Absolute Rate Constants for Reactions of α-Carbethoxy and α-Cyano Radicals

Martin Newcomb,* John H. Horner, Michelle A. Filipkowski, Chau Ha, and Seung-Un Park[1]

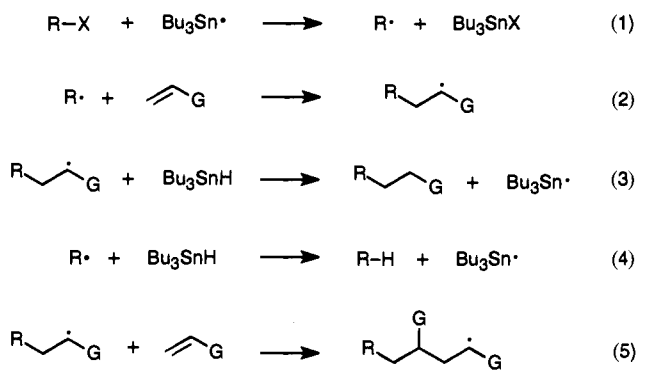
Contribution from the Department of Chemistry, Wayne State University, Detroit, Michigan 48202-3489

Received July 13, 1994. Revised Manuscript Received February 2, 1995[⊗]

Abstract: Absolute rate constants were measured for cyclizations of α-carbethoxy- and α-cyano-substituted radicals and for reactions of these radicals with Bu_3SnH. 2-Pyridinethioneoxycarbonyl ester radical precursors were employed in direct, laser-flash kinetic studies of cyclizations of $^{\bullet}CRX-(CH_2)_m-CH{=}CPh_2$ (**4a**: R = H, X = CO_2Et, m = 3; **4b**: R = H, X = CO_2Et, m = 4; **4c**: R = CH_3, X = CO_2Et, m = 3; **4d**: R = CH_3, X = CN, m = 3) over the temperature range 0−60 °C. Radical **4a** was produced in two conformations that cyclized faster than they equilibrated by rotation of the carbethoxy group. Radicals **4b,c** apparently cyclized slower than rotation of the carbethoxy group. At 20 °C, the rate constants were 5.4×10^7 and 2.0×10^7 (**4a**), 7×10^5 (**4b**), 3.3×10^5 (**4c**), and 2.1×10^5 (**4d**) s^{-1}. The α-carbethoxy group had no kinetic effect on the cyclizations of the secondary radicals **4a,b**, which occurred with rate constants slightly greater than those of the analogous secondary alkyl radicals (i.e., **4**: R = H, X = CH_3). However, the cyclizations of the tertiary radicals **4c,d** were substantially reduced in rate in comparison to that of the analogous tertiary alkyl radical with increases in $\Delta G^{\ddagger}$ at 20 °C of 2.0−2.2 kcal/mol. The latter kinetic results are ascribed to a steric effect in radicals **4c,d** enforced by the structure of the delocalized radical system. Rate constants and Arrhenius functions for reactions of **4b**, **4c**, and **4d** with Bu_3SnH were determined by indirect methods; at 20 °C, these hydrogen atom transfer reactions occur with rate constants of 3×10^6, 2×10^5, and 3×10^5 M^{-1} s^{-1}, respectively. The kinetic values for reactions with Bu_3SnH can be incorporated into synthetic planning.

Interest in radical reactions in general has increased rapidly in recent years as new radical-based methods have been shown to be important in syntheses.[2] Most useful radical methods involve chain reaction sequences, a simple case of which is exemplified by the tin hydride mediated addition in Scheme 1. A radical (R•) produced by atom abstraction from a precursor, in this case an alkyl halide (eq 1), adds intermolecularly to a reagent (or cyclizes) to give a new radical (eq 2), and the product radical thus formed is trapped by the tin hydride to give the desired product (eq 3). However, tin hydride trapping of the initial radical (eq 4) and an addition reaction of the product radical to a second molecule of reagent (eq 5) are competing side reactions. Because of the competing reactions in radical chain sequences, knowledge of the rate constants of the various elementary steps is required in order to adjust concentrations such that the desired sequence will be efficient. When absolute rate constants are known, one can calculate the appropriate reagent concentrations in advance of experimentation, and many absolute rate constants for reactions of simple alkyl radicals have been cataloged.[3,4] However, few are available for reactions of radicals substituted with donor and acceptor groups. The numerous successful radical-based syntheses involving such substituted radicals are testaments to the skills of synthetic chemists who most often have determined the correct reagent concentrations (and, therefore, also the relative rate constants for competing radical processes) by trial and error.

Scheme 1



Most of the synthetically useful absolute kinetic values for alkyl radical reactions derive from a few direct measurements of second-order reactions.[4] The most important set of such studies was reported by Ingold *et al.* for reactions of radicals with Bu_3SnH,[5] but kinetic values for reactions of alkyl radicals with PhSH[6] and for nitroxyl radical couplings[7] are also noteworthy. These absolute second-order rate constants have been incorporated into a number of unimolecular "radical

[⊗] Abstract published in *Advance ACS Abstracts*, March 15, 1995.

(1) Department of Chemistry, Konkuk University, Seoul, Korea.

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(7) Johnston, L. J.; Scaiano, J. C.; Ingold, K. U. *J. Am. Chem. Soc.* **1984**, *106*, 4877−4881. Chateauneuf, J.; Lusztyk, J.; Ingold, K. U. *J. Org. Chem.* **1988**, *53*, 1629−1632. Beckwith, A. L. J.; Bowry, V. W.; Moad, G. *J. Org. Chem.* **1988**, *53*, 1632−1641. Beckwith, A. L. J.; Bowry, V. W.; Ingold, K. U. *J. Am. Chem. Soc.* **1992**, *114*, 4983−4992. Bowry, V. W.; Ingold, K. U. *J. Am. Chem. Soc.* **1992**, *114*, 4992−4996.

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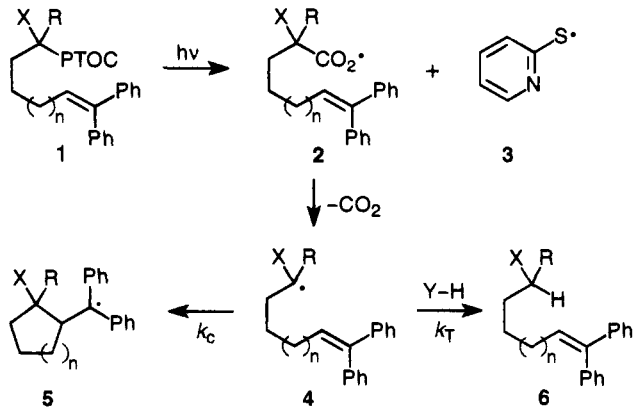
Scheme 2



a: X = CO_2Et, R = H, n = 1
b: X = CO_2Et, R = H, n = 2
c: X = CO_2Et, R = Me, n = 1
d: X = CN, R = Me, n = 1

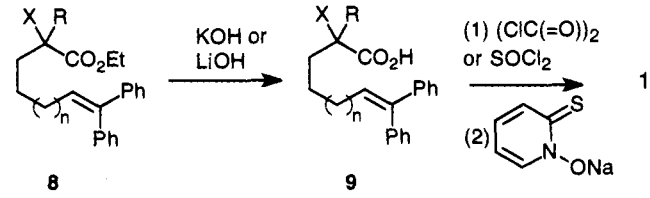
clocks"[8] and then into other second-order radical reactions by indirect kinetic methods.[4] Our group has developed an alternative approach for measuring radical reaction rate constants that employs direct measurements of unimolecular radical kinetics.[9] The rate constants for the unimolecular rearrangements can be used for calibration of second-order processes via indirect kinetic methods, and in optimal situations, the unimolecular reactions can be used as indicator reactions for the direct measurement of second-order kinetics. In this work, we report absolute rate constants for cyclization reactions of α-carbethoxy- and α-cyano-substituted radicals and second-order rate constants for reactions of these radicals with Bu_3SnH.

Radical Precursors and Reaction Characterizations

The experimental design followed the general method shown in Scheme 2. PTOC esters[10] **1** were employed as radical precursors for studies conducted with a 2 ns resolution kinetic spectrometer. The PTOC radical precursors have a long wavelength λ_{max} at 350−370 nm and are cleaved by 355 nm light from a Nd-YAG laser to give acyloxyl radicals **2** and the 2-pyridylthiyl radical (**3**).[9a,11] Rapid decarboxylations of radicals **2** gave the desired radicals **4**, the cyclizations of which were readily followed by monitoring the strong absorbance of the diphenylalkyl radical moiety in radicals **5**. When no trapping agents were present, the kinetics of cyclizations of radicals **4** (and any background reactions that consume **4** such as reaction with oxygen) were obtained. In the presence of a competitive radical trapping agent, the loss of radicals **4** was accelerated due to formation of both **5** and trapped product **6**, and the observed rate constants (k_{obs}) were given by eq 6, where k_0 is

$$k_{obs} = k_0 + k_c + k_T[Y-H] \qquad (6)$$

Scheme 3



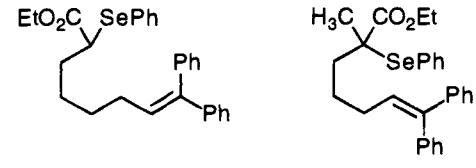
a: X = CO_2Et, R = H, n = 1
b: X = CO_2Et, R = H, n = 2
c: X = CO_2Et, R = Me, n = 1
d: X = CN, R = Me, n = 1

the (pseudo first order) rate constant for all background reactions consuming **4**, k_c is the rate constant for cyclization, k_T is the rate constant for trapping, and [Y−H] is the concentration of a hydrogen atom transfer trapping agent.

The PTOC precursors employed in the direct studies were prepared by a common route (Scheme 3). Alkylation of diethyl malonate and diethyl methylmalonate with 5-bromo-1,1-diphenyl-1-pentene and diethyl malonate with 6-bromo-1,1-diphenyl-1-hexene gave the diesters **8a−c**. For the precursor to **1d**, ethyl cyanoacetate was alkylated twice, first with 5-bromo-1,1-diphenyl-1-pentene and then with iodomethane, to give cyano ester **8d**. Compounds **8** were saponified to give the monocarboxylic acids **9**, which were converted to the corresponding acyl chlorides and then to PTOC esters **1** by reaction with the sodium salt of *N*-hydroxypyridine-2-thione. Generally, we prefer to purify PTOC esters for use in kinetic studies. However, whereas PTOC esters **1c,d** could be purified by silica gel chromatography with partial decomposition, precursors **1a,b** decomposed upon attempted purification. Therefore, samples of **1a,b** were used as obtained from the preparative reactions.

