T. Hiyama, *J.*

Organomet. Chem. **1999**, *576*, 248 – 253; c) S. Ito, K. Munakata, A. Nakamura, K. Nozaki, *J. Am. Chem. Soc.* **2009**, *131*, 14606 – 14607; d) S. Noda, A. Nakamura, T. Kochi, W. C. Lung, K. Morokuma, K. Nozaki, *J. Am. Chem. Soc.* **2009**, *131*, 14088 – 14100; e) E. Drent, R. van Dijk, R. van Ginkel, B. van Oort, R. I. Pugh, *Chem. Commun.* **2002**, 964 – 965; f) E. Drent, P. H. M. Budzelaar, *Chem. Rev.* **1996**, *96*, 663 – 681.

[13] For the use of this ligand in the formylation of triflate derivatives, see: H. Neumann, A. Sergeev, M. Beller, *Angew. Chem.* **2008**, *120*, 4965 – 4969; *Angew. Chem. Int. Ed.* **2008**, *47*, 4887 – 4891.

[14] For selected use of aryl and alkenyl triflate derivatives in synthesis, see: a) P. D. Henley, J. D. Kilburn, *Chem. Commun.* **1999**, 1335 – 1336; b) A. X. Xiang, D. A. Watson, T. Ling, E. A. Theodorakis, *J. Org. Chem.* **1998**, *63*, 6774 – 6775; c) L. Wang, W. Shen, *Tetrahedron Lett.* **1998**, *39*, 7625 – 7628; d) A. Brennführer, H. Neumann, M. Beller, *Synlett* **2007**, 2537 – 2540.

[15] a) W. Scott, J. E. McMurry, *Acc. Chem. Res.* **1988**, *21*, 47 – 54; b) K. Ritter, *Synthesis* **1993**, 735 – 762.

