Competition of Mechanisms in Nucleophilic Substitution of Vinyl Halides. An Unequivocal Example of the Vinylic $S_{RN}1$ Route[1]

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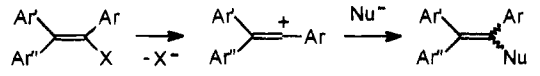
In a search for an unambiguous example of the vinylic $S_{RN}1$ route, several vinyl bromides and iodides were reacted mostly with $^-CH_2COCMe_3$, and sometimes with $^-CH_2COPh$, $^-CH(Me)COEt$, and $(EtO)_2PO^-$ ions, under Fe^{2+}- or photostimulation in Me_2SO. Vinyl halides having *vinylic* hydrogens, such as β-bromostyrene, gave acetylenic products, e.g., phenylacetylene or a tertiary PhC≡C-substituted alcohol, whereas vinyl halides with *allylic* hydrogens, such as $Me_2C{=}C(I)CHMe_2$, gave a substituted allene. Reduction products of the halogen, as well as substitution and rearranged substitution products, were also formed. The operation of ionic elimination–addition routes accounts for formation of most of the products, while the reduction products arise from an intermediate vinyl radical. $Ph_2C{=}C(Br)Ph$ (**20**) and $Me_2C{=}C(Br)Ph$ (**25**) gave both substitution and reduction products, but $Me_2C{=}C(Br)$-*t*-Bu (**23**) gave only a reduction product. Formation of substitution products from the conjugated **20** and **25** was ascribed to a reaction *via* a vinylic $S_{RN}1$ route, while lack of substitution in **23** is related to its nonconjugated system and to the consequent higher energy that the radical anion of the substitution product would have. The one here reported seems to be the first case of an exclusive genuine vinylic $S_{RN}1$ process.

The vinylic system may be regarded as occupying an intermediate position between saturated and aromatic systems.[2] From this feature stems a multiplicity of mechanistic routes of nucleophilic vinylic substitution (S_NV).[2,3] For example, suitable structural features may enable an S_N1-like reaction *via* a vinyl cation (eq 1),[4]



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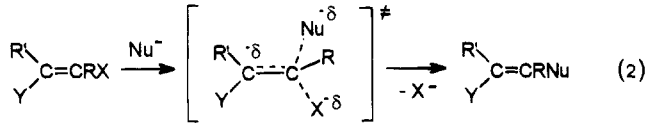
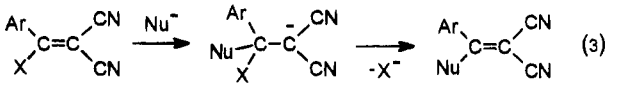
while a single-step, sometimes S_N2-like, route was also suggested (eq 2).[2,3,5,6 a] However, a more common route



(2)

is a multistep nucleophilic addition–elimination[2,3,6] initiated by nucleophilic addition to the double bond to yield a carbanion, which expels the leaving group (e.g., eq 3). Vinyl halides also undergo a variety of elimination–addition routes with an anionic nucleophile. An α,β-elimination to an acetylene (eq 4),[2,3] which subsequently adds the nucleophile, proceeds with greater ease than the analogous aromatic reaction *via* arynes. An α,α-elimination–addition route *via* a carbene (eq 5), or an α,β′-elimination–addition route *via* an allene (eq 6) are also documented.[2]



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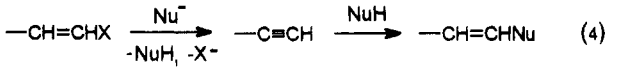

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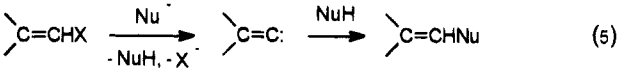

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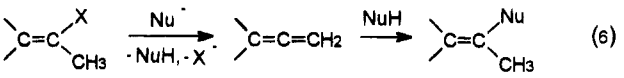

(6)

In comparison with this variegated array of ionic S_NV pathways, examples of substitutions initiated by a SET are scanty.[2] Bunnett and co-workers had extensively investigated the $S_{RN}1$ route which initiates by SET in aromatic systems[7] and presented evidence[8] in favor of a $S_{RN}1$-like pathway by a ketone enolate ion or thiophenoxide ion with some vinyl halides, including β-bromostyrene **1** (cf. Scheme 1, where Vy = vinyl). However, a recent reinvestigation of the reaction of β-bromostyrene with pinacolone enolate ion **2** revealed that the substitution product is formed also by an accompanying nonradical α,β-elimination–addition route,[1,9] so that the operation of a vinylic $S_{RN}1$ route is not unequivocal.

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Scheme 1

$$VyX \xrightarrow{hv/Y^-} VyX^{\bullet -} \quad (M1)$$

$$VyX^{\bullet -} \rightarrow Vy^{\bullet} + X^- \quad (M2)$$

$$Vy^{\bullet} + Y^- \rightarrow VyY^{\bullet -} \quad (M3)$$

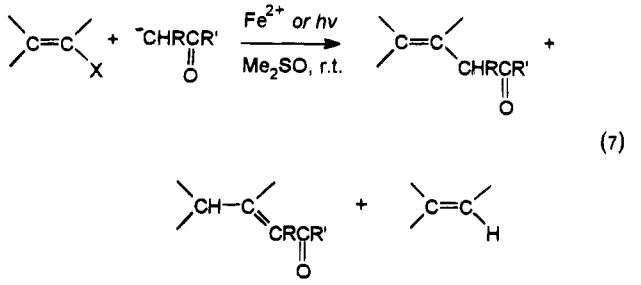
$$VyY^{\bullet -} + VyX \rightarrow VyY + VyX^{\bullet -} \quad (M4)$$

$$Vy^{\bullet} + SH \rightarrow VyH + S^{\bullet} \quad (M5)$$

We now provide experimental details on this reinvestigation and add more examples. By modifying the structure of the substrate, we were able to single out a genuine $S_{RN}1$ pathway of vinylic substitution, but only in the case of *conjugated* vinyl halides. In contrast, *unconjugated* vinyl halides provide products arising only from other mechanistic routes. An explanation of this finding is offered.

Results and Discussion

The general scheme of eq 7 applies for all the reactions studied. A vinyl halide reacts with a 3-fold excess of a nucleophile in Me_2SO solution at room temperature with

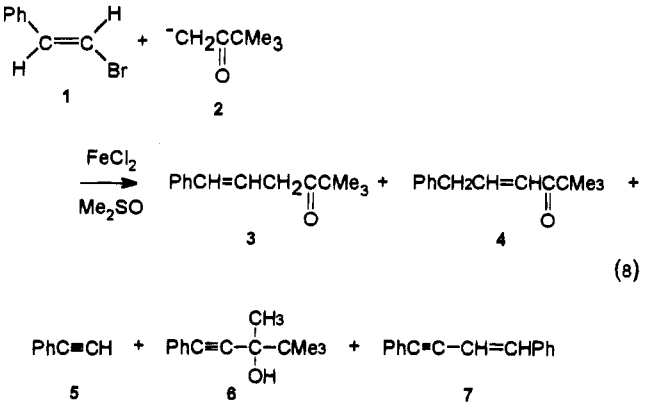


(7)

$FeCl_2$ catalyst[10] ($FeCl_2$/substrate molar ratio = 0.4) or under photostimulation by "350 nm" lamps. The enolate ion **2** of 3,3-dimethyl-2-butanone (pinacolone), generated *in situ* from the parent ketone by the use of an almost stoichiometric amount of *t*-BuOK,[11] was chosen as the reference nucleophile, since it is known to undergo clean $S_{RN}1$ substitution processes in aromatic systems.[12,13] Hydrodehalogenation competes with the nucleophilic substitution to extents which are strongly dependent on the substrate (vide infra). The experiments were run under N_2, and the product compositions were monitored by gas chromatography on samples withdrawn during the reaction. The reaction conditions, the products, and their yields are given in Table 1, where VyX, VyY, and VyH are the precursor halide, its substitution product(s), and its reduction product, respectively.

In analogy with the $S_{RN}1$ scheme of chain substitution of aryl halides, stimulation by ferrous ion[10] or by UV light is required to initiate the electron transfer from the nucleophile (Y^-) to the vinyl halide, forming the vinylic radical anion (Scheme 1).[7,13] Fragmentation of the latter combination of the resulting vinyl radical with the nucleophile to form the product radical anion and subsequent electron exchange of the latter with a substrate molecule had to led to the vinylic substitution product (step M4). Alternatively, competitive hydrogen atom abstraction by the radical from the solvent SH could lead to the reduced product (step M5).

Reactions of Pinacolone Enolate Ion with β-Bromostyrene. To test the above expectations, we effected the ferrous ion stimulated reaction of pinacolone enolate ion (**2**) with the commercially available *trans*-β-bromostyrene (**1**), a substrate which had been employed previously.[8] After 10 min reaction all the substrate had disappeared and five compounds (**3**–**7**) were formed. The major component of the mixture was the tertiary alcohol **6**, which had not been reported in the original investigation[8] (eq 8). The direct substitution product **3**, obtained



mainly in the *E* configuration, which had previously been reported as the main product,[8] and its tautomer **4** were formed in smaller amounts (Table 1, entry 1). Phenylacetylene (**5**), but *not* styrene,[8] and the eneyne **7** were also formed. The amount of **3** and **4** progressively increases with time at the expense of **6** (and **5**), and after 3 h **3** predominates in the mixture.[9] It is possible that the early investigators[8] failed to recognize **6** because they had not sampled the reaction at early stages, but only after 5 h, and also due to the very similar retention times, even on capillary columns, of the structural isomers **3** and **6**. Separation of **3** from **6** by careful column chromatography was made feasible by letting reaction 8 to proceed for only 15 min (to obtain mainly **6**) or for 4 h (to obtain mainly **3** and **4**). The reaction products were characterized by NMR and HRMS.

