Radical Ion Probes. 3. The Importance of Resonance vs Strain Energy in the Design of SET Probes Based upon the Cyclopropylcarbinyl → Homoallyl Radical Rearrangement

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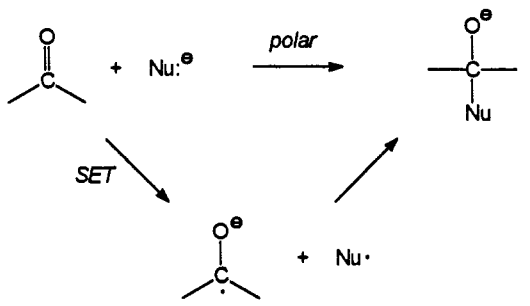
Abstract: Aryl cyclopropyl ketones have frequently been used as probes for single-electron transfer in organic reactions. The implicit assumption in these studies is that upon one-electron reduction, the corresponding arylcyclopropylketyl anions will undergo ring opening in analogy to the cyclopropylcarbinyl free radical. Earlier work in our laboratory has shown that ring opening of arylcyclopropylketyl anions is kinetically and thermodynamically unfavorable when the only substituents on the cyclopropane ring are alkyl or H. This sluggishness is attributable to a loss of resonance energy upon ring opening which is not fully compensated by the relief of cyclopropane ring strain. Consequently, aryl cyclopropyl ketones are unsuitable probes for single-electron transfer. In this paper, we examine the effect of radical-stabilizing substituents (phenyl and vinyl) on the ring opening of arylcyclopropylketyl anions. We have studied the mechanism, kinetics, and products of decay of radical anions generated electrochemically from *trans*-1-benzoyl-2-phenylcyclopropane and 1-benzoyl-2-vinylcyclopropane. The radical anions generated from these precursors each undergo ring opening ($k \approx 10^{6-7}$ s^{-1}) which is estimated to be exothermic by ca. 2 kcal/mol.

Introduction

The importance of single-electron transfer (SET) as a reaction pathway in organic systems has become evident over the past 30 years. Many organic reactions (e.g., nucleophilic addition to carbonyl compounds, Scheme 1), previously rationalized solely on the basis of two-electron (polar) pathways, are now believed to involve some component of SET.[1] Nonetheless, the experimental detection of SET in organic reactions is often difficult. Product analysis is usually uninformative because both mechanisms produce the same product(s). The unique characteristic of the SET pathway is that paramagnetic intermediates (free radicals and radical ions) are formed; consequently, experiments must be designed which exploit this difference.

A popular approach for the detection of SET pathways in organic and bioorganic systems has involved the incorporation of functional groups (i.e., probes) into the substrates which yield rearranged products if a free radical or radical ion is generated. Probe substituents (e.g., cyclopropyl groups) have been utilized extensively to detect ketyl and ketyl anion intermediates.[2-17]

Scheme 1



Incorporation of a rearrangeable probe into the substrate solves the problem that both processes (SET and polar) yield the same product by diverting any paramagnetic intermediate to a *different* product. In order for this approach to be successful, the rearrangement reaction should (ideally) be both fast and irreversible. Rearrangement rates for a variety of free radicals have been accurately determined in the past two decades and have enjoyed great success both as diagnostic tools for radical intermediacy and as "clocks" for ascertaining absolute rate constants for competing bimolecular processes.[18]

Unfortunately, this same level of sophistication has not yet been achieved in the case of radical ions. Often it is simply *assumed* that the same structural features which lead to rearrangement of a free radical will (by analogy) also lead to rearrangement of a radical ion. In earlier work, we have shown that this assumption can be misleading. Specifically, while the cyclopropylcarbinyl → homoallyl radical rearrangement (**1** → **2**, eq 1) is essentially irreversible ($K_{eq} = 10^5$) and occurs with a forward rate constant on the order of 10^8 s^{-1} at room temperature,[19] the analogous ring opening of the phenylcyclopropylketyl anion (**3** → **4**, eq 2) is nearly *8 orders of magnitude slower*, with an equilibrium constant which overwhelmingly favors the ring-closed form ($K_{eq} = 2 \times 10^{-8}$).[20] We have suggested that the loss of

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(1) Eberson, L. *Electron Transfer Reactions in Organic Chemistry*; Springer-Verlag: New York, 1987.
(2) Neckers, D. C.; Schaap, A. P.; Hardy, J. *J. Am. Chem. Soc.* **1966**, *88*, 1265. Neckers, D. C. *Tetrahedron Lett.* **1965**, 1889.
(3) Pereyre, M.; Godet, J.-Y. *Tetrahedron Lett.* **1970**, 3653. Godet, J.-Y.; Pereyre, M. *J. Organomet. Chem.* **1972**, *40*, C23. Godet, J.-Y.; Pereyre, M.; Pommier, J.-C.; Chevolleau, D. *J. Organomet. Chem.* **1973**, *55*, C15.
(4) Shiota, H.; Ohkata, K.; Hanafusa, T. *Chem. Lett.* **1974**, 1153.
(5) Miyaura, N.; Itoh, M.; Sasaki, N.; Suzuki, A. *Synthesis* **1975**, *5*, 317.
(6) Bagnell, L.; Meisters, A.; Mole, T. *Aust. J. Chem.* **1975**, *28*, 821.
(7) House, H. O.; Weeks, P. D. *J. Am. Chem. Soc.* **1975**, *97*, 2778. House, H.; Prabhu, A.; Wilkins, J.; Lee, L. *J. Org. Chem.* **1976**, *41*, 3067.
(8) Loots, M.; Dayrit, F.; Schwartz, J. *Bull. Soc. Chim. Belg.* **1980**, *89*, 897.
(9) Jullien, R.; Stahl-Lariviere, H.; Zann, D.; Nadjo, L. *Tetrahedron* **1981**, *37*, 3159.
(10) Chung, S. K. *J. Org. Chem.* **1981**, *46*, 5457. Chung, S. K.; Dunn, L. B., Jr. *J. Org. Chem.* **1984**, *49*, 935.
(11) Hwu, J. *J. Chem. Soc., Chem. Commun.* **1985**, *8*, 452.
(12) Russell, G. A.; Dedolph, D. F. *J. Org. Chem.* **1985**, *50*, 2378.
(13) Tanner, D. D.; Diaz, G. E.; Potter, A. *J. Org. Chem.* **1985**, *50*, 2149. Yang, D.; Tanner, D. D. *J. Org. Chem.* **1986**, *51*, 2267.
(14) Meinhart, J.; Grubbs, R. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 171.
(15) Castellino, A. J.; Bruice, T. C. *J. Am. Chem. Soc.* **1988**, *110*, 1313.
(16) Zelechonok, Y.; Silverman, R. B. *J. Org. Chem.* **1992**, *57*, 5785.
(17) Vedejs, E.; Duncan, S. M.; Haight, A. R. *J. Org. Chem.* **1993**, *58*, 3056.
(18) Griller, D.; Ingold, K. U. *Acc. Chem. Res.* **1980**, *13*, 317.

