varing the positions and isotropic vibrational amplitudes of the C, O, and Fe atoms led to $R = 0.089$. Six further cycles of least-squares refinement of the atomic parameters with anisotropic vibrational amplitudes for the C, O, and Fe atoms converged to $R = 0.068$. A difference Fourier map calculated at this stage revealed peaks of density appropriate to all hydrogen atoms. Keeping the vibrational amplitudes for the hydrogens fixed (B(H) = B(C) + 1.0 Å)[2] and refining with anisotropic U's for all the C, O, and Fe atoms, we obtained a final R of 0.033. The atomic scattering factors were taken from the literature.[12]

All the calculations were performed on the FACOM M-200 computer in the computer center of Kyushu University with the Universal Crystallographic Computation Program System UNICS II.[13]

Registry No. 1, 17346-16-6; 3, 36343-88-1; 5, 78149-25-4; 6, 78109-52-1; 10, 62515-93-9; 11, 78184-56-2; 14, 78109-53-2; 15, 78149-18-5; 16, 78109-54-3; 17, 12193-69-0; 19, 78128-45-7; 20, 78128-46-8; 21, 78109-55-4; 22, 78109-56-5; $Fe_2(CO)_9$, 15321-51-4.

Supplementary Material Available: Selected torsion angles (Table III), atomic parameters (Table IV), and coordinates for hydrogen atoms (Table V) (3 pages). Ordering information is given on any current masthead page.

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Studies of Tertiary Amine Oxides. 4. Thermal Rearrangement of *N*-Aryl Amine Oxides to *O*-Arylhydroxylamines

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Substituted *N*-aryl cyclic amine oxides undergo novel thermal rearrangement to *O*-arylhydroxylamines. Electron-withdrawing substituents are essential for the rearrangement and must be ortho or para relative to the >N→O function. The mechanism of the rearrangement is best described by an intramolecular cyclic process. Kinetic results are in agreement with the cyclic process but are inconsistent with a homolytic dissociation–recombination mechanism.

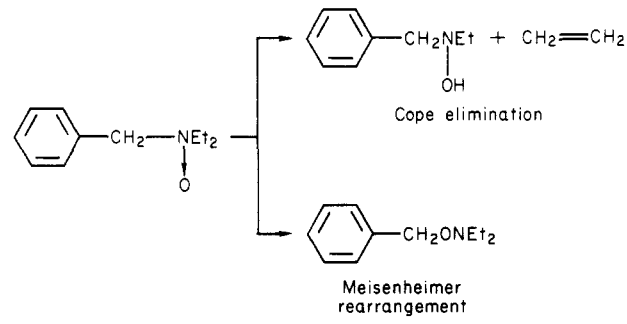
Tertiary amine *N*-oxides (**1**) are a class of organic compounds that have received considerable attention in part because of their role in the microsomal[1] and plant[2] metabolism of tertiary amines and in part because of the interesting thermal rearrangement they undergo to the corresponding *O*-alkylhydroxylamines **2** (eq 1).

$$\underset{\mathbf{1}}{R_1R_2R_3N{\rightarrow}O} \rightarrow \underset{\mathbf{2}}{R_1R_2NOR_3} \qquad (1)$$

Meisenheimer et al.[3] were the first to recognize this reaction, which then became known as the Meisenheimer rearrangement. However, with these *N*-oxides having a β-hydrogen atom, an elimination reaction,[4] often referred to as the Cope elimination, might take place, yielding an olefin. For such compounds, elimination and isomerization are often found to be competitive, and *N*,*N*-diethylbenzylamine *N*-oxide (**3**), for example, on being heated afforded *N*-ethyl-*N*-benzylhydroxylamine, ethylene, and *O*-benzyl-*N*,*N*-diethylhydroxylamine (**4**) (Scheme I).

The type of group which could migrate in the Meisenheimer rearrangement (R_3 in eq 1) is rather closely defined. The groups that are known to show a tendency for migration from N to O include allyl,[5] benzyl,[6-9] neopentyl,[10] tetrachloropyridyl,[11] and homoadamantyl.[12] We have recently[13] reported on the migration of a benzene nucleus from N to O in substituted dimethylaniline oxides. This paper describes the scope and limitations of this type of migration.

