[5.1.1]non-4-ene (16) had a GC t_r of 5.81 min (oven 168 °C): ^{1}H NMR ($CDCl_3$) 6.44 (t, 1 H) ppm.

3-Allyl-1,3-dideuterio-2,4-dithiabicyclo[3.1.1]heptane (15-d_2). A solution of *trans*-3-deuterio-3-mercaptocyclobutyl tosylate **2a**-d_1 (60 mg, 0.23 mmol) in 4 mL of THF was cooled to 0 °C under argon and treated with *n*-butyllithium (1.6 M, 0.19 mL, 0.3 mmol) in hexane. The reaction mixture was stirred at 0 °C for 15 min, warmed to 25 °C, and stirred for 30 min. Workup as for **15** followed by preparative HPLC gave the title compound (6 mg, 30%): GC t_r 5.23 min (oven 168 °C); ^{1}H NMR ($CDCl_3$) 5.88–5.74 (m, 1 H), 5.23–5.07 (m, 2 H), 3.26 (t, J = 6.35 Hz, 1 H), 2.89–2.77 (m, 2 H), 2.65 (dd, 1 H), 2.49 (d, J = 6.84 Hz, 2 H), 2.10 (dd, 1 H) ppm; ^{13}C NMR ($CDCl_3$) 133.70, 118.05, 44.82, 38.73, 38.35, 32.93 ppm; mass spectrum (GC–MS), *m/e* (relative intensity) 176 (M + 2, 0.3), 175 (M + 1, 1.1), 174 (M^+, 16.5), 135 (8), 134 (7), 133 (M – C_3H_5, 100), 89 (5), 88 (5), 87 (18), 86 (74), 85 (18).

Reaction of 1:1 *cis*-3-Deuterio-3-mercaptocyclobutyl Tosylate (2b-d_1) and *trans*-3-Mercaptocyclobutyl Tosylate (2a) with Base. A 1:1 mixture of **2b**-d_1 and **2a** (120 mg total, 0.46 mmol) in 7 mL of THF was treated with *n*-butyllithium (1.6 M, 0.32 mL, 0.51 mmol) at 0 °C. The reaction mixture was stirred at 0 °C for 15 min, warmed to room temperature, and stirred for an additional 30 min. Workup and preparative HPLC as in the case of **15** gave **15** with ca. 18% deuterium incorporation as determined by integration of the ^{1}H NMR spectrum. In another experiment a 3.3:1 mixture of **2a** and **2b**-d_1 was treated with *n*-butyllithium. Workup as above followed by HPLC analysis showed ca. 13% deuterium incorporation into **15**.

***cis*-1,3-Bis(allylthio)cyclobutane (20).** A mixture of **15** (35 mg, 0.2 mmol) and excess allyl bromide (0.25 g, 2 mmol) was heated under reflux for 20 h. Excess allyl bromide was removed, and the residue was subjected to preparative TLC (1:1 hexane–methylene chloride) to give the title compound as an oil (25 mg, 63%): GC t_r 7.44 min (oven 168 °C); ^{1}H NMR ($CDCl_3$) 5.84–5.70 (m, 2 H), 5.04 (t, 4 H), 3.23 (q, 2 H), 3.09 (d, 4 H), 2.72–2.62 (m, 2 H), 2.04–1.94 (m, 2 H) ppm; ^{13}C NMR ($CDCl_3$) 134.86, 116.54, 39.36, 34.58, 33.96 ppm; mass spectrum (GC–MS), *m/e* (relative intensity) 202 (M^+ + 2, 0.1), 201 (M^+ + 1, 0.5), 200 (M^+, 8.1), 161 (8), 160 (8), 159 (91), 87 (10), 86 (7), 85 (100), 75 (2), 74 (2), 73 (41).

***cis*-1,3-Cyclobutanedithiol (21). (a) From 20.** Ammonia (10 mL) was condensed in a three-necked flask fitted with a dry ice condenser and a gas inlet tube. *cis*-1,3-Bis(allylthio)cyclobutane (**20**) (20 mg, 0.1 mmol) in ether (2 mL) was added, the solution was cooled to –78 °C, and sodium (10 mg, 0.43 mmol) was added. The mixture was stirred at –78 °C for 30 min, then the flask was warmed to room temperature, and the ammonia was evaporated. Methanol and solid ammonium chloride were added. Evaporation of the solvent gave the title compound (10 mg, 83%) as an oil: GC t_r 3.31 min (oven 130 °C); ^{1}H NMR ($CDCl_3$) 3.23–3.15 (m, 2 H), 3.0–2.96 (m, 2 H), 2.04–1.96 (m, 2 H), 1.83 (d, 2 H) ppm; ^{13}C NMR 47.80, 28.55 ppm; mass spectrum (GC–MS), *m/e* (relative intensity) 122 (M^+ + 2, 2.5), 121 (M^+ + 1, 1.8), 120 (M^+, 30), 89 (2), 88 (2), 87 (33), 85 (20), 61 (13), 60 (100), 59 (52), 55 (23), 53 (19).

