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Anodic Oxidation of Methyl α-Dimethylsilyldihydrocinnamate. A Novel Silicon γ-Aryl Effect

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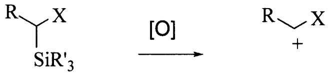
The anodic oxidation of methyl 3-phenyl-2-dimethylsilylpropionate occurs at a potential almost 1 V positive of that required to oxidize other α-silyl esters. Semiempirical and ab initio calculations on the model compound 1-phenyl-2-trimethylsilylethane indicate that electron removal from these two compounds is highly stereoelectronically dependent. Both molecules exist almost exclusively in a conformation in which the phenyl group and silicon atom are anti and the side chain is perpendicular to the aromatic ring. This conformation has a higher energy HOMO orbital and lower computed ionization potential than the only other significantly populated conformation of 1-phenyl-2-trimethylsilylethane. Finally, the ab initio calculations show that in the cation radical of this model compound the ipso carbon of the aromatic ring and the side chain carbon bound to silicon draw significantly closer together than in the neutral species; an electrostatic potential map of the cation radical shows that the ipso carbon bears the highest degree of positive charge of any of the benzenoid carbons. We interpret these data, taken together, as an indication that this cation radical is stabilized by overlap of the rear lobe of the carbon−silicon bond with the p-orbital of the ipso carbon.

Introduction

Yoshida[1−3] and others[4−6] have shown that anodic oxidation of benzylic silanes (**1a**) and those bearing carbocation-stabilizing atoms at the α-position (**1b**) affords the corresponding cationic species (**2**) (eq 1). We have become interested in the possibility of producing less stable carbocations by anodic oxidation of the corresponding silanes. In particular, we were interested in the possibility of generating a carbocation α to a carbonyl group (**2c**) in this manner. Although species of type **2c** have previously been prepared by solvolytic routes[7,8] and it is believed that they enjoy a degree of π-stabilization by the carbonyl group,[9] the electronegative inductive effect of the carbonyl group still tends to destabilize such cations. Controlled anodic production of **2c** might permit carrying out a variety of trapping reactions not possible under solvolytic conditions.



(1)

1a, X = benzyl
b, X = OR or SR
c, X = C(=O)R

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To implement an anodic strategy to the preparation of species **2c**, one requires an α-silyl carbonyl compound (**1c**). We chose to examine silyl esters. Silylation of ester enolates generally affords the corresponding enol silyl esters by kinetically controlled O-silylation.[10,11] Although a few examples of formation of C-silylated products have been reported,[12,13a] the only generally useful method for C-silylation until recently involved methyldiphenylsilyl chloride as the silylating agent.[13b] We felt that the presence of phenyl groups attached to silicon in these species would create ambiguities in the nature of the reaction intermediates. Following up an earlier report by Miura,[14] we recently showed[15] that ester enolates are C-silylated in excellent yields with dimethylchlorosilane.

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[1] Yoshida, J.-i.; Murata, T.; Isoe S. *Tetrahedron Lett.* **1986**, *27*, 3373.

[2] Yoshida, J.-i.; Itoh, M.; Isoe, S. *J. Chem. Soc., Chem. Commun.* **1993**, 547.

[3] Yoshida J.-i.; Ishichi, Y.; Nishiwaki, K.; Shiozawa, S.; Isoe, S. *Tetrahedron Lett.* **1992**, *33*, 2599.

[4] Koizumi, T.; Fuchigami, T.; Nonaka, T. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 219.

[5] Koizumi, T.; Fuchigami, T.; Nonaka, T. *Electrochim. Acta* **1988**, *33*, 1635.

[6] Porter, J. M.; Xuan, X.; Blackman, B.; Hsu, D.; Fry, A. J. *Tetrahedron Lett.* **1997**, *38*, 7147.

[7] Creary, X. *Acc. Chem. Res.* **1985**, *18*, 3−8.

[8] Bégué, J.-P.; Charpentier-Morize, M. *Acc. Chem. Res.* **1980**, *13*, 207.

[9] Dixon, D. A.; Eades, R. A.; Frey, R.; Gassman, P. G.; Hendewerk, M. L.; Paddon-Row: M. N.; Houk, K. N. *J. Am. Chem. Soc.* **1984**, *106*, 3885.