The instability of the various PTOC precursors containing an α-substituted electron-withdrawing group is noteworthy. As a general class, the PTOC esters have been widely applied in synthetic conversions most often without isolation, but our group has conducted a number of radical kinetic studies using purified PTOC esters that could be handled and stored for weeks or months without decomposition as long as they were shielded from light. However, precursors **1** used in this work were substantially less stable. PTOC esters **1c,d** could be stored for short periods, although **1d** decomposed upon standing for weeks at room temperature. The precursors to the secondary radicals (PTOC esters **1a,b**) were quite reactive as noted above.[12]

We briefly explored the use of another type of radical precursor for both direct and indirect studies. α-Phenylseleno carbonyl compounds are known to be useful radical precursors in tin hydride mediated reactions.[13] We prepared the phenyl selenides **10b,c** by decarboxylation of acids **9**, deprotonation



10b **10c**

of the esters, and reaction of the ester enolates with diphenyl

(8) Griller, D.; Ingold, K. U. *Acc. Chem. Res.* **1980**, *13*, 317−323. For a discussion of indirect methods and lists of calibrated alkyl radical reactions and radical clocks, see ref 4.

(9) (a) Ha, C.; Horner, J. H.; Newcomb, M.; Varick, T. R.; Arnold, B. R.; Lusztyk, J. *J. Org. Chem.* **1993**, *58*, 1194−1198. (b) Newcomb, M.; Horner, J. H.; Shahin, H. *Tetrahedron Lett.* **1993**, *34*, 5523−5526. (c) Johnson, C. C.; Horner, J. H.; Tronche, C.; Newcomb, M. *J. Am. Chem. Soc.* **1995**, *117*, 1684−1687.

(10) The acronym PTOC derives from 2-pyridinethioneoxycarbonyl. For an overview of these radical precursors, see the following: Barton, D. H. R.; Crich, D.; Motherwell, W. B. *Tetrahedron* **1985**, *41*, 3901−3924.

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(12) The instability problem prevented studies of a secondary nitrile radical using the PTOC precursor **1** (X = CN, R = H, *n* = 1). The appropriate carboxylic acid (**8**: X = CN, R = H, *n* = 1) was prepared as above. However, the PTOC ester, although apparently formed in low yield by the reaction sequence of Scheme 2 as determined by NMR spectroscopic analysis of the crude product, was quite impure and decomposed upon silica gel chromatography.

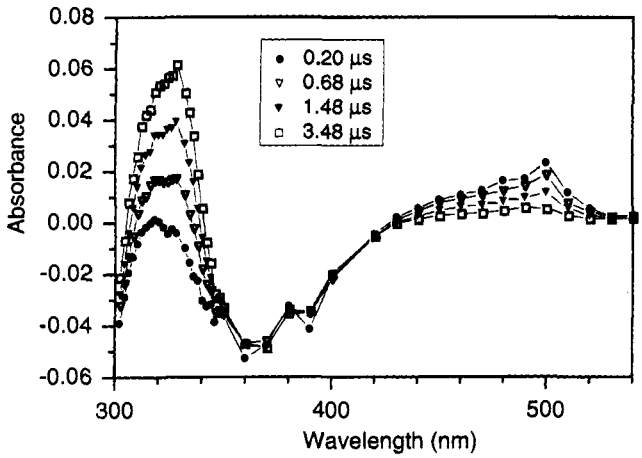
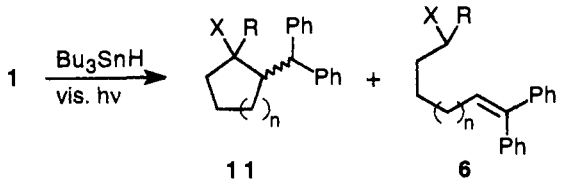


Figure 1. Time-resolved spectrum obtained upon irradiation of **1b**. The diphenylalkyl radical **5b** has λ_{max} at ca. 330 nm. Radical **3** has λ_{max} at ca. 490 nm.

diselenide. Compounds **10** were stable and proved to be useful for indirect studies with tin hydride, but they could not be used in direct studies because the phenylselenyl radical produced upon 266 nm irradiation of **10** absorbed strongly in the region of absorbance of the diphenylalkyl radical moiety.

The growth of a distinctive signal for diphenylalkyl radicals with λ_{max} at ca. 330 nm in the laser flash kinetic studies of radicals **4** (see Figure 1) clearly indicated that 5-*exo* cyclizations of **4a,c,d** and a 6-*exo* cyclization of **4b** occurred to give cyclic radicals **5**. In indirect kinetic studies and preparative reactions conducted in the presence of Bu_3SnH, carbocycles **11** and acycles **6** were identified by GC and mass spectral analyses.



One diastereomer of **11b** and both diastereomers of **11a** and **11c** (ca. 1:1 ratio) and **11d** (ca. 2:1 ratio) were observed by GC. Authentic samples of acycles **6** were available from thermal decarboxylations of acids **9**. Cyclic products **11** were isolated from preparative reactions and identified by ^1H NMR spectroscopy although some samples of **11** obtained by chromatography were contaminated with acycles **6**.

For the 6-*exo* cyclization of **4b**, there was a possibility that a 1,5-hydrogen abstraction reaction competed with cyclization. Such a reaction would not be apparent in kinetic measurements of the cyclization reaction because these provide only the total rate constants for disappearance of **4b** although, if the internal abstraction was a significant process, we might have observed an unusual UV spectrum for the radical products. The internal hydrogen abstraction reaction also cannot be detected by analysis of the products of a conventional tin hydride mediated reaction, but its intrusion would be detectable in the products formed in a reaction conducted in the presence of Bu_3SnD because it would result in C(6) deuteration of **6b**.

A reaction of PTOC **1b** was run in the presence of 0.25 M Bu_3SnD at ca. 30 °C, and products **6b** and **11b** were isolated as a mixture by chromatography and analyzed by NMR spectroscopy. The ^2H NMR spectrum at 76 MHz contained major signals from deuterium on the diphenylmethyl position of **11b** (δ 3.99) and C(2) of **6b** (δ 2.26) and minor signals from chemical impurities. No signal was apparent at δ 2.12 (protons at C(6) of **6b**). In the ^1H decoupled ^{13}C NMR spectrum (125 MHz) of the deuterated mixture, the only 1:1:1 triplets were those from the diphenylmethyl carbon of **11b** and C(2) of **6b** and we could not observe any signal for the singlet that would arise from the C(2) position of **6b** that was not deuterated. On the basis of the signal-to-noise ratio in the ^2H NMR spectrum, we conclude that an internal hydrogen abstraction reaction of radical **4b** must have accounted for less than 2% of the total reactions of **4b**. From the ratio of **11**:**6** and the above value, the rate of the 1,5-hydrogen transfer reaction must have been less than 4% that of the cyclization reaction.

Cyclization Kinetics

Direct kinetic studies of the cyclizations of radicals **4** were obtained with THF solutions of PTOC esters **1** flowing through a cell in a laser-based kinetic spectrometer. The growth of the signal from the diphenylalkyl radical species (**5**) at 330 nm (Figure 1) was monitored. Radicals **4b–d** were studied at temperatures between 0 and 60 °C. Radical **4a** was studied over a more limited temperature range (0–40 °C) because the dynamic resolution of our instrument was exceeded at higher temperatures. Representative kinetic results are given in the supplementary material. Temperature-dependent functions for the cyclizations, the calculated rate constants at 20 °C, and experimental rate constants at 20 °C are given in Table 1. For comparison purposes, we have also included in Table 1 kinetic data for cyclizations of analogous unsubstituted alkyl radicals[14] and methoxy substituted radicals.[9c]

The precision of the measured rate constants deserves comment. Each kinetic value is an average of multiple, typically 15, individual measurements. The individual measurements often had uncertainties at 2σ that were below 1% of the value, but this error level only reflects the signal-to-noise ratios in the kinetic traces. Apparently, a major source of random errors was temperature fluctuation, and sets of rate constants for **4b–d** collected under constant conditions generally had uncertainties at 2σ that averaged 6% of the value. For **4a**, two species were present (see below), and the data required a double exponential solution; here the average uncertainties at 2σ were 18% with a maximum uncertainty of 40%.

Despite the precision that was possible in the kinetic measurements, the rate constants for the slower cyclizations of **4b–d** contain small systematic errors. These result because k_{obs} is the sum of the rate constants for all reaction channels of **4** (see eq 6). Radical–radical reactions and radical reactions with residual oxygen can result in a value for k_0 in eq 6 in the range of 1×10^4 to 1×10^5 s^{-1}, thus contributing noticeably to k_{obs} and leading to an overestimation of k_c. Further, the 2-pyridylthiyl radical (**3**) can add to the PTOC precursors **1** to provide a second source of radicals **4**; the "slow" production of **4** from this reaction could result in an underestimation of k_c.

A variety of studies were performed in an attempt to factor out the minor contributions to k_{obs} for **4b–d** with limited success. When the laser power was attenuated from 50 to 2 mJ with solutions of a given concentration of precursor **1**, decreases in k_{obs} for **4c** of up to 20% and for **4d** of up to 15% were found. When a series of studies were performed at constant laser power with solutions of **1** decreasing in concentration from ca. 2×10^{-5} to 5×10^{-7} M, k_{obs} for **4c** increased by up to 30% and k_{obs} for **4d** increased by up to 10%. Of course, for both decreasing laser power and decreasing concentrations of **1**, the signal-to-noise ratios became poorer due to the reduced

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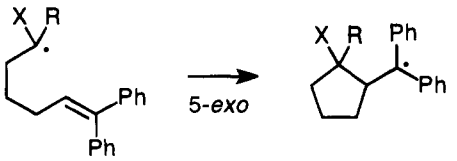
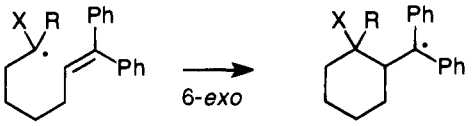
(14) Horner, J. H.; Lakshmipathy, G.; Newcomb, M. Unpublished results.

Table 1. Arrhenius Functions and Rate Constants for Radical Cyclizations

entry	R	X	log k (s^{-1})[a]	$k_{(20)}$ (s^{-1})[b]	k_{obs} (s^{-1})[c]	ref
			 5-*exo*			
1	H	H	$9.8 - 3.0/\theta$	4×10^7		14
2	H	Me	$9.9 - 3.4/\theta$	2×10^7		14
3a (**4a**)[d]	H	CO_2Et	$(9.9 \pm 0.3) - (2.9 \pm 0.4)/\theta$	5.4×10^7	$(6.0 \pm 0.8) \times 10^7$	this work
3b (**4a**)[e]			$(11.1 \pm 0.3) - (5.1 \pm 0.4)/\theta$	2.0×10^7	$(1.8 \pm 0.2) \times 10^7$	this work
4	H	OMe	$9.3 - 2.3/\theta$	4×10^7		9c
5	Me	Me	$9.4 - 3.2/\theta$	1×10^7		14
6 (**4c**)	Me	CO_2Et	$(10.0 \pm 0.8) - (6.0 \pm 1.1)/\theta$	3.3×10^5	$(3.6 \pm 0.3) \times 10^5$	this work
7 (**4d**)	Me	CN	$(9.8 \pm 0.5) - (6.0 \pm 0.6)/\theta$	2.1×10^5	$(2.3 \pm 0.1) \times 10^5$	this work
			 6-*exo*			
8	H	H	$9.7 - 5.4/\theta$	5×10^5		14
9	H	Me	$9.0 - 5.0/\theta$	2×10^5		14
10 (**4b**)[f]	H	CO_2Et	$(8.6 \pm 0.5) - (3.7 \pm 0.5)/\theta$	7×10^5	$(6.1 \pm 0.3) \times 10^5$	this work
11	H	OMe	$8.8 - 4.9/\theta$	1.4×10^5		9c

[a] Arrhenius function with errors at 2σ; $\theta = 2.3RT$ in kcal/mol. [b] Rate constant at 20 °C calculated from the Arrhenius function. [c] Measured rate constant at 20.0 ± 0.3 °C with an error at 2σ. [d] Major isomer of **4a**. [e] Minor isomer of **4a**. [f] The estimated errors in the Arrhenius function are greater than three times the standard deviation in the measured values (see text).

production of radicals **4**. The net result was that the values of k_{obs} at any given temperature usually did not converge to a common value for a series of studies in which we varied both the laser power and concentration of **1**. Therefore, for **1c,d** we have given k_{obs} values obtained at the lowest concentration at which reasonable signal-to-noise levels were obtained (ca. 5×10^{-6} M) and we estimate that these values could contain systematic errors of 10−15%.