(b) From 15. A solution of **15** (42 mg, 0.244 mmol) in 1 mL of THF was added to a slurry of red mercuric oxide (106 mg, 0.5 mmol) and boron trifluoride etherate (70 mg, 0.5 mmol) in 15% aqueous THF (0.42 mL). The red mercuric oxide gradually dissolved and a white precipitate appeared. The mixture was stirred for 30 min, ethyl ether was added, and hydrogen sulfide was bubbled into the solution for 15 min. Precipitated salts were removed by filtration through a pad of Celite and $MgSO_4$. Removal of the solvent left an oil, which was found by GC and GC–MS analysis to be a 1:1 mixture of **21** and **15**.

Acknowledgment. We thank Professors John Katzenellenbogen and Shelton Bank for helpful suggestions and Jon Zubieta for an X-ray crystallographic structural determination. Jean-Alex Laffitte was generously supported by a fellowship from Societe Nationale Elf Aquitaine. We gratefully acknowledge support for this work by the donors of the Petroleum Research Fund, administered by the American Chemical Society, the National Science Foundation, the Northeastern New York Chapter of the American Heart Association, and the John Simon Guggenheim Memorial Foundation. A grant from the National Science Foundation provided support for our Varian XL-300 NMR spectrometer.

Registry No. **1a**, 103562-47-6; **1b**, 103562-48-7; **2a**, 103562-49-8; **2a**-d_1, 103562-51-2; **2b**, 103562-50-1; **2b**-d_1, 103562-52-3; **4**, 103562-53-4; **5a**, 103562-54-5; **5b**, 103562-55-6; **6a**, 103562-56-7; **6b**, 103562-57-8; **7a**, 103562-58-9; **7a**-d_1, 103562-60-3; **7b**, 103562-59-0; **7b**-d_1, 103562-61-4; **8a**, 103562-62-5; **8a**-d_1, 103562-64-7; **8b**, 103562-63-6; **8b**-d_1, 103562-65-8; **9a**, 103562-66-9; **9b**, 103562-67-0; **10a**, 103562-68-1; **10b**, 103562-69-2; **11**, 103562-70-5; **15**, 103562-71-6; **15**-d_2, 103562-72-7; **15** (D-labeled), 103562-73-8; **16**, 103562-74-9; **20**, 103562-75-0; **21**, 103562-76-1; TsCl, 98-59-9; TBAF·3H_2O, 87749-50-6; TBAF·3D_2O, 103562-77-2; Me_3SiCH_2Cl, 2344-80-1; Me_3SiCH_2SH, 18165-76-9; Me_3SiCl, 75-77-4; 3,4-dihydro-2*H*-pyran, 110-87-2; 2-tetrahydropyranyl (trimethylsilyl)methyl sulfide, 98194-90-2; epichlorohydrin, 106-89-8; allyl bromide, 106-95-6.

Supplementary Material Available: Tables of crystal data, atomic coordinates, bond lengths, bond angles, anisotropic temperature factors, and hydrogen coordinates for **8b** and 2D proton NMR spectra of **15** and **16** (11 pages). Ordering information is given on any current masthead page.

Tandem Pd-Catalyzed Elimination–Cyclization

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Attempted generation of 2-(trimethylsilyl)buta-1,3-diene by palladium-catalyzed elimination of 3-acetoxy-2-(trimethylsilyl)-1,3-butadiene led instead to 3-(trimethylsilyl)-1,3,7-octatriene, a potentially useful building block. Such a product presumably arises by a palladium-catalyzed dimerization of the desired diene. Indeed, the intermediate diene can be smoothly intercepted by the presence of an equivalent amount of a dienophile during the elimination reaction to give good yields of the desired Diels–Alder adducts. The effect of the choice of metal on this reaction is explored. The mechanistic implications of these observations are discussed.

The potential utility of 2-silylated-1,3-butadienes in Diels–Alder reactions has led to a number of routes based upon the chemistry of 1,4-disubstituted-2-butenes.[1] These routes do not easily lend themselves for the preparation

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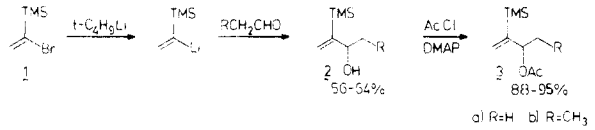
of the trimethylsilyl analogue. The ready availability of 1-bromo-1-(trimethylsilyl)ethene (1) from (trimethylsilyl)ethene[2] suggested a simple route based upon the metal-catalyzed elimination of allyl esters to dienes.[3] The mildness of the elimination conditions should permit the Diels–Alder reaction to proceed in tandem with the elimination—thereby precluding the need to isolate the labile dienes. In this paper, we report the realization of this approach.

Preparation of Reagents. The vinyllithium generated from 1 by metal–halogen exchange[5] easily adds to acetaldehyde and propionaldehyde. As reported by Chan, no advantage accrues to utilizing 2 equiv of *tert*-butyllithium;[6]

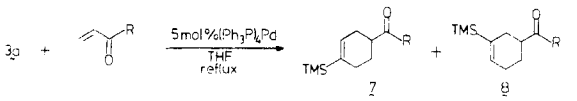


thus only 1 equiv is routinely employed for the metal–halogen exchange. Acetylation proceeds uneventfully to give the allyl acetates **3**. Their good stability permits them to be stored for long times and used as needed.

