Supporting Information for

Cyclopropylcarbinyl → Homoallyl-Type Ring Opening of Ketyl Radical Anions. Structure/Reactivity Relationships and the Contribution of Solvent/Counterion Reorganization to the Intrinsic Barrier

J. M. Tanko, Jason G. Gillmore, Robert Friedline, and M'hamed Chahma*

Department of Chemistry, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

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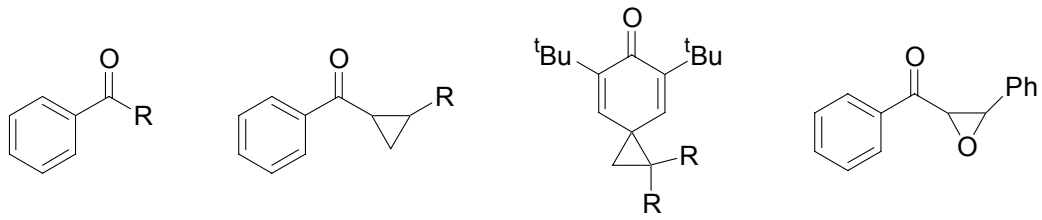
Experimental

Materials. Acetonitrile (Aldrich) was stirred over CaH_2 (1 g/100 mL) for three days, then distilled from P_2O_5 (2 g/100 mL) under an inert atmosphere. *trans*-4,4'-Dimethoxystilbene (DMS, Aldrich) was recrystallized from methanol. Tetrabutylammonium azide was obtained from TCI and used as received. Acetophenone (**4**), *t*-butyl phenyl ketone (**5**), and cyclopropyl phenyl ketone (**6**) were obtained from Aldrich and vacuum distilled before use. *trans*-1-Benzoyl-2-phenylcyclopropane (**7**),[1] 5,7-di-*t*-butylspiro[2.5]octa-4,7-dien-6-one (**8**),[2-5] 1,1-dimethyl-5,7-di-*t*-butylspiro[2.5]octa-4,7-dien-6-one (**9**),[2-5] and 2,3-epoxy-1,3-diphenylpropan-1-one (**10**)[6] were prepared according to published procedures.



4: R = CH_3 **6**: R = H **8**: R = H **10**

5: R = ^{t}Bu **7**: R = Ph **9**: R = CH_3

General. Steady-state UV/visible spectra were recorded on a Hewlett Packard diode array spectrometer (HP8452A). Laser flash photolysis (LFP) experiments were conducted using an Applied Photophysic LKS.60 spectrometer using the third harmonic of a Continuum Surelite I-10 Nd:YAG laser (4 – 6 ns pulse, 355nm). Transient signals were monitored by a Hewlett Packard Infinium digital oscilloscope and analyzed with the Applied Photophysics SpectraKinetic Workstation software package (v. 4.59). Samples were prepared in a dry environment, degassed by bubbling Ar through the solution for 15 min., and passed through a flow cell to ensure fresh sample at a rate of 2 mL/min.

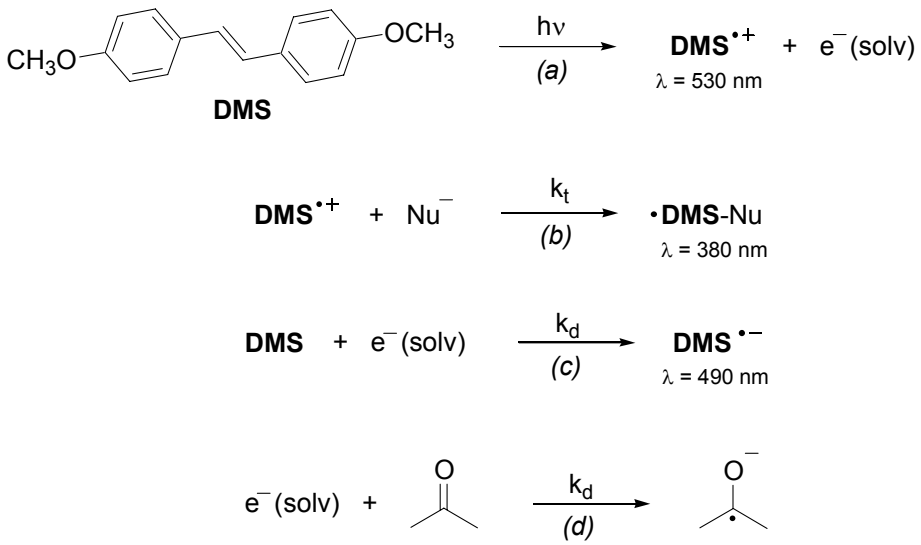
Molecular orbital calculations were performed using Spartan '04 (Wavefunction Inc., 18401 Von Karman Avenue, Suite 370, Irvine, CA 92612) at the HF/6-31G* level to obtain the LUMO for ketones **7** and **10**, and at the B3LYP/6-31G* level to obtain the thermochemical parameters for ring-opening of neutral cyclopropylcarbinyl radicals. For the latter, vibrational frequencies and full thermodynamic