The kinetic studies of **4b** presented a special problem that might be linked to the instability of precursor **1b**. For some batches of **1b**, apparently reasonable kinetic data were obtained. However, for others, precursor **1b** decomposed rapidly upon dilution as determined by observation of the UV spectra of the solutions. Similar behavior was found with one batch of precursor **1a**. This phenomenon was batch dependent in that the decomposition upon dilution either always or (apparently) never occurred for a specific batch of **1b**. Attempts to identify the decomposition products were not successful. When solutions containing decomposed **1b** were investigated by LFP, a UV spectrum with a long wavelength λ_{max} at ca. 312 nm grew in slowly (ca. 1×10^6 s^{-1} at 30 °C), but no signal was produced at 330 nm. The kinetics for **4b** were reproducible with "stable" batches of **1b**, and we have estimated a possible error in the kinetics of **4b** of 20%.

With the caveat that the slow cyclizations contain small systematic errors, we may consider the precision of the Arrhenius functions in Table 1. These varied slightly for the slower cyclizations when concentrations of precursors and laser power were changed, and the limited temperature range over which the PTOC precursors could be employed[15] affected the precision in all cases. The Arrhenius functions for **4c,d** listed in Table 1 are the average values, and the errors at 2σ encompass the range of values found. The function for **4d** contains errors estimated from the results with the other systems studied. The precisions in the Arrhenius functions are comparable to or somewhat better than those usually obtained for unimolecular radical reactions because most such kinetic studies involve indirect competition methods[4] where the experimental errors are compounded by those in the Arrhenius functions for the trapping reactions.

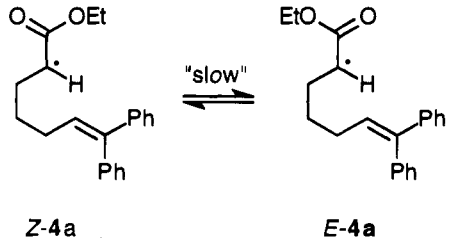
Perhaps the most unusual kinetic result was that the cyclization of radical **4a** was substantially better described by a double exponential growth than by a single exponential function, whereas the other radical cyclizations were well described by single exponential growth functions. A typical comparison of single versus double exponential solutions for a data trace for **4a** is shown in Figure 2. Further confirmation that two processes were being observed was found in the good behavior of the two Arrhenius functions for radical **4a** (Figure 3) and unchanging populations of the two contributing components in the kinetic analyses at various temperatures. Thus, we are confident that the improved double exponential solutions were not artifacts resulting from random fittings. These kinetic results indicate that cyclization reactions of two isomers were being measured[16] and that the two species did not interconvert on the time scale of the cyclization reactions. In Table 1, we have given the Arrhenius functions and rate constants for cyclizations of both isomers of **4a**.

The relatively slow isomerization process available for radical **4a** is conformational equilibration by rotation about the partial double bond between the carbon bearing the radical and the carbethoxy group, i.e. the equilibration between (*E*)-**4a** and (*Z*)-**4a**. Such conformational isomerizations of carboalkoxy-substituted radicals were studied by ESR and muonium spin resonance methods by Fischer *et al.* and were found to occur with rate constants of ca. $1-2 \times 10^6$ s^{-1} at 20 °C.

(15) Because the PTOC precursors absorb light strongly, dilute, flowing solutions (as opposed to concentrated, static solutions) must be employed. Equilibrations at temperatures far from room temperature (especially at low temperatures) are difficult. The thermal instability of the PTOC precursors in general and specifically of those used in this work further exacerbates the situation by precluding high-temperature studies.

(16) We note in passing that individual isomers of **4a** can produce both cyclic diastereomers. Therefore, product analyses are uninformative.

(17) (a) Lung-min, W.; Fischer, H. *Helv. Chem. Acta* **1983**, *66*, 138–147. (b) Strub, W.; Roduner, E.; Fischer, H. *J. Phys. Chem.* **1987**, *91*, 4379–4383.



Z-**4a** *E*-**4a**

The conformer population ratio of **4a** was ca. 3:1 between 0 and 40 °C. The radical populations were not at equilibrium but in a ratio that was a function of the conformer population of precursor **1a**. This ratio was not necessarily equal to that of the populations of the **1a** conformers because it is possible that the extinction coefficients and quantum efficiencies for homolysis of the different precursor conformations were not the same. However, given that the chromophore absorbing 355 nm light is in the pyridine-2-thione group, we believe it is likely that the radical populations closely reflected the precursor populations.

Lung-min and Fischer deduced that the *Z* conformer of $CH_3C^{\bullet}HCO_2Et$ was stabler than the *E* conformer by about 0.6 kcal/mol.[17a] Because the major isomer of **4a** cyclized faster than (and with a lower activation energy than) the minor isomer, it seems likely that the major isomer was the less stable *E* conformer. Such a conclusion is equivocal, however, because the origin of the differences in the activation energies for cyclization of the two conformers is not apparent.

In any event, the rate constants for conformational isomerizations of the carboalkoxy-substituted radicals should be noted by those employing such intermediates in synthetic applications. Our kinetic results show that the conformations of **4a** interconvert at 20 °C less rapidly than 2×10^7 s^{-1} whereas those for radicals **4b,c** appear to equilibrate at 20 °C more rapidly than 6×10^5 s^{-1} (see below). These values nicely straddle and, thus, confirm the rate constants for the conformational equilibration of simple α-carboalkoxy radicals ($(1-2) \times 10^6$ s^{-1} at 20 °C) reported by Fischer *et al.*,[17] and that value apparently is one that should be generally applied for interconversions of such radicals. Recently, there has been considerable synthetic interest in the control of 1,2-asymmetric induction in radical reactions including reactions of α-carboalkoxy species.[18] In such studies, it is important to note that the diastereoselectivity of exceptionally fast reactions might be influenced by the radical conformer populations and that control of the *precursor* conformational populations could influence the overall stereoselectivity.[19]

Radical **4d**, with the linear cyano substituent, could not exist in slowly interconverting conformations. For radicals **4b,c**, which cyclized about 2 orders of magnitude less rapidly than did radical **4a**, we cannot determine if slowly interconverting conformations were produced. The kinetic results of each were well described by single exponential functions, but it is possible that two conformations were present that cyclized with essentially the same rate constants or that the radicals were produced in predominantly one conformation. However, in light of the reported rate constants for carbethoxy group rotation in α-radicals,[17] we believe it is most likely that conformational interconversions were faster than cyclizations for **4b,c**.

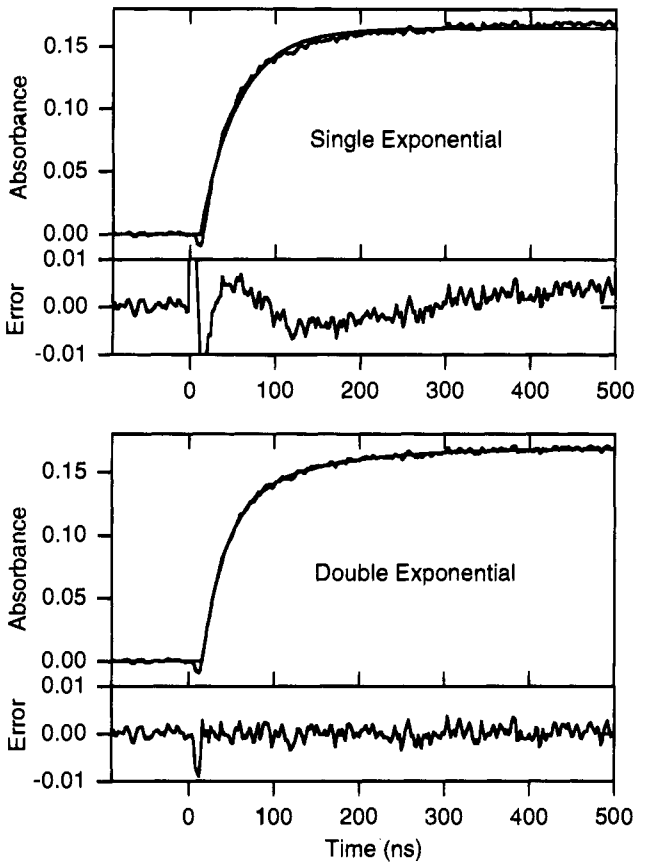


Figure 2. Single versus double exponential solutions for a data trace from radical **4a**. The data trace and simulated fits are shown on the absorbance plots, and the errors of the fits are shown under each absorbance plot.

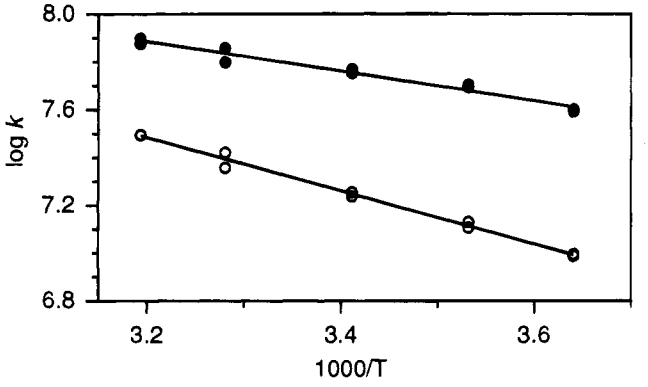


Figure 3. Arrhenius functions for cyclizations of the two isomers of **4a**.

Despite effects of electron-withdrawing groups on the α-C−H bond dissociation energy (BDE) values,[20,21] which are typically

(18) Hart, D. J.; Huang, H.-C.; Krishnamurthy, R.; Schwartz, T. *J. Am. Chem. Soc.* **1989**, *111*, 7507−7519. Hart, D. J.; Krishnamurthy, R. *Synlett* **1991**, 412−414. Giese, B.; Bulliard, M.; Zeitz, H.-G. *Synlett* **1991**, 425−427. Hart, D. J.; Krishnamurthy, R. *J. Org. Chem.* **1992**, *57*, 4457−4470. Porter, N. A.; Giese, B.; Curran, D. P. *Acc. Chem. Res.* **1991**, *24*, 296−304. Giese, B.; Damm, W.; Wetterich, F.; Zeitz, H.-G.; Rancourt, J.; Guindon, Y. *Tetrahedron Lett.* **1993**, *34*, 5885−5888. Guidon, Y.; Yoakim, C.; Gorys, V.; Ogilvie, W. W.; Delorme, D.; Renaud, J.; Robinson, G.; Lavallée, J.-F.; Slassi, A.; Jung, G.; Rancourt, J.; Durkin, K.; Liotta, D. *J. Org. Chem.* **1994**, *59*, 1166−1178. See also the discussions and references in each.