Scheme I



4

Results and Discussion

Syntheses. The tertiary amines **5** were prepared by reaction of the appropriate secondary amine and *o*- or

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Table I. Properties of the Tertiary Amines 5[a]

compd	yield, %	mp, °C (lit. value) [recryst solvent]	λ_{max},[b] nm (ϵ_{max})	^{1}H NMR,[d] δ aryl	^{1}H NMR,[d] δ CH_3
5a	100	103-104 (105)[16] [EtOH]	390 (21 676), 232 (8250)	8.1, 6.8[c] (J = 9.7)	
5b	92	151-152 (152-153)[16] [HOAc]	375 (19 057), 238 (7789)	8.2, 6.9[c] (J = 9.7)	
5c	95	78-80 (81)[17] [n-hexane]	250 (14 252)	7.9-6.87 (m, 4 H)	
5d	82	39-40 (40-41)[18] [benzene]		7.8-6.9 (m, 4 H)	
5e	98	62-64 (59.5-60.5)[16] [EtOH]	390 (20 940), 237 (7161)	8.08, 6.76[c] (J = 9.7)	1.2 (d, J = 6.6)
5f	90	20-21	250 (13 897)	7.7-6.9 (m, 4 H)	0.84 (d, J = 6.6)
5g	97	63-65 (64-64.5)[16]	388 (21 427), 237 (8707)	8.1, 6.8[c] (J = 9.7)	1.0 (d, J = 6.6)
5h	96		252 (14 362)	7.8-6.8 (m, 4 H)	0.9 (d, J = 6.6)
5i	94	88-90 (89.9-90.3)[16] [EtOH]	389 (20 973), 237 (7887)	8.1, 6.8[c] (J = 9.7)	1.0 (d, J = 6.6)
5j	92	44-46 [EtOH]	252 (13 525)	7.8-6.8 (m, 4 H)	1.0 (d, J = 6.6)

[a] Satisfactory analytical data were obtained for all new compounds. [b] Solvent is dioxane. [c] Appears as an AB quartet; the higher value corresponds to the two protons ortho to NO_2, and the lower value corresponds to the protons ortho to N. [d] J values are given in hertz.

Table II. Properties of the Tertiary Amine Oxides[a] 6

compd	yield, %	mp, °C picrate	mp, °C HCl adduct	λ_{max},[b] nm (ϵ_{max})	^{1}H NMR,[f] δ aryl	^{1}H NMR,[f] δ CH_3
6a	67		150-153	254 (9162)	8.34 (s, 4 H)	
6b	70	157-159	121-123	252 (8380)	8.4 (s, 4 H)	
6c	70		180-182	243 (2872)	7.8-7.4 (m, 4 H)	
6d	96	179-181		241 (2640)	8.3-7.9 (m, 1 H), 7.75-7.6 (m, 3 H)	
6e	75		160-163	254 (8350)	8.3, 8.05[c] (J = 9.0)	1.1, 0.9[e] (d, J = 7.0)
6f	80		176-180	243 (2338)	7.3-7.7 (m, 4 H)	1.1, 1.26[d] (d, J = 7.0)
6g	65		162-166	255 (8380)	8.32 (s, 4 H)	1.0 (J = 7.0)
6h	80		185-187	242 (2638)	7.9-7.4 (m, 4 H)	0.95, 1.32[e] (d, J = 7.0)
6i	77		164-167	254 (8240)	8.32, 8.14[c] (J = 9.0)	1.1 (J = 7.0)
6j	70		190-192	241 (2824)	7.85-7.5 (m, 4 H)	1.1 (d, J = 7.0)

[a] Satisfactory analytical data were obtained for all compounds. [b] Solvent is dioxane. [c] AB quartet. [d] Two doublets; relative intensities 1:1.4 at 25 °C. [e] Two doublets; relative intensities 3:1 at 25 °C. [f] J values are given in hertz.

p-nitrofluorobenzene (Table I). The action of *m*-chloroperbenzoic acid on the tertiary amines **5** produced the *N*-oxides **6**, but in low yields. Oxidation of **5** with performic acid, however, produced the crystalline *N*-oxides **6** in good yields (Table II). These *N*-oxides are hygroscopic and thus were stored as their picrates or hydrochlorides. However, good spectral data (IR, NMR, UV) of the free *N*-oxides were obtained to permit their full characterization. In the ^{1}H NMR spectra, a considerable downfield shift for the aromatic and the alkyl protons relative to the corresponding amines is clearly noticed. Such a downfield shift is expected on introduction of the polar N→O group in the molecule. For the *p*-nitro *N*-oxides (**6a,b,g**), the aromatic protons appeared as a single line about δ 8 in contrast to the same protons in the corresponding amines (**5a,b,g**) which appeared as an AB quartet. Evidently, the deshielding influences of the N→O function and the NO_2 group are equal, thus making J/δ for the aromatic ring protons so large that the spectrum looked like a single-line A_2 system. This is one of the cases of the so called "deceptively simple AB spectra".[14] On the other hand, the aromatic protons of the *N*-oxides **6e** and **6i** appeared as an AB quartet with coupling constants of 9 Hz. It is of interest to note that the methyl protons in **6e** and **6f** appeared as two doublets (Table II) in contrast to the same protons in the other *C*-methyl *N*-oxides which are indicated by one doublet. The appearance of two doublets for the methyl group in **6e** and **6f** could not be due to axial and equatorial methyl signals owing to slow