[10] Chan, T.-H. In *Comprehensive Organic Synthesis*; Heathcock, C. H., Ed.; Elsevier: Oxford, UK, 1991; Vol. 2, p 604.

[11] Sheldrake, G. N. In *Comprehensive Organic Functional Group Transformations*; Kirby, G. W., Ed.; Elsevier: Oxford, UK, 1995; Vol. 4, p 831.

[12] Ainsworth, C.; Chen, F.; Kuo, Y.-N. *J. Organomet. Chem.* **1972**, *46*, 59.

[13] (a) Rathke, M. W.; Sullivan, D. L. *Synth. Commun.* **1973**, *3*, 67. (b) Larson, G. L.; Maldonado, V. C. d.; Fuentes, L. M.; Torres, L. E. *J. Org. Chem.* **1988**, *53*, 633.

10.1021/jo030264e CCC: $25.00

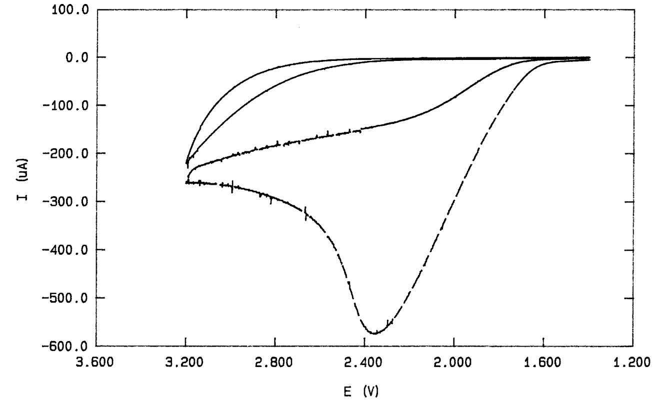
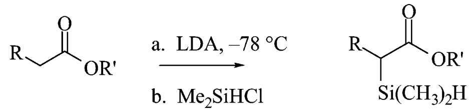


FIGURE 1. (a) Dashed line: voltammogram of methyl 3-phenyl-2-dimethylsilylpropionate (**3d**) in trifluoroacetic acid containing 0.1 M tetrabutylammonium tetrafluoroborate at 100 mV s^{-1} vs Ag/0.1 M $AgNO_3$. (b) Solid line: background.

The four 2-dimethylsilyl esters **3a**−**d** were prepared and characterized by a series of ^1H and ^{13}C NMR spectroscopic experiments and molecular mechanics calculations. The unusual anodic behavior of **3d** will be the focus of this paper.



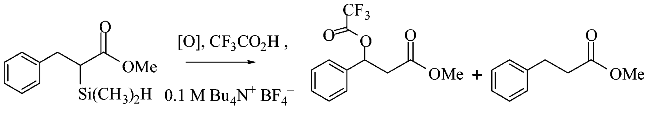
3a, R = Me; R' = *i*-Pr, 91%
b, R = Et; R' = *i*-Pr, 93%
c, R = Pentyl; R' = Et, 95%
d, R = $C_6H_5CH_2$; R' = Me, 89%

Results

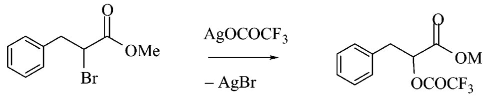
Cyclic Voltammetry. Silyl esters **3a**−**d** were examined by cyclic voltammetry at 100 mV s^{-1} at a glassy carbon electrode in trifluoroacetic acid (TFA) containing 0.1 M tetrabutylammonium tetrafluoroborate (TBATFB), with potentials measured relative to Ag/0.1 M $AgNO_3$ reference.[16] TFA was used because its anodic limit is more positive than that of more commonly used solvents such as acetonitrile; no voltammetric waves were observable in these media. Even in TFA, esters **3a**−**c** exhibited no voltammetric peak before the solvent breakdown potential of roughly +3.3 V. However, ester **3d** exhibited a broad anodic peak at −2.38 V (Figure 1). No reverse wave is observable on the reverse scan, indicating that the initial electron transfer generates a species that undergoes rapid chemical reaction. For comparison purposes, the oxidation peak potential of the model compound 1-phenyl-2-trimethylsilylethane[17] (**4**), prepared by trimethylsilylation of the corresponding Grignard reagent, was found to be +1.88 V. The difference between the oxidation potentials of **3d** and **4** is about what one would expect for the inductive effect of the additional carbomethoxy group in **3d** upon the oxidation potential of **4**. As we will see below, **4** is in fact an excellent model for electron removal from **3d**.