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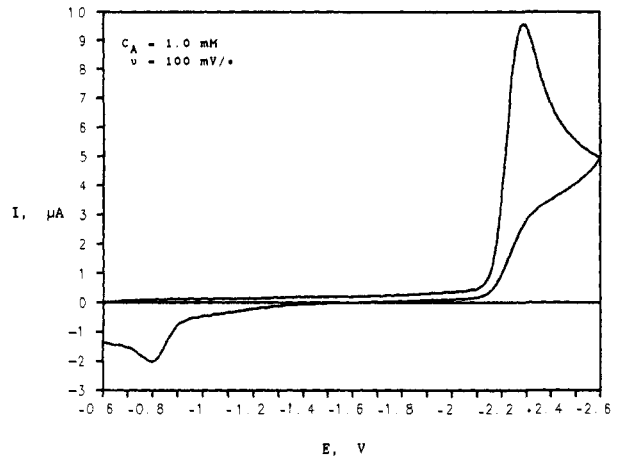
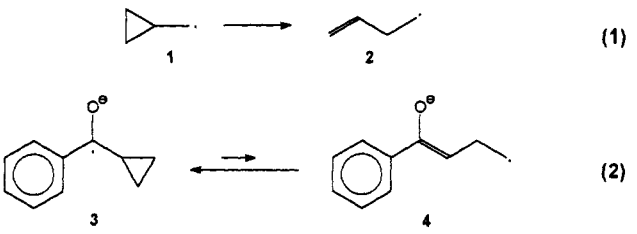


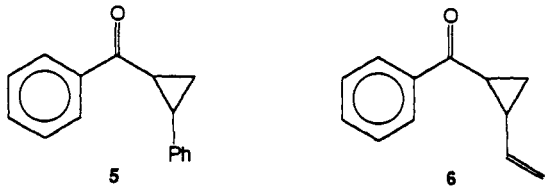
Figure 1. Cyclic voltammogram of 1-benzoyl-2-phenylcyclopropane (5).

resonance energy associated with the ring opening is responsible for the apparent stability of the radical anion and that similar considerations are likely important factors influencing the kinetics and thermodynamics of radical ion rearrangements in general.[20] In this paper we expand upon this theme by examining how placement of radical-stabilizing substituents on the cyclopropyl ring facilitate arylcyclopropylketyl anion ring opening.



Results

A. Voltammetry. The mechanism and kinetics of decay of radical anions generated by the electrochemical reduction of *trans*-1-benzoyl-2-phenylcyclopropane (**5**) and 1-benzoyl-2-vinylcyclopropane (**6**) were studied by cyclic and linear sweep voltammetry. All measurements were conducted at 23 °C in *N,N*-dimethylformamide (DMF) with 0.5 M tetra-*n*-butylammonium tetrafluoroborate as the supporting electrolyte. Gold and 0.1 M Ag^+/Ag (+0.337 V vs SCE) electrodes were used as working and reference, respectively.

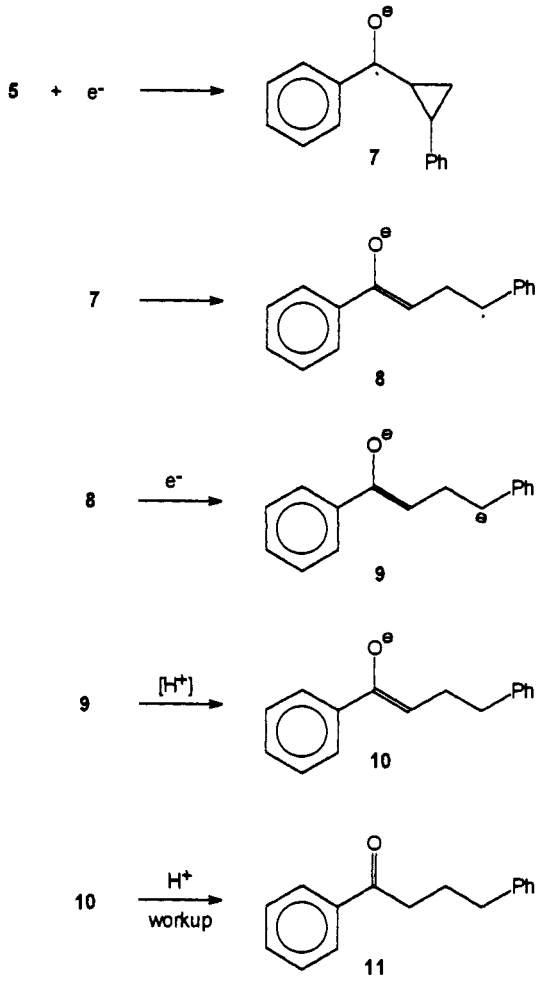


B. *trans*-1-Benzoyl-2-phenylcyclopropane (5).[21] The cyclic voltammogram corresponding to the reduction of **5** at 100 mV/s is presented in Figure 1. Noteworthy features associated with this voltammogram are (a) a reduction peak at –2.3 V with no corresponding reverse wave and (b) an apparent oxidation wave at –0.8 V.