A product composition very comparable to that of entry 1 was obtained when running reaction 8 under photostimulation, and also with $FeCl_2$ in liquid ammonia (Table 1, entries 2 and 3). Aryl chlorides are generally less reactive than aryl bromides in $S_{RN}1$ processes,[7] but no major difference in reactivity and products distribution was noticed when running reaction 8 with β-chlorostyrene (Table 1, entry 4). This finding, along with the formation of substantial amounts of **5** in reaction 8, and the puzzling formation of **6**, suggested a possible competition between the expected $S_{RN}1$ route and an ionic α,β-elimination–addition substitution route (Scheme 2).[9] Due to the excess of the enolate, a fast *syn* β-elimination of HBr from commercial (*E*)-β-bromostyrene to give **5** would take place. Deprotonation of **5** (pK_a 28.7)[11] and addition of its anion $\mathbf{5}^-$ to the neutral ketone would afford

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(11) The pK_a values quoted in this paper are in Me_2SO and are from private communications of Prof. Bordwell or from: Bordwell, F. G. *Acc. Chem. Res.* **1988**, *21*, 456. Previous studies[12] had shown that a small excess of *t*-BuOK (pK_a 32.2) in Me_2SO is sufficient to convert pinacolone (pK_a 27.7) fully to its enolate ion.

(12) Galli, C.; Bunnett, J. F. *J. Am. Chem. Soc.* **1981**, *103*, 7140.

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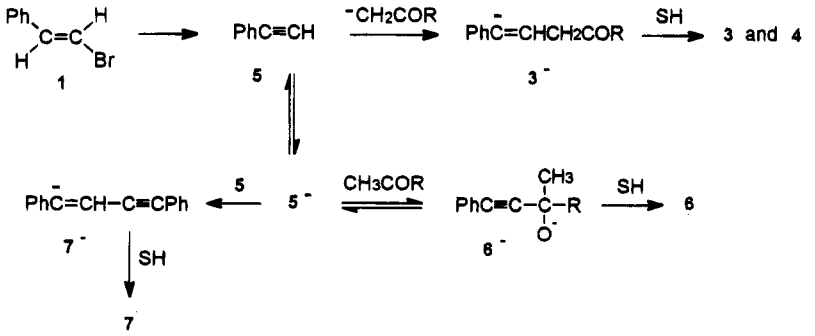
Table 1. Reactions of Nucleophiles and Vinyl Halides[a]

entry no.	substrate (VyX)	nucleophile (Y^-)	stimulant	solvent	reaction time (min)	products yield[b] (%) VyX left[b] (%)	VyH or **5**	VyY[c]	alcohol[d]	others
1	**1**	**2**	$FeCl_2$	Me_2SO	10	0	27	**3** (21) + **4** (7)	**6** (42)	**7** (2)
					60	0	23	**3** (35) + **4** (9)	**6** (21)	**7** (3)
					180	0	16	**3** (45) + **4** (14)	**6** (9)	**7** (6)
2	**1**	**2**	*hν*	Me_2SO	10	0	0.3	**3** (1) + **4** (0.4)	**6** (94)	
					60	0	0.2	**3** (40) + **4** (11)	**6** (45)	
					180	0		**3** (61) + **4** (26)	**6** (6)	
3	**1**	**2**	$FeCl_2$	NH_3	300	9	2	**3** (46) + **4** (18)	**6** (23)	
4	β-chloro-styrene	**2**	$FeCl_2$	Me_2SO	10	0	3	**3** (30) + **4** (12)	**6** (44)	
					60	0	2	**3** (48) + **4** (16)	**6** (20)	
					180	0	0	**3** (71) + **4** (22)	**6** (3)	
5	**5**	**2**	$FeCl_2$	Me_2SO	10		25	**3** (5) + **4** (2)	**6** (61)	**7** (2)
					60		22	**3** (27) + **4** (7)	**6** (38)	**7** (3)
					180		9	**3** (52) + **4** (8)	**6** (8)	**7** (6)
6	**5**	**2**		Me_2SO	10		22	**3** (5) + **4** (2)	**6** (68)	**7** (2)
					60		20	**3** (41) + **4** (8)	**6** (30)	**7** (3)
					180		17	**3** (61) + **4** (8)	**6** (7)	**7** (4)
7[e]	**1**	**2**	$FeCl_2$	Me_2SO	10	0	66	**3** (5) + **4** (1)	**6** (20)	**7** (3)
					180	0	53	**3** (11) + **4** (1)	**6** (19)	**7** (5)
8[e]	**5**	**2**	$FeCl_2$	Me_2SO	10		59	**3** (3) + **4** (0)	**6** (33)	**7** (2)
					180		46	**3** (21) + **4** (4)	**6** (21)	**7** (4)
9	**1**	**2**		Me_2SO	10	0	28	**3** (20) + **4** (3)	**6** (42)	**7** (2)
					180	0	12	**3** (41) + **4** (12)	**6** (10)	**7** (4)
10[f]	**1**	**2**	$FeCl_2$	Me_2SO	180	40	41	**3** (0) + **4** (0)	**6** (14)	
11[g]	**1**	**2**	$FeCl_2$	Me_2SO	10	0	23	**3** (19) + **4** (7)	**6** (48)	
					180	0	9	**3** (63) + **4** (16)	**6** (9)	**7** (2)
12	**1**	$CH_3\bar{C}HCOEt$	$FeCl_2$	Me_2SO	10	0	28	**8** (4) + **9** (17)	**10** (39)	
					60	0	20	**8** (32) + **9** (6)	**10** (13)	**7** (3)
					180	0	18	**8** (17) + **9** (0)	**10** (8)	**7** (4)
13	**1**	$^-CH_2COPh$	$FeCl_2$	Me_2SO	10	7	3	**11** (5) + **12** (9)		
					60	2	5	**11** (4) + **12** (18)		
					180	1	7	**11** (16) + **12** (45)		
14	**5**	$^-CH_2COPh$	$FeCl_2$	Me_2SO	10		60	**11** (6) + **12** (3)		
					60		54	**11** (8) + **12** (6)		
					180		22	**11** (16) + **12** (44)		
15	**1**	$(EtO)_2PO^-$	$FeCl_2$	Me_2SO	10	85	11			
					180	88	12			
16[h]	**1**	$(EtO)_2PO^-$ + **2**	$FeCl_2$	Me_2SO	3	42	39		**6** (14)	
17	**1**	$(EtO)_2PO^-$	*hν*	Me_2SO	10	0	50			
18	**13**	**2**	$FeCl_2$	Me_2SO	10	55				**15**[i]
					60	13				**15**[i]
					180	4				**15**[i]
19	**13**	**2**	*hν*	Me_2SO	180	16				**15**[i]
20	**13**	**2**	*hν*	NH_3	45	34				**15**[i]
21[e]	**13**	**2**	$FeCl_2$	Me_2SO	10	82				**15**[i]
					60	62				**15**[i]
22	**13**	**2**		Me_2SO	10	74				**15**[i]
					60	56				**15**[i]
23	**16**	**2**	$FeCl_2$	Me_2SO	10	25	**17**[i]			
					60	9	**17**[i]			
24	**16**	**2**	*hν*	Me_2SO	10	60	**17**[i]			
					60	10	**17**[i]			
25[e]	**16**	**2**	$FeCl_2$	Me_2SO	10	101				
					180	72		**19**[j]		
26	**20**	**2**	*hν*	Me_2SO	10	53	**22** (2)	**21** (38)		
					60	34	**22** (4)	**21** (55)		
27[e]	**20**	**2**	*hν*	Me_2SO	10	96	**22** (1)	**21** (1)		
					60	93	**22** (4)	**21** (2)		
28	**20**	**2**	$FeCl_2$	Me_2SO	10	79	**22** (16)	**21** (1)		
					60	71	**22** (21)	**21** (2)		
29	**23**	**2**	$FeCl_2$	Me_2SO	10	24	**24** (71)			
					60	20	**24** (76)			
30	**23**	**2**	*hν*	Me_2SO	10	17	**24** (62)			
					60	15	**24** (43)			
31	**25**	**2**	$FeCl_2$	Me_2SO	10	21	**29** (19)	**27** (10) + **26** (6) + **28** (2)		
					60	1	**29** (28)	**27** (14) + **26** (6) + **28** (3)		
32	**25**	**2**	*hν*	Me_2SO	10	16	**29** (14)	**27** (12) + **26** (7) + **28** (3)		
					60	4	**29** (17)	**27** (10) + **26** (4) + **28** (2)		
33[j]	**25**	**2**	$FeCl_2$	Me_2SO	10	0	**29** (32)	**27** (34) + **26** (20) + **28** (6)		
					60	0	**29** (25)	**27** (27) + **26** (11) + **28** (4)		

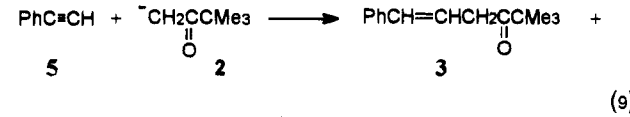
[a] Typical conditions: VyX, 0.5 mmol; Y^-, 1.6 mmol; $FeCl_2$, 0.21 mmol; Me_2SO, 25 mL. [b] By GLC; typical uncertainty, ±4%. [c] Substitution product(s). [d] Addition product. [e] In the presence of 0.2 mmol of *p*-dinitrobenzene. [f] 1.1 mmol of enolate ion. [g] 2.2 mmol of enolate ion. [h] 1.0 mmol of enolate ion; 1.0 mmol of $(EtO)_2PO^-$. [i] Not quantified. [j] 2.6 mmol enolate ion.

