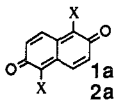
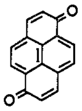
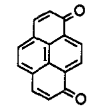
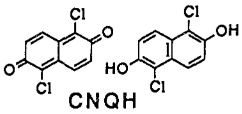
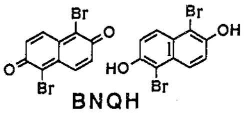
pyrenoquinones (**3a** and **4a**),[16] and their corresponding hydroquinones (**1b**–**4b**).[17] Grinding[18] a solid quinone and hydroquinone


1a: X=Cl
2a: X=Br


3a


4a


CNQH


BNQH

gave powders of the corresponding quinhydrone.[19] The CT transition energies (eV) measured for the compressed pellets of powders dispersed into KBr are 1.70, 1.58, 1.43, and 1.42 eV for **1a**–**1b**, **2a**–**2b**, **3a**–**3b**, and **4a**–**4b**, respectively. Apparently, smaller energies of the CT gaps are observed for these extended conjugated quinhydrones compared with that of BQH (2.34 eV).

Single crystals of **1a**–**1b** (CNQH) and **2a**–**2b** (BNQH) were successfully grown by a diffusion method in benzene as black lustrous plates. Their crystal structure analysis showed the alternately stacked quinone and hydroquinone components and the existence of two-dimensional H-bonded CT networks (Figure 2).[20] These are the first examples of the *extended conjugated quinhydrones* whose characteristic features are similar to those of BQH.[24] Similarly, the four extended conjugated quinhydrones have shown pressure-response spectral characteristics.[25] Thus, Figure 3a presents this type of behavior for the O–H stretching region of CNQH as a typical example. New bands appearing around 2500 cm^{-1} at higher pressure can be attributed to the contribution of a PET state. In addition, electronic absorption spectra in the CT transition energy regions showed decreasing energies with increasing pressure. Figure 3b presents such a behavior for CNQH, together with that of BQH.

In conclusion, the extended conjugated quinhydrones confirm our molecular design strategy for stabilization of the cooperative PET systems formed by H-bonded neutral radicals. A closer insight into the concept and design strategy might lead to a new aspect of molecular assemblies with unique solid-state properties originated in the PET radicals.

Acknowledgment. This work was supported in part by a Grant-in-Aid for Scientific Research on Priority Areas (No. 01648003) from the Ministry of Education, Science and Culture, Japan.

Supplementary Material Available: Tables 1–11 of crystal data, final atomic coordinates, equivalent isotropic thermal parameters, intramolecular distances and angles, and final thermal parameters of non-H atoms for the crystal structures of CNQH, BNQH, and **1b** and experimental details of the crystal growth of CNQH and BNQH (10 pages). Ordering information is given on any current masthead page.

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[14] **2a** was prepared by a similar procedure to that used for preparation of **1a**.

[15] The reduction potentials (V vs SCE) of the quinones: **1a**, –0.09; **2a**, –0.09, in Et_4NClO_4/dimethylformamide. **3a**, –0.44, –0.79; **4a**, –0.44, –0.80, in *n*-Bu_4NClO_4/benzonitrile.

[16] Fatiadi, A. J. *J. Chromatogr.* **1965**, *20*, 319–324.

[17] **1b**: ref 10. **2b**: Paul, von H.; Zimmer, G. *J. Prakt. Chem.* **1962**, *4*, 219–224. **3b** and **4b**: Tintel, C.; Terheijden, J.; Lugtenburg, J.; Cornelisse, J. *Tetrahedron Lett.* **1987**, *28*, 2057–2060.

[18] Patil, A. O.; Curtin, D. Y.; Paul, I. C. *J. Am. Chem. Soc.* **1984**, *106*, 348–353. Rastogi, R. P.; Singh, N. B. *J. Phys. Chem.* **1966**, *70*, 177–180.

[19] The four new quinhydrones gave satisfactory elemental analyses as having 1:1 stoichiometry.