Preparative Scale Electrolysis. Controlled potential electrolysis of **3d** in TFA/0.1 M TBATFB at a carbon cloth anode in a divided cell at room temperature afforded a 1:2 mixture of methyl 3-trifluoroacetoxydihydrocinnamate (**5**) and methyl dihydrocinnamate (**6**). The ratio of **5** to **6** was 1:1 and 2:1 when electrolysis was carried out at 0 and −20 °C, respectively. The same results were obtained employing constant current electrolysis. While **5** is a true anodic product, a control experiment established that **6** is produced by direct reaction between **3d** and TFA; this reaction apparently proceeds more slowly at lower temperature, improving the efficiency of the anodic conversion of **3d** to **5**.

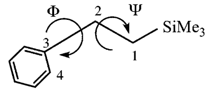
The structure of **5** was established by synthesis of an authentic sample. A commercial sample of methyl 3-hydroxydihydrocinnamate was dissolved in trifluoroacetic anhydride at room temperature for 10 min to afford **5** cleanly. An alternate structure originally considered for the electrolysis product was methyl 2-trifluoroacetoxydihydrocinnamate (**8**). However, an authentic sample of **8** prepared in 85% yield by silver-assisted S_N2 reaction between methyl 2-bromodihydrocinnamate (**7**) and silver trifluoroacetate (THF, room temperature, 30 min) exhibited different spectroscopic properties from the electrolysis product.



3d **5** **6**



7 **8**



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Conformational Characterization of Model Compound 4. The unique ease of oxidation of ester **3d** appears to be associated with the β-phenyl group. Because the electron-transfer process was presumed to be sensitive to stereoelectronic factors,[18] the conformational energy surface of the conformationally less complex model substance **4** was explored by a series of AM1 semiempirical calculations.[19] As will be seen, this substance is a good conformational and electronic model for ester **3d**. Silane **4** possesses two rotatable bonds whose orientation should significantly affect the energy of the system: Φ, the C_4−C_3−C_2−C_1 dihedral angle, and Ψ, the C_3−C_2−C_1−Si $_{\text{dihedral}}$ angle. Angles Φ and Ψ were rotated in 30° increments from 0° to 360° and the AM1 energy of each combination was computed with full geometry optimization, requiring (because of the symmetry of the system) 91 separate AM1 computations. The resulting surface was found to contain only three low-lying

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[14] Miura, K.; Sato, H.; Tamaki, K.; Ito, H.; Hosomi, A. *Tetrahedron Lett.* **1998**, *39*, 2585.

[15] Kaimakliotis, C.; Fry, A. J. *J. Organomet. Chem.* **2003**, *671*, 126−130.

[16] This reference electrode is +0.35 V vs sce.

[17] Negishi, E.-i.; Swanson, D. R.; Rousset, C. J. *J. Org. Chem.* **1990**, *55*, 5406.

[18] Yoshida, J. In *Electrochemistry V*; Steckhan, E., Ed.; Springer-Verlag: New York, 1994; Vol. 170, p 39.

TABLE 1. Computed Energies of Neutral 1-Phenyl-2-trimethylsilylethane and Its Cation Radical as a Function of Conformation

conformation[a]	neutral[b]	cation radical[b]	IP (eV)[c,d]
A	-719.551144	-719.262265	7.861
B/**C**	-719.549208	-719.253461	8.048
$E_{\mathbf{A}} - E_{\mathbf{B/C}}$[e]	0.001936	0.008804	0.187[f]

[a] Ab initio density functional calculations at the B3LYP/6-31G* level with full geometry optimization. [b] Energy of species in hartrees (1 H = 627.5 kcal mol $^{-1}$). [c] Ionization potential = $E_{\text{neutral}} - E_{\text{cation}}$. [d] 1 eV = 0.0367 H = 23.06 kcal mol $^{-1}$. [e] Difference in energy between conformation **A** and conformation **B**/**C** (in hartrees). [f] Difference in ionization potential between conformation **A** and conformation **B**/**C** (in eV).

