Electron Transfer from Organolithium and Grignard Reagents.   Reactions with Peroxides

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Abstract: The facile reaction of alkyllithium and Grignard reagents with peroxides provides an important basis for delineating one-electron transfer process in organometallic compounds.   Thus, the rapid reaction of ethyllithium and di-*tert*-butyl peroxide affords ethyl *tert*-butyl ether and lithium *tert*-butoxide, accompanied by *n*-butane, ethylene, and ethane.   A thorough material balance is achieved through an accounting of all the *tert*-butyl and ethyl fragments among these products.   The product distribution can be quantitatively related to the known values for the relative rates of the combination and disproportionation reactions of *tert*-butoxy and ethyl radical, which are postulated to arise *via* a single mechanistic pathway involving a rate-limiting charge transfer between the peroxide and the alkyllithium species.   Comparison of the rates and products show that organolithium and Grignard reagents react by similar mechanisms, in which the reactivity of the organometal is related to the electrochemical oxidative decomposition potential of the alkyl group.   Since product formation proceeds from an alkoxy–alkyl radical pair, the cage reaction and diffusion of radicals are carefully described by trapping experiments, viscosity effects, β scission of alkoxy radicals, and the observation of CIDNP.

A nions and particularly carbanions are electron-rich species and thus susceptible to oxidation by various electron acceptors such as molecular oxygen, nitro and halogen compounds, as well as free radicals and inorganic oxidants.[1-3]   The substitution-labile alkyllithium and magnesium compounds can be considered as carbanionoids; and indeed the facile autoxidation of Grignard reagents as well as the reaction of alkyllithium with alkyl halides are two recent and relevant examples of electron-transfer processes.[1,4,5]

Electron-transfer reactions of organometals are important and merit clear delineation for several reasons. First, there are indications of free-radical intermediates in the widely employed condensation reactions of Grignard and organolithium reagents with other substrates such as carbonyl compounds which are known to be electron acceptors (*i.e.*, ketyl formation).[6]   Second, in substitution processes the classical distinction which is commonly invoked between ionic mechanisms, *e.g.*, SN2 and free-radical coupling (SH2) is obscured by charge-transfer contributions.[7,8]   Third, the interconversion of anions and radicals can provide an efficient chain process for a variety of substitution reactions.[9-11]
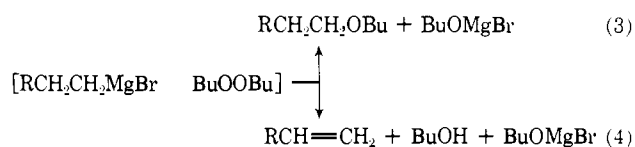
Various organometallic reagents, particularly those of magnesium and lithium react with organic peroxides to produce ethers as represented in eq 1.[12]   The use of

$$R-m + XO-OR' \longrightarrow R-OR' + m-OX \qquad (1)$$
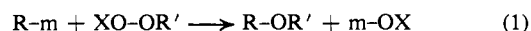
tert-butyl peresters, for example, constitutes a convenient method for the synthesis of *tert*-butyl ethers.[13]   These substitution reactions occurring on a peroxidic oxygen atom are of intrinsic mechanistic interest, since they provide a unique opportunity to examine one-electron processes in organometallic compounds in a quantitative manner.   Earlier, it had been proposed that alkyllithium reacts quantitatively according to eq 2

$$RLi + (CH_3)_3CO-OC(CH_3)_3 \longrightarrow$$
$$R-OC(CH_3)_3 + LiOC(CH_3)_3 \quad (2)$$
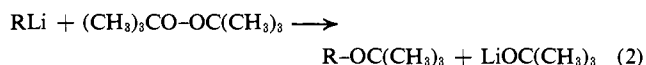
by an SN2 process.[14,15]   An analogous reaction of di-*tert*-butyl peroxide with Grignard reagents was first studied by Gilman.[16]   Campbell, *et al.*, subsequently reported that the Grignard moiety also produced alkene and alkyl dimer in addition to ether.[17]   They assumed that a molecular complex was an intermediate which decomposed by two concomitant heterolytic processes, *e.g.*

$$[RCH_2CH_2MgBr \quad BuOOBu] \begin{array}{c} \nearrow RCH_2CH_2OBu + BuOMgBr \qquad (3) \\ \\ \searrow RCH=CH_2 + BuOH + BuOMgBr \quad (4) \end{array}$$

(1) G. A. Russell, A. G. Bemis, E. J. Geels, E. G. Janzen, and A. J. Moye, *Advan. Chem. Ser.*, **No. 51**, 112 (1965); see also G. A. Russell, *et al.*, *J. Amer. Chem. Soc.*, **86**, 1804 (1964); **88**, 5491 (1966); *Chem. Soc., Spec. Publ.*, **No. 24**, 271 (1970).
(2) R. D. Guthrie, *J. Amer. Chem. Soc.*, **91**, 6201 (1969); **92**, 7219 (1970).
(3) H. E. Zieger, I. Angres, and L. Maresca, *J. Amer. Chem. Soc.*, **95**, 8201 (1973); N. I. Delyagina, *et al.*, *J. Chem. Soc., Chem. Commun.*, 457 (1973).
(4) C. Walling and S. A. Buckler, *J. Amer. Chem. Soc.*, **77**, 6032 (1955); C. Walling and A. Cioffari, *ibid.*, **92**, 6609 (1970).
(5) H. R. Ward, R. G. Lawler, and R. A. Cooper in "Chemically Induced Magnetic Polarization," A. R. Lepley and G. L. Closs, Ed., Wiley-Interscience, New York, N. Y., 1973, Chapter 7.
(6) (a) C. G. Screttas, *J. Chem. Soc., Chem. Commun.*, 869 (1972); Abstracts, VIth International Conference on Organometallic Chemistry, Amherst, Mass., Aug 13, 1973, No. 26; (b) *cf.* also E. A. Hill, *ibid.*, Abstract No. 30; (c) T. Holm, *ibid.*, Abstract No. 32; (d) B. Miller, *J. Amer. Chem. Soc.*, **95**, 8458 (1973).
(7) S. Bank and D. A. Noyd, *J. Amer. Chem. Soc.*, **95**, 8203 (1973).
(8) G. A. Russell in "Free Radicals," Wiley-Interscience, New York, N. Y., 1973, Chapter 7.
(9) J. F. Bunnett, *Accounts Chem. Res.*, **5**, 139 (1972).
(10) J. F. Garst in ref 8, Chapter 9.
(11) G. A. Russell, *Pure Appl. Chem.*, **4**, 67 (1971); N. Kornblum, *ibid.*, **4**, 81 (1971).

(12) (a) G. A. Razuvaev, V. A. Shushunov, V. A. Dodonov, and T. G. Brilkina, in "Organic Peroxides," Vol. 3, D. Swern, Ed., Wiley-Interscience, New York, N. Y., 1972; (b) T. G. Brilkina and V. A. Shushunov, "Reactions of Organometallic Compounds with Oxygen and Peroxides," Iliffe Books Ltd., London, 1969.
(13) S. O. Lawesson and N. C. Yang, *J. Amer. Chem. Soc.*, **81**, 4230 (1959).
(14) Y. N. Baryshnikov and G. I. Vesnovskaya, *Zh. Obshch. Khim.*, **39**, 529 (1969).
(15) G. A. Baramki, H. S. Chang, and J. T. Edward, *Can. J. Chem.*, **40**, 441 (1962).
(16) H. Gilman and C. H. Adams, *J. Amer. Chem. Soc.*, **47**, 2816 (1925).
(17) T. W. Campbell, W. Burney, and T. L. Jacobs, *J. Amer. Chem. Soc.*, **72**, 2735 (1950).

Table I. Reaction of Ethyllithium and Di-*tert*-butyl Peroxide in Toluene at 25° [a]

| EtLi, mmol | DTBP, mmol | Products, mmol | | | | | Recovery[b] | |
		C_2H_6	C_2H_4	C_4H_{10}	BuOEt[c]	BuOLi[d]	EtLi	DTBP
0.73	1.88	0.28	0.08	0.04	0.28	0.71	0	1.34
1.75	0.65	0.33	0.10	0.05	0.30	0.85	0.85	0
1.57	1.78	0.58	0.19	0.09	0.56	1.56	0	0.80
3.14	1.65	0.96	0.29	0.15	0.86	2.50	0.65	0.01
3.99	5.71	1.57	0.46	0.25	1.38	3.93	0	0.18

[a] In 10 ml of solvent. [b] mmol recovered after 3 hr. [c] Ethyl *tert*-butyl ether. [d] Lithium *tert*-butoxide.
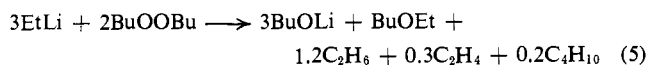
More recently, Morrison and coworkers[18] showed that the alkene, alkane, and alkyl dimers formed in the reaction with Grignard reagents are derived *via* alkyl radicals. A mechanism similar to that presented by Campbell, *et al.*, was suggested for ether formation.[17] The hydrocarbons were considered to arise by a competing *homolysis* of the intermediate complex to alkyl and *tert*-butoxy radicals followed by the well-known bimolecular reactions of alkyl radicals.

