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Diazo Reagents in Copper(I)-Catalyzed Olefination of Aldehydes

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Abstract: The olefination of aldehydes to synthesize unsaturated ketones, esters, amides and phosphonates using diazo reagents and triphenylphosphine in the presence of copper(I) iodide as catalyst, is described. Good to excellent *E:Z* selectivities as well as yields were obtained for a large variety of aliphatic, aromatic and heteroaromatic aldehydes. The reaction showed also an excellent functional group compatibility and aldehydes were selectively reacted in the presence of ketone, nitro, amine, ether, acetal, thioether and halide groups. The use of a cost-effective copper salt as a catalyst is advantageous compared to previously reported expensive transition metal complexes. The method was used in the total synthesis of the scutifoliamide A, a biologically active compound that exhibits antifungal activity.

Keywords: alkenes; C−C bond formation; conjugated esters; phosphorus ylides; Wittig reaction

Introduction

Copper complexes are known to catalyze numerous carbon-carbon bond forming reactions.[1] For instance, copper(I) salts were reported as catalysts for the formation of stabilized antimony, arsenic and tellurium ylides from diazo carbonyl reagents to perform olefination of carbonyl compounds.[2] The low cost and the wide availability of copper complexes are among the advantages of using such a strategy. Recently, we have reported the use of copper catalysts as an inexpensive alternative to rhodium complexes[3] for the methylenation of aldehydes and ketones with trimethylsilyldiazomethane, triphenylphosphine and 2-propanol.[4] A phosphonium ylide intermediate was identified as the reactive olefination species. Overall the copper-catalyzed methylenation reaction exhibits a better functional group compatibility, particularly with nitrogen-containing substrates. A number of transition metal complexes derived from Mo,[5] Re,[6] Fe,[7] Ru,[8] Co[9] and Ir[10] are known to catalyze the olefination of carbonyl compounds[11] with diazo carbonyl reagents, in most cases, diazoacetate derivatives. Not only the use of a cost-effective catalyst, such as a copper(I) salt, would be beneficial, but also the use of other diazo reagents would be highly desirable to further expand the scope of these synthetic methods. Herein we report the olefination of aldehydes with a variety of diazo reagents and triphenylphosphine in the presence of copper iodide to produce conjugated esters, ketones, amides and phosphonates in good to excellent yields.

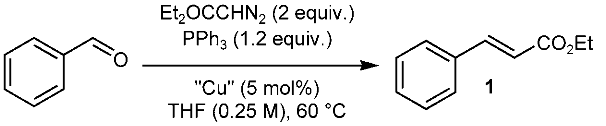
Results and Discussion

Copper(I) salts have been shown to catalyze the methylenation reaction with trimethylsilyldiazomethane, 2-propanol and triphenylphosphine.[4] A variety of copper(I) and copper(II) complexes were tested in the olefination of benzaldehyde with ethyl diazoacetate and triphenylphosphine (Table 1). The corresponding conjugated ester **1** was obtained in good to excellent yields, favoring the *E*-diastereomer, in the presence of many copper(I) catalysts (entries 1–4 and 6–8), with the notable exception of copper oxide (entry 5).

Copper(II) complexes were less active, even though it was still possible in some cases to obtain the desired product in good yields (entries 9, 11, 12, 14, 15 and 17). Better results were observed when hydrate complexes were used (entries 16 *vs.* 17). The best catalyst was the cationic copper tetrafluoroborate hydrate complex (entry 14), although we pursued our study with the cheaper and more readily available copper(I) iode complex (entry 4).

The optimization of the reaction conditions revealed that neither an increase nor a decrease of the

Table 1. Various copper complexes as catalysts for the olefination of benzaldehyde with ethyl diazoacetate.



Entry	Catalyst (5 mol%)	Time [h]	Yield [%][a]	E:Z[b]
1	CuCl	16	87	95:5
2	$CuCl/AgPF_6$	16	79	97:3
3	CuBr·DMS	16	86	95:5
4	**CuI**	**10**	**94**	**95:5**
5	Cu_2O	16	56[c]	97:3
6	CuCN	16	78	98:2
7[d]	$Cu(MeCN)_4PF_6$	16	90	98:2
8[d]	$(CuOTf)_2$·Bz	16	92	97:3
9	$CuCl_2$	16	76	96:4
10	CuO	16	12[c]	n.d.
11	$Cu(OAc)_2$	7	88	95:5
12	$Cu(OTf)_2$	16	79	96:4
13	CuF_2	16	33[c]	96:4
14	$Cu(BF_4)_2·x\,H_2O$	5	97	93:7
15	$Cu(acac)_2$	16	84	96:4
16	$CuSO_4$ anhydrous	7	37[c]	95:5
17	$CuSO_4·5\,H_2O$	7	90	96:4

