show anti stereoselection.[8] The results are shown in Table I.

In order to study the chirality transfer in these systems, optically active (*R*),(*Z*)-**1a** and **1c** were prepared. Asymmetric reduction of 2-methyl-4-hexyn-3-one with *B*-3-pinanyl-9-borabicyclo[3.3.1]nonane (*R*-Alpine-Borane)[9] afforded (*R*)-2-methyl-4-hexyn-3-ol of 91% ee in good yield.[10] Partial hydrogenation of the secondary propargylic alcohol gave (*R*),(*Z*)-2-methyl-4-hexen-3-ol without detectable racemization.[11] The optically active (*R*),(*Z*)-allylic ethers **1a** ($[\alpha]^{24}_{D}$ −0.3° (*c* 2.28, THF)) and **1c** ($[\alpha]^{25}_{D}$ +10.60° (*c* 2.52, THF)) were easily prepared from the alcohol and allyl and benzyl chloride, respectively, in the presence of sodium hydride in refluxing THF.

The [2,3] Wittig rearrangement of (*R*),(*Z*)-allylic ethers **1a** and **1c** produced (*syn*,*E*)-**2a** and (*anti*,*E*)-**3a** in a 11:1 ratio and (*syn*,*E*)-**2c** and (*anti*,*E*)-**3c** in a 13:1 ratio, respectively. The assignment of syn and anti stereochemistry by NMR may be misleading.[12] Therefore, the relative and absolute stereochemistry was determined by conversion of optically active (*syn*,*E*)-**2c**[13] ($[\alpha]^{24}_{D}$ +15.67° (*c* 2.33, EtOAc)) to the known (2*S*,3*S*)-3-hydroxy-2-methyl-3-phenylpropanoic acid[14] and is in agreement with the prediction from the five-membered cyclic transition state.[3,4] NMR lanthanide shift study, Eu(hfc)$_3$, of the optically active (3*R*,4*R*),(*E*)–**2a** ($[\alpha]^{25}_{D}$ +29.89° (*c* 1.79, THF)) showed the alcohol was 91% ee. Since the enantiomeric purity is identical with that of the starting material the rearrangement proceeded with essentially 100% transmission of chirality.

The mechanism of this reaction is not fully understood.[3,4] Presumably the relative stereochemistry is fixed with a high degree of control by way of the five-membered cyclic transition state (Scheme II). For the rearrangement of (*Z*)-allylic ethers, the isopropyl group is less hindered in the equatorial position (transition states A and B) and leads to the (*E*)-olefin with a high degree of selectivity. The substituent *R* is also less hindered in transition state A and thus leads to (*syn*,*E*)-**2** as the major product. Due to the severe interactions in transition states C and D, none of the *cis*-olefin was observed. The reason for the poor diastereoselectivity observed with the (*E*)-allylic ether is somewhat less obvious and must await further information.[15] However, transition state A predicts the major product. In rearrangment of the optically active ether, the chirality of the starting material fully determines the face of double bond on which the new carbon–carbon bond forms (i.e., *re* face for (*R*),(*Z*)-**1a**).

The enantiomeric purity of the product (3*R*,4*R*)-**2a** is essentially the same as the enantiomeric purity of the α-pinene. Thus the chirality of the pinene is transferred to the two new centers of alcohol **2a** with nearly 100% efficiency. Since both enantiomers of optically pure α-pinene can be obtained and recycled,[16] both enantiomers of the optically pure **2a** should be available. The development of a more diastereoselective process and the application of this reaction to the synthesis of natural products are in progress.

Acknowledgment. We thank the Herman Frasch Foundation, administered by the American Chemical Society, the National Institutes of Health (GM24517), and the Cancer Research Coordinating Committee of the University of California for financial support.

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[8] Previous examples show that [2,3] sigmatropic rearrangements of *Z* substrates exhibit syn stereoselection, whereas the *E* substrates show anti stereoselection (cf. ref 4).