Because no reverse wave was observed in this system (at scan rates up to 50 V/s and temperatures as low as –20 °C, we were compelled to study this system utilizing linear sweep voltammetry. Experimentally, this involved observing the effect of substrate concentration and sweep rate on the peak potential (E_p). The pertinent plots are available as supplementary material. Analysis of these plots yields $\delta E_p/\delta \log(\nu) = -33.4(\pm 1.3)$ mV/decade and $\delta E_p/\delta \log(C_A) = -2.7(\pm 1.7)$ mV/decade. These results are consistent with an EC or ECE mechanism, for which the theoretical response is $\delta E_p/\delta \log(\nu) = -29.5$ mV/decade and $\delta E_p/\delta \log(C_A) = 0.0$ mV/decade.[22]

Controlled potential electrolysis of **5** (1.6 equiv of electrons, Au electrode, 0.2 M n-Bu_4NBF_4 in DMF) yields 21% recovered starting material and 73% γ-phenylbutyrophenone (**11**). (Similar results were reported by Mandell et al. for reduction carried out in $EtOH/H_2O$ buffer, Na^+ counterion.[23]) A mechanism consistent with these observations is presented in Scheme 2. Ring opening of ketyl anion **7** yields distonic radical anion **8**. The reduction potential of benzyl radical has been reported (–1.77 V vs 0.1 M Ag^+/Ag);[24] we infer that the reduction potential of **8** is similar and hence considerably more positive than the reduction

Scheme 2



(19) (a) Maillard, B.; Forrest, D.; Ingold, K. U. *J. Am. Chem. Soc.* **1976**, *98*, 7024. (b) Kinney, R. J.; Jones, R. D.; Bergman, R. G. *J. Am. Chem. Soc.* **1978**, *100*, 7902. (c) Beckwith, A. L. J.; Moad, G. *J. Chem. Soc., Perkin Trans. 2* **1980**, 1473. (d) Effio, A.; Griller, D.; Ingold, K. U.; Beckwith, A. L. J.; Serelis, A. K. *J. Am. Chem. Soc.* **1980**, *102*, 1734. (e) Mathew, L.; Warketin, J. *J. Am. Chem. Soc.* **1986**, *108*, 7981. (f) Beckwith, A. L. J.; Bowry, V. W.; Moad, G. J. *J. Org. Chem.* **1988**, *53*, 1632. (g) Newcomb, M.; Glenn, A. G. *J. Am. Chem. Soc.* **1989**, *111*, 275. (h) Beckwith, A. L. J.; Bowry, V. W. *J. Org. Chem.* **1989**, *54*, 2681.

(20) Tanko, J. M.; Drumright, R. E. *J. Am. Chem. Soc.* **1992**, *114*, 1844.

(21) Preliminary results for this substrate have been reported: Tanko, J. M.; Drumright, R. E. *J. Am. Chem. Soc.* **1990**, *112*, 5362.

(22) (a) Parker, V. D. In *Comprehensive Chemical Kinetics, Vol. 26, Electrode Kinetics: Principles and Methodology*; Bamford, C. H., Compton, R. G., Eds.; Elsevier: New York, 1986; pp 145–202. (b) Andrieux, C. P.; Saveant, J. M. In *Investigation of Rates and Mechanisms of Reactions, Part II*; Bernasconi, C., Ed.; Wiley: New York, 1986; pp 305–390.

(23) Mandell, L.; Johnston, J. C.; Day, R. A., Jr. *J. Org. Chem.* **1978**, *43*, 1616.

(24) Wayner, D. D. M.; McPhee, D. J.; Griller, D. *J. Am. Chem. Soc.* **1988**, *110*, 132.

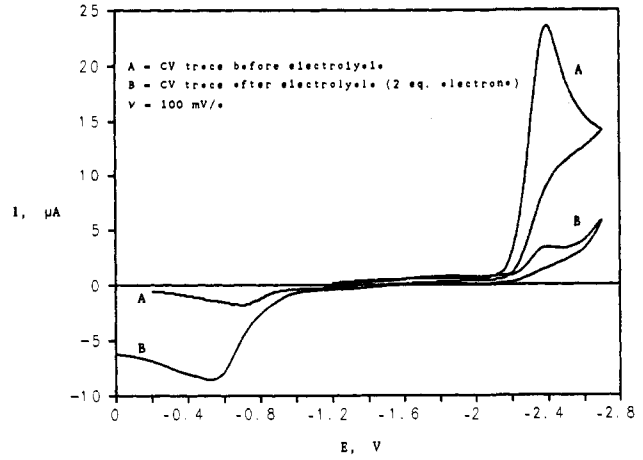


Figure 2. Cyclic voltammogram of 1-benzoyl-2-phenylcyclopropane (**5**) before (A) and after (B) electrolysis.

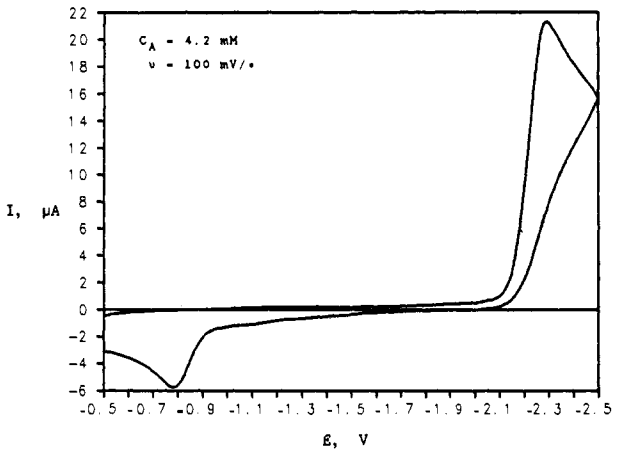
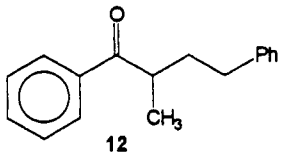


Figure 3. Cyclic voltammogram of 1-benzoyl-2-vinylcyclopropane (6).

potential of the starting ketone. Consequently, a second electron transfer forming dianion **9** is likely under these conditions. Because the ring opening step (**7** → **8**) is rate limiting, our results do not allow us to ascertain whether the second electron transfer is heterogeneous (ECE; **8** + e^- → **9**) or homogeneous (ECE_h, **7** + **8** → **9** + **5**).[25]

On the basis of the deuterium labeling and trapping experiments described below, it is likely that the benzylic anion portion of **8** is protonated under the reaction conditions forming enolate ion **10**. We ascribe the oxidation wave at –0.8 V in the CV of **5** to enolate **10**.[26] Cyclic voltammograms taken before and after electrolysis (Figure 2) clearly show the buildup of **10** during electrolysis at the expense of the starting ketone. This oxidation wave disappears when the reaction is quenched with either CH_3I or H^+. The isolated product, γ-phenylbutyrophenone (**11**), is not formed until aqueous workup.