In this report we wish to assess quantitatively the origin of ether, alkane, alkene, and alkyl dimers from the rapid thermal reaction between alkyllithium and Grignard reagents with alkyl peroxides. Free-radical intermediates are probed by the use of trapping experiments, viscosity studies, β scission of *tert*-alkoxy radicals, and the observation of CIDNP. We wish to show that all of these results can be accommodated by a single mechanism involving a facile electron-transfer process between the organometal and the alkyl peroxide, followed by reactions of alkyl and alkoxy radicals within the solvent cage and after diffusion.

Results

Stoichiometry. Ethyl *tert*-butyl ether is formed as a major product together with lithium *tert*-butoxide in the reaction between ethyllithium and di-*tert*-butyl peroxide (DTBP). However, a complete accounting of the material balance shows that ethane, ethylene, and *n*-butane are also produced in significant amounts. The stoichiometric yields of these products were examined in toluene solutions at various concentrations of the reactants listed in Table I.

In a typical procedure, a solution of ethyllithium in toluene was treated with di-*tert*-butyl peroxide for 3 hr at 25° under the exclusion of air. The hydrocarbon products were analyzed first by quantitative gas chromatography using the internal standard method after careful calibration. The mixture was then quenched with excess acetic acid and the unreacted ethyllithium determined as ethane by difference. Equation 5 summarizes the data in Table I, and it quantitatively accounts for the *tert*-butoxy groups and more than 95% of the ethyl groups; eq 5 is more or less independent of the concentration of the reactants. The reaction was also carried out in pentane, dodecane, benzene, and solutions containing diethyl ether with essentially the same results (*cf.* Table VII, Experimental Section).

Ethylmagnesium bromide also reacts readily with DTBP in ethereal solutions according to an earlier

$$3EtLi + 2BuOOBu \longrightarrow 3BuOLi + BuOEt +$$
$$1.2C_2H_6 + 0.3C_2H_4 + 0.2C_4H_{10} \quad (5)$$

study by Morrison, *et al.*[18] The product distribution shown in Table II is remarkably similar to that obtained

Table II. A Comparison of the Reactions of Ethylmagnesium Bromide and Ethyllithium with DTBP

| C_2H_5M | Products (mol/mol) | | | | |
	C_2H_6	C_2H_4	C_4H_{10}	$BuOC_2H_5$	BuOM
C_2H_5MgBr[a]	0.50	0.19	0.062	0.60	1.39
C_2H_5Li[b]	0.51	0.16	0.072	0.46	1.31

[a] In ether, from ref 18. [b] In toluene.

with ethyllithium. We infer that similar mechanistic pathways are involved in the reactions of both alkyllithium and Grignard reagents under these conditions.

Kinetic Studies. The reactions of alkyllithium and Grignard reagents with DTBP were followed by periodically extracting an aliquot of the reaction mixture and quenching it with acetic acid. Figures 1 and 2 show the kinetic dependence on the concentrations of DTBP and ethyllithium, respectively. The rate of the reaction is first order in DTBP in the presence of excess ethyllithium. Similarly, the variation in rate follows an approximately first-order dependence on ethyllithium in the first 10% of reaction. Ethyllithium is most likely a hexamer; however, ambiguity as to the degree of aggregation under reaction conditions limits the necessity for further detailed kinetic studies at this point.[19]

The effects of varying the structure of the alkyl group on the rates of these reactions were examined with various Grignard reagents in order to minimize complications anticipated from the varying degree of aggregation in alkyllithiums. Furthermore, the rates of reaction of DTBP with Grignard reagents are somewhat slower, and allow a more accurate determination of the kinetics. When DTBP was treated with an excess of Grignard reagent, the reactions were found to be cleanly first order in DTBP. The rates of reactions were followed by the disappearance of DTBP and are summarized in Table III. The products formed under these conditions were determined earlier by Morrison and Epstein and are reproduced in Table VIII (Experimental Section) for convenience since they are not generally available.[18]

Effect of Solvent Viscosity. Changes in the solvent viscosity were examined in order to probe for cage effects in the apparent free radical origin of some of the reaction products. A series of *n*-alkanes was chosen so that the viscosity could be changed uniformly with minimal complications from other solvent effects. Increasing the solvent viscosity from 0.24 to 0.54, as

(18) (a) S. Herbstman, Ph.D. Thesis, New York University, 1963; (b) J. Epstein, Ph.D. Thesis, New York University, 1965.

(19) H. L. Lewis and T. L. Brown, *J. Amer. Chem. Soc.*, **92**, 4664 (1970), and earlier papers, 88, 2174, 4134 (1966); 90, 3245 (1968).
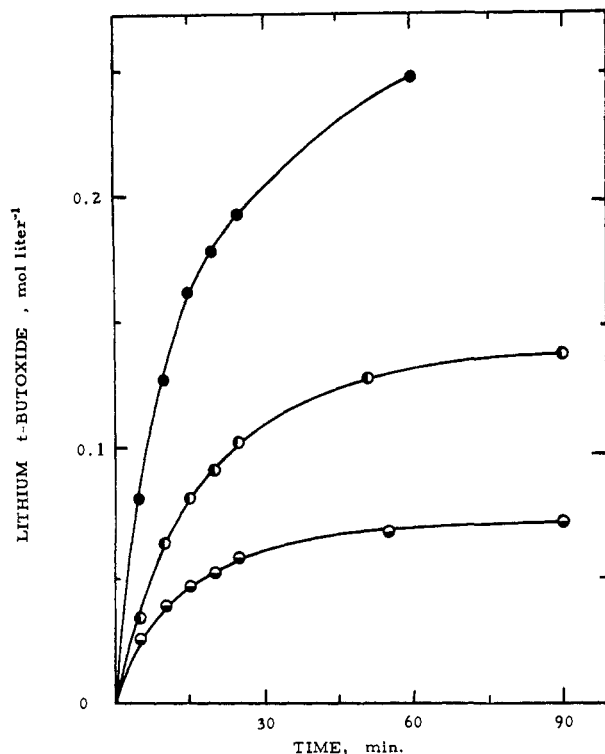
Figure 1. Reaction of 0.174 M di-*tert*-butyl peroxide in toluene: (●) 0.316 M, (◐) 0.166 M, and (◒) 0.082 M ethyllithium at 25° to form lithium *tert*-butoxide.

Table III. Relative Rates of Reaction of DTBP with Various Grignard Reagents[a]

RMgBr R	Rate constant 10^3 (l. mol^{-1} sec^{-1})	Relative rate[b]
tert-Butyl	4.8	1800
Isopropyl	1.6	590
Ethyl	0.14	52
Methyl	0.0027	1.0
Phenyl	0[c]	0

[a] Pseudo-first-order kinetics for reactions containing 1 M RMgBr in ether at 22°. [b] Methyl = 1.0. [c] No detectable reaction after 100 hr.

Table IV. Effect of Solvent Viscosity on the Yields of Butane and *tert*-Butyl Ether[a]

Solvent	Viscosity, cP	n-C$_4$H$_{10}$[b]	n-C$_2$H$_5$OBu[c]
Pentane	0.24	0.109	0.533
Hexane	0.33	0.099	0.568
Heptane	0.41	0.085	0.592
Octane	0.54	0.064	0.608

[a] In reaction of 3.45 mmol of EtLi and 1.50 mmol of DTBP in 10 ml of appropriate solvent at 20°. [b] Mol per mol of EtLi consumed. [b] Mol per mol of *t*-BuO radical generated assuming one *t*-BuO from each DTBP consumed.

shown in Table IV, caused a uniform increase in the amount of ether produced per mole of ethyllithium consumed. A corresponding decrease in the yield of n-butane was observed.