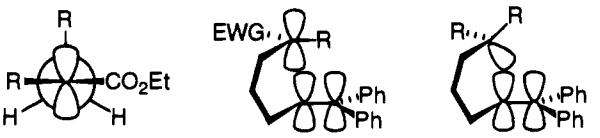
(19) There is an interesting counterintuitive corollary. Because both the cyclization and tin hydride trapping (see below) reactions of a tertiary α-carbethoxy radical are slower than those of the secondary systems, it is possible that such diastereoselective effects of precursor populations can be realized in a reaction of a secondary system but not in the corresponding reaction of the analogous tertiary system.

(20) One may compare the C−H BDE values of various substituted methanes. Ethane has a BDE of 98 kcal/mol.[21a] The value of 98 kcal/mol for acetone given in a classic review[21a] appears to be too great; the BDE values from gas phase appearance energies (92 kcal/mol)[21b] and from a thermodynamic cycle (94 kcal/mol)[21c] are more consistent with ESR studies.[21d] Acetonitrile has a C−H BDE value of 93−95 kcal/mol.[21a,e] The C−H BDE value of ethyl acetate is estimated to be 95 kcal/mol.[21c,f]

ascribed to the stability of the radical thus formed, the carbethoxy substitution in the secondary radicals **4a,b** (entries 3 and 10 in Table 1) had little effect on the rate constants for cyclizations, which were slightly greater than those of the analogous secondary alkyl radicals (entries 2 and 9).[22] The practice of associating C−H BDEs with the expected kinetics of a radical reaction is often unwise because it carries the tacit (and reasonable) assumption that a linear free energy relationship exists but ignores the energies of the bonds *formed* in the radical reactions. For example, inspection of the rate constants for the 5-*exo* cyclizations of the primary, secondary, and tertiary alkyl radicals in Table 1 (entries 1, 2, and 5) shows that the $\Delta G^{\ddagger}$ terms reflect only a small portion of the differences in the C−H BDE values for methyl, methylene, and methine groups.[21a]

In light of the above comments, the marked reduction in the cyclization rate constants for the electron-withdrawing group substituted tertiary radicals **4c,d** (entries 6 and 7) in comparison to that of the analogous tertiary alkyl radical (entry 5) may seem surprising. The absence of a kinetic effect in cyclizations of secondary radicals **4a,b** and a pronounced reduction in the rate constants for cyclizations of the tertiary radicals **4c,d**, taken together, suggest that the latter originates not from resonance stabilization of the radicals *per se* but rather from a steric effect that is enforced by this resonance. This conclusion is supported by the fact that the reductions in the rate constants for cyclizations of **4c,d** derive mainly from increases in the activation energies, an increase that is not present in the analogous tertiary alkyl radical (entry 5).

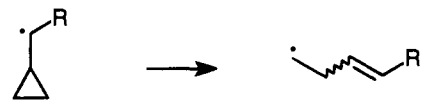
The kinetic effects in cyclizations of the tertiary radicals are rationalized by considering that delocalization in α-carbonyl- and α-cyano substituted radicals results in planar radical centers[18,23] requiring substantially higher energies to deform to pyramidal centers than do alkyl radicals. Recent work aimed at understanding the factors involved in 1,2-asymmetric induction in reactions of α-carboalkoxy radicals has indicated that the preferred conformation for these radicals is that shown in structure **12**.[18] In cyclizations of radicals **4c,d**, a late pyramidalization of the radical center will result in a steric interaction between the alkene moiety and the methyl group in **13** (R = Me) that will not be present in the secondary radical **4a** (i.e., **13**: R = H). In an all alkyl-substituted tertiary radical, which is either pyramidal or planar with a low energy barrier to pyramidalization,[24] the tertiary alkyl radical should cyclize through a highly pyramidalized transition structure resembling **14** in which the steric effects of the alkyl groups at C(1) are reduced in comparison to those in **13**. A similar proposal was offered by Fischer and co-workers to rationalize the slow rates of reactions of benzyl radicals with alkenes.[23b]



12 **13** **14**

Other features of the kinetic data in Table 1 are in concert with expectations. Overall, the diphenylethene moiety accelerates both the 5-*exo* and 6-*exo* cyclizations by about 2 orders of magnitude in comparison to analogous cyclizations of the parent radicals containing an unsubstituted terminal alkene group.[25,26] For intermolecular additions to substituted alkenes, Fischer has reported that, at about room temperature, the carbo-*tert*-butoxymethyl radical (t-$BuO_2CCH_2^{\bullet}$) and the 1-cyano-1-methylethyl radical ($NCCMe_2^{\bullet}$) add to 1,1-diphenylethene >200 times faster and ca. 200 times faster, respectively, than they add to C(1) of simple terminal alkenes.[27c] The nearly constant differences in the rate constants for matched pairs of 5-*exo* and 6-*exo* cyclizations (entries 1−4 and 8−11) of 2 orders of magnitude are consistent with rate constants for cyclizations of the analogous simple alkenyl radical clocks.[25] It is noteworthy that this kinetic effect results mainly from enthalpic differences although the 5-*exo* cyclizations also appear to enjoy a small entropic advantage.

Little absolute kinetic data for unimolecular reactions of radicals substituted with electron-withdrawing groups is available for comparison to our results. In a recent contribution, Beckwith and Bowry reported a study of the (*tert*-butoxycarbonyl)cyclopropylmethyl radical (**15a**), which ring opens to a mixture of radicals **16a**.[28] By employing nitroxyl radical



15 **16**

a: R = CO_2CMe_3; **b**: R = Me

trapping methods, they estimated that ring opening of **15a** at 80 °C was 0.02−0.05 times as fast as ring openings of the cyclopropylcarbinyl radical[29] and the methylcyclopropylmethyl

(21) (a) McMillen, D. F.; Golden, D. M. *Annu. Rev. Phys. Chem.* **1982**, *33*, 493−532. (b) Holmes, J. L.; Lossing, F. P.; Terlouw, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 1086−1087. (c) Bordwell, F. G.; Harrelson, J. A., Jr.; Zhang, X. *J. Org. Chem.* **1991**, *56*, 4448−4450. (d) Nonhebel, D. C.; Walton, J. C. *J. Chem. Soc., Chem. Commun.* **1984**, 731−732. (e) Kanabus-Kaminska, J. M.; Gilbert, B. C.; Griller, D. *J. Am. Chem. Soc.* **1989**, *111*, 3311−3314. (f) Bordwell, F. G.; Zhang, X.-M.; Alnajjar, M. S. *J. Am. Chem. Soc.* **1992**, *114*, 7623−7629.

(22) We note that the absence of a rate reduction in the cyclizations of secondary carbethoxy-substituted radicals **4a,b** cannot be ascribed to a substantially enhanced reactivity of an electron deficient radical center with the diphenylethene moiety. The electron rich methoxy-substituted radicals (entries 4 and 11) cyclize with rate constants that also are similar to those of the corresponding alkyl radicals. In addition, a similar kinetic effect has been observed in reactions of the 1-carbethoxy-5-hexenyl radical, which cyclizes with rate constants approximately equal to those of the 5-hexenyl and 1-methyl-5-hexenyl radicals (Filipkowski, M. A.; Newcomb, M. Unpublished results).

(23) (a) Khalil, S. M.; Jarjis, H. M. *Z. Naturforsch., Sec. A.* **1991**, *46*, 898−908. (b) Héberger, K.; Walbiner, M.; Fischer, H. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 635−636.

(24) Pyramidalized *tert*-butyl radical: Pacansky, J.; Koch, W.; Miller, M. D. *J. Am. Chem. Soc.* **1991**, *113*, 317−328. Planar *tert*-butyl radical: Aburaqabh, A.; Symons, M. C. R. *Chem. Phys. Lett.* **1991**, *183*, 171−175. See also the discussions and references in each.

(25) Rate constants for 5-*exo* cyclizations of simple alkenyl radicals at 25 °C are 2.3×10^5 s^{-1} (5-hexenyl),[5a] 1.3×10^5 s^{-1} (1-methyl-5-hexenyl),[26a,b] and 3×10^5 s^{-1} (1,1-dimethyl-5-hexenyl).[26c] The 6-*exo* cyclization of the 6-heptenyl radical is about 2 orders of magnitude slower than the cyclization of the 5-hexenyl radical.[26d]

(26) (a) Lusztyk, J.; Maillard, B.; Deycard, S.; Lindsay, D. A.; Ingold, K. U. *J. Org. Chem.* **1987**, *52*, 3509−3514. (b) Beckwith, A. L. J.; Easton, C. J.; Lawrence, T.; Serelis, A. K. *Aust. J. Chem.* **1983**, *36*, 545−556. (c) Chatgilialoglu, C.; Ferreri, C.; Lucarni, M. *J. Org. Chem.* **1991**, *56*, 6399−6403. (d) Beckwith, A. L. J.; Moad, G. *J. Chem. Soc., Chem. Commun.* **1974**, 472−473.

(27) (a) Beranek, I.; Fischer, H. In *Free Radicals in Synthesis and Biology*; Minisci, F., Ed.; Kluwer: Amsterdam, 1989; pp 303−316. (b) Héberger, K.; Fischer, H. *Int. J. Chem. Kinet.* **1993**, *25*, 249−263. (c) Wu, J. Q.; Beranek, I.; Fischer, H. *Helv. Chim. Acta* **1995**, *78*, 194−214. See also: (d) Giese, B.; He, J.; Wolf, M. *Chem. Ber.* **1988**, *121*, 2063−2066.

(28) Beckwith, A. L. J.; Bowry, V. W. *J. Am. Chem. Soc.* **1994**, *116*, 2710−2716.

(29) (a) Newcomb, M.; Glenn, A. G. *J. Am. Chem. Soc.* **1989**, *111*, 275−277. (b) Bowry, V. W.; Lusztyk, J.; Ingold, K. U. *J. Am. Chem. Soc.* **1991**, *113*, 5687−5698.