calculations were performed on the cyclopropane ring-closed and ring-opened structures. The vibrational frequencies were not scaled.

Results

The major reactions pertinent to the use of DMS to generate radical anions from carbonyl compounds are summarized in Scheme S1. As reported previously by Mathivanan, *et al*.,[7] laser excitation (355 nm) of DMS generates a transient absorbance at 530 nm attributable to formation of $DMS^{\bullet+}$ (Figure S1) according to Scheme S1, reaction a. The shoulder at 490 nm is attributable to $DMS^{\bullet-}$, formed by trapping of the solvated electrons by DMS (Scheme S1, reaction c). The absorbance of both $DMS^{\bullet+}$ and $DMS^{\bullet-}$ interfere with absorbance of the desired ketyl anion, typically 470 – 500 nm for $Ph(C=O^{\bullet-})R$. Fortunately, these interfering absorbances are easily eliminated.

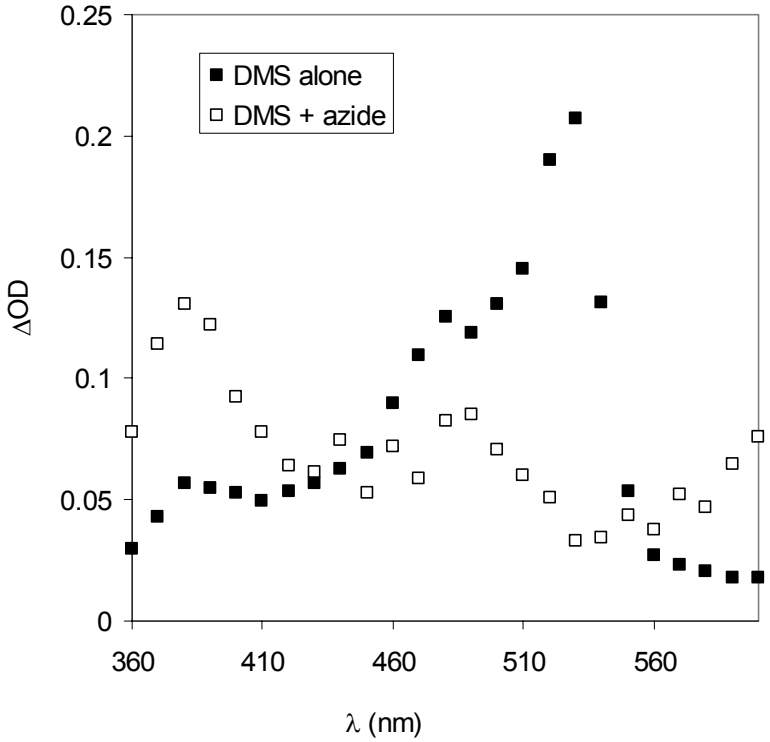
Scheme S1



The signal arising from $DMS^{\bullet+}$ can be eliminated via reaction with an appropriate nucleophile. Mathivanan, *et al*. report that azide and acetate anions readily react with $DMS^{\bullet+}$ at a diffusion-controlled rate, presumably via nucleophilic addition (Scheme S1, reaction b).[7] As seen in Figure S1, photoionization of DMS in the presence of 0.01 M tetra-*n*-butylammonium azide completely eliminates the signal attributable to $DMS^{\bullet+}$ at 530 nm and a new signal is observed at 380 nm, presumably attributable to the trapping product, •DMS-Nu. (This signal at 380 nm was not noted previously

because the earlier workers did not record transient spectra below 400 nm); the signal at 490 nm ($DMS^{\bullet-}$) remains.