β Scission of *tert*-Alkyl Radicals. As a further probe into the apparent radical nature of the process, the reaction between ethyllithium and triptyl *tert*-butyl peroxide (2,3,3-trimethyl-2-butyl *tert*-butyl peroxide) was examined. Under these circumstances the yields of products derived from the fragmentation of an inter-
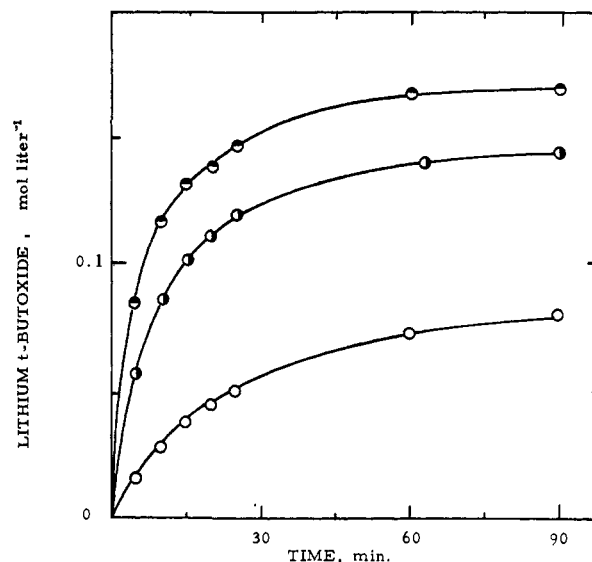

Figure 2. Reaction of 0.216 M ethyllithium in toluene: (◓) 0.284 M, (◑) 0.174 M, and (○) 0.061 M di-*tert*-butyl peroxide at 25° to form lithium *tert*-butoxide.

mediate *tert*-alkoxy radical would be optimum due to the extreme instability of triptoxy radical as previously documented.[20]

$$(CH_3)_3C\text{-}C(CH_3)_2O\cdot \longrightarrow (CH_3)_3C\cdot + (CH_3)_2CO$$

A solution of ethyllithium (2.92 mmol) in n-octane was treated with triptyl *tert*-butyl peroxide (1.71 mmol) for 4.5 hr at 25° and then quenched with acetic acid. The products obtained included those anticipated by analogy to the reaction with DTBP. Thus, triptyl alcohol (0.63 mmol), *tert*-butyl alcohol (0.99 mmol), triptyl ethyl ether (0.36 mmol), *tert*-butyl ethyl ether (0.43 mmol), ethane (0.62 mmol), ethylene (0.23 mmol), and butane (0.05 mmol) were all identified. Moreover, substantial quantities of products attributable to the fragmentation of triptoxy radical, including isobutane (0.17 mmol), isobutylene (0.21 mmol), and *tert*-amyl alcohol (0.37 mmol) were also obtained in addition to 0.81 mmol of unreacted ethyllithium and 0.34 mmol of recovered triptyl *tert*-butyl peroxide.

Radical Trapping with Styrene. The effect of styrene was investigated as a free-radical trap in the reaction of DTBP and ethyllithium under conditions which were identical with those above with the exception of added styrene. Under these circumstances 54% of the ethyl groups were trapped by styrene, and the yield of butane was reduced by 86% and ethyl *tert*-butyl ether by 65% as shown in Table V. The trapping experiments were somewhat complicated by the competing anionic polymerization reaction which is known[21] to be initiated by lithium alkyls. However, when control experiments using styrene and ethyllithium were carried out under conditions equivalent to those above, only 9% of the ethyl groups present were trapped. Moreover, the presence of styrene did not affect the reduction of DTBP under these conditions since the yield of lithium *tert*-butoxide was largely unaffected. The adducts to styrene were not characterized.

(20) C. Walling and A. Padwa, *J. Amer. Chem. Soc.*, **85**, 1593 (1963).

(21) (a) A. G. Evans and D. B. George, *J. Chem. Soc.*, 4653 (1961); 141 (1962); (b) C. E. H. Bawn and A. Ledwith, *Quart. Rev., Chem. Soc.*, **16**, 361 (1962).

Table V. Effect of Styrene on the Reaction of Ethyllithium and Di-*tert*-butyl Peroxide[a]

Additive	Products, mmol					Recovery, mmol	
	C_2H_6	C_2H_4	C_4H_{10}	EtOBu	BuOLi	DTBP[b]	EtLi[c]
	0.956	0.287	0.148	0.861	2.50	0.010	0.650
Styrene[d]	0.462	0.071	0.020	0.301	2.64	0.000	0.402

[a] Ethyllithium (3.14 mmol) and DTBP (1.65 mmol); average for three runs in 10 ml of toluene at 25°. [b] Unreacted di-*tert*-butyl peroxide after 3.0 hr. [c] Determined as additional ethane upon quenching with acetic acid. [d] 4.5 mmol of styrene added.
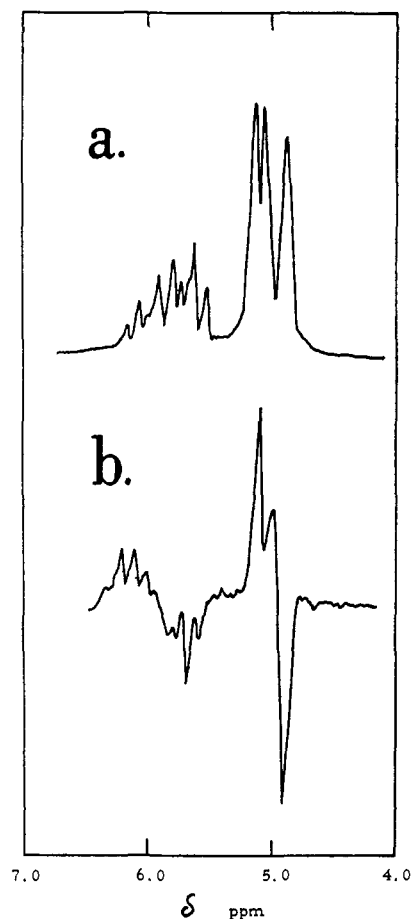

Figure 3. Pmr spectrum of the olefinic region between δ 4 and 7: (a) normal spectrum, (b) spectrum taken during the reaction between ethyllithium and di-*tert*-butyl peroxide at 30°.
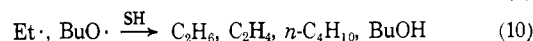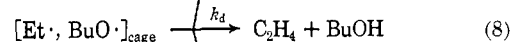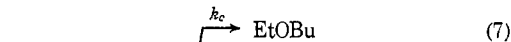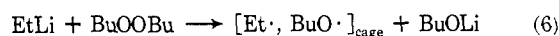
Observation of CIDNP. The reaction of butyllithium with DTBP was carried out under argon in the probe of a 60-MHz spectrometer at ambient temperature in order to examine the spectrum for CIDNP (chemically induced dynamic nuclear polarization). Only that portion of the spectrum between δ 3 and 7 ppm (which encompasses the olefinic protons and the α protons of *n*-butyl *tert*-butyl ether) was sufficiently clear for study. Examination of the olefinic portion of the spectrum shown in Figure 3 revealed the pattern of enhanced absorption and emission (AE multiplet effect). The resonance of the ethereal α protons, however, did not exhibit any observable polarization and the intensity increased approximately monotonically as the reaction proceeded.

Discussion

The nonintegral stoichiometry presented in eq 1 for the facile reaction between ethyllithium and di-*tert*-butyl peroxide in toluene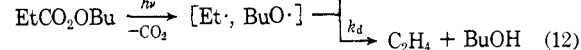 suggests the participation of several simultaneous reactions. In order to facilitate the presentation of our conclusions, we first introduce in Scheme I the mechanistic framework on which the following discussion will be based.

Scheme I

$$EtLi + BuOOBu \longrightarrow [Et\cdot, BuO\cdot]_{cage} + BuOLi \quad (6)$$

$$[Et\cdot, BuO\cdot]_{cage} \begin{cases} \xrightarrow{k_c} EtOBu & (7) \\ \xrightarrow{k_d} C_2H_4 + BuOH & (8) \\ \xrightarrow{k_{diff}} Et\cdot + BuO\cdot & (9) \end{cases}$$

$$Et\cdot, BuO\cdot \xrightarrow{SH} C_2H_6, C_2H_4, n\text{-}C_4H_{10}, BuOH \quad (10)$$

Free-Radical Nature of the Reaction. The occurrence of free-radical processes during the reaction between ethyllithium and dialkyl peroxide is suggested by the formation of *n*-butane from ethyllithium, the β scission of the triptoxy moiety from triptyl *tert*-butyl peroxide, the observation of CIDNP, and the trapping effect observed with styrene. Four independent lines of evidence, enumerated as I–IV below, lead to the conclusion that ethyl *tert*-butyl ether arises from the cross-combination of ethyl and *tert*-butoxy radical pairs in a solvent cage as represented in eq 7.

I. The sharply diminished yield of ethyl *tert*-butyl ether in the presence of styrene is taken as evidence for the free-radical origin of this product. However, *tert*-butoxy radicals are known to be extremely short lived in solution due to facile hydrogen abstraction processes,[22] and bimolecular reactions with radicals are unlikely outside of cage effects.[23] For example, *tert*-butoxy and ethyl radical pairs generated in solution by photolysis of *tert*-butylperoxy propionate afford ethyl *tert*-butyl ether exclusively by cross-combination within the solvent cage as given in eq 11.[24] Cross-combination

$$EtCO_2OBu \xrightarrow[-CO_2]{h\nu} [Et\cdot, BuO\cdot] \begin{cases} \xrightarrow{k_c} EtOBu & (11) \\ \xrightarrow{k_d} C_2H_4 + BuOH & (12) \end{cases}$$

of ethyl and *tert*-butoxy radicals subsequent to diffusion from the cage was shown to be unimportant. The high yield of ether observed in the present investigation is attributed to a similar combination of radical pairs within a solvent cage.

