C−C-Bond Formation by the Palladium-Catalyzed Cycloisomerization/Dimerization of Terminal Allenyl Ketones: Selectivity and Mechanistic Aspects

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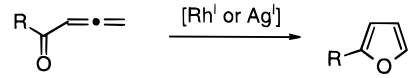
The scope of the palladium-catalyzed cyclization/dimerization of terminal allenyl ketones **1** to the 2,4-disubstituted furans **3** has been investigated. Simplified and improved conditions almost exclusively provided the dimer **3**, accompanied by only traces of the easily separable monomer **2**. The formation of an isomer of **3**, the unconjugated ketone **4**, was completeley suppressed. Under these mild conditions, besides the normal functional group tolerance known for palladium-catalyzed reactions, an interesting selectivity was observed with functional groups that are known to react either in palladium-catalyzed reactions or reactions catalyzed by other transition-metals. Thus aryl halides, terminal alkynes, 1,6-enynes, and α-allenic alcohols were tolerated. In the latter example the selective reaction of only one out of two different allenes was achieved. Mechanistic investigation indicated a Pd(II)/Pd(IV)-cycle involving palladium(II)-γ-alkoxyvinylcarbene and furylpalladium(IV) hydride intermediates, although a second pathway for the formation of the dimer **3** which also involves Pd(IV)-intermediates like the 3,4-dimethylenepalladacyclopentane **23** and the 3-methylenepalladacyclobutane-like structure **15** (respectively **25**) could not completely be excluded.

Introduction

While alkynes are frequently used in transition-metal-catalyzed cross-coupling, addition, cycloaddition, or cycloisomerization reactions,[1] the use of the isomeric allenes is much less popular. This probably originates from the fact that many transition-metal fragments, which catalyze such reactions, also cause an unspecific oligomerization[2,3] or a polymerization[4] of allenes. During the last years improved catalyst-systems and milder conditions have been developed. This led to an increase in the use of allenes in organic synthesis.[5] Among them is Marshall's[6] discovery that allenyl ketones[7] **1** can selectively be rearranged into furans **2** under mild conditions by Rh(I) or Ag(I) catalysts. This was a landmark in the area of transition-metal-catalyzed furan synthesis.



1 **2**

Similar isomerizations had been observed several years before in flash vacuum thermolysis reactions of allenyl ketones by Jullien[8] and Huntsman,[9] but only the transition-metal-catalysis made possible this transformation with highly functionalized, nonvolatile substrates.[10] This principle was applied by Marshall in efforts to synthesize macrocyclic furan marine natural products.[6] The importance of the furan moiety, which is frequently found in natural products and in important pharmaceuticals as well as in flavoring, aroma, and fragrance compounds[11] and is often used as building block in organic synthesis, has always been the driving force for the numerous synthetic efforts for the synthesis of furans.[11,12]

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(6) (a) Marshall, J. A.; Robinson, E. D. *J. Org. Chem.* **1990**, *55*, 3450−3451. (b) Marshall, J. A.; Wang, X. *J. Org. Chem.* **1991**, *56*, 960−969. (c) Marshall, J. A.; Wang, X. *J. Org. Chem.* **1992**, *57*, 3387−3396. (d) Marshall, J. A.; Bartley, G. S. *J. Org. Chem.* **1994**, *59*, 7169−7171. (e) Marshall, J. A.; Wallace, E. M.; Coan, P. S. *J. Org. Chem.* **1995**, *60*, 796−797. (f) Marshall, J. A.; Sehon, C. A. *J. Org. Chem.* **1995**, *60*, 5966−5968.

(7) (a) Huché, M. *Tetrahedron* **1980**, *36*, 331−342. (b) Larock, R. C.; Chow, M.-S.; Smith, S. J. *J. Org. Chem.* **1986**, *51*, 2623−2624. (c) Bernard, D.; Doutheau, A.; Gore, J. *Tetrahedron* **1987**, *43*, 2721−2732.

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(9) Huntsman, W. D.; Yin, T.-K. *J. Org. Chem.* **1983**, *48*, 3813−3814.

(10) The reverse transformation of furans to allenyl ketones can be achieved by the photorearrangement of some silylfurans, see: Barton, T. J.; Hussmann, G. P. *J. Am. Chem. Soc.* **1983**, *105*, 6316−6318.

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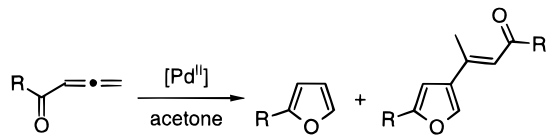
Marshall's furan synthesis attracted our interest, since many questions concerning the mechanism arose. Seven months after we started our investigation, Marshall published his own results[6d] on the mechanism of the reaction, which were in accord with our findings. Furthermore we observed that Cu(I)-, Rh(II)-, Ru(II)-, and Pd(II)-catalyzed the cycloisomerization of allenyl ketones to furans as well. In the case of terminal allenyl ketones, Pd(II) caused a cyclization/dimerization, leading to the 2,4-disubstituted furans **3**.[13]



1 **2** **3**

The latter reaction-pathway combines a C−O bond formation, a C−H bond breaking and formation, and—different from Marshall's cycloisomerization—a C−C bond formation. The importance of such reactions is documented by the fact that the synthesis of furans with certain substitution patterns, i. e. bearing substituents at both the 3 and 4 positions, is still a topic in organic synthesis.[12a,14]

Here we report simplified and improved conditions for the selective formation of **3**, describe interesting chemoselectivities, and discuss mechanistic aspects.

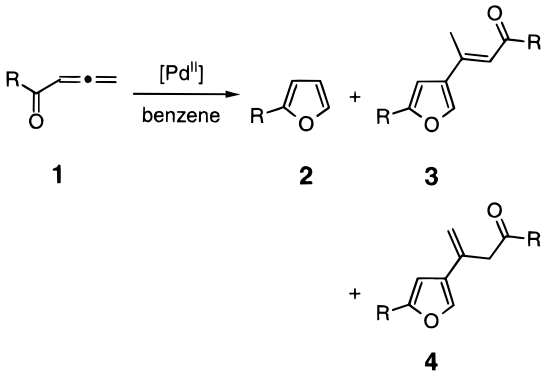
Results and Discussion

1. Initial Observation. Several late transition-metal complexes and some Lewis-acids were tested toward their ability to cycloisomerize **1a**[15] in benzene. Different from Lewis-acids like $AlCl_3$, $ZnBr_2$, and $Hg(OAc)_2$, transition-metals in the form of CuCl, $AgNO_3$, $Rh_2(OAc)_4$, $[RuCl_2(CO)_3]_2$,[16] and Pd catalysts were active. The latter turned out to be most effective.[13] Interestingly, in addition to the expected 2-methylfuran (**2a**) two new products **3a** and **4a** were formed with the Pd catalysts.[17] Initially, Trost's TCPC^{TFE}-modification[18] of Maitlis' palladol catalyst[19] was most effective for the formation of the dimers **3a** and **4a**.

Table 1. Reaction of 1a with the TCPC^{TFE} Catalyst in C_6D_6

entry	[**1a**] (mol/L)	% catalyst	ratio **2a**:**3a**:**4a**[a]	isolated yield of **3a** + **4a**,[b] %
1	0.25	0.40	1.0:0.9:0.5	55
2	0.50	0.20	1.0:1.2:0.3	54
3	1.00	0.10	1.0:1.5:0.3	59
4	2.00	0.10	1.0:1.7:0.3	59
5	4.19	0.10	1.0:2.2:0.2	64
6	7.47	0.05	1.0:2.5:0.1	63
7	11.4[c]	0.05	1.0:7.4:traces	76

[a] By ^{1}H NMR. [b] **2a** was too volatile to be separated from the solvent. **3a** and **4a** could be separated by HPLC only. [c] Neat **1a**.



