130799-53-0; (±)-**29**, 130799-54-1; (±)-**30**, 130799-55-2; (±)-**31**, 130856-19-8; (±)-**32**, 130856-20-1; (±)-**33**, 130799-56-3; (±)-**34**, 130799-57-4; (±)-**35**, 130799-58-5; (±)-**36**, 130799-59-6; (±)-**39**, 122700-15-6; (±)-**40**, 122700-16-7; (±)-*cis*-**40**, 122700-22-5; (±)-**41**, 122797-75-5; (±)-**42**, 122722-23-0; cyclohexenone trimethylsilyl enol ether, 54781-19-0; 1,3-dimethoxybenzene, 151-10-0; 3-methoxyphenol MOM ether, 57234-28-3; 1-methoxy-3-(methoxymethoxy)-5-pentylbenzene, 80393-04-0; 3-methoxy-5-pentylphenol, 41408-15-5; 3-(2-hydroxy-6-methoxy-4-pentylphenyl)-2-cyclohexen-1-one, 130799-49-4; 1,3-bis(methoxymethoxy)-5-pentylbenzene, 94450-80-3; olivetol, 500-66-3.

Supplementary Material Available: Summary of structural details, tables of atomic coordinates, bond lengths, bond angles, and anisotropic thermal parameters for **10**, summary of X-ray analysis of **10**, experimental details for **13** and **24**, and ^{1}H NMR spectra of **7**, **12**, **17**, **18**, **25**, **26**, **28**, **35**, **36**, **39**, **41**, 1-methoxy-3-(methoxymethoxy)-5-pentylbenzene, and 1,3-bis(methoxymethoxy)-5-pentylbenzene (23 pages). Ordering information is given on any current masthead page.

Palladium-Catalyzed Cross-Coupling of β-(Methanesulfonyl)oxy Enones with Organostannanes

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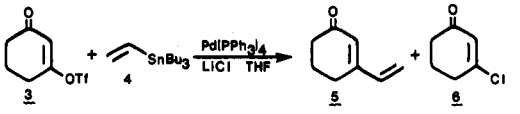
β-(Methanesulfonyl)oxy enones, derived from 1,3-diones, cross-couple with vinylstannanes in 50-80% yields when a substoichiometric amount of $Pd(PPh_3)_4$ and stoichiometric lithium bromide are used. Phenyltributylstannane affords low yields of cross-coupled product. Tetrabutyltin, tributyltin hydride, and ethynyltributyltin do not couple under the reaction conditions. The reaction is proposed to involve in situ formation of the β-bromo enone, oxidative addition to the Pd(0) catalyst, transmetalation, and reductive elimination to afford cross-coupled products. The analogous enol phosphates undergo coupling in low yields, the major product resulting from regeneration of the 1,3-dione.

Palladium-catalyzed carbon-carbon bond-forming reactions have become common methodology for synthetic organic chemists.[1] The chemistry is usually performed under mild conditions, with good tolerance for functionality on the substrates. The ability to couple a wide variety of electrophiles such as organoiodides, bromides, and triflates with nucleophiles (exemplified by organozincs, cuprates, and organotins) in the presence of a catalytic amount of palladium complexes provides new routes into organic compounds. An electrophile that has been little exploited in this field is the methanesulfonate (mesylate) group. We wish to report our success in the coupling of β-mesyloxy enones with vinyl- and allylstannanes in the presence of a palladium(0) catalyst.

Results and Discussion

During a project directed toward the total synthesis of C-ring oxygenated steroids, the need arose for the synthesis of a fully conjugated dienone that was constrained to an *all-Z* geometry. 1-Acetyl-2-vinylcyclohexene (**1**) was chosen as a model for these studies. The synthesis of β-substituted enones from 1,3-diones traditionally involves protection as the β-alkoxy analogue, reaction with a Grignard reagent and then acidic workup.[2] Synthesis of dienone **1** was envisioned to follow Weiler's more recent two-step conversion of 1,3-diones into β-substituted enones.[3] Reaction of 2-acetyl-1-cyclohexanone with diethyl chlorophosphate in the presence of sodium hydride afforded the thermodynamic phosphate **2**. However, treatment of phosphate **2** with bromomagnesium divinylcopper did not afford any of the desired product.

