A Putatively Unfeasible Heck Reaction − From Cyclopentenones to Annulated Ring Systems

Gerald Dyker,*[a] Hardy Markwitz,[a] and Gerald Henkel[a]

Keywords: Annulation / Palladium / Allylic compounds / Alcohols / Michael addition

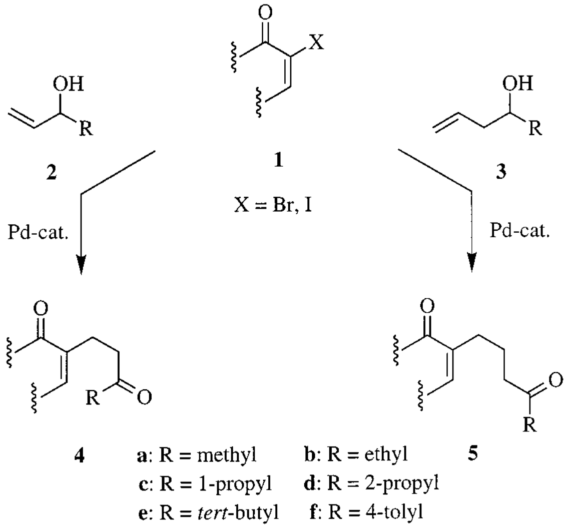
2-Iodocyclopentenones undergo a Heck reaction with allylic and homoallylic alcohols, in acceptable yields, to give dicarbonyl compounds useful for the construction of annulated cyclopentanones. In contrast, the corresponding iodo-substituted cyclohexenones, cycloheptenones and acyclic α,β-unsaturated ketones are far less or even unsuitable for Heck reactions of this type.

Introduction

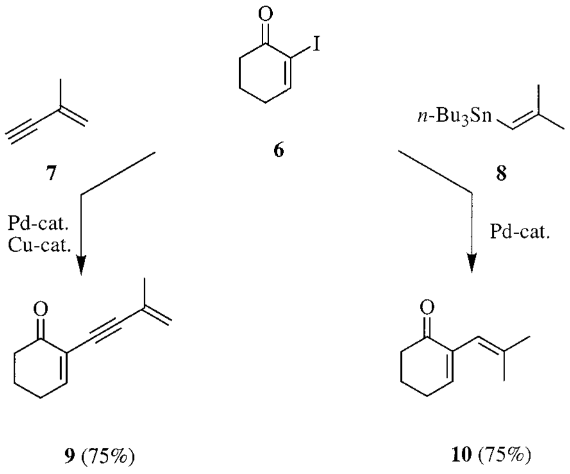
The combination of the Heck reaction[1] with classical carbonyl reactions has proved to be a powerful strategy for the efficient and facile construction of annulated ring systems: the Heck reaction with allylic and homoallylic alcohols as olefinic coupling components leads to carbonyl compounds[2] that are prone to undergo subsequent ring closure reactions depending on the presence of appropriate neighboring functional groups, such as additional carbonyl groups for aldol type reactions, α,β-unsaturated ketones for Michael addition reactions, or amines for imine formation.[3] In this article we summarize our efforts to apply α-halo-α,β-unsaturated ketones **1** as coupling components in the Heck reaction with allylic and homoallylic alcohols **2** and **3**, respectively (Scheme 1). We anticipated the resulting coupling products **4** and **5** as interesting candidates for various ring closure reactions.

Results and Discussion

A literature survey revealed that Heck reactions of α-halo-α,β-unsaturated carbonyl compounds are virtually unknown, with the special exception of an iodouridine.[4] For instance, vinyl bromide **11** was reported to fail in the Heck reaction with acrylic acid methyl ester and other alkenes.[5] Nevertheless, related palladium-catalyzed reactions such as the Sonogashira and the Stille coupling reaction were successfully demonstrated with 2-iodocyclohexenone **6** (Scheme 2) to give cross-conjugated products like **9** and **10**.[6] These coupling processes have in common the rapid trapping of the intermediary vinyl-palladium species with an organometallic component (an organocuprate or an organotin compound in Scheme 2). Clearly, α-halo-α,β-unsaturated ketones **1** were reputed to be unsuitable for Heck reactions and, indeed, our own attempt to couple **6** with the homoallylic alcohol **3f** was a failure too.



Scheme 1. Heck reactions of α-halo-α,β-unsaturated ketones with allylic and homoallylic alcohols in general

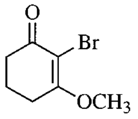


Scheme 2. Sonogashira and Stille coupling reactions of 2-iodocyclohexenone **6**

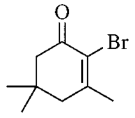
---

[a] Fachbereich 6, Institut für Synthesechemie der Gerhard-Mercator-Universität Duisburg,
Lotharstrasse 1, 47048 Duisburg, Germany,
E-mail: dyker@uni-duisburg.de
[b] Fakultät für Chemie, OC II, Ruhr-Universität Bochum,
Universitätsstrasse 150, 44780 Bochum, Germany,
Tel. +49(234)32−24551
Fax: (internat.) +49-234/32-14353,
E-mail: Gerald.Dyker@ruhr-uni-bochum.de

1434−193X/01/0713−2415 $ 17.50+.50/0



11



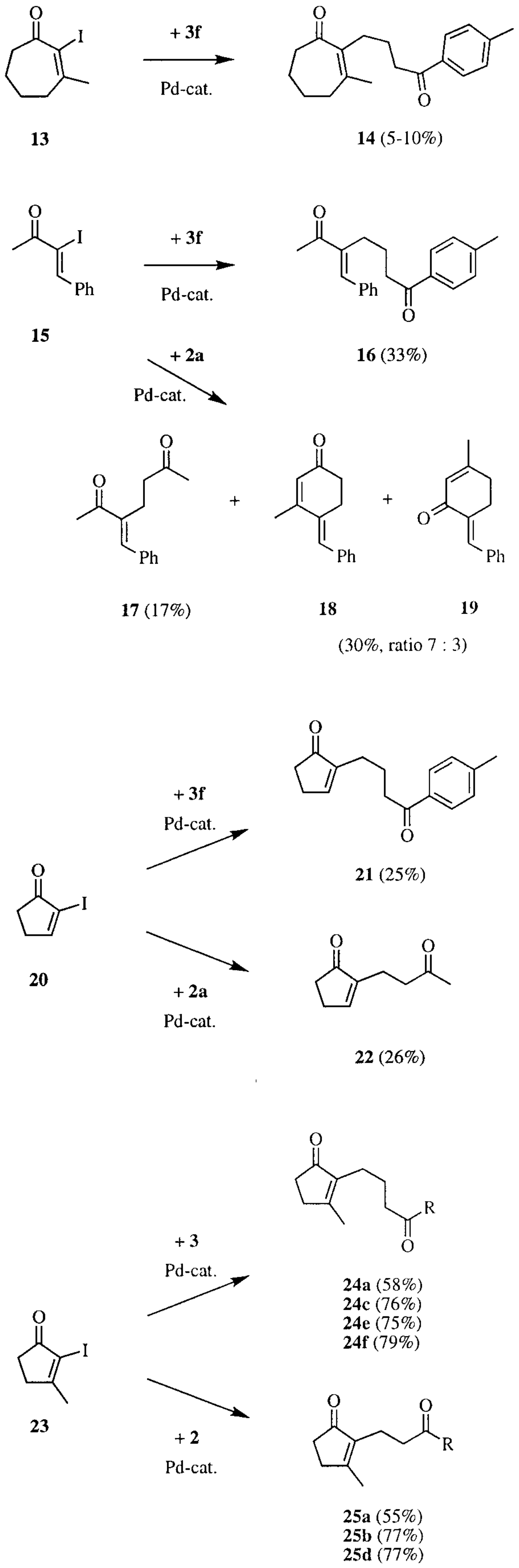
12

As a working hypothesis, we concluded that the palladium-catalyzed dehydration with aromatization to give phenols is presumably kinetically favored compared to the rather sluggish Heck reaction. Therefore we tested 2-bromoisophorone (**12**) in the coupling reaction with **3f**; in this case the geminal methyl groups should prevent the aromatization. However, C−C coupling products could not be detected and hydrodehalogenation to give isophorone was observed instead.

When we changed to the cycloheptenone **13** we were able to isolate at least a small yield of the desired coupling product **14**, indicating that the distance or the angle of torsion between the carbonyl group and the palladium atom of the intermediary vinylpalladium species might have a decisive influence on the reactivity of the olefinic coupling component (Scheme 3). An even more flexible substrate, the acyclic vinyliodide **15**, led to a significantly higher yield of the tolyl-substituted coupling product **16**. In the case of allylic alcohol **2a** as the olefinic coupling component a domino process was observed, consisting of a Heck reaction and cyclizing aldol condensation: the product ratio of the dienones **18** and **19** presumably mirrors the kinetic control of the regiochemistry of the cyclization step caused by the difference in acidity of the two methyl groups of the primary coupling product **17**.