Figure S1. Photoionization of *trans*-dimethoxystilbene (DMS) in the absence and presence of a nucleophile (*n*-Bu_4NN_3) in CH_3CN solvent; spectra taken 0.2 μs after laser firing



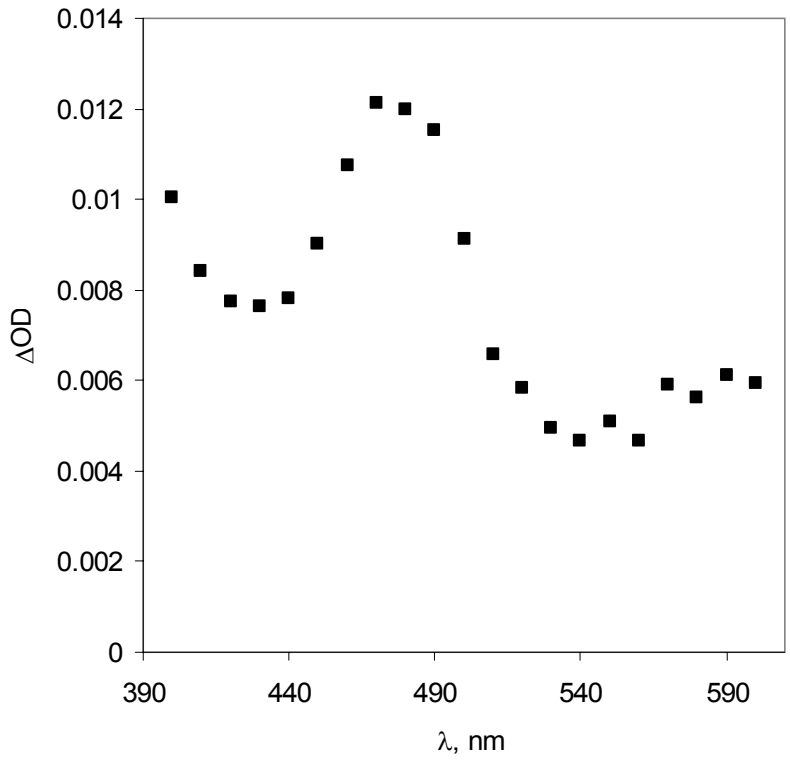
The rate constant (k_t) and Arrhenius parameters for trapping of $DMS^{\bullet+}$ by N_3^- were determined by measuring the observed rate constant for $DMS^{\bullet+}$ decay as function of N_3^- concentration at several temperatures ranging from 10 – 70 ^oC. At room temperature, $k_t = 1.84 \times 10^{10}$ $M^{-1}s^{-1}$, log(A) = 8.85(± 0.07) and E_a = 1.99 (± 0.10) kcal/mol, values consistent with a diffusion-controlled reaction.

For the purpose of generating the radical anions of interest, interference from $DMS^{\bullet-}$ can be reduced by using an excess of carbonyl compound. As noted by Mathivanan, *et al.*, trapping of solvated electrons by DMS and the carbonyl compound (Scheme S1, reactions c and d, respectively) are both diffusion controlled, which means the only way to favorably manipulate the rates of these two competing bimolecular processes is via concentration.[7] Fortunately, the extinction coefficient of DMS at 355 nm is very large relative to the ketones used in this study. For these experiments, a protocol

where [DMS] = 3.0 x 10^{-4} M and the concentration of the ketone was 6.0 x 10^{-3} M ensured that DMS was the major absorbing (> 10 : 1) species at 355 nm, and that the ketone was the major acceptor of solvated electrons by a 20 : 1 margin. A concentration of 0.01 M *n*-Bu_4NN_3 ensured that $DMS^{\bullet+}$ was short lived ($t_{1/2}$ = 3.7 ns).