Methyl Iodide Quenching Experiments. Controlled current electrolysis of **5** (0.68 equiv of electrons) followed by quenching with an excess of CH_3I yielded 54% recovered starting material plus compounds **12**, **13**, and **14** in yields of 29, 4, and 6%, respectively. No products attributable to quenching of dianion **9** were detected, supporting the proposition that this species is protonated prior to workup. Clearly, **12** and **13** result from C and O alkylation of enolate anion **10**. Isolation of a small amount of **14** suggests that the starting ketone undergoes deprotonation to some extent during electrolysis.



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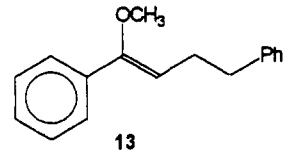

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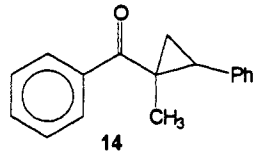

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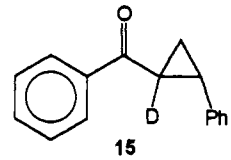
Deuterium Labeling Experiments. Controlled current electrolysis of 1-benzoyl-1-deuterio-2-phenylcyclopropane (**15**, 1.5 equiv of electrons) yielded recovered starting material (24%) and γ-phenylbutyrophenone (71%) with ca. 11% deuterium incorporation (7.5% at the α-position; 3.5% at the γ-position). These observations suggest that the starting ketone is only a minor proton source for the quenching of dianion **9**. (The recovered starting material contained only 10% of the original deuterium label. No attempt was made to locate the deuterium lost from the substrate during electrolysis.) Tetraalkyl ammonium salts have been shown to be proton donors to potent bases. Consequently, it is reasonable to suppose that the supporting electrolyte is the major proton source for quenching of the dianion.[27-29]



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C. 1-Benzoyl-2-vinylcyclopropane (6). The cyclic voltammogram corresponding to the reduction of **6** is presented in Figure 3. This voltammogram is very similar to that obtained for the reduction of **5**, namely, (a) a reduction wave is observed at –2.2 V with no corresponding oxidation wave even at scan rates as high as 50 V/s and (b) an oxidation wave is observed at –0.8 V. Linear sweep voltammetry experiments yielded $\delta E_p/\delta \log(\nu) = -38.9 \pm 3.1$ mV/decade and $\delta E_p/\delta \log(C_A) = 0.7 \pm 1.7$ mV/decade, again consistent with a first-order process.

The theoretical response of peak potential to scan rate for an EC process, $\delta E_p/\delta \log(\nu) = -29.5$ mV/decade, is predicted on the assumption that the chemical step is rate limiting.

$$A + e^- \overset{k_s}{\rightleftharpoons} B \qquad (E)$$

$$B \overset{k}{\rightarrow} C \qquad (C)$$

The observed response, $\delta E_p/\delta \log(\nu) = -38.9$ mV/decade, suggests a competition between the E and C steps for kinetic control.[30] Additional indication that the heterogeneous electron transfer step is partially contributing to the kinetics is provided by the fact that the LSV peaks are somewhat broadened.[30] ($E_p - E_{p/2}$ increases with increasing sweeprate from 60 mV at 25 mV/s to 70 mV at 1000 mV/s.)

Constant current electrolysis of **6** (1 equiv of electrons) yielded 26% recovered starting material and **16** and **17** in 28% and 23% yield, respectively.

(25) Amatore, C.; Saveant, J. M. *J. Electroanal. Chem.* **1977**, *85*, 27. Amatore, C.; Saveant, J. M. *J. Electroanal. Chem.* **1978**, *86*, 227.

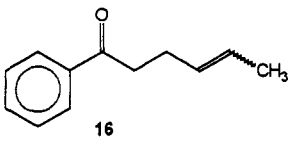
(26) This assignment appears reasonable because the reported oxidation potential of the sodium enolate phenylacetone is –0.54 V vs Ag/Ag^+; see: House, H. *Acc. Chem. Res.* **1976**, *9*, 59.

(27) Grimshaw, J.; Trocha-Grimshaw, J. *J. Chem. Soc., Perkin Trans. 2* **1975**, 218.

(28) Alvarado de la Torre, R.; Sease, J. *J. Am. Chem. Soc.* **1979**, *101*, 1687.

(29) Vieira, K.; Mubarak, M.; Peters, D. *J. Am. Chem. Soc.* **1984**, *106*, 5372.

(30) Nadjo, L.; Saveant, J. M. *J. Electroanal. Chem. Interfacial Electrochem.* **1973**, *48*, 113.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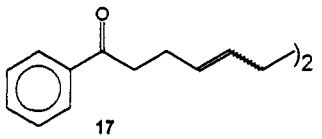
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A mechanism consistent with these observations is presented in Scheme 3. Ring opening of radical anion **18** yields distonic radical anion **19**, which partitions itself between reduction and dimerization pathways. The fact that the major product of the electrolysis of **6** is a dimer, while for **5** only reduced product is produced, is consistent with the fact that the reduction potential of an allyl radical is more negative than that of a benzylic radical.[31] We infer that the oxidation wave observed at –0.8 V in the CV of **6** represents oxidation of the product enolate ions.

D. Estimates of the Rate Constants for Ring Opening of 7 and 18. While the absence of a reverse wave in the CVs of **5** and **6** does not allow an accurate assignment of the rate constant for ring opening of **7** and **18**, it is possible to make a rough estimate. Assuming that the formal reduction potentials of **5** and **6** are similar to phenyl cyclopropyl ketone ($E°$ = –2.42 V vs 0.1 M Ag^+/Ag)[20] and that an EC mechanism is operative, then from the difference between E_{pc} and $E°$ it is possible to estimate the rate constant for ring opening using eq 3.[22b,30]

$$E_p = E° - 0.78\frac{RT}{F} + \frac{RT}{2F}\ln\left(\frac{k}{\nu}\right)\left(\frac{RT}{F}\right) \qquad (3)$$

At 50 mV/s, the peak potentials for **7** and **18** are –2.24 and –2.28 V, respectively. On this basis, we estimate that the rate constant of ring opening of **7** is 1×10^7 s^{-1}. Similarly, for **18**, $k \geq 5 \times 10^5$ s^{-1}.[32]

E. AM1 SCF-MO Calculations. The enthalpies of ring opening ($\Delta H°$) for several cyclopropylketyl anions pertinent to this work were calculated utilizing AM1 (half-electron approximation)[33] and are summarized in Table 1.