β-(Trifluoromethanesulfonyl)oxy (trifloxy) enones are known to undergo oxidative addition reactions with palladium(0).[4] Reaction conditions for the coupling of β-trifloxy enones with organostannanes were developed in analogy with the known palladium-catalyzed cross-coupling of vinyl triflates with organostannanes in the presence of stoichiometric LiCl.[5,6] Treatment of triflate **3** with vinyltributylstannane (**4**) in the presence of 3 equiv of LiCl and 5 mol % of $Pd(PPh_3)_4$ afforded a 1:1 mixture of the vinyl-substituted product **5** along with 3-chlorocyclohex-2-en-1-one (**6**). All attempts to achieve cross-coupling of



3 **4** **5** **6**

independently prepared[8] chloro enone **6** with vinyltin **4** failed. Michael addition of chloride therefore acts to remove starting material from the reaction and lowers yields of cross-coupled products. Palladium-catalyzed reaction of **3** with **4** in the absence of LiCl returned starting materials. Formation of chloro enone **6** suggested that LiCl was not an acceptable stabilizing halide[6,7] for the cross-coupling of β-sulfonyloxy enones and that a more reactive halide, such as bromide,[1] would be required.

Because the β-position of an enone is activated toward oxidative addition, the corresponding (methanesulfonyl)-oxy (mesyloxy) enone should react in a manner analogous

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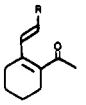
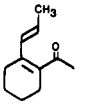
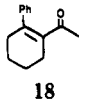
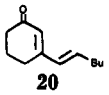
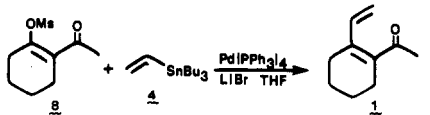
Table I. Palladium-Catalyzed Cross-Coupling of β-Mesyloxy Enones with Organostannanes[a]

entry	mesylate	organotin	product	isolated yield (%)
1	 8	 R = H (4)	 1	69
2	8	R = H (9)[b]	1	74
3	8	R = Bu (10)	11	79
4	8	R = Ph (12)	13	57
5	8	 14	 15	63[c]
6	8	 16	15	24[d]
7	8	$PhSnBu_3$ (17)	 18	33
8	 19	10	 20	50[e]
9	 21	4	 22	82[f]

[a] Reaction conditions: 1.5 equiv of LiBr, 5.0 mol % of $Pd(PPh_3)_4$, 1.00 equiv of mesylate and 1.2 equiv of stannane in THF at 80 °C for 36 h. [b] Vinyltrimethylstannane was used. [c] The trans, cis, and allyl isomers were obtained in a 69:3:29 ratio. No attempt was made to separate isomers. [d] No attempt was made to optimize the conditions for this reaction. The trans, cis, and allyl isomers were obtained in a 93:7:0 ratio. No attempt was made to separate isomers. [e] The trans and cis isomers were obtained in a 91:9 ratio. No attempt was made to separate isomers. [f] The ester resulting from cross-coupling was isolated and characterized as carboxylic acid 22 after saponification.

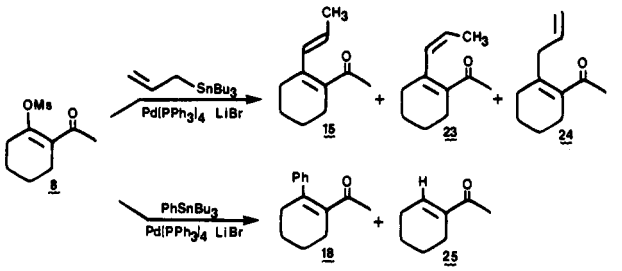
to that of the triflate but afford greater stability. 2-(Mesyloxy)-1-acetylcyclohexene (8) was synthesized from 2-acetylcyclohexanone (7) (MsCl, Et_3N, 70%) and immediately subjected to cross-coupling conditions. Reaction of mesylate 8 with tributylvinylstannane in the presence of substoichiometric $Pd(PPh_3)_4$ and 1.2 equiv of LiBr afforded a 69% yield of 2-ethenyl-1-acetylcyclohexene (1) (Table I, entry 1). As shown in Table I, the reaction appears to be general for a variety of mesyloxy enones and vinylstannanes.