1 **2** **3** **4**

A HETCOR and a 1-D INADEQUATE experiment were necessary to verify the structure of **3a**.[13,20] Meanwhile the structural assignment has been confirmed by X-ray analysis of two crystalline derivatives (see below).

Since the new products **3a** and **4a** were dimers of **1a**, it should be possible to shift the product ratio in favor of **3a** and **4a** by increasing the concentration of **1a**. The results obtained with TCPC^{TFE} at different concentrations are shown in Table 1. With higher concentrations of **1a** the yields of **3a** and **4a** went up. These conversions were easily possible on a preparative scale (11.2 mmol in Table 1, entry 6). But this procedure was synthetically unsatisfying, since even with neat **1a** only a ratio of 1.0:7.4 was achieved (Table 1, entry 7), and the option to use neat substrates only exists for liquids with relatively low viscosity. Furthermore, with the Pd(II) catalysts (more than 1100 turnovers, Table 1, entry 6) much higher substrate to catalyst ratios than with the Ag(I) (5.6 turnovers)[6c] or the Rh(I) catalysts (8.5 turnovers)[6a] were possible.[21]

2. The Acetone/TCPC^{TFE}-System. For further improvement of the yield of **3a** the solvent dependency was crucial. The product ratio obtained in different solvents is depicted in Table 2. While most of the solvents gave results comparable to C_6D_6, acetone provided **3a** as the major product; the isomer **4a** was not observed any more (Table 2, entry 4). In all of these experiments a superimposition of the solvent dependency of the ratio of **2a**:**3a**:**4a** and an increasing preference of the monomer

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(15) Buono, G. *Synthesis* **1981**, 872−872.

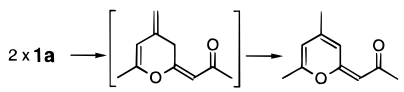
(16) Like TCPC (see ref 18) this complex catalyses enyne-methathesis: Chatani, N.; Morimoto, T.; Muto, T.; Murai, S. *J. Am. Chem. Soc.* **1994**, *116*, 6049−6050.

(17) All new compounds were characterized by NMR, infrared, mass spectroscopic data, high-resolution mass spectra in most cases and by elemental analyses. See Supporting Information.

(18) TCPC^{TFE} = tetrakis[(2,2,2-triflouroethoxy)carbonyl]palladacyclopentadiene, see: Trost, B. M.; Trost, M. K. *J. Am. Chem. Soc.* **1991**, *113*, 1850−1852.

(19) Moseley, K.; Maitlis, P. M. *J. Chem. Soc., Chem. Commun.* **1971**, 1604−1605.

(20) The ^{1}H NMR of **3a** contained singlets only. Another compound that would provide comparable ^{1}H and ^{13}C NMR spectra, would be a α-alkylidene pyran formed by Diels−Alder reaction and subsequent double bond migration:



For a related [4 + *X*] reaction of carbon monoxide (*X* = 1) instead of an allenic double bond (*X* = 2), see: Sigman, M. S.; Kerr, C. E.; Eaton, B. E. *J. Am. Chem. Soc.* **1993**, *115*, 7545−7546. Sigman, M. S.; Eaton, B. E.; Heise, J. D. Kubiak, C. P. *Organometallics* **1996**, *15*, 2829−2832. But NOE-data and UV-spectra do not agree with this structure, too.

(21) We also tried the Ag(I)-catalyst with our substrates and were able to achieve a turnover-number of 100, but under the same conditions as applied for the Pd-catalysts the reactions needed 1−2 weeks.

Table 2. Reaction of 1a with the TCPC^{TFE} Catalyst in Different Solvents[a]

entry	solvent	ratio **2a**:**3a**:**4a**[b]	isolated yield of **3a** + **4a**,[c] %
1	pentane	1.0:2.9:0.3	65
2	$CDCl_3$	1.0:1.4:0.4	60
3	ethyl acetate	1.0:2.5:0.2	63
4	acetone-d_6	1.0:8.8:0.3	86
5	ethanol	1.0:4.2:traces	74
6	methanol	1.0:7.1:traces	63
6	THF	1.0:1.9:0.2	60
7	diethyl ether	1.0:1.7:0.2	59
8	DMSO	*d*	–

[a] At 1 M concentration and with 0.1% of catalyst, compare Table 1, entry 3. [b] By ^{1}H NMR. [c] **3a** and **4a** could be separated by HPLC only. [d] Reaction inhibited. Only some unidentified material was formed.

Table 3. Reaction of 1a with Different Transition-Metal Catalysts in Acetone-d_6[a]

entry	catalyst	ratio of **2a**:**3a**:**4a**[b]	isolated yield of **3a** + **4a**,[c] %
1	1.0% CuCl	1.0:traces:0[d,e]	–
2	1.0% $AgNO_3$	1.0:0:0[d,e]	–
3	1.0% $Rh_2(OAc)_4$	1.0:0:0[e]	–
4	0.5% $[Ru(Cl)_2(CO)_3]_2$	1.0:0:0[d]	–
6	0.1% TCPC^{TFE}/PPh_3	*f*	–
7	0.1% TCPC^{TFE}	1.0:8.8:0.3	86
8	0.4% $Pd(OAc)_2$	1.0:2.4:0.1	71

[a] At 1 M concentration. Compare to Table 1, entry 3, and Table 2. [b] By ^{1}H NMR. [c] **3a** and **4a** could be separated by HPLC only. [d] Other material forms as well. [e] Proceeds slowly. [f] No reaction at room temperature. Polymerizes at 50 °C.

Table 4. Reaction of 1a with Different Pd^{II} Catalysts in Acetonitrile-d_3[a]

entry	catalyst	ratio of **2a**:**3a**:**4a**[b]
1	TCPC^{TFE}	<1.0:20:traces
2	$Pd(OAc)_2$	1.0:16:2.0
3	$Pd(acac)_2$	<1.0:20:0
4	$PdCl_2(MeCN)_2$	<1.0:20:0
5	$PdSO_4$	1.0:5.0:traces
6	PdI_2	<1.0:20:0
7	$PdBr_2$	<1.0:20:0

[a] At 1 M concentration. Compare to Table 1, entry 3, Table 2, and Table 3. [b] By ^{1}H NMR.

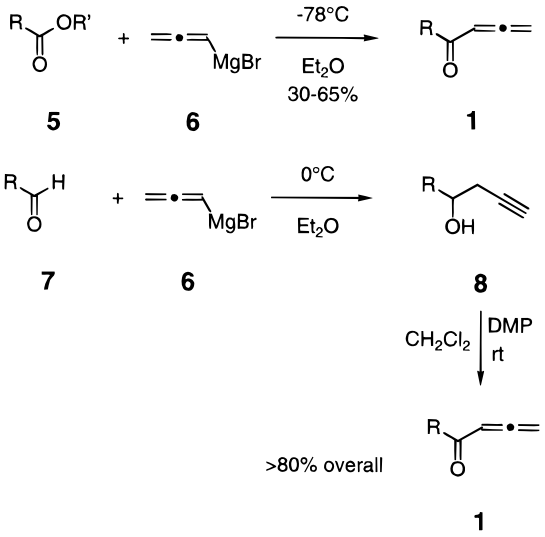
2a with decreasing concentration of **1a** during the progress of the reaction was observed.

The other transition-metal catalysts were tested in this solvent again. However TCPC^{TFE} was still the best catalyst (Table 3). Triphenylphosphine as additional ligand inhibited the reaction (Table 3, entry 6).[22]

3. The Acetonitrile/$PdCl_2(MeCN)_2$-System. Finally we discovered acetonitrile to be the solvent of choice for a selective formation of **3** (Table 4, entry 1). Since the TCPC^{TFE} catalyst is not readily available,[23] we looked for other Pd(II) catalysts (Table 4, entries 2–7).