Attempted Elimination to 2-(Trimethylsilyl)buta-1,3-diene. On the basis of our earlier observations[3] and those of Tsuji,[4] palladium-catalyzed elimination of **3a** should generate 2-(trimethylsilyl)buta-1,3-diene (**4**). In

the event, heating **3a** with 5 mol % of $(Ph_3P)_4Pd$ (**6**), generated in situ by reduction of palladium acetate with *n*-butyllithium in the presence of triphenylphosphine,[7] and triethylamine in refluxing THF does *not* produce the diene. Capillary VPC indicates one major component with three very minor components. GC–mass spectroscopy reveals all of the compounds are isomeric. Mass spectral data of the major constituent reveals a formula of $C_{11}H_{20}Si$. The NMR data indicates a terminal vinyl adjacent to a methylene group [δ 4.95, dd, J = 12, 1.2 Hz; 5.00, dd, J = 17, 1.2 Hz; 5.83 m] and a terminal vinyl attached to a non-hydrogen bearing carbon [δ 5.10, dd, J = 11, 1.2 Hz; 5.12, dd, J = 17.5, 1.2 Hz; 6.63, ddd, J = 17.5, 11, 1.1 Hz] in addition to a vinylic hydrogen adjacent to a saturated methylene group [δ 5.80, td, 6.8, 1.1 Hz]. The small coupling between the protons at δ 5.80 and 6.63 suggests the latter corresponds to a 3-substituted-1,3-butadiene fragment. The octatriene **5** uniquely accommodates the spectral diene. The known palladium-catalyzed dimerization of butadienes to octatrienes[8] suggests that the desired diene **4** is produced but that its conversion to **5** occurs faster than its formation under the reaction conditions.

Elimination–Cycloaddition. Detouring the presumed intermediate formation of the desired diene **4** into cycloaddition chemistry may offer a solution to the inability to easily generate the diene in good isolated yields. Addition of 1 equiv of methyl vinyl ketone to allyl acetate (**3a**) in



the presence of 5 mol % of **6** generated as described above and 1 equiv of triethylamine smoothly leads to the desired Diels–Alder adducts in 72% yield. As noted by other authors, the silicon substituent is not a strong directing group.[1,9] Both regioisomers are produced with the "para" type of adduct predominating (2:1).

For determination of the effect of base and catalyst on this process, both were varied in the reaction of **3a** with methyl acrylate. Table I summarizes the results. While we have previously shown that molybdenum catalysts[3b] effect eliminations of allyl acetates to dienes in good yields, the tandem molybdenum-catalyzed elimination–cycloaddition proceeded in appreciably lower yields than the palladium-catalyzed reactions. The absence of tertiary amine bases has only a minor effect on yield. Higher temperatures cause a slight dimunition of yield.

Table II summarizes the cycloadditions with our adopted standard conditions of utilizing 5 mol % of palladium catalyst **6** generated in situ and stoichiometric amounts of allyl acetate (**3a**), dienophile, and triethylamine. In all cases, the stated yields correspond to isolated pure product. The regioselectivity observed corresponds approximately to that observed in other reports.[1] The adduct from dimethyl maleate **9** is the same produced from

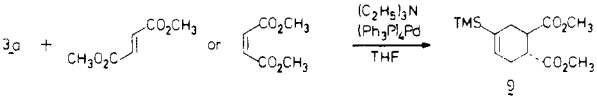


Table I. Effect of Reaction Conditions on Tandem Elimination–Cycloaddition of 3a with Methyl Acrylate[a]

entry	catalyst (none)	base	solvent	% 7 + 8	7:8
1	$(Ph_3P)_4Pd$ (**5**)	$(C_2H_5)_3N$	THF	63	64:36
2	$(Ph_3)_4Pd$[b] (**5**)	none[d]	THF	61	67:33
3	$(Ph_3P)_4Pd$ (**5**)	$(C_2H_5)_3N$	dioxane	58	63:37
4	$(Ph_3P)Pd$[c] (**5**)	none[d]	DME	55	57:43
5	$Mo(CO)_6$ (**10**)	BSA	toluene	32	64:36
6	$(bpy)Mo(CO)_3(CH_3CN)$ (**10**)	$(C_2H_5)_3N$	toluene	25	53:47

[a] All reactions were carried out at the reflux temperature of the stated solvent at 0.07–0.1 M concentration of substrate overnight. [b] An addition of 7 mol % of triphenylphosphine is present. [c] In addition 2.5 mol % of dppe and 5 mol % of triphenylphosphine is present. [d] Phosphines may also serve as a base but only catalytic amounts of phosphine are present.

Table II. Tandem Elimination–Cycloaddition[a]

entry	dienophile	reaction time (h)	yield of adducts	ratio 7:8
1	methyl acrylate	10	63	64:36
2	ethyl acrylate	10	70	67:33
3	*n*-butyl acrylate	8	69	53:47
4	acrylonitrile	12	68	59:41
5	acrylamide	12	50	56:44
6	methyl vinyl ketone	5	72	66:34
7	ethyl vinyl ketone	5	68	71:29
8	dimethyl maleate	12	62	
9	dimethyl fumarate	12	50	

[a] All reactions performed according to the general procedure.