Coupling reactions were run in refluxing THF from 24 to 48 h. Reaction at higher temperatures using *p*-dioxane as solvent tended to afford lower isolated yields of product. The presence of enone 25 in the product mixture suggests that competing radical processes are ongoing. Use of greater than 2 equiv of LiBr occasionally led to lower yields of coupled products as a result of competitive regeneration of 1,3-dione 7.

Removal of tributyltin chloride from the product mixture was best achieved by washing with 10% NH_4OH solution followed by filtration of the reaction through a small pad of silica gel. Under these conditions the product of the cross-coupling of ester mesylate 21 (Table I, entry 9) was partially hydrolyzed, leading to only a 50% yield of methyl 2-vinyl-1-cyclopentenecarboxylate. A higher yield of cross-coupled product could be achieved by saponification of the reaction mixture after coupling (LiOH, MeOH, H_2O) to give the carboxylic acid.

In general, vinylstannanes afford good yields of cross-coupled products. There appears to be little advantage to using trimethylvinylstannane over the tributyl analogue (Table I, entries 1 and 2). Stereochemistry about the olefin of the nucleophile is not preserved. The product obtained from coupling of mesylate 8 with (*Z*)-prop-1-en-1-yltributylstannane (16) predominantely isomerized during the course of the reaction to *E* dienone 15 (Table I, entry 6). Similarly, coupling of 8 with allyltributyltin produced *E* dienone 15, *Z* dienone 23, and the allylic isomer 24 in a 69:3:28 ratio (Table I, entry 5).



As observed with vinyl triflates,[6] phenyltributylstannane did not act as an efficient nucleophile, though a 33% yield of the desired β-phenyl compound could be obtained, along with acetylcyclohexene (25) and biphenyl (entry 7). Addition of BHT as a radical inhibitor did not increase the yield of the desired product, but acted to slow the reaction. Surprisingly, the use of tributyltin hydride did not afford reduced product 25 under the reaction conditions. Reaction of mesylate 8 with tributyltin acetylide does not lead to coupled products, nor does the treatment of 8 with 1-hexyne, $Pd(PPh_3)_2Cl_2$, and CuI, typical alkyne coupling conditions.[7] In these cases starting material was returned. Coupling of mesylate 8 with tetrabutyltin produced acetylcyclohexene (25) in moderate amounts.

Kowalski and Fields have shown that β-mesyloxy enones rapidly undergo Michael addition with halides at room temperature followed by loss of mesylate to afford 3-halo enones.[8] We propose that the mechanism of cross-coupling involves first the in situ formation of the corresponding β-bromo enone 26. Oxidative addition of bromo enone 26 with Pd(0) affords organopalladium(II) bromide 27. Transmetalation with the organostannane followed by reductive elimination leads to the observed cross-coupled products and regenerates the palladium(0) catalyst. In support of this mechanism we have observed the presence of β-bromo enones in the product mixture from reactions that were stopped prior to completion. In addition, we and others[9] have observed that β-bromo and β-iodo enones readily undergo palladium-catalyzed cross-coupling reactions.

In conclusion, we have shown that β-mesyloxy enones couple with vinylstannanes in the presence of a palladium(0) catalyst and stoichiometric LiBr. Arylstannanes afford lower yields, and tetraalkyltins, tin hydride, and tin acetylide do not appear to couple. The palladium-catalyzed cross-coupling of β-mesyloxy enones offers a complimentary approach to the Weiler reaction of the corresponding phosphate. In addition, this study indicates that

(9) For example, see: Stille, J. K.; Sweet, M. P. *Tetrahedron Lett.* 1989, *30*, 3645–3648.

β-mesyloxy enones may be used in place of the more expensive, less stable[10] trifloxy analogues for some metal-catalyzed reactions.

Experimental Section

^1H and ^{13}C NMR spectra were obtained in $CDCl_3$. Capillary gas chromatographic analyses were run on a chromatograph equipped with a 0.53 mm × 5 m methyl silicon column and a flame ionization detector. Low resolution GC-mass spectra (LRMS) were obtained at an ionization potential of 70 eV. Thin-layer chromatography was performed on EM silica gel 60F-254 plates. Column chromatographic purification of reaction mixtures were performed with Woelm 230–400-mesh silica gel. Radial chromatography was performed on a Harrison Research Chromatatron.