II. Ethyl and *tert*-butoxy radical pairs are capable of cross-disproportionation (eq 8) in addition to cross combination, the ratios (k_d/k_c) of which are listed in Table VI for these radical pairs generated from the aforementioned reactions of ethyllithium and ethyl-

(22) (a) D. J. Carlsson and K. U. Ingold, *J. Amer. Chem. Soc.*, **89**, 4891 (1967); (b) C. Walling and V. P. Kurkov, *ibid.*, **89**, 4895 (1967); (c) P. Gray, R. Shaw, and J. Thynne, *Progr. React. Kinet.*, **4**, 68 (1968).

(23) (a) T. Koenig, in ref 8, Chapter 4, p 157 ff; (b) T. Koenig, J. G. Huntington, and W. R. Mabey, *Tetrahedron Lett.*, 4417 (1973); (c) T. Koenig and J. M. Owens, *J. Amer. Chem. Soc.*, **95**, 8484 (1973).

(24) R. A. Sheldon and J. K. Kochi, *J. Amer. Chem. Soc.*, **92**, 5175 (1970).

magnesium bromide with DTBP as well as from the photolysis of *tert*-butylperoxy propionate. The agreement among the values of k_d/k_c in Table VI lies well within the margin of medium effects.
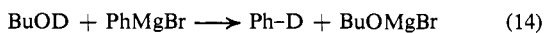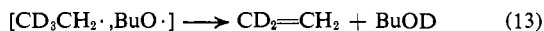
Table VI. Ratio of Cross-Disproportionation to Cross-Combination of Ethyl and *tert*-Butoxy Radical Pairs from Various Sources[a]

Source	Solvent	Temp, °C	k_d/k_c
EtLi + DTBP	Toluene	25	0.302
EtMgBr + DTBP[b]	Ether	35	0.301
EtCO₂OBu + hv[c]	Decalin	30	0.316

[a] Corrected for ethylene generated by disproportionation of ethyl radicals using k_d/k_c for ethyl radicals in solution of 0.185. [b] Reference 18. [c] Reference 24.

The disproportionation and combination of the caged alkoxy–alkyl radical pair is analogous to the same process experienced by a pair of alkyl radicals. Extensive studies have shown that disproportionation and combination of two alkyl radicals are competitive processes which are intimately and inextricably intertwined.[25] Thus, any evidence that cross-disproportionation occurs must consider cross-combination as a simultaneous process.

Morrison and Epstein[18] have supplied independent evidence for the cross-disproportionation process in the reaction between ethylmagnesium bromide and di-*tert*-butyl peroxide. They made use of the fact that phenylmagnesium bromide is inert to DTBP, but can be readily neutralized by *tert*-butyl alcohol by acid displacement to afford benzene. The reaction of 2,2,2-trideuterioethylmagnesium bromide with DTBP in the presence of excess phenylmagnesium bromide afforded benzene-d_1 in 90% yield and proves that cross-disproportionation of ethyl and *tert*-butoxy radical pairs

$$[CD_3CH_2\cdot, BuO\cdot] \longrightarrow CD_2{=}CH_2 + BuOD \quad (13)$$

$$BuOD + PhMgBr \longrightarrow Ph\text{-}D + BuOMgBr \quad (14)$$

occurs in this system. These workers, however, do not suggest that these same radical pairs might also undergo cross-combination to form the mixed ether, although later studies[24] described above have a direct bearing on this conclusion. Unfortunately, phenyllithium reacts readily with DTBP and this valuable probe cannot be extended to the reaction with alkyllithium. Nevertheless, the similarity between the reactions of DTBP with alkyllithium and with Grignard reagents suggests that similar mechanisms are involved with both organometals.

III. The effect of the solvent viscosity on the product distribution is also consistent with a mechanism in which ethyl and *tert*-butoxy radicals are produced in pairs. Thus, increasing solvent viscosity results in increased yields of ethyl *tert*-butyl ether, which is expected for a cage product.[23] The yields of *n*-butane, presumably formed in noncage processes (*vide infra*), drop sharply as the viscosity of the medium increases.

Koenig and Owens have developed a useful model to account for the effects of solvent viscosity (η) on the relative rates of combination, disproportionation, and diffusion of alkyl *tert*-butoxy radical pairs generated during pyrolysis of peresters in solution.[23] From the

(25) M. Gibian and R. C. Corley, *Chem. Rev.*, 73, 441 (1973).

sec-butyl–*tert*-butoxy radical pair, they define a function, $(1/Y - 1)$ where Y is the yield of ether, which is linear with $\eta^{-3/4}$ over the range of viscosities studied. Moreover, they noted that

$$1/Y - 1 = k_d/k_c + k_{diff}/k_c \quad (15)$$

where k_d, k_c, and k_{diff} are the rate constants for disproportionation, combination, and diffusion of the radical pair. It then follows from eq 15 that the linear plot of the ether and viscosity functions has an intercept which is given by k_d/k_c.

We have carried out the same procedure in Figure 4 for the presumed radical pairs generated in the reaction of ethyllithium with DTBP in pentane, hexane, heptane, and octane. Indeed, the plot is linear and the intercept is 0.32, which also corresponds to the reported value for k_d/k_c of the ethyl-*tert*-butoxy radical pair previously obtained independently from the perester.[24] Similarly, the yield of butane plotted against $\eta^{-3/4}$ in Figure 4 passes reasonably close to the origin, in accord with the formulation (*vide infra*) that no butane would be found in a system of infinite viscosity.[26]

Finally, the formation of ethyl *tert*-butyl ether by cage combination of ethyl and *tert*-butoxy radical pairs readily explains why previous efforts to prepare secondary alkyl or tertiary alkyl *tert*-butyl ethers by analogous reactions have been uniformly unsuccessful.[12] Thus, the ratio k_d/k_c for the reaction of *tert*-butoxy radicals with ethyl radicals in solution is 0.32. The corresponding value for isopropyl radicals is 2.4, and with *tert*-butyl radicals the ratio increases to 19.[24] Clearly such large ratios of k_d/k_c further enhanced by the decreased efficiency of cage reactions will doubtlessly combine to reduce the mixed ether to a minor product.

IV. An important check on the proposed intermediacy of *tert*-butoxy radical is the fragmentation study employing triptyl *tert*-butyl peroxide. Whereas the β scission of *tert*-butoxy radical to acetone and methyl radical is slow relative to the hydrogen abstraction from solvent, the corresponding fragmentation of

$$(CH_3)_3CO\cdot \longrightarrow CH_3\cdot + (CH_3)_2CO$$
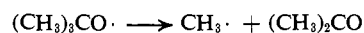
triptoxy radical is rapid. It has, in fact, been esti-

$$(CH_3)_3C(CH_3)_2CO\cdot \longrightarrow (CH_3)_3C\cdot + (CH_3)_2CO \quad (16)$$

mated[20] that the rate of the β scission to triptoxy radical is more than 15,000 times faster than that of *tert*-butoxy radical.

Thus, the isobutylene and isobutane obtained (*vide supra*) in the reaction of ethyllithium with triptyl *tert*-butyl peroxide are the result of disproportionation and solvent abstraction by *tert*-butyl radicals produced by fragmentation of triptoxy radicals (eq 16). It follows that *tert*-amyl alcohol which is also produced in substantial quantities (27%) is the product of the subsequent reaction between the acetone produced in eq 16 and an additional equivalent of ethyllithium (eq 17).