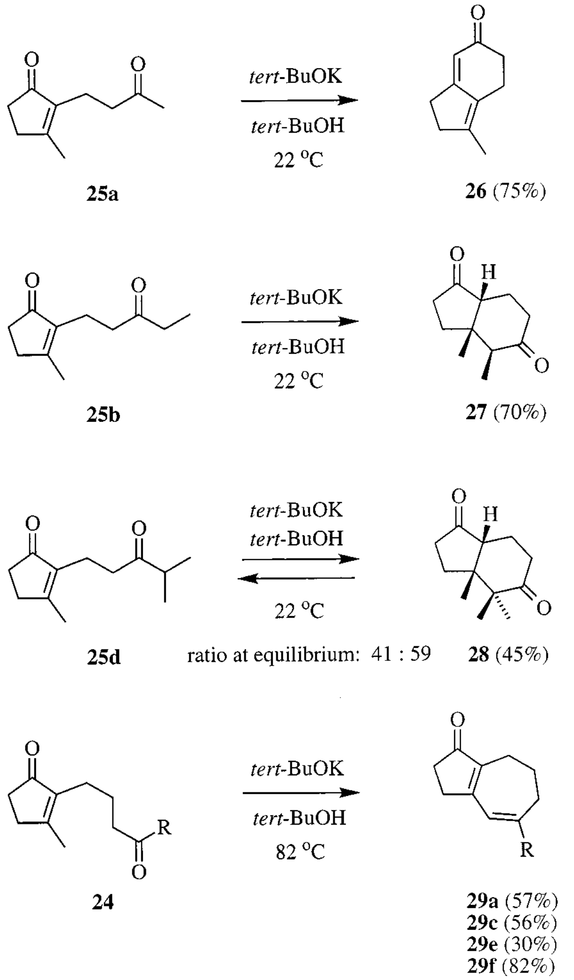
Starting with 2-iodocyclopentenone **20** and our test alkenes **3f** and **2a** a rather small amount of coupling products **21** and **22** was obtained. In contrast, an additional methyl group in the 3-position caused a dramatic increase of the yield: in the coupling reaction of **23** with a variety of allylic and homoallylic alcohols **2** and **3**, yields in the range of 70−80% were generally achieved. Blocking the crucial 3-position is obviously an important factor for preventing unwanted competing reactions.

Based on this encouraging and efficient entry to cyclopentenones **24** and **25** with an oxofunctionalized side-chain, we had a closer look at the ring closure reactions of these compounds. Potassium *tert*-butoxide was the base of choice to test intramolecular aldol and related reactions under moderate conditions (Scheme 4). For compound **25a** deprotonation at the α-acidic methyl group and subsequent 1,2-addition at the α,β-unsaturated ketone followed by condensation is the preferred reaction pathway. Dienone **26** was distinguished from its regioisomer **30** by chemical means: treatment with anisylmagnesium bromide gave a small amount of indene **31**, which was easy to identify by NMR spectroscopy and clearly derives from structure **26**. Surprisingly, under the same reaction conditions the ethyl-substituted homologue **25b** let to the formation of the 1,4-addition product **27** (Figure 1). The stereochemistry of this 6-



Scheme 3. Attaching a functionalized side-chain to α,β-unsaturated ketones

endo-trig cyclization was determined by the X-ray structure analysis of **27**.[7]



Scheme 4. Base-catalyzed annulation reactions of functionalized cyclopentenones

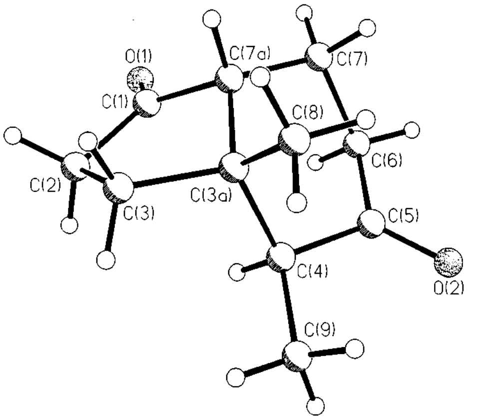
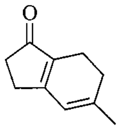
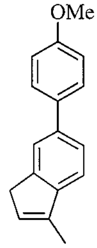


Figure 1. Crystal structure of dione **27**

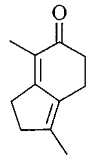
In order to achieve a rather high selectivity for product **27** the moderate reaction temperature of 22 °C is crucial.



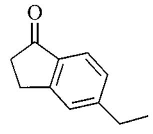
30



31



32

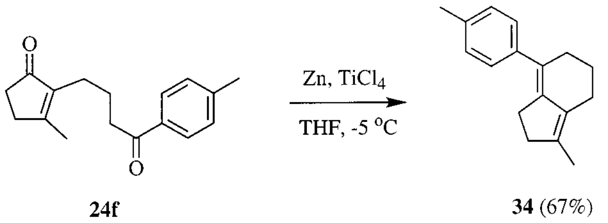


33

At reflux temperature a product mixture is obtained, from which a 50% yield of **27** and two minor by-products **32** (7%) and **33** (5%) were isolated. Compound **32** is, of course, a homologue of **26**, but indanone **33** derives from a third reaction pathway: deprotonation of the 3-methyl group of **25b** and subsequent intramolecular aldol condensation followed by an oxidative aromatization.

The transformation of **25d** was of special interest, because we anticipated that the intramolecular Michael addition to product **28** should be sterically disfavored: despite the formation of two contiguous quaternary centers this was, to our surprise, the preferred mode of reaction, giving rise to a 41:59 equilibrium between **25d** and **28** at room temperature.

The cyclization of substrates of type **24** proceeds similar to the reaction pathway to indanone **33**. Annulated cycloheptadienes **29** are isolated exclusively in moderate to good yields. In addition we tested the intramolecular McMurry reaction[8] with substrate **24f** and obtained the desired cyclization product **34**. In contrast, the related Pinacol formation from **24f** failed under various reaction conditions (Scheme 5).[9]



Scheme 5. Intramolecular McMurry reaction of **24f**

In summary, we have developed a short route from 2-iodocyclopentenones to various annulated ring systems, with a Heck reaction as key step, which formerly appeared unfeasible. The similarity of these ring systems to terpenoids demands the testing of further applications of this type of reaction sequence.

Experimental Section

General: M.p. (uncorrected): Reichert Thermovar. – IR: Perkin–Elmer 983. – UV: Perkin–Elmer 554. – NMR: Bruker DRX 500, Bruker WM 300. – ^{1}H NMR spectra (500 MHz or 300 MHz) were recorded in CDCl$_3$ with TMS as the internal standard; ^{13}C NMR spectra (125.8 MHz or 75.5 MHz) were measured with CDCl$_3$ as the solvent and the internal standard. – MS: MAT

311A (70 eV). − For analytical TLC precoated plastic sheets "POLYGRAM SIL G/UV254" from Macherey−Nagel & Co. were used. The iodoalkenones **15**, **20** and **23** were prepared according to published procedures.[11−13]

Synthesis of 2-Iodo-3-methylcyclohept-2-en-1-one (13): To a solution of 3-methylcyclohept-2-en-1-one[10] (1.55 g, 12.5 mmol) in pyridine/dichloromethane (1:1, 20 mL) was added a solution of iodine (12.7 g 50.0 mmol) in pyridine/dichloromethane (1:1, 60 mL) within 150 min. at room temperature under argon. After an additional 45 h of stirring at room temperature diethyl ether (150 mL) was added and the organic phase was washed successively with water (80 mL), 1 N HCl (3 × 80 mL), again with water (80 mL) and twice with an aqueous 20% $Na_2S_2O_3$ solution (60 mL). The organic phase was filtered through silica and concentrated. The crude product was purified by flash chromatography (silica, petroleum ether/methyl *tert*-butyl ether, 15:1) to give **13** (1.17 g, 37%) as a yellow oil. − IR (film): $\tilde{\nu}$ = 2937 cm^{-1} (m), 2864 (w), 1669 (s), 1586 (m), 1449 (m), 1419 (w), 1370 (w), 1313 (w), 1245 (m), 1233 (w), 1203 (w), 1161 (w), 1125 (w), 1033 (w), 1006 (w), 878 (w), 844 (w). − ^1H NMR (300 MHz): δ = 1.70−1.85 (m, 4 H), 2.32 (s, 3 H), 2.58−2.69 (m, 4 H). − ^{13}C NMR (75.5 MHz): δ = 21.2 (t), 23.8 (t), 34.3 (q), 34.5 (t), 39.0 (t), 106.0 (s), 160.3 (s), 199.8 (s). − MS (70 eV; 130 °C): *m*/*z* (%) = 251 (9), 250 (100) [M^+], 235 (28), 221 (21), 208 (26), 95 (51), 82 (25), 81 (19), 80 (25), 79 (18), 67 (50), 55 (34), 53 (34). − $C_8H_{11}IO$ (250.1): calcd. C 38.42, H 4.43; found C 38.56, H 4.37.

Palladium-Catalyzed Coupling Reactions of α-Iodo-α,β-unsaturated Ketones 1 (X = I) with the Allylic and Homoallylic Alcohols 2 and 3. − General Procedure: A mixture of 1 mmol of a vinyl iodide of type **1**, 2 mmol of unsaturated alcohols **2** or **3**, *N*,*N*-diisopropylethylamine (1.03 g, 8.00 mmol), LiCl (127 mg, 3.00 mmol), $Pd(OAc)_2$ (12.0 mg, 53 μmol), and dry DMF (10 mL) in a sealed tube (for convenience) was stirred under N_2 at 100 °C for 42−71 h. The reaction mixture was then diluted with 50 mL of water and extracted three times with 25 mL of ethyl acetate. The combined organic extract was reextracted with 30 mL of water, filtered through silica and concentrated. Excess starting material and volatile by-products were removed at 125 °C/0.3 mbar in a kugelrohr oven. The crude product mixture was fractionated by flash chromatography (silica gel; eluent: petroleum ether with b.p. 50−70 °C and methyl *tert*-butyl ether (3:1 to 15:1) and the isolated products were dried in vacuo or distilled with a kugelrohr apparatus.