Scheme 2



6^-, the conjugate base of **6**, in a fast but reversible step. Addition of 5^- to **5** will give 7^-. A presumably slower but irreversible addition of **2** to **5** would lead to **3** and to its tautomer **4** *via* 3^-. Protonation of the anionic intermediates gives the final products. As a consequence of competition between the fast reversible formation of **6** and the slower irreversible formation of **3** + **4**, the amount of the latter will increase at the expense of **6** with time, as was indeed observed. A check experiment was conducted with the enolate ion of acetone, which had been previously used as nucleophile.[8] A distribution of products qualitatively analogous to those reported for **2** was observed by GC–MS, where again the amount of a compound, presumably $PhC{\equiv}CC(OH)Me_2$ (showing a $M^+ - H_2O$ *m/z* ion fragment), decreased with time, while the amounts of the tautomeric substitution products $PhCH{=}CHCH_2COCH_3$ and $PhCH_2CH{=}CHCOCH_3$ (both having $M^+ - COCH_3$ ion fragments) increased. This reaction was not investigated in detail.

Since **5** is a key intermediate in the proposed elimination–addition route (Scheme 2), support for its role is required. Indeed, reaction of **5** with **2** (eq 9) in the



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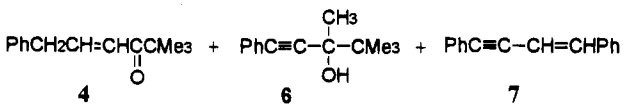
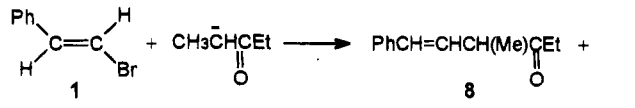


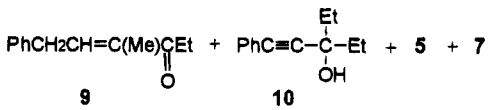
presence[14] or absence of Fe^{2+} ion gave the same products with a similar distribution as in the reaction of **1** with **2** (Table 1, entries 5 and 6), confirming the pivotal role of **5** as well as the lack of effect of ferrous stimulation in the ionic elimination–addition route. When reaction 8 was conducted in the presence of the electron scavenger *p*-dinitrobenzene, the yield of **6** was largely unaffected, while the yield of the substitution products **3** + **4** was *depressed* but not completely *suppressed* (Table 1, entry 7; see also entry 8). The ionic elimination–addition pathway to **6** and to **3** + **4** should not be affected by the scavenger, while the $S_{RN}1$ route (leading to **3** + **4**) should be suppressed due to interception of the ET in steps M1 and M4.[7] Finally, reaction of **1** with **2** in the absence of ferrous catalysis or of photostimulation did provide **3** + **4** and **6** in amounts (Table 1, entry 9) not far from the catalyzed experiments (Table 1, entries 1 and 2). We therefore conclude, in contrast to previous conclusions,[8] that the substitution products **3** + **4** are mainly formed by the elimination–addition route. Even if part of them arises from a vinylic $S_{RN}1$ route, β-bromostyrene is not the substrate of choice for observing an exclusive and unambiguous $S_{RN}1$ vinylic substitution route.

In spite of its mechanistic complexity, reaction 8 does have synthetic allure: after 4 h at room temperature, the alcohol **6** and also **5** have almost disappeared and the yield of the two tautomers **3** + **4** ranges from 60 to 90% (Table 1, entry 4, at 3 h). This is quite satisfactory for a simple one pot C–C bond-forming reaction occurring under mild conditions, especially when the precursor is an unactivated vinyl halide. The yields depend on the enolate:substrate ratio and increase on increasing the excess of enolate from a 2:1 ratio (Table 1, entry 10), through the "standard" 3:1 ratio (Table 1, entry 1) to 4:1 ratio (Table 1, entry 11). No aldol condensation products were ever observed, which is also the case in general in aromatic $S_{RN}1$ reactions.[7,13]

Reactions of Other Nucleophiles with β-Bromostyrene. The effect of the structure of the nucleophile was tested by reacting **1** with the enolate of 3-pentanone (eq 10). The distribution of the products **5**, **7**, and **8**-**10**

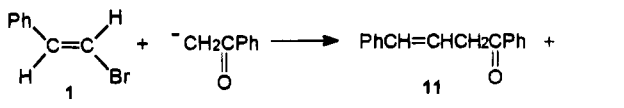


(10)

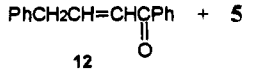


obtained (Table 1, entry 12) qualitatively resembles that of the analogous products obtained in reaction 8.

In contrast with the reaction of the aliphatic enolates, reaction of the enolate of acetophenone (eq 11) gave the



(11)



unrearranged **11** and the rearranged **12** substitution products and **5**, but no tertiary alcohol and no **7**; some of the starting material was recovered (Table 1, entry 13).

(14) The $FeCl_2$ in this experiment was added in order to use conditions as similar as possible to the conditions of entry 1 (where $FeCl_2$ is present), with which comparison is made.

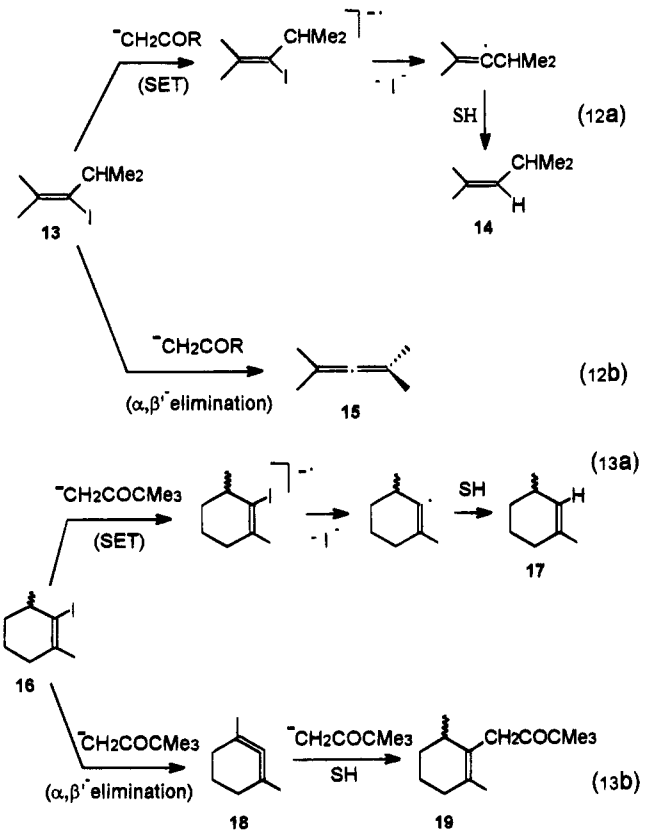
This may reflect the higher acidity of acetophenone (pK_a 24.7)[11] than of pinacolone (pK_a 27.7),[11] which makes the HBr elimination from **1** to **5** more difficult and, above all, the subsequent deprotonation of **5** (pK_a 28.7)[11] very unfavorable. If the equilibrium concentration of $\mathbf{5}^-$ is low, formation of the tertiary alcohol cannot compete with formation of **11** and **12** by the $S_{RN}1$ and by the ionic addition routes (compare with the analogous case of **2** in Scheme 2). A control experiment corroborates this conclusion. Reaction of $PhCOCH_2^-$ with **5** (Table 1, entry 14; see eq 9 for an analogous case) gives no tertiary alcohol. The lower conversion to **11** and **12** (Table 1, entries 13 and 14) is ascribed to the lower nucleophilicity of $^-CH_2COR$ when R = Ph than when R = *t*-Bu in the addition step to **5**.

Diethyl phosphite ion gave no Fe^{2+}-induced reaction with **1** (Table 1, entry 15), but part of the substrate was converted to **5** in a $(EtO)_2PO^-$-initiated elimination. The sluggishness of this process is ascribed to the lower basicity[15] of $(EtO)_2PO^-$ compared with a ketone enolate. In a competitive experiment of $(EtO)_2PO^-$ and **2** for **1**, only **5** and **6** (a **2**-derived product) were formed (Table 1, entry 16) with no $(EtO)_2PO$-incorporation product. This is surprising since in the $S_{RN}1$ reaction of aryl halides $(EtO)_2PO^-$ is a well-behaved nucleophile,[7] which is more reactive than enolate ions in competition experiments.[12] Photostimulation improved the efficiency of the hydrodehalogenation of **1** with $(EtO)_2PO^-$ (Table 1, entry 17).

Interference by α,β′-Elimination. It is clear from above that the ionic elimination–addition route should be excluded in a search for an unambiguous vinylic $S_{RN}1$ route. Hence, 2,4-dimethyl-3-iodo-2-pentene (**13**), which lacks a vinylic hydrogen, was prepared and investigated. Surprisingly, its reaction with **2** gave no substitution product either under Fe^{2+} or *hν* stimulation in Me_2SO or in liquid NH_3 (Table 1, entries 18–20). However, **13** was consumed in these experiments, in a process which was retarded but not suppressed in the presence of the electron scavenger *p*-$C_6H_4(NO_2)_2$ (Table 1, entry 21). This indicates that electron-induced deiodination takes place, but that the resulting vinyl radical is involved in a process faster than capture of the nucleophile, such as, for example, H-atom abstraction to give **14**.[16]

The loss of the vinyl iodide **13** in the presence of $FeCl_2$ (Table 1, entry 18) or in the absence of any form of catalysis (Table 1, entry 22) follows semiquantitatively the same pattern, thus confirming the presence of an ionic reaction accompanying the electron-induced one. A GC–MS analysis of the crude reaction product revealed ca. 10–20% of a compound, with a GC retention time very close to that of the solvent, whose molecular ion and fragmentation pattern were consistent with 2,4-dimethyl-2,3-pentadiene (**15**). The most plausible mechanism for the formation of allene **15** is an ionic α,β′-elimination (eq 12b; cf. eq 6), competing with the loss of **13** by the radical reduction route (eq 12a).