All of them selectively formed **3** and since it is probably the easiest available soluble Pd(II)-source, the $PdCl_2(MeCN)_2$ catalyst[24] was used from then on. The effect was clearly a solvent effect. In other solvents like benzene, acetone, or $CDCl_3$, several substrates provided a complex product mixture with $PdCl_2(MeCN)_2$. The Lewis-acidity of $PdCl_2$ in acetone is too strong but TCPC^{TFE}, which is less Lewis-acidic, still shows a selective reaction in acetone. A further discussion of these solvent effects will be given in the mechanistic section.

4. Other Substrates. So far acetylallene (**1a**) was used as a test system. The other allenyl ketones were conveniently prepared by two methods: Either by the direct addition of allenylmagnesium bromide **6** to esters **5** at −78 °C[25] or by the addition of **6** to aldehydes **7** followed by a Dess−Martin oxidation of the homopropargylic alcohols **8**.[26]



The first route consisted of one step only; but the yields were low (30−65% depending on the substituent R). The second, longer route provided excellent yields (usually more than 80% over two steps). In principle there exist numerous other ways for the synthesis of α-allenyl ketones.[7,15,27] For our investigation we chose the fastest access.

The substrates **1b**-**1**π were subjected to the TCPC^{TFE}/acetone or later to the $PdCl_2(MeCN)_2$/MeCN conditions. The results are summarized in Table 5.[17] For some substrates we applied both conditions in order to secure that in acetonitrile higher yields of the dimer **3** were formed in all cases (Table 5, entries 1, 3, 4, and 20).

Selectivity Concerning the Allenyl Ketone Group. The selectivity of the dimerization was remarkable.

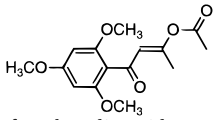
(22) Wallow, T. I.; Novak, B. M. *J. Org. Chem.* **1994**, *59*, 5034−5037. Farina, V.; Kapadia, S.; Krishnan, B.; Wang, C.; Liebeskind, L. S. *J. Org. Chem.* **1994**, *59*, 5905−5911. For the formation of oxaphospholes from allenyl ketones and phosphines, see ref 7a and ref 2, p 161.

(23) Only TCPC can be purchased since 1995 (1,2,3,4-tetrakis-(methoxycarbonyl)-1,3-butadiene-1,4-diyl)palladium).

(24) Hegedus, L. S. In *Organometallics in Synthesis*; Schlosser, M., Ed.; John Wiley & Sons: Chichester, 1994; pp 448−448.

(25) Couffignal, R.; Gaudemar, M. *Bull. Soc. Chim. Fr.* **1969**, 898−903. Couffignal, R.; Gaudemar, M. *Bull. Soc. Chim Fr.* **1969**, 3218−3222. Couffignal, R.; Gaudemar, M. *Bull. Soc. Chim. Fr.* **1970**, 3157−3160. These reactions are always accompanied by a second addition of **6** to either the intermediate propargyl or allenyl ketone, leading to tertiary alcohols as side products.

(26) Boeckman, R. J., Jr. In *Encyclopedia of Reagents for Organic Synthesis*; Paquette, L. A., Ed; John Wiley & Sons: Chichester, 1995; vol. 7, pp 4982−4987. Speicher, A.; Bomm, V.; Eicher, T. *J. Prakt. Chem.* **1996**, *338*, 588−590. In the case of allenyl ketones with an electron-rich substituent R (**1s**, **1u**, **1**π) the addition of acetic acid (set free by the DMP) to the allene was observed as side reaction. The (*E*)-configuration of the double-bond in the adduct to **1u**, the olefin **28u**, was proven by X-ray analysis:[75]

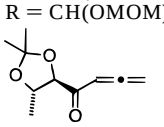
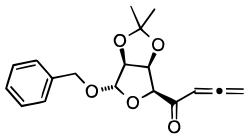


28u

For such additions of carboxylic acids to allenes, see: Smadja, W. *Chem. Rev.* **1983**, *83*, 263−320. Pasto, D. J. *Tetrahedron* **1984**, *40*, 2805−2827.

(27) Secondary α-allenic alcohols (or homopropargylic alcohols) are readily oxidized (or oxidized/isomerized) to allenyl ketones by DMP, MnO_2, chromium oxidants etc., see ref 2.

Table 5. Results of the TCPC^{TFE}-Catalyzed Reaction of 1a-1π

entry	allenyl ketone		cond.[a]	ratio[b] **2**:**3**	isol yield, % **2**	isol yield, % **3**
1	**1a**	R = CH_3	A	1.0:8.8	–	86
			B	1.0:30	–	89
2	**1b**	R = $(CH_2)_2CH_3$	A	1.0:4.7	–	76
3	**1c**	R = $CH(CH_2)_4$	A	1.0:3.0	3	67
			B	1.0:3.8	–	82
			C	1.0:0.25	–	25
				:0.12 (**4c**)		(13)
4	**1d**	R = $C(CH_3)_3$	A	1.0:1.0	–	33
				:0.2 (**4d**)		(7)
			B	1.0:2.9	11	54
5	**1e**	R = $CH_2C_6H_5$	A	1.0:6.0	4	76
6	**1f**	R = $CH(OTBDMS)CH_3$	A	1.0:3.6	8	84
7	**1g**	R = $CH(OMOM)CH_3$	A	1.0:2.8	–	42
8	**1h**		B	1.0:17	–	83
9	**1i**		B	1.0:14	2	85
10	**1j**	R = $(CH_2)_3OH$	B	1.0:4.0	8	79
11	**1k**	R = CH_2Cl	A	1.0:2.2	–	60
12	**1l**	R = CCl_3	A	*c*	–	21
13	**1m**	R = $CH_2CH(CH_3)(CH_2)_2CH{=}C(CH_3)_3$	B	1.0:7.2	4	78
14	**1n**	R = $C(CH_2)_3CCH_2CH{=}CH_2$	B	1.0:2	–	83
15	**1o**	R = $CH{=}CHC_6H_5$	A	*c*	6	74
16	**1p**	R = $C{\equiv}CC_6H_5$	A	*c*	6	18
17	**1q**	R = C_6H_5	A	1.0:6.1	5	81
18	**1r**	R = 4-$(OCH_3)C_6H_4$	A	*c*	4	81
19	**1s**	R = 3,4-$(OCH_3)_2C_6H_3$	A	*c*	5	60
20	**1t**	R = 2,5-$(OCH_3)_2C_6H_3$	A	1.0:7.2	5	75
			B	1.0:32	–	81
21	**1u**	R = 2,4,6-$(OCH_3)_3C_6H_2$	B	*c*	4	78
22	**1v**	R = 4-$[CH(OCH_2CH_3)_2]C_6H_4$	A	1.0:5.4	4	85
23	**1w**	R = 4-$(CHO)C_6H_4$	B	*c*	5	72
24	**1x**	R = 4-$(CO_2CH_3)C_6H_4$	A	*c*	5	84
25	**1y**	R = 2-FC_6H_4	A	1.0:16	4	76
26	**1z**	R = 2-ClC_6H_4	A	1.0:9.0	–	90
27	**1α**	R = 3-ClC_6H_4	A	1.0:8.2	3	73
28	**1*β***	R = 4-ClC_6H_4	B	*c*	5	89
29	**1*χ***	R = 2-BrC_6H_4	A	1.0:10	–	72
30	**1*δ***	R = 3-BrC_6H_4	A	*c*	3	82
31	**1ϵ**	R = 2-IC_6H_4	A	1.0:11	4	91
32	**1*ϕ***	R = 3-IC_6H_4	A	*c*	5	45
33	**1*γ***	R = 1-naphthyl	B	*c*	4	81
34	**1*η***	R = 9-anthryl	B	*c*	–	91
35	**1*τ***	R = 2,4,6-$(CH_3)_3C_6H_2$	B	1.0:7.9	–	86
36	**1*θ***	R = 2-furyl	A	1.0:4.1	–	72
37	**1*κ***	R = 3-furyl	A	1.0:5.5	–	69
38	**1*λ***	R = 2-thienyl	A	1.0:9.4	–	75
39	**1*μ***	R = $C(CO_2CH_3)(CH_2C{\equiv}CH)_2$	B	1.0:14	–	61
40	**1*ν***	R = 3-$(CH(OH)CH{=}C{=}CH_2)C_6H_4$	B	1.0:0.5	38	43
41	**1π**	R = 4-$(CH(OH)CH{=}C{=}CH_2)C_6H_4$	B	1.0:0.6	40	37