[a] Combined yields of *E*- and *Z*-isomers after flash chromatography.
[b] Determined by GC-MS analysis of the crude reaction mixture.
[c] Determined by ^1H NMR with bibenzyle as an internal standard.
[d] Slow addition of ethyl diazoacetate.

stoichiometry of the reagents, or of the catalyst loading led to an improvement in yield of the alkene (Table 2, entries 1–7). The yield also decreased when running a more diluted or more concentrated reaction (entries 8–10). The reaction can be performed in numerous solvents, but none of them gave better results than THF (entries 12–21). Furthermore, it was not possible to run the reaction at room temperature while maintaining yields higher than 90% and a time below 16 h. Overall, the best reaction conditions are the ones described in entry 3 of Table 2. Such reaction conditions provided a TON of about 20 and a TOF of about 2. These values are within the range obtained with other commercially available catalysts for such an olefination reaction.[7a,c,9a] Only the iron(II) phthalocyanine complex showed a better efficiency.[7h] However, the cost of copper iodide is two to three orders of magnitude lower than the other commercially available catalysts, and thus it clearly is the most cost-effective catalyst to use in such a reaction. More importantly, neither the slow addition of ethyl diazoacetate reagent, nor the use of a drybox or Schlenk line techniques are necessary.[12]

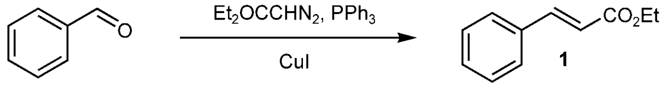
These reaction conditions were tested with a large variety of aliphatic aldehydes (Table 3). Not only were the products from linear aldehydes obtained in excellent yields (entries 1–5), but also sterically hindered aldehydes were converted to conjugated esters in good yields under these reaction conditions (entries 6 and 7). Various chiral enantiopure aldehydes were reacted to produce the desired conjugated esters with complete retention of the stereochemistry (entries 8–12). Moreover, an excellent functional group compatibility was observed, as ethers, secondary and tertiary amines, thioethers and acetals were not affected under the olefination reaction conditions (entries 8–12). In all cases, the corresponding conjugated ester was obtained in good yields. Conjugated aldehydes led also to the desired product in excellent yields (entries 13 and 14).

Aromatic and heteroaromatic aldehydes were also excellent substrates (Table 4). Electron-poor and electron-rich-substituted benzaldehydes were efficiently converted to the conjugated esters in good to excellent yields and *E:Z* selectivities (entries 1–7). Aromatic ethers, substituted anilines, nitro compounds, bromides, esters and aliphatic secondary amines were tolerated under these reaction conditions (entries 1–9). Furthermore, thiophene-, furan-, pyridine-, protected pyrrole- and indole-substituted carboxaldehydes were converted to the corresponding conjugated esters in good to excellent yields (entries 10–15). Clearly the efficiency of the copper catalyst is not affected by these functional groups.

The copper-catalyzed olefination reaction was also tested with aldehyde substrates containing aliphatic, aromatic and benzyloxymethyl ketones (Table 5). In all cases, the reaction proceeded with high chemoselectivity to produce exclusively the monoalkene product in good yields and *E* selectivities. This is in sharp contrast with results obtained using standard olefination procedures. For instance, a complex mixture of products resulting from unselective reactions was observed when attempting to synthesize **30** using the phosphorane reagent generated by deprotonation of the phosphonium salt with NaHMDS or under the mild Roush–Masamune reaction conditions.[13]

Beside diazoacetates, very few other diazo carbonyl reagents have been tested in transition metal-catalyzed olefination reactions.[7f] To enlarge the scope of this reaction, other ketones, amides and phosphonate-derived diazo reagents[14] were prepared and tested in the olefination of various aldehydes (Table 6). For instance, the less reactive diazoacetophenone produced unsaturated acetophenone from aliphatic, aromatic and heteroaromatic aldehydes in 58–74% yields and in 88:12 to 98:2 diastereoselectivities (entries 1, 4, 8 and 14). Unsaturated amides including Weinreb amides[15] were also obtained in 72–87% yields favoring the *E*-diastereomer (entries 2, 5, 7, 9–11, 13 and

Table 2. Optimization on the reaction conditions of the copper-catalyzed olefination of benzaldehyde with ethyl diazoacetate.