(1) Fleming, I.; Taddei, M. *Synthesis* **1985**, 899. Sato, F.; Uchiyama, H.; Samaddar, A. K. *Chem. Ind. (London)* **1984**, 743. Batt, D. G.; Ganem, B. *Tetrahedron Lett.* **1978**, 3323.

(2) Boeckman, R. K., Jr.; David, M.; Ganem, B.; Halvey, N. *Org. Synth.* **1978**, *58*, 152.

(3) (a) Trost, B. M.; Verhoeven, T. R.; Fortunak, J. M. *Tetrahedron Lett.* **1979**, 2301. (b) Trost, B. M.; Lautens, M. *Tetrahedron Lett.* **1983**, *24*, 4525.

(4) Tsuji, J.; Yamakawa, J.; Kaito, M.; Mandai, T. *Tetrahedron Lett.* **1978**, 2075. Matsushita, H.; Negishi, E. *J. Org. Chem.* **1982**, *47*, 416.

(5) Chan, T. H.; Mychajlowskij, W.; Ong, B. S.; Harpp, D. N. *J. Org. Chem.* **1978**, *43*, 1526. Also see: Mikami, K.; Kisha, N.; Nakai, T. *Chem. Lett.* **1982**, 1643.

(6) Neumann, H.; Seebach, D. *Chem. Ber.* **1978**, *111*, 2785.

(7) Trost, B. M.; Nanninga, T. N. *J. Am. Chem. Soc.* **1985**, *107*, 1293.

(8) For a review, see: Tsuji, J. *Organic Synthesis with Palladium Compounds*; Springer-Verlag: Berlin, 1980; pp 90–124.

(9) Carter, M. J.; Fleming, I.; Percival, A. *J. Chem. Soc., Perkin Trans. 1*, **1981**, 2415.

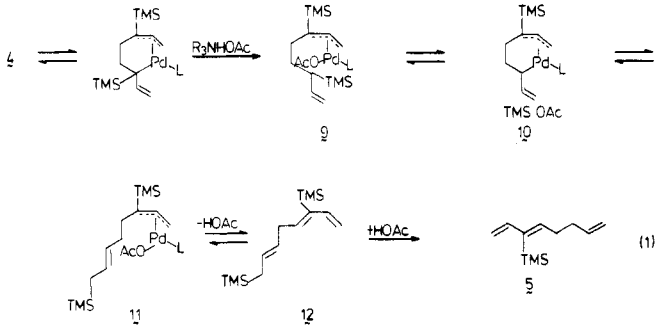
dimethyl fumarate. The ease of isomerization of dimethyl maleate to the thermodynamically more stable dimethyl fumarate in the presence of a phosphine presumably accounts for this result.

No cycloaddition was observed with cyclohex-2-en-1-one, dimethyl benzylidenemalonate, or norbornene. In each case, varying amounts of triene **5** can be isolated—a fact which indicates that the diene **4** is produced but not trapped under standard operating conditions.

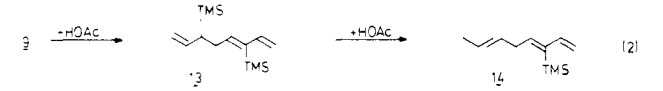
Discussion

This work reveals a limitation in the palladium-catalyzed eliminations of allyl carboxylates to dienes. When sufficiently simple dienes are the products, palladium-catalyzed oligomerization is apparently faster than the elimination. Indeed, the cleanliness of this dimerization to **5** makes this C(8) building block readily available. Previous work, mainly by the group of Tsuji,[10] reveals the utility of the butadiene oligomers in synthesis. The presence of the trimethylsilyl substituent provides an additional degree of flexibility for structural elaboration.[11]

The selectivity of this dimerization is curious. Equation 1 outlines a possible explanation in which the silicon

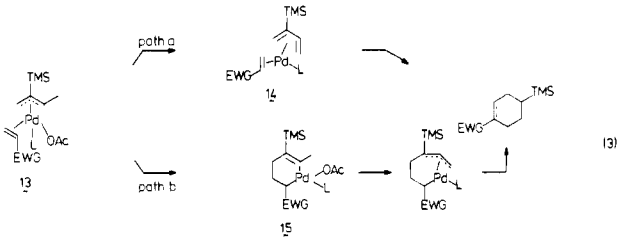


substituent promotes a head-to-head coupling. Such a regioselectivity is in contrast to unsymmetrical dienes like isoprene in which head-to-head dimers are normally minor products. Perhaps the ability of silicon to stabilize an adjacent carbon–metal bond extends to the transition metals like palladium. Such an effect would favor the proposed head to head coupling as depicted. A major feature to explain is the formation of a monosilylated 1,3,7-octatriene. In the simplest explanation, intermediate **9** could lose the elements of acetic acid to generate the triene **13** (eq 2). However, protodesilylation of **13** should



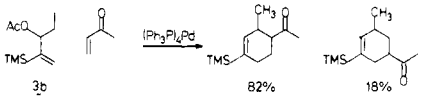
generate triene **14** not **5**. Such a route then requires that either **13** isomerizes to **12** faster than protodesilylation or palladium somehow promotes protodesilylation to **5**. Neither possibility appears attractive. Alternatively, the triene **5** would be expected to derive more straightforwardly from a chemoselective desilylation of the allylsilane subunit of disilylated triene **12**. Postulation of more rapid desilylation of the allyl silane vs. the vinylsilane of **12** is in accord with earlier results.[11] Whereas, the formation of **9** and the conversion of **11** to **12** follow current thoughts of the mechanism of the palladium-catalyzed dimerization,[8] the formation of **11** from **9** is not precedented. Nevertheless, nucleophilic and Lewis acid promoted isomerizations of allylsilanes are well documented.[11,12] Furthermore, the addition of allylsilanes to Pd(2) species is also well precedented.[13] Further discussion of this interesting transformation must await additional experimentation.