Coupling Reaction of 2-Iodo-3-methylcyclohept-2-en-1-one (13) with 1-(4-Tolyl)but-3-en-1-ol (3f): Compounds **13** (250 mg, 1.00 mmol) and **3f** (324 mg, 2.00 mmol) were allowed to react for 71 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.80 (weak), 0.54 (**3f**), 0.49 (**14**), 0.09 (**13**). A mixture of petroleum ether and methyl *tert*-butyl ether (15:1) was used as eluent for the flash chromatography. The fraction with R_f = 0.49 was isolated and distilled in a kugelrohr oven at 200 °C/0.4 mbar to give 15 mg (5%) of 3-methyl-2-[4-(4-methylphenyl)-4-oxobutyl]cyclohept-2-en-1-one (**14**) as a yellow oil; with a fourfold excess of **3f**, double the amount of catalyst, a lower reaction temperature (60 °C) and a prolonged reaction time (95 h) the yield of **14** increased to 10%. − IR (film): $\tilde{\nu}$ = 2935 cm^{-1} (m), 2865 (m), 1678 (s), 1654 (s), 1606 (m), 1570 (w), 1451 (m), 1407 (m), 1373 (m), 1320 (w), 1294 (w), 1261 (m), 1232 (m), 1202 (w), 1180 (m), 979 (w), 811 (w). − ^1H NMR (300 MHz): δ = 1.63−1.83 (m, 6 H), 1.98 (s, 3 H), 2.32−2.38 (m, 4 H), 2.41 (s, 3 H), 2.50−2.54 (m, 2 H), 2.95 (t, *J* = 7.3 Hz, 2 H), 7.23−7.27 (m, 2 H), 7.83−7.87 (m, 2 H). − ^{13}C NMR (75.5 MHz): δ = 21.2 (t), 21.6 (q), 23.0 (q, CH_3), 23.9 (t), 23.9 (t), 28.6 (t), 34.4 (t), 38.3 (t), 41.8 (t), 128.2 (d), 129.3 (d), 134.7 (s), 138.1 (s), 143.6 (s), 150.6 (s), 200.0 (s), 206.6 (s). − MS (70 eV; 135 °C): *m*/*z* (%) = 285 (4), 284 (18) [M^+], 251 (11), 152 (12), 151 (100), 150 (19), 147 (43), 135 (12), 134 (59), 122 (11), 119 (96), 105 (14), 93 (10), 92 (10), 91 (51), 79 (12), 55 (11). − $C_{19}H_{24}O_2$ (284.4): calcd. C 80.24, H 8.51; found C 79.73, H 8.48. − HRMS: calcd. 284.1776; found 284.1772.

Coupling Reaction of (3*Z*)-3-Iodo-4-phenylbut-3-en-2-one (15) with 1-(4-Tolyl)but-3-en-1-ol (3f): Compounds **15**[11] (272 mg, 1.00 mmol) and **3f** (324 mg, 2.00 mmol) were allowed to react for 44 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl (4:1), silica gel]: R_f = 0.76, 0.57 (weak), 0.49 (**16**), 0.40. A mixture of petroleum ether and methyl *tert*-butyl ether (3:1) was used as eluent for the flash chromatography. The fraction with R_f = 0.49 was isolated and distilled in the kugelrohr oven at 225 °C/0.3 mbar to give 102 mg (33%) of (5*E*)-5-benzylidene-1-(4-methylphenyl)heptane-1,6-dione (**16**) as an orange oil. − IR (film): $\tilde{\nu}$ = 3028 cm^{-1} (w), 2930 (m), 1663 (s), 1606 (m), 1571 (w), 1491 (w), 1446 (m), 1407 (m), 1353 (m), 1322 (w), 1263 (m), 1230 (m), 1215 (m), 1181 (m), 1154 (w), 1019 (w), 808 (w), 760 (w), 696 (m). − ^1H NMR (300 MHz): δ = 1.85−1.95 (m, 2 H), 2.40 (s, 3 H), 2.46 (s, 3 H), 2.57−2.62 (m, 2 H), 2.99 (t, *J* = 7.3 Hz, 2 H), 7.23−7.26 (m, 2 H), 7.29−7.47 (m, 5 H), 7.82−7.86 (m, 2 H). − ^{13}C NMR (75.5 MHz): δ = 21.6 (q), 23.8 (t), 25.9 (t), 26.1 (q), 38.5 (t), 128.2 (d), 128.7 (d), 128.7 (d), 129.2 (d), 129.3 (d), 134.6 (s), 135.6 (s), 140.4 (d), 142.2 (s), 143.7 (s), 199.6 (s), 200.1 (s). − MS (70 eV; 50 °C): *m*/*z* (%) = 307 (5), 306 (22) [M^+], 288 (16), 215 (11), 173 (14), 172 (23), 169 (11), 135 (15), 134 (98), 129 (40), 128 (14), 119 (100), 115 (14), 105 (14), 92 (15), 91 (58), 77 (14), 65 (16), 43 (66). − $C_{21}H_{22}O_2$ (306.4): calcd. C 82.32, H 7.24; found C 82.40, H 7.16.

Coupling Reaction of (3*Z*)-3-Iodo-4-phenylbut-3-en-2-one (15) with But-3-en-2-ol (2a): Compounds **15**[11] (272 mg, 1.00 mmol) and **2a** (144 mg, 2.00 mmol) were allowed to react for 43 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.77, 0.66, 0.57 (**18**+**19**), 0.40 (**17**). A mixture of petroleum ether and methyl *tert*-butyl ether (5:1) was used as eluent for the flash chromatography.

The first fraction with R_f = 0.57 was distilled in a kugelrohr oven at 160 °C/0.4 mbar to give 60 mg (30%) of a 7:3 mixture of the regioisomers **18** and **19** as a yellow oil. − IR (film): $\tilde{\nu}$ = 3024 cm^{-1} (w), 2955 (w), 2903 (w), 2848 (w), 1663 (s), 1598 (m), 1491 (w), 1443 (m), 1391 (w), 1337 (w), 1316 (w), 1298 (w), 1275 (w), 1262 (m), 1228 (m), 1205 (w), 1175 (w), 1155 (w), 1025 (w), 1005 (w), 876 (w), 767 (m), 735 (m), 699 (m). − ^1H NMR (300 MHz): signals of (4*E*)-4-benzylidene-3-methylcyclohex-2-en-1-one (**18**): δ = 2.19 (s, 3 H), 2.46 (t, *J* = 7.0 Hz, 2 H), 2.96−3.02 (m, 2 H), 5.99 (s, 1 H), 6.93 (s, 1 H), 7.27−7.42 (m, 5 H); signals of (6*E*)-6-benzylidene-3-methylcyclohex-2-en-1-one (**19**): δ = 2.00 (s, 3 H), 2.34 (t, *J* = 6.0 Hz, 2 H), 2.96−3.02 (m, 2 H), 6.10 (s, 1 H), 7.27−7.42 (m, 5 H), 7.59 (s, 1 H); the isomers were distinguished by a NOESY spectrum of the mixture, especially by the positive NOE effect between the methyl group and the benzyl-H of isomer **18**. − ^{13}C NMR (75.5 MHz): signals of **18**: δ = 20.7 (q), 26.7 (t), 37.1 (t), 127.6 (d), 127.7 (d), 128.4 (d), 129.2 (d), 131.2 (d), 135.8 (s), 136.5 (s), 155.5 (s), 199.0 (s); signals of **19**: δ = 24.4 (q), 26.2 (t), 30.6 (t), 127.4 (d), 128.1 (d), 128.3 (d), 129.7 (d), 134.2 (s), 134.3 (d), 135.9 (s), 161.3 (s), 188.6 (s). − MS (70 eV; 130 °C): *m*/*z* (%) = 199 (18), 198 (100) [M^+], 197 (66), 183 (17), 155 (39), 153 (11), 142 (13), 141 (18), 129 (10), 128 (13), 115 (22), 91 (26), 77 (10). − $C_{14}H_{14}O$ (198.3): calcd. C 84.81, H 7.12; found C 84.87, H 7.16.

The second fraction with R_f = 0.40 was distilled in the kugelrohr oven at 200 °C/0.4 mbar to give 37 mg (17%) of (3*E*)-3-benzylideneheptane-2,6-dione (**17**) as a yellow oil. − IR (film): $\tilde{\nu}$ = 3058 cm^{-1} (w), 3001 (w), 2931 (w), 1711 (s), 1661 (s), 1623 (m), 1491 (w), 1444 (m), 1385 (m), 1353 (m), 1320 (w), 1276 (w), 1244 (m), 1216 (m), 1162 (m), 1088 (w), 1026 (w), 971 (w), 950 (w), 927 (w), 748 (m), 697 (m). − ^{1}H NMR (300 MHz): δ = 2.13 (s, 3 H), 2.46 (s, 3 H), 2.58−2.61 (m, 2 H), 2.76−2.79 (m, 2 H), 7.35−7.43 (m, 5 H), 7.54 (s, 1 H). − ^{13}C NMR (75.5 MHz): δ = 20.9 (t), 26.0 (q), 29.7 (q), 42.6 (t), 128.8 (d), 128.9 (d), 129.1 (d), 135.3 (s), 141.0 (d), 141.1 (s), 200.0 (s), 207.9 (s). − MS (70 eV; 130 °C): *m/z* (%) = 216 (5) [M$^+$], 173 (24), 159 (21), 158 (21), 155 (28), 131 (13), 129 (21), 115 (15), 91 (18), 43 (100). − $C_{14}H_{16}O_2$ (216.3): calcd. C 77.75, H 7.46; found C 77.85, H 7.54.

In a control experiment with a prolonged reaction time of 73 h a 40% yield of a mixture of **18** and **19** was obtained, again in the ratio 7:3; the primary product **17** was not detected in this case.