The reaction of 1,3-dimethyl-2-iodocyclohexene (**16**) with **2** took a similar course with a slight variation (eq 13). The hydrodeiodination product **17** is formed in ca.



5–10% yield according to GC–MS analysis (Table 1, entries 23 and 24). In the presence of *p*-dinitrobenzene, less **16** was consumed and **17** was not formed. Instead, a new peak of ca. 5–10% appeared in the GC–MS analysis, which displayed a molecular ion and a fragmentation pattern consistent with the substitution product **19** (Table 1, entry 25). We conclude that, in analogy with the behavior of **13** and in spite of the cyclic structure of **16**, an α,β′-elimination–addition route (eq 13b) *via* the bent allene 1,3-dimethyl-1,2-cyclohexadiene (**18**) takes place. Such reaction has precedents, even in a cyclohexenyl system.[17] This route competes with the radical reduction (eq 13a). Suppression of the latter by *p*-dinitrobenzene enabled the formation of the substitution product **19** by nucleophilic addition to the central carbon[17] of **18** (eq 13b). That **18**, but not **15**, adds the nucleophile is probably due to the relief of strain in the reaction of the former. The vinyl radicals formed in the radical pathway of both **13** and **16** do not react with the nucleophile, but instead abstract hydrogen atom from the medium.

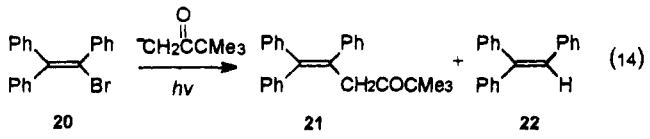
The $S_{RN}1$ Route. Both **13** and **16**, which give no $S_{RN}1$ substitution, are *unconjugated* vinyl halides, whereas the *conjugated* **1** gives some $S_{RN}1$ substitution (Table 1, entry 1). The question arises if this structural difference is responsible for the different chemical behavior. We therefore prepared the conjugated vinyl halides triphenylvinyl bromide (**20**) and 1-bromo-1-phenyl-2-methylpropene (**25**), and the nonconjugated halide 1-bromo-2,4,4-trimethyl-2-butene (**23**), all of which lack β- and β′-hydrogens, and studied their substitution.

Photostimulated reaction of **20** with **2** (eq 14; Table 1, entry 26) indeed gave 38–55% yield of the substitution

(15) A pK_a of 15 is given by Hammond, P. R. *J. Chem. Soc.* **1962**, 1365.

(16) (a) We have no direct evidence for formation of **14**: its presumably low bp makes coelution with the solvent during GC analysis very likely, as also suggested by the low mass balance. (b) Low recovery of reaction products after long reaction times was sometimes observed (vide infra); we cannot exclude interference by side processes, such as radical polymerization of the vinylic compounds.

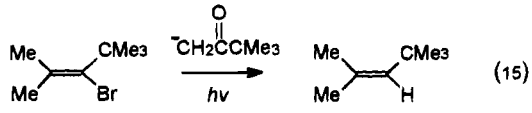
(17) Bottini, A. T.; Corson, F. P.; Fitzgerald, R.; Frost K. A., Jr. *Tetrahedron* **1972**, *28*, 4883.



(14)

product **21**,[18] along with 2–4% of the hydrodebromination product **22**. Strong inhibition by the electron scavenger was observed, with almost complete recovery of **20** (Table 1, entry 27). However, under ferrous ion catalysis the reduction product **22** became predominant (Table 1, entry 28). A reduction of the radical intermediate of the $S_{RN}1$ cycle by Fe^{2+} to a carbanion (which is then protonated) is possible and was already documented.[10a]

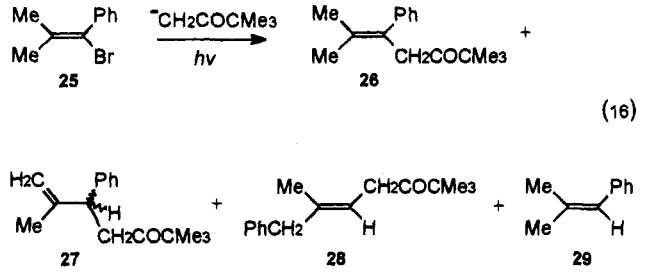
In contrast, both the Fe^{2+}- and *hν*-induced reaction of **23** with **2** gave only the hydrodebromination product **24** (Table 1, entries 29 and 30) (eq 15). Formation of **24** is



(15)

significantly inhibited (by ca. 50%) in the presence of a 40% molar amount of *p*-dinitrobenzene. We conclude that ET-induced dehalogenation took place with both **20** and **23** but that only in the case of the conjugated **20** the intermediate radical was involved in the $S_{RN}1$ route of Scheme 1. This is consistent with the behavior of **1** as compared with **13** and **16** and is corroborated by the results of the reaction of **25**.

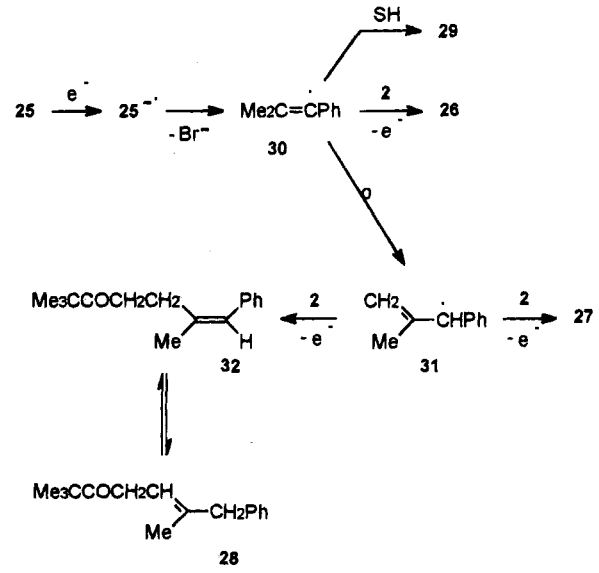
The reaction of **25** with **2** was more complicated.[16b] The substitution product **26** was indeed isolated in 6% yield, but two of its isomers **27** and **28**, the former (10% yield) predominating over the latter (2%), were also formed (Table 1, entry 31) together with the hydrodebrominated product **29** (19%) (eq 16). As with **23**, both the Fe^{2+}- and



(16)

the *hν*-stimulated techniques gave analogous results (Table 1, entries 31 and 32), and 40% molar amount of the ET scavenger inhibited the reaction (by ca. 50%). *Increase of the enolate/substrate ratio to 5 gave higher* conversion to products (Table 1, entry 33). Scheme 3 gives a tentative explanation to the observed reaction course. The radical anion $\mathbf{25}^{\bullet-}$ is formed by ET and loses Br^- to give the radical **30**, which partitions to three reaction routes. Hydrogen abstraction from the solvent

Scheme 3



gives **29**, reaction with the nucleophile gives the substitution product **26**, and rearrangement by a 1,3-hydrogen shift[20] presumably produces the radical **31**. The latter gives the major rearranged substitution product **27**, thus adding a new variant to the multitude of vinylic substitution reactions,[2] or reacts with the nucleophile at C*γ* to give another rearranged substitution product (**32**). This product is not isolated but undergoes an allylic rearrangement to an *E*/*Z* mixture of its isomer **28**. The reason for this shift from the more conjugated to the less conjugated isomer is not obvious and may be due to reduced steric hindrance around the double bond. All the products were isolated and characterized.[16b]

$S_{RN}1$ vs Other Substitution Routes. Two important conclusions arise from the present study. First, as found in other systems,[2] substitution in unactivated vinylic substrates frequently occurs by elimination–addition routes when vinylic or allylic hydrogens are present. We find now that these processes occur and even predominate under ET conditions. Second, once these competitive ionic routes cannot take place, an unambiguous evidence for the operation of a vinylic $S_{RN}1$ route is found. Comparison with aryl halides shows that their $S_{RN}1$ route is much less affected by competitive ionic route,[7,13] probably due to the strain in the cyclic intermediate formed in the elimination in aromatic systems.

Why do only conjugated vinyl halides undergo the $S_{RN}1$ route in our case? Obviously, a conjugated vinyl halide is easier to reduce (e.g., for **1** the reduction potential is −1.98 V vs SCE)[21] than an unconjugated vinyl halide, where the reduction potential is more negative than −2.4 V (for bromo and chloro derivatives).[22] However, this

(18) Steric inhibition of coplanarity[19] of the three phenyl groups in **20** certainly reduces, but does not suppress, conjugation with the double bond: see the well-known case of the trityl cation (Koh, L. L.; Eriks, K. *Acta Crystallogr.* **1971**, *B27*, 1405).