Discussion

Table 1 provides a summary of known thermodynamic and kinetic parameters pertaining to the ring opening of several cyclopropylcarbinyl radicals and structurally related cyclopropylketyl anions. Ring opening of the unsubstituted cyclopropylcarbinyl radical (**1**) is fast and essentially irreversible.[19] In contrast, the benzylcyclopropyl radical (**22**) ring opens 1 order of magnitude slower and is endothermic undoubtedly due to resonance stabilization of the ring-closed radical.[34] Placement of a phenyl group on the cyclopropane ring, however, appears to completely compensate for the loss of resonance energy suffered by the benzylcyclopropyl radical upon ring opening. (The rate constant for ring opening of (2-phenylcyclopropyl)benzyl radical, **24** → **25**, is slightly faster than that of cyclopropylcarbinyl radical.[35])

In the case of the radical anions, however, substitution on the cyclopropane ring does not fully compensate for the loss of resonance energy associated with ring opening. Ring opening of cyclopropylketyl anion (**26** → **27**) is estimated to be exothermic by 11 kcal/mol. In contrast, ring opening of phenylcyclopropylketyl anion (**3** → **4**) is *endothermic* by 11 kcal/mol, a value in good agreement with the estimated equilibrium constant (K_{eq} = 2×10^{-8}; $\Delta G°$ = +10 kcal/mol).[20] These results attest to the importance of resonance stabilization in the ring-closed form, which is lost upon ring opening (Scheme 4). Relief of cyclopropane ring strain does not compensate for this loss of resonance energy. The net consequence is that this substrate is wholly unsuitable as a probe substrate for SET.

Verification of the extensive delocalization of unpaired electron density into the aromatic ring is provided by an ESR study of phenylcyclopropylketyl anion. Because the hyperfine splitting in ketyl anions is profoundly affected by solvent and counterion,[36] we elected to record the spectrum under conditions identical to those of our voltammetric measurements (DMF solvent and *n*-Bu_4NBF_4 as the supporting electrolyte).[37]

In close analogy to the acetophenone ketyl anion,[38] the ambient temperature ESR spectrum of phenylcyclopropylketyl anion reveals hindered rotation about the C_{Ar}–(C=O) bond and exhibits relatively high a^H values for the ortho and para positions. These data clearly indicate substantial unpaired electron delocalization into the aromatic ring (Table 2).

It is possible to *partially* compensate for this loss of resonance energy associated with ring opening of arylcyclopropylketyl anions by placing radical-stabilizing substituents (e.g., vinyl or aryl) on the cyclopropyl ring as demonstrated by **7** → **8**[39] and **18** → **19** (Table 1). These substituents are able to stabilize the radical portion of the ring-opened (distonic) radical anion via resonance, making the reaction kinetically and thermodynamically more favorable. However, these substituents do not fully compensate for the loss of resonance energy associated with ring opening, and the rate constants for these rearrangements still fall several orders of magnitude below that of cyclopropylcarbinyl (and related) free radical rearrangements.

Thus, although the radical anion probes discussed herein are far superior to those without radical-stabilizing substituents on the cyclopropane ring, they have not yet achieved the "hypersensitivity" of their free radical counterparts. Future work in our laboratory will focus on the development and characterization of substantially more sensitive SET probes.

Experimental Section

General Considerations. Melting points were determined on a Thomas Hoover capillary melting point apparatus and are uncorrected. Nuclear magnetic resonance spectra (^1H, ^2H, ^{13}C) were obtained on either a 200-MHz or 270-MHz Bruker FT NMR spectrometer. All chemical shift values are reported in δ units relative to Me_4Si (δ 0.00 ppm) in deuteriochloroform (^2H spectra run in $CHCl_3$). Infrared spectra were recorded on a Perkin-Elmer model 1600 FT-IR spectrometer, and IR bands are reported in inverse centimeters. Both low- and high-resolution mass spectral data were obtained from a VG Analytical Model 7070 E-HF double-focusing, magnetic sector, high-resolution mass spectrometer. Electron impact ionization (70 eV) was employed unless otherwise stated. Low-resolution GC/MS was performed on a Hewlett-Packard Model 5890 gas chromatograph with an HP methylsilicone capillary column (12 m × 0.2 mm) interfaced to an HP 5097B EI mass spectrometer and an HP series computer. ESR spectra were recorded in an IBM/Bruker ER 200. Gas chromatographic analyses were performed on a Hewlett-Packard HP 5890 instrument equipped with both FID and TCD

(31) Jaun, B.; Schwarz, J.; Breslow, R. *J. Am. Chem. Soc.* **1980**, *102*, 5741.

(32) Since the kinetics of this system are partially governed by the heterogeneous electron transfer step, this estimate represents a *lower* limit for the rate constant for ring opening of **18**.

(33) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902.

(34) Bowry, V. W.; Lusztyk, J.; Ingold, K. U. *J. Chem. Soc., Chem. Commun.* **1990**, 923.

(35) Hollis, R.; Hughes, L.; Bowry, V. W.; Ingold, K. U. *J. Org. Chem.* **1992**, *57*, 4284.