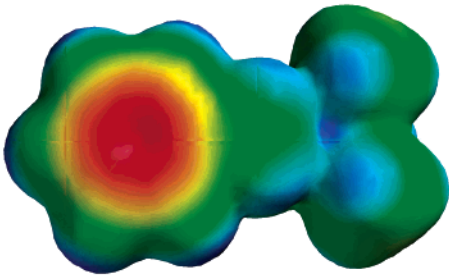


FIGURE 2. Electrostatic potential map of 1-phenyl-2-trimethylsilylethane (**4**) computed at the DFT/6-31G* level. Color scheme: red, regions of high negative charge; yellow, low negative charge; blue, regions of high positive charge; green, low positive charge.

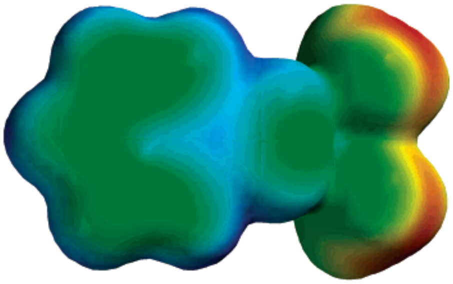


FIGURE 3. Electrostatic potential map of the cation radical of 1-phenyl-2-trimethylsilylethane (**4**) computed at the DFT/6-31G* level. Color scheme: red, regions of high negative charge; yellow, low negative charge; blue, regions of high positive charge; green, low positive charge.

minima: **A**, $\Phi = 90°$, $\Psi = 180°$; **B**, $\Phi = 120°$, $\Psi = 90°$; and **C,** $\Phi = 300°$, $\Psi = 90°$. No other minima were found. Conformation **A**, in which the phenyl and trimethylsilyl groups are anti, is lower energy than **B** and **C**, which are enantiomers and of course of equal energy. Exploration of the potential energy surface in the vicinity of the minima with a finer mesh grid showed that while the global minimum **A** is indeed at $\Phi = 90°$, $\Psi = 180°$, the other two minima are actually centered at $\Phi = 62°$, $\Psi =$ 105° and 285°, respectively. While relative AM1 energies are meaningful, in general their absolute values are far less so; the energies of these conformations were therefore recomputed by density functional ab initio theory at the 6-31G* level with full geometry optimization, using the B3LYP functional (Table 1).[19] Conformation **A** is still the global minimum and has the same geometry ($\Phi = 90°$, $\Psi = 180°$) at this computational level. However, conformation **B**/**C** optimizes to a new geometry ($\Phi = 69°$, $\Psi =$ 67°), starting from the AM1 minimum ($\Phi = 62°$, $\Psi =$ 105°) when all geometry constraints are removed. From the data of Table 1, conformation **A** can be computed to be 1.21 kcal lower in energy than **B** or **C**. With use of this value, a Maxwell−Boltzmann calculation then indicates that **4** exists about 88% in the anti conformation **A**. An extensive conformational energy search had shown earlier that in its global minimum energy conformation silyl ester **3d** has exactly the same anti backbone geometry ($\Phi = 90°$, $\Psi = 180°$) as **A**.[15] Therefore, conclusions reached from examination of the stereoelectronic dependence of the electron-transfer properties of **4** should be directly transferable to **3d**.

The B3LYP/3-21G computations were then repeated for the corresponding radical cations of **A** and **B**/**C** (Table 1). Since the difference between the energy of the neutral and radical cation is the computed ionization potential (IP), the IP of the **A** conformation of **4** is seen to be 0.187 eV less than that of **B/C**. It is also instructive to examine the differences between the electron distribution in neutral **4** and in its corresponding radical cation (Figures 2 and 3, which represent electrostatic potential energy maps for the two species). Whereas the carbon atoms of the benzene ring are uniformly negative in neutral **4**, the ring becomes highly positive in the corresponding cation radical; *in particular, the ipso carbon bears a distinctly higher positive charge than the other ring carbons.* A final point of significance is the fact that at the B3LYP/6-31G* level, the distance between C_1 and C_3 of the anti conformation is shorter by 0.20 Å (2.346 Å vs 2.550 Å) in the radical cation, associated with a decrease of 12.3° in the $C_1-C_2-C_3$ angle in going from the neutral species to the cation radical (113.0° vs 100.7°). From the data of Table 1, one may further conclude that the **A** conformation of the cation radical is considerably more stable (0.008804 H, or 5.5 kcal) relative to that of **B**/**C** than the neutral species (1.2 kcal), suggesting the existence of a special electronic effect in the cation. Another useful conclusion may be reached by plotting the HOMO energy of **4** as a function of Ψ while maintaining Φ fixed at 90° (Figure 4). It may be noted that while the total energy of the system decreases, the HOMO energy steadily increases as Ψ increases from 0° (benzene ring and silicon eclipsed) to 180°.