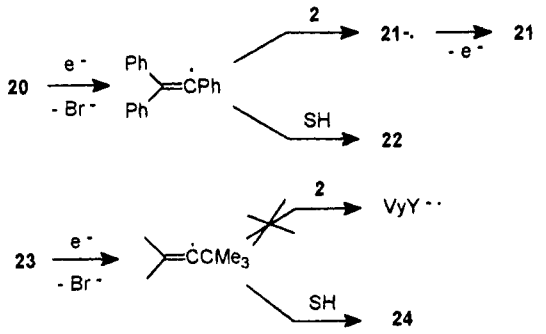
(19) As an example, in triarylethylenes more crowded than **20**, the Ar–C=C torsional angles are usually 50–60° (Kaftory, M.; Biali, S. E.; Rappoport, Z. *J. Am. Chem. Soc.* **1985**, *107*, 1701). For the closely related $Ph_2C{=}C(Br)C_6H_4OMe$-*p*, the torsion angles are 47.6°, 68.6°, and 46.8° (Kaftory, M.; Apeloig, Y.; Rappoport, Z. *J. Chem. Soc., Perkin Trans. 2* **1985**, 29). Indeed, our MM calculations for **20** indicate Ph–C=C torsional angles of 44°, 60°, and 50°.

(20) Hydrogen rearrangements in radicals are uncommon; see: (a) Giese, B. In *Radicals in Organic Synthesis: Formation of C–C Bonds*; Baldwin J. E. Ed.; Organic Chemistry Series; Pergamon Press: Oxford, 1986; Vol. 5, p 20. (b) Wilt, J. W. In *Free Radicals*; Kochi, J. K., Ed.; Wiley-Interscience: New York, 1973; Vol. 1, Chapter 8, Free Radical Rearrangement. However, tautomerization in radical cations of alkenes has been reported: (c) Arnold, D. R.; Mines, S. A. *Can. J. Chem.* **1987**, *65*, 2312.

(21) Polarography gives −1.98 V for **1** and −1.60 V for **20** *vs* SCE in DMF: Miller, L. L.; Riekena, E. *J. Org. Chem.* **1969**, *34*, 3359. Recent determination of the reduction potentials of the same compounds by cyclic voltammetry in THF *vs* SCE gives −2.24 and −1.86 V, respectively (Gentili, P. Work in progress).

(22) *Encyclopedia of Electrochemistry of the Elements*; Bard, A. J., Lund, H., Eds.; M. Dekker: New York, 1980; Vol. XIV.

Scheme 4



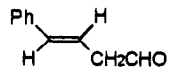
feature does not explain the results, since both **20** and **23** do afford the hydrodehalogenation product from an ET step. Consequently, under both modes of initiation, *both* halides form a radical anion which loses X^- to form the vinyl radical. That both vinyl radicals derived from **20** and **23** are formed by ET is corroborated by the inhibition by the electron scavenger. The partition to different routes and products is determined at a later stage, when the unconjugated vinyl radical is involved only in H-atom abstraction (to give **24**), while the conjugated vinyl radical mainly (but not exclusively) combines with the nucleophile to give the radical anion of the substitution product (i.e., $\mathbf{21}^{\bullet-}$) which then gives **21** (Scheme 4).

The odd electron in $\mathbf{21}^{\bullet-}$ is in a σ^* SOMO, but intramolecular ET from the σ^* to the π^* MO is feasible.[12,13,23] The π^* MO encompasses the vinylic system as well as unsaturated moieties attached to it, such as the phenyl group(s) of **21**, **26**, or **3**, thus increasing the stability of the radical anion compared with that derived from an unconjugated vinylic precursor and making easier the formation of the substitution products deriving from a conjugated radical anion. The unconjugated radical anion of the *unobserved* substitution product from **23** is likely to be of higher energy than that formed from **20**, and consequently, the H-abstraction route becomes competitive and even exclusive, in this case.

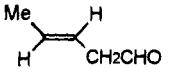
A multiple conjugation increases the stability of a π-system, and particularly lowers its LUMO: this is beneficial to the $S_{RN}1$ substitution, since the odd electron in the radical anion resides in a LUMO orbital.

MO Calculations. Support for this explanation comes from calculation of the LUMO energies of the possible products derived from either a conjugated or a nonconjugated double bond. Whereas the orbitals of interest would be the SOMO's of the two radical anions, energy calculations for odd-electron species are more ambiguous and more complicated than calculations of closed shell neutral species. Hence, we calculated the LUMO's of the neutral products, assuming that the order of energies will be qualitatively parallel to the energies of the SOMO's of the corresponding radical anions. In order to reduce the time of the calculation, we adopted the *simplified* model structures **33** and **34**, respectively, of our actual conjugated and unconjugated products.

An *ab initio* calculation was performed with the Gaussian-90 program,[24a] with the 6-31G* basis set, and a fixed geometry for the molecules with standard bond lengths and angles. The LUMO energies obtained were 3.2 eV for **33** and 4.2 eV for **34**. We believe that even



33



34

with the approximations involved, a gap of 1 eV is sufficiently large to reflect the qualitative order of the energies of the SOMO's of the radical anions derived from **33** and **34**. The values are in the direction anticipated, i.e., the radical anion derived from the unconjugated product **34** would be of a much higher energy than that derived from **33**. Consequently, its formation is hampered compared with the hydrogen abstraction pathway by the precursor radical (in Scheme 4), a pathway of presumably lower energy. In contrast, competition between the two pathways will have higher probability in the conjugated vinyl radical.

Semiempirical calculations on **33** and **34**, by employing the commercially available package HyperChem[24b] which initially optimizes the geometries, confirm the outcome of the *ab initio* calculations. In this case, the energies were −0.36 and 0.73 eV,[25] the LUMO of the conjugated "product" **33** being again ca. 1.1 eV lower than that of the "product" **34**.

Conclusions. Our investigation gives additional examples to the well-known competition of several nucleophilic vinylic substitution routes of unactivated substrates,[2] corrects a previous claim for a vinylic $S_{RN}1$ variant, but finds an unambiguous example for it in another system. We notice that other systems, for which the $S_{RN}1$ vinylic reaction was previously suggested by Bunnett and co-workers,[8] are nonconjugated. Competition of other non-$S_{RN}1$ routes for several of them, or for other few systems where the $S_{RN}1$ route was invoked or implied,[26] cannot be unequivocally excluded. We concede that we cannot foresee at present how general our conclusions are.

The study left unaddressed the question of stereochemistry in the vinylic $S_{RN}1$ reaction and, in particular, the stereochemistry of the vinyl radical and the possible rotation in the intermediate radical anions. The vinyl radical may retain an sp^2 bent geometry, but an sp-hybridization and linear geometry at C_α are more plausible, judging by analogy with vinyl cations, where the linear ion is more stable than the bent ion.[4d,27] Conflict-

(23) Riederer, H.; Hüttermann, J.; Symons, M. C. R. *J. Chem. Soc., Chem. Commun.* **1978**, 313.

(24) (a) GAUSSIAN 90: Frisch, M. J.; Head-Gordon, M.; Trucks, G. W.; Foresman, J. B.; Schlegel, H. B.; Raghavachari, K.; Robb, M. A.; Binkley, J. S.; Gonzalez, C.; Defrees, D. J.; Fox, D. J.; Whiteside, R. A.; Seeger, R.; Melius, C. F.; Baker, J.; Martin, R. L.; Kahn, L. R.; Stewart, J. J. P.; Topiol, S.; Pople, J. A. Gaussian, Inc., Pittsburgh, PA, 1990. (b) HyperChem is a trademark of Autodesk, Inc., 2320 Marinship Way, Sausalito, CA 94965; see: Teppen, B. J. *J. Chem. Inf. Comput. Sci.* **1992**, *32*, 757.

(25) For a comparison with compounds presenting similar structural features, the LUMO energies of styrene and ethylene are 0.26 and 1.73 eV, respectively, from electron transmission spectroscopy (Distefano, G.; Giumanini, A. G.; Modelli, A.; Poggi, G. *J. Chem. Soc., Perkin Trans. 2* **1985**, 1623): an energy gap of ca. 1.5 eV is present, in good agreement with our calculations for **33** and **34**.

(26) (a) Hershberger, J.; Russell, G. A. *Synthesis* **1980**, 475. (b) Berdinkov, E. A.; Vafina, A. A.; Polushina, V. L.; Zaripova, F. R.; Tantasheva, F. R.; Il'yasov, A. V. *Bull. Acad. Sci. USSR, Div. Chem. Sci.* **1981**, *30*, 2320.

(27) (a) Apeloig, Y.; Schleyer, P. v. R.; Pople, J. A. *J. Org. Chem.* **1977**, *42*, 3004. (b) Mayr, H.; Schneider, R.; Wilhelm, D.; Schleyer, P. v. R. *Ibid.* **1981**, *46*, 5336. Recent calculations had shown that the bridged parent vinyl cation is more stable than the linear ion: (c) Pople, J. A. *Chem. Phys. Lett.* **1987**, *137*, 10. (d) Lindh, R.; Rice, J. E.; Lee, T. J. *J. Chem. Phys.* **1991**, *94*, 8008.

ing evidence on this point appears in the literature.[20b,28] After delineating here the structural requirements of the vinylic $S_{RN}1$ reaction, we plan to study in the future *E*/*Z* pairs of appropriate vinylic substrates in order to probe the stereochemical questions.