[9] Reductions of alkynyl ketones with *R*-Alpine-Borane (prepared from 91.3% (+)-α-pinene and 9-BBN) always give (*R*)-propargyl alcohols. (a) Midland, M. M.; McDowell, D. C.; Hatch, R. L.; Tramontano, A. *J. Am. Chem. Soc.* **1980**, *102*, 867. (b) Midland, M. M.; Graham, R. S. *Org. Synth.*, submitted for publication. (c) Brown, H. C.; Pai, G. G. *J. Org. Chem.* **1982**, *47*, 1606. (d) Midland, M. M.; Tramontano, A.; Kazubski, A.; Graham, R. S.; Tsai, D. J. S.; Cardin, D. B. *Tetrahedron*, in press.

[10] NMR lanthanide shift study with Eu(hfc)$_3$ showed the alcohol to be 95.6% *R* and 4.4% *S*, 91% ee. The absolute configuration was confirmed by conversion to the known β-methyl-γ-lactone (cf. ref 9d).

[11] (a) Lindlar, H.; Dubuis, R. *Org. Synth.* **1966**, *46*, 89. (b) Chan, K. K.; Cohen, N.; DeNobel, J. P.; Specian, A. C.; Saucy, G. *J. Org. Chem.* **1976**, 3497.

[12] Heng, K. K.; Simpson, J.; Smith, R. A. J.; Robinson, W. T. *J. Org. Chem.* **1981**, *46*, 2932.

[13] NMR lanthanide shift study of optically active (*syn*,*E*)-**2b** with Eu(hfc)$_3$ showed the alcohol was 88% ee.

[14] (a) Evans, D. A.; McGee, L. R. *J. Am. Chem. Soc.* **1981**, *103*, 2876. (b) Masamune, S.; Choy, W.; Kerdesky, F.; Imperiali, B. *J. Am. Chem. Soc.* **1981**, *103*, 1566. (c) Heathcock, C. H.; White, C. T.; Morrison, J. J.; Van Derveer, D. *J. Org. Chem.* **1981**, *46*, 1296.

[15] For example, the structure of the allylic anion may play an important role. Hartmann, J.; Muthukrishnan, R.; Sclosser, M. *Helv. Chim. Acta* **1974**, *57*, 2261.

[16] Brown, H. C.; Jadhav, P. K.; Desai, M. C. *J. Org. Chem.* **1982**, *47*, 4583. Enriched α-pinene is also available from Aldrich Chemical Co.

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Peroxide Radical Cations in Solution

Summary: Bicyclic bis(tertiary) peroxides **2** and **3** give long-lived radical cations at room temperature, despite their high oxidation potentials ($E^{\circ\prime}$ = 2.18 and 2.29 V vs. SCE, respectively). The ESR spectra of the radical cations are reported, and the reason for oxidation being so much harder for peroxides than for hydrazines is discussed.

Sir: Davies and co-workers[2a] suggested that the broad singlet ESR spectrum with $g = 2.0091$ detected upon photolysis of di-*tert*-butyl peroxide (**1**) in solvents containing trifluoroacetic acid was $\mathbf{1}^{+}$, and Symons and co-workers[2b] recently have obtained the *g* tensor components for radiolytically generated $\mathbf{1}^{+}$ in a CFCl$_3$ matrix at 77 K (g_{av} = 2.0084). We have recently observed ESR spectra of radical cations of dioxetanes from tetraalkyl-substituted olefins.[3] We report here that although $\mathbf{1}^{+}$ is unstable at room temperature, two tertiary dialkyl peroxides that have COOC angles held near 0° by bicyclic strutures give long-lived radical cations at room temperature, allowing measurement of the thermodynamically significant formal potential for electron loss ($E^{\circ\prime}$) by using cyclic voltammetry. Although electron removal is thermodynamically difficult, the radical cations of dihydroascaridole (**2**) and 1,5-dimethyl-6,7-dioxabicyclo[3.2.1]octane (**3**)[4] prove to be long-lived in 20:1:1 CH_2Cl_2:CF_3CO_2H:$(CF_3CO)_2O$.[5] The

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[1] (a) University of Wisconsin. (b) University of Cincinnati.