[a] A = TCPC^{TFE}/acetone; B = $PdCl_2(MeCN)_2$/acetonitrile; C = TCPC^{TFE}/benzene. [b] By ^{1}H NMR. [c] Not determined.

Since the conversion readily proceeded at room temperature (some reactions were conducted at 0 °C), no Diels–Alder reaction between the furyl-group of either product **2** or **3** and the allenyl ketone was observed.[28] No [2 + 2] cycloadducts known from transition-metal-catalyzed dimerization of unfunctionalized allenes were detected.[2,3d] The trisubstituted double bond in **3** was selectively formed with (*E*)-configuration and, under the improved conditions, no isomeric nonconjugated β,γ-unsaturated ketone **4** was observed.

Selectivity Concerning the Substituent R. In the alkyl series with increasing steric bulk of R more of the monomer **2** was formed (Table 5, entries 1–4). While a disubstituted α-C atom still gave a reasonable yield of **3** (Table 5, entry 3), a trisubstituted α-C atom led to equal amounts of **2** and **3** along with some **4** (Table 5, entry 4). When this quarternary α-C atom was less sterically hindered like in the bicyclo[1.1.1]pentane **1n** (entry 14), the percentage of the dimer increased again. α-Siloxy and α-alkoxy substituents were tolerated well. Here TBDMS-protected (Table 5, entry 6), MOM-protected (Table 5, entry 7), ketalic (Table 5, entries 8, 9), and acetalic (entry 9) substrates were tolerated. The chiral center α to the ketone in **1h** and **1i** did not racemize; no diastereomers were formed. The carbohydrate in entry 9 also shows a benzyl ether protecting group. The

(28) Either a normal Diels–Alder reaction with the furan as electron-rich 1,3-diene and the allenyl ketone as electron-poor dienophile or a Diels–Alder reaction with inverse electron-demand, i.e. the allenyl ketone as 1-oxa-1,3-diene and one double bond of the furan as dienophile are possible: Bertrand, M.; Le Gras, J. *Bull. Soc. Chim. Fr.* **1967**, 4336–4343. Gras, J.-L.; Galledou, B. S.; Bertrand, M. *Bull. Soc. Chim. Fr.* **1988**, 757–767.

protection of the hydroxyl group was not necessary, entries 10, 40, and 41 show examples with free hydroxyl groups. This was remarkable, since mercury,[29,30] silver,[31,32] and palladium[29,33] were also known to catalyze the nucleophilic addition of such functional groups to allenes. In entries 11 and 12 α-halogen ketones were used as substrates (forming benzylic chlorides as products), here Marshall's silver catalyst would remove the chlorine. The low yields of isolated product **3l** were due to decomposition of the products during chromatographic workup—the ^{1}H NMR spectra taken during the reaction showed a clean conversion. When **3k** was purified by chromatography a yield of 36% was obtained; the yield given in entry 11 originates from distillation of the crude product.

Further unsaturation in the molecule was tolerated; in entries 5 and 9 benzyl groups were present. In entries 13 and 14 a remote olefin and in entry 15 a conjugated olefin are shown. Conjugated alkynes caused problems, the yield dropped to 18%, and large amounts of polymer were formed (entry 16). Placing the triple bond in a more remote position eliminated these problems (entry 39).

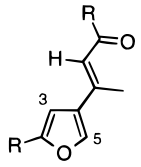
In the aryl series the reaction proceeded well with hydrocarbon substituents on the aromatic ring (entries 17, 33, 34, and 35). Alkoxy substituents were tolerated in any position (entry 18−21). Other oxygen-containing functionalities were a benzylic acetal (entry 22), an aromatic aldehyde (entry 23), and a carboxylic ester (entry 24). All halogens were tolerated, independent of the position on the phenyl substituent (entries 25−32). With an sp^2-carbon α to the ketone steric bulk did not seem to be a problem. So *ortho*-substituted (entries 20, 25, 26, 29, and 31) and *ortho,ortho*-disubstituted phenyl groups (entries 21, 35) as well as polycyclic aromatic substrates containing one (entry 33) or two (entry 34) *peri*-hydrogens reacted without problem.

In the heterocyclic series furyl (entries 36 and 37) and thienyl substituents (entry 38) gave satisfying results.

Since acetonitrile was used as the solvent in many cases, it is obvious that the nitrile functionality in the substrate will be tolerated, too.

Selectivity Concerning Functional Groups That Are Known To React under Transition-Metal Catalysis. As far as other possible reactions with transition-metals are concerned, the aryl halides did not cause any problems (entries 25−32). In Pd(0)-catalyzed reactions aryl halides are known to react with allenes[5e,f] and an activation of acceptor-substituted halides toward oxidative addition has been reported.[34] The substrate **1*μ*** (entry 39) was remarkable in two aspects. Firstly, it contains two terminal alkynes. These are known to add to allenes bearing electron-withdrawing groups in palladium-catalyzed reactions.[5d] With Marshall's Ag catalyst a precipitate, probably the silver acetylide, formed and no catalysis was observed. Secondly, **1*μ*** contained a 1,6-diyne and an 1,6-enyne subunit (the latter in form of an 1,6-allenyne). These are known to cyclize to five-membered carbocycles in palladium-catalyzed reactions,[35] and cpCo(CO) causes the formation of six-membered rings,[5g] but we did not observe such side reactions. Most spectacular were the reactions of **1*ν*** and **1*π*** (entries 40 and 41). Here one allene can be addressed specifically in the presence of a second allenic moiety (both terminal). To our knowledge this is unique in transition-metal catalysis. Furthermore the other allenic moiety was an α-allenic alcohol. These are known to cyclize to dihydrofurans when exposed to Hg(II)[30] or Ag(I) catalysts.[32] In entries 40 and 41 the monomer dominated, which will be discussed in the mechanistic section.

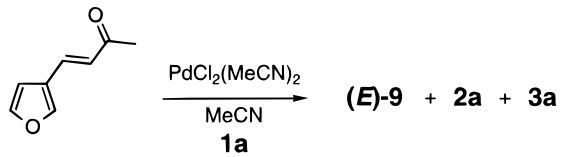
X-ray Structure Analyses of the Products. With the two dimers **3t** and **3*η***, X-ray structure determination was possible.[75] Both show the same relative arrangement of the furan and the α,*β*-unsturated ketone in the side chain, which is also in accordance with the NOE-data of **3a**, **3h**, **3*θ***, and **3*κ*** obtained in solution. The olefinic hydrogen atom of the trisubstituted double bond points toward the hydrogen atom at the 3-position of the furan, and the methyl group points toward the hydrogen atom at the 5-position. The C=O double bond of the ketone and the olefin occupy an s-cis-conformation.