The transient absorption spectrum for the radical anion of phenyl cyclopropyl ketone (**6**$^{\bullet-}$) generated by the DMS photoionization protocol is presented in Figure S2. The observed λ_{max} for **6**$^{\bullet-}$ is identical to that reported for acetophenone radical anion (**4**$^{\bullet-}$) and other structurally related ketyls anions, generated using the DMS method and other well-established procedures.[7]

Figure S2. Transient absorption spectrum of the radical anion generated from phenyl cyclopropyl ketone (**6**$^{\bullet-}$) taken 0.2 μs after laser firing (CH_3CN solvent; 0.01 M *n*-Bu_4NN_3 present to trap $DMS^{\bullet+}$)



Although the observed absorption spectrum of **6**$^{\bullet-}$ was consistent with the formation of an aromatic ketyl anion, the unusually high rate of decay ($k_d \approx 10^6$ s^{-1}) was unexpected (See Figure 1, a in the manuscript). Previous electrochemical experiments revealed that **6**$^{\bullet-}$ was considerably longer lived,

with a lifetime on the order of seconds, under similar conditions (DMF solvent, *n*-Bu_4N^+ counterion)[8,9] leading to the suspicion that the observed rate constant for decay cannot be attributed to cyclopropane ring opening. This was further confirmed by examining aromatic ketones whose radical anions were known to be persistent. (For example, generated electrochemically, $\mathbf{5}^{\bullet-}$ is known to persist for well over an hour at room temperature!)[9] The results are summarized in Table S1. All these ketyl anions are found to decay with an *apparent* first order rate constant on the order of 1 x 10^6 s^{-1}. The temperature dependence of the apparent first order rate constants for decay of these "persistent" radical anions were similar, as were the apparent activation energies and log(A) values derived from the temperature profile.

Table S1. Summary of results obtained for the transient absorption spectra and apparent rate constants for decay of "persistent" radical anions $\mathbf{4}^{\bullet-} \rightarrow \mathbf{6}^{\bullet-}$

Radical anion	λ_{max} (nm)	k_d (s^{-1})[a]	E_a (kcal/mol)[a]	log(A)[a]
$\mathbf{4}^{\bullet-}$	460 – 490	6.9 x 10^5	5.88(51)	9.94(36)
$\mathbf{5}^{\bullet-}$	490	8.3 x 10^5	5.24(35)	9.52(24)
$\mathbf{6}^{\bullet-}$	480	1.1 x 10^6	5.92(91)	9.86(65)

[a]Apparent rate constant and activation parameters for decay assuming first (or pseudo first) order kinetics. CH_3CN solvent; 0.01 M *n*-Bu_4NN_3 present to trap $DMS^{\bullet+}$.

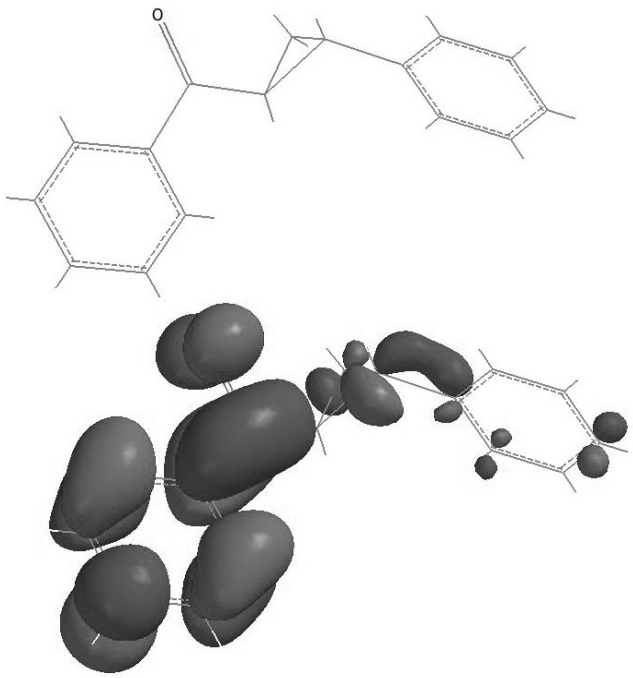
In their experiments, Mathivanan, *et al*. observed a similar decay of $\mathbf{4}^{\bullet-}$ on the order of μs, which was attributed to "quenching by residual oxygen that is difficult to completely remove from flow samples."[7] It is clear in order for this method to yield meaningful results for the radical anions of interest, the ring opening process must occur with a rate constant significantly greater than 10^6 s^{-1}.