Entry	PPh_3 (equiv.)	EDA (equiv.)	Catalyst loading [x mol%]	Solvent C [mol/L]	Temp. [°C]	Time [h]	Yield [%][a]	E:Z[b]
1	1.1	1.4	5	THF, 0.25	60	16	35[c]	96:4
2	1.2	1.5	5	THF, 0.25	60	16	70	95:5
3	**1.2**	**2**	**5**	**THF, 0.25**	**60**	**10**	**94**	**95:5**
4	1.2	2.5	5	THF, 0.25	60	10	92	96:4
5	2	2	5	THF, 0.25	60	16	43[c]	96:4
6	1.2	2	2.5	THF, 0.25	60	16	70	97:3
7	1.2	2	10	THF, 0.25	60	6	90	94:6
8	1.2	2	5	THF, 0.10	60	16	79	94:6
9	1.2	2	5	THF, 0.50	60	5	75	94:6
10	1.2	2	5	THF, 1.00	60	3	35[c]	92:8
11	1.2	2	5	THF, 0.25	25	24	85	94:6
12	1.2	2	5	DCM, 0.25	25	16	81	96:4
13	1.2	2	5	DCM, 0.25	40	16	90	94:6
14	1.2	2	5	DCE, 0.25	25	24	66	97:3
15	1.2	2	5	DCE, 0.25	80	16	83	96:4
16	1.2	2	5	Dioxane, 0.25	25	24	87	94:6
17	1.2	2	5	Dioxane, 0.25	50	6	58	96:4
18	1.2	2	5	Benzene, 0.25	25	24	69	96:4
19	1.2	2	5	Benzene, 0.25	80	16	86	97:3
20	1.2	2	5	Toluene, 0.25	25	16	76	96:4
21	1.2	2	5	Toluene, 0.25	80	16	85	97:3

[a] Combined yields of *E*- and *Z*-isomers after flash chromatography.

[b] Determined by GC-MS analysis of the crude reaction mixture.

[c] Determined by ^{1}H NMR with bibenzyl as an internal standard.

15). Finally, the Seyferth reagent[16] was reacted with aliphatic and aromatic aldehydes to produce unsaturated phosphonates in 54–69% yields and in 89:11 to 98:2 *E:Z* ratio (entries 3, 6 and 12).

The use of more functionalized and diversified diazo reagents should enable more convergent synthetic strategies for the preparation of complex molecules, thus limiting the number of required functional group manipulations. For instance, the total synthesis of scutifoliamide A (**50**), an antifungal amide recently isolated from *Piper scutifolium*,[17] was achieved in 4 steps and 40% overall yield starting from commercially available 1-bromo-3,4-(methylenedioxy)benzene. The synthetic strategy featured an olefination reaction with the diazoisobutylamide of the aldehyde derived from propargylic alcohol **48**. The unsaturated amide **49** was produced in 75% yield and in 92:8, *E:Z* ratio. Scutifoliamide A (**50**) was then obtained after a hydrogenation reaction with Lindlar catalyst (Scheme 1).

Conclusions

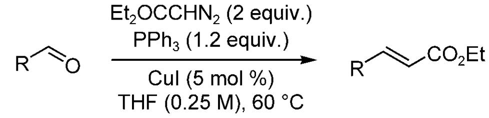
Copper(I) iodide proved to be a general, cost-effective catalyst for the olefination of aldehydes using a variety of diazo reagents and triphenylphosphine under non-basic conditions. Unsaturated ketones, esters, amides and phosphonates were produced in good to excellent yields and diastereoselectivities. The total synthesis of scutifoliamide A was achieved using the copper-catalyzed olefination reaction as a key step.

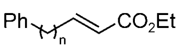
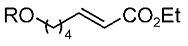
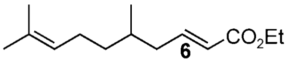
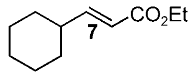
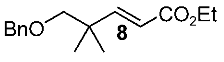
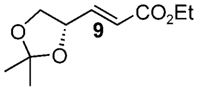
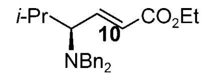
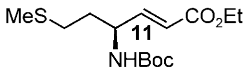
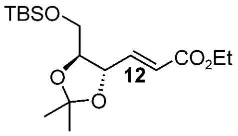
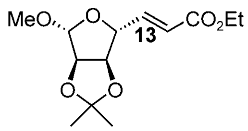
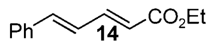
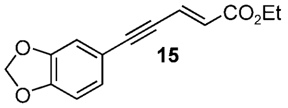
Experimental Section

General Procedure for the Copper-Catalyzed Olefination of Aldehydes

To a solution of copper(I) iodide (10 mg, 0.050 mmol) and triphenylphosphine (315 mg, 1.20 mmol) in THF (4 mL) under an argon atmosphere, was added the aldehyde (1.00 mmol). The mixture was heated to 60 °C and then the diazo compound (2.00 mmol) was added in a single portion. The solution was stirred until the reaction was completed by GC or TLC analysis. The resulting mixture was cooled to

Table 3. copper-catalyzed olefination of aliphatic aldehydes with ethyl diazoacetate.