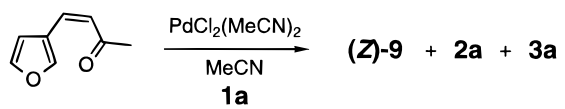
3

Mechanistic Considerations

1. Experiments Concerning the Mechanism. The first problem we addressed was the (*E*)-selectivity in the formation of the trisubstituted double bond. When the reactions were monitored by ^{1}H NMR spectroscopy, no indication for the intermediacy of the (*Z*)-isomer was found. In addition, we subjected (*E*)-**9** and (*Z*)-**9** to the $PdCl_2(MeCN)_2$/MeCN conditions. No change was observed. Then **1a** was added to the mixture of (*E*)-**9**/$PdCl_2(MeCN)_2$ or (*Z*)-**9**/$PdCl_2(MeCN)_2$. While **2a** and **3a** were formed as expected, still no isomerization of (*E*)-**9** or (*Z*)-**9** was observed.



(*E*)-9



(*Z*)-9

Analogous experiments were performed with the double bond isomers **3d** and **4d**. No double bond migration took place.

(29) Walkup, R. D.; Guan, L.; Kim, S. W.; Kim, Y. S. *Tetrahedron Lett.* **1992**, *33*, 3969−3972 and literature cited therein.

(30) Gelin, R.; Gelin, S.; Albrand, M. *Bull. Soc. Chim. Fr.* **1972**, 1946−1949.

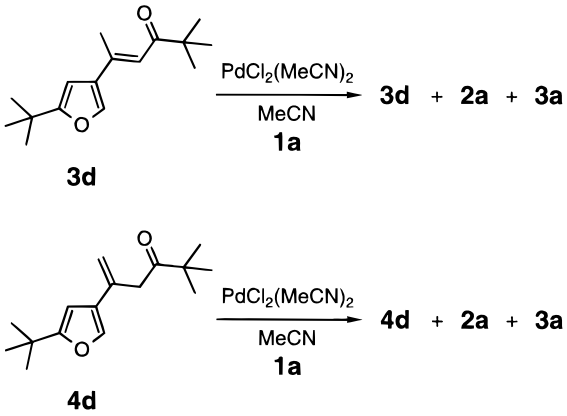
(31) Chilot, J.-J.; Doutheau, A.; Gore, J. *Tetrahedron Lett.* **1982**, *23*, 4693−4696 and literature cited therein.

(32) Gelin, R.; Albrand, M.; Gelin, S. *C. R. Acad. Sci. Ser. C* **1969**, *269*, 241−244. Olsson, L.-I.; Claesson, A. *Synthesis* **1979**, 743−745. Saimoto, H.; Hiyama, T.; Nozaki, H. *J. Am. Chem. Soc.* **1981**, *103*, 4975−4977. Nikam, S. S.; Chu, K.-H.; Wang, K. K. *J. Org. Chem.* **1986**, *51*, 745−747. Marshall, J. A.; Yu, R. H.; Perkins, J. F. *J. Org. Chem.* **1995**, *60*, 5550−5555 and literature cited therein.

(33) (a) Alper, H.; Hartstock, F. W.; Despeyroux, B. *J. Chem. Soc., Chem. Commun.* **1984**, 905−906. (b) Walkup, R. D.; Mosher, M. D. *Tetrahedron* **1993**, *49*, 9285−9294. (c) Walkup, R. D.; Guan, L.; Mosher, M. D.; Kim, S. W.; Kim, Y. S. *Synlett* **1993**, 88−90.

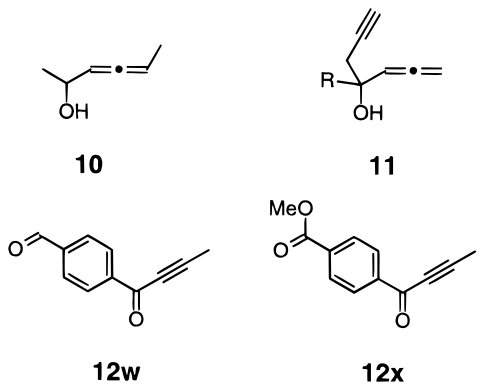
(34) Fitton, P.; Rick, E. A. *J. Organomet. Chem.* **1971**, *28*, 287−291. Bumagin, N. A.; Beletskaya, I. P. *Russ. Chem. Rev.* **1990**, *59*, 1174−1184.

(35) Trost, B. M. *Acc. Chem. Res.* **1990**, *23*, 34−42.



These experiments proved that the α,β-unsaturated (*E*)-olefin **3** was the direct product of the catalytic cycle and not the product of a subsequent isomerization of a product mixture ((*E*/*Z*)-**3** and/or **4**) into a thermodynamically most stable product by either $PdCl_2(MeCN)_2$ or any of the intermediates of the catalytic cycle.

The next experiments dealt with two aspects: The ability of other related, unsaturated molecules to participate in the dimerization reaction and the ability of these structures to cycloisomerize. In entry 40 and 41 of Table 5, it was already shown that α-allenic alcohols don't react with the $PdCl_2(MeCN)_2$ catalyst and that they are not incorporated in the dimerization step (with **1*ν*** and **1*π*** this would lead to polymerization). Additionally the two α-allenic alcohols **10** and **11** turned out to be inert under the $TCPC^{TFE}$/acetone and the $PdCl_2(MeCN)_2$/MeCN conditions.



The alkynyl ketones **12w** and **12x** (isomers of the allenyl ketones **1w** and **1x**) also did neither cyclize nor were incorporated in the product of the cycloisomerization/dimerization of allenyl ketones under our standard conditions.

These experimental results indicated a higher reactivity of the allenyl ketones compared to olefins, alkynes, or other allenes in the cycloisomerization/dimerization reaction. The high reactivity of the allenic ketones is also nicely demonstrated by the failure of their isomers **12w** and **12x**, respectively, to cycloisomerize under the same mild conditions.[36]

The next series of experiments dealt with the nature of the hydrogen migration. We started with the cyclization/dimerization of **1a** in acetone/D_2O, MeCN/D_2O (always a large excess of D_2O compared to **1a**), and MeOH-d_4. In all cases only some deuterium was incorporated (between 40% and 60%) at the allylic methyl group of **3a** only and position 4 of **2a**. In the case of **3a** ^{13}C-NMR and low-energy ionization mass spectroscopy proved that only one deuterium was incorporated. This indicated that the hydrogen migration is intramolecular to a large extent. Neither in the case of D_2O-addition nor in the case of H_2O-addition an increase in the reaction-rate was observed. These experiments also exclude tautomerization of **1** under the reaction conditions. Otherwise one would expect deuterium also to enrich (due to concentration and primary kinetic isotope effect) in position 5 of **2a** and position 5 and the allylic methyl group of **3a**. If R has a hydrogen atom α to the ketone, this position should also incorporate deuterium by keto−enol tautomerism, which was not observed.

Then deuterium labeled (80% monodeuteration at position 5) 5-D-**1a** was cycloisomerized/dimerized. Here a primary kinetic isotope effect of 3.1 (at 22 °C) was observed.[37] Within experimental error the value was identical for both products **2a** and **3a**. This is a necessary but not sufficient condition for a formation of **2a** and **3a** through the same intermediate undergoing the hydrogen migration.

Two additional crossover experiments between **1a** and **1s** (one partner monodeuterated, the other undeuterated in each of the experiments) showed only deuteration at the expected positions of the statistically formed four dimers. This is an additional proof for the intramolecularity of the hydrogen-migration. Differing from the deuterium exchange with the solvent (see above), no deuterium exchange between the intermediates was observed due to the low concentration of these intermediates of the catalytical cycle.[13]

In the next experiment we again focused on the possible participation of tautomers of **1**. When **1d** is stirred with $D_2O/NaHCO_3/Et_2O$ almost complete deuteration of the vinylic hydrogens was observed, while in the absence of a base **1d** remained unchanged. This excludes tautomers of **1** as substrates entering the catalytic cycle.