The data pertaining to the radical anions generated from **7** → **9** is discussed below and summarized in Table 1 of the manuscript. Variable temperature experiments were conducted, but the data was not of sufficient quality to allow reliable activation parameters to be reported. In all cases, however, the shallow temperature dependence of the rate constant suggested the activation energies were well below

the 6 kcal/mol threshold associated with the competing radical anion decay process observed for $\mathbf{4}^{\bullet-} \rightarrow \mathbf{6}^{\bullet-}$.

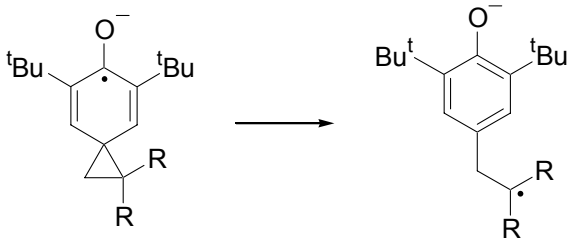
Using the DMS photoionization method, the radical anion of 1-benzoyl-2-phenylcyclopropane (**7**) was successfully generated (λ_{max} = 530 nm). The observed red shift for $\mathbf{7}^{\bullet-}$ is attributed to extended conjugation through the cyclopropyl group. Indeed, MO calculations (HF/6-31G*) reveal that the LUMO of the neutral ketone encompasses the entire molecule, rather than being confined to the benzoyl group (Figure S3). As anticipated, the kinetic trace for this species (Figure 1, b in the manuscript) indicates that $\mathbf{7}^{\bullet-}$ decays in well under 1 μs, consistent with a ring opening process.

Figure S3. Lowest unoccupied molecular orbital (LUMO) of 1-benzoyl-2-phenylcyclopropane (**7**) obtained from HF/6-31G* MO calculations (top: molecular framework; bottom: molecular framework and LUMO superimposed)



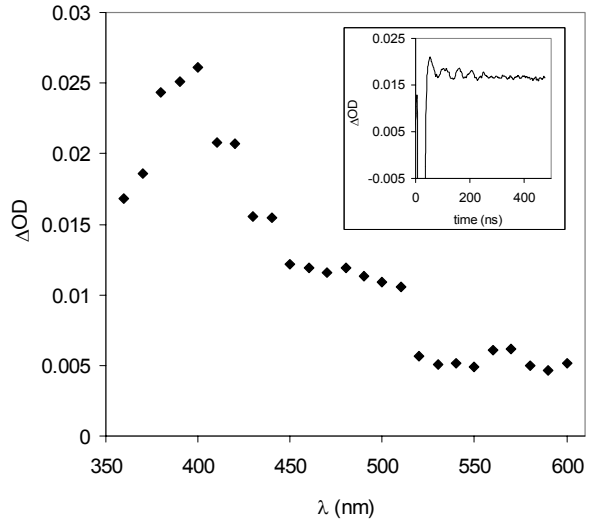
Rather than a transient decay of radical anion at ~ 480 nm, there was an "instantaneous" buildup at λ ≈ 400 nm for spirodienones **8** and **9** (Figure S4), corresponding to formation of a phenoxide anion (Eq. 2). This assignment was confirmed by observing that the anion 2,4,6-tri-tert-butylphenol, generated

with potassium *t*-butoxide in CH_3CN exhibited λ_{max} at 410 nm. Because the rate is at the upper limit of detection, the derived rate constants are best viewed as crude estimates.