[2] (a) Cookson, P. G.; Davies, A. G.; Roberts, B. P.; Tse, M.-W. *J. Chem. Soc., Chem. Commun.* **1976**, 1002. (b) Chandra, H.; Rao, D. N. R.; Symons, M. C. R. *J. Chem. Res. Synop.* **1983**, 68.

[3] Lopez, J. Ph.D. Thesis, University of Basel, 1982. Kapp, D. L., unpublished work.

[4] Wilson, R. M.; Rekers, J. W. *J. Am. Chem. Soc.* **1981**, *103*, 206.

[5] Cyclic voltammetry blanks in CH_2Cl_2 show substantial current above +2 V vs. SCE. Addition of trifluoroacetic acid and anhydride (see Hammerich, O.; Parker, V. D. *Electrochim. Acta* **1973**, *18*, 537) allows scanning to much higher potential, presumably because of removal of trace impurities.

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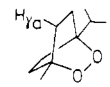

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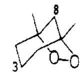

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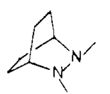

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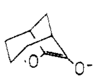
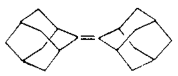


$5^{-\cdot}$



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ESR spectrum of electrolytically generated 2^+ shows a g factor of 2.0091 and consists of a broadened 1:4:6:4:1 quintet, $a(4H_{\gamma_a})$ = 4.7 G. It is not surprising that only an averaged H_{γ_a} splitting was resolved, because of the lack of symmetry in the molecule. The H_{γ_a} splitting for an analogous hydrazine radical cation, 4^+, is 2.6 G.[6] It is already known that β splittings for methyl groups attached to oxygen are unusually large: radiolytically generated Me_2O^+ in a fluorocarbon matrix shows a 43-G methyl splitting,[7a] a factor of 1.25 larger than the 34.3-G methyl splitting of Me_2NH^+ in solution. The 1.8 ratio of γ_a splittings for 2^+ to 4^+ suggests that homohyperconugation is even more sensitive to the change from nitrogen- to oxygen- centered spin density than is hyperconjugation. The more symmetrical 3^+ gives a complex ESR signal, g = 2.0084, which was successfully simulated (see Figure 1) with use of $a(2H) = 4.8_1$ G (H_{2a}/H_{4a}), $a(2H) = 0.7_1$ (H_{2e}/H_{4e}), and single hydrogen splittings of 1.6_1 (H_{8a}), 0.4_9, 0.2_5, and 0.1_5. The methyl splittings are under 0.05 G, as shown by the simulations. A very different pattern of long-range splittings was found by Russell and co-workers[8] for semidione 5: 4.00 g (H_{8a}), 1.09 (H_{8e}), 0.51 (3 H), and 0.2 (1 H). The reason for this difference is that the hydrogens on C_3 and C_8 lie in the nodal plane of the antisymmetric singly occupied molecular orbital of 3^+ (the O,O π^* orbital), while the SOMO for semidione for 5 is symmetrical.

Cyclic voltammetry experiments showed that 2^+ decomposes noticeably during a 200 mV/s scan, although its reduction wave was large enough to be observed, so $E^{\circ\prime}$ could be measured, while 3^+ showed no evidence of decomposition at all. Cyclic voltammetry data for 1-3 are summarized in Table I. Di-*tert*-butyl peroxide (1) shows only a completely irreversible oxidation wave at room temperature (E_{+}^{ox} = 2.27 at 200 mV/s scan rate). The lifetime of 1^+ at -78 °C is long enough to allow observation of both oxidation and reduction waves, but their large separation (caused by slow heterogeneous electron transfer) precludes accurate determination of $E^{\circ\prime}$, although the data in Table I suggest it must be close to that of 3.