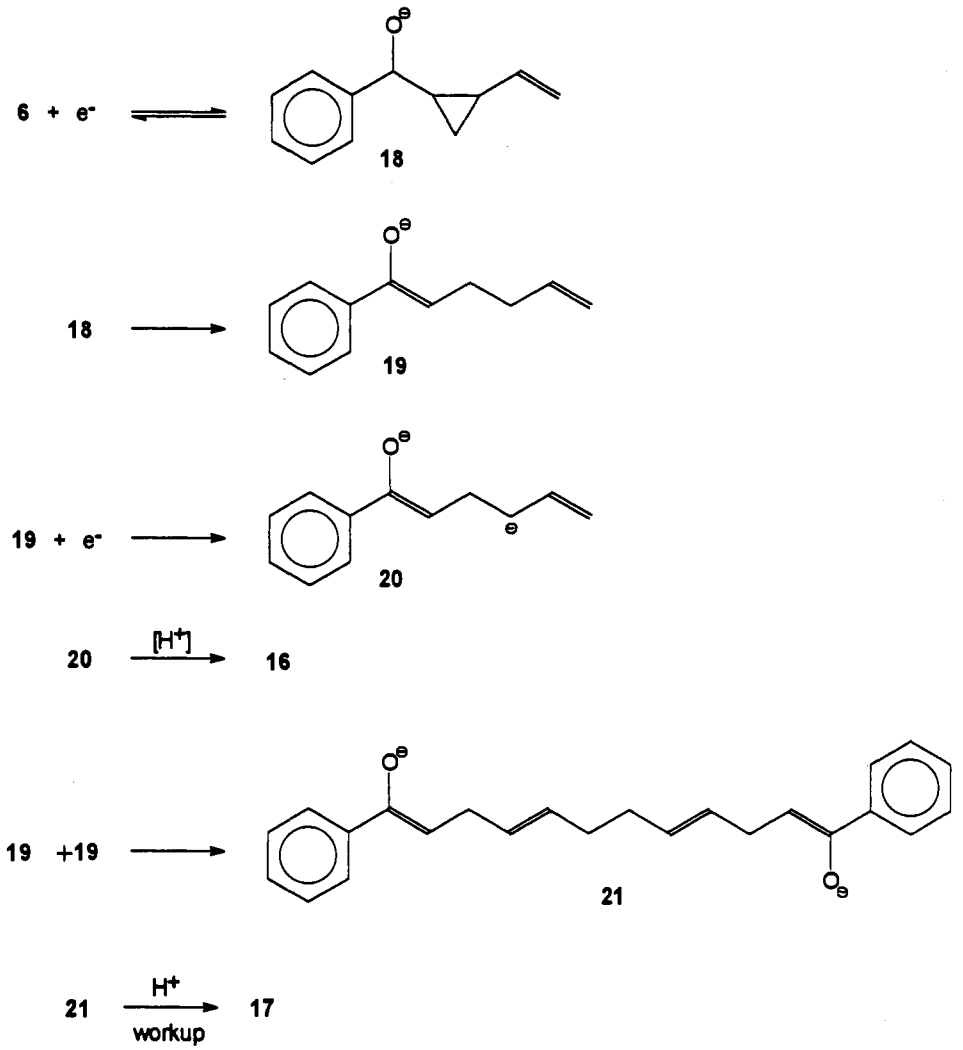
(36) See Hirota, N. In *Radical Ions*; Kaiser, E. T., Kevan, L., Eds.; Wiley: New York, 1968; pp 35–85.

(37) An ESR spectrum for phenylcyclopropylketyl anion has been recorded previously by Bauld et al. via reduction of phenyl cyclopropyl ketone with K in DME. The only hyperfine coupling constant reported was for the cyclopropyl methine hydrogen (0.86 G) obtained by comparison of the spectral widths of the hydrido and deuterated. See: Bauld, N. L.; McDermed, J. D.; Hudson, C. E.; Rim, Y. S.; Zoeller, J., Jr.; Gordon, R. D.; Hyde, J. S. *J. Am. Chem. Soc.* **1969**, *91*, 6666.

(38) Steinberger, N.; Fraenkel, G. *J. Chem. Phys.* **1964**, *40*, 723.

(39) Tanner has also examined the radical anion derived from the radical-initiated reduction of 1-benzoyl-2-phenylcyclopropane with DMBI in acetonitrile. A major point which emerges from this work is that *ring opening is reversible for this system as well!* (This reversibility could not be detected in our study because distonic radical anion **8** is rapidly reduced to dianion **9** at potentials where the starting ketone is reduced; Scheme 2.) See: Tanner, D. D.; Chen, J. J.; Luelo, C.; Peters, P. M. *J. Am. Chem. Soc.* **1992**, *114*, 713. Miyaura, N.; Itoh, M.; Sasaki, N.; Suzuki, A. *Synthesis* **1975**, *5*, 317. Corey, E.; Chaykovsky, M. *J. Am. Chem. Soc.* **1965**, *87*, 1353.

Scheme 3



detectors, and an HP 3393A reporting integrator. Analyses were accomplished on either an Alltech RSL-200 (nonpolar) capillary column (30 m × 0.25 mm) or a Supelco SE-54 (low polarity) capillary column (15 m × 0.25 mm). Flash chromatography was performed on silica gel (EM Science, 230–400 mesh) using hexane/ethyl acetate solvent mixtures (weight ratio of silica to substrate ~ 200:1). Thin-layer chromatography (TLC) was performed on precoated silica gel 60 F-254 plates purchased from EM Science.

Electrochemical Measurements. The instrumentation and procedures employed for cyclic and linear sweep voltammetry and for bulk electrolyses have been described earlier. Voltammetric measurements were performed on solutions which contained 0.5 M *n*-Bu_4NBF_4 in DMF at room temperature using a 1.6-mm-diameter gold working electrode (BAS), 0.1 M Ag^+/Ag reference (+0.337 V vs SCE), and Pt auxiliary. The ESR spectrum of phenylcyclopropylketyl anion was obtained by electrolytic reduction of phenyl cyclopropyl ketone at a Hg pool electrode (0.2 M *n*-Bu_4NBF_4 in DMF).

Materials. *N,N*-dimethylformamide (DMF, Aldrich HPLC grade, 99%+) was purified before use as described earlier. Phenyl cyclopropyl ketone (Aldrich) was used as received. Tetra-*n*-butylammonium tetrafluoroborate (*n*-Bu_4NBF_4) was prepared by the method of House and crystallized 4× from ethyl acetate/pentane before use. 1-Benzoyl-2-vinylcyclopropane[40] and *trans*-1-benzoyl-2-phenylcyclopropane[41] were prepared according to literature procedures.