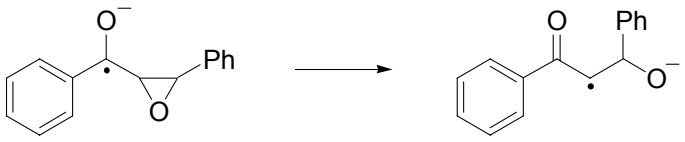


(**2**)

Figure S4. Transient absorption spectrum of the radical anion generated from 5,7-di-*t*-butylspiro[2.5]octa-4,7-dien6-one (**8**) taken 10 ns after laser firing in CH_3CN (0.01 M *n*-Bu_4NN_3 present to trap $DMS^{\bullet+}$). Insert: Transient "buildup" monitored at 400 nm

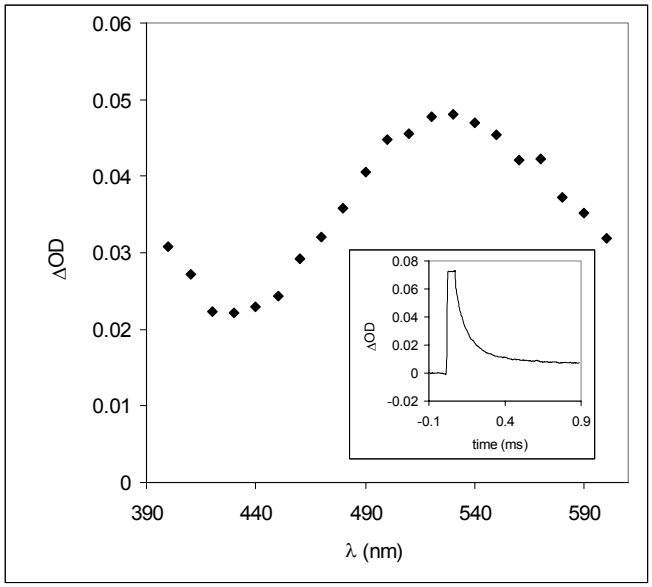


The radical anion generated by photoinduced electron transfer to epoxyketone **10** was shown by Hasegawa to undergo ring opening as depicted in Eq. 3.[10,11] The transient spectrum for this radical anion produced by the DMS method exhibits λ_{max} at 530 nm and decays in less than a microsecond (Figure S5), permitting measurement of the rate constant for ring opening.



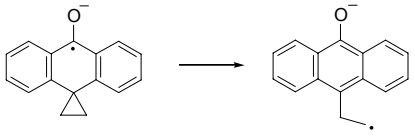
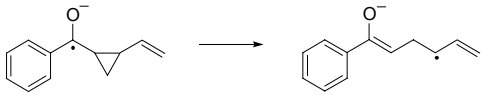
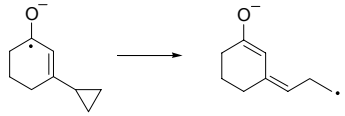
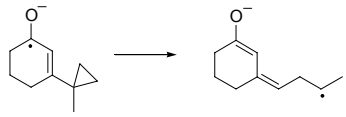
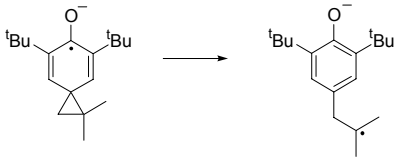
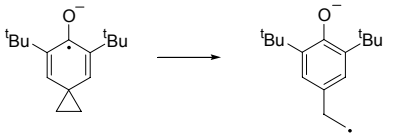
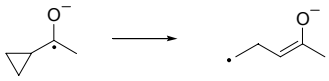
(3)

Figure S5. Transient absorption spectrum of the radical anion generated from epoxyketone (**10**) taken 0.1 μs after laser firing in CH_3CN (0.01 M *n*-Bu_4NN_3 present to trap $DMS^{\bullet+}$). Insert: Transient "buildup" monitored at 530 nm.