It is unusual that compounds as hard to oxidize as 2 and 3 give long-lived cation radicals. Parker[10] was unable to see radical cation reduction waves for fused-ring aromatic hydrocarbons with IP_v values over 7.5 eV. Long-lived radical cations can be observed under very Lewis acidic conditions. For example, Bock and Kaim[11] see long-lived radical cations for silicon-substituted compounds with IP_v up to 8.0 eV in their $AlCl_3/CH_2Cl_2$ experiments, but we observed only irreversible oxidation by CV for their more difficultly oxidized compounds.[12] We presume that $AlCl_3$ complexation of the neutral compound removes the base decomposing the cation radical under cyclic voltammetry conditions. Thermodynamic measurement of the ease of electron loss cannot be made under such conditions, however, because the neutral and cationic forms must be equilibrated to measure $E^{\circ\prime}$. The long lifetimes for 2^+ and 3^+ require an unusual decrease in the rate of their decomposition reactions compared to other radical cations that are thermodynamically as difficult to form. Bis(tertiary) peroxide cations lack $C_\alpha H$ bonds to break, what is usually the fastest mode of heteroatom-centered cation decomposition, and addition of the cation to the neutral material is unfavorable on both electronic and steric grounds. A plausible reason for the increase in lifetime of 2^+ and 3^+ over 1^+ is that the latter decomposes by CO bond stretching, which is inhibited by the bicyclic systems.

Comparison of $E^{\circ\prime}$ and IP_v values for hydrocarbons, peroxides, and hydrazines demonstrates a significant point. Fused-ring aromatic hydrocarbons give a linear $E^{\circ\prime 9}$ vs. $IP_v{}^{13}$ relationship. Solvation effects appear in $E^{\circ\prime}$ and not in IP_v, so compounds with different solvent stabilization would fall off the line. Under the conditions of Table I, anthracene, pyrene, and perylene are 0.11 ± 0.03 V higher in $E^{\circ\prime}$ than under Parker's conditions ($E^{\circ\prime}$ is sensitive to supporting electrolyte and solvent, so comparisons need to be made under the same conditions). $E^{\circ\prime}$ for 2 is 0.26 V less than the predicted $E^{\circ\prime}$ for a fused-ring aromatic

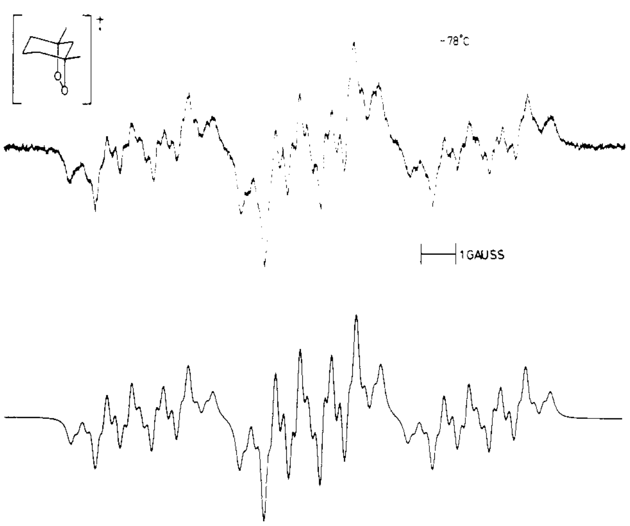

Figure 1. Experimental and simulated (below) ESR spectrum of 3^+. The simulation used the splittings reported in the text, with a methyl splitting of 0.04 G and a Lorenzian line width of 0.12 G.

Table I. Electrochemical Results for Dialkyl Peroxide Oxidation[a]

	room temp		-78 °C		
compd	$E^{\circ\prime}$, V	ΔEp, V	$E^{\circ\prime}$, V	ΔEp, V	IP_v, eV[b]
1	irrev		2.3	0.43	8.83
2	2.18	0.10	2.14	0.16	8.50
3	2.29	0.09	2.3	0.40	

[a] At a Pt disc electrode in 20:1:1 $CH_2Cl_2:CF_3CO_2H:(CF_3CO)_2O$, 0.1 M in tetrabutylammonium tetrafluoroborate, 200 mV/s scan rate, vs. SCE. [b] From ref 9.

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(9) (a) Brown, R. S. *Can. J. Chem.* **1975**, *53*, 3439. (b) Rademacher, P.; Ellig, W. *Ann. Chim.* **1979**, 1473. Although this paper estimates 35° twist in the bicyclic ring of 2, we do not accept such a large twist. It is based on assuming no interaction between the O–O π system and the C=C π system in ascaridole, and interaction is expected (see ref 15).