Scheme II

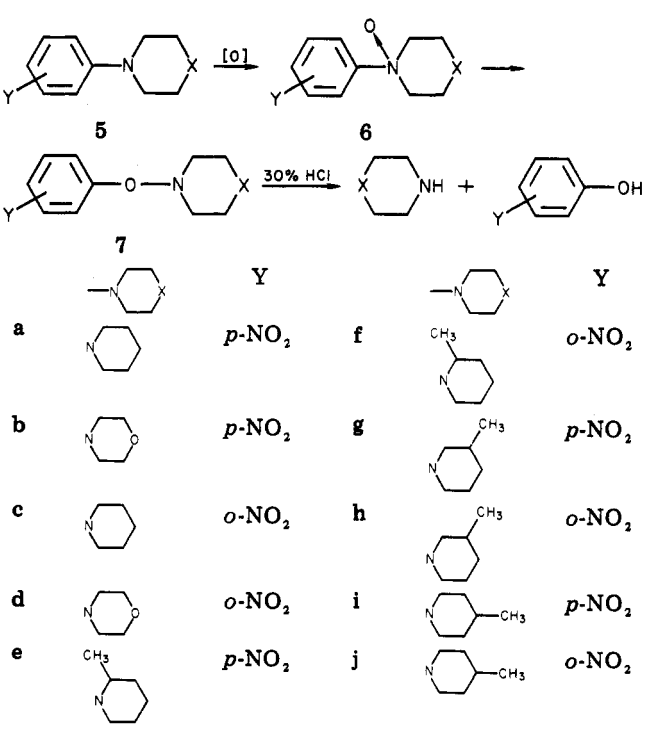

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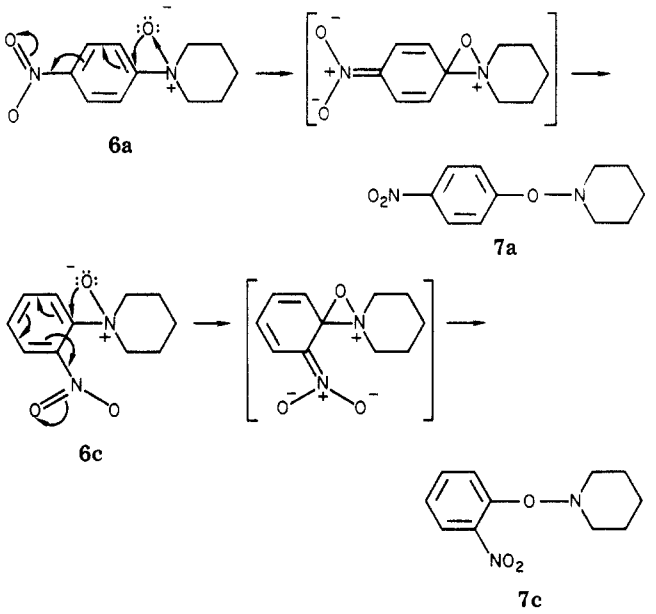
Table III. Properties of *O*-Arylhydroxylamines[a] 7

compd	yield,[b] %	λ_{max},[c] nm (ϵ_{max})	^{1}H NMR, δ aryl	^{1}H NMR, δ CH_3
7a	97	228 (6250), 308 (11 476)	8.2, 7.1[d] (J = 9.8)	
7b	86	230 (5280), 310 (12 300)	8.17, 7.2[d] (J = 9.7)	
7c	92	238 (5640), 255 (3860), 328 (2504)	7.96-6.76 (m, 4 H)	
7d	80	238, 257, 326	7.9-6.8 (m, 4 H)	
7e	99	230 (5851), 310 (10 180)	8.16, 7.25[d] (J = 9.8)	1.03 (d, J = 6.4)
7f	90	237 (5342), 256 (4870), 328 (1882)	7.95-6.8 (m, 4 H)	0.9 (d, J = 6.4)
7g	98	228 (5692), 309 (11 330)	8.15, 7.15[d] (J = 9.8)	1.0 (d, J = 6.4)
7h	89	289 (5336), 257 (3662), 330 (2238)	7.96-6.8 (m, 4 H)	0.96 (d, J = 6.4)
7i	90	228 (5051), 308 (11 050)	8.16, 7.15[d] (J = 9.6)	0.97 (d, J = 6.4)
7j	90	237 (5664), 254 (5610), 332 (2040)	7.94-6.78 (m, 4 H)	0.95 (d, J = 6.4)