1-Acetylcyclohexanone was prepared by the treatment of the pyrrolidine enamine of cyclohexanone with acetic anhydride.[11] Phenyltributylstannane[12] and vinyltributylstannane[13] were prepared from the corresponding Grignard reagents and tributyltin chloride. (*E*)-Hex-1-en-1-yltributylstannane and (*E*)-1-(tributylstannyl)-2-phenylethene were prepared by the addition of tributyltin hydride to hexyne and phenylacetylene, respectively.[14,15] $Pd(PPh_3)_4$ was prepared according to literature methods.[16] Tetrahydrofuran (THF) was doubly distilled from potassium. All reactions were performed under positive argon pressure.

The purity of all title compounds was judged to be ≥90% by GC, ^1H NMR, and ^{13}C NMR determinations.

General Procedure for the Coupling of 1,3-Diones with Organostannanes. 2-[(Methanesulfonyl)oxy]-1-acetylcyclohexene (8). Mesylate 8 was prepared by using a modified literature procedure.[8] To a mixture of 2-acetylcyclohexanone (2.0 mL, 15.4 mmol) in DME (150 mL) at 0 °C were added triethylamine (10.6 mL, 75.5 mmol, 4.9 equiv) and then mesyl chloride (3.6 mL, 46.5 mmol, 3.0 equiv). The reaction mixture was then allowed to warm to room temperature for 12 h, diluted with Et_2O (100 mL), and washed with water (120 mL). The aqueous layer was back-extracted with Et_2O (3 × 50 mL), and the organic layers were combined, washed with water (2 × 50 mL) and a saturated NaCl solution (2 × 50 mL), dried ($MgSO_4$), and filtered through a 4 × 7 cm pad of silica gel. Concentration under reduced pressure afforded a brown oil, which was distilled to give 8 (2.3 g, 70%): bp (bulb-to-bulb) 120–125 °C (0.85 mmHg); IR (neat) 1660, 1360, 1180 cm^{-1}; ^1H NMR (360 MHz) δ 1.63–1.66 (m, 2 H), 1.74–1.77 (m, 2 H), 2.35–2.37 (m, 2 H) 2.38 (s, 3 H), 2.50–2.51 (m, 2 H), 3.20 (s, 3 H); ^{13}C NMR (91 MHz) δ 20.9, 22.0, 25.1, 28.7, 30.2, 39.1, 128.6, 149.6, 199.1.

β-Mesyloxy enones decompose on standing neat at room temperature for several hours,[8] but can be stored in CH_2Cl_2 at 10 °C for several days. The mesylates were generally used in coupling reactions without further purification immediately after formation.

2-Ethenyl-1-acetylcyclohexene (1, Table I, Entry 1). To a slurry of LiBr (0.20 g, 2.3 mmol, 1.5 equiv) and $Pd(PPh_3)_4$ (0.089 g, 0.077 mmol, 4.8 mol %) in THF (5 mL) was added a solution of mesylate 8 (0.35 g, 1.6 mmol) and vinyltributyltin (0.58 g, 1.8 mmol, 1.2 equiv) in THF (10 mL). The resulting mixture was heated to 80 °C for 36 h, cooled, diluted with CH_2Cl_2 (40 mL), and washed with water (50 mL). The aqueous layer was back-extracted with CH_2Cl_2 (20 mL), and the combined organics were washed with a 10% NH_4OH solution (3 × 30 mL), water (2 × 30 mL), and a saturated NaCl solution (2 × 30 mL), dried ($MgSO_4$), and filtered through a 3 × 2 cm pad of silica gel. Concentration under reduced pressure afforded a yellow oil, which was purified by column chromatography (SiO_2, 4 × 10 cm, 2.5% EtOAc/hexanes) followed by bulb-to-bulb distillation to give 1 (0.17 g, 69%): bp (bulb-to-bulb) 75–90 °C (0.6 mmHg); TLC (5% EtOAc/hexanes) R_f 0.62; IR (neat) 3030, 2940, 1670, 1610, 990, 910 cm^{-1}; ^1H NMR (360 MHz) δ 1.57–1.59 (m, 4 H), 2.17 (s, 3 H), 2.14–2.34 (m, 4 H), 5.01 (d, J = 11.0 Hz, 1 H), 5.22 (d, J = 17.9 Hz, 1 H), 6.65 (dd, J = 17.9, 11.0 Hz, 1 H); ^{13}C NMR (91 MHz) δ 21.4 (t, J = 128.1 Hz), 21.6 (t, J = 133.6 Hz), 24.5 (t, J = 126.1 Hz), 26.7 (t, J = 126.5 Hz), 29.7 (q, J = 127.6 Hz), 114.2 (t, J = 158.6 Hz), 134.9 (s), 135.5 (d, J = 155.4 Hz), 137.9 (s), 204.7 (s); LRMS m/z (rel intensity) 150 (59); HRMS calcd for $C_{10}H_{14}O$ 150.1045, found 150.1025. Anal. Calcd for $C_{10}H_{14}O$: C, 79.96; H, 9.39. Found: C, 79.48, H, 9.55.