Table 2. Arrhenius Functions and Rate Constants for Tin Hydride Trapping Reactions

radical	$\log(k_T/k_c \cdot M)^a$	$\log(k_T \cdot M \cdot s)^a$	$k_{(20)}$ $(M^{-1}\,s^{-1})^b$
4b	$-(0.4_5 \pm 0.3) + (1.5 \pm 0.4)/\theta$	$(8.1_5 \pm 0.6) - (2.2 \pm 0.6)/\theta$	3×10^6
4c	$-(1.5 \pm 0.3_5) + (1.7 \pm 0.5)/\theta$	$(8.5 \pm 0.9) - (4.3 \pm 1.2)/\theta$	2×10^5
4d	$-(3.0 \pm 0.6) + (4.3 \pm 0.7)/\theta$	$(6.8 \pm 0.8) - (1.7 \pm 0.9)/\theta$	3×10^5

[a] Errors at 2σ; $\theta = 2.3RT$ in kcal/mol. [b] Calculated rate constant at 20 °C.

radical (**15b**).[29b,30] They[28] ascribed the kinetic result to the radical-stabilizing effect of the ester group in **15a**. However, our results indicate that radical stability *per se* will not control the kinetics entirely, and the new π-bond formed in the α,β-unsaturated ester system produced by opening of **15a** to **16a** is stabler than an unconjugated analog. If there is a significant kinetic retardation[30] in the ring opening of **15a**, then its origin might be a function of the planar structure of the radical rather than the inherent stability of the radical. For example, a planar cyclopropylcarbinyl radical center might experience an energy penalty in aligning with the breaking C–C bond. Computational studies of the rearrangement of **15a** to **16a** should provide interesting results.

The absence of a kinetic effect with electronic origins in the cyclization reactions of substituted radicals **4** is in marked contrast to the well-known dramatic kinetic effects found in reactions that result in *formation* of α-carboalkoxy and α-cyano radicals. For example, acrylate esters and acrylonitrile react in intermolecular processes with simple alkyl radicals about a 1000 times faster than does a simple alkene.[31] Similar kinetic accelerations of about 3 orders of magnitude over that of the unsubstituted parent have been observed in intramolecular reactions of radicals containing electron acceptors at the incipient radical center. These include the 5-*exo* cyclization of a 5-hexenyl radical containing nitrile substitution at the terminus of the π system,[32] the cyclizations of radicals **16a** studied by Beckwith and Bowry,[28,33] and ring openings of cyclopropylcarbinyl radicals containing carboalkoxy groups at C(2).[34]

Kinetics of Reactions with Bu_3SnH

In the context of syntheses of small organic compounds, hydrogen atom transfer trappings of α-carbethoxy and α-cyano radicals by Bu_3SnH are undoubtedly among the most common bimolecular reactions of these radicals. They represent one of the chain steps in the overall sequence for addition of an alkyl radical to an α,β-unsaturated ester or nitrile under tin hydride mediated conditions.

As noted in the introductory comments, bimolecular rate constants for trapping reactions of radicals **4** can, in principle, be determined directly. In this type of experiment, the cyclization of radicals **4** serves as the indicator reaction and the observed rate constant contains both the cyclization rate constant and a pseudo-first-order rate constant for trapping (see Scheme 2 and eq 6). However, a number of experimental problems limited direct measurements in this work. These included the instability of the PTOC radical precursors, which appeared to be increased in the presence of the trapping agent, and a practical limitation on the ratio of k_c/k_T, which should be approximately 0.1 M for best results. Attempts to determine Arrhenius functions for tin hydride trappings directly gave poor results, and we abandoned this approach in favor of an indirect method. A directly measured rate constant for tin hydride trapping of carbethoxy-substituted radical **4b** at 26 °C was quite precise, and the one measured for reaction of **4c** with tin hydride at 15 °C was reasonably precise (see below).

The indirect kinetic method for measuring trapping rate constants is more versatile than the direct method once the rate constants for cyclization of the "radical clocks" are known because the indirect method relies on analyses of the product mixtures which can be quite sensitive.[4] Indirect methods have been routinely employed in cases where the rate constant for a radical clock reaction and a pseudo-first-order rate constant for a trapping reaction differ by more than 1 order of magnitude. For indirect studies, the ratio of rate constants for trapping (k_T) and cyclization (k_c) is determined from eq 7, where (U/R) is

$$k_T/k_c = (U/R)([Bu_3SnH]_m)^{-1} \qquad (7)$$

the ratio of unrearranged to rearranged products and $[Bu_3SnH]_m$ is the average concentration of the tin hydride. Our studies were performed with large excesses of tin hydride such that pseudo-first-order trapping kinetics were realized. The ratios of rate constants from eq 7 at various temperatures were used to determine relative Arrhenius functions for the competition reactions which were then added to the Arrhenius functions for cyclization to give the temperature-dependent functions for trapping. The kinetic results are provided in the supplementary material.

Table 2 contains measured relative Arrhenius functions and calculated absolute Arrhenius functions for tin hydride trapping of the α-carbethoxy- (**4b,c**) and α-cyano-substituted (**4d**) radicals and the rate constants for these hydrogen atom transfer reactions at 20 °C. The errors in the Arrhenius functions are greater than those obtained in direct kinetic studies of second-order reactions of tin hydride with alkyl radicals[5] in part because we have compounded errors in the direct and indirect method. Errors in the indirect method appear to derive from two factors. First, because the PTOC precursors were unstable, initiation of radical chain reactions might have occurred before temperature equilibration in some of the reactions of **4c,d** in which precursors **1** were employed. The phenylselenyl precursor **10b** was used for all of the indirect studies of radical **4b**, and selenide precursor **10c** was used for the high-temperature studies of **4c**. The reduced error levels in the Arrhenius functions for these reactions in comparison to the reactions of **4d** support the conjecture. Second, the high concentrations of organotin compounds in the reaction mixtures resulted in analytical

(30) The kinetic result must be viewed with some caution. Rate constants for reactions of nitroxyl radicals with α-carboalkoxy radicals are not known, and Beckwith and Bowry estimated that this coupling reaction was 0.2 times as fast as an alkyl radical–nitroxyl radical coupling.[28] However, nitroxyl radical couplings are generally insensitive to radical stabilities.[4,7] If the coupling reaction of the carboalkoxy-substituted radical occurred with a rate constant equal to that of a secondary alkyl radical, then the ring opening of **15a** would still be slower than that of **15b** but only by a factor of 5. Preliminary results from our laboratory suggest that the rate constants for ring openings of an α-carbethoxy-substituted cyclopropylcarbinyl radical system and its parent, unsubstituted analog are comparable (Newcomb, M.; Tanaka, N.; Bovier, A.; Horner, J. H.; Martinez, F. N. Unpublished results).

(31) (a) Giese, B. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 753–764. (b) Caronna, T.; Citterio, A.; Ghirardini, M.; Minisci, F. *Tetrahedron* **1977**, *33*, 793–796.

(32) Park, S.-U.; Chung, S.-K.; Newcomb, M. *J. Am. Chem. Soc.* **1986**, *108*, 240–244. Newcomb, M.; Varick, T. R.; Ha, C.; Manek, M. B.; Yue, X. *J. Am. Chem. Soc.* **1992**, *114*, 8158–8163.

(33) Effio, A.; Griller, D.; Ingold, K. U.; Beckwith, A. L. J.; Serelis, A. K. *J. Am. Chem. Soc.* **1980**, *102*, 1734–1736.

(34) Beckwith, A. L. J.; Bowry, V. W. *J. Org. Chem.* **1989**, *54*, 2681–2688. Newcomb, M.; Choi, S.-Y. *Tetrahedron Lett.* **1993**, *34*, 6363–6364. Choi, S.-Y.; Newcomb, M. *Tetrahedron* **1995**, *51*, 657–664.

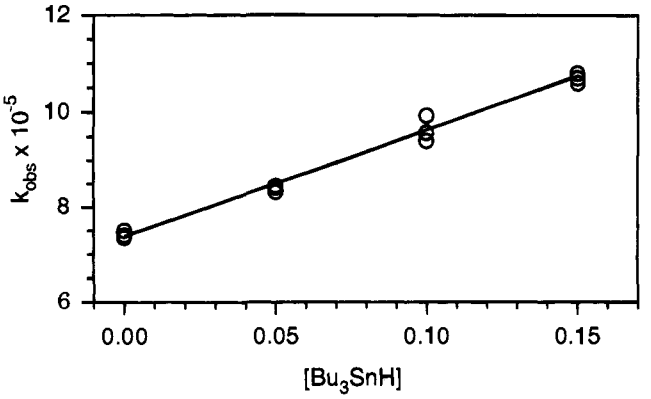


Figure 4. Observed rate constants for reactions of radical **4b** at 26 °C in the presence of Bu_3SnH.

problems; rather than analyzing the product mixtures immediately after the reactions, we first treated the reaction mixtures with iodine and washed with a KF solution to remove organotin products.

The indirect kinetic values for the tin hydride reactions, especially those in the vicinity of room temperature, appear to be reasonably accurate despite the imprecision of the Arrhenius functions. A direct study of tin hydride trapping of radical **4b** at 26 °C using PTOC precursor **1b** was performed with several concentrations of trapping agent (Figure 4). As shown in eq 6, k_{obs} for formation of cyclic radical **5** is a function of both k_c and k_T. From the slope of the plot of k_{obs} versus the concentration of tin hydride, we obtained a value for k_T of (2.25 ± 0.15 (2σ)) × 10^6 M^{-1} s^{-1}, in excellent agreement with the value of 3 × 10^6 M^{-1} s^{-1} at 26 °C calculated from the indirect data. A similar direct study of tin hydride trapping of radical **4c** at 15 °C gave a value for k_T of (0.8 ± 0.2) × 10^5 M^{-1} s^{-1}, a less satisfactory but acceptable agreement with the value of 2 × 10^5 M^{-1} s^{-1} calculated from the indirect data.

Some features of the kinetics of tin hydride trapping of the electron-deficient radicals are noteworthy. Because C−H bonds are formed in these reactions, the C−H BDEs should be reasonable indicators of kinetic effects. However, tin hydride is an electron rich hydrogen atom donor making the reactants "polarity matched", and any polar contributions in the transition states for the hydrogen atom transfers to the electron-deficient radicals should be favorable. The two conflicting factors, a kinetic reduction in comparison to an alkyl radical reaction due to radical stability and a kinetic acceleration due to polarization in the transition state, apparently balance each other in the reaction of the secondary radical **4b**. This reaction occurs with a rate constant at room temperature that is approximately equal to those reported for reactions of simple primary and secondary alkyl radicals with the hydrogen atom donor.[35]

The rate constants for reactions of the tertiary carbethoxy-substituted radical **4c** and the tertiary cyano-substituted radical **4d** with tin hydride were reduced in comparison to that reported for reaction of a tertiary alkyl radical with this agent.[35] With the limited data, one can only speculate on the details of these kinetic effects which amount to about a 1 kcal/mol increase in $\Delta G^{\ddagger}$ for reactions of radicals **4c,d** in comparison to an alkyl radical or to radical **4b**. We believe that, as in the case of the cyclizations, they are more likely to involve steric effects resulting from the planar structures of the delocalized radicals **4c,d** than inherent electronic effects of these "stabilized" radicals. An electronic effect appears to be excluded by the

(35) Rate constants at 25 °C of about 2 × 10^6 M^{-1} s^{-1} have been measured for reactions of Bu_3SnH with primary, secondary, and tertiary alkyl radicals.[5]

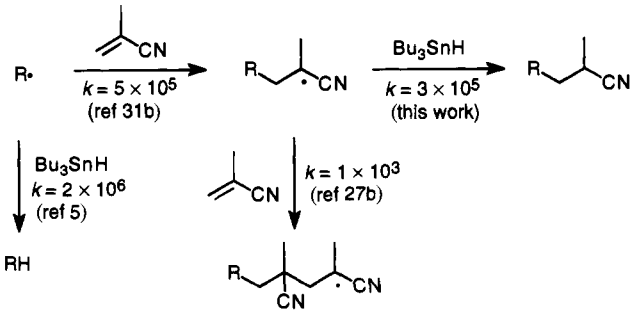


Figure 5. Absolute rate constants at 25 °C (in units of M^{-1} s^{-1}) for competing processes in the tin hydride mediated addition of an alkyl radical to α-methylacrylonitrile.

facts that (1) the electron-withdrawing group in **4b** does not lead to a kinetic reduction in comparison to a secondary alkyl radical and (2) an electron-withdrawing group at a tertiary radical center does not result in any increased stability in comparison to one at a secondary radical center.[36] The carbethoxy and cyano groups are "smaller" in 1,3 interactions than a methyl group, so **4c,d** should not present larger steric barriers to the tin hydride than does a saturated tertiary alkyl radical *if the transition structures are similar*, and one is left with the conclusion that they cannot be similar. Our rationalization, then, is that the radical centers in the transition structures for reactions of **4c,d** with the tin hydride are substantially less pyramidalized than that for reaction of an alkyl radical and that the low extent of pyramidalization results in increased steric effects.