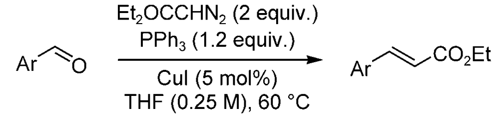


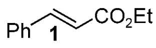
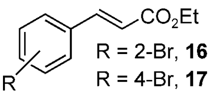
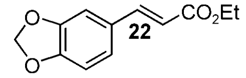
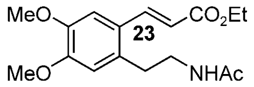
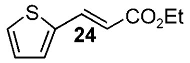
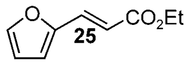
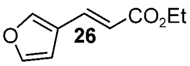
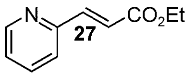
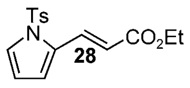
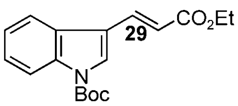
Entry	Product		Yield [%][a]	E:Z ratio[b]
1		n = 1, **2**	82	95:5
2		n = 2, **3**	86	93:7
3		R = Bn, **4**	81	88:12
4		R = TBS, **5**	74	93:7
5	 **6**		86	91:9
6	 **7**		77	95:5
7	 **8**		72	94:6
8	 **9**		76	93:7
9	 **10**		69	97:3
10	 **11**		82	93:7
11	 **12**		84	98:2
12	 **13**		73	94:6
13	 **14**		92	93:7
14	 **15**		84	92:8

[a] Combined yields of E- and Z-isomers after flash chromatography.

[b] Determined by GC-MS analysis of the crude reaction mixture.

Table 4. Copper-catalyzed olefination of aromatic aldehydes with ethyl diazoacetate.



Entry	Product		Yield [%][a]	E:Z ratio[b]
1	 **1**		94	95:5
2		R = 2-Br, **16**	92	91:9
3		R = 4-Br, **17**	94	98:2
4		R = 2-CO_2Me, **18**	88	95:5
5		R = 4-NMe_2, **19**	78	89:11
6		R = 4-NHBoc, **20**	72	>99:1
7		R = 4-NO_2, **21**	78	98:2
8	 **22**		73	96:4
9	 **23**		58	94:6
10	 **24**		96	>99:1
11	 **25**		79	93:7
12	 **26**		72	95:5
13	 **27**		61	92:8
14	 **28**		83	98:2
15	 **29**		62	93:7

[a] Combined yields of E- and Z-isomers after flash chromatography.

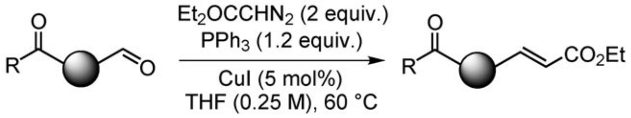
[b] Determined by GC-MS analysis of the crude reaction mixture.

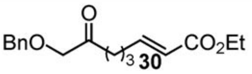
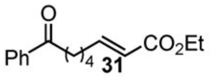
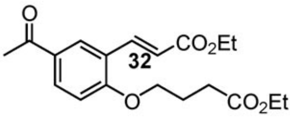
room temperature and the solvent was removed under reduced pressure. The residue was purified by flash chromatography on silica gel.

Synthesis of Scutifoliamide A

3-(Benzo[*d*][1,3]dioxol-6-yl)prop-2-yn-1-ol (48):[18] Pd-$(MeCN)_2Cl_2$ (8.0 mg, 0.030 mmol), CuI (4.0 mg, 0.020 mmol), and $[(t\text{-}Bu)_3PH]BF_4$ (19 mg, 0.065 mmol) were placed in a vessel which was backfilled with argon. Dioxane (1.0 mL), $HN(i\text{-}Pr)_2$ (166 mL, 1.20 mmol) then 1-bromo-3,4-(methylenedioxy)benzene 5-bromobenzo[*d*][1,3]dioxole (120 μL, 1.00 mmol), and propargyl alcohol (116 μL, 2.00 mmol) were added and stirred at room temperature overnight. The reaction mixture was diluted with EtOAc (10 mL), filtered through a plug of silica gel. The solvent was removed under reduced pressure to afford the alcohol **48** as a yellow solid after flash chromatography (25% EtOAc/hexanes); yield: 134 mg (76%); R_f 0.35 (40% EtOAc/hexanes); mp 73 °C (lit. 75.5–76 °C);[19] ^1H NMR

Table 5. Copper-catalyzed chemoselective olefination of ketoaldehydes.