Coupling Reaction of 2-Iodo-2-cyclopent-2-en-1-one (20) with 1-(4-Tolyl)but-3-en-1-ol (3f): Compounds **20**[12] (208 mg, 1.00 mmol) and **3f** (324 mg, 2.00 mmol) were allowed to react for 46 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.86, 0.77 (both weak), 0.57 (**3f**), 0.23 (**21**). The fraction with R_f = 0.23 was isolated by flash chromatography (also petroleum ether/ethyl acetate, 4:1) and dried in vacuo to give 60 mg (25%) of 2-[4-(4-methylphenyl)-4-oxobutyl]cyclopent-2-en-1-one (**21**) as colorless crystals with m.p. 92 °C (from petroleum ether). − IR (KBr): $\tilde{\nu}$ = 3043 cm^{-1} (w), 2938 (m), 2900 (w), 2865 (w), 1689 (s), 1674 (s), 1630 (w), 1603 (m), 1571 (w), 1455 (w), 1441 (w), 1408 (w), 1365 (m), 1305 (w), 1296 (w), 1268 (w), 1240 (m), 1199 (m), 1179 (m), 1061 (w), 1026 (w), 1000 (w), 992 (w), 982 (w), 814 (w), 789 (m), 740 (m). − ^{1}H NMR (300 MHz): δ = 1.80−1.91 (m, 2 H), 2.16−2.22 (m, 2 H), 2.30−2.31 (m, 2 H), 2.32 (s, 3 H), 2.47−2.51 (m, 2 H), 2.89 (t, *J* = 7.3 Hz, 2 H), 7.15−7.18 (m, 2 H), 7.28−7.31 (m, 1 H), 7.74−7.78 (m, 2 H). − ^{13}C NMR (75.5 MHz): δ = 21.6 (q), 22.4 (t), 24.3 (t), 26.5 (t), 34.5 (t), 37.9 (t), 128.1 (d), 129.2 (d), 134.5 (s), 143.7 (s), 145.8 (s), 157.8 (d), 199.4 (s), 209.7 (s). − MS (70 eV; 95 °C): *m/z* (%) = 242 (8) [M$^+$], 158 (23), 147 (27), 134 (71), 119 (100), 92 (10), 91 (44), 65 (18), 55 (15). − $C_{16}H_{18}O_2$ (242.3): calcd. C 79.31, H 7.49; found C 79.37, H 7.47.

Coupling Reaction of 2-Iodo-2-cyclopent-2-en-1-one (20) with But-3-en-2-ol (2a): Compounds **20**[12] (208 mg, 1.00 mmol) and **2a** (144 mg, 2.00 mmol) were allowed to react for 43 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.54 (weak), 0.14 (**22**). The fraction with R_f = 0.14 was isolated by flash chromatography (petroleum ether/methyl *tert*-butyl ether, 2:1) and further purified by distillation in the kugelrohr apparatus at 150 °C/0.3 mbar to give 40 mg (26%) of 2-(3-oxobutyl)cyclopent-2-en-1-one (**22**) as a colorless oil. − IR (film): $\tilde{\nu}$ = 2925 cm^{-1} (m), 1700 (s), 1630 (m), 1439 (m), 1357 (m), 1298 (w), 1251 (m), 1200 (w), 1163 (m), 1073 (w), 1038 (w), 1002 (m), 792 (w). − ^{1}H NMR (300 MHz): δ = 2.14 (s, 3 H), 2.38−2.41 (m, 2 H), 2.43−2.50 (m, 2 H), 2.54−2.59 (m, 2 H), 2.66 (t, *J* = 7.2 Hz, 2 H), 7.34−7.36 (m, 1 H). − ^{13}C NMR (75.5 MHz): δ = 19.3 (t), 26.5 (t), 29.8 (q), 34.6 (t), 41.3 (t), 144.8 (s), 158.6 (d), 207.6 (s), 209.7 (s). − MS (70 eV; 95 °C): *m/z* (%) = 153 (7), 152 (54) [M$^+$], 138 (19), 110 (46), 109 (100) [M$^+$ − COCH$_3$], 95 (29), 82 (84), 81 (35), 79 (24), 68 (11), 67 (34), 54 (12), 53 (15), 43 (75), 41 (21), 39 (19). − $C_9H_{12}O_2$ (152.2): calcd. C 71.03, H 7.95; found C 70.96, H 7.94.

Coupling Reaction of 2-Iodo-3-methylcyclopent-2-en-1-one (23) with Pent-4-en-2-ol (3a): Compounds **23**[13] (222 mg, 1.00 mmol) and **3a** (172 mg, 2.00 mmol) were allowed to react for 44 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.23, 0.17 (both weak), 0.09 (**24a**). The fraction with R_f = 0.09 was isolated by flash chromatography (petroleum ether/methyl *tert*-butyl ether, 2:1) and further purified by distillation in the kugelrohr apparatus at 125 °C/0.4 mbar to give 104 mg (58%) of 3-methyl-2-(4-oxopentyl)cyclopent-2-en-1-one (**24a**) as a colorless oil. − IR (film): $\tilde{\nu}$ = 2918 cm^{-1} (m), 1696 (s), 1643 (s), 1441 (m), 1408 (m), 1385 (m), 1357 (m), 1302 (w), 1179 (w), 1160 (m), 1074 (w). − ^{1}H NMR (300 MHz): δ = 1.61−1.71 (m, 2 H), 2.07 (s, 3 H), 2.13 (s, 3 H), 2.16−2.21 (m, 2 H), 2.35−2.44 (m, 4 H), 2.48−2.51 (m, 2 H). − ^{13}C NMR (75.5 MHz): δ = 17.2 (q), 22.2 (t), 22.5 (t), 29.9 (q), 31.6 (t), 34.3 (t), 43.2 (t), 139.9 (s), 171.0 (s), 208.7 (s), 209.5 (s). − MS (70 eV; 85 °C): *m/z* (%) = 181 (3), 180 (18) [M$^+$], 137 (20), 124 (10), 123 (100), 110 (46), 109 (11), 95 (14), 81 (10), 79 (15), 67 (17), 43 (28), 41 (10). − $C_{11}H_{16}O_2$ (180.3): calcd. C 73.30, H 8.95; found C 73.20, H 8.91.

Coupling Reaction of 2-Iodo-3-methylcyclopent-2-en-1-one (23) with Hept-1-en-4-ol (3c): Compounds **23**[13] (222 mg, 1.00 mmol) and **3c** (228 mg, 2.00 mmol) were allowed to react for 45 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.63, 0.29 (both weak), 0.23 (**24c**). The fraction with R_f = 0.23 was isolated by flash chromatography (also petroleum ether/ethyl acetate, 4:1) and further purified by distillation in the kugelrohr apparatus at 150 °C/0.3 mbar to give 158 mg (76%) of 3-methyl-2-(4-oxoheptyl)cyclopent-2-en-1-one (**24c**) as a slightly yellow oil. − IR (film): $\tilde{\nu}$ = 2961 cm^{-1} (m), 2935 (m), 2874 (m), 1782 (w), 1696 (s), 1644 (m), 1443 (w), 1409 (w), 1384 (m), 1302 (w), 1178 (w), 1127 (w), 1074 (w). − ^{1}H NMR (300 MHz): δ = 0.90 (t, *J* = 7.4 Hz, 3 H), 1.52−1.70 (m, 4 H), 2.07 (s, 3 H), 2.18 (t, *J* = 7.7 Hz, 2 H), 2.35−2.41 (m, 6 H), 2.48−2.51 (m, 2 H). − ^{13}C NMR (75.5 MHz): δ = 13.8 (q), 17.6 (t), 17.9 (q), 22.3 (t), 22.5 (t), 31.6 (t), 34.3 (t), 42.3 (t), 44.7 (t), 140.0 (s), 171.0 (s), 209.6 (s), 211.0 (s). − MS (70 eV; 85 °C): *m/z* (%) = 208 (17) [M$^+$], 137 (24), 123 (100), 110 (47), 95 (10), 86 (24), 84 (38), 79 (10), 67 (15), 43 (16), 41 (14), 40 (35). − $C_{13}H_{20}O_2$ (208.3): calcd. C 74.96, H 9.68; found C 74.86, H 9.70.

Coupling Reaction of 2-Iodo-3-methylcyclopent-2-en-1-one (23) with 2,2-Dimethyl-5-hex-1-en-3-ol (3e): Compounds **23**[13] (222 mg, 1.00 mmol) and **3e** (256 mg, 2.00 mmol) were allowed to react for 43 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.80, 0.63, 0.43 (all weak), 0.29 (**24e**). The fraction with R_f = 0.29 was isolated by flash chromatography (petroleum ether/ethyl acetate, 5:1) and further purified by distillation in the kugelrohr apparatus at 150 °C/0.3 mbar to give 167 mg (75%) of 3-methyl-2-(5,5-dimethyl-4-oxohex-1-yl)cyclopent-2-en-1-one (**24e**) as a slightly yellow oil. − IR (film): $\tilde{\nu}$ = 2966 cm^{-1} (m), 2870 (m), 1699 (s), 1645 (m), 1478 (m), 1443 (m), 1408 (w), 1385 (m), 1366 (m), 1306 (w), 1225 (w), 1179 (w), 1100 (w), 1074 (w), 1000 (w). − ^{1}H NMR (300 MHz): δ = 1.13 (s, 9 H), 1.56−1.66 (m, 2 H), 2.08 (s, 3 H), 2.13−2.18 (m, 2 H), 2.35−2.39 (m, 2 H), 2.48−2.58 (m, 4 H). − ^{13}C NMR (75.5 MHz): δ = 17.3 (q), 22.3 (t), 22.7 (t), 26.5 (q), 31.6 (t), 34.3 (t), 36.2 (t), 44.1 (s), 140.2 (s), 170.9 (s), 209.5 (s), 215.8 (s). − MS (70 eV; 85 °C): *m/z* (%) = 222 (11) [M$^+$], 166 (12), 165 (100), 138 (13), 137 (72), 123 (67), 119 (36), 110 (33), 109 (16), 95 (11), 81 (12), 79 (14), 67 (21), 57 (23), 43 (13), 41 (32), 40 (59), 39 (11). − $C_{14}H_{22}O_2$ (222.3): calcd. C 75.63, H 9.97; found C 75.50, H 9.92.