$$EtLi + (CH_3)_2CO \longrightarrow CH_3CH_2(CH_3)_2COLi \quad (17)$$
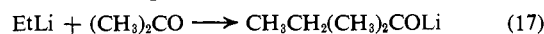
(26) (a) While this result is in agreement with the proposed mechanism, it must be stressed that there is no requirement that the plot be linear over the entire range of viscosities since the yield of butane must level off at some finite value as the fluidity is increased further. (b) There is substantially more cage combination and disproportionation observed in the present reaction compared to the perester decomposition studied by Koenig and Owens.[23c] Part of the discrepancy can be accounted for, as they suggest, by the intervention of a molecule of CO₂ in the radical pair derived from the perester.
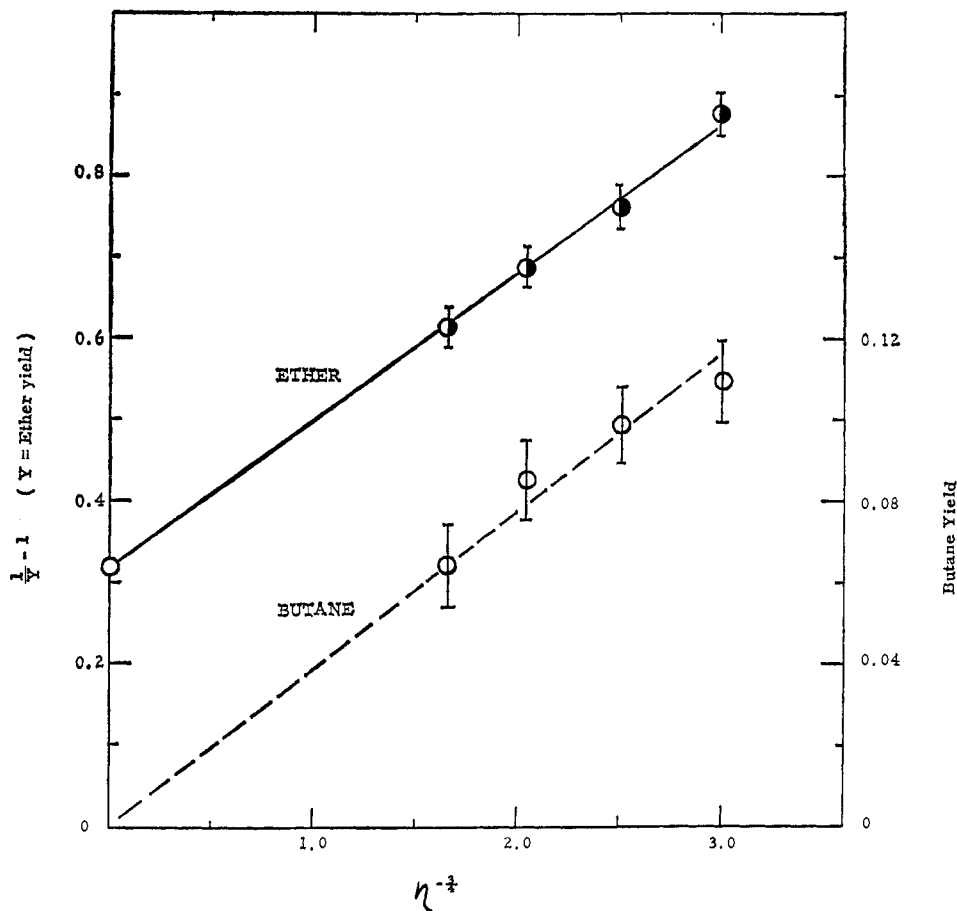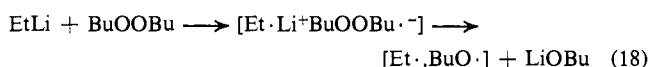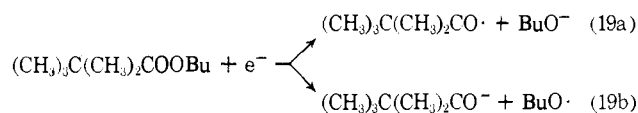
Figure 4. Viscosity dependences of the Y = yield of ethyl *tert*-butyl ether (mol/mol of ethyllithium) and the yield of butane formed during the reaction between ethyllithium and di-*tert*-butyl peroxide at 25° plotted according to Koenig and Owens.

We interpret the observation of these products as unequivocal evidence for the intermediacy of alkoxy radicals in these reactions.

Radical-Generating Step. The kinetics of the reaction indicate that ethyllithium and DTBP are both present in the rate-limiting transition state. Assuming for the moment that ethyl and *tert*-butoxy radicals are produced in pairs in this reaction, we might ask how these radicals be generated. One possibility is represented by a rate-limiting transfer of an electron from ethyllithium to the peroxide, with subsequent homolysis of the metastable radical ion.[27] In the case of triptyl *tert*-butyl peroxide

$$\text{EtLi} + \text{BuOOBu} \longrightarrow [\text{Et}\cdot\text{Li}^+\text{BuOOBu}\cdot^-] \longrightarrow$$

$$[\text{Et}\cdot,\text{BuO}\cdot] + \text{LiOBu} \quad (18)$$

it is clear from the product distribution that electron transfer occurs with almost equal facility to either of the peroxidic oxygen atoms in eq 19.

$$(CH_3)_3C(CH_3)_2CO\cdot + BuO^- \quad (19a)$$

$$(CH_3)_3C(CH_3)_2COOBu + e^- \overset{\nearrow}{\underset{\searrow}{}}$$

$$(CH_3)_3C(CH_3)_2CO^- + BuO\cdot \quad (19b)$$

Electron transfer between alkyllithium and dialkyl peroxide is analogous to the charge-transfer mechanism proposed for the reaction of alkyllithium with

(27) Ethyllithium aggregates[19] are no doubt involved. Despite the similarity between alkyllithium and Grignard reagents, the role of aggregates in electron-transfer reactions and in subsequent reactions of radicals is unknown, and we are unable to make meaningful comments at this juncture.

alkyl iodides.[3,28] The parallel between dialkyl peroxides and alkyl halides as oxidants is not unreasonable since they both have an accessible lowest unoccupied molecular orbital to which an electron can be transferred.[29] Esr and optical evidence for the formation of the anion radical of DTBP has been presented.[30] Access to the peroxidic atoms in DTBP is sterically hindered by the bulk of the flanking *tert*-butyl groups and accounts for its extreme inertness to a variety of reagents including strong acids.[31] The facile reaction observed between ethyllithium and DTBP is thus consistent with an outer-sphere transfer of an electron in eq 18, which does not necessarily require intimate approach of the interacting species.[32]

Further evidence for an electron-transfer process is provided by the comparative rate data given in Table III, in which the relative rates for various Grignard reagents, RMgBr, are shown to follow the order: *tert*-butyl > isopropyl > ethyl > methyl > phenyl. This sequence is that expected for the process: $R^- \rightarrow$

(28) See, *e.g.*, H. R. Ward, *Accounts Chem. Res.*, **5**, 18 (1972).

(29) (a) T. Yonezawa, *et al.*, *Bull. Chem. Soc. Jap.*, **35**, 1814 (1962); **36**, 217 (1963); (b) K. Ohkubo and M. Okada, *ibid.*, **44**, 2869 (1971).

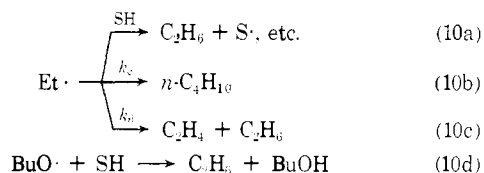(30) T. Shida, *J. Phys. Chem.*, **72**, 723 (1968).

(31) R. Hiatt in ref 12a, p 1.

(32) (a) J. F. Garst in ref 8, Chapter 9, p 503 ff; (b) W. L. Reynolds and R. W. Lumry, "Mechanisms of Electron Transfer Reactions," Ronald Press, New York, N. Y., 1966. (c) The formation of a peroxide ion radical as an intermediate is not demanded by the data at hand. The stereochemistry of the alkyl group in the ethers will be examined in a subsequent study, using systems such as the 7-norbornenyl (*cf.* J. K. Kochi, *et al.*, *J. Amer. Chem. Soc.*, **95**, 1516 (1973)), cyclopropyl (*cf.* H. M. Walborsky and J.-C. Chen, **93**, 671 (1971), and ω-hexenyl (*cf.* K. U. Ingold, ref 8, p 97)).

R· + e⁻, since it reflects both decreasing stability of the radical and increasing stability of the carbanion.

It is noteworthy that a similar order of stabilities was ascertained by Evans in his electrochemical examination of Grignard reagents.[33] In these studies, plots of the current *vs.* potential were obtained for various Grignard reagents in ether at 22°, and the discharge potentials were measured. If, as Evans suggested, the cathode reaction is the same for each Grignard reagent, the anodic data should reflect the ease of oxidation of the various carbanionoids. Indeed, Figure 5 shows that there is a reasonable linear correlation between the rate (log k) of reaction of Grignard reagents with DTBP represented in Table III with the discharge potentials determined by Evans. However, in view of the widely differing degrees of aggregation of Grignard reagents in ethyl ether solution,[34] and the criticism of Evans' experimental approach,[35] these results must for the present be regarded as merely indicative. A more rigorous investigation of this problem using monomeric Grignard reagents in THF solutions is currently in progress. Nevertheless, we feel that these results qualitatively support a rate-determining, one-electron transfer process.