Those familiar with synthetic applications of radical reactions are well aware of the fact that alkyl radical addition to an α,β-unsaturated ester or nitrile in a tin hydride mediated reaction results in high yields of monoadducts. Qualitatively, this occurs mainly because the addition reaction of an alkyl radical to the α,β-unsaturated system is substantially faster than the addition reaction of the α-carbonyl or α-cyano radical to a second α,β-unsaturated molecule. Therefore, tin hydride efficiently traps the electron-deficient radical but not the alkyl radical. For some cases, the kinetic values determined in this work can be combined with other rate constants to give a complete kinetic description of the competing reactions as demonstrated in Figure 5.

Conclusions

The kinetic values reported in this work provide the beginnings of a kinetic scale for reactions of α-carbethoxy- and α-cyano-substituted radical reactions. The calibrated cyclization reactions of radicals **4** can be used in indirect studies of bimolecular rate constants as we have demonstrated in the determinations of the rate constants for tin hydride trapping reactions, and the tin hydride trapping kinetics reported here can be used in synthetic planning. In regard to synthetic applications, a notable result from the cyclization kinetics is our confirmation of the rates of conformational interconversions of α-carboalkoxy radicals reported by Fischer;[17] this suggests that the diastereoselectivities of very fast reactions could be influenced by the populations of the radical precursors. An apparently general reduction in the kinetics of reactions of tertiary radicals containing electron-withdrawing groups in comparison to those of both secondary radicals with withdrawing groups and unsubstituted tertiary alkyl radicals was ascribed predominantly to steric effects associated with the planar radical center.

(36) For example, the benzenecarbonyl group in ($Me_2C^{\bullet}COPh$) afforded about 1 kcal/mol less stabilization than that in ($MeCH^{\bullet}COPh$).[21f]

Experimental Section

General Procedure. Reagents were purchased from Aldrich Chemical Co. unless noted. Tetrahydrofuran (THF) was distilled from potassium benzophenone under nitrogen immediately before use, and benzene was distilled from CaH_2 under nitrogen immediately before use. Bu_3SnH was prepared by a reported method,[37] and Bu_3SnD was prepared by $LiAlD_4$ reduction of Bu_3SnCl. 5-Bromo-1,1-diphenyl-1-pentene and 6-bromo-1,1-diphenyl-1-hexene were prepared by reaction of the corresponding acyl chlorides with excess PhMgBr followed by TsOH-catalyzed dehydration of the resulting alcohols in benzene.

Unless noted, ^1H and ^{13}C NMR spectra of solutions in $CDCl_3$ were obtained at 300 and 75 MHz, respectively; chemical shifts are reported relative to internal TMS or the center line of $CDCl_3$ (δ = 77.00). Melting points are uncorrected. Analytical GC was accomplished on gas chromatographs equipped with flame ionization detectors; data were processed with computer-based chromatography software (ChromPerfect Direct, Justice Innovation, Inc.). Wide bore capillary SE-54 columns (Alltech) were used for GC separations. GC−mass spectrometry was accomplished with a Hewlett-Packard model 5791 mass selective detector interfaced to an HP model 5890 gas chromatograph; a 25 m × 0.25 mm DB-5 capillary column (J&W Scientific) was employed. High-resolution mass spectrometry was performed by the Central Instrumentation Facility at Wayne State University.

Unless noted, the purities of all compounds were >95% as determined from the ^1H NMR spectra.

Representative Procedure for Preparation of PTOC Esters 1. To a suspension of 430 mg of 60% NaH in oil (10.8 mmol) in 50 mL of 10:1 THF/DMF at 0 °C was added dropwise 1.37 mL (9.0 mmol) of diethyl malonate. After being stirring for 30 min at 0 °C, a solution of 3.0 g (9.0 mmol) of 6-bromo-1,1-diphenyl-1-hexene in 5 mL of DMF was added via cannula, and the resulting mixture was allowed to warm to room temperature and was heated at reflux for 3 h. The reaction mixture was cooled to room temperature and treated with 25 mL of saturated aqueous NH_4Cl solution. The mixture was extracted three times with ether, and the combined ethereal extracts were washed with saturated aqueous NaCl solution and dried ($MgSO_4$). Concentration of the organic phase gave a residue that was purified by silica gel chromatography (3:1 hexanes/ethyl acetate) to give 2.2 g (62%) of diester **8b**.

A mixture of the diester **8b** (1.15 g, 2.8 mmol) and 170 mg (3.1 mmol) of KOH in 25 mL of 95% EtOH was heated at reflux for 3 h. The mixture was cooled and concentrated. The residue was dissolved in water, and the resulting solution was acidified to pH 2 with HCl. The mixture was extracted twice with ether, and the combined ethereal extracts were washed with saturated aqueous NaCl solution and dried ($MgSO_4$). Concentration gave a residue that was purified by chromatography on silica gel (1:1 hexanes/ethyl acetate) to give 630 mg of acid **9b** (59%) and 287 mg (24%) of unreacted **8b**.

To a solution of 400 mg (1.1 mmol) of acid **9b** in 10 mL of dry benzene at room temperature was added 0.28 mL (3.3 mmol) of oxalyl chloride. Dry DMF (2 drops) was added (gas evolution), and the resulting mixture was stirred for 3 h. Solvent and excess oxalyl chloride were removed at reduced pressure, and the residue was dissolved in 10 mL of benzene. The resulting solution was transferred via cannula into a light-shielded vessel containing a suspension of 240 mg (1.6 mmol) of *N*-hydroxypyridine-2-thione sodium salt (Olin Chemical) and ca. 5 mg of DMAP in 10 mL of benzene, and the mixture was stirred for 1.5 h. The reaction mixture was washed with a cold, saturated aqueous $KHSO_4$ solution, 10% aqueous $NaHCO_3$ solution, and saturated aqueous NaCl solution. After drying ($MgSO_4$), the solution was concentrated to give 280 mg (54%) of **1b**.

Ethyl 2-Carbethoxy-7,7-diphenyl-6-heptenoate (8a) was obtained in 62% yield as an oil. ^1H NMR: δ 7.40−7.10 (m, 10 H), 6.00 (t, 1 H, J = 7.4 Hz), 4.15 (q, 4 H, J = 7.2 Hz), 3.20 (t, 1 H, J = 7.6 Hz), 2.20 (q, 2 H, J = 7.4 Hz), 1.90 (q, 2 H, J = 7.4 Hz), 1.45 (pent, 2 H, J = 7.6 Hz), 1.20 (t, 3 H, J = 7.2 Hz). HRMS: calcd for $C_{24}H_{28}O_4$, 380.1988; found, 380.1992.

Ethyl 2-Carbethoxy-8,8-diphenyl-7-octenoate (8b) was obtained in 62% yield as a yellow oil. ^1H NMR: δ 7.40−7.20 (m, 10 H), 6.10 (t, 1 H, J = 7.6 Hz), 4.25 (q, 4 H, J = 7.2 Hz), 3.35 (t, 2 H, J = 7.2 Hz), 2.20 (q, 2 H, J = 7.2 Hz), 1.95 (q, 2 H, J =7.2 Hz), 1.50 (pent, 2 H, J = 7.2 Hz), 1.40 (m, 2 H), 1.30 (t, 3 H, J = 7.2 Hz). ^{13}C NMR: δ 169.4, 142.7, 141.9, 140.2, 129.9, 129.5, 128.2, 128.1, 127.2, 126.9, 61.2, 52.0, 29.5, 29.4, 28.6, 27.0, 14.1. HRMS: calcd for $C_{25}H_{30}O_4$, 394.2144; found, 394.2147.

Ethyl 2-Carbethoxy-2-methyl-7,7-diphenyl-6-heptenoate (8c) was obtained in 70% yield as a pale yellow oil. ^1H NMR: δ 7.50−7.15 (m, 10 H), 6.10 (t, 1 H, J = 7.3 Hz), 4.20 (q, 4 H, J = 7.2 Hz), 2.20 (dd, 2 H, J = 14.7, 7.3 Hz), 1.90 (m, 2 H), 1.45 (m, 2 H), 1.45 (s, 3 H), 1.30 (t, 3 H, J = 7.2 Hz). ^{13}C NMR: δ 172.5, 142.4, 142.3, 140.3, 130.0, 129.3, 128.4, 128.3, 127.4, 127.1, 127.0, 61.3, 53.8, 35.3, 30.1, 24.9, 20.0, 14.2. HRMS: calcd for $C_{25}H_{30}O_4$, 394.2144; found, 394.2139.

Ethyl 2-Cyano-2-methyl-7,7-diphenyl-6-heptenoate (8d) was prepared by sequential alkylation of ethyl cyanoacetate with 5-bromo-1,1-diphenyl-1-pentene and iodomethane. Compound **8d** was obtained in 84% yield. ^1H NMR: δ 7.25 (m, 10 H), 6.03 (t, 1 H, J = 7.2 Hz), 4.25 (q, 2 H, J = 7.2 Hz), 2.21 (m, 2 H), 1.90 (m, 1 H), 1.66 (m, 6 H), 1.35 (t, 3 H, J = 7.2 Hz). ^{13}C NMR: δ 169.3, 142.7, 142.3, 139.8, 129.7, 128.2, 128.1, 127.8, 127.1, 127.0, 119.9, 62.6, 43.8, 37.6, 29.1, 25.6, 23.3, 13.9. Mass spectrum [*m/e* (relative intensity)]: 347 (67, M^+), 332 (2), 319 (7), 302 (5), 290 (46), 274 (34), 256 (7), 232 (13), 218 (12), 193 (100), 178 (39), 165 (25), 152 (7), 129 (14), 115 (74), 91 (42).