Coupling Reaction of 2-Iodo-3-methylcyclopent-2-en-1-one (23) with 1-(4-Tolyl)but-3-en-1-ol (3f): Compounds **23**[13] (222 mg, 1.00 mmol) and **3f** (324 mg, 2.00 mmol) were allowed to react for 42 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.86, 0.74 (both weak), 0.54 (**3f**), 0.20 (**24f**). The fraction with R_f = 0.20 was isolated by flash chromatography (also petroleum ether/ethyl acetate, 4:1) and dried in vacuo to give 202 mg (79%) of 3-methyl-2-[4-(4-methylphenyl)-4-oxobutyl]cyclopent-2-en-1-one (**24f**) as colorless crystals with m.p. 45 °C (from petroleum ether). − IR (KBr): $\tilde{\nu}$ = 3043 cm^{-1} (w), 2915 (m), 1690 (s), 1677 (s), 1642 (m), 1606 (m), 1449 (w), 1404 (w), 1383 (m), 1358 (m), 1339 (w), 1228 (m), 1205 (w), 1182 (w), 1168 (w), 809 (w). − ^{1}H NMR (300 MHz): δ = 1.78−1.87 (m, 2 H), 2.07 (s, 3 H), 2.28 (t, *J* = 7.7 Hz, 2 H), 2.34−2.37 (m, 2 H), 2.40 (s, 3 H), 2.47−2.50 (m, 2 H), 2.94 (t, *J* = 7.2 Hz, 2 H), 7.23−7.27 (m, 2 H), 7.82−7.85 (m, 2 H). − ^{13}C NMR (75.5 MHz): δ = 17.3 (q), 21.6 (q), 22.4 (t), 23.0 (t), 31.6 (t), 34.3 (t), 38.0 (t), 128.1 (d), 129.3 (d), 134.6 (s), 140.1 (s), 143.7 (s), 171.0 (s), 199.7 (s), 209.5 (s). − MS (70 eV; 85 °C): *m/z* (%) = 256 (20) [M$^+$], 238 (23), 147 (67), 137 (11), 134 (79), 123 (75), 119 (100), 110 (12), 92 (12), 91 (58), 65 (20), 55 (25), 40 (16). − $C_{17}H_{20}O_2$ (256.4): calcd. C 79.65, H 7.86; found C 79.62, H 7.87.

Coupling Reaction of 2-iodo-3-methylcyclopent-2-en-1-one (23) with But-3-en-2-ol (2a): Compounds **23**[13] (222 mg, 1.00 mmol) and **2a** (144 mg, 2.00 mmol) were allowed to react for 47 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.74, 0.63 (both weak), 0.14 (**25a**). The fraction with R_f = 0.14 was isolated by flash chromatography (petroleum ether/methyl *tert*-butyl ether, 2:1) and further purified by distillation in the kugelrohr apparatus at 150 °C/0.3 mbar to give 91 mg (55%) of 3-methyl-2-(3-oxo-1-butyl)cyclopent-2-en-1-one (**25a**) as colorless crystals with m.p. 43 °C (from dichloromethane/petroleum ether, ref.:[14] oil with bp. 76 °C/0.01 Torr). − IR (KBr): $\tilde{\nu}$ = 2951 cm^{-1} (w), 2919 (w), 1708 (s), 1689 (s), 1641 (m), 1440 (w), 1415 (w), 1375 (m), 1356 (m), 1338 (m), 1305 (w), 1274 (m), 1177 (m), 1164 (m), 1073 (w). − ^{1}H NMR (300 MHz): δ = 2.10 (s, 3 H), 2.12 (s, 3 H), 2.33−2.36 (m, 2 H), 2.43 (t, *J* = 7.3 Hz, 2 H), 2.49−2.52 (m, 2 H), 2.62 (t, *J* = 7.3 Hz, 2 H). − ^{13}C NMR (75.5 MHz): δ = 17.2 (q), 17.5 (t), 29.7 (q), 31.6 (t), 34.2 (t), 41.1 (t), 138.7 (s), 171.3 (s), 207.9 (s), 209.5 (s). − MS (70 eV; 120 °C): *m/z* (%) = 167 (4), 166 (32) [M$^+$], 124 (27), 123 (100), 109 (14), 95 (15), 81 (18), 79 (12), 67 (17), 43 (30). − $C_{10}H_{14}O_2$ (166.22): calcd. C 72.26, H 8.49; found C 72.20, H 8.50.

Coupling Reaction of 2-Iodo-3-methylcyclopent-2-en-1-one (23) with Pent-1-en-3-ol (2b): Compounds **23**[13] (222 mg, 1.00 mmol) and **2b** (173 mg, 2.00 mmol) were allowed to react for 43 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.54 (weak), 0.17 (**25b**). The fraction with R_f = 0.17 was isolated by flash chromatography (petroleum ether/methyl *tert*-butyl ether, 2:1) and further purified by distillation in the kugelrohr apparatus at 125 °C/0.4 mbar to give 138 mg (77%) of 3-methyl-2-(3-oxo-1-pentyl)cyclopent-2-en-1-one (**25b**) as a colorless oil. − IR (KBr): $\tilde{\nu}$ = 2975 cm^{-1} (m), 2916 (m), 1696 (s), 1645 (m), 1442 (w), 1411 (w), 1384 (m), 1348 (w), 1303 (w), 1268 (w), 1177 (w), 1115 (w), 1072 (w). − ^{1}H NMR (300 MHz): δ = 1.03 (t, *J* = 7.3 Hz, 3 H), 2.09 (s, 3 H), 2.33−2.51 (m, 8 H), 2.59 (t, *J* = 6.9 Hz, 2 H). − ^{13}C NMR (75.5 MHz): δ = 7.8 (q), 17.3 (q), 17.7 (t), 31.7 (t), 34.3 (t), 35.9 (t), 39.8 (t), 139.0 (s), 171.3 (s), 209.6 (s), 210.8 (s). − MS (70 eV; 135 °C): *m/z* (%) = 181 (6), 180 (46) [M$^+$], 151 (18), 124 (35), 123 (100), 109 (14), 95 (13), 81 (16), 79 (11), 67 (14), 57 (17). − $C_{11}H_{16}O_2$ (180.3): calcd. C 73.30, H 8.95; found C 73.20, H 8.96.

Coupling Reaction of 2-Iodo-3-methylcyclopent-2-en-1-one (23) with 4-Methylpent-1-en-3-ol (2d): Compounds **23**[13] (222 mg, 1.00 mmol) and **2d** (173 mg, 2.00 mmol) were allowed to react for 43 h according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.66 (weak), 0.29 (**25d**), 0.11 (weak). The fraction with R_f = 0.29 was isolated by flash chromatography (petroleum ether/methyl *tert*-butyl ether, 2:1) and further purified by distillation in the kugelrohr apparatus at 150 °C/0.4 mbar to give 149 mg (77%) of 3-methyl-2-(4-methyl-3-oxopent-1-yl)cyclopent-2-en-1-one (**25d**) as a colorless oil. − IR (KBr): $\tilde{\nu}$ = 2969 cm^{-1} (m), 2925 (m), 2875 (w), 1696 (s), 1645 (m), 1466 (w), 1443 (w), 1408 (w), 1384 (m), 1347 (w), 1303 (w), 1177 (w), 1074 (w). − ^{1}H NMR (300 MHz): δ = 1.06 (d, *J* = 7.0 Hz, 6 H), 2.10 (s, 3 H), 2.33−2.35 (m, 2 H), 2.43 (t, *J* = 7.3 Hz, 2 H), 2.48−2.51 (m, 2 H), 2.56 (q, *J* = 7.0 Hz, 1 H), 2.64 (t, *J* = 7.3 Hz, 2 H). − ^{13}C NMR (75.5 MHz): δ = 17.3 (q), 17.7 (t), 18.2 (q), 31.7 (t), 34.3 (t), 37.8 (t), 40.9 (d), 139.0 (s, C-2), 171.3 (s), 209.7 (s), 214.0 (s). − MS (70 eV; 130 °C): *m/z* (%) = 195 (4), 194 (24), 151 (84), 124 (17), 123 (100), 109 (12), 95 (12), 81 (16), 79 (11), 70 (14), 43 (23), 41 (15). − $C_{12}H_{18}O_2$ (194.3): calcd. C 74.19, H 9.34; found C 74.16, H 9.40.

Base-Catalyzed Cyclization Reactions of Dicarbonyl Compounds 24 and 25. − General Procedure: Dicarbonyl compound **24** or **25** (0.37−1.34 mmol) and 2 equiv. of potassium *tert*-butoxide (0.74−2.68 mmol) in 10−45 mL dry *tert*-butyl alcohol were stirred under argon for between 30 min. and 4 h at room temperature (22 °C) or 15−90 min. at reflux temperature (82 °C). After addition of 50−150 mL of water, the *tert*-butyl alcohol was distilled off on a rotary evaporator and the remaining aqueous layer extracted three times with 30 mL of ethyl acetate. The combined organic layer was filtered through a small pad of silica and concentrated to give an oily crude product, which was fractionated by flash chromatography [silica gel, with petroleum ether (b.p. 50−70 °C) and methyl *tert*-butyl ether (2:1 to 8:1) as eluent]. The isolated products were dried in vacuo or distilled in a kugelrohr apparatus.