The ability to intercept the diene **4** in an intermolecular Diels–Alder reaction is gratifying. Initially, we felt that the efficiency of the interception may arise from the initial formation of a mixed Pd(0) intermediate such as **13** which may undergo direct formation of the cycloadduct either by a palladium-templated Diels–Alder reaction (eq 3, path a) or by a co-oligomerization type mechanism (eq 3, path



b). While such pathways are feasible, the straightforward explanation of a normal Diels–Alder reaction of the forming diene with free dienophile also is consistent with our observations. Since the diene is present in low concentration at any given moment, the large amount of dienophile present assures the cross-coupling Diels–Alder reaction dominates over the palladium-catalyzed homocoupling of the diene. The regioselectivity seen is comparable to that observed with related 2-silylated-1,3-butadienes—a fact also suggestive of a normal thermal reaction. The independence of the regioselectivity with respect to the employment of the palladium catalyst **6** or molybdenum hexacarbonyl also supports the idea that a simple cycloaddition accounts for the adducts. On the other hand, bpy $Mo(CO)_3(CH_3CN)$ does give a significantly different ratio which might suggest an alternative pathway here.

The versatility of this route can be seen by the use of other aldehydes in the reaction with (1-lithiovinyl)trimethylsilane. Reaction of this organolithium with propionaldehyde creates the homologue **2b** which is acetylated to the acetate **3b**. Subjecting **3b** to our standard condi-



tions using methyl vinyl ketone forms the expected cycloadducts with a higher regioselectivity than the parent diene. Thus, it can be expected that, with appropriately substituted dienes, high regioselectivity should be expected.

A limitation of this method is exemplified by the loss of olefin geometry in the reaction with methyl maleate. The catalyst is known to rapidly isomerize this olefin and probably accounts for this observation. Outside of this problem, the conditions for the elimination appear quite compatible with the cycloaddition. Variation of the carboxylate leaving group can also permit modification of the reaction conditions such as lowering the temperature for elimination. In the present case, thermal Diels–Alder reactions of the silylated diene require temperatures on

(10) For a leading reference, see: Tsuji, J. *J. Organomet. Chem.* **1986**, *300*, 281.

(11) For reviews, see: Chan, T. H.; Fleming, I. *Synthesis* **1979**, 761. Burkhofer, L.; Stuhl, O. *Topics Curr. Chem.* **1980**, *88*, 33. Fleming, I. *Compr. Org. Chem.* **1979**, *3*, 539. Magnus, P. D.; Sarkar, T.; Djusic, D. *Compr. Organomet. Chem.* **1982**, *7*, 515. Weber, W. P. *Silicon Reagents for Organic Synthesis*; Springer Verlag: Berlin, 1983. Calas, R. *J. Organomet. Chem.* **1980**, *200*, 11.

(12) Hosomi, A.; Shirahata, A.; Sakurai, H. *Chem. Lett.* **1978**, 901. Trost, B. M.; Yoshida, J.; Lautens, M. *J. Am. Chem. Soc.* **1983**, *105*, 4494.

(13) Kliegman, J. M. *J. Organomet. Chem.* **1971**, *29*, 73. Itoh, K.; Fukui, M.; Kurachi, Y. *Chem. Commun.* **1977**, 500. Hayashi, T.; Konishi, M.; Kumada, M. *Ibid.* **1983**, 736. Corriu, R. J. P.; Escudie, N.; Guerin, C. *J. Organomet. Chem.* **1984**, *271*, C7.

Table III. Experimental Details for Tandem Elimination–Cycloaddition

dienophile mg, mmol	3a mg, mmol	$Pd(OAc)_2$, mg	n-C_4H_9Li, mL of 1.5 M	Ph_3P, mg	dioxane, mL	$(C_2H_5)_3N$, mg	adduct mg, %
methyl vinyl ketone							
38 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	74, 70
45 mg, 0.64	120 mg, 0.64	7	0.042	42	6	63	90, 73
ethyl vinyl ketone							
45 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	76, 68
methyl acrylate							
46 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	71, 63
92 mg, 1.08	200 mg, 1.08	12	0.070	70	15	100	140, 64
ethyl acrylate							
54 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	86, 71
100 mg, 1.0	200 mg, 1.08	12	0.070	70	15	100	170, 69
n-butyl acrylate							
69 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	94, 69
acrylonitrile							
29 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	65, 68
38 mg, 0.70	130 mg, 0.70	8	0.046	45	7	72	84, 67
acrylamide							
38 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	53, 50
dimethyl maleate							
77 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	90, 62
dimethyl fumarate							
77 mg, 0.54	100 mg, 0.54	6	0.035	35	5	54	73, 50
64 mg, 0.44	80 mg, 0.43	5	0.029	28	5	45	72, 50

the order of 60–70 °C, thereby, use of acetate is quite satisfactory. Previous syntheses of 2-silylated-1,3-butadienes have not provided the trimethylsilyl derivative. The convenience of the trimethylsilyl group frequently makes it the silicon substituent of choice. This method resolves the problem of availability of this diene. The ease of forming the requisite allyl carboxylate and the high chemical stability of the latter make this tandem elimination–cycloaddition quite a convenient approach and one that can be envisioned to be generalized to Diels–Alder reactions with other difficulty accessible or unstable dienes.