Ethyl 2-Carboxy-7,7-diphenyl-6-heptenoate (9a) was obtained in 90% yield as an oil. ^1H NMR: δ 10.5 (bs, 1 H), 7.50−7.10 (m, 10 H), 6.10 (t, 1 H, J = 7.4 Hz), 4.25 (q, 2 H, J = 7.1 Hz), 3.40 (t, 1 H, J = 7.4 Hz), 2.20 (q, 2 H, J = 7.2 Hz), 1.90 (q, 2 H, J = 7.2 Hz), 1.55 (m, 2 H), 1.30 (t, 3 H, J = 7.1 Hz). ^{13}C NMR: δ 174.8, 169.2, 142.5, 142.3, 140.0, 129.8, 129.7, 128.1, 128.2, 127.2, 127.0, 126.9, 61.7, 51.5, 29.2, 28.3, 27.5, 14.0.

Ethyl 2-Carboxy-8,8-diphenyl-7-octenoate (9b) was obtained in 59% yield as an oil. ^1H NMR: δ 11.2 (bs, 1 H), 7.40−7.20 (m, 10 H), 6.10 (t, 1 H, J = 7.4 Hz), 4.25 (q, 2 H, J = 7.2 Hz), 3.40 (t, 1 H, J = 7.3 Hz), 2.15 (q, 2 H, J = 7.2 Hz), 1.95 (m, 2 H), 1.55 (m, 2 H), 1.40 (pent, 2 H, J = 7.2 Hz), 1.30 (t, 3 H, J = 7.2 Hz). ^{13}C NMR: δ 175.3, 169.2, 142.7, 142.0, 140.2, 129.9, 129.4, 128.2, 128.1, 127.2, 126.9, 126.8, 61.7, 51.7, 29.5, 29.4, 28.6, 26.9, 14.0.

Ethyl 2-Carboxy-2-methyl-7,7-diphenyl-6-heptenoate (9c) was obtained in 50% yield (80% based on recovered starting material) as a clear, viscous oil. ^1H NMR: δ 11.5−10.5 (bs, 1 H), 7.50−7.10 (m, 10 H), 6.10 (t, 1 H, J = 7.1 Hz), 4.25 (q, 2 H, J = 7.2 Hz), 2.20 (m, 2 H), 1.90 (m, 2 H), 1.45 (m, 2 H), 1.45 (s, 3 H), 1.35 (t, 3 H, J = 7.2 Hz).

2-Cyano-2-methyl-7,7-diphenyl-6-heptenoic Acid (9d) was obtained in 97% yield as a pale yellow solid. Mp: 65−66 °C. ^1H NMR: δ 9.0 (bs, 1 H), 7.23 (m, 10 H), 6.03 (t, 1 H, J = 7 Hz), 2.20 (m, 2 H), 1.94 (m, 1 H), 1.70 (s superimposed on m, 6H). ^{13}C NMR: δ 173.56, 142.82, 142.31, 139.84, 129.74, 128.22, 128.09, 127.94, 127.16, 127.03, 119.45, 43.70, 37.47, 29.09, 25.62, 23.22. HRMS: calcd for the $(M + 1)^+$ peak of $C_{21}H_{21}NO_2$, 319.1572; found, 319.1577.

1-[[(1-Carbethoxy-6,6-diphenyl-5-hexenyl)carbonyl]oxy]-2(1*H*)-pyridinethione (1a) was obtained in 60% crude yield as a yellow oil. The product was judged to be ca. 90% pure on the basis of its ^1H NMR spectrum; the major contaminant appeared to be unreacted acid **9a**. Compound **1a** decomposed upon attempted silica gel chromatography. The crude product was employed in the kinetic studies. ^1H NMR: δ 7.70 (d, 1 H, J = 7.8 Hz), 7.55 (d, 1 H, J = 7.8 Hz), 7.40−7.15 (m, 11 H), 6.60 (t, 1 H, J = 7.5 Hz), 6.10 (t, 1 H, J = 7.4 Hz), 4.30 (q, 2 H, J = 7.1 Hz), 3.75 (t, 2 H, J = 7.3 Hz), 2.30−2.10 (m, 3 H), 1.95 (m, 1 H), 1.70 (m, 1 H), 1.55 (m, 1 H), 1.35 (t, 3 H, J = 7.1 Hz). ^{13}C NMR: δ 175.6, 167.9, 165.2, 142.5, 142.4, 140.2, 137.3, 133.4, 129.8, 128.6, 128.2, 128.0, 127.2, 127.0, 126.9, 112.6, 62.2, 49.7, 29.2, 28.3, 27.3, 14.1.

1-[[(1-Carbethoxy-7,7-diphenyl-6-heptenyl)carbonyl]oxy]-2(1*H*)-pyridinethione (1b) was obtained as a yellow, viscous oil in 55% crude yield. The product was judged to be 90−95% pure on the basis of its ^1H NMR spectrum. Compound **1b** decomposed upon attempted silica gel chromatography. The crude product was employed in the kinetic studies. ^1H NMR: δ 7.67 (dd, 1 H, J = 7.5, 1.5 Hz), 7.55 (dd, 1 H, J = 7.5, 1.5 Hz), 7.45−7.15 (m, 11 H), 6.60 (dt, 1 H, J = 7.2, 2.0 Hz),

(37) Hayashi, K.; Iyoda, J.; Shiihara, I. *J. Organomet. Chem.* **1967**, *10*, 81−94.

6.10 (t, 1 H, J = 7.3 Hz), 4.20 (q, 2 H, J = 7.1 Hz), 3.70 (t, 1 H, J = 7.5 Hz), 2.20−1.90 (m, 4 H), 1.60−1.45 (m, 4 H), 1.25 (t, 3 H, J = 7.1 Hz). ^{13}C NMR: 175.6, 167.9, 165.2, 142.7, 142.0, 140.2, 137.4, 133.4, 129.4, 129.3, 128.2, 128.0, 127.2, 126.9, 126.8, 112.6, 62.1, 49.7, 29.4, 29.3, 28.6, 26.7, 14.1.

1-[[(1-Carbethoxy-1-methyl-6,6-diphenyl-5-hexenyl)carbonyl]oxy]-2(1*H*)-pyridinethione (1c) was obtained in 60% yield after silica gel chromatography as a yellow, viscous oil that was >95% pure on the basis of its ^{1}H NMR spectrum. ^{1}H NMR: δ 7.60 (dd, 1 H, J = 9.2, 1.5 Hz), 7.45 (dd, 1 H, J = 9.2, 1.5 Hz), 7.35−7.10 (m, 11 H), 6.55 (dt, 1 H, J = 7.0, 1.5 Hz), 6.05 (t, 1 H, J = 7.3 Hz), 4.20 (q, 2 H, J = 7.1 Hz), 2.10 (dd, 2 H, J =14.7, 7.3 Hz), 1.95 (m, 2 H), 1.60 (s, 3 H), 1.60−1.50 (m, 2 H), 1.25 (t, 3 H, J = 7.1 Hz). ^{13}C NMR: δ 176.3, 171.2, 168.0, 142.7, 142.4, 140.2, 137.8, 137.5, 133.5, 130.0, 129.1, 128.5, 128.2, 127.6, 127.1, 112.8, 62.2, 53.7, 35.6, 29.9, 24.8, 20.1, 14.3.

1-[[1-Cyano-1-methyl-6,6-diphenyl-5-hexenyl)carbonyl]oxy]-2(1*H*)-pyridinethione (1d) was obtained in 53% yield after silica gel chromatography as a heavy oil that was 80−90% pure on the basis of its ^{1}H NMR spectrum. ^{1}H NMR: δ 7.57 (d, 1 H, J = 7.8 Hz), 7.55 (d, 1 H, J = 6.9 Hz), 7.25 (m, 11 H), 6.66 (t, 1 H, J = 6.3 Hz), 6.06 (t, 1 H, J = 7.2 Hz), 2.21 (m, 3 H), 1.80 (m, 6 H). ^{13}C NMR: δ 137.6, 137.0, 133.3, 129.8, 128.3, 128.1, 127.8, 127.2, 127.1, 113.2, 43.2, 37.5, 29.1, 25.5, 23.7.

Ethyl 8,8-Diphenyl-2-(phenylselenyl)-7-octenoate (10b). To a flame-dried flask under nitrogen equipped with a stir bar were added 0.05 mL (0.36 mmol) of distilled diisopropylamine and 15 mL of dry THF. The solution was cooled to 0 °C, and 0.16 mL (0.36 mmol of a 2.31 M titrated solution) of *n*-BuLi in hexanes was added by syringe. The resulting mixture was stirred at 0 °C for 30 min and then cooled to −78 °C. A solution of 110 mg (0.33 mmol) of ester **6b** in 5 mL of THF was added slowly by cannula. The mixture was warmed to −50 °C for 30 min and then cooled to −78 °C. A solution of 100 mg (0.33 mmol) of diphenyl diselenide in 5 mL of THF was added dropwise. The reaction was allowed to warm room temperature over 1 h. A saturated aqueous solution of NH_4Cl was added. The mixture was separated, and the aqueous phase was extracted with ether. The combined organic phases were washed with a saturated aqueous NaCl solution and dried ($MgSO_4$). Concentration of the mixture gave a residue that was purified by silica gel chromatography (3:1 hexanes/ether) to give 55 mg (35%) of compound **10b** as a pale yellow oil. ^{1}H NMR: δ 7.60−7.15 (m, 10 H), 6.10 (t, 3 H, J = 7.4 Hz), 4.10 (q, 2 H, J = 7.1 Hz), 3.60 (dd, 1 H, J = 8.6, 6.6 Hz), 2.10 (q, 2 H, J = 7.2 Hz), 1.90 (m, 1 H), 1.75 (m, 1 H), 1.50−1.30 (m, 4 H), 1.20 (t, 3 H, J = 7.1 Hz). ^{13}C NMR: δ 173.0, 143.2, 142.3, 140.1, 135.6, 129.9, 129.6, 129.0, 128.2, 128.1, 127.2, 126.9, 126.8, 60.9, 43.6, 31.6, 29.5, 28.7, 27.7, 14.0. HRMS: calcd for $C_{28}H_{30}O_2Se$, 478.1411; found, 478.1405.

Ethyl 2-Methyl-7,7-diphenyl-2-(phenylselenyl)-6-heptenoate (10c) was prepared from ester **6c** by same procedure as that described above for preparation of **10b**. Compound **10c** was obtained in 47% yield as an oil. ^{1}H NMR: δ 7.60 (d, 2 H, J = 4.0 Hz), 7.50−7.20 (m, 13 H), 6.15 (t, 3 H, J = 7.3 Hz), 4.20 (dq, 2 H, J = 7.2, 3.7 Hz), 2.25 (q, 2 H, J = 7.2 Hz), 2.00 (m, 1 H), 1.40−1.75 (m, 3 H), 1.50 (s, 3 H), 1.35 (t, 3 H, J = 7.2 Hz). ^{13}C NMR: δ 174.0, 143.2, 142.5, 140.1, 137.2, 130.1, 129.5, 129.4, 128.9, 128.8, 128.4, 127.5, 127.1, 61.3, 50.1, 37.8, 30.0, 26.0, 22.7, 14.3. HRMS: calcd for $C_{28}H_{30}O_2Se$, 478.1411; found, 478.1412.