Cyclization of 25a; 1-Methyl-2,3,6,7-tetrahydro-5*H*-inden-5-one (26): Compound **25a** (90 mg, 0.54 mmol) in 15 mL of dry *tert*-butyl alcohol was treated with potassium *tert*-butoxide for 50 min. at 22 °C according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.83, 0.63 (both weak), 0.37 (**26**). The fraction with R_f = 0.37 was isolated by flash chromatography [petroleum ether/methyl *tert*-butyl ether (1:1 as eluent] and distilled in the kugelrohr oven at 150 °C/0.1 mbar to give 60 mg (75%) of **26** as a slightly yellow oil.[14] For comparison this reaction was performed at reflux temperature (20 min.); as a result the yield of **26** decreased to 68%. − IR (film): $\tilde{\nu}$ = 2909 cm^{-1} (w), 2845 (w), 1738 (w), 1710 (w), 1653 (s), 1634 (m), 1602 (m), 1437 (w), 1394 (w), 1282 (w), 1253 (w), 1215 (m), 1198 (w), 845 (w). − ^{1}H NMR (300 MHz): δ = 1.92 (s, 3 H, CH$_3$), 2.42−2.47 (m, 2 H), 2.54−2.59 (m, 2 H), 2.62−2.70 (m, 4 H), 5.77 (s, 1 H). − ^{13}C NMR (75.5 MHz): δ = 15.3 (q), 20.5 (t), 28.6 (t), 35.5 (t), 36.6 (t), 116.3 (d), 133.7 (s), 151.1 (s), 172.1 (s), 198.8 (s). − MS (70 eV; 130 °C): *m/z* (%) = 149 (13), 148 (100) [M$^+$], 133 (50), 120 (17), 119 (15), 106 (28), 105 (47), 92 (17), 91 (40), 85 (17), 79 (16), 77 (17), 41 (17). − $C_{10}H_{12}O$ (148.2): calcd. C 81.04, H 8.16; found C 80.96, H 8.13.

For the chemical proof of its structure 110 mg (0.74 mmol) of **26** was treated with an excess amount of preformed 4-anisylmagnesium bromide (approximately 2 mmol) in 16 mL THF for 2 h at room temperature. After addition of 50 mL of diethyl ether and 50 mL of saturated aqueous ammonium chloride solution the water layer was extracted twice with 30 mL of diethyl ether and the combined organic layer was concentrated on a rotary evaporator. The residue was distilled in the kugelrohr apparatus at 230 °C/0.4 mbar. TLC [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.83, 0.77, 0.34. The fraction with R_f = 0.83 was isolated by flash chromatography (petroleum ether/dichloromethane, 3:1) and crystallized from petroleum ether/dichloromethane to give 14 mg (6%) of 6-(4-methoxyphenyl)-3-methyl-1*H*-indene (**31**) as colorless crystals with m.p. 112 °C. − ^{1}H NMR (500 MHz): δ = 2.19 (dd, *J* = 3.8, 2.2 Hz, 3 H), 3.37 (t, *J* = 2.1 Hz, 2 H), 3.85 (s, 3 H), 6.21 (dd, *J* = 3.4, 1.9 Hz, 1 H), 6.96−6.99 (m, 2 H), 7.37 (d, *J* = 7.8 Hz, 1 H), 7.50 (dd, *J* = 7.8, 1.6 Hz, 1 H), 7.54−7.57 (m, 2 H), 7.64 (dd, *J* = 1.6, 0.7 Hz, 1 H). − ^{13}C NMR (125 MHz): δ = 13.1 (q), 37.8 (t), 55.4 (q), 114.2 (d), 119.0 (d), 122.2 (d), 124.9 (d), 128.2 (d), 128.9 (d), 134.5 (s), 137.4 (s), 139.8 (s), 144.9 (s), 145.1 (s), 158.9 (s). − MS (70 eV; 90 °C): *m*/*z* (%) = 238 (12), 237 (20), 236 (100) [M$^+$], 223 (12), 221 (43), 178 (19). − HRMS: calcd. for $C_{17}H_{16}O$: 236.1201; found 236.1181

Cyclization of 25b at 22 °C; (3a*R,4*R**,7a*S**)-2,3,3a,6,7,7a-Hexahydro-3a,4-dimethylindene-1,5(4*H*)-dione (27):** Compound **25b** (100 mg, 0.56 mmol) in 15 mL of dry *tert*-butyl alcohol was reacted with potassium *tert*-butoxide for 30 min. at 22 °C according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.31 (**27**), 0.20, 0.14. The fraction with R_f = 0.31 was isolated by flash chromatography [petroleum ether/methyl *tert*-butyl ether (4:1) as eluent] and crystallized from petroleum ether to give 70 mg (70%) of **27** as colorless crystals with m.p. 76 °C. − IR (film): $\tilde{\nu}$ = 2971 cm^{-1} (m), 2954 (m), 2880 (w), 1730 (s), 1704 (s), 1467 (w), 1449 (w), 1384 (w), 1353 (w), 1344 (w), 1326 (w), 1301 (w), 1290 (w), 1257 (w), 1114 (w), 1098 (w), 1052 (w). − ^{1}H NMR (300 MHz): δ = 1.00 (d, *J* = 6.7 Hz, 3 H, 9-H), 1.05 (s, 3 H, 8-H), 1.66−1.74 (m, 1 H, 3-H$_a$), 1.82−1.90 (m, 1 H, 7-H), 2.10−2.16 (m, 1 H, 3-H$_b$), 2.11−2.14 (m, 1 H, 7a-H), 2.17−2.27 (m, 3 H, 4-H, 6-H), 2.33−2.41 (m, 1 H, 2-H$_b$), 2.45−2.52 (m, 2 H, 2-H$_a$, 7-H). − ^{13}C NMR (75.5 MHz): δ = 8.3 (q, C-9), 20.8 (t, C-7), 21.4 (q, C-8), 31.8 (t, C-3), 34.4 (t, C-2), 38.1 (t, C-6), 47.5 (d, C-4), 47.9 (s, C-3a), 57.1 (d, C-7a), 212.2 (s), 217.5 (s). − MS (70 eV; 130 °C): *m*/*z* (%) = 181 (17), 180 (100) [M$^+$], 136 (45), 124 (21), 123 (37), 120 (22), 112 (55), 110 (20), 109 (25), 96 (29), 95 (22), 93 (35), 84 (19), 82 (26), 81 (22), 70 (23), 69 (57), 67 (31), 55 (36), 41 (40). − $C_{11}H_{16}O_2$ (180.3): calcd. C 73.30, H 8.95; found C 73.33, H 8.99.

X-ray Structure Analysis of 27:[7] Siemens P4RA four-circle diffractometer, Mo-K_α radiation (λ = 0.71073 Å), graphite monochromator, rotating anode generator, scintillation counter, 150 K, empirical absorption corrections, SHELXL-97 programs, direct methods, least-squares refinements on F^2, one scaling factor, one isotropic extinction parameter.

Crystal Data: Monoclinic, space group $P2_1/c$, a = 10.087(2), b = 7.114(1), c = 13.926(2) Å, β = 95.18(2)°, V = 995.2 Å^3, Z = 4, ρ = 1.203 g·cm^{-3}, λ (Mo-K_α) = 0.081 mm^{-1}, transmission range 0.881−0.848, crystal dimensions ca. 0.67 × 0.24 × 0.22 mm, ω-scan, $2\theta_{max}$ = 54°, 2161 independent reflections, R (R_w) = 0.0404 (0.1057) for 1883 observed reflections [$I > 2\sigma(I)$], 120 variables, all heavy atoms anisotropic, H atoms at idealized positions.

A single crystal of the title compound was mounted on top of a glass capillary with silicone grease and cooled down to 150 K with a cold nitrogen stream of the cooling device of a Siemens P4RA four-circle diffractometer equipped with a rotating anode tube and a graphite monochromator. Accurate cell dimensions were determined at 150 K from the setting angles of 18 centered reflections with $20 < 2\theta < 30°$. Integrated intensities were collected by the ω scan technique with scan rates varying from 6 to 30 °/min and a total scan range of 1.0°. During data collection, the intensity of a standard reflection, monitored every 199 reflections, as well as the intensity profiles indicated stable measuring conditions. The intensity data were corrected for Lorentz, polarization and absorption effects. The structure was solved by direct methods and subsequent difference Fourier synthesis in the monoclinic space group $P2_1/c$. After anisotropic refinement of the heavy atom framework (SHELXL-97), H atoms were added on idealized positions. One common isotropic temperature factor was refined for the otherwise riding H atoms.

Cyclization of 25b at 82 °C: Compound **25b** (240 mg, 1.34 mmol) in 45 mL of dry *tert*-butyl alcohol was reacted with potassium *tert*-butoxide for 15 min. at 82 °C according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.57 (**33**), 0.43 (**32**), 0.31 (**27**), 0.23 (weak), 0.14 (**25b**). The crude product was fractionated by flash chromatography [petroleum ether/dichloromethane (2:1) as eluent].

First fraction: 10 mg (5%) of 5-ethylindan-1-one (**33**) as a yellow oil, whose NMR spectra were in agreement with reported data.[16] − ^{1}H NMR (300 MHz): δ = 1.27 (t, *J* = 7.6 Hz, 3 H), 2.67−2.69 (m, 2 H, 3-H), 2.73 (q, *J* = 7.6 Hz, 2 H), 3.11 (t, *J* = 5.9 Hz, 2 H, 2-H), 7.21 (dt, *J* = 7.9, 0.6 Hz, 1 H, 6-H), 7.30 (dd, *J* = 1.5, 0.6 Hz, 1 H, 4-H), 7.68 (d, *J* = 7.9 Hz, 1 H, 7-H). − ^{13}C NMR (75.5 MHz): δ = 15.4 (q), 25.7 (t), 29.3 (t), 36.4 (t), 123.7 (d), 125.8 (d), 127.5 (d), 135.0 (s), 152.0 (s), 155.8 (s), 206.7 (s, C-1).

Second fraction: 15 mg (7%) of 1,4-dimethyl-2,3,6,7-tetrahydro-5*H*-inden-5-one (**32**) as a yellow oil. − ^{1}H NMR (500 MHz): δ = 1.77 (s, 3 H, CH$_3$), 1.88 (s, 3 H, CH$_3$), 2.46 (t, *J* = 7.7 Hz, 2 H), 2.54−2.56 (m, 2 H), 2.59−2.64 (m, 4 H). − ^{13}C NMR (125 MHz): δ = 11.3 (q, CH$_3$), 15.0 (q, CH$_3$), 20.6 (t), 28.0 (t), 35.7 (t), 36.5 (t), 123.0 (s), 133.6 (s), 147.9 (s), 166.7 (s), 198.4 (s, C-5).