[20] Crystal data were collected on a Rigaku AFC-5R diffractometer with graphite-monochromated Cu Kα radiation. The structures were solved by the Monte Carlo direct method[21] with the aid of the MULTAN-78 program system[22] and refined on F^2 by a full-matrix least-squares technique with analytical absorption correction.[23] Two independent molecules which lie on an inversion center were found in each crystal. H atoms on carbons were allocated from a differential Fourier map and were refined with isotropic temperature factors equivalent to the bonded carbon atoms. H atoms of oxygens were not found. The quinone and the hydroquinone components can unambiguously be distinguished by comparing the bond lengths. Crystal data are as follows: **1a**–**1b**, $C_{20}H_{10}Cl_4O_4$, triclinic, $P1$, $Z = 1$, $a = 7.487$ (7) Å, $b = 8.121$ (7) Å, $c = 7.763$ (4) Å, $\alpha = 80.93$ (6)°, $\beta = 102.59$ (7)°, $\gamma = 110.59$ (7)°, $V = 429.4$ (7) Å^3, $D_{measd} = 1.75$, $D_{calcd} = 1.77$, $R = 0.063$, $R_w = 0.062$; **2a**–**2b**, $C_{20}H_{10}Br_4O_4$, triclinic, $P1$, $Z = 1$, $a = 7.703$ (2) Å, $b = 8.041$ (1) Å, $c = 7.926$ (2) Å, $\alpha = 81.12$ (2)°, $\beta = 99.16$ (2)°, $\gamma = 108.61$ (1)°, $V = 455.9$ (2) Å^3, $D_{measd} = 2.37$, $D_{calcd} = 2.31$, $R = 0.048$, $R_w = 0.053$. The interplanar distances between the donor and the acceptor are 3.32 and 3.36 Å, and the hydrogen-bonded O···O distances are 2.712 (7) and 2.727 (7) Å, for CNQH and BNQH, respectively.

[21] Furusaki, A. *Acta Crystallogr.* **1979**, *A35*, 220–224.

[22] Main, P.; Hull, S. E.; Lessinger, L.; Germain, G.; Declercq, J. P.; Woolfson, M. M. *MULTAN78*; Universities of York and Louvain: York, England, and Louvain, Belgium, 1978.

[23] Katayama, C.; Sakabe, N.; Sakabe, K. *Acta Crystallogr.* **1972**, *A28*, S207.

[24] Sakurai, T. *Acta Crystallogr.* **1965**, *19*, 320–330. Sakurai, T. *Acta Crystallogr.* **1968**, *B24*, 403–412.

[25] The optical characterizations of the PET systems under high pressures will be published elsewhere. The EPR study which gives a more direct proof of the presence of the neutral radical state is under investigation.

Racemization and Geometrical Isomerization of (2*S*,3*S*)-Cyclopropane-*1*-^{13}*C*-*1*,*2*,*3*-d_3 at 407 °C: Kinetically Competitive One-Center and Two-Center Thermal Epimerizations in an Isotopically Substituted Cyclopropane

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Teresa B. Freedman,*[,†] Laurence A. Nafie,*[,†]
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Shortly after the thermal interconversion of the cis and trans isomers of 1,2-dideuteriocyclopropane was discovered in 1958,[1] Setser and Rabinovitch[2] recognized that if one could only determine rate constants k_i and k_{ij} corresponding to one-center and two-center epimerization processes for substituted cyclopropanes, one would have some basis for discriminating among alternative mechanistic models. For a number of substituted cyclopropanes, this desideratum has been achieved,[3] but for cyclopropanes substituted only with isotopic labels—systems most relevant to theoretical work on these stereomutations and trimethylene diradical transition structures—it has remained an unmet challenge. We now report that by preparing the chiral isomers of cyclopropane-*1*-^{13}*C*-*1*,*2*,*3*-d_3 and following the thermal stereomutations summarized in Scheme I, a determination of the relative importance of these two types of stereomutation processes in the parent hydrocarbon has finally been secured.

These isotopically labeled cyclopropanes are ideally suited for the problem at hand, since each carbon–carbon bond is CHD–CHD and thus, neglecting possible very small ^{13}C kinetic isotope effects, only two epimerization rate constants must be found: k_1 and k_{12}. Here k_1 represents the rate constant for one-center epimerization at a single carbon atom when one adjacent C–C bond breaks. There are two experimentally accessible kinetic parameters, $k_i = (8k_1 + 4k_{12})$, for the rate of approach to equilibration of the geometrical isomers, and $k_\alpha = (4k_1 + 4k_{12})$, for the rate of loss of optical activity.

Syntheses of both chiral forms of the quadruply labeled cyclopropane depended on the reaction of methyl propenoate-*3*-^{13}*C*-*2*,*3*-d_2 with methyl chloroacetate-*2*,*2*-d_2 in DMSO-d_6 promoted

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[1] Rabinovitch, B. S.; Schlag, E. W.; Wiberg, K. B. *J. Chem. Phys.* **1958**, *28*, 504–505.