Experimental Part

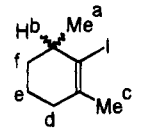
Instrumentation. NMR spectra were taken in $CDCl_3$ on Bruker WP 80 SY or AC 300 instruments and on a Varian XL 300 instrument. IR spectra (in $CHCl_3$) were recorded with a Nicolet 510 FT-IR instrument. GLC analyses were performed on two capillary columns, namely, a 25 m × 0.20 mm methyl silicone gum and a 30 m × 0.25 mm SE-54. Preparative GC separations were executed on a Carlo Erba Fractovap ATC/f gas chromatograph, fitted with a 2 m × 4 mm SE-30 packed column. GC–MS analyses were performed on a HP 5980 gas chromatograph equipped with a 12 m × 0.20 mm methyl silicone gum capillary column and coupled to a HP 5970 mass selective detector. HRMS determinations were carried out on a Extrel 2001 ICR spectrometer, equipped with a double cell and operating at 8 T. A RISC/6000 Model 550 computer was employed to perform the calculations with the Gaussian-90 program. A Rayonet RPR-100 reactor, equipped with 16 lamps emitting in the 350 nm region (Pyrex filtered) was employed for photochemical induction of the reactions.

Materials. Commercially available (*E*)-β-bromostyrene (Janssen) and (*E*)-β-chlorostyrene (ICN Biomedicals) were used as received.[29] The ketones employed as nucleophiles were distilled from anhydrous K_2CO_3. Freshly sublimed *t*-BuOK was used to generate the enolate ions. Ferrous chloride was dried in a drying pistol over P_2O_5 at 110 °C under vacuum. Commercial Me_2SO (C. Erba RPE, 99.5%) was thoroughly purged with argon for 1 h prior to use to remove volatile acidic impurities (thiols), while distillation from CaH_2 proved to be less satisfactory.[10a] Ammonia was distilled from sodium directly into the reaction flask.

Synthesis of Reactants. Triphenylvinyl bromide (**20**) was prepared according to Koelsch.[30] Compounds **13** and **16** were prepared according to the method of Pross and Sternhell[31] by treating the hydrazones of diisopropyl ketone (Fluka) and of 2,6-dimethylcyclohexanone (Aldrich), respectively, with iodine and triethylamine. Further treatment of the reaction mixtures with *t*-BuOK in boiling *t*-BuOH removed the diiodo derivatives.[8] Chromatography on silica gel with 1:1 petroleum ether 40–70 °C/$CHCl_3$ eluent gave pure **13** and **16**, in 18% and 2% overall yields, respectively.

3-Iodo-2,4-dimethyl-2-pentene (13): MS m/z 224 (M^+; 30), 97 ($M^+ - I$; 27), 55 ($Me_2C{=}CH^+$; 100); ^1H NMR δ 2.3 (m, 1H, CH), 1.9 (s, 3H, Me *cis* to I), 1.8 (s, 3H, Me *trans* to I), 0.9 (d, 6H, Me_2CH).

2-Iodo-1,3-dimethylcyclohexene (16): MS *m*/*z* 236 (M^+; 77), 109 ($M^+ - I$; 100), 79 ($M^+ - I - 2Me$; 40), 67 ($M^+ - I - CMe_2$; 87); ^1H NMR δ 2.6 (m, 1H, H^b), 2.1 (m, 2H, CH_2^d), 1.8 (bs, 3H, Me^c), 1.2 (d, 3H, Me^a), 1.6–0.9 (m, 4H, CH_2^e and CH_2^f).



Attempted Preparation of 1-Iodo-1-phenyl-2-methylpropene. Attempts to prepare this compound, the iodo analogue of **25**, by Pross and Sternhell's method[31] gave only low yields. Reaction of isopropyl phenyl ketone with hydrazine gave mainly the corresponding azine rather than the hydrazone. When this crude material reacted with iodine and triethylamine, a mixture containing the vinyl iodide admixed with unreacted ketone and other impurities, whose separation was difficult, was obtained. Due to the poor yield (ca. 8%), this procedure was abandoned.

1-Bromo-1-phenyl-2-methylpropene (25). Synthesis of **25** was carried out by bromination[32] of 3 mL (20 mmol) of 2-methyl-1-phenylpropene (Aldrich; **29**) with 1 mL of Br_2 (20 mmol) in 2 mL of CCl_4 and subsequent dehydrobromination[33a] of the dibromo derivative (3.2 g; 11 mmol) with 1.7 g of KOH powder (26 mmol) and 18-crown-6 (26 mg; 0.1 mmol) in 10 mL of petroleum ether at ca. 40 °C for 8 h. After distillation of the crude product, bp 46–48 °C (at 1–2 Torr), **25** was still slightly contaminated with precursor **29**, and it was finally purified by preparative gas chromatography, giving 450 mg (19% yield) of pure **25**: ^1H NMR δ 7.3–7.2 (m, 5H, Ph), 2.05 (s, 3H, CH_3 *cis* to Br), 1.72 (s, 3H, CH_3 *trans* to Br); HRMS 212.0017, $C_{10}H_{11}{}^{81}Br$ requires 212.0018.

3-Bromo-2,4,4-trimethyl-2-pentene (23). Bromination[32] of commercial (Aldrich) 2,4,4-trimethyl-2-pentene (**24**) (9.5 mL; 61 mmol) with 3.5 mL of Br_2 (66 mmol) in 7 mL of CCl_4 and subsequent dehydrobromination[33b] of the dibromo derivative (12.6 g; 46 mmol) with 10 g of *t*-BuOK (90 mmol) and 18-crown-6 (25 mg; 0.1 mmol) in boiling hexane (45 mL) for 2 h gave a brown liquid which was distilled (bp 86–89 °C at 50 Torr) and then chromatographed on silica gel using graded mixtures of petroleum ether and CH_2Cl_2 and finally purified by preparative gas chromatography to give 400 mg (4% yield) of **23**: IR 1605 (C=C); ^1H NMR δ 1.94 (s, 3H, Me), 1.93 (s, 3H, Me), 1.33 (s, 9H, CMe_3); ^{13}C NMR 133.4 (BrC=), 129.9 (Me_2C=), 40.1 (CMe_3), 32.1 (CMe_3), 30.3 (CH_3 *trans* to Br), 22.6 (CH_3 *cis* to Br); HRMS 192.0329, $C_8H_{15}{}^{81}Br$ requires 192.0331.

General Procedure. Details on the ferrous stimulated reactions have been given before.[10] Experiments under photostimulation were conducted similarly. Quantitative GC analyses were done by the internal standard (i.e., biphenyl) method; authentic samples of the products were employed for determination of the gas chromatographic response factors. The yields given in Table 1 are the average of at least three injections (typical error: ±4%).

Synthesis of Products. According to convenience, either the reaction scheme of eq 7 or that of eq 9 was used to synthesize the products. Separation of the *isomeric* reaction products by column chromatography was in general troublesome: very often, only small portions of the compounds had GC purity (on capillary columns) above 95%; in addition, some of the products were obtained in minute amounts. In early attempts of characterization, samples of the more abundant compounds were subjected to microanalyses, but the values obtained were unreasonably wrong (10–20% off) in spite of gas chromatographic purity (≥99%) and appropriate NMR spectrum. It is likely that the vinylic compounds are thermally labile, and some decomposition and/or polymerization can occur. HRMS was therefore adopted for the determination of elemental compositions of chromatographically pure samples. However, structural assignment was based mainly upon ^1H and ^{13}C NMR spectroscopies, particularly in the case of the isomeric compounds; accordingly, HRMS was taken only on the most abundant among the isomers. Interpretation of NMR spectra in difficult cases was aided by decoupling experiments, to clarify coupling patterns in the ^1H NMR spectra, and by APT or DEPT experiments, to clarify multiplicity in the ^{13}C NMR spectra. Carbon and proton NMR spectra are included in the supplementary material to demonstrate the purity of each compound.

Products 3, 4, 6, and 7. (a) Reaction of 1.9 g of pinacolone (19 mmol), 2.6 g of sublimed *t*-BuOK (23 mmol), 0.35 g of dried $FeCl_2$ (2.7 mmol) and 1.16 g of (*E*)-β-bromostyrene (6.2 mmol) in 50 mL of Me_2SO at room temperature was quenched after 4 h by addition of salted water. The solution was extracted with diethyl ether, washed with water, dried (Na_2SO_4), and

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(29) Analysis by GC–MS revealed that the commercial samples were 90/10 and 80/20 *E*/*Z* mixtures, respectively.

(30) Koelsch, C. F. *J. Am. Chem. Soc.* **1932**, *54*, 2045.

(31) Pross, A.; Sternhell, S. *Aust. J. Chem.* **1970**, *23*, 989.

(32) *Vogel's Textbook of Practical Organic Chemistry*, 5th ed.; Longman: Harlow, Essex, 1989; p 510.

(33) (a) Dehmlow, E. V.; Lissel, M. *Tetrahedron* **1981**, *37*, 1653; (b) *Liebigs Ann. Chem.* **1980**, 1.

evaporated to give a mixture that was flash-chromatographed on silica gel with 3:1 petroleum ether (40–70 °C)/$CHCl_3$ eluent and afforded 190 mg of **1,4-diphenylbut-3-en-1-yne (7)**, mp 94–96 °C (subl), as a 10:1 mixture of the *E* (J = 17 Hz) and *Z* (J = 12 Hz) isomers: ^{1}H NMR δ 7.4–7.3 (m, 10H, Ph), 7.06 (d, 1H, CH, J = 17 Hz), 6.72 (d, 1H, CH, J = 12 Hz), 6.40 (d, 1H, CH, J = 17 Hz), 5.94 (d, 1H, CH, J = 12 Hz); ^{13}C NMR δ 141.2 (CH=*C*HPh), 136.3 (*C*$^{Ph}_{ipso}$CH=), 131.5, 128.7, 128.5, 128.3, 128.2, 126.3, 123.4 (*C*$^{Ph}_{ipso}$C≡), 108.1 (*C*H=CHPh), 91.7 (PhC≡), 88.9 (≡*C*–); assignment was confirmed by APT; IR 2198 (C≡C; w); HRMS 204.0904, $C_{16}H_{12}$ requires 204.0933.