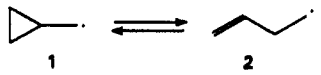
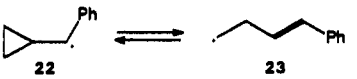
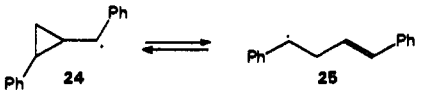
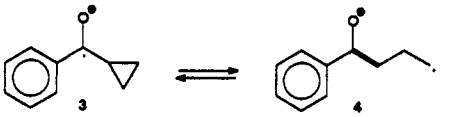
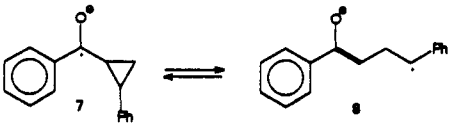
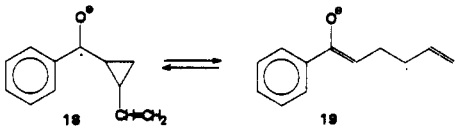
1-Benzoyl-1-deuterio-2-phenylcyclopropane (15). A flame-dried flask under argon was charged with 30 mL of D_2O and 1.7 g (74 mmol) of sodium. 1-Benzoyl-2-phenylcyclopropane (4.2 g, 19 mmol) in 30 mL of 1,4-dioxane (Fisher) was then added to the flask. The reaction mixture was refluxed 3 days, poured into 100 mL of water, and extracted three times with 30-mL portions of diethyl ether. The organic layers were combined, washed with water, dried over magnesium sulfate, and concentrated. The crude viscous oil was crystallized from petroleum ether to yield 50% of a white solid (mp 44–45 °C) containing better than 95% deuterium label, as determined by comparison of the MS spectra of the deuterio and hydrido isomers: ^1H NMR ($CDCl_3$) δ 1.55 (m, 1H), 1.95 (m, 1H), 2.7 (m, 1H), 7.1–7.6 (m, 8H), 8.05 (m, 2H); ^2H NMR ($CHCl_3$) δ 2.94 (s); MS *m/e* (relative intensity) 224 (2.9), 223 (M^+, 17.8), 222 (14.7), 221 (1.2), 118 (16.9), 117 (11.8), 116 (17.8), 105 (100), 77 (44).

Bulk Electrolyses (General). All experiments were performed on solutions which contained 0.2 M *n*-Bu_4NBF_4 in DMF. A conventional H-cell, with the two compartments separated by a medium glass frit (22 mm diameter) was utilized. Fifty milliliters of the electrolyte solution was partitioned equally between the two compartments of the H-cell under argon. The electroactive substrate was added to the cathodic compartment, and both compartments were purged with argon for 30 min. A 0.127 mm × 25 mm × 25 mm piece of gold foil served as the working electrode. All electrolysis experiments were performed at ambient temperature (23 °C). Constant-current electrolyses were performed at currents from 35 to 50 mA. Constant-potential electrolyses were performed (with positive-feedback *iR* compensation) at potentials approximately 300 mV beyond the CV peak potential. After electrolysis, the cathodic compartment was quenched and the contents were poured into 30–40 mL of water and extracted 4× with 20 mL of ether. The combined organic extracts were washed with water, dried ($MgSO_4$), and evaporated. The reaction products were separated by flash chromatography and characterized. Product yields and spectral data are summarized below.

A. Electrolysis of 1-Benzoyl-2-phenylcyclopropane (5): HCl Quench. 5 (120 mg, 0.54 mmol) was electrolyzed at –2.35 V for 1 h (82 C; 1.6

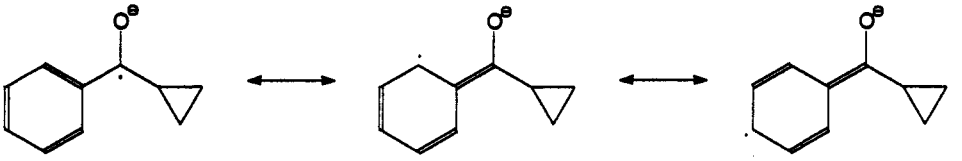
(40) Miyaura, N.; Itoh, M.; Sasaki, N.; Suzuki, A. *Synthesis* **1975**, *5*, 317.
(41) Corey, E.; Chaykovsky, M. *J. Am. Chem. Soc.* **1965**, *87*, 1353.

Table 1. Kinetic and Thermodynamic Parameters Pertaining to Ring Opening of Cyclopropylcarbinyl Radicals and Related Radical Anions

reaction	k_1, s^{-1}	k_{-1}, s^{-1}	ΔH°, kcal/mol
 1 2	1.2×10^{8}[a]	5×10^{3}[b]	-3.1[b]
 22 23	1×10^{6}[c]	1.2×10^{7}[c]	+3.3[c]
 24 25	3.6×10^{8}[d]		
 26 27			-11
 3 4	≤ 2[e]	8×10^{7}[e]	+11
 7 8	1×10^{7}		-2
 18 19	$\geq 5 \times 10^{5}$		-2

[a] Reference 19. [b] Reference 19d. [c] Reference 34. [d] Reference 35. [e] Reference 20.

Scheme 4



equiv of electrons). Quenching with 5% aqueous HCl and workup yielded a viscous yellow oil comprising two components. GC response factors on authentic samples were determined relative to diphenyl ether, and the reaction mixture was analyzed by GC. This electrolysis yielded 21% of recovered starting material and 73% of 4-phenylbutyrophenone (**11**).

B. Electrolysis of 5: Methyl Iodide Quench. Electrolysis of 211 mg (0.95 mmol) of **5** for 30 min at 35 mA (0.68 equiv of electrons), quenching with 300 μL (4 molar equiv) of methyl iodide, workup, and flash chromatography with ethyl acetate/hexane yielded (1) 113 mg (54%) of recovered starting material and the following.

(2) 2-Methyl-4-phenylbutyrophenone (**12**) (66 mg, 29%): ^{1}H NMR ($CDCl_3$) δ 1.15 (d, 3H, J = 8.3 Hz), 1.65 (m, 1H), 2.05 (m, 1H), 2.55 (t, 2H, J = 7.8 Hz), 3.4 (m, 1H), 7.0–7.5 (m, 8H), 7.8 (m, 2H); IR (cm^{-1}) 3061, 3026, 2968, 2938, 2860, 1682, 1596, 1579, 1496, 1448, 1226, 974, 700.

(3) 1,4-Diphenyl-1-methoxybut-1-ene (**13**) (8.5 mg, 4%): ^{1}H NMR ($CDCl_3$) δ 2.5–2.8 (m, 4H), 3.4 (s, 3H), 5.4 (t, 1H, J = 7.8 Hz), 7.0–7.5 (m, 5H); IR (cm^{-1}) 3083, 3060, 3025, 2929, 2854, 1601, 1493, 1452, 1629, 1074.

(4) 1-Benzoyl-1-methyl-2-phenylcyclopropane (**14**) (14 mg, 6%): ^{1}H NMR ($CDCl_3$) δ 1.3 (s, 3H), 1.6 (m, 1H), 2.0 (m, 1H), 2.45 (m, 1H), 7.1–7.6 (m, 8H), 7.8 (m, 2H); IR (cm^{-1}) 3060, 3027, 2970, 2940, 1670, 1497, 1448, 1224, 974, 700.