[a] Satisfactory analytical data were obtained for all compounds. [b] Reaction time is 3 h for the *p*-nitro compounds and 12 h for the *o*-nitro compounds. [c] Solvent is dioxane. [d] AB quartet.

Scheme III



ring inversion or to mixtures of isomers (methyl cis or trans to phenyl) since similar effects are absent in the 4-methyl compounds. It is most likely due to the steric hindrance to rotation about Ph–N bond in addition to the chirality in the piperidine ring. Both of these factors appear to influence the environment of the methyl group in **6e** and **6f**. Further work to resolve this problem is in progress.

The amine oxides **6** undergo thermal rearrangement to the *O*-arylhydroxylamines **7** in high yields when heated in dioxane (Table III, Scheme II). The structure of the rearrangement products was established by IR, NMR, elemental analysis, and hydrolysis. Thus treatment of **7** with 30% hydrochloric acid afforded the corresponding substituted phenols having identical properties with those of reference samples.

The rearrangement **6** → **7** is reminiscent of the Meisenheimer isomerization of tertiary *N*-oxides. The electron deficiency of the aryl carbon (directly attached to the N–O function) brought about by the NO_2 and the *N*-oxide groups provides the impetus for this novel rearrangement. In agreement with this hypothesis, the presence of an electron-donating group (e.g., CH_3) instead of NO_2 prevents the hydroxylamine formation, and such *N*-oxides are thermally stable.

The mechanism of the rearrangement is best described by an intramolecular cyclic process (S_Ni, Scheme III) rather than a homolytic process as suggested for Meisenheimer transformation in other systems. The benzyl group migrates from N to O via radical intermediates during rearrangement of benzyldimethylamine oxide[7] and *N*-benzyl-*N*-methylaniline *N*-oxide.[6,8,9] Neopentyl[10] and homoadamantyl[12] groups also migrate via free radicals during thermolysis of their *N*-oxides.

Table IV. Rearrangement of 6 in Dioxane

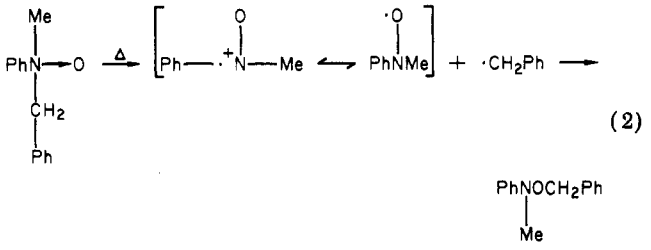
compd	temp, °C	10^4k,[a] s^{-1}	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
6a	55.6	4.26 ± 0.15	21.8 ± 0.6	−8 ± 1.8
	61.9	7.01 ± 0.29		
	68.0	14.32 ± 0.52		
	73.9	25.13 ± 1.84		
	79.7	42.15 ± 2.2		
6b	65.3	1.55 ± 0.08	24.1 ± 0.92	−5 ± 2.6
	70.1	2.91 ± 0.16		
	74.3	3.87 ± 0.42		
	80.2	6.70 ± 0.45		
	85.2	13.21 ± 0.83		
6c	78.6	0.81 ± 0.05	26.9 ± 0.52	−1 ± 1.4
	83.1	1.42 ± 0.06		
	85.8	1.93 ± 0.07		
	88.4	2.53 ± 0.11		

[a] Each value is the average of at least three consistent runs.

Kinetics. The rate of rearrangement of **6a–c** was measured in dioxane at four or five temperatures by following the disappearance of the *N*-oxide or the appearance of the rearrangement product as a function of time by UV techniques. The reaction is followed up to 75–90% completion, and in every case good first-order kinetics were observed. Table IV describes the results of the kinetic studies.