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hydrocarbon with the same $\mathrm{IP_v}$. Monoolefin **6** shows $E^{\circ\prime} = 1.62$ V under the conditions of Table I and has an $\mathrm{IP_v}$ value of 7.84 eV.[14] Its $E^{\circ\prime}$ is 0.28 V lower than the predicted $E^{\circ\prime}$ from the aromatic hydrocarbon $\mathrm{IP_v}$ vs. $E^{\circ\prime}$ line. $E^{\circ\prime}$ is surprisingly insensitive to the bulk of alkyl groups near the formal charge-bearing atoms. Large structural changes, even in the atoms bearing the formal charge, have a very small effect on solvent stabilization differences for these two species with two-atom π systems and bulky alkyl groups. Although **2** and **6** show nearly identical oxidation behavior in an $\mathrm{IP_v}$ vs. $E^{\circ\prime}$ plot, they differ greatly from tetraalkylhydrazines, which also give two-atom π system cations. For example, tetramethylhydrazine has an $E^{\circ\prime}$ value 1.82 V below the line[15] and **4**, 1.41 V below the line.[16] As previously discussed in detail,[17] there is a large relaxation energy difference between the vertical and adiabatic cations from a hydrazine, caused by rehybridization from approximately sp^3 lone pairs in the neutral form to nearly pure p lone pairs in the adiabatic cation. A similar rehybridization obviously does not occur upon oxidation of peroxides. The electron being lost from a peroxide is from the antibonding combination of the pure p lone pairs. The two lone pairs on a divalent oxygen need to be considered as a pure p pair and a much more stabilized s rich pair,[18] and not (as organic chemists usually do currently[19]) as two sp^3 lone pairs.[20]

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(14) Mollère, P. D.; Houk, K. N.; Bomse, D. S.; Morton, T. H. *J. Am. Chem. Soc.* **1976**, *98*, 4732.

(15) $E^{\circ\prime}$ is 0.33 V, $\mathrm{IP_v}$ is 8.27 eV; Nelsen, S. F.; Kessel, C. R.; Brien, D. J. *J. Am. Chem. Soc.* **1980**, *102*, 702.

(16) $E^{\circ\prime}$ is 0.07 V, $\mathrm{IP_v}$ is 7.46 eV; Nelsen, S. F.; Hollinsed, W. C.; Grezzo, L. A.; Parmelee, W. P. *J. Am. Chem. Soc.* **1979**, *101*, 7347.

(17) (a) Nelsen, S. F. *Isr. J. Chem.* **1979**, *18*, 45. (b) Nelsen, S. F. *Acc. Chem. Res.* **1981**, *14*, 131.

(18) (a) Jorgenston, W. L.; Salem, L. "The Organic Chemist's Book of Orbitals"; Academic Press: New York, 1973; p 42. (b) Photoelectron spectroscopists have always done so, because $\mathrm{IP_v}$ for divalent oxygen clearly has a p orbital band shape (see ref 8).

(19) (a) Deslongchamps, P. "Stereoelectronic Effects in Organic Chemistry"; Pergamon Press: New York, 1983. (b) Kirby, A. J. "The Anomeric Effect and Related Stereoelectronic Effects at Oxygen"; Springer-Verlag: Berlin, 1983.

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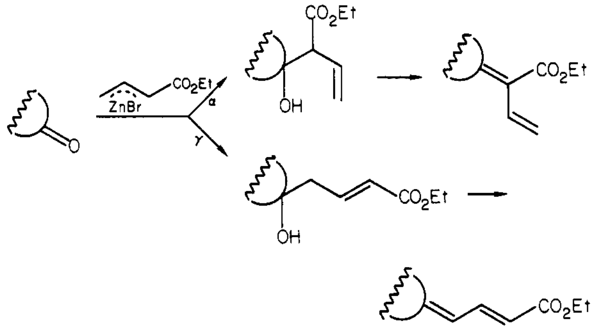
Regioselectivity in the Reformatsky Reaction of 4-Bromocrotonate. Role of the Catalyst and the Solvent in the Normal vs. Abnormal Modes of Addition to Carbonyl Substrates†

Summary: The regioselectivity of addition of the organozinc reagent derived from ethyl 4-bromocrotonate to 10 carbonyl substrates was found to be dependent on the polarity of solvents and the hardness of metal catalysts.