Discussion

Voltammetry. While the oxidation potential of the silyl ester **3d** is approximately +2.4 V (Figure 1), those of esters **3a**−**c** are greater than +3.3 V, the decomposition potential of our solvent system. This enormous difference of at least 0.9 V points to a powerful effect of the aryl group on the initial electron-transfer process to stabilize the initial radical cation by upward of 20 kcal mol^{-1}.

The Anodic γ-Effect. The very large effect of the phenyl group on the oxidation potential of **3d** relative to the other silyl esters **3a**−**c** demands explanation. We applied a variety of computational methods to understand the nature of this effect. Primary among these were quantum mechanical calculations on model compound **4**. Silane **4** is a reasonable model for **3d** for the following reasons: (a) the actual electrophore (oxidizable unit) of **3d** appears to be its β-phenylethylsilane substructure and

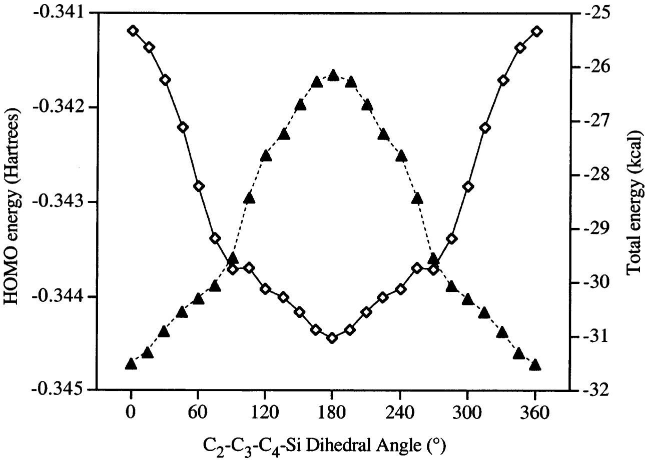
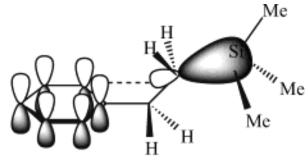


FIGURE 4. (a) Black triangles: HOMO energy of 1-phenyl-2-trimethylsilylethane (**4**) computed at the AM1 level as a function of Ψ, the $C_3-C_2-C_1-Si$ dihedral angle. (b) Open diamonds: total energy of **4** computed at the AM1 level as a function of Ψ, the $C_3-C_2-C_1-Si$ dihedral angle. The dihedral angle Φ is fixed at 90° throughout.

(b) the phenyl and silyl groups were shown to be anti (Ψ = 180°) and the side chain is perpendicular to the benzene ring (Φ = 90°) in both compounds. AM1 calculations were used to explore the conformational surface of **4**. This was not feasible with **3d** because of its larger number of rotatable bonds, but its conformational properties had been explored in detail previously by molecular mechanics.[15] Taken together, the molecular mechanics, AM1, and ab initio computations point to two clear conclusions: **4** and **3d** exist, at a conservative estimate, close to 90% in the anti conformation and this conformation has an ionization potential that is lower by about 4.3 kcal (0.187 eV) than that of the other low-energy conformation. We then ask what property of the anti conformation accounts for the relative ease with which it gives up an electron. A significant part of the answer to this question can be seen in Figure 4: the HOMO orbital of **4** is highest in energy when the silicon atom is anti to the benzene ring, i.e., in the molecule's most highly populated conformation. This conclusion in itself simply begs the question. Rather, it is more appropriate to ask what it is specifically about the anti conformation (Ψ = 180°) that drives up the energy of the HOMO and thus allows it to give up an electron more readily than for any other value of Ψ. We believe that interaction between the highest filled orbital of the benzene ring (via C_3, the ipso carbon) and the rear lobe of the carbon−silicon bond is the cause of the increase in the HOMO energy. This is illustrated in structure **9**. We refer to this phenomenon as the "anodic γ-aryl effect" although similar situations should arise with other appropriately oriented π and silicon groups, even when the groups are separated by a longer chain or where a π-system other than benzene is located at the γ-position.