The last experiment dealt with the oxidation state of the palladium intermediates. We were able to conduct the reaction with **1a** under 1 atm of pure dioxygen!

2. The Nature of the Catalyst. Since palladium chloride, bromide, iodide, acetate, acetylacetonate, and $TCPC^{TFE}$ gave similar results, these ligands on palladium obviously do not directly participate in the reaction. Therefore their possible participation, e.g. in the sense of a halopalladation step (which would be impossible with $TCPC^{TFE}$), is omitted in the discussion below.

We will discuss Pd(II)/Pd(IV)-cycles for the following reasons: One could imagine that Pd(II) is initially reduced to Pd(0) by the organic substrate,[38] and then the analogous Pd(0)/Pd(II)-cycles could be formulated. But in the absence of stabilizing ligands one would expect Pd(0) to precipitate as palladium-black. This was not observed. Furthermore we were able to conduct the reaction with **1a** under 1 atm of pure dioxygen. This experiment excludes Pd(0) intermediates in the catalytic cycle since these are known to react rapidly with oxy-

(36) If one regards the chemoselectivities, the assumption of a higher reactivity of allenyl ketones is necessary with any mechanism.

(37) Recently similar values have been reported for the β-H-elimination in Pd(II) complexes, see: Keinan, E.; Kumar, S.; Dangur, V.; Vaya, J. *J. Am. Chem. Soc.* **1994**, *116*, 11151−11152.

(38) Stille, J. K.; Groh, B. L. *J. Am. Chem. Soc.* **1987**, *109*, 813−817.

(39) Maitlis, P. M.; Espinet, P.; Russell, M. J. H., ref 1b, vol. 6, pp 243−263 (specific pp 256−259). Mimoun, H. In *The Chemistry of Functional Groups, Peroxides*; Patai, S., Ed; John Wiley & Sons: London, 1983; pp 463−482. Heumann, A.; Jens, K.-J.; Réglier, M. *Progr. Inorg. Chem.* **1994**, *42*, 483−576 and literature cited therein.

gen;[39] thus many turnovers of the catalytic cycle should be impossible with Pd(0). In addition, the aryl halides, especially the aryl iodides **1ε** and **1φ**, should immediately undergo oxidative addition to a Pd(0) intermediate.[40] Then this arylpalladium(II) compounds would carbometalate another allene, thus leading to the kind of products described by Goré and others.[41] Furthermore the addition of nucleophiles to olefins is a domain of Pd(II) catalysts as exemplified by the Wacker oxidation[42] and related reactions.[43]

If one accepts that Pd(0) is not involved and if one takes into consideration the intramolecularity of the hydrogen migration, it becomes necessary to formulate Pd(IV) intermediates with any mechanism for the formation of **3**. Organometallic Pd(IV) complexes are well known in the literature.[44] Even Pd(IV)-hydride species have been proposed;[44a,45] these proposals experience further support by the recent isolation[46] and in one case crystallographic characterization[47] of the related organo-Pt(IV)-hydride complexes. The solvent dependency of the ratio of **2**:**3** (see Tables 2 and 4) is also in accordance with the proposed Pd(IV) intermediates. Since Pd(IV) shows an octahedral coordination of six ligands, the solvent must occupy two coordination sites. Good donor ligands (like MeCN,[48] acetone, EtOH, MeOH; nitrogen and oxygen donor ligands are preferred for Pd(IV)[44] and Pt(IV)[46]) will stabilize (stabilize does not mean that the compound is stable, for a catalytic cycle with high turnover frequency and numbers reactive intermediates are essential) the Pd(IV) intermediate, thus more of **3** is formed. With weaker donor ligands (like $CDCl_3$, ethers, and benzene) the Pd(IV)-H species will form **2** by reductive elimination before this intermediate can add to a second allene (pathway A, see below) or the formation of the Pd(IV)-cycle does not take place that readily (pathway B). The exclusive formation of the monomer **2** with the Ag(I) catalyst could be explained by the mechanism proposed by Marshall,[6d] where the hydrogen moves by a 1,2-H-shift rather than by a β-H-elimination (see below), thus avoiding an unfavorable Ag(III) intermediate but also preventing C−C-bond formation.

3. Possible Mechanisms. There are two mechanisms (pathways A and B) which are in accordance with the experimental results. Due to reasons to be discussed at the end of the description of pathway B we prefer pathway A. Other existing mechanistic possibilities, which include steps and intermediates known from other palladium-catalyzed reactions, but which do not harmonize with our experiments, will be discussed only briefly (pathways C−E).

Pathway A. First the terminal double bond of the allenyl ketone coordinates to the palladium(II) (this double bond is less substituted and more electron rich). The coordination bends the allene,[3c,d] thus bringing the terminal carbon within reach of the carbonyl oxygen (at least in an s-cis conformation, **13**). Usually α,β-unsaturated carbonyl compounds with bulky substituents at the carbonyl group prefer the s-cis conformation necessary for ring-closure.[49] We were able to obtain X-ray structures from **1α** and **1η**.[50] While **1η** shows an s-trans conformation, **1α** occupies an s-cis conformation. The distance of the oxygen and the terminal carbon of the allene in **1α** is 3.64 Å; coordination to palladium should bent the allene, and thus the oxygen−carbon distance discussed above should decrease substantially.[51]

Then an oxypalladation of the double bond leads to an intermediate **14** (Scheme 1).[43,52] **14** is a γ-donor-substituted vinylcarbene complex,[53,54] but also resembles a σ-complex of an electrophilic aromatic substitution at

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(41) (a) Hughes, R. P.; Powell, J. *J. Organomet. Chem.* **1973**, *60*, 409−425. (b) Ahmar, M.; Barieux, J.-J.; Cazes, B.; Gore, J. *Tetrahedron* **1987**, *43*, 513−526. (c) Cazes, B. *Pure Appl. Chem.* **1990**, *62*, 1867−1878.

(42) (a) Eilbracht, P. In *Houben Weyl*; Helmchen, G., Hoffmann, R. W., Mulzer, J., Schaumann, E., Eds.; Thieme: Stuttgart, 1995; vol. E21c, pp 2702−2712. For Cl^- from $PdCl_2$ as nucleophile, see: (b) Godleski, S. A. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Semmelhack, M. F., Eds.; Pergamon Press: Oxford, 1991; vol. 4, pp 585−661 (specific pp 587−588). (c) Davies, J. A. In *Comprehensive Organometallic Chemistry II*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Puddephatt, R. J., Eds.; Pergamon Press: Oxford, 1995; vol. 9, pp 291−390 (specific p 330).

(43) Hosokawa, T.; Murahashi, S.-I. *Acc. Chem. Res.* **1990**, *23*, 49−54. For examples with $PdCl_2(MeCN)_2$, see: Pearlman, B. A.; McNamara, J. M.; Hasan, I.; Hatakeyama, S.; Sekizaki, H.; Kishi, Y. *J. Am. Chem. Soc.* **1981**, *103*, 4248−4251. Hosokawa, T. Nakajima, F.; Iwasa, S.; Murahashi, S.-I. *Chem. Lett.* **1990**, 1387−1390. Kumar, R. J.; Krupadanam, G. L. D.; Srimannarayana, G. *Synthesis* **1990**, 535−538. Saito, S.; Hara, T.; Takahashi, N.; Hirai, M.; Moriwake, T. *Synlett* **1992**, 237−238.