Experimental Section

General Methods. All reactions were performed under nitrogen in flame-dried glassware. ^1H NMR spectra were recorded on a Bruker WP 200 or WP 270 spectrometer. Chemical shifts are reported in δ units downfield from internal Me_4Si. Splitting patterns are designated as s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), and b (broad). ^{13}C NMR spectra were recorded on a Bruker WP 270 spectrometer. Infrared spectra were taken on a Perkin-Elmer 1420 ratio recording spectrometer. Mass spectra were determined with either a AEI MS902 or Kratos DS-55 mass spectrometer. Thin-layer, preparative-layer, and flash chromatography silica gel was supplied by E. Merck AG (Darmstadt). All solvents were dried and distilled immediately prior to use.

Preparation of 3-Acetoxy-2-(trimethylsilyl)-1-butene (3a) and 3-Acetoxy-2-(trimethylsilyl)-1-pentene (3b). A solution of *tert*-butyllithium (10.8 mL, 20 mmol, 1.85 M) in pentane was added slowly to a solution of 3.6 g (20 mmol) of (1-bromovinyl)trimethylsilane in 80 mL of anhydrous ether at −78 °C. After 2 h at −78 °C, 0.88 g (20 mmol) of acetaldehyde was added, and the mixture was allowed to warm to room temperature. After quenching with 50 mL of water and drying the organic layer ($MgSO_4$), the organic solution was concentrated in vacuo at 120 mmHg and the crude residue purified by chromatography (silica gel, 1:1 hexane–ether) to give 1.84 g (64%) of the desired alcohol: ^1H NMR) δ 5.79 (dd, J = 2.1, 1.5 Hz, 1 H), 5.37 (dd, J = 2.2, 1.1 Hz, 1 H), 4.47 (bq, J = 7.2 Hz, 1 H), 1.54 (bs, 1 H), 1.27 (d, J = 7.2 Hz, 3 H), 0.13 (s, 9 H).

Acetyl chloride (3.14 g, 40 mmol) was added slowly to a mixture of 1.44 g (10 mmol) of the above alcohol, 3.2 g (40 mmol) of pyridine, and 122 mg (1 mmol) of DMAP at 0 °C. After being warmed overnight, the reaction moisture was poured into 20 mL of water and 40 mL of ether. After drying ($MgSO_4$) and evaporation in vacuo (120 mmHg) of the organic layer, the resulting oil was purified by flash chromatography (silica gel, hexane–ether 4:1) to give 1.77 g (95% yield): IR ($CHCl_3$) 1730 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 5.70 (t, J = 2 Hz, 1 H), 5.50 (q, J = 7.2 Hz, 1 H), 5.34 (dd, J = 2.2, 0.83 Hz, 1 H), 2.05 (s, 3 H), 1.26 (d, J = 7.2 Hz, 3 H), 0.10 (s, 9 H).

In exactly identical fashion, **3b** was prepared in 50% overall yield: IR ($CHCl_3$) 1720 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 5.70 (dd, J = 2.5, 1.4 Hz, 1 H), 5.41 (dd, J = 2.5, 0.8 Hz, 1 H), 5.23 (rt, J = 7 Hz, 1 H), 2.00 (s, 3 H), 1.60 (quint, J = 7 Hz, 2 H), 0.85 (t, J = 7 Hz, 3 H), 0.09 (s, 9 H).

General Procedure for Tandem Elimination–Cycloaddition. Stirring a combination of 5 mol % palladium acetate, 25 mol % triphenylphosphine, and 10 mol % n-butyllithium (1.5 M in hexane) in 5 mL of dioxane for 1 h generated a yellow solution of the palladium(0) catalyst. At room temperature, 1 equiv of **3**, 1 equiv of dienophile, and 1 equiv of triethylamine was added sequentially. After being refluxed for the stated time, the mixture was diluted with 10 mL of ether and the organic layer washed with 2 × 5 mL of water. The organic layer was dried ($MgSO_4$), and the solvents were removed in vacuo (120 mmHg). Flash chromatography on silica gel using either 4:1 hexane–ether or 7:3 hexane–ethyl acetate followed by Kugelrohr distillation gave the pure adducts. The regioisomeric ratios were determined by capillary VPC (25-m SE-30 column) and/or ^1H NMR spectroscopy. Details for each run are summarized in Table III.

Spectral Data. 7, 8 (R = CH_3) (R_f 0.40, 4:1 hexane–ether): IR ($CHCl_3$) 1700, 1610 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 5.94 (bs, 1 H), 2.5–2.7 (m, 1 H), 2.14 and 2.15 (two s, 3 H), 1.9–2.2 (m, 4 H), 1.4–1.6 (m, 2 H), 0.0082 and 0.0085 (two s, 9 H). Anal. Calcd for $C_{11}H_{20}OSi$: 196.1283. Found: 196.1277.