Effects analogous to this have been reported previously. Yoshida has observed that in silanes in which one carbon atom separates the π-system and the silicon atom, e.g., benzyl and allyl silanes, the HOMO energy is highest and ionization potential lowest when the carbon−silicon bond is perpendicular to the plane of the π-system, i.e., parallel to the p-orbitals of the π-system.[18] It is believed that the increase in HOMO energy arises by interaction between the filled carbon−silicon σ-bond and the nearby π-system. We argue here for a similar interaction, but involving the rear lobe of the C−Si σ bond. There is precedent, both experimental and theoretical, for this hypothesis. Shiner and co-workers have reported a silicon γ-effect upon solvolysis of alkyl sulfonates, in which sulfonates bearing a trialkylsilyl group at the γ-position ionize substantially faster that those lacking this substituent.[21−23] This neighboring group effect exhibits a pronounced stereoelectronic preference, which is opposite to that expected in the absence of participation by silicon: the equatorial *cis*-brosylate **10** ionizes 89 times faster than the axial trans-isomer **11** in 2,2,2-trifluoroethanol,[21] whereas equatorial sulfonates ionize 3−4 times slower than equatorial sulfonates.[24] High-level ab initio computations showed that stabilization of the incipient positive charge in such ionizations is maximal when the developing p-orbital is aligned collinearly with the rear lobe of the carbon−silicon bond.[23]



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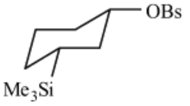

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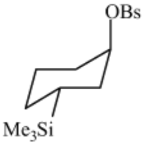

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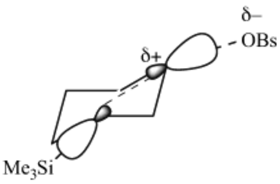

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Mechanism of Formation of Trifluoroacetoxy Ester 5. Formation of rearranged ester **5** is excellent evidence for initial generation of a cation (**14**) α to the ester carbonyl group. By analogy to mechanisms previously postulated for the anodic oxidation of silanes of type **1a** and **1b**,[1,2,6,18,25] we suggest the following sequence of events for the anodic conversion of **3d** to **5**. Initial removal of an electron from **3d** by the electrode takes place from conformation **A** to afford a radical cation (**3d**$^{+\bullet}$) in which most of the charge is carried by the benzene ring, particularly by the ipso carbon (C_3); electron density is supplied by the carbon−silicon bond via overlap of its rear lobe with the π-system. Nucleophilic attack upon the silicon atom of the radical cation by solvent (probably by an addition−elimination mechanism) would afford radical **13**; anodic oxidation of **13** at the very positive electrode potential being employed would then afford **14**. Rearrangement of **14** to **15** by hydride migration and

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(19) Spartan '02 for Macintosh; Wave Function, Inc.: Irvine, CA.

(20) Bernardi, F.; Bottoni, A.; Garavelli, M. *Quant. Struct.−Act. Relat.* **2002**, *21*, 128.

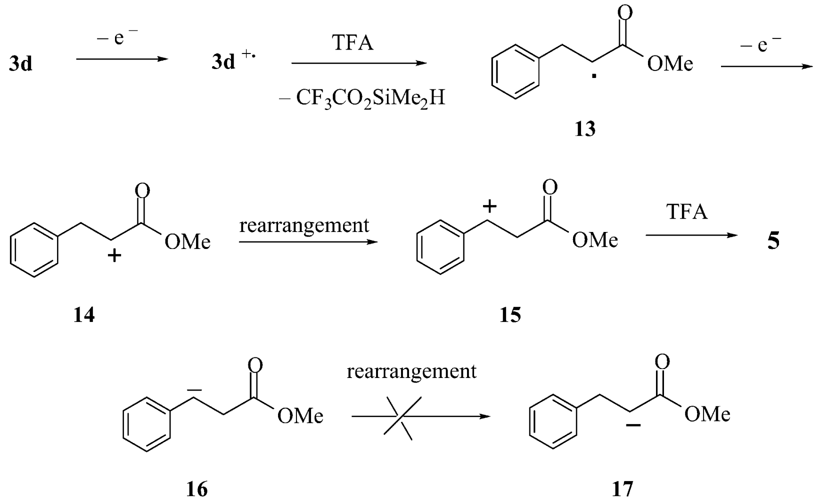
(21) Shiner, V. J., Jr.; Ensinger, M. W.; Kriz, G. S.; Halley, K. A. *J. Org. Chem.* **1990**, *55*, 653−661.