[2] Setser, D. W.; Rabinovitch, B. S. *J. Am. Chem. Soc.* **1964**, *86*, 564–574.

[3] Baldwin, J. E. *J. Chem. Soc., Chem. Commun.* **1988**, 31–32 and references therein.

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Scheme I

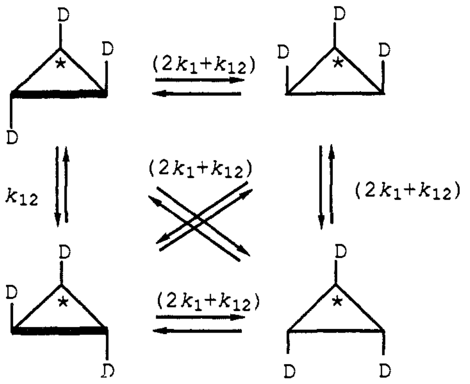

Table I. Loss of Optical Activity for (2*S*,3*S*)-Cyclopropane-*1*-^{13}*C*-*1,2,3*-d_3 at 407.0 °C Determined by VCD Spectroscopy

time, min	pressure (Torr) sample	pressure (Torr) ref^a	$\lvert\Delta A/\Delta A_{\text{ref}}\rvert$	α_{rel} exptl^b	α_{rel} calcd^c
180	56.30	43.98	0.9065	0.7081	0.7140
360	81.30	53.59	0.7836	0.5165	0.5120
600	75.50	43.35	0.5918	0.3398	0.3278
960	85.40	44.72	0.2919	0.1529	0.1679

^{a}The reference sample was the 2*S*,3*S* isomer. ^{b}Calculated from the equation α_{rel} = (ref(Torr)/sample(Torr)) × $\lvert\Delta A/\Delta A_{\text{ref}}\rvert$. ^{c}Calculated from the nonlinear least-squares derived equation α_{rel} = 0.999 exp(−(3.10 × 10^{-5} s^{-1})*t*).

by NaH to give dimethyl cyclopropane-*trans*-1,2-dicarboxylate-*3*-^{13}*C*-*1,2,3*-d_3,[4] followed by the same steps for resolution, functional-group modifications, and gas chromatographic purification that proved effective in earlier preparations of the chiral cyclopropanes-*1,2*-d_2.[5] These cyclopropanes, derived from completely separated diastereomeric precursors, are believed to be optically pure; the incorporation of isotopic labels was estimated from NMR and mass spectral data to be 98% ^{13}C and at least 97% deuterium at each carbon. Racemic quadruply labeled material having trans 2,3-d_2 was prepared as well.

The chiral isomers, the first having optical activity dependent on a ^{13}C label to be examined by vibrational circular dichroism (VCD) spectroscopy,[6] exhibited pronounced CD features in the C–H stretching region. The experimental spectra, showing complementary CD characteristics for the two enantiomers in qualitative agreement with theoretical predictions,[7] are reproduced in Figure 1.

Thermal equilibration of geometrical isomers in the gas phase with pentane as a bath gas and total pressures ranging from 680 to 690 Torr at 407.0 °C was followed by two independent methods. By FTIR spectroscopy, eight reaction mixtures were analyzed in two spectral regions, 2170–2150 and 2290–2260 cm^{-1}, each having distinct absorption features ascribable to the chiral isomers and to one of the achiral forms. For the first-order approach to geometrical equilibrium, rate constant k_i was found to be (4.59 ± 0.09) × 10^{-5} s^{-1}. Through tunable diode laser (TDL) spectroscopic analyses[8] of starting material and four kinetic reaction mixtures, following absorption features near 2265 cm^{-1}, k_i was found to be (4.63 ± 0.20) × 10^{-5} s^{-1}, a gratifying corroboration of the FTIR result.