7, 8 (R = CH_2CH_3) (R_f 0.45, 4:1 hexane–ether): IR ($CHCl_3$) 1700, 1610 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 5.94 (bs, 1 H), 2.4–2.6 (m, 3 H), 1.3–2.2 (m, 6 H), 1.0 (t, J = 8 Hz, 3 H), −0.0012 and −0.005 (two s, 9 H). Anal. Calcd for $C_{12}H_{22}OSi$: 210.1440. Found: 210.1450.

7, 8 (R = CO_2CH_3) (R_f 0.55, 4:1 hexane–ether): IR ($CHCl_3$) 1720, 1610 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 5.94 (bs, 1 H), 3.66 and 3.67 (two s, 3 H), 2.4–2.6 (m, 1 H), 2.0–2.3 (m, 4 H), 1.5–1.7 (m, 2 H), 0.024 and 0.048 (two s, 9 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 176.5, 176.3, 136.9, 138.3, 134.6, 133.2, 51.4, 39.6, 39.2, 29.0, 26.0, 25.7, 25.5, 24.8, −2.27. Anal. Calcd for $C_{11}H_{20}O_2Si$: 212.1232. Found: 212.1222.

7, 8 (R = $CO_2C_2H_5$) (R_f 0.55, 4:1 hexane–ether): IR ($CHCl_3$) 1720, 1610 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 5.94 (bs, 1 H), 4.10 and 4.11 (two q, J = 7 Hz, 2 H), 2.4–2.6 (m, 1 H), 1.8–2.3 (m, 5 H), 1.5–1.7 (m, 1 H), 1.20 and 1.25 (two t, J = 7 Hz, 3 H), 0.00 and 0.02 (two s, 9 H). Anal. Calcd for $C_{11}H_{22}O_2Si$: 226.1389. Found: 226.1402.

7, 8 (R = $CO_2C_4H_9$-n) (R_f 0.60, 4:1 hexane–ether): IR ($CHCl_3$) 1720, 1610 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 5.93 (bs, 1 H), 4.0 (t, J = 6.5 Hz, 2 H), 2.4–2.6 (m, 1 H), 1.9–2.3 (m, 5 H), 1.5–1.7

(m, 3 H), 1.35 (sextet, J = 7 Hz, 2 H), 0.88 and 0.89 (two t, J = 7 Hz, 3 H), 0.00 and -0.01 (two s, 9 H). Anal. Calcd for $C_{14}H_{26}O_2Si$: 254.1702. Found: 254.1711.

7, 8 (R = CN) (R_f 0.45, 4:1 hexane-ether): IR ($CHCl_3$) 2210 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 5.87 and 5.98 (two bs, 1 H), 2.7-2.9 (m, 1 H), 1.8-2.8 (m, 6 H), 0.03 (s, 9 H); ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 146.5, 137.7, 134.6, 130.8, 122.4, 29.8, 29.6, 25.7, 25.2, 24.9, 24.6, 24.5, -2.4. Anal. Calcd for $C_{10}H_{17}NSi$: 179.1130. Found: 179.1128.

7, 8 (R = $CONH_2$): mp 85 °C (R_f 0.50, 7:3 hexane-ethyl acetate); IR ($CHCl_3$) 1680, 1540 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 6.38 (bs, 1 H), 5.93 (bs, 1 H), 5.52 (bs, 1 H), 1.8-2.5 (m, 6 H), 1.5-1.7 (m, 1 H), 0.01 and 0.03 (two s, 9 H). Anal. Calcd for $C_{10}H_{19}NOSi$: 197.1235. Found: 197.1225.

9 (R_f 0.50, 4:1 hexane-ether): IR ($CHCl_3$) 1750 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 5.92 (bs, 1 H), 3.70 (s, 3 H), 3.68 (s, 3 H), 2.80 (m, 2 H), 2.43 (m, 2 H), 2.17 (m, 2 H), 0.045 (s, 9 H). Anal. Calcd for $C_{13}H_{22}O_4Si$: 270.1287. Found: 270.1273.

Preparation of 3-(Trimethylsilyl)-1,3,7-octatriene (5). Stirring 9 mg (5 mol %) of palladium acetate, 52 mg (25 mol % of triphenylphosphine, and 0.053 mL (10 mol %, 1.5 M in hexane) of n-butyllithium in 2 mL of THF at room temperature for 1 h generates a yellow solution. At the same temperature, 150 mg (0.80 mmol) of acetate **3a** and 81 mg (0.81 mmol) of triethylamine were added sequentially and the resulting solution was refluxed overnight. Following the same workup as above gave, after flash chromatography eluting with hexane, 45 mg (62% yield) of the triene **5**: IR ($CHCl_3$) 1635 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 6.63 (ddd, J = 17.5, 11.0, 1.1 Hz, 1 H), 5.80 (m, 2 H), 5.12 (dd, J = 17.5, 1.2 Hz, 1 H), 5.10 (dd, J = 11.0, 1.2 Hz, 1 H), 5.00 (dd, J = 17.0, 1.5 Hz, 1 H), 4.95 (dd, J = 12.0, 1.5 Hz, 1 H), 2.30 (m, 2 H), 2.10 (m, 2 H), 0.10 (s, 9 H). Anal. Calcd for $C_{11}H_{19}Si$: 180.1290. Found: 180.1182.