In earlier chromatographic fractions we had detected **5**, admixed with residual pinacolone, and identified it by GC–MS and by the GC retention time with respect to a pure sample. Styrene was never detected; in the early investigation[8] it had been given among the products, but perhaps it was confused with **5**.

Further chromatographies on alumina with the same eluent of two fractions, which had been collected after **7** from the above chromatography, allowed separation of the two isomers **3** and **4**.

2,2-Dimethyl-6-phenyl-5-hexen-3-one (3) (PhCH^A=CH^B-CH$_2$^{C}COCMe$_3$): IR 1705 (C=O, s); ^{1}H NMR δ 7.35–7.20 (m, 5H, Ph), 6.65–6.61 (d, 1H, CH^A), 5.95–5.85 (dt, 1H, CH^B), 3.50 (dd, 2H, CH$_2$^{C}), 1.13 (s, 9H, CMe$_3$); J_{AB} = 12, J_{AC} = 1.8, J_{BC} = 7.0 (Hz); ^{13}C NMR δ 213.7 (C=O), 137.1 (*C*$^{Ph}_{ipso}$CH=), 131.6 (Ph*C*H=), 128.6, 128.3, 127.0, 124.6 (=*C*HCH$_2$), 44.4 (*C*Me$_3$), 36.2 (*C*H$_2$CO), 26.5 (C*Me*$_3$); assignment was confirmed by DEPT and by decoupling experiments; MS m/z 202 (M$^+$; 1), 145 (M$^+$ – CMe$_3$; 1), 117 (M$^+$ – COCMe$_3$; 15), 115 (16), 85 (COCMe$_3^+$; 21), 57 (CMe$_3^+$; 100); HRMS 202.1311, $C_{14}H_{18}O$ requires 202.1352.

2,2-Dimethyl-6-phenyl-4-hexen-3-one (4) (PhCH$_2$^{C}H^B=CH^{A}COCMe$_3$): IR 1690 (C=O, w); ^{1}H NMR δ 7.40–7.20 (m, 5H, Ph), 6.45–6.41 (asym d, 1H, CH^A), 6.36–6.30 (dt, 1H, CH^B), 3.43 (d, 2H, CH$_2$^{C}), 1.18 (s, 9H, CMe$_3$); J_{AB} = 15.5, J_{AC} = 0.6, J_{BC} = 6.0 (Hz); ^{13}C NMR δ 192.5 (conjugated C=O), 141.8 (CH$_2$*C*H=), 138.0, 132.9, 127.4, 126.3, 123.4 (=*C*HCO), 44.5 (*C*Me$_3$), 40.7 (PhCH$_2$C=), 26.4 (C*Me*$_3$); MS m/z 202 (M$^+$; 6), 145 (M$^+$ – CMe$_3$; 1), 117 (M$^+$ – COCMe$_3$; 17), 115 (16), 85 (COCMe$_3^+$; 17), 57 (CMe$_3^+$; 100). The ^{1}H NMR spectra of **3** and **4** were remarkably well simulated by the program Daisy,[34] employing the above-given coupling constants. The unequivocal assignment of the structures was provided by the ^{13}C NMR spectra: a conjugated C=O (δ 192.5) for **4** and a nonconjugated C=O (δ 213.7) for **3**. Assignment by IR is less reliable, due to the low intensity of the conjugated carbonyl.

(b) 2,2,3-Trimethyl-5-phenylpent-4-yn-3-ol (6). Reaction of 1.9 g of pinacolone (19 mmol), 3 g of *t*-BuOK (26 mmol), and 0.60 g of **5** (6 mmol) in 50 mL of Me_2SO for 15 min gave, after analogous workup and chromatographic separation, **6** (0.66 g; 54%), which was finally microdistilled from bulb to bulb (oil pump): IR 2245 (C≡C, w), 3600–3500 (OH, m); ^{1}H NMR δ 7.44–7.26 (m, 5H, Ph), 1.97 (s, 1H, OH; disappears on shaking with D_2O), 1.54 (s, 3H, C*H*$_3$COH), 1.12 (s, 9H, CMe$_3$); ^{13}C NMR δ 131.6, 130.6, 128.3, 123.6, 92.9 (≡*C*COH), 83.9 (PhC≡), 74.4 (*C*OH), 38.5 (*C*Me$_3$), 26.3 (*C*H$_3$COH), 25.3; MS m/z 202 (M$^+$; 1), 184 (M$^+$ – H_2O; 43), 169 (M$^+$ – H_2O – Me; 21), 145 (M$^+$ – CMe$_3$; 100), 128 (38), 57 (CMe$_3^+$; 23); HRMS 202.1307; $C_{14}H_{18}O$ requires 202.1352.

Products 8, 9, and 10. Reaction of 1.63 g of 3-pentanone (19 mmol), 2.95 g of *t*-BuOK (26 mmol), and 0.61 g of **5** (6 mmol) in 50 mL of Me_2SO for 8 h gave, after workup as above, a residue (1.33 g) which was chromatographed on silica gel with 3:1 petroleum ether (40–70 °C)/$CHCl_3$ eluent to give 0.79 g (70%) of **4-methyl-6-phenyl-5-hexen-3-one (8)**, PhCH^A=CH^{B}CH^C(CH$_3$^{D})COCH$_2$^{E}CH$_3$^{F}: IR 1713 (C=O, s); ^{1}H NMR δ 7.4–7.2 (m, 5H, Ph), 6.5 (asym d, 1H, CH^A), 6.1 (dd, 1H, CH^B), 3.4 (m, 1H, CH^C), 2.7–2.5 (m, 2H, CH$_2$^{E}), 1.3 (d, 3H, CH$_3$^{D}), 1.1 (t, 3H, CH$_3$^{F}); J_{AB} = 16.0, J_{BC} = 8.0 (Hz); ^{13}C NMR δ 211.9 (C=O), 136.8 (*C*$^{Ph}_{ipso}$CH=), 131.8 (PhCH=), 129.1 (PhCH=*C*H), 128.5, 127.5, 126.2, 50.4 (*C*HCO), 34.0 (CO*C*H$_2$), 16.3 (*C*H$_3$CH), 7.7 (*C*H$_3$CH$_2$); MS m/z 188 (M$^+$; 6), 170 (M$^+$ – H_2O; 45), 160 (M$^+$ – CH$_2$=CH$_2$; 26), 141 (21), 131 (M$^+$ – EtCO; 100), 115 (36), 91 (C$_7$H$_7^+$; 43), 57 (EtCO$^+$;4 5); HRMS 188.1151, $C_{13}H_{16}O$ requires 188.1195.

The remainder of the above chromatography was further chromatographed on silica gel with toluene as eluent, and a fraction of 0.19 g was collected; by GC it was a 3:1 mixture of **9** and **8**: ^{1}H NMR δ 6.7 (t, 1H, PhCH$_2$C*H*=), 3.6 (d, 2H, PhC*H*$_2$-CH=), 1.9 (s, 3H, C*H*$_3$C=) are the unequivocal signals of **9**; MS m/z 188 (M$^+$; 13), 131 (M$^+$ – EtCO; 100), 115 (15), 91 (C$_7$H$_7^+$; 34), 57 (EtCO$^+$; 26).

When the above reaction was repeated, using a reaction time of only 20 min, and the crude product (1.61 g) was chromatographed under the same conditions, it yielded 0.85 g (75%) of **3-ethyl-5-phenylpent-4-yn-3-ol (10)**: IR 2228 (C≡C; w) and 3600–3500 (OH, m); ^{1}H NMR δ 7.3–7.2 (m, 5H, Ph), 2.3 (s, 1H, OH), 1.7 (q, 4H, CH$_2$), 1.1 (t, 6H, CH$_3$); ^{13}C NMR δ 131.6, 128.2, 128.1, 122.9, 91.7 (PhC≡*C*), 84.4 (Ph*C*≡), 72.5 (*C*OH), 34.4 (*C*H$_2$), 8.6 (*C*H$_3$); MS m/z 188 (M$^+$; 4), 170 (M$^+$ – H_2O; 13), 159 (M$^+$ – Et; 100), 115 (17), 91 (C$_7$H$_7^+$; 10), 57 (EtCO$^+$; 27); HRMS 188.1176, $C_{13}H_{16}O$ requires 118.1195.