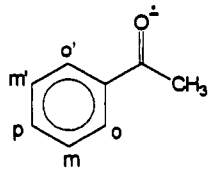
C. Electrolysis of 5 Monitored by CV. An electrolysis of 141 mg (0.63 mmol) of **5** at 35 mA for 68 min (2.3 equiv of electrons) was monitored with a planar platinum electrode (0.5 mm in diameter) before, during, and after the electrolysis experiment. After electrolysis, the cathodic compartment was quenched with 4 molar equiv of methyl iodide, worked up, and analyzed by GC. This electrolysis yielded recovered starting material (8%), 1,4-diphenyl-1-methoxybut-1-ene (**13**, 4%), 2-methyl-4-phenylbutyrophenone (**12**, 62%), 4-phenylbutyrophenone (**11**, 1%), and 1-benzoyl-1-methyl-2-phenylcyclopropane (**14**, 4%).

D. 1-Benzoyl-1-deuterio-2-phenylcyclopropane (15). Electrolysis of 136 mg (0.61 mmol) of **15** at 30 mA for 50 min (1.5 equiv of electrons), quenching with 5% aqueous HCl, and workup yielded a viscous yellow oil. Flash chromatography yielded the following.

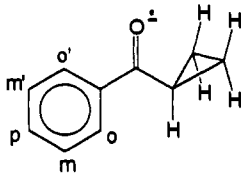
(1) Recovered starting material (scrambled label) (33 mg, 24%): MS m/e (relative intensity) 224 (0.81), 223 (5.52), 222 (24.32), 221 (18.91), 219 (0.24), 105 (100). Approximately 90% of the deuterium label was lost in the recovered starting material. This was estimated by comparing the mass spectrum of this sample to the mass spectrum of the authentic hydrido and deuterio isomers.

(2) 4-Phenylbutyrophenone (**11**) (97 mg, 71%): MS m/e (relative intensity) 226 (0.50), 225 (4.08), 224 (15.14), 120 (100), 105 (50.27), 91 (13.3), 77 (37.02); ^{2}H NMR ($CHCl_3$) δ 2.7 (s), 2.9 (s), relative ratio 1:2.5. The total deuterium incorporated into this product was estimated

Table 2. Estimated Hyperfine Splitting Constants and Atomic Orbital Spin Populations (ρ^{π}_i) in Radical Anions Generated from Phenyl Cyclopropyl Ketone and Acetophenone



22



3

	a^{H}_i, G		p_Z orbital spin populations (ρ^{π}_i)[a]	
	3[b]	**22**[c,d]	**3**	**22**
o	3.712	3.71	0.156	0.157
o′	4.251	4.21	0.177	0.179
m	0.875	0.93	0.067	0.045
m′	1.070	1.60	0.040	0.037
p	6.597	6.45	0.272	0.278

[a] Calculated from experimentally observed hyperfine splitting using the McConnell equation, $\rho^{p}_i = a^{H}_i/23.07$. [b] Hyperfine splittings for the cyclopropyl hydrogens were 1.15 (1H), 0.585 (2H), and 0.125 (2H). [c] Values taken from ref 38. [d] Hyperfine splittings for the methyl hydrogens were 6.735 G.

by comparison of the mass spectrum of this sample to the mass spectrum of the fully hydrido isomer. The distribution of deuterium in the molecule was estimated on the basis of the relative intensity of signals in the ^{2}H NMR spectrum of this sample. We estimate a total deuterium incorporation of 11% distributed between the positions α and γ to the carbonyl in a ratio of 2.5:1.

E. Electrolysis of 1-Benzoyl-2-vinylcyclopropane (6). Electrolysis of 148 mg (0.86 mmol) of 6 at 35 mA for 40 min (1.01 equiv of electrons), quenching with 5% aqueous HCl, workup, and flash column chromatography yielded (1) 39 mg (26%) of recovered starting material and the following.

(2) 5-Benzoyl-2-pentene (**16**) (mixture of *cis* and *trans*) (42 mg, 28%): ^{1}H NMR ($CDCl_3$) δ 1.65 (m, 3H), 2.45 (m, 2H), 3.05 (t, 2H, J = 7.6 Hz), 5.5 (m, 2H), 7.5 (m, 3H), 7.9 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 12.66 and 17.80 (*cis* and *trans* methyls), 21.69, 27.13, 38.37, and 38.48 (*cis* and *trans* methylenes), 125.08 (methine), 125.88 (quartet), 128.00, 128.50, 128.85, and 132.86 (methines), 199.74 (carbonyl carbon); IR (cm^{-1}) 3061, 3016, 2919, 2857, 1688, 1598, 1580, 1449, 1409, 1358, 1203, 969, 744, 690; MS *m/e* (relative intensity) 175 (1.2), 174 (10.1), 159 (4.8), 145 (5.7), 120 (16.3), 105 (100), 77 (46.6); HRMS for $C_{12}H_{14}O$, calc 174.104 465 2, found 174.102 890.

(3) 1,10-Dibenzoyl-3,7-decadiene (**17**) (34 mg, 23%): ^{1}H NMR ($CDCl_3$) δ 2.1 (m, 4H), 2.45 (m, 4H), 3.0 (t, 4H, J = 8.1 Hz), 5.5 (m, 4H), 7.5 (m, 6H), 7.95 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 27.22, 32.47, 38.56 (methylenes), 128.06, 128.55, 128.97, and 132.92 (methines), 137.10 (quartet), 199.73 (carbonyl carbon); IR (cm^{-1}) 3061, 2922, 2850, 1686, 1597, 1580, 1448, 1410, 1363, 1203, 970, 743, 690; MS *m/e* (relative intensity) 348 (0.2), 347 (1.8), 346 (6.2), 328 (8.2), 278 (7.6), 227 (11.3), 226 (20), 208 (4.6), 199 (7.0), 173 (18.8), 120 (9.2), 105 (100), 77 (40); HRMS for $C_{24}H_{26}O_2$, calc 346.193 280 3, found 346.191 605.

Acknowledgment. We gratefully acknowledge the National Science Foundation (CHEM-9113448) for financial support.

Supplementary Material Available: LSV plots of peak potential (E_p) vs log(ν) and log(C_A) for the reduction of 1-benzoyl-2-phenylcyclopropane (**5**) and 1-benzoyl-2-vinylcyclopropane (**6**) (4 pages). This material is contained in many 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.