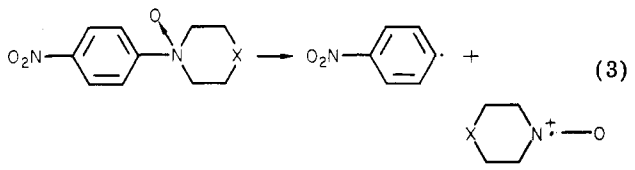
The energy of activation for the isomerization **6** → **7** in dioxane is about 10 kcal smaller than the energy of activation found for the isomerization of *N*-benzyl-*N*-methylaniline *N*-oxide (35 kcal/mol) as reported by Schöllkopf[8] and is consistent with greater ease of rearranging the *N*-oxides **6**. The entropy change associated with the isomerization **6** → **7** deserves further comment. The normal effect of converting the dipolar *N*-oxide to the neutral substituted hydroxylamine should lead to a positive change in entropy. If the aryl group in **6** migrated through a cyclic transition state (Scheme III), a negative entropy of activation would be expected. Hence, a combination of the two effects, the removal of the dipole and a cyclic transition state, might lead to a small positive or even negative entropy change as found in the present study. In fact, the negative entropy of activation for the rearrangement **6** → **7**, although small, indicates a considerable decrease in randomness in the activated complex in agreement with the proposed mechanism (Scheme III). On the other hand, Schöllkopf et al.[8] found that the rearrangement of *N*-benzyl-*N*-methylaniline *N*-oxide in methanol is associated with a positive $\Delta S^{\ddagger}$ (+33 eu), and

this was taken to indicate a cleavage-recombination mechanism (eq 2).



(2)

Similar results were obtained by Shulman et al.[7] for the rearrangement of benzyldimethylamine oxide in which $\Delta S^{\ddagger}$ was +8 eu. The negative entropy of activation found in this study in addition to the great ease of rearrangement is strong evidence against dissociation into radicals (eq 3)



(3)

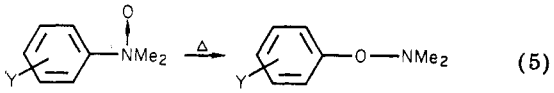
and more in support of an intramolecular cyclic process (Scheme III). Moreover, phenyl radicals are generally much less stable than benzyl radicals. Further justification for the intramolecularity of the rearrangement comes from the observation that mixed rearrangement of **6b** and **6c** produced only the hydroxylamines **7b** and **7c** with no crossover products as shown by thin-layer chromatographic analysis.

It is shown, from the kinetic results, that a simple proportionality between $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ exists for the rearrangement of **6a–c** according to the mathematical expression[15] shown in eq 4, where δ is an operator and β is

$$\delta\Delta H^{\ddagger} = \beta\delta\Delta S^{\ddagger} \quad (4)$$

the isokinetic temperature. Table IV clearly indicates a linear relationship between $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ for rearrangement of **6a–c**. Such correlation indicates that these quantities are caused by a change in the strength of the interaction involving just a single mechanism.

The position of the electron-withdrawing group on the benzene nucleus is of utmost importance. It must be ortho or para relative to the >N–O function, since only in these positions can the NO_2 group delocalize the incoming negative charge carried by the attacking oxygen (Scheme III). The more effective the delocalization of the negative charge is, the greater the ease of the rearrangement. This was shown with substituted *N,N*-dimethylaniline *N*-oxides[13] (eq 5). The migration of the benzene nucleus



(5)

Y = *p*-NO_2, *o*-NO_2, *p*-CN, *p*-PhCO

takes place only when the substituent is ortho or para relative to >N–O. With the *m*-nitro compound (eq 5, Y = *m*-NO_2) no isomerization could be detected, and the *N*-oxide was recovered uncharged quantitatively.

It is important to stress further the effect of the electron-withdrawing substituents on the course of the rearrangement since unsubstituted *N*-oxide (eq 5, Y = H) does not undergo rearrangement even at elevated temperature, and *N*-oxides with electron-donating substituents (eq 5, Y = CH_3, Cl) on heating show no tendency to undergo rearrangement.

Experimental Section

Instrumentation. Nuclear magnetic resonance (NMR) spectra were recorded for identification purposes in deuteriochloroform solutions on Varian A-60D and Bruker WH90 spectrometers. Chemical shifts are expressed in parts per million (δ) with tetramethylsilane as the internal marker. Ultraviolet spectra were recorded on a Pye-Unicam SP-1800 spectrophotometer. Melting points were determined with a Gallenkamp apparatus and are uncorrected.