Compounds **11**, **13**, **15**, **18**, and **20** were purified by column chromatography (SiO_2, 2.5% EtOAc/hexane) or radial chromatography (SiO_2, 2.5% EtOAc/hexane) prior to distillation. No attempt was made to separate mixtures of isomers.

2-((*E*)-Hex-1-en-1-yl)-1-acetylcyclohexene (11, Table I, entry 3): yield, 0.35 g (79%); bp (bulb-to-bulb) 85–110 °C (0.5 mmHg); TLC (2.5% EtOAc/hexanes) R_f 0.15; IR (neat) 2920, 2860, 1650, 1410, 950 cm^{-1}; ^1H NMR (360 MHz) δ 0.91 (q, J = 7.1 Hz, 3 H), 1.3–1.5 (m, 4 H), 1.6–1.8 (m, 2 H), 2.1–2.3 (m, 4 H), 2.3–2.5 (m, 4 H), 2.27 (s, 3 H), 5.85 (dt, J = 15.6, 7.0 Hz, 1 H), 6.46 (d, J = 15.6 Hz, 1 H); ^{13}C NMR (91 MHz) δ 13.9 (q, J = 124.0 Hz), 22.1 (t, J = 133.3 Hz), 22.2 (t, J = 125.1 Hz), 22.3 (t, J = 124.7 Hz), 26.1 (t, J = 126.4 Hz), 27.2 (t, J = 126.4 Hz), 30.0 (t, J = 127.9 Hz), 31.5 (t, J = 125.8 Hz), 32.9 (q, J = 119.0 Hz), 128.8 (d, J = 153.6 Hz), 132.7 (d, J = 148.8 Hz), 135.8 (s), 136.9 (s), 205.8 (s); LRMS m/z (rel intensity) 206 (1); HRMS calcd for $C_{14}H_{22}O$ 206.1672, found 206.1679. Anal. Calcd for $C_{14}H_{22}O$: C, 81.49; H, 10.75. Found: C, 81.78, H, 10.48.

2-((*E*)-2-Phenyl-1-ethenyl)-1-acetylcyclohexene (13, Table I, entry 4): yield, 0.39 g (57%); bp (bulb-to-bulb) 130–140 °C (0.5 mmHg); TLC (2.5% EtOAc/hexanes) R_f 0.13; IR (neat) 3010, 2890, 1660, 1560, 1420, 1340, 940 cm^{-1}; ^1H NMR (360 MHz) δ 1.70–1.72 (m, 4 H), 2.32 (s, 3 H), 3.46–3.48 (m, 4 H), 6.69 (d, J = 16.2 Hz, 1 H), 7.22 (d, J = 16.2 Hz, 1 H), 7.27–7.42 (m, 5 H); ^{13}C NMR (91 MHz) δ 22.0, 22.1, 25.9, 27.6, 30.0, 126.6, 126.7, 127.6, 128.5, 129.8, 136.8, 137.3, 138.2, 205.2; LRMS m/z (rel intensity) 226 (76); HRMS calcd for $C_{16}H_{18}O$ 226.1359, found 226.1363. Anal. Calcd for $C_{16}H_{18}O$: C, 84.91; H, 8.02. Found: C, 84.65, H, 7.81.