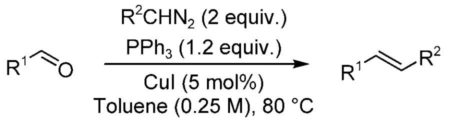


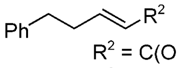
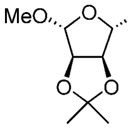
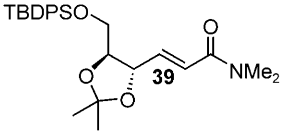
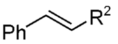
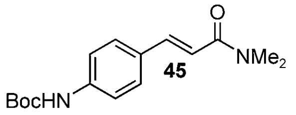
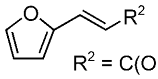
Entry	Product	Yield [%][a]	E:Z ratio[b]
1	 **30**	65	96:4
2	 **31**	81	96:4
3	 **32**	86	92:8

[a] Combined yields of *E*- and *Z*-isomers after flash chromatography.

[b] Determined by GC-MS analysis of the crude reaction mixture.

Table 6. Copper-catalyzed olefination of aldehydes with various diazocarbonyl reagents.



Entry	Product	Yield [%][a]	E:Z ratio[b]
1	 R^2 = C(O)Ph, **33**	69	88:12
2	R^2 = C(O)NMe$_2$, **34**	87	89:11
3	R^2 = P(O)(OMe)$_2$, **35**	69	89:11
4	 R^2 = C(O)Ph, **36**	58	93:7
5	R^2 = C(O)N(OMe)Me, **37**	83	96:4
6	R^2 = P(O)(OMe)$_2$, **38**	67	95:5
7	 **39**	77	93:7
8	 R^2 = C(O)Ph, **40**	74	90:10
9	R^2 = C(O)NMe$_2$, **41**	84	>99:1
10	R^2 = C(O)N(OMe)Me, **42**	72	96:4
11	R^2 = C(O)NHCH$_2$*i*-Pr, **43**	77	90:10
12	R^2 = P(O)(OMe)$_2$, **44**	54	98:2
13	 **45**	77	97:3
14	 R^2 = C(O)Ph, **46**	74	98:2
15	R^2 = C(O)NMe$_2$, **47**	82	97:3

[a] Combined yields of *E*- and *Z*-isomers after flash chromatography.

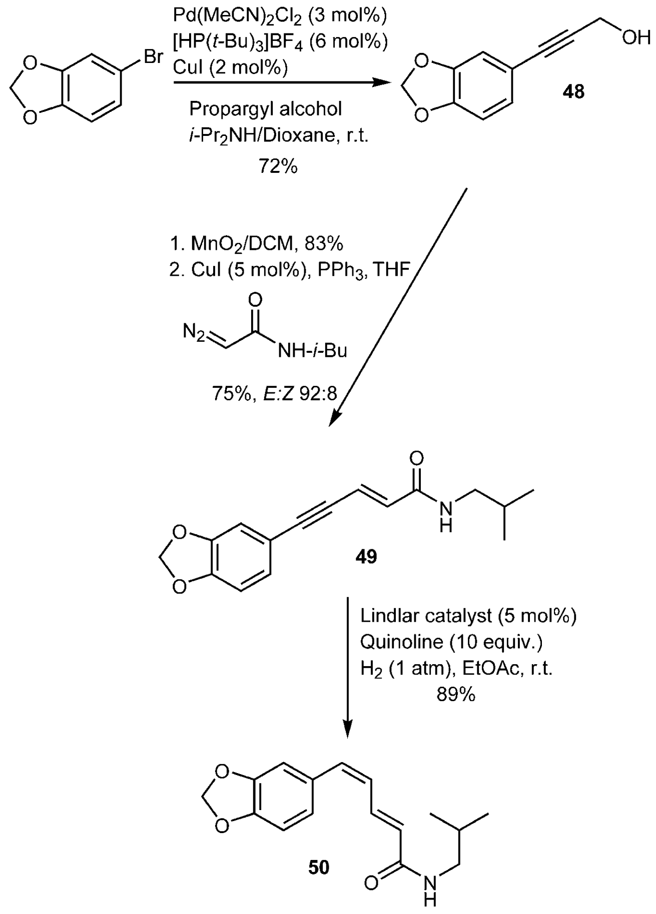
[b] Determined by GC-MS analysis of the crude reaction mixture.