Subsequent Radical Reactions. The other major products, ethane and *n*-butane, as well as more ethylene and *tert*-butyl alcohol, are generated according to Scheme I from *free* radicals represented in eq 10. Ethyl

$$\text{Et·} \begin{cases} \xrightarrow{SH} C_2H_6 + S·. \text{ etc.} & (10a) \\ \xrightarrow{k_c} n\text{-}C_4H_{10} & (10b) \\ \xrightarrow{k_d} C_2H_4 + C_2H_6 & (10c) \end{cases}$$

$$\text{BuO· + SH} \longrightarrow C_2H_6 + \text{BuOH} \qquad (10d)$$

radicals upon escaping the solvent cage afford *n*-butane, ethane, and more ethylene by self-combination and disproportionation. Hydrogen abstraction from the solvent SH by *tert*-butoxy and ethyl radicals afford additional *tert*-butyl alcohol and ethane, respectively. Ethyllithium is also consumed by *tert*-butyl alcohol to generate more ethane and lithium *tert*-butoxide. It is
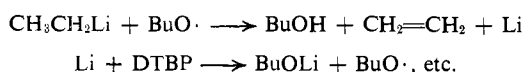
$$\text{EtLi + BuOH} \longrightarrow C_2H_6 + \text{BuOLi} \qquad (20)$$
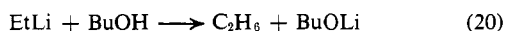
indeed possible to make a quantitative accounting of the products from known values of the disproportionation/combination ratios (k_d/k_c) previously measured for ethyl and ethyl as well as ethyl and *tert*-butoxy radical pairs as shown in Table IX (Experimental Section).[36]

(33) (a) W. V. Evans, F. N. Lee, and C. N. Lee, *J. Amer. Chem. Soc.*, **57**, 485 (1935); (b) W. V. Evans, *ibid.*, **64**, 2865 (1942). (c) The kinetic experiments in Table III were deliberately carried out at relatively high concentrations of Grignard reagent in order to approximate conditions used by Evans, *et al.*, in the electrochemical experiments. Thus, the Schlenk equilibrium and aggregation are factors which must be taken into account in the quantitative interpretation of the data.

(34) F. Walker and E. C. Ashby, *J. Amer. Chem. Soc.*, **91**, 3845 (1969).

(35) T. Prarras and R. E. Dessy, *J. Amer. Chem. Soc.*, **88**, 5132 (1966).

(36) (a) An alternative mechanism for the formation of alkene is represented by the induced decomposition of the organometal by *tert*-butoxy radicals *via* a chain mechanism such as

$$\text{CH}_3\text{CH}_2\text{Li + BuO·} \longrightarrow \text{BuOH + CH}_2{=}\text{CH}_2 + \text{Li}$$

$$\text{Li + DTBP} \longrightarrow \text{BuOLi + BuO·, etc.}$$

This possibility is of particular interest when considered in light of the known k_d/k_c ratios cited above. Thus, if the alkene were not arising from radical cross-disproportionation, it follows that the ether could not be formed by cross-combination but would have to arise from some
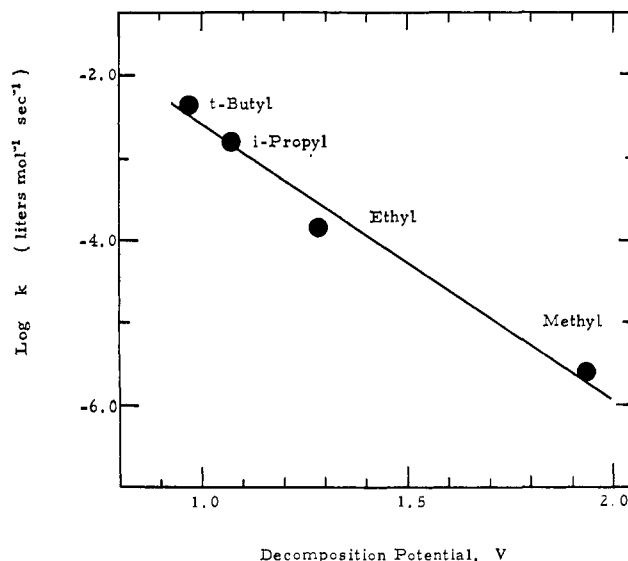

Figure 5. Correlation of the rates of reactions of various Grignard reagents and di-*tert*-butyl peroxide as a function of the oxidative decomposition potentials determined by Evans.

Interpretation of CIDNP Results. The effectiveness of CIDNP as a mechanistic probe for one-electron transfer reactions has been thoroughly demonstrated by Ward, Lawler, and Cooper in the reaction of alkyllithium with alkyl halides.[5] In the present investigation CIDNP proved similarly useful in verifying several aspects of the mechanism. Thus, in the proposed Scheme I, alkene is generated in two different ways, that is both by geminate disproportionation of the initial *tert*-butoxy alkyl radical pair (eq 8) and by diffusive encounters between alkyl radicals (eq 10c). This is shown for the general case of alkyllithium RLi in Scheme II. From which source then does the olefin originate which is responsible for the observed polarization? The Kaptein equations[37] allow us to predict
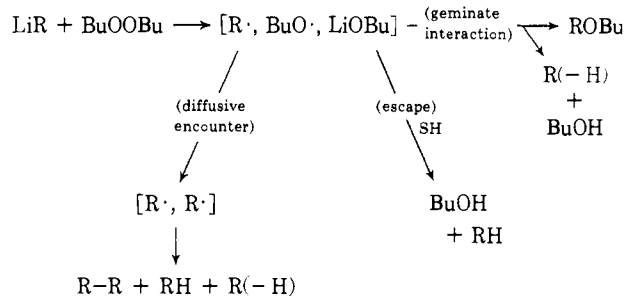
$$\Gamma_{ne} = \mu\epsilon\Delta gA_i \qquad (21)$$

$$\Gamma_{me} = \mu\epsilon A_iA_jJ_{ij}\sigma_{ij} \qquad (22)$$

other (presumably heterolytic) route.[32c] While the evidence developed throughout this paper seems to support our proposed mechanism, we wish to cite one additional piece of evidence which bears on such an induced decomposition. Thus, a comparison of CD_3CH_2MgBr and CH_3CH_2MgBr toward DTBP shows that only 1.19 times more ethylene is formed relative to ethyl *tert*-butyl ether from the protiated Grignard reagent compared to the deuterated analog.[18] If the ether were to arise from a heterolytic pathway, it is unlikely that its rate formation would be greatly affected by isotopic substitution. Moreover, if the ethylene were to be formed by induced decomposition of the organometallic (process similar to equation above), cleavage of a carbon–hydrogen bond would be involved and we anticipate a substantial (primary) isotope effect. The small size of the observed effect is not consistent with such a process. We feel that the significance of the observed isotope ratio lies in its effect on the ratio of cross-disproportionation to cross-combination (k_d/k_c) of ethyl and *tert*-butoxy radical pairs in solution. In fact, such a ratio has been determined[25] for ethyl radical pairs in solution and a value of 1.41 has been reported. This is consistent with the 1.19 figure for ethyl and *tert*-butoxy radical pairs, particularly in view of the higher reactivity (lower selectivity) of *tert*-butoxy compared ethyl radicals. Similar effects (1.15 for *n*-PrMgBr and 1.16 for *i*-PrMgBr) were determined for other Grignard reagents. (b) The similarity in the yields of ethers derived from DTBP and triptyl *tert*-butyl peroxide is also noteworthy. Since triptoxy radicals fragment very rapidly, their lifetime would be too short to participate effectively in radical chain process for ether formation. Previous studies showed that fragmentation of similar alkoxy radicals may not effectively compete with cage processes.[24]

(37) R. Kaptein, *Chem. Phys. Lett.*, **2**, 261 (1968); *J. Amer. Chem. Soc.*, **94**, 6262 (1972).

Scheme II

$$LiR + BuOOBu \longrightarrow [R\cdot, BuO\cdot, LiOBu] - \overset{(geminate\ interaction)}{\longrightarrow} ROBu$$

both the net effect, Γ_{ne}, and the multiplet effect, Γ_{me}, which would arise in either case. The results in Figure 3 immediately suggests that the observed polarization is due to disproportionation of alkyl radical pairs generated by diffusive encounters in the following manner. We observe no net effect, which is consistent with interaction between identical alkyl radicals where $\Delta g = 0$, and the observed AE multiplet effect is predicted as follows. The parameters μ and ϵ will both be positive for the products of diffusive encounter between alkyl radicals. The hyperfine coupling constants A_i and A_j will be negative (for the α protons) and positive (for the β protons), respectively. In addition, vicinal coupling constant J_{ij} for alkenes are known to have a positive sign, and the parameter σ_{ij} is defined as being positive when nuclei i and j belong to the same radical. Thus in eq 22, $\Gamma_{me} = + + - + + + = -$ and an AE multiplet effect is as predicted. This fact is also reasonable in another respect. Since no polarization is observed in the product of geminate combination of *tert*-butoxy and butyl radical pairs (*i.e.*, in *tert*-butyl *n*-butyl ether), no polarization should be observed in the 1-butene formed by geminate disproportionation of the same two radicals.