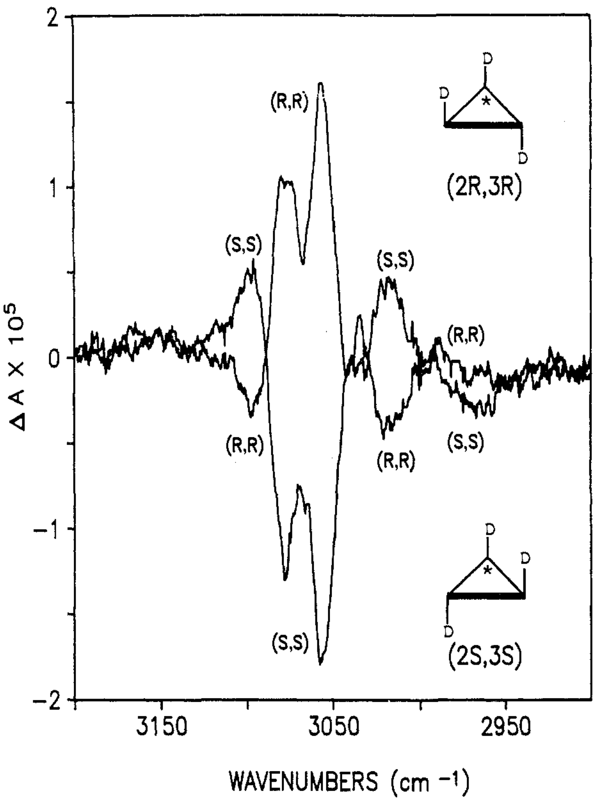

Figure 1. Gas-phase vibrational circular dichroism spectra for both chiral forms of cyclopropane-*1*-^{13}*C*-*1,2,3*-d_3 in the C-H stretching region. For each, the observed spectrum was measured by using 5-mg samples in a 5 cm path length cell at 83.6 Torr and referenced to a spectrum for racemic cyclopropane-*1*-^{13}*C*-*1*-*d*-*2,3*-*trans*-d_2.

The loss of optical activity in reaction mixtures derived from (2*S*,3*S*)-cyclopropane-*1*-^{13}*C*-*1,2,3*-d_3 as a function of time was followed by VCD;[9] the VCD spectra, base-line corrected[9] with spectra measured for equal-time reaction mixtures from racemic starting material, compared with spectra for the optically pure 2*S*,3*S* isomer, gave the data summarized in Table I; a nonlinear least-squares analysis provided the rate constant k_α = (3.10 ± 0.07) × 10^{-5} s^{-1}.

From the experimental values for k_i = (8k_1 + 4k_{12}) and k_α = (4k_1 + 4k_{12}) may be derived the rate constants k_1 = (0.38 ± 0.02) × 10^{-5} s^{-1} and k_{12} = (0.40 ± 0.03) × 10^{-5} s^{-1}. They are not significantly different; each makes a comparably important contribution to stereomutations in this quadruply labeled cyclopropane, which behaves thermally very much like functional-group-substituted cyclopropanes.[3] The kinetic evidence indicates that the double rotation mechanism does *not* predominate by a substantial factor, and there is thus no reason to interpret stereomutations in isotopically substituted cyclopropanes as orbital-symmetry-controlled two-center conrotatory epimerizations.

Work on thermal equilibrations among the three isomers of cyclopropane-*1,2*-d_2 reported by Berson and Pedersen in 1975 led them to conclude that the double methylene rotation mechanism operates to the virtual exclusion of any other pathway.[10] These authors were acutely aware of uncertainties about the kinetic

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(4) Cianciosi, S. J.; Baldwin, J. E., manuscript in preparation.

(5) Cianciosi, S. J.; Spencer, K. M.; Freedman, T. B.; Nafie, L. A.; Baldwin, J. E. *J. Am. Chem. Soc.* **1989**, *111*, 1913–1315.

(6) Freedman, T. B.; Nafie, L. A. In *Topics in Stereochemistry*; Eliel, E. L., Wilen, S. H., Eds.; Wiley: New York, 1987; Vol. 17, pp 113–205.

(7) Freedman, T. B.; Cianciosi, S. J.; Ragunathan, N.; Baldwin, J. E.; Nafie, L. A. *J. Am. Chem. Soc.* Submitted for publication.

(8) Glenar, D. A.; Hill, A. *Rev. Sci. Instrum.* **1986**, *57*, 2493–2498. Glenar, D. A.; Lewis, D. K. *Appl. Spectrosc.* **1989**, *43*, 283–288. Baldwin, J. E.; Cianciosi, S. J.; Glenar, D. A.; Hoffman, G. J.; Wu, I.-W.; Lewis, D. K. Presented at the 199th National Meeting of the American Chemical Society, Boston, MA, April 24, 1990; paper PHYS 99. Since 1989 a 2250–2300-cm^{-1} laser diode, a monochromator grating blazed for 4.4 μm, and an EG&G/PARC 4203 signal averager have been added to the system, and other mechanical and electronic improvements have decreased system noise and drift.