(300 MHz, CDCl$_3$): δ=6.96 (dd, *J*=8, 2 Hz, 1H), 6.87 (d, *J*=2 Hz, 1H), 6.74 (d, *J*=8 Hz, 1H), 5.96 (s, 2H), 4.46 (br s, 2H), 1.85 (br s, 1H); ^{13}C NMR (75 MHz, CDCl$_3$): δ=148.0, 147.3, 126.3, 115.6, 111.6, 108.3, 101.2, 85.5, 85.5, 51.6; IR (neat): ν=3270, 2951, 2255, 1717, 1490, 1447, 1172, 907, 731 cm^{-1}; HR-MS (ESI): *m/z*=282.9519, calcd. for $C_{10}H_8O_3Ag$ [M+Ag]$^+$: 282.9524.

(*E*)-5-(Benzo[*d*][1,3]dioxol-6-yl)-*N*-isobutylpent-2-en-4-ynamide (49): To a solution of MnO$_2$ (200 mg, 11.3 mmol) in DCM was added the alcohol (200 mg, 1.13 mmol). The mixture was stirred at room temperature overnight. The reaction mixture was filtered through a plug of Celite®. The mixture was concentrated to give the desired aldehyde as yellow solid after flash chromatography (25% EtOAc/hexanes); yield: 163 mg (83%); R_f 0.42 (40% EtOAc/hexanes); mp 78 °C; ^{1}H NMR (300 MHz, CDCl$_3$): δ=9.38 (s, 1H), 7.19 (dd, *J*=8, 2 Hz, 1H), 7.02 (d, *J*=2 Hz, 1H), 6.83 (d, *J*=8 Hz, 1H), 6.04 (s, 2H); ^{13}C NMR (75 MHz, CDCl$_3$): δ=176.6, 150.6, 147.7, 129.5, 112.7, 112.3, 108.9, 101.9, 96.0, 88.0; IR (neat): ν=2902, 2181, 1655, 1489, 907 cm^{-1}; HR-MS (ESI): *m/z*=175.0392, calcd, for $C_{10}H_7O_3$ [M+H]$^+$: 175.0395.

To a solution of copper(I) iodide (5.0 mg, 0.030 mmol) and triphenylphosphine (181 mg, 0.690 mmol) in toluene (2 mL) under an argon atmosphere, was added the aldehyde (100 mg, 0.570 mmol). The mixture was heated to 60 °C and then the diazo compound (1.14 mmol) was added in a single portion. The solution was stirred overnight. The resulting mixture was cooled to room temperature and the solvent was removed under reduced pressure. The amide **49** was obtained as a yellow gum after flash chromatography on silica gel (20% EtOAc/hexanes); yield: 116 mg (75%); R_f 0.15 (20% EtOAc/hexanes); ^{1}H NMR (300 MHz, CDCl$_3$): δ=7.00 (dd, *J*=8, 2 Hz, 1H), 6.92 (d, *J*=15 Hz, 1H), 6.90 (d, *J*=2 Hz, 1H), 6.77 (d, *J*=8 Hz, 1H), 6.26 (d, *J*=15 Hz, 1H), 5.99 (s, 2H), 5.55 (s (br), 1H), 3.18 (t, *J*=7 Hz, 2H), 1.89–1.75 (m, 1H), 0.93 (d, *J*=7 Hz, 6H); ^{13}C NMR (75 MHz, CDCl$_3$): δ=164.7, 148.5, 147.4, 131.7, 126.9, 121.6, 115.6, 111.6, 108.5, 101.4, 96.6, 85.4, 47.0, 28.5, 20.1; IR (neat): ν=3296, 2962, 2197, 160, 1610, 1220, 1040 cm^{-1}; HR-MS (ESI): *m/z*=272.1271, calcd. for $C_{16}H_{18}NO_3$ [M+H]$^+$: 272.1281.