The absence of CIDNP polarization in the α-proton absorbance of the ether is not without precedent. The CIDNP spectra of the products of the photolysis of a variety of peresters was recently examined by Jurch who observed no CIDNP activity in the ethers formed in that reaction.[38] This result is particularly significant in that the photolysis of peresters has been thoroughly investigated by a variety of conventional means, most recently by Koenig[23c] and it is virtually certain that the ether produced does in fact originate from cage combination of alkyl and alkoxy radical pairs.[24] The absence of polarization may be a result of the extreme rapidity with which *tert*-butoxy radicals react, either by cage combination or disproportionation with alkyl radicals or by solvent hydrogen abstraction. The fast rate of reaction may prevent *tert*-butoxy and alkyl radical pairs from achieving the necessary separation for observation of the CIDNP phenomenon.

Conclusion

The rapid thermal reaction between ethyllithium and di-*tert*-butyl peroxide proceeds by an electron-transfer process outlined in Scheme I to afford ethyl and *tert*-butoxy radicals as important intermediates. Ether is an exclusive product of cage combination of the radical pair. Ethylene and butane are derived from disproportionation reactions and combination of ethyl radicals. Triptyl *tert*-butyl peroxide reacts with ethyl-

(38) G. R. Jurch, Jr., private communication.

lithium by a similar process but also leads to β scission of the triptoxy moiety which can only occur *via* an intermediate triptoxy radical. These results together with the kinetics, the effect of solvent viscosity, and the observation of CIDNP are in accord with a mechanism presented in Scheme I in which electron transfer from alkyllithium to peroxide constitutes the rate-limiting process.

Experimental Section

Materials. Toluene was reagent grade material (Mallinckrodt) distilled from sodium benzophenone radical anion under argon prior to use. Pentane, hexane, heptane, octane, and dodecane were all reagent grade solvents distilled from calcium hydride under argon prior to use. Lithium was reagent grade (Foote Chemical Co.) and was used without further purification. Anhydrous $MnCl_2$ (Baker and Adamson) was dried *in vacuo* at 130° for 50 hr. Styrene and di-*tert*-butyl peroxide were freshly distilled prior to use.

Ethyl *tert*-butyl ether was prepared by dehydration of ethanol and *tert*-butyl alcohol using the procedure by Norris and Rigby.[39]

Analysis. Liquid products were analyzed by gas chromatography (glc) using a 6-ft column of 15% FFAP on Firebrick at 65°, except when ethyl *tert*-butyl ether was contained in hexane and heptane solvents in which case it was determined on an 8-ft SF 96 column at 87°. Benzene was employed as an internal standard and careful calibration was carried out under the reaction conditions. Gaseous products were analyzed by glc (10-ft Porapak Q or 20-ft Dowtherm A) after quenching the reaction with acetic acid. Internal standards employed were isobutane for analysis of butane and either methane or carbon dioxide for the analysis of ethylene and ethane.

Preparation of Ethyllithium in Hydrocarbon Solvents. A 500-ml, three-necked flask equipped with addition funnel, condenser, and stirring bar was scrupulously cleaned, dried, and flushed with argon. To the flask was added 200 ml of pentane and 2.5 g (0.12 mol) of lithium wire cut in small pieces. To the addition funnel was added 100 ml of pentane and 9.0 ml (13.6 g, 0.35 mol) of ethyl bromide. The system was flushed again with argon and a positive pressure of argon maintained throughout the preparation. The solution of ethyl bromide was added dropwise over 0.5 hr, and the mixture was refluxed with continued stirring for 5 hr. The solid residue was allowed to settle and the clear supernatant siphoned off and stored at $-20°$. Ethyllithium crystallized after several hours. The pentane was removed with a siphon and the last traces of solvent were evaporated *in vacuo*. The appropriate hydrocarbon solvent (usually 100 ml) was added, and the solution was agitated for 15 min to hasten the dissolution of the ethyllithium, the concentration of which was determined both by acidimetric titration and by quenching followed by quantitative glc analysis of ethane.

tert-Butyl triptyl peroxide was prepared by the reaction of *tert*-butyl hydroperoxide with triptyl alcohol monohydrate using the procedure of Milas and Perry,[40] bp 46.0–46.5° (8 Torr). *Anal.* Calcd for $C_{11}H_{24}O_2$: C, 70.1; H, 12.9. Found: C, 70.15; H, 12.7.

Triptyl Ethyl Ether. Magnesium triptoxy iodide was prepared by the dropwise addition of 30.0 g (0.30 mol) of pinacolone to 0.30 mol of methylmagnesium iodide in 250 ml of ether. After stirring for 1 hr the ether was stripped and replaced with 200 ml of dry HMPA. This mixture was refluxed with excess ethyl bromide for 24 hr. The liquid phase was then dissolved in pentane and extracted with water. The pentane phase was subsequently eluted over an alumina column (Woelm activity I) and the solvent was stripped. Distillation *in vacuo* afforded 5.85 g (13%) of the ether, bp 59° (35 Torr). *Anal.* Calcd for $C_9H_{20}O$: C, 74.9; H, 13.9. Found: C, 74.96; H, 13.69.

Reaction of Ethyllithium with Di-*tert*-butyl Peroxide (Typical Procedure). All reactions were carried out in triplicate in 125-ml erlenmeyer flasks which were scrupulously cleaned, dried, and sealed with a gas-tight rubber septum and flushed with argon for 15 min. A solution of 10 ml of 0.314 M ethyllithium in toluene was added by means of a hypodermic syringe. If styrene was to be used, 0.5 ml of styrene was injected. The flask was placed in a constant-

(39) R. H. Norris and F. C. Rigby, *J. Amer. Chem. Soc.*, **54**, 2095 (1932).

(40) N. A. Milas and L. H. Perry, *J. Amer. Chem. Soc.*, **68**, 1938 (1946).

Table VII. Stoichiometry of the Reaction between Ethyllithium and Di-*tert*-butyl Peroxide in Various Solvents[a]

| EtLi, mmol | DTBP, mmol | Solvent[b] | \-\-\-\-\-\-\-\-\-\-\-\-\-\-\-\-\-Products, mmol\-\-\-\-\-\-\-\-\-\-\-\-\-\-\-\- | | | | | \-\-\-Recovery[c]\-\-\- | |
			C_2H_6	C_2H_4	C_4H_{10}	BuOEt[d]	BuOLi[e]	EtLi	DTBP
1.54	0.84	T	0.55	0.18	0.09	0.53	1.50	0	0.80
1.70	2.86	T	0.67	0.20	0.10	0.59	1.67	0	1.72
3.31	1.85	T	1.03	0.32	0.16	0.86	2.74	0.43	0.03
0.89	0.80	B	0.33	0.12	0.06	0.33	0.87	0	0.16
0.96	2.26	B	0.29	0.13	0.08	0.34	0.93	0	1.50
1.23	1.67	B	0.40	0.16	0.08	0.43	1.20	0	0.88
1.23	1.67	B & E[f]	0.40	0.17	0.11	0.38	1.19	0	0.75

[a] Reactions carried out in duplicate or triplicate in 10 ml of solvent at 25°. [b] Solvent: T = toluene, B = benzene. [c] mmol recovered after 3 hr. [d] Ethyl *tert*-butyl ether. [e] Lithium *tert*-butoxide. [f] 10% ether in benzene.

Table VIII. Products of the Reaction between Alkylmagnesium Bromides and Di-*tert*-butyl Peroxide[a]

| RMgX R | \-Products, mmol\- | | | | | | |
	BuOR	BuOMgBr	Total BuO	(R + H)	(R–H)	(R–R)	Total R
Methyl	1.38	8.70	10.08	2.05		2.92	9.27
Ethyl	3.00	6.95	9.95	2.49	0.96	0.31	7.09
n-Propyl	3.17	6.66	9.83	2.31	0.90	0.35	7.08
n-Butyl	3.69	6.38	10.07	1.16	0.39	0.42	6.08
n-Hexyl	3.96	6.08	10.04	1.00	0.40	0.36	6.08
Isobutyl	2.95	7.11	10.06	2.28	1.17	0.21	6.82
Isopropyl	2.01	8.11	10.12	2.97	2.43	0.27	7.95
tert-Butyl		10.10	10.10	4.90	4.05	0.40	9.75
sec-Butyl	2.04	8.05	10.09	2.06	1.76	0.27	6.40
Benzyl	3.35	6.60	9.95	0.25		1.30	6.20

[a] Reaction of 5.0 mmol of DTBP with excess RMgBr at 35°, from ref 18.