(9) Spencer, K. M.; Cianciosi, S. J.; Baldwin, J. E.; Freedman, T. B.; Nafie, L. A. *Appl. Spectrosc.* **1990**, *44*, 235–238.

(10) Berson, J. A.; Pedersen, L. D. *J. Am. Chem. Soc.* **1975**, *97*, 238–240. Berson, J. A.; Pedersen, L. D.; Carpenter, B. K. *J. Am. Chem. Soc.* **1976**, *98*, 122–143. Berson, J. A. *Annu. Rev. Phys. Chem.* **1977**, *28*, 111–132. Berson, J. A. In *Rearrangements in Ground and Excited States*; de Mayo, P., Ed.; Academic Press: New York, 1980; Vol. I, pp 311–390. Carpenter, B. K. *Determination of Organic Reaction Mechanisms*; Wiley: New York, 1984; pp 62–67.

(11) Hoffmann, R. *J. Am. Chem. Soc.* **1968**, *90*, 1475–1485.

isotope effects that might be of importance, and of limitations associated with experimental uncertainties in the two rate constants measured: from their observed k_i/k_α value, an extreme double rotation/single rotation ratio of 85/15 was derived, based on assumptions least favorable to the double rotation process, while a 98/2 ratio was deduced under more plausible assumptions.[10] Yet they harbored no doubt that the theoretically predicted[11] double rotation mechanism predominated by a substantial factor.

We believe that this conclusion was based on an extremely accurate experimental estimation of the ratio of the two accessible kinetic parameters, k_i and k_α,[12] and on some reasonable but nevertheless erroneous assumptions regarding kinetic isotope effects which were employed as this ratio was interpreted. Fresh consideration of the several distinct sorts of secondary deuterium isotope effects which might be of importance in such thermal reactions seems clearly warranted.

Acknowledgment. We thank the National Science Foundation for support of this work at Syracuse University through CHE 87-21656 (to J.E.B.), the National Institutes of Health for support through GM 23567 (to L.A.N. and T.B.F.), and the Research Corporation for support at Colgate University through a Cottrell College Science Grant and a William and Flora Hewlett Foundation Grant.

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(12) Cianciosi, S. J.; Ragunathan, N.; Freedman, T. B.; Nafie, L. A.; Baldwin, J. E. *J. Am. Chem. Soc.* **1990**, *112*, 8204-8206.

Synthetically Useful Dianions via Reductive Lithiation of Tetrahydrofurans by Aromatic Radical Anions

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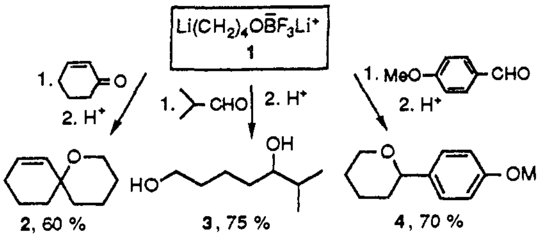
Reductive cleavages of epoxides[1] (at −78 °C) and oxetanes[2] (at 0 °C) by lithium 4,4′-di-*tert*-butylbiphenylide[3] (LDBB) provide β-lithio- and γ-lithioalkoxides, respectively. Reaction of the latter with carbonyl compounds results in pentaspiroannulation to substituted tetrahydrofurans or spiroacetals.[2,4] It would be very useful if the six-membered analogues of these heterocycles would be available from δ-lithioalkoxides generated by reductive lithiation of tetrahydrofurans (THFs). However, THFs cleave only at temperatures at which the resulting dianions do not survive.[5]

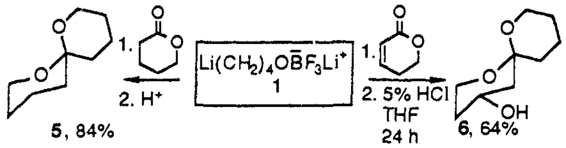
Reductive lithiations of epoxides and oxetanes are thought to involve transfer of an electron to an antibonding orbital (LUMO) of the heterocycle followed by ring cleavage to an intermediate possessing an oxyanion and a carbon radical.[6] We now report two methods which greatly facilitate the reductive lithiation of THFs by stabilizing both the LUMO and the open-chain intermediate.