(2*E*,4*Z*)-5-(Benzo[*d*][1,3]dioxol-6-yl)-*N*-isobutylpenta-2,4-dienamide (50): A vessel containing a mixture of (*E*)-5-(benzo[*d*][1,3]dioxol-6-yl)-*N*-isobutylpent-2-en-4-ynamide **49** (20.0 mg, 0.074 mmol), quinoline (87.0 µL, 0.74 mol) and Lindlar catalyst (5% Pd on CaCO$_3$ poisoned with Pb, 8.0 mg) in ethyl acetate (1.0 mL) was evacuated and flushed with H$_2$ three times. The reaction mixture was stirred at



Scheme 1.

room temperature under H_2 (1 atm) for 1 h and then filtered through a plug of Celite®. The plug was rinsed with ethyl acetate (3×5 mL) and the solution was concentrated under reduced pressure to afford scutifoliamide A (**50**) as a yellow oil after flash chromatography (10% EtOAc/hexanes); yield: 18 mg (89%); R_f 0.09 (20% EtOAc/hexanes); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 7.72$ (dd, $J = 15$, 12 Hz, 1H), 6.83–6.78 (m, 3H), 6.62 (d, $J = 12$ Hz, 1H), 6.22 (t, $J = 12$ Hz, 1H), 5.98 (d, $J = 15$ Hz, 1H), 5.96 (s, 2H), 5.60 (s (br), 1H), 3.18 (t, $J = 6$ Hz, 2H), 1.85–1.75 (m, 1H), 0.92 (d, $J = 7$ Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 165.9$, 147.7, 147.4, 136.6, 136.0, 130.6, 126.3, 125.9, 123.4, 109.2, 108.3, 101.1, 46.9, 28.6, 20.1; IR (neat): ν = 3036, 1663, 1501, 1314, 1118 cm^{-1}; HR-MS (ESI): $m/z = 274.1435$, calcd. for $C_{16}H_{20}O_3$ $[M+H]^+$: 274.1437.

Supportin Information

Analytical characterization data for all compounds are available in the Supporting Information.

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References

[1] a) S. Woodward, *Angew. Chem. Int. Ed.* **2005**, *44*, 5560–5562; b) T. D. Nelson, R. D. Crouch, *Org. React.* **2004**, *63*, 265–555; c) I. P. Beletskaya, A. V. Cheprakov, *Coord. Chem. Rev.* **2004**, *248*, 2337–2364; d) W. Kirmse, *Angew. Chem. Int. Ed.* **2003**, *42*, 1088–1093; e) A. J. Clark, *Chem. Soc. Rev.* **2002**, *31*, 1–11; f) A. Alexakis, C. Benhaim, *Eur. J. Org. Chem.* **2002**, 3221–3236; g) *Modern Organocopper Chemistry*, (Ed.: N. Krause), Wiley-VCH, Verlag, **2002**, 368 pp.

[2] a) Y. Liao, Y. Z. Huang, *Tetrahedron Lett.* **1990**, *31*, 5897–5900; b) Z. L. Zhou, Y. Z. Huang, L. L. Shi, *Tetrahedron* **1993**, *49*, 6821–6830. The formation of stabilized phosphonium ylides was shown to be inefficient under these reaction conditions.

[3] a) H. Lebel, V. Paquet, C. Proulx, *Angew. Chem. Int. Ed.* **2001**, *40*, 2887–2890; b) G. A. Grasa, Z. Moore, K. L. Martin, E. D. Stevens, S. P. Nolan, V. Paquet, H. Lebel, *J. Organomet. Chem.* **2002**, *658*, 126–131; c) H. Lebel, V. Paquet, *Org. Lett.* **2002**, *4*, 1671–1674; d) H. Lebel, D. Guay, V. Paquet, K. Huard, *Org. Lett.* **2004**, *6*, 3047–3050; e) H. Lebel, V. Paquet, *Organometallics* **2004**, *23*, 1187–1190; f) H. Lebel, V. Paquet, *J. Am. Chem. Soc.* **2004**, *126*, 320–328; g) V. Paquet, H. Lebel, *Synthesis* **2005**, 1901–1905.

[4] H. Lebel, M. Davi, S. Diez-Gonzalez, S. P. Nolan, *J. Org. Chem.* **2007**, *72*, 144–149.

[5] X. Y. Lu, H. Fang, Z. J. Ni, *J. Organomet. Chem.* **1989**, *373*, 77–84.

[6] a) W. A. Herrmann, M. Wang, *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 1641–1643; b) W. A. Herrmann, P. W. Roesky, M. Wang, W. Scherer, *Organometallics* **1994**, *13*, 4531–4535; c) E. M. Carreira, B. E. Ledford, *Tetrahedron Lett.* **1997**, *38*, 8125–8128; d) R. Harrison, A. Mete, L. Wilson, *Tetrahedron Lett.* **2003**, *44*, 6621–6624; e) A. M. Santos, C. C. Romao, F. E. Kuhn, *J. Am. Chem. Soc.* **2003**, *125*, 2414–2415; f) X. Y. Zhang, P. Chen, *Chem. Eur. J.* **2003**, *9*, 1852–1859; g) F. E. Kuhn, A. Scherbaum, W. A. Herrmann, *J. Organomet. Chem.* **2004**, *689*, 4149–4164; h) A. M. Santos, F. M. Pedro, A. A. Yogalekar, I. S. Lucas, C. C. Romao, F. E. Kuhn, *Chem. Eur. J.* **2004**, *10*, 6313–6321; i) F. M. Pedro, S. Hirner, F. E. Kuhn, *Tetrahedron Lett.* **2005**, *46*, 7777–7779; j) R. M. Hua, J. L. Jiang, *Curr. Org. Synth.* **2007**, *4*, 151–174.