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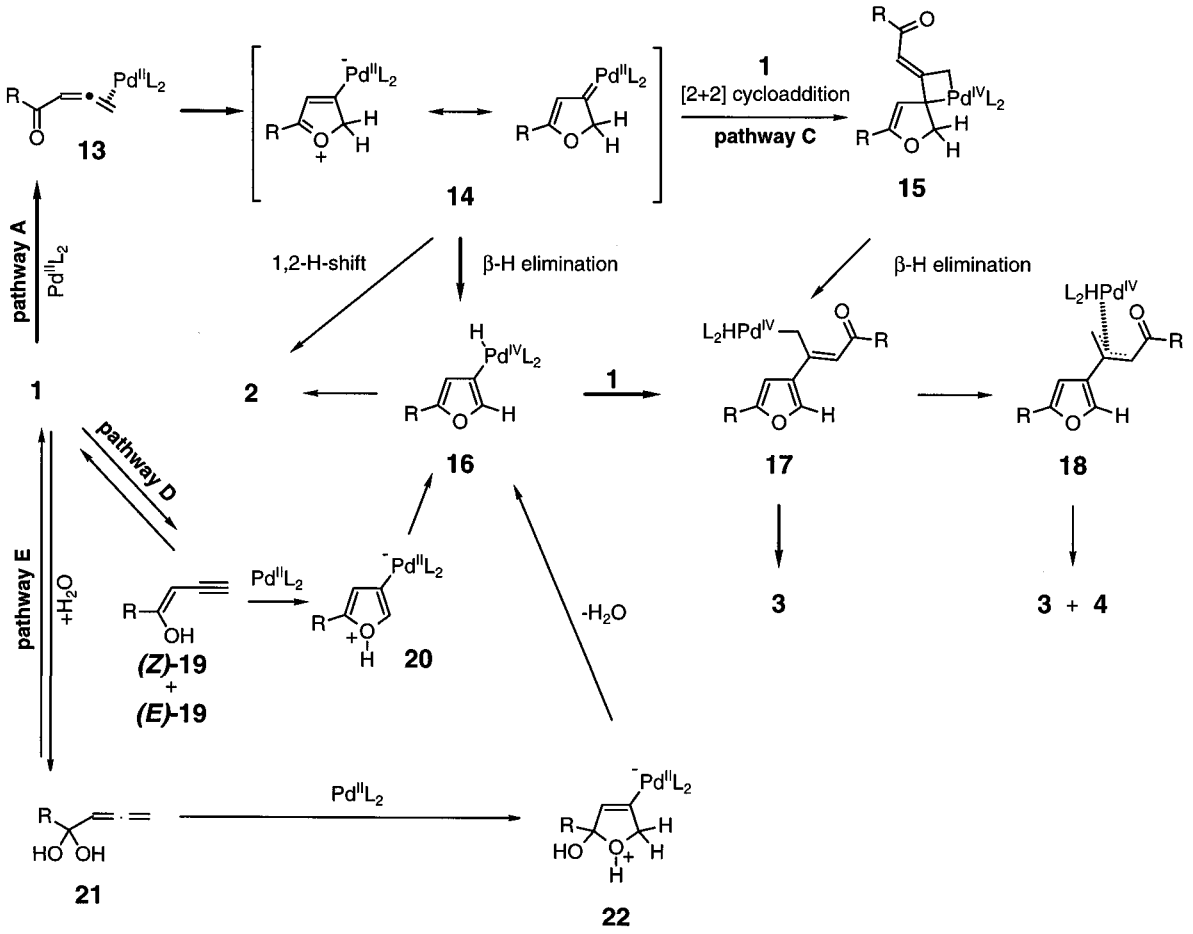
Scheme 1



the furan.[55] The protonated furan is acidic,[54b] and the d-electron-pair at Pd is an internal base.[56] β-H-elimination would form the aromatic furan in the furyl−hydrido complex **16**.[6d] Such β-H-eliminations of carbene complexes have been proposed.[53a,57,58] The fact that in protic deuterated solvents 40−60% of the hydrogen remains in the product is also a proof for the intramolecularity of the major part of the H-migration (C−H to Pd−H to C−H). Due to a certain acidic character of the intermediate Pd(IV)-H species some of the hydrogen is exchanged by the deuterium of the solvent; the H/D exchange may to some extent also result from nonintramolecular H-migration.

Now **16** can form **2** by reductive elimination. The formation of olefins by a 1,2-shift from carbene complexes is well known in the literature[59] and might proceed directly (1,2-H-shift forming the π-coordinated olefin complex without change in the oxidation state of the metal, probably true for the Ag(I)-catalysts)[60] or as described above (β-H-elmination followed by reductive elimination).[61] The direct 1,2-H-shift would not allow the formation of the dimer **3** by the same pathway.

16 also could carbopalladate the terminal double bond of a second allenyl ketone (to **17**).[41,62] The selectivity for this more electon rich double bond may be explained by the electron deficiency of the Pd(IV) intermediate. The palladium also preferentially coordinates to the less hindered face of this double bond, which is anti to the carbonyl-substituent. This would explain the (*E*)-selectivity in the formation of the trisubstituted double bond. The regiochemistry of the carbopalladation can be explained by steric (the palladium complex ends up on the less substituted carbon) and electronic factors (the nucleophilic furyl carbon gets attached to the more electrophilic central carbon of the allene). Carbopalladations of allenes are known to favor C−C bond formation at the central carbon of the allene.[5a,b,d,i,33a,c,41b,63] In the case of a hydropalladation, instead of a carbopalladation, the hydrogen should end up at the central carbon of the allene,[5h,i] which neither we observed nor has been

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observed in reactions where alkynylPdH[5d] or other PdH intermediates[5i,62] add to allenes.

In entry 40 and 41 of Table 5 the monomer is formed preferentially. This can be interpreted by a blocking of the coordination site for the second allenyl ketone by the α-allenic alcohol. Here the relative rates of reductive elimination versus carbopalladation favors the furans **2**. This can be explained by the allenyl ketones being extremely effective trapping reagents for such intermediates, but unfortunately also cyclize under these conditions and thus trap themselves.

No polymers are formed, since arylPdH species (**16**) are more stable than alkylPdH species (**17**) (for the higher stability of arylPd versus alkylPd in the formal oxidation state Pd(IV)[44]), the latter reductively eliminates R−H much faster.

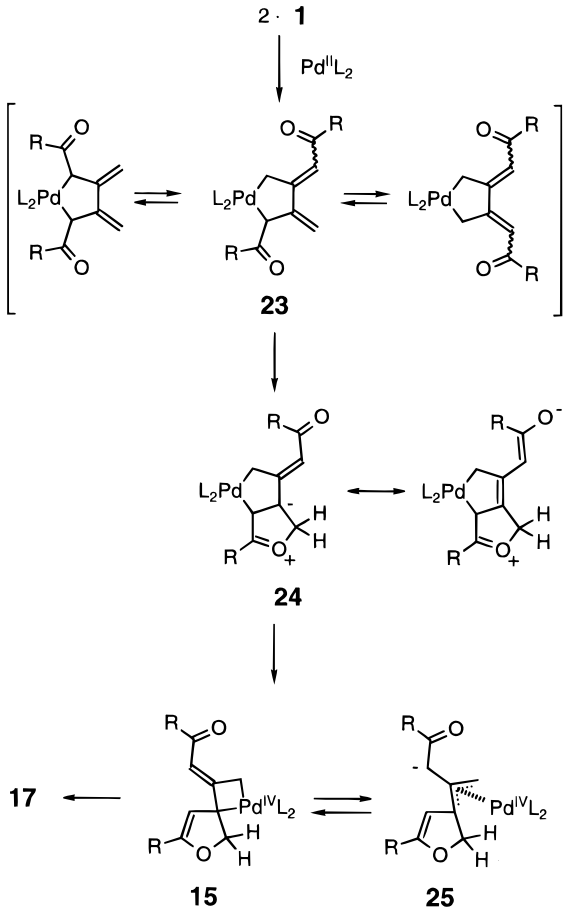
Finally the product **3** is formed by a fast subsequent reductive elimination from the σ-allyl complex **17**. Rearrangement to an π-allyl complex **18** and reductive elimination could explain the byproduct **4**.