2-((*E*)-Prop-1-en-1-yl)-1-acetylcyclohexene (15, Table I, entries 5 and 6): yield (entry 5), 0.25 g (63%); bp (bulb-to-bulb) 90–100 °C (0.5 mmHg); TLC (5% EtOAc/hexanes) R_f 0.13; IR (neat) 2930, 1655, 1565, 970 cm^{-1}; ^1H NMR (360 MHz) δ 1.62–1.64 (m, 2 H), 1.69–1.76 (m, 2 H), 1.76 (d, J = 6.1 Hz, 3 H), 2.21–2.28 (m, 4 H), 2.24 (s, 3 H), 5.84 (dq, J = 6.1, 15.6, 1 H), 6.47 (d, J = 15.6, 1 H); ^{13}C NMR (91 MHz) δ 18.6 (q, J = 129.3 Hz), 22.0 (t, J = 138.0 Hz), 22.2 (t, J = 133.0 Hz), 26.0 (t, J = 125.1 Hz), 27.1 (t, J = 126.2 Hz), 29.9 (q, J = 127.8 Hz), 127.2 (d, J = 158.1 Hz), 130.1 (d, J = 147.1 Hz), 135.6 (s), 136.8 (s), 205.6 (s); LRMS (*E* dienone **15**) m/z (rel intensity) 164 (4); HRMS calcd for $C_{11}H_{16}O$ 164.1248, found (*E* dienone **15**) 164.1204. Anal. Calcd for $C_{11}H_{16}O$: C, 80.43; H, 9.82. Found: C, 80.19, H, 9.86.

No attempt was made to separate the mixture of isomers described in entries 5 and 6. The ratio of *E* dienone **15**:*Z* dienone **23**:allylic dienone **24** was determined by GC and GC/MS to be 69:3:28 for entry 5 and 93:7:0 for entry 6.

2-Phenyl-1-acetylcyclohexene (18, Table I, Entry 7). Reaction of mesylate 8 (0.45 g, 2.1 mmol) with stannane **17** (1.72 g, 4.7 mmol, 2.3 equiv) as described followed by purification by radial chromatography (SiO_2, 2.5% EtOAc/hexanes) afforded biphenyl, followed by **18** (0.14 g, 33%) and 1-acetylcyclohexene (**25**, 0.02 g, 7%).

2-Phenyl-1-acetylcyclohexene (18): bp (bulb-to-bulb) 80–100 °C (0.25 mmHg); TLC (5% EtOAc/hexane) R_f 0.13; IR (neat) 3020, 2920, 1650, 1420, 1350, 710 cm^{-1}; ^1H NMR (360 MHz) δ 1.20–1.42 (m, 2 H), 1.69–1.73 (m, 2 H), 1.67 (s, 3 H), 2.37–2.41 (m, 4 H), 7.14–7.17 (m, 2 H), 7.29–7.32 (m, 3 H); ^{13}C NMR (91 MHz) δ 21.9 (t, J = 128.0 Hz), 22.6 (tm, J = 123.7 Hz), 26.3 (t, J = 129.5 Hz), 30.3 (q, J = 127.6 Hz), 32.3 (t, J = 125.5 Hz), 127.6 (dm, J = 160.5 Hz), 127.7 (dd, J = 159.7, 10.0 Hz), 128.3 (dd, J = 160.7, 7.4 Hz), 137.6, 142.7, 143.5, 206.3; LRMS m/z (rel intensity) 200 (27); HRMS calcd for $C_{14}H_{16}O$ 200.1201, found 200.1191. Anal. Calcd for $C_{14}H_{16}O$: C, 83.96; H, 8.05. Found: C, 83.73, H, 7.83.

The GC, IR, NMR, and LRMS of **25** were identical with those of a commercial standard.

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3-[(Methanesulfonyl)oxy]-2-cyclohexenone (19).[8] Mesylate **19** was prepared (2.92 g, 85%) from 1,3-cyclohexanedione (2.02 g, 18.0 mmol) and mesyl chloride (2.81 g, 24.6 mmol, 1.36 equiv) by following a literature procedure:[8] TLC (EtOAc) R_f 0.60; IR (neat) 3040, 1680, 1660, 1360 cm^{-1}; ^1H NMR (90 MHz) δ 2.17 (apparent pent, J = 6.1 Hz, 2 H), 2.21 (t, J = 6.3 Hz, 2 H), 2.68 (t, J = 5.9 Hz, 2 H), 3.33 (s, 3 H), 6.09 (br s, 1 H).