[7] a) G. A. Mirafzal, G. L. Cheng, L. K. Woo, *J. Am. Chem. Soc.* **2002**, *124*, 176–177; b) G. L. Cheng, G. A. Mirafzal, L. K. Woo, *Organometallics* **2003**, *22*, 1468–1474; c) Y. Chen, L. Huang, M. A. Ranade, X. P. Zhang, *J. Org. Chem.* **2003**, *68*, 3714–3717; d) Y. Chen, L. Huang, X. P. Zhang, *Org. Lett.* **2003**, *5*, 2493–2496; e) Y. Chen, L. Huang, X. P. Zhang, *J. Org. Chem.* **2003**, *68*, 5925–5929; f) V. K. Aggarwal, J. R. Fulton, C. G. Sheldon, J. de Vicente, *J. Am. Chem. Soc.* **2003**, *125*, 6034–6035; g) W. Sun, F. E. Kuhn, *Tetrahedron Lett.* **2004**, *45*, 7415–7418; h) V. B. Sharma, S. L. Jain, B. Sain, *Catal. Lett.* **2004**, *98*, 141–143.

[8] a) O. Fujimura, T. Honma, *Tetrahedron Lett.* **1998**, *39*, 625–626; b) F. E. Kuhn, A. M. Santos, A. A. Jogalekar, F. M. Pedro, P. Rigo, W. Baratta, *J. Catal.* **2004**, *227*, 253–256; c) W. Sun, F. E. Kuhn, *Appl. Catal. A* **2005**,

285, 163–168; d) W. Sun, B. S. Yu, F. E. Kuhn, *Tetrahedron Lett.* **2006**, *47*, 1993–1996; e) F. M. Pedro, A. M. Santos, W. Baratta, F. E. Kuhn, *Organometallics* **2007**, *26*, 302–309.

[9] a) M.-Y. Lee, Y. Chen, X. P. Zhang, *Organometallics* **2003**, *22*, 4905–4909; b) E. Ertuerk, A. S. Demir, *Tetrahedron* **2008**, *64*, 7555–7560.

[10] H. Lebel, C. Ladjel, *Organometallics* **2008**, *27*, 2676–2678.

[11] a) F. E. Kuhn, A. M. Santos, *Mini-Rev. Org. Chem.* **2004**, *1*, 55–64; b) Z. H. Zhang, J. B. Wang, *Tetrahedron* **2008**, *64*, 6577–6605.

[12] Similar yields were obtained when using solvent from the bottle.

[13] M. A. Blanchette, W. Choy, J. T. Davis, A. P. Essenfeld, S. Masamune, W. R. Roush, T. Sakai, *Tetrahedron Lett.* **1984**, *25*, 2183–2186.

[14] a) J. N. Bridson, J. Hooz, *Org. Synth.* Coll. Vol. VI, **1988**, p 386; b) P. A. Bartlett, N. I. Carruthers, B. M. Winter, K. P. Long, *J. Org. Chem.* **1982**, *47*, 1284–1291; c) T. Toma, J. Shimokawa, T. Fukuyama, *Org. Lett.* **2007**, *9*, 3195–3197; d) S. Ohira, *Synth. Commun.* **1989**, *19*, 561–564.

[15] S. Nahm, S. M. Weinreb, *Tetrahedron Lett.* **1981**, *22*, 3815–3818.

[16] D. Seyferth, R. S. Marmor, *Tetrahedron Lett.* **1970**, 2493–2496.

[17] J. V. Marques, R. O. S. Kitamura, J. H. G. Lago, M. C. M. Young, E. F. Guimarães, M. J. Kato, *J. Nat. Prod.* **2007**, *70*, 2036–2039.

[18] a) T. Hundertmark, A. F. Littke, S. L. Buchwald, G. C. Fu, *Org. Lett.* **2000**, *2*, 1729; b) M. R. Netherton, G. C. Fu, *Org. Lett.* **2001**, *3*, 4295.

[19] W. A. Nugent, D. L. Thorn, R. L. Harlow, *J. Am. Chem. Soc.* **1987**, *109*, 2788.