(22) (a) Ensinger, M. W.; Shiner, V. J., Jr. *Stud. Org. Chem. (Amsterdam)* **1987**, *31*, 41−58. (b) Adcock, W.; Coope, J.; Shiner, V. J., Jr.; Trout, N. A. *J. Org. Chem.* **1990**, *55*, 1411−1412.

(23) Davidson, E. R.; V. J. Shiner, J. *J. Am. Chem. Soc.* **1986**, *108*, 3135−3137.

(24) Winstein, S.; Holness, N. J. *J. Am. Chem. Soc.* **1955**, *77*, 5562.

SCHEME 1



final reaction with solvent would then afford **5**. Rearrangement moves the positive charge further away from the carbonyl group and should be particularly thermodynamically favorable in the case of **14**, since the resulting cation **15** is benzylic. We ruled out an alternative pathway from **14** to **5** involving proton loss to afford methyl cinnamate followed by conjugate addition of TFA to the latter by a control experiment in which a TFA solution of methyl cinnamate was found to be unchanged under the reaction conditions. Similar rearrangements of carbocations α to carbonyl groups are well precedented.[26,27] More than thermodynamics may be involved, however. Rearrangement of homoenolate **16** to **17** by proton migration in the opposite sense likewise should clearly be highly exothermic, yet we have shown that **16** can be generated and captured by a variety of electrophiles without any observable formation of **17**.[28] As we have pointed out,[28] conversion of **16** into **17** is forbidden on orbital symmetry grounds, whereas rearrangement of **14** to **15** is orbital symmetry allowed.

Conclusions

The remote phenyl group is intimately involved in the initial removal of an electron from the phenyl group of **3d**, resulting in a dramatic lowering of its oxidation potential compared to that of the non-aryl esters **3a**–**c**. Ab initio computational studies have been carried out on the phenethylsilane **4**, which we consider to be an excellent model for **3d** because they share the same essential geometry. The computations have shown that the effect has a strong stereoelectronic component, requiring that the phenyl and silyl groups be anti ($\Psi = 180°$) and the side chain be perpendicular to the benzene ring ($\Phi = 90°$). In this orientation the ipso carbon of the ring is ideally situated to interact with silicon through the rear lobe of the carbon–silicon sp^3 bond. This critical geometry is exhibited by **3d** as well as **4**. We presume that such stabilization can be achieved in any silane in which the carbon–silicon bond has the same orientation with respect to a remote π-system, no matter what the length of the chain connecting them.[18,23]

We finally return to the initial aim of this study, to produce a cation α to an ester carbonyl group (**2c**). Technically, by generating cation **14** we have achieved this aim. However, the requirement for the γ-phenyl group for ready oxidation indicates that the role of the ester group is minimal in this anode process. The significance of the present work lies in its elucidation of the novel role of the aryl group in stabilizing the initial cation radical. Recent ab initio computations on the silyl esters **3a**–**c** have shown, though, that the corresponding cation radicals do derive stabilization by interaction between the ester group and the silyl group.[29] It should be possible to oxidize **3a**–**c** in less readily oxidized solvents, e.g., nitromethane.[30,31] We also note that the very phenyl group that stabilizes the initial cationic intermediate stabilizes the transition state for rearrangement of **14** by hydride migration. The present work could be elaborated in a variety of ways for synthetic applications. Replacement of silicon by germanium or tin should permit generation of such cations at lower potentials, opening the possibility of trapping by a variety of added nucleophiles, and incorporation of an appropriate nucleophilic group such as a carbon–carbon double bond into the silyl ester precursor may allow intramolecular trapping before rearrangement can occur.