Table IX. Reaction of Ethyllithium and DTBP.[a] Product Material Balance

	Et + H	Et–H	Et–Et	BuOEt	BuOLi	Et–S[b]
(1) Base yield	0.96	0.29	0.15	0.86	2.50	0.09
(2) Yield minus known products of radical disp. and comb.	0.66	−0.01	0.00	0.00	2.22	0.00
(3) Above minus *t*-BuOLi required thus far to generate ·Et	0.66	−0.01	0.00	0.00	0.65	0.00
(4) Above minus known products of solvent H abstraction	−0.01	−0.01	0.00	0.00	−0.02	0.00

[a] In reaction consisting of 3.14 mmol of EtLi and 1.65 mmol of DTBP in 10 ml of toluene at 25° for 3 hr. [b] Determined as the excess of *t*-BuOLi over observed ethyl groups.

temperature bath, and, after equilibration, 0.241 g (1.65 mmol) of di-*tert*-butyl peroxide was injected with a hypodermic syringe. After 3.0 hr, 10 ml of methane was added as an internal standard, and ethane was determined by glc. The reaction was quenched by addition of 1.0 ml of acetic acid and 10.0 ml of isobutane was added. Gaseous products were determined by glc. A 1.0-ml solution of 10% benzene in toluene was added and liquid products were determined. The results are shown in Tables I and VII.

Kinetic Study of Reaction (Typical Procedure). A stirring bar was placed in a 250-ml round-bottomed flask which was then sealed with a gas-tight rubber septum and flushed with argon for 15 min. The flask was placed in a constant-temperature bath at 25° and 20.0 ml of 0.216 *M* ethyllithium was injected with a hypodermic syringe, followed by 2.0 ml of 10% benzene in toluene as an internal standard. To initiate reaction, 0.575 g (3.94 mmol) of di-*tert*-butyl peroxide was injected. Aliquots of 1 ml each were withdrawn at regular intervals and quenched immediately with 0.10 ml of acetic acid. Liquid products were determined by glc.

Reaction of Grignard Reagents with DTBP. The stoichiometry of the reaction of DTBP with a variety of Grignard reagents has been studied by Morrison, *et al.*,[18] and the product distribution is remarkably similar to that obtained with alkyllithium. Since these data have not previously been available in the general literature, they are reproduced in Table VIII.

Quantitative Assessment of the Origin of Products. It has already been noted that k_d/k_c for the ethyl and *tert*-butoxy radical pairs is known[24] to have a value of 0.32 in decalin solution at 30°.

Moreover, Dixon, Stefani, and Swarc[41] have shown that in toluene solution the value of k_d/k_c for ethyl radicals is 0.185.

In the proposed scheme, the butane and ethyl *tert*-butyl ether arise solely from radical combinations in eq 10b and 7, respectively. Furthermore, it is disproportionation of these same radical pairs which gives rise to all of the ethylene. Using as an example the data from Table V, we can predict the yield of ethylene from the yield of butane (0.15 mmol) and of ethyl *tert*-butyl ether (0.86 mmol) as: 0.185 × 0.15 + 0.32 × 0.86 = 0.30 mmol. Furthermore, disproportionation in eq 10c would produce 0.03 mmol of ethane and that in eq 8 would yield 0.27 mmol of *tert*-butyl alcohol, which on further reaction with ethyllithium would be converted to 0.27 mmol of additional ethane. The products which remain unaccounted for after substracting out the radical products derived in this manner are summarized on the second line of Table IX.

The radical disproportionation and combination products discussed thus far require 1.57 mmol of ethyl radicals. In the proposed scheme, ethyl radicals can be generated only by eq 6 and must be accompanied by an equal quantity of lithium *tert*-butoxide, which is deducted from the remaining products on line 3 of Table IX. Since the yield of ethane exceeds that of ethylene, the excess could be derived by hydrogen abstraction from solvent either by ethyl radicals (eq 10a) or indirectly *via tert*-butoxy radicals (eq 10d and

(41) P. S. Dixon, A. P. Stefani, and M. Swarc, *J. Amer. Chem. Soc.*, **85**, 2551 (1963); see also R. A. Sheldon and J. K. Kochi, *ibid.*, **92**, 4395 (1970).

16). It is not possible in the present investigation to determine the relative extent to which each of these processes occurs. It is clear, however, that either mechanism for hydrogen abstraction from the solvent requires ethane and lithium *tert*-butoxide to be generated in equal amounts. Thus, the extent of hydrogen abstraction is given by the excess of ethane over ethylene, *i.e.*, $0.96 - 0.29 = 0.67$ mmol. Subtraction of 0.67 mmol each of ethane and lithium *tert*-butoxide from the products in line 4 of Table IX, thus quantitatively accounts for the products of the reaction within the limits of experimental error. A similar analysis is equally applicable to other runs in Tables I and VII.

Physicochemical Properties of Schiff Bases. III.[1]
Substituent Effects on the Kinetics of Hydrolysis of
N-Salicylidene-2-aminopropane Derivatives

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Abstract: The hydrolysis kinetics of five substituted N-salicylidene-2-aminopropanes has been studied between pH 0 and 14. Analysis of the observed rate constants as a function of pH leads to the following conclusions. The mechanism at acidic pH's is the same as that of the nonhydroxylic compounds. At neutral pH, the predominant reaction is the addition of water to the neutral quinoid tautomer. At alkaline pH's, the analysis of the substituent effects confirms that the rate-determining step is the addition of hydroxide ion to the neutral quinoid tautomer.

The mechanism of hydrolysis of Schiff bases derived from amines and aromatic aldehydes has been investigated by various authors.[3] These studies have established the existence of two rate-determining steps: formation of an amino alcohol intermediate, RCHOH-NHR', at neutral or alkaline pH's; decomposition of this intermediate at acidic pH's. The formation of the amino alcohol may occur through two different reactions: addition of water or addition of hydroxide ion to the protonated Schiff base. The presence in the benzylidene ring of hydroxy substituent in the ortho or para position with respect to the azomethine group introduces some modifications in this mechanism. According to Reeves[3c] who studied various derivatives of benzylideneaniline, the $o\text{-}O^-$ substituent has an intramolecular catalytic effect on the formation of the intermediate. Hoffmann, *et al.*,[4] have investigated the hydrolysis of substituted salicylideneanilines. They reached the conclusion that more than one mechanism is at play, at pH 5.5 as well as at pH 12. However, their sole argument is that the observed constants do not follow a Hammett correlation.

In the preceding papers,[1] the influence of the tautomeric equilibrium between the phenolimine and the ketoamine forms has been investigated in the cases of *o*- and *p*-hydroxy-substituted benzylideneisopropylamines.
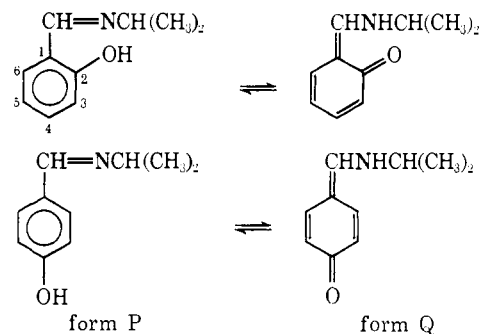
In part I[1a] it has been shown that this equilibrium

form P   form Q

introduces a new kinetically important reaction for the formation of the intermediate in alkaline media, the addition of hydroxide ion to the neutral ketoamine tautomer. The present study brings new evidence in favor of this latter mechanism. It also points out that a new mechanism occurs at neutral pH for the salicylidene derivatives, *i.e.*, the addition of water to the neutral ketoamine tautomer.

Experimental Section

Kinetic measurements were carried out at 30° and ionic strength 0.1 (between pH 1 and 13) as described in part I, except in the pH range between 12 and 14 where the rates of hydrolysis are too large and the variations of optical density between the Schiff bases and the corresponding aldehydes are too small. In this region, kinetic measurements were carried out with a Durrum D110 stopped flow spectrophotometer. pH values were measured as described in part I. The Schiff bases were prepared as described in part II. Commercially available isopropylamine, salicylaldehyde, and *p*-hydroxybenzaldehyde were used to follow the kinetics of the formation reaction. The formation equilibrium constant, K_F, defined as $K_F = [S]/[ald][am]$ where $[S] = [P] + [Q]$, was determined for the salicylideneisopropylamine following the procedure of Green, *et al.*[5]

(1) (a) Part I: W. Bruyneel, J. J. Charette, and E. de Hoffmann, *J. Amer. Chem. Soc.*, **88**, 3808 (1966); (b) part II: R. Herscovitch, J. J. Charette, and F. de Hoffmann, *ibid.*, **95**, 5135 (1973).

(2) University of Louvain.

(3) (a) A. V. Willi, *Helv. Chim. Acta*, **39**, 1193 (1956); (b) E. H. Cordes and W. P. Jencks, *J. Amer. Chem. Soc.*, **84**, 832, 4319 (1962); (c) W. Reeves, *J. Org. Chem.*, **30**, 3129 (1965).

(4) J. Hoffmann, J. Klicnar, V. Sterba, and M. Vecera, *Collect. Czech. Chem. Commun.*, **35**, 1387 (1970).

(5) P. W. Green and P. W. Alexander, *Aust. J. Chem.*, **18**, 399 (1965).