This pathway resembles the formation of furans by FVT of allenyl ketones (see Introduction). Huntsman recognized that one hydrogen must migrate to the central carbon of the allene, no matter whether first cyclization and then migration or first migration and then cyclization occurs, and that it was necessary to discuss carbene intermediates. The metal catalyst now stabilizes these high energy intermediates (by forming carbene complexes), thus opening a pathway with a lower energy of activation. The metal also prolongs the lifetime of the intermediates, so the additional C−C-coupling is possible.

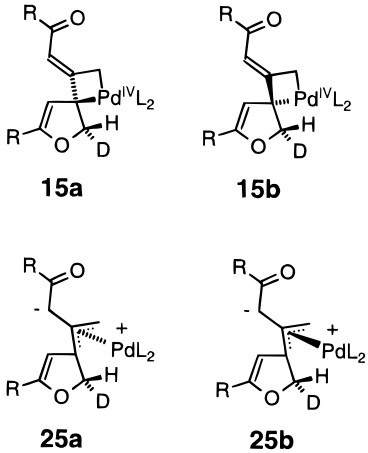
Pathway B. The reaction is initiated by the formation of the palladacyclopentane **23** (Scheme 2).[5c,64] Here the first step forms the C−C bond between the central carbon atoms of the two allenes. Several isomers of **23** are conceivable, which maybe interconvert by allyl-shifts of the metal.[65] Nucleophilic attack of oxygen to the neighboring exocyclic double bond forms the intermediate **24**. A 1,2-shift of the metal eliminates the positive charge on the oxygen and leads to the 3-methylenepalladacyclobutene **15** or a trimethylenemethane-like intermediate **25**.[66] Now β-H-elimination forms the furan **17**, and the reaction is finished as described above. Here we are not certain how the specific formation of the (*E*)-olefin in the product **3** can be explained.

The identical primary kinetic isotope effects of 3.1 (at 22 °C) observed in the formation of **2a** and **3a**[37] is a necessary but not sufficient condition for a formation of

Scheme 2



2a and **3a** through the intermediates and thus a weak argument against pathway B (since this pathway leads to **3** only). Still, the palladium would eliminate the hydrogen or the deuterium from the syn-face, and none of the complexes **15a** and **15b** (or **25a** and **25b**) should be preferred either sterically or electronically. Thus in pathway B a primary kinetic isotope effect could be only explained if the Pd changes the faces faster than the β-hydrogen elimination occurs.



More evidence against pathway B is provided by the cyclization of **1*μ*** (Table 5, entry 39). If a palladacycle is formed, it would be difficult to understand why in the case of **1*μ*** an intramolecular incorporation of the alkyne to the intermediate **26** is not preferred. Then **27** would form, but we could not detect **27** or products derived from **27**.

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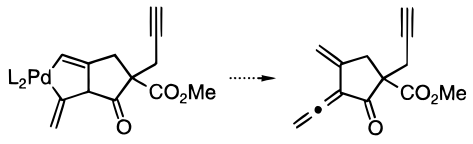

26 **27**

Pathway C. In this pathway only the transformation of **14** to **17** differs from pathway A. Here the C−C bond is not formed by carbopalladation but by a [2 + 2] cycloaddition of the carbene complex and the less hindered face of the terminal double bond of the allene (intermediate **15**; for other possible forms of **15** see pathway B).[67,68] Subsequent β-H-elimination leads to **17**, and then the reaction proceeds similar to pathway A. This means that the formation of the monomer **2** and the dimer **3** branch before the β-H-elimination. As in pathway B there should not exist any preference for either of the two [2 + 2] cycloadducts **15a** and **15b** (respectively, **25a** and **25b**). Therefore no primary kinetic isotope effect would be possible.

Pathway D. Here **16** is formed by an alternative mechanism. **1** might exist in an equilibrium with its tautomer **19**. With a (*Z*)-configuration at the double bond such 1-buten-3-yn-1-ol substructures are known to cyclize to furans in palladium-catalyzed reactions. When 2-hydroxy-haloarenes and terminal alkynes are cross-coupled in the presence of palladium catalysts, the 2-alkynylphenols cannot be isolated. The reactions proceed to the isomeric benzofurans,[69] unless the hydroxyl group is protected.[70] In the case of the *tert*-butyl and aryl substituents **19** would be the only possible tautomer of **1**. Other substituents which possess an α-hydrogen could also form an enol in the other direction, but our experiments exclude the participation of such tautomers.

Pathway E. This is another alternative for the formation of **16**. First a hydrate **21** is formed, and then an oxypalladation of the terminal double bond leads to intermediate **22**. Similar steps are known from the formation of 2,5-dihydrofurans from α-allenic alcohols[30,32] and have also been suggested by Utimoto for the cyclization of β-acetylenic ketones by Pd catalysts[71] and by Walkup for the Pd-catalyzed cyclization of γ-allenic alcohols.[33b]

The intermediate **22** (which could also be formed by the addition of H_2O to **14**) then forms the aromatic furan system **16** by loss of water. One proton of the methylene group in the heterocycle may be transferred to the palladium by a β-H-elimination or leave to the solvent. Finally **16** carbopalladates a second molecule **1** as described above. This carbopalladation may also take place before the elimination of water.

Traces of water might always be present, and if the rate-determining step is not the formation of the hydrate, one would not expect a rate enhancement by additional water. However the reaction of **1*τ*** (Table 5, entry 35) provides a strong evidence against pathway E. One would at least expect a much slower reaction, since the formation of the tetrahedral sp^3-center in the ketone hydrate from the trigonal sp^2-center in the ketone is usually avoided due to steric hinderance in the mesityl system.[72] But the cycloisomerization/dimerization of **1*τ*** was finished within the normal time.

Conclusions and Further Studies

By the choice of $PdCl_2(MeCN)_2$ catalyst and acetonitrile solvent, the dimers **3** could be obtained in preparatively useful yields under mild conditions. Only traces of the monomer **2** were observed, and the isomer **4** was not detected. Neither water nor oxygen needs to be excluded for a successful catalysis. Many functionalities and protecting groups that are frequently used in organic synthesis were tolerated. Among them are functional groups such as aryl bromides, terminal alkynes, 1,6-enynes, and α-allenic alcohols that are all known to react in palladium-catalyzed reactions; therefore, tandem sequences seem possible. α-Halogen ketones and terminal alkynes that cannot be isomerized with Marshall's silver catalysts also reacted well. On the basis of several control experiments and the observed intriguing selectivities, we favor pathway A for the mechanism of the reaction although pathway B could not be excluded. Only a complete understanding of the mechanism might enable us to transfer this exciting selectivity to other reactions.

Intramolecular macrocyclization of 1,*n*-diallenyl diketones is another interesting field that is currently under investigation. The formation of **3**, which contains an dendralenic[73] double bond arrangement, also opens an easy route to substrates for diene-transmissive Diels−Alder reactions.[74]

Acknowledgment. A.S.K.H. is grateful to the *Fonds der Chemischen Industrie* for a Justus von Liebig fellowship and to Prof. Dr. J. Mulzer for his generous support. This work was further supported by the *Deutsche Forschungsgemeinschaft* (Ha 1932/3-1 and Ha 1932/3-2). Some noble metal salts were donated by the Degussa AG. We thank S. Guffler for a generous gift of **1n**.

Supporting Information Available: Characterization data for **1**−**5**, **8**−**12**, **28**, and intermediates **29**−**37** and methods of preparation (50 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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