Experimental Section

Methyl 3-Trifluoroacetoxydihydrocinnamate (5). Methyl 3-hydroxydihydrocinnamate (Aldrich) (0.36 g, 2 mmol) was dissolved in trifluoroacetic anhydride (0.63 g, 3 mmol). Acylation was complete after 10 min as determined by ^{1}H NMR and GC-MS. Concentration and distillation in vacuo afforded **5** (0.55 g, 100%). Samples obtained by preparative gas chromatography were used for spectroscopic experiments and submitted for elemental analysis; ^{1}H NMR ($CDCl_3$) δ 7.4 (s, 5H), 6.34 (dd, $J = 7.0$ and 4.5 Hz, 1H), 3.7 (s, 3H), 3.13 (dd, $J = 10$ and 7.0 Hz, 1H), 2.85 (dd, $J = 10$ and 4.5 Hz, 1H); COSY

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(25) Taylor, K.; Miura, K.; Akinfaderin, F.; Fry, A. J. *J. Electrochem. Soc.* **2003**, *150*, D85.
(26) Creary, X.; Geiger, C. C. *J. Am. Chem. Soc.* **1982**, *104*, 4151.
(27) Koga, K.; Wu, C. C.; Yamada, S.-i. *Tetrahedron Lett.* **1971**, *12*, 2283.
(28) DiMauro, E.; Fry, A. J. *Tetrahedron Lett.* **1999**, *40*, 7945.
(29) Kaimakliotis, C. Unpublished computations.
(30) Chiba, K.; Sonoyamo, J.; Tada, M. *J. Chem. Soc., Perkin Trans. 1* **1996**, 1435.
(31) Mann, C. K. *Electroanal. Chem.* **1969**, *3*, 57.

spectra substantiated the expected AA′X coupling pattern of the protons at δ 6.34, 3.13, and 2.85; MS *m*/*z* (%) 276 (32), 216 (69), 203 (28), 131 (40), 105 (100). A satisfactory microanalysis could not be obtained because of the tendency of the material to both hydrolyze and undergo elimination upon standing.

Methyl 2-Bromodihydrocinnamate (7).[32] The following procedure was considered more convenient than the literature procedure involving bromination of benzylmalonic ester.[32] A solution of **6** (3.28 g, 20 mmol) in 20 mL of dry THF under nitrogen at −78 °C was treated with lithium diisopropylamide monotetrahydrofuran complex (22 mmol). The resulting solution was added dropwise over a period of 10 min to 600 mL of a 0.04 M solution of bromine in THF at −78 °C and allowed to warm to room temperature over 4 h while being stirred. The mixture was then treated with concentrated hydrochloric acid and extracted with water containing sufficient sodium thiosulfate to discharge the bromine color. The solution was dried over $MgSO_4$ and distilled in vacuo to afford **7** (4.63 g, 95%): ^{1}H NMR ($CDCl_3$) δ 7.25 (m), 4.41 (dd, $J = 9.0$ and 7.0 Hz, 1H), 3.71 (s, 3H), 3.46 (dd, $J = 14$ and 9.0 Hz, 1H), and 3.23 (dd, $J = 14$ and 7.0 Hz, 1H).

Methyl 2-Trifluoroacetoxydihydrocinnamate (8). Bromo ester **7** (0.73 g, 3 mmol) and silver trifluoroacetate (0.88 g, 4 mmol) were stirred in anhydrous THF at room temperature. A gray precipitate of AgBr began forming within minutes and reaction was complete after 30 min (^{1}H NMR and GC-MS). Filtration and evaporation afforded **8** as a clear liquid (0.70 g, 85%) whose spectrum showed no starting material or other products: ^{1}H NMR ($CDCl_3$) δ 7.42 (m, 5H), 5.43 (dd, $J = 7.0$ and 4.5 Hz, 1H), 3.68 (s, 3H), 3.11 (dd, $J = 10$ and 7.0 Hz, 1H), and 2.83 (dd, $J = 10$ and 4.5 Hz, 1H); COSY spectrum was consistent with the presence of an AA′X system; MS *m*/*e* (%) 276 (2), 217 (9), 163 (10), 162 (100), 131 (15), 91 (19), and 77 (44). A satisfactory microanalysis could not be obtained because of the tendency of the material to hydrolyze upon standing. A mixture of high molecular weight products was produced when the reaction was carried out at 60°; similar behavior was observed for the reaction between methyl 2-bromopropionate and silver trifluoroacetate.

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Supporting Information Available: General experimental procedures, ^{1}NMR spectra of compounds **5**, **7**, and **8**, and table of AM1 energy for **4** as a function of rotation around angles Φ and Ψ. This material is available free of charge via the Internet at http://pubs.acs.org.

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(32) Reinheckel, H.; Iovchev, A.; Spasov, S. L. *Monatsh. Chem.* **1965**, *96*, 1185.