The IR and NMR of **19** were identical with those reported.[8] The mesylate was immediately used for cross-coupling without further purification.

3-((*E*)-Hex-1-en-1-yl)-2-cyclohexenone (20, Table I, Entry 8). Treatment of **19** (0.22 g, 1.20 mmol) and stannane **10** (0.46 g, 1.20 mmol, 1.0 equiv) as described above afforded a yellow oil, which was purified by radial chromatography (SiO_2, 2.5% EtOAc/hexane) followed by distillation to give **20** as a colorless oil (0.10 g, 50%): bp (bulb-to-bulb) 75–90 °C (0.8 mmHg); TLC (5% EtOAc/hexane) R_f 0.11; IR (neat) 3040, 2970, 1660, 1630, 1585, 980, 900 cm^{-1}; ^1H NMR (360 MHz) δ 0.86 (t, J = 7.2 Hz, 3 H), 1.24–1.42 (m, 4 H), 1.94–2.02 (m, 2 H), 2.13–2.18 (m, 2 H), 2.35 (t, J = 6.0 Hz, 2 H), 2.42 (t, J = 6.0 Hz, 2 H), 5.82 (br s), 6.14 (br s); ^{13}C NMR (91 MHz) δ 13.8 (q, J = 124.6 Hz), 22.2 (t, J = 130.9 Hz), 22.3 (t, J = 129.2 Hz), 25.0 (t, J = 125.7 Hz), 30.9 (t, J = 127.0 Hz), 32.8 (t, J = 124.0 Hz), 37.6 (t, J = 128.0 Hz), 126.2 (d, J = 160.4 Hz), 131.3 (d, J = 162.2 Hz), 139.0 (d, J = 153.5 Hz), 157.5 (s), 200.2 (s); LRMS m/z (rel intensity) 178 (33); HRMS calcd for $C_{12}H_{18}O$ 178.1358, found 178.1368. Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.43, H, 9.91.

Trace peaks in the ^{13}C NMR at δ 157.5, 138.7, 128.7, and 127.3 indicated the presence of the Z isomer. No attempt was made to separate the mixture of isomers. The E dienone:Z dienone ratio of 91:9 was determined by GC.

Methyl 2-[(Methanesulfonyl)oxy]cyclopentenecarboxylate (21). Mesylate **21** was prepared by using a modified literature method.[8] Treatment of methyl 2-oxocyclopentanecarboxylate (0.62 mL, 4.99 mmol) with mesyl chloride (1.00 mL, 12.9 mmol, 2.59 equiv) as described above afforded **21** (0.78 g, 71%): bp (bulb-to-bulb) 120–125 °C (0.55 mmHg); TLC (25% EtOAc/hexanes) R_f 0.21; IR (neat) 1720, 1360, 1150 cm^{-1}; ^1H NMR (300 MHz) δ 1.95–2.00 (m, 2 H), 2.62–2.67 (m, 2 H), 2.77–2.83 (m, 2 H) 3.25 (s, 3 H), 3.75 (s, 3 H); ^{13}C NMR (91 MHz) δ 20.9, 22.0, 25.1, 28.7, 30.2, 39.1, 128.6, 149.6, 199.1. The mesylate was immediately used for cross-coupling without further purification.