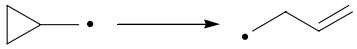
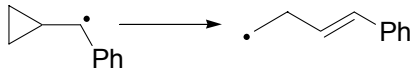
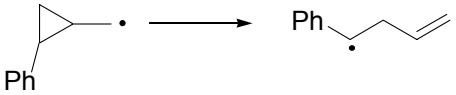
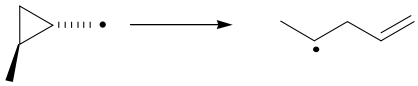
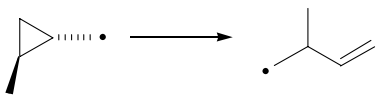
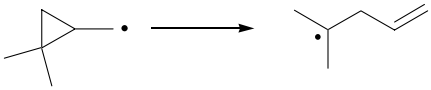
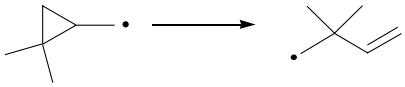
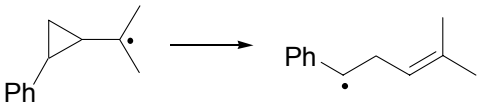
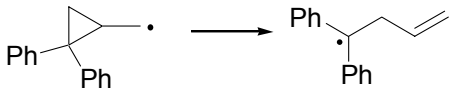
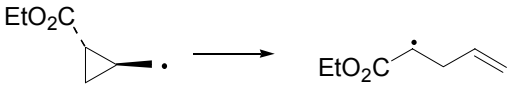
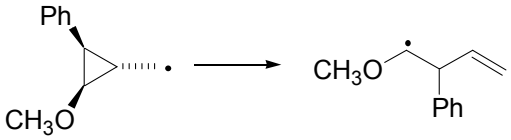
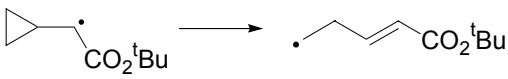
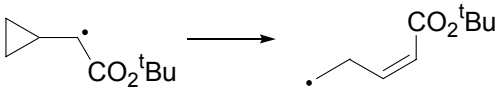
The rate constants and ΔG^o values used to construct Figure 2 in the manuscript are summarized in Tables S2 and S3.

Table S2. Kinetic and thermodynamic data for rearrangement of cyclopropyl- and cyclobutyl-containing radical anions derived from carbonyl compounds

system	k_o (s^{-1})	ΔG^o (kcal/mol)
	< 10 [a]	6.0
	1.4×10^{2} [b]	3.0
	2.4×10^{5} [c]	-4.7
	1.6×10^{6} [b]	-7.6
	2.5×10^{6} [b]	-8.8
	3.0×10^{6} [b, c] 9.6×10^{6} [e]	-3.4
	$>10^{7}$ [d] $>3 \times 10^{8}$ [e]	-18
	$>10^{7}$ [d] $>3 \times 10^{8}$ [e]	-15
	$>10^{7}$ [f]	-4.9

[a]References 8 and 9. [b]Reference 12. [c]Reference 13. [d]References 14 and 15. [e]This work. [f]References 16 and 17.

Table S3. Kinetic and thermodynamic data for cyclopropylcarbinyl → homoallyl rearrangements of neutral free radicals

system	k_o (s^{-1})	ΔG^o (kcal/mol)	References
	8.3×10^7	-5.9	18-21
	9.0×10^4	3.7	19,22
	1.9×10^{11}	-19.3	23,24
	1.1×10^8	-8.2	20
	1.0×10^8	-4.5	20
	6.8×10^8	-11.7	20,21
	8.5×10^7	-3.2	20,21
	7.2×10^{10}	-18.1	23
	4.3×10^{11}	-24.8	24,25
	7.5×10^{10}	-20.0	26
	4.6×10^9	-9.8	27
	7.4×10^5	1.3	22
	8.4×10^4	1.3	22

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