Sir: The Reformatsky reaction constitutes a mild and versatile method for the formation of carbon–carbon bonds.[1] Although most of the literature reports deal with the additions of α-bromoacetates to carbonyl compounds as means of a two-carbon homologation, several extensions of this reaction involving the halocarbonyl compounds as well as the electrophilic substrates are known.[1,2] Of these variations the reactions of unsaturated halo esters with carbonyl substrates particularly appealed to us since they provided a potential means of preparation of functionalized dienes required in our synthetic design of cyclopentanoid sesquiterpenes (eq 1).[3,4] The four-carbon homologation depicted in eq 1 is subject to expected regiochemical problems arising from the behavior of the delocalized reagents of this type.



(1)

In fact, only two reports described any attempts at regioselection, and both of these reports described experiments of limited scope.[5,6] Thus if a reliable method of regiodistinction for the additions of a crotonate unit to carbonyls existed, it would augment the compendium of synthetic methods dealing with reactions of delocalized species with electrophiles[7] where the problem of regiochemistry has not been adequately solved for various nucleophilic species derived from crotonate.

Further careful inspection of literature data also revealed that the normal or γ-mode of addition predominated in modest yields in all of the relatively few cases studied.[1] We suspected that these low yields reflected the outcome of the product isolation rather than the true profiles of the reactions since we have shown that the adducts of ethyl 4-bromocrotonate with various cyclopentanones were unstable under the conditions of their purification (distillation, chromatography, acid or base treatment).[3,4,8] In most instances, however, such purification is unnecessary since the free hydroxyls are usually immediately acetylated

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(1) Reviews: (a) Rathke, M. W. *Org. React* **1975**, *22*, 423. (b) Gaudemar, M. *Organomet. Chem. Rev. A* **1972**, 8, 183.

(2) Variations of the Reformatsky reaction not included in the reviews above: (a) Orsini, F.; Pelizzoni, F. *Synth. Commun.* **1983**, *13*, 523 (alkylation with halides). (b) Stamm, H.; Steudle, H. *Tetrahedron* **1979**, *35*, 647 (additions to nitrones). (c) Kryczka, B.; Laurent, A.; Marquet, B. *Tetrahedron* **1978**, *34*, 3291 (additions to azirines). (d) Furukawa, M.; Okawara, T.; Noguchi, Y.; Terawaki, Y. *Chem. Pharm. Bull. Jpn.* **1978**, *26*, 260. Bellassoued, M.; Arous-Chtara, R.; Gaudemar, M. *J. Organomet. Chem.* **1982**, *231*, 185 (additions to imines). (e) Fauvarque, J. F.; Jutand, A. *Ibid.* **1977**, *132*, C17; **1979**, *177*, 273 (arylations); **1981**, *209*, 109 (vinylations). (f) Lucas, M.; Guette, J. P. *Tetrahedron* **1978**, *34*, 1685 (assymetric induction. (g) Mladenova, M.; Blagoev, B.; Kurtev, B. *Bull. Soc. Chim. Fr.* **1979**, II-78 (use of α-bromo amides).

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(6) Bellasoued, M.; Dardoize, F.; Frangin, Y.; Gaudemar, M. *J. Organomet. Chem.* **1981**, *219*, C1.

(7) For studies on the regioselection of crotonate-type nucleophiles, see for example: (a) Pffefer, P. E.; Silbert, L. S.; Kinsel, E. *Tetrahedron Lett.* **1973**, 1163. (b) Yoshimoto, M.; Ishida, N.; Hiraoka, T. *Ibid.* **1973**, 39. (c) Ahlbrecht, H.; Vonderheit, C. *Synthesis* **1975**, 512, (d) Evans, D. A.; Andrews, G. C.; Buckwalter, B. *J. Am. Chem. Soc.* **1974**, *86*, 5560.

(8) Hudlicky, T.; Koszyk, F. J., unpublished observations.

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