Third fraction: 120 mg (50%) of dione **27**.

Fourth fraction: 21 mg (9%) of recovered starting material **25b**.

Cyclization of 25d at 22 °C; (3a*R,7a*R**)-2,3,3a,6,7,7a-Hexahydro-3a,4,4-trimethylindene-1,5(4H)-dione (28):** Compound **25d** (132 mg, 0.68 mmol) in 25 mL of dry *tert*-butyl alcohol were treated with potassium *tert*-butoxide for 4 h at 22 °C according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.57 (weak), 0.31 (**28**), 0.23 (**25d**). According to the ^{1}H NMR spectrum of the crude product the ratio between product **28** and starting material **25d** was 59:41. Flash chromatography [petroleum ether/methyl *tert*-butyl ether (2:1) as eluent]: the first fraction was distilled in the kugelrohr oven at 175 °C/0.4 mbar to give 59 mg (45%) of **28** as a colorless oil. − IR (film): $\tilde{\nu}$ = 2964 cm^{-1} (m), 2878 (m), 1740 (s), 1706 (s), 1467 (m), 1412 (w), 1391 (m), 1377 (m), 1367 (w), 1317 (w), 1271 (w), 1236 (w), 1164 (m), 1121 (m), 1108 (w), 1096 (m), 1058 (m). − ^{1}H NMR (500 MHz): δ = 1.03 (s, 3 H, 9-H), 1.05 (s, 3 H, 10-H), 1.16 (s, 3 H, 8-H), 1.71−1.80 (m, 3 H, 3-H, 7-H), 2.02−2.08 (m, 1 H, 7-H), 2.26−2.41 (m, 4 H, 2-H, 6-H, 7a-H), 2.64−2.71 (m, 1 H, 6-H). − ^{13}C NMR (75.5 MHz): δ = 18.1 (q), 21.6 (q), 23.9 (q), 24.1 (t), 29.6 (t), 34.2 (t), 35.3 (t), 48.5 (s), 49.8 (s), 53.5 (d), 214.9 (s), 218.5 (s). − MS (70 eV; 130 °C): *m*/*z* (%) = 195 (7), 194 (37) [M$^+$], 123 (16), 112 (27), 109 (11), 107 (25), 96 (15), 83 (100), 81 (12), 70 (10), 67 (16), 55 (42), 43 (15), 41 (22). − $C_{12}H_{18}O_2$ (194.3): calcd. C 74.19, H 9.34; found C 74.02, H 9.34.

Second fraction: 36 mg (27%) of recovered starting material **25d**.

Cyclization of 24a at 82 °C; 3,6,7,8-Tetrahydro-5-methyl-2*H*-azulen-1(2*H*)-one (29a): Compound **24a** (110 mg, 0.61 mmol) in 15 mL of dry *tert*-butyl alcohol was treated with potassium *tert*-butoxide for 30 min. at reflux temperature according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.37 (**29a**), 0.14 (weak), 0.09 (weak). Flash chromatography [petroleum ether/methyl *tert*-butyl ether (2:1) as eluent] and subsequent kugelrohr distillation at 100 °C/0.4 mbar gave 56 mg (57%) of **29a** as a colorless oil. − IR (film): ṽ = 2924 cm^{-1} (m), 1727 (w), 1685 (s, C=O), 1610 (s), 1443 (m), 1392 (w), 1375 (m), 1285 (m), 1223 (w), 1154 (w). − ^{1}H NMR (300 MHz): δ = 1.78−1.85 (m, 2 H, 7-H), 1.96 (s, 3 H), 2.37−2.45 (m, 6 H), 2.51−2.55 (m, 2 H), 5.86 (s, 1 H, 4-H). − ^{13}C NMR (75.5 MHz): δ = 22.7 (t, C-7), 25.5 (t), 27.9 (q, CH_3), 30.7 (t), 34.1 (t), 37.5 (t), 121.8 (d, C-4), 139.2 (s, C-8a), 153.7 (s), 164.1 (s), 209.0 (s, C-1). − MS (70 eV; 130 °C): *m/z* (%) = 163 (13), 162 (94) [M^+], 147 (39), 134 (17), 120 (81), 119 (62), 106 (21), 105 (100), 92 (24), 91 (68), 79 (22), 77 (24), 65 (16), 41 (18). − $C_{11}H_{14}O$ (162.2): calcd. C 81.44, H 8.70; found C 81.47, H 8.63.

Cyclization of 24c at 82 °C; 3,6,7,8-Tetrahydro-5-propyl-2*H*-azulen-1(2*H*)-one (29c): Compound **24c** (198 mg, 0.95 mmol) in 11 mL of dry *tert*-butyl alcohol was reacted with potassium *tert*-butoxide for 30 min. at reflux temperature according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.74 (weak), 0.51 (**29c**), 0.23 (weak). Flash chromatography [petroleum ether/methyl *tert*-butyl ether (8:1) as eluent] and subsequent kugelrohr distillation at 150 °C/0.4 mbar gave 101 mg (56%) of **29c** as a colorless oil. − IR (film): ṽ = 2957 cm^{-1} (m), 2929 (m), 2869 (m), 1688 (s, C=O), 1609 (s), 1443 (w), 1424 (w), 1399 (w), 1375 (m), 1284 (m), 1222 (w), 1154 (w), 1091 (w), 988 (w). − ^{1}H NMR (300 MHz): δ = 0.93 (t, *J* = 7.3 Hz, 3 H), 1.46−1.58 (m, 2 H), 1.77−1.85 (m, 2 H, 7-H), 2.16 (t, *J* = 7.5 Hz, 2 H), 2.37−2.46 (m, 6 H, 3-H, 6-H, 8-H), 2.53−2.58 (m, 2 H, 2-H), 5.83 (s, 1 H, 4-H). − ^{13}C NMR (75.5 MHz): δ = 13.8 (q), 21.3 (t), 22.8 (t, C-7), 25.9 (t), 30.9 (t), 34.1 (t), 35.7 (t), 43.6 (t), 121.3 (d, C-4), 139.1 (s), 157.4 (s), 164.2 (s), 209.2 (s, C-1). − MS (70 eV; 130 °C): *m/z* (%) = 191 (16), 190 (100) [M^+], 175 (14), 162 (15), 161 (17), 148 (63), 147 (59), 134 (20), 133 (55), 120 (15), 119 (62), 117 (15), 106 (17), 105 (62), 92 (18), 91 (59), 79 (16), 77 (16), 41 (20). − $C_{13}H_{18}O$ (190.3): calcd. C 82.06, H 9.54; found C 81.90, H 9.46.

Cyclization of 24e at 82 °C; 5-*tert*-Butyl-3,6,7,8-tetrahydro-2*H*-azulen-1(2*H*)-one (29e): Compound **24e** (81 mg, 0.37 mmol) in 10 mL of dry *tert*-butyl alcohol was treated with potassium *tert*-butoxide for 90 min. at reflux temperature according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.43 (**29e**), 0.21 (**24e**). Besides 27 mg (33%) of starting material **24e**, flash chromatography [petroleum ether/methyl *tert*-butyl ether (6:1) as eluent] and subsequent kugelrohr distillation at 150 °C/0.4 mbar gave 23 mg (30%) of **29e** as a colorless oil. − IR (film): ṽ = 2962 cm^{-1} (m), 2927 (m), 2870 (m), 1734 (w), 1690 (s), 1607 (m), 1465 (w), 1443 (w), 1386 (m), 1362 (w), 1283 (m), 1217 (w), 1146 (w), 866 (w). − ^{1}H NMR (300 MHz): δ = 1.12 (s, 9 H), 1.76−1.84 (m, 2 H, 7-H), 2.37−2.47 (m, 6 H, 3-H, 6-H, 8-H), 2.56−2.61 (m, 2 H, 2-H), 5.88 (s, 1 H, 4-H). − ^{13}C NMR (75.5 MHz): δ = 24.0 (t, C-7), 26.9 (t), 28.5 (q), 31.1 (t), 31.4 (t), 33.9 (t), 38.0 (s), 117.7 (d, C-4), 139.2 (s), 164.6 (s), 164.6 (s), 209.8 (s, C-1). − MS (70 eV; 130 °C): *m/z* (%) = 205 (8), 204 (45) [M^+], 189 (27), 162 (15), 161 (70), 148 (12), 147 (31) [$M^+ - C_4H_9$], 137 (15), 119 (33), 105 (22), 93 (14), 91 (19), 86 (16), 84 (25), 57 (100), 41 (35). − $C_{14}H_{20}O$ (204.3): calcd. C 82.30, H 9.87; found C 82.15, H 9.80.