Products 11 and 12. A mixture of 2.88 g of CH_3COPh (24 mmol), 3.6 g of *t*-BuOK (32 mmol), and 1.42 g of **1** (8 mmol) in 50 mL of Me_2SO was irradiated in a Rayonet reactor for 5 h. Workup with diethyl ether as above gave 3.43 g of a residue, which was chromatographed on silica gel with toluene as eluent. The main fraction of 0.79 g was crystallized from EtOH/H_2O to yield 0.58 g (33%) of **1,4-diphenylprop-2-en-1-one (12)**, as a pale yellow solid, mp 68–72 °C, PhCH$_2$^{A}-CH^B=CH^{C}COPh, as an unresolved, perhaps 2:1 *E*:*Z* (by GC), mixture: IR 1685 (conjugated C=O; m); ^{1}H NMR δ 7.90–7.89 and 7.6–7.2 (m, 10H, Ph), 6.52 (asym d, 1H, CH^C), 6.50 (dt, 1H, CH^B), 3.9 (d, 2H, CH$_2$^{A}); J_{AB} = 5.7, J_{BC} = 16.5 (Hz); ^{13}C NMR δ 198.0 (Ph*C*=O), 136.9, 133.5 (*C*H=CHCO), 133.2 (=*C*HCO), 132.1, 128.7, 128.2, 127.5, 127.1, 42.7 (PhCH$_2$); MS m/z 222 (M$^+$; 4), 117 (M$^+$ – COPh; 6), 115 (13), 105 (PhCO$^+$; 100), 77 (Ph$^+$; 34); HRMS 222.1056, $C_{16}H_{14}O$ requires 222.1039. Another fraction of 0.25 g contained **11**, **1,4-diphenylprop-3-en-1-one**, PhCH^C=CH^{B}CH$_2$^{A}COPh, as an unresolved, perhaps 3:1 *E*:*Z* (by GC) mixture, contaminated (ca. 20%) with **12**: ^{1}H NMR δ 8.0–7.8 and 7.5–7.2 (m, 10H, Ph), 6.9–6.6 (d, 1H, CH^C), 6.3–5.9 (dt, 1H, CH^B), 3.9 (dd, 2H, CH$_2$^{A}); J_{AB} = 7.0, J_{BC} = 11.9, J_{AC} = 1.7 (Hz); ^{13}C NMR δ 197.6 (Ph*C*=O), 136.2, 133.0, 131.8 (Ph*C*H=), 128.4, 128.0, 126.9, 123.7 (PhCH=*C*H), 38.1 (*C*H$_2$CO); MS m/z 222 (M$^+$; 70), 221 (M$^+$ – 1; 100), 145 (M$^+$ – Ph; 26), 115 (50), 105 (PhCO$^+$; 52), 77 (Ph$^+$; 74).

Reaction with 13. In this case, inspection of the crude reaction mixture by GC–MS revealed a peak of a compound very close to the solvent and to excess pinacolone: MS m/z 96 (M$^+$; 80), 81 (M$^+$ – Me; 100), 79 (55), 53 (60). From this, the structure of the allene **2,4-dimethyl-2,3-pentadiene (15)** was inferred. No evidence could be gathered of the reduction product **2,4-dimethyl-2-pentene (14)**, and it is assumed that, if it is formed (as in the case of **17**, **22**, **24**, and **29**), it coeluted with the solvent.[16a]

Reaction with 16. In this case, inspection of the crude reaction mixture by GC–MS revealed a peak whose mass spectrum was consistent with the reduced product **1,3-dimethylcyclohexene (17)**: MS m/z 110 (M$^+$; 40), 95 (M$^+$ – Me; 100), 82 (28), 67 (60). In the presence of p-$C_6H_4(NO_2)_2$, **17** was not found, while a new peak appeared, whose mass spectrum was consistent with **1,3-dimethyl-2-(3,3-dimethyl-2-oxobutan-1-yl)cyclohexene (19)**: MS m/z 208 (M$^+$; 5), 151 (M$^+$ – CMe$_3$; 8), 123 (M$^+$ – COCMe$_3$; 13), 108 (123$^+$ – Me; 100), 93 (28), 85 (Me$_3$CO$^+$; 6), 81 (15), 57 (Me$_3$C$^+$; 70).

Products 21 and 22. Reaction of 0.96 g of pinacolone (9.6 mmol), 1.4 g of *t*-BuOK (12 mmol) and 1.0 g of **20** (3 mmol) in 50 mL of Me_2SO was conducted in the photochemical reactor for 3 h. After the usual workup, the crude mixture (2.1 g) was chromatographed on silica gel with toluene and then with 1:1 toluene/diethyl ether eluents to yield 140 mg (18%) of **22** and 640 mg (60%) of **21** as pure samples.

(34) Daisy is a NMR simulation program and is distributed by Bruker.

1,1,2-Triphenylethene (22): mp 67–69 °C (from EtOH/H_2O; lit.[35] mp 70–71 °C); ^{1}H NMR δ 7.4–7.2 (m, 10H, Ph), 7.1–7.0 (m, 5H, Ph), 7.0–6.9 (s, 1H, =CH), in agreement with the Sadtler Handbook;[36] MS m/z 256 (M^+; 26), 255 ($M^+ - 1$; 100), 178 (M^+ – PhH; 15).

2,2-Dimethyl-5,6,6-triphenyl-5-hexen-3-one (21): mp 165–168 °C (from EtOH/H_2O); IR 1706 (C=O, s); ^{1}H NMR δ 7.3–7.2 (m, 5H, Ph), 7.2–7.1 (m, 5H, Ph), 7.0–6.9 (m, 5H, Ph), 3.7 (s, 2H, CH_2CO), 0.9 (s, 9H, CMe_3); ^{13}C NMR δ 213.4 (C=O), 142.9 (Ph_2C=), 142.4, 142.3, 130.6, 129.5, 129.1, 128.2, 127.8, 127.4, 127.0, 126.3, 126.0, 44.6 (CH_2CO), 44.2 (CMe_3), 26.3 (Me_3); HRMS 354.223, $C_{26}H_{26}O$ requires 354.200.

Products 26, 27, and 28. Reaction of 2.0 g of pinacolone (20 mmol), 3.2 g of *t*-BuOK (28 mmol), and 1.2 g of **25** (5 mmol) in 30 mL of Me_2SO was conducted under photostimulation for 3 h. Distillation of the crude product (2.3 g) at 15 Torr gave four fractions boiling at the 50–100 °C range, which contained mixtures of **26-29**. These were separately chromatographed on silica gel with petroleum ether (40–70 °C) eluent or with petroleum ether/CH_2Cl_2 mixtures. Further chromatographies of the enriched fractions allowed separation of **26**, **27**, and **28** with purity in the range of 85–90% for each compound.

2,2,6-Trimethyl-5-phenyl-5-hepten-3-one (26): ^{1}H NMR δ 7.3–7.1 (m, 5H, Ph), 3.33 (s, 2H, CH_2CO), 1.56 (s, 6H, Me), 1.13 (s, 9H, CMe_3); ^{13}C NMR δ 214.2 (C=O), 139.4 (Ph*C*=), 128.9, 128.5, 128.4, 128.0 (Me_2C=), 44.3 (CMe_3), 38.1 (CH_2CO), 26.5 (Me_3), 23.5 (CH_3 *cis* to Ph), 16.2 (CH_3 *trans* to Ph); assignment was confirmed by DEPT; MS m/z 230 (M^+; 9), 173 ($M^+ - CMe_3$; 4), 145 ($M^+ - Me_3CCO$; 9), 131 ($M^+ - Me_3CCOCH_2$; 12), 117 (9), 115 (8), 85 (Me_3CCO^+; 15), 57 (Me_3C^+; 100).

2,2,6-Trimethyl-5-phenyl-6-hepten-3-one (27), CH_2=$C(CH_3)CH_X(Ph)CH_AH_BCOCMe_3$: IR 1703 (C=O, s); ^{1}H NMR δ 7.3–7.1 (m, 5H, Ph), 4.85 (d, 2H, CH_2=), 3.85 (t, 1H, CH_X-Ph; $J_{AX} = J_{BX} = 7.2$ Hz), 3.0–2.9 (dd, 2H, CH_AH_BCO; $J_{AB} = 17.3$ Hz), 1.62 (s, 3H, CH_3), 1.02 (s, 9H, CMe_3); ^{13}C NMR 213.6 (C=O), 147.4 (=*C*Me), 142.9 ($C^{Ph}_{ipso}CH$), 128.3, 127.8, 126.4, 109.5 (CH_2=), 46.8 (Ph*C*H), 44.1 (CMe_3), 41.5 (CH_2CO), 26.1 (Me_3), 22.3 (CH_3C=); assignment was confirmed by DEPT; MS m/z 230 (M^+; 3), 173 ($M^+ - CMe_3$; 28), 145 ($M^+ - Me_3CCO$; 8), 131 ($M^+ - Me_3CCOCH_2$; 51), 117 (7), 115 (11), 91 ($C_7H_7^+$; 17), 85 (Me_3CCO^+; 11), 57 (Me_3C^+; 100); HRMS 230.1684, $C_{16}H_{22}O$ requires 230.1665.

2,2,6-Trimethyl-7-phenyl-5-hepten-3-one (28), $PhCH_2C(CH_3^X)$=$C(H^A)CH_2^BCOCMe_3$: ^{1}H NMR δ 7.3–7.1 (m, 5H, Ph), 5.45 (tq, 1H, CH=), 3.36 (s, 2H, $PhCH_2$), 3.26 (dq, 2H, CH_2CO), 1.53 (s, 3H, CH_3C=), 1.16 (s, 9H, CMe_3); $J_{AB} = 6.8$, $J_{AX} = 1.1$ (Hz); ^{13}C NMR δ 214.1 (C=O), 139.9 (*C*=CH), 137.4 ($C^{Ph}_{ipso}CH_2$), 128.8, 128.2, 126.0, 118.8 (*C*H=), 46.2 (Ph*C*H_2), 44.3 (CMe_3), 36.0 (CH_2CO), 26.5 (Me_3), 16.0 (CH_3C=); assignment was confirmed by APT; MS m/z 230 (M^+; 12), 173 ($M^+ - CMe_3$; 2), 145 ($M^+ - Me_3CCO$; 8), 131 ($M^+ - Me_3CCOCH_2$; 9), 117 (6), 115 (6), 91 ($C_7H_7^+$; 11), 85 (Me_3CCO^+; 12), 57 (Me_3C^+; 100).

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Supplementary Material Available: Copies of ^{1}H and ^{13}C NMR spectra of **3, 4, 6,** (*E* + *Z*)-**7, 8 + 9, 10–13, 16, 21, 23,** and **25–28** (33 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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