Acycles 6b−d were obtained by thermal decarboxylations of acid **9b** (neat, 170 °C) or the sodium carboxylates of **9c,d** (DMSO, 150 °C).

Ethyl 8,8-Diphenyl-7-octenoate (6b) was obtained in 80% yield as a pale yellow oil. ^{1}H NMR: δ 7.40 −7.20 (m, 10 H), 6.10 (t, 1 H, J = 7.5 Hz), 4.20 (q, 2 H, J = 7.1 Hz), 2.30 (t, 2 H, J = 7.5 Hz), 2.20 (q, 2 H, J = 7.2 Hz), 1.65 (m, 2 H), 1.50 (m, 2 H), 1.35 (m, 2 H), 1.30 (t, 3 H, J = 7.1 Hz). ^{13}C NMR: δ 174.0, 142.8, 142.0, 140.3, 129.9, 129.8, 128.2, 127.0, 126.9, 126.8, 60.2, 34.3, 29.6, 28.8, 24.8, 14.3. HRMS: calcd for $C_{22}H_{26}O_2$, 322.1933; found, 322.1928.

Ethyl 2-Methyl-7,7-diphenyl-6-heptenoate (6c) was obtained in 95% yield as a pale yellow oil. ^{1}H NMR: δ 7.40−7.10 (m, 10 H), 6.00 (t, 1 H, J = 7.4 Hz), 4.10 (q, 2 H, J =7.3 Hz), 2.35 (m, 1 H), 2.10 (q, 2 H, J = 7.2 Hz), 1.60 (m, 1 H), 1.35 (m, 3 H), 1.20 (t, 3 H, J = 7.3 Hz), 1.10 (d, 3 H, J = 6.8 Hz). ^{13}C NMR: δ 176.8, 142.9, 142.1, 140.4, 130.1, 129.7, 128.4, 128.3, 127.4, 127.1, 60.3, 39.6, 33.5, 29.8, 27.7, 17.2, 14.4. HRMS: calcd for $C_{22}H_{26}O_2$, 322.1933; found, 322.1937.

2-Methyl-7,7-diphenyl-6-heptenenitrile (6d) was obtained in 84% yield as an oil. ^{1}H NMR: δ 7.30 (m, 10 H), 6.05 (t, 1 H, J = 6 Hz), 2.25 (m, 1 H), 2.16 (m, 2 H), 1.57 (m, 4 H), 1.27 (d, 3 H, J = 6 Hz). ^{13}C NMR: δ 142.53, 142.42, 139.97, 129.78, 128.50, 128.25, 128.12, 127.16, 127.02, 122.90, 33.43, 28.90, 27.16, 25.25, 17.90. Mass spectrum [*m/e* (relative intensity)]: 275 (61, M^+), 260 (5.6), 247 (9), 232 (21), 218 (10), 193 (100), 178 (38), 165 (24), 115 (75), 91 (29). HRMS: calcd for $C_{20}H_{21}N$, 275.1674; found, 275.1670.

Cyclic Products 11 were obtained from reactions of the corresponding PTOC esters in the presence of low concentrations of Bu_3SnH. GC−mass spectral analysis indicated that two diastereomers were produced for **11a,c,d** and that one diastereomer of **11b** was formed. A mixture of diastereomers of **11a** was isolated. Compound **11b** isolated by chromatography was contaminated with acyclic product **6b**. For both **11c,d**, a single diastereomer was isolated by chromatography. A representative reaction follows. PTOC ester **1d** (40 mg, 0.096 mmol) was placed in a shielded 25 mL round-bottomed flask containing a stir bar. The flask was sealed with a septum and flushed with nitrogen. Dry and degassed THF (10 mL) and 336 mg (1.15 mmol) of Bu_3SnH were added via syringe. The shield was removed, and the reaction mixture was irradiated at room temperature with a 150 W tungsten filament lamp at a distance about 0.6 m for 5 h. The reaction mixture was concentrated, and the residue was purified by chromatography on silica gel (9:1 hexanes/ethyl acetate) to give 10 mg (0.036 mmol, 38%) of product **11d** as a single diastereomer.

Ethyl 2-(Diphenylmethyl)cyclopentanecarboxylate (11a) was obtained as an oil in 66% yield as a 1:1 mixture of diastereomers. ^{1}H NMR: δ 7.4−7.1 (m, 10 H), 4.01 (d, 0.5 H, J = 11.8 Hz), 3.91 (dq, 0.5 H, J = 10.6, 7.2 Hz), 3.81 (dq, 0.5 H, J = 10.5, 7.2 Hz), 3.77 (dq, 0.5 H, J = 10.6, 7.2 Hz), 3.66 (dq, 0.5 H, J = 10.5, 7.2 Hz), 3.64 (d, 0.5 H, J = 11.6 Hz), 3.29 (dq, 0.5 H, J = 11.0, 7.4 Hz), 2.93 (m, 0.5 H), 2.81 (dt, 0.5 H, J = 7.3, 3.2 Hz), 2.45 (dt, 0.5 H, J = 8.6, 7.2 Hz), 1.97 (m, 0.5 H), 1.88 (m, 0.5 H), 1.8−1.5 (m, 3 H), 1.4−1.2 (m, 2 H), 1.02 and 1.03 (overlapping t, 3 H total, J = 7.2 Hz for each). MS [*m/z* (relative intensity)]: 308 (M^+, 6), 263 (5), 262 (10), 234 (3), 168 (18), 167 (100), 165 (13), 152 (7), 105 (15), 77 (8). HRMS: calcd for $C_{21}H_{24}O_2$, 308.1776; found, 308.1780.

Ethyl 2-(Diphenylmethyl)cyclohexanecarboxylate (11b) was obtained as an oil in 24% yield. ^{1}H NMR: δ 7.45−7.15 (m, 10 H), 4.00 (d, 1 H, J = 8.6 Hz), 3.85 (dq, 2 H, J = 7.3, 3.6 Hz), 2.80 (ddd, 1 H, J = 15.7, 8.6, 3.6 Hz), 2.25 (m, 1 H), 1.65 (m, 4 H), 1.55 (m, 1 H), 1.30 (m, 2 H), 1.25 (t, 3 H, J = 7.3 Hz). HRMS: calcd for $C_{22}H_{26}O_2$, 322.1933; found, 322.1937.

Ethyl 1-Methyl-2-(diphenylmethyl)cyclopentanecarboxylate (11c) was obtained as an oil in 25% yield. ^{1}H NMR: δ 7.30−7.10 (m, 10 H), 4.00 (dq, 1 H, J = 10.9, 7.0 Hz), 3.95 (d, 1 H, J = 8.9 Hz), 3.85 (dq, 1 H, J = 10.9, 7.0 Hz), 2.65 (m, 1 H), 2.10 (m, 1 H), 1.55 (m, 2 H), 1.50 (m, 3 H), 1.15 (t, 3 H, J = 7.0 Hz), 0.8 (s, 3 H). ^{13}C NMR: δ 178.0, 145.4, 144.0, 128.4, 128.1, 127.9, 127.2, 126.3, 126.0, 60.0, 54.8, 54.7, 51.6, 41.7, 33.5, 25.8, 22.8, 14.1. HRMS: calcd for $C_{22}H_{26}O_2$, 322.1933; found, 322.1937.

1-Cyano-1-methyl-2-(diphenylmethyl)cyclopentane (11d) was obtained as an oil in 38% yield. ^{1}H NMR: δ 7.45 (d, 2 H, J = 7.5 Hz), 7.26 (m, 8 H), 3.72 (d, 1 H, J = 12 Hz), 3.21 (m, 1 H), 2.28 (m, 1 H), 1.86 (m, 1 H), 1.71 (m, 4 H), 1.30 (s, 3 H). ^{13}C NMR: δ 129.84, 128.69, 128.20, 127.52, 127.15, 126.48, 54.24, 51.01, 41.75, 37.75, 30.22, 21.48, 19.14. MS [*m/e* (relative intensity)]: 275 (8.7, M^+), 167 (100), 152 (8.5), 115 (3.5), 91 (4.6). HRMS: calcd for $C_{20}H_{21}N$, 275.1674; found, 275.1677.

Direct Kinetic Studies were performed with an Applied Photophysics LK-50 kinetic spectrometer employing a Spectron Nd-YAG laser. Solutions of precursors **1** in THF were thermally equilibrated in a jacketed addition funnel while being purged with nitrogen or helium for >15 min. Solutions flowed through a 1 × 1 cm^2 Suprasil cell contained in a temperature-regulated well in the spectrometer. For studies of reactions with Bu_3SnH, a solution of precursor **1** and a solution of tin hydride were purged with nitrogen, placed in 50 mL gas-tight syringes, and pumped via a syringe pump through stainless

steel coils immersed in a regulated bath. The flowing solutions mixed in a tee for ca. 5 s before entering the flow cell. Temperatures were measured with a thermocouple contained in a well in the flow cell about 1 cm above the irradiation zone. Multiple kinetic runs, typically 15, were recorded at 328−330 nm, analyzed, and averaged for each kinetic point. Representative kinetic data are supplied in the supplementary material.

Indirect Kinetic Studies were performed by the general methods previously described.[4] Phenyl selenide **10b** was the radical precursor for studies of **4b** (temperature range of 1−77 °C). PTOC ester **1c** (−15 to 45 °C) and phenyl selenide **10c** (60 °C) were the radical precursors for studies of **4c**. PTOC ester **1d** (−40 to 22 °C) was the radical precursor for studies of **4d**. Mixtures of the radical precursor, Bu_3SnH, and a hydrocarbon standard (and AIBN for reactions employing a phenyl selenide precursor) in THF were placed in tubes containing a small stir bar under an inert atmosphere. After equilibration at the desired temperature, the solutions were irradiated. For reactions employing PTOC ester precursors, the solutions were irradiated with a 150 W tungsten filament lamp at a distance of ca. 0.5 m for ca. 15−60 min. For reactions employing a phenyl selenide precursor, the solutions were irradiated in a photochemical reactor with 300 nm bulbs (70 W) for 60−90 min. After irradiation, the reaction mixtures were treated with iodine until a faint red color persisted. The mixtures were then washed twice with saturated aqueous KF solution, once with saturated aqueous $Na_2S_2O_3$ solution, and once with saturated aqueous NaCl solution and dried ($MgSO_4$). The reaction mixtures were analyzed by GC. The products were identified by GC and GC−mass spectral comparison to authentic samples; for reactions of **4c,d**, the unisolated cyclic products were identified by mass spectral fragmentation patterns which were similar to those of the corresponding isolated cyclic products. Yields were calculated with predetermined response factors; for reactions of **4c,d**, the unisolated cyclic product was assumed to have the same response factor as the isolated cyclic product. The kinetic results are given in the supplementary material.

Acknowledgment. We are grateful to the National Science Foundation for financial support (CHE-9117929). We thank Prof. Dr. Hanns Fischer for providing us with kinetic results from his group's studies and a manuscript in advance of publication.

Supplementary Material Available: Tables of kinetic results for cyclizations of radicals **4** and reactions of radicals **4b−d** with Bu_3SnH (9 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

JA942266+