Cyclization of 24f at 82 °C; 3,6,7,8-Tetrahydro-5-(4-methylphenyl)-2*H*-azulen-1(2*H*)-one (29f): Compound **24f** (256 mg, 1.00 mmol) in 11 mL of dry *tert*-butyl alcohol was treated with potassium *tert*-butoxide for 60 min. at reflux temperature according to the general procedure. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.51 (weak), 0.40 (**29f**), 0.20 (**24f**). Flash chromatography [petroleum ether/methyl *tert*-butyl ether (5:1) as eluent] gave 194 mg (82%) of **29f** as a yellow solid with m.p. 70 °C (from petroleum ether). − IR (film): ṽ = 3023 cm^{-1} (w), 2922 (m), 2862 (w), 1685 (s, C=O), 1625 (m), 1593 (s), 1563 (w), 1509 (m), 1441 (m), 1411 (w), 1382 (m), 1287 (s), 1262 (w), 1236 (w), 1219 (m), 1147 (w), 998 (w), 818 (m). − ^{1}H NMR (300 MHz): δ = 1.96−2.00 (m, 2 H, 7-H), 2.37 (s, 3 H), 2.42−2.45 (m, 2 H), 2.52−2.55 (m, 2 H), 2.64−2.67 (m, 2 H), 2.87−2.89 (m, 2 H), 6.25 (s, 1 H, 4-H), 7.16−7.18 (m, 2 H), 7.33−7.35 (m, 2 H). − ^{13}C NMR (125 MHz): δ = 21.2 (q), 23.2 (t, C-7), 26.4 (t), 31.1 (t), 34.1 (t), 35.3 (t), 122.8 (d, C-4), 126.2 (d), 129.2 (d), 138.2 (s), 139.9 (s), 140.8 (s), 153.7 (s), 163.5 (s), 209.3 (s, C-1). − MS (70 eV; 85 °C): *m/z* (%) = 239 (19), 238 (100) [M^+], 223 (25), 210 (22), 196 (32), 195 (29), 182 (16), 181 (46), 167 (17), 166 (14), 165 (26), 105 (21), 91 (14). − $C_{17}H_{18}O$ (238.3): calcd. C 85.68, H 7.61; found C 85.62, H 7.62.

Intramolecular McMurry reaction of 24f; 2,4,5,6-Tetrahydro-3-methyl-7-(4-methylphenyl)-1*H*-indene (34): Titanium tetrachloride (0.7 mL, 6.0 mmol) was added at room temperature to zinc powder (1.3 g, 20 mmol) in 25 mL of dry THF. After cooling to between −5 and −10 °C a solution of **24f** (256 mg, 1.00 mmol) in 25 mL of dry THF was added dropwise under stirring within 5 h. Stirring was continued for 4 h at between −5 and −10 °C and for 15 h at room temperature. The mixture was then hydrolysed with 50 mL of 10% aqueous sodium carbonate solution. After removing most of the THF on the rotary evaporator the residual aqueous mixture was extracted three times with 40 mL of diethyl ether and the combined organic extracts were filtered through a pad of silica and concentrated. TLC of the crude product [petroleum ether/ethyl acetate (4:1), silica gel]: R_f = 0.91 (**34**), 0.14 (weak). Flash chromatography (petroleum ether as eluent) gave 150 mg (67%) of **34** as a colorless oil. − IR (film): ṽ = 3021 cm^{-1} (w), 2926 (m), 2836 (m), 1624 (w), 1510 (m), 1437 (w), 1356 (w), 1266 (w), 1038 (w), 814 (m). − ^{1}H NMR (300 MHz): δ = 1.78 (s, 3 H), 1.75−1.83 (m, 2 H, 5-H), 2.33 (s, 3 H), 2.28−2.44 (m, 6 H), 2.63−2.68 (m, 2 H), 7.11−7.13 (m, 2 H), 7.23−7.26 (m, 2 H). − ^{13}C NMR (125 MHz): δ = 14.5 (q), 21.1 (q), 23.1 (t), 23.3 (t), 28.2 (t), 30.1 (t), 36.0 (t), 124.6 (s), 127.0 (d), 128.7 (d), 135.0 (s), 135.4 (s), 137.5 (s), 140.4 (s), 143.1 (s). − MS (70 eV; 130 °C): *m/z* (%) = 225 (19), 224 (100) [M^+], 223 (13), 209 (41), 207 (11), 181 (16), 119 (10), 105 (13), 91 (12). − $C_{17}H_{20}$ (224.4): calcd. C 91.01, H 8.99; found C 91.13, H 8.91.

Acknowledgments

Financial support of the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie and a generous donation of palladium acetate by Degussa AG are gratefully acknowledged.

---

[1] J. Tsuji, *Palladium Reagents and Catalysts: Innovations in Organic Synthesis*, Wiley, Chichester, **1995**.

[2] [2a] J. B. Melpolder, R. F. Heck, *J. Org Chem.* **1976**, *41*, 265−272. − [2b] A. J. Chalk, S. A. Magennis, *J. Org Chem.* **1976**,*41*, 273−278, 1206−1209. − [2c] Y. Tamaru, Y. Yamada, Z. Yoshida, *J. Org. Chem.* **1978**, *43*, 3396−3398. − [2d] W. Smadja, S. Czernecki, G. Ville, C. Georgoulis, *Organometallics* **1987**, *6*, 166−169. − [2e] R. C. Larock, W.-Y. Leung, S. Stolz-Dunn, *Tetrahedron Lett.* **1989**, *30*, 6629−6632. − [2f] S.-K. Kang, K.-Y. Jung, C.-H. Park, E.-Y. Namkoong, T.-H. Kim, *Tetrahedron Lett.* **1995**, *36*, 6287−6290.

[3] [3a] G. Dyker, P. Grundt, *Tetrahedron Lett.* **1996**, *37*, 619−622. − [3b] G. Dyker, P. Grundt, H. Markwitz, G. Henkel, *J. Org. Chem.* **1998**, *63*, 6043−6047. − [3c] G. Dyker, A. Thöne, *J.*

Prakt. Chem./Chemiker-Ztg. **1999**, *341*, 138−141. − [3d] G. Dyker, P. Grundt, *Helv. Chim. Acta* **1999**, *82*, 588−596. − [3e] G. Dyker, P. Grundt, *Eur. J. Org. Chem.* **1999**, 323−327. − [3f] G. Dyker, H. Markwitz, *Synthesis* **1998**, 1750−1754.

[4] S. I. Khan, M. W. Grinstaff, *J. Org. Chem.* **1999**, *64*, 1077−1078.

[5] M. S. Furness, T. P. Robinson, D. J. Goldsmith, J. P. Bowen, *Tetrahedron Lett.* **1999**, *40*, 459−462.

[6] [6a] E. Negishi, Z. R. Owczarczyk, D. R. Swanson, *Tetrahedron Lett.* **1991**, *32*, 4453−4456. − [6b] V. Farina, G. P. Roth, *Tetrahedron Lett.* **1991**, *32*, 4243−4246. − [6c] C. R. Johnson, J. P. Adams, M. P. Braun, C. B. W. Senanayake, *Tetrahedron Lett.* **1992**, *33*, 919−922. − [6d] P. Margaretha, S. Reichow, W. C. Agosta, *J. Org. Chem.* **1994**, *59*, 5393−5396. − [6e] D. L. Comins, S. P. Joseph, X. Chen, *Tetrahedron Lett.* **1995**, *36*, 9141−9144. − [6f] A. E. Graham, D. McKerrecher, D. H. Davies, R. J. K. Taylor, *Tetrahedron Lett.* **1996**, *36*, 7445−7448. − [6g] M. W. Miller, C. R. Johnson, *J. Org. Chem.* **1997**, *62*, 1582−1583. − [6h] P. Margaretha, S. Reichow, W. C. Agosta, *J. Org. Chem.* **1994**, *59*, 5393−5396. − [6i] T. Kamikubo, K. Ogasawara, *Heterocycles* **1998**, *47*, 69−72. E. Negishi, *J. Organomet. Chem.* **1999**, *576*, 179−194.

[7] Crystallographic data (excluding structure factors) for the structure included in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-151979. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [Fax: (internat.) + 44-1223/336-033; E-mail: deposit@ccdc.cam.ac.uk]..

[8] T. Mukaijama, T. Sato, J. Hanna, *Chem. Lett.* **1993**, 1041−1044.

[9] [9a] G. A. Molander, C. Kenny, *J. Org. Chem.* **1988**, *53*, 2132−2134. − [9b] G. A. Molander, C. Kenny, *J. Am. Chem. Soc.* **1989**, *111*, 8236−8246. − [9c] H.-F. Gŗtzmacher, E. Neumann, *Chem. Ber.* **1993**, *126*, 1495−1497. − [9d] J. L. Namy, J. Souppe, H. B. Kagan, *Tetrahedron Lett.* **1983**, *24*, 765−766. − [9e] H. J. Lim, G. Keum, S. B. Kang, B. Y. Chung, Y. Kim, *Tetrahedron Lett.* **1998**, *39*, 4367−4368. − [9f] D. Guijarro, B. Mancheno, M. Yus, *Tetrahedron* **1993**, *49*, 1327−1334. − [9g] B. Kammermeier, G. Beck, D. Jacobi, H. Jendralla, *Angew. Chem.* **1994**, *106*, 719−721; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 685−687. − [9h] M. Kang, J. Park, A. W. Konradi, S. F. Pedersen, *J. Org. Chem.* **1996**, *61*, 5528−5531. − [9i] M. Nazare, H. Waldmann, *Angew. Chem.* **2000**, *112*, 1171−1174; *Angew. Chem. Int. Ed. Engl.* **2000**, *39*, 1125−1128.

[10] Y. Ito, S. Fujii, T. Saegusa, *J. Org. Chem.* **1976**, *41*, 2073−2074.

[11] F. Bellina, A. Carpita, D. Ciucci, M. De Santis, R. Rossi, *Tetrahedron* **1993**, *49*, 4677−4698.

[12] J. M. McIntosh, *Can. J. Chem.* **1971**, *49*, 3045−3047.

[13] C. R. Johnson, J. P. Adams, M. P. Braun, C. B. W. Senanayake, P. M. Wovkulich, M. R. Uskokovic, *Tetrahedron Lett.* **1992**, *33*, 917−918.

[14] H. Stetter, A. Mertens, *Chem. Ber.* **1981**, *114*, 2479−2490.

[15] J.-M. Coustard, J.-C. Jacquesy, *Tetrahedron Lett.* **1972**, *14*, 1341−1344.

[16] H. Neudeck, K. Schlögl, *Monatsh Chem.* **1979**, *110*, 541−565.

Received December 8, 2000
[O00630)