Methyl 2-Ethenyl-1-cyclopentenecarboxylate. Treatment of **22** (0.67 g, 3.04 mmol) and stannane **4** (1.18 g, 3.72 mmol, 1.2 equiv) as described above afforded a yellow oil, which was purified by radial chromatography (SiO_2, 2.5% EtOAc/hexanes) followed by distillation to give the methyl ester as a colorless oil (0.10 g, 50%): bp (bulb-to-bulb) 63–68 °C (0.70 mmHg); TLC (25% EtOAc/hexanes) R_f 0.76; IR (neat) 3030, 1710, 1630, 1585, 900 cm^{-1}; ^1H NMR (300 MHz) δ 1.85 (tt, J = 8.9, 8.9 Hz, 2 H), 2.65 (t, J = 8.9 Hz, 2 H), 2.71 (t, J = 8.9 Hz, 2 H), 3.73 (s, 3 H), 5.40 (d, J = 17.6 Hz, 1 H), 5.41 (d, J = 10.8 Hz, 1 H), 7.51 (dd, J = 17.6, 10.8 Hz, 1 H); ^{13}C NMR (75 MHz) δ 21.2 (t, J = 130.6 Hz), 33.6 (t, J = 129.4 Hz), 34.3 (t, J = 129.3 Hz), 51.2 (q, J = 146.6 Hz), 120.5 (t, J = 157.8 Hz), 129.6 (s), 131.7 (d, J = 162.2 Hz), 152.1 (s), 166.2 (s); LRMS m/z (rel intensity) 152 (24).

2-Ethenyl-1-cyclopentenecarboxylic Acid (22, Table I, Entry 9). In a separate experiment, the mixture resulting from reaction of mesylate **21** (0.58 g, 2.65 mmol) with **4** (1.02 g, 3.20 mmol, 1.2 equiv) as described was treated with LiOH (15 mL, 10% in 50% MeOH/H_2O) for 12 h and then washed with hexanes (3 × 25 mL). The aqueous layer was acidified (pH 2), saturated with NaCl, and extracted with Et_2O (3 × 20 mL). The combined organics were washed with water (2 × 20 mL) and saturated NaCl solution (2 × 20 mL), dried (Na_2SO_4), and concentrated to give **22** as a yellow-white solid (0.30 g, 82%): mp 98–101 °C; TLC (50% EtOAc/1% HOAc/hexanes) R_f 0.48; IR ($CDCl_3$) 3000 (br), 1670, 1620, 1560, 950 cm^{-1}; ^1H NMR (300 MHz) δ 1.89 (tt, J = 7.6 Hz, 2 H), 2.71 (d, J = 7.6 Hz, 2 H), 2.75 (d, J = 7.6 Hz, 2 H), 5.43 (d, J = 8.9 Hz, 1 H), 5.47 (d, J = 15.8 Hz, 1 H), 7.26 (s, 1 OH), 7.56 (dd, J = 8.9, 15.8 Hz, 1 H); ^{13}C NMR (75 MHz) δ 21.1 (t, J = 128.0 Hz), 34.0 (t, J = 123.5 Hz), 34.1 (t, J = 132.0 Hz), 121.3 (t, J = 157.3 Hz), 129.2 (s), 131.8 (d, J = 159.2 Hz), 154.7 (s), 171.2 (s); LRMS m/z (rel intensity) 138 (50); HRMS calcd for $C_8H_{10}O_2$ 138.0681, found 138.0676. Anal. Calcd for $C_8H_{10}O_2$: C, 69.55; H, 7.30. Found: C, 69.79; H, 6.92.

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Supplementary Material Available: ^1H and ^{13}C NMR spectra for compounds **1**, **11**, **13**, **15**, **18**, **20**, and **22** (14 pages). Ordering information is given on any current masthead page.

Heteroaromatic Fused Derivatives of Tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane

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A series of rigid *syn*-orthocyclophanes is prepared by the Friedländer condensation of appropriate *o*-aminobenzaldehyde derivatives with tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-2,7-dione. The reaction may proceed in a stepwise fashion so that unsymmetrical layered compounds can be prepared. These species can be further elaborated by oxidation to quinolinequinones or *N*-oxides and quaternization to quinolinium salts. Molecular mechanics calculations agree closely with X-ray analysis in describing the structural properties of these cyclophanes. Analysis of the ^1H NMR and UV spectra as well as the reduction potentials of these molecules support a moderate electronic interaction between the decks. Initial investigations regarding their ability to serve as cleft-type hosts are described.

Introduction

Ever since the pioneering work of Cram and associates, the field of cyclophane chemistry has continued to capture the interest of the chemical community.[1] The principal attraction of these compounds lies in their ability to juxtapose two aromatic rings close to one another in parallel planes. This orientation is accomplished by the use of two or more bridges whose number, position, and length govern the properties of the system. Considerable attention has been devoted to [*m.n*]para- and [*m.n*]metacyclophanes while the corresponding orthocyclophanes have received

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