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Registry No. **1**, 13683-41-5; **2a**, 66374-47-8; **2b**, 103202-40-0; **3a**, 103202-20-6; **3b**, 103202-21-7; **5**, 103202-37-5; **6**, 14221-01-3; **7** (R = CH_3), 103202-22-8; **7** (R = CH_2CH_3), 103202-24-0; **7** (R = CO_2CH_3), 103202-26-2; **7** (R = $CO_2C_2H_5$), 103202-28-4; **7** (R = $CO_2C_4H_9$-n), 103202-30-8; **7** (R = CN), 103202-32-0; **7** (R = $CONH_2$), 103202-34-2; **8** (R = CH_3), 103202-23-9; **8** (R = CH_2CH_3), 103202-25-1; **8** (R = CO_2CH_3), 103202-27-3; **8** (R = $CO_2C_2H_5$), 103202-29-5; **8** (R = $CO_2C_4H_9$-n), 103202-31-9; **8** (R = CN), 103202-33-1; **8** (R = $CONH_2$), 103202-35-3; **9**, 103202-36-4; BSA, 10416-59-8; $(bpy)Mo(CO)_3(CH_3CN)$, 26748-33-4; $Mo(CO)_6$, 13939-06-5; $Pd(OAc)_2$, 3375-31-3; acetaldehyde, 75-07-0; propanal, 123-38-6; methyl vinyl ketone, 78-94-4; ethyl vinyl ketone, 1629-58-9; methyl acrylate, 96-33-3; ethyl acrylate, 140-88-5; n-butyl acrylate, 141-32-2; acrylonitrile, 107-13-1; acrylamide, 79-06-1; dimethyl maleate, 624-48-6; diethyl fumarate, 624-49-7; 4-acetyl-3-methyl-1-(trimethylsilyl)cyclohexene, 103202-38-6; 5-acetyl-3-methyl-1-(trimethylsilyl)cyclohexene, 103202-39-7; toluene, 108-88-3.

Regioselective Side-Chain Nitration of Polymethylbenzenes Directed by an Acyl Function and Its Application to the Synthesis of Polysubstituted Phthalic Acid Derivatives

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Nitration of three types of tetramethylacetophenones and pentamethylacetophenone with fuming nitric acid in acetic anhydride was carried out. The product distributions were compared with those estimated from substituent effects. A variety of acylpentamethylbenzenes including pentamethylbenzoic acid were reacted with the nitrating system to give regioselectively 2-(nitromethyl)-3,4,5,6-tetramethylacylbenzenes. The selective nitrations of some benzoic acid derivatives followed by an alkaline treatment have been found to provide the N-hydroxyphthalimide derivatives, which are readily converted to the phthalic anhydrides and the phthalazines.

Electrophilic nitration of polysubstituted benzenes has been extensively studied with respect to the problem of the ipso substitution mechanism.[1] Most of these studies have focused their attention on the mechanistic details with very little interest in the synthetic aspects of the reaction.[2] This is because ipso substitution generally gives a complex mixture of products (due to various modes of decomposition of the resulting Wheland intermediate (W_i)).

In anticipation that an acyl function, with a strong electron-withdrawing ability, would direct the decomposition of the Wi, we have undertaken nitration of acylpolymethylbenzenes with fuming nitric acid in acetic anhydride. First, the nitrations of 2,3,4,6-, 2,3,5,6-, and 2,3,4,5-tetramethylacetophenones (**1-3**) and pentamethylacetophenone (**4**) were carried out to establish the product distributions. Based on the results, our preparative work has been extended to the nitration of a variety of acylpentamethylbenzenes **5** and benzoic acid derivatives **7** substituted with a methyl group at the 2-, 3-, and 6-positions. The nitration of **5** and **7** has been found to give products selectively nitrated on the methyl group ortho to the acyl and carboxyl moieties. The regioselective side-chain nitration of the benzoic acids **7** followed by an alkaline treatment has resulted in the N-hydroxyphthalimides **10** which were easily converted to the phthalic anhydrides **11** and phthalazines **12**. Our paper also reports a convenient procedure for the preparation of the polysubstituted phthalic acid derivatives which are not accessible by usual methods.[3]

Results

Nitration of Polymethylacetophenones. Nitration of polymethylacetophenones **1-4** with 2 equiv of fuming

(1) (a) Schofield, K. In *Aromatic Nitration*; Cambridge University Press: London, 1980; p 171. (b) Hartshorn, S. R. *Chem. Soc. Rev.* **1974**, *3*, 169. (c) Moodie, R. B.; Schofield, K. *Acc. Chem. Res.* **1976**, *9*, 287.
(2) Suzuki, H, *Synthesis* **1977**, 217.

(3) A portion of this work has been reported in a short communication: Keumi, T.; Morita, T.; Mitzui, T.; Jōka, T.; Kitajima, H. *Synth. Commun.* **1985**, 223.

0022-3263/86/1951-3439$01.50/0