The first method involves complexation of the oxygen atom of THF by a Lewis acid. By inducing a formal positive charge on the oxygen atom, the acid should lower the energy of the σ^* orbital that accepts the electron. It should also stabilize the resulting open-chain oxyanion (e.g., the radical precursor of **1**). Gratifyingly, THF is found to be instantaneously cleaved by LDBB (2 equiv) in the presence of boron trifluoride etherate (1 equiv) at −80 °C, yielding 4-lithiobutoxide probably best represented by **1** (eq 1).[7]

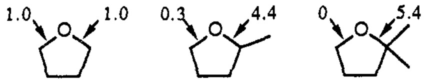
Scheme I

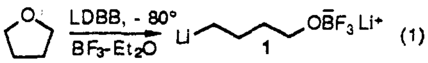


Scheme II



Scheme III



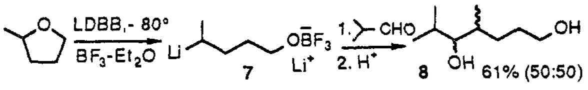
 (1)

The experimental procedure requires dropwise addition of $BF_3{\cdot}Et_2O$ (neat) to the preformed 0.4 M solution of LDBB in THF at −80 °C. The reaction is strongly exothermic, and its completion can easily be recognized by the color change of the solution from dark greenish-blue to dark red. We have found that the stability of **1** is limited even under such mild conditions, presumably because of transfer of the BF_3 from oxygen to carbon.[9]

Some reactions of **1** with aldehydes and ketones are shown in Scheme I. Those coupling products (1,5-diols) which are able to form stabilized carbocations can be easily cyclized to useful tetrahydropyrans, as demonstrated for 2-cyclohexen-1-one and 4-methoxybenzaldehyde.[10]

δ-Lithiobutoxides are particularly useful synthons in the preparation of [5.*n*] spiroketal units, compounds of great biological interest.[4] Scheme II presents simple and efficient one-pot syntheses of the major and minor components (**5** and **6**) of the olive fruit fly pheromone. Our preparation of **6**, considering its simplicity and the ready availability of the starting materials, compares very favorably to alternative methods.[11] The successful monoaddition of **1** to lactones also indicates that the Lewis acid may help to prevent the opening of the initially formed lactolate ring acting in a manner similar to that of an oxophilic organocerium species.[4]

Whereas substituted epoxides and oxetanes in uncatalyzed reductive lithiations cleave predominantly so as to produce the most branched alcohol,[1,2,6] the opposite regioselectivity is found in the BF_3-induced reductive opening of 2-substituted THFs. 2-Methyltetrahydrofuran, also used as solvent, yields predominantly the most substituted carbanion **7** (eq 2). Scheme III



(2)

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(1) Bartmann, E. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 653. Cohen, T.; Jeong, I.; Mudryk, B.; Bhupathy, M.; Awad, M. A. *J. Org. Chem.* **1990**, *55*, 1528.

(2) Mudryk, B.; Cohen, T. *J. Org. Chem.* **1989**, *54*, 5657.

(3) Freeman, P. K.; Hutchinson, L. L. *J. Org. Chem.* **1980**, *45*, 1924.

(4) Mudryk, B.; Shook, C. A.; Cohen, T. *J. Am. Chem. Soc.* **1990**, *112*, 6389.

(5) Eisch, J. J. *J. Org. Chem.* **1963**, *28*, 707.

(6) Dorigo, A. E.; Houk, K. N.; Cohen, T. *J. Am. Chem. Soc.* **1989**, *111* 8976.

(7) Certain special 4-lithiobutoxides can be produced by reductive lithiation of 4-(phenylthio)- or 4-chloroalkoxides.[4,8]

(8) Barluenga, J.; Fernandez, J. R.; Florez, J. *Synthesis* **1983**, 736.

(9) Eis, M. J.; Wrobel, J. E.; Ganem, B. *J. Am. Chem. Soc.* **1984**, *106*, 3693.

(10) Products were chromatographically pure and characterized by ^{1}H NMR and HRMS.

(11) Baker, R.; Herbert, R. H. *J. Chem. Soc., Perkin Trans. 1* **1987**, 1123 and citations therein. Greck, C.; Grice, P.; Ley, S. V.; Wonnacott, A. *Tetrahedron Lett.* **1986**, *27*, 5277. Smith, A. B., III; Thompson, A. S. *J. Org. Chem.* **1984**, *49*, 1469.

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