(A) General Procedure for Preparation of the Tertiary Amines. A mixture of *p*-nitrofluorobenzene or *o*-nitrofluorobenzene (0.094 mol) and the appropriate secondary amine (0.282 mol) in dimethyl sulfoxide (50 mL) was stirred for 24–90 h at 50–100 °C. The tertiary amine was precipitated by the addition of water and recrystallized from the appropriate solvent (Table I).

(B) General Procedure for Preparation of Tertiary Amine Oxides. To an ice-cooled solution of the appropriate amine (0.025 mol) in 50–100 mL of 98% formic acid was added 17.5 mL of 30% hydrogen peroxide slowly. The reaction mixture was stirred for 12–36 h at room temperatur. The formic acid was neutralized with solid anhydrous sodium carbonate with cooling and stirring followed by extraction with four 150-mL portions of chloroform. The combined chloroform extracts were evaporated in vacuo, and the resulting *N*-oxide was washed with dry ether until the ether was no longer colored. The crude product was purified by column chromatography using basic aluminum oxide. The *N*-oxide was released by elution with methanol–chloroform (1:3) and recrystallized from ethanol–ether. The ether washings from oxidation of the amine **5a** were combined and the resulting yellow semisolid was chromatographed on alumina with 1:1 chloroform–petroleum ether as eluant, yielding 25% of the hydroxylamine **7a**. The appearance of rearrangement products was also observed during oxidation of the *p*-nitrophenylamines **5b,e,g,i** in a yield between 10% and 30%. The *N*-oxide hydrochlorides were prepared by passing dry HCl gas into a solution of the *N*-oxide in chloroform to the point of turbidity. Refrigeration produced the hydrochlorides (**6**·HCl) which were recrystallized from ethanol–ether (Table II).

(C) General Procedure for the Rearrangement of the *N*-Oxides. A suspension of the amine oxide (1.5 g) in dry dioxane (70 mL) was heated at reflux with constant stirring for 3 h (*p*-nitro compounds) or 12 h (*o*-nitro compounds). After the mixture cooled, the solvent was stripped off, and the semisolid product was chromatographed on neutral alumina with chloroform–petroleum ether as the eluent, giving the *O*-arylhydroxylamines **7** (Table III).

Hydrolysis of the *O*-Arylhydroxylamines 7. A known weight of the hydroxylamine **7** was refluxed for 2 h in 3 equiv of 30% HCl. The reaction mixture was extracted with ether. The combined ethereal extracts were dried (K_2CO_3), and the solvent was evaporated. The pale yellow solid was characterized as *o*-nitrophenol (mp 42–44 °C) or *p*-nitrophenol (mp 113–114 °C) by comparison with authentic samples (mixture melting point, IR, NMR).

Kinetic Measurements. Reaction rates were determined spectrophotometrically by noticing the absorbance at λ_{max} of the *N*-oxide **6** or the product **7** as a function of time. Runs were carried out in triplicate to 70–90% completion at four or five temperatures. A stream of water at constant temperature was circulated from a thermostat through the jacket of the cell house of the UV spectrophotometer (Pye-Unicam Sp 1800 with a thermostat attachment). The temperature of the UV cuvette was maintained constant within ±0.2 °C. A stock solution was obtained by dissolving 0.01 g of a freshly prepared amine oxide in 10 mL of dry dioxane. A 0.2–0.6-mL sample of this solution was diluted with a thermostated solvent in a 10-mL volumetric flask

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(16) H. Suhr, *Justus Liebigs Ann. Chem.*, **689**, 109–117 (1965).
(17) M. Seikel, *J. Am. Chem. Soc.*, **62**, 750 (1940).
(18) C. B. Kremer, M. Meltsner, and L. Greenstein, *J. Am. Chem. Soc.*, **61**, 2552 (1939).

to obtain a (1–6) × 10^{-4} M solution of the amine oxide. Measurement of absorbance at λ_{max} for the *N*-oxide or the rearrangement product began immediately.

Reaction rate constants were calculated from the slope of ln $(A_t - A_\infty)$ vs. time for experiments in which the rate of the disappearance of the *N*-oxide was followed or from ln $(A_\infty - A_t)$ vs. time in cases where the rate of product formation was followed. In all cases the least-squares plots of log $(A_t - A_\infty)$ or log $(A_\infty - A_t)$ vs. time were linear. An Arrhenius plot of ln k vs. $1/T$ gives the energy of activation and the frequency factor from which the entropy of activation could be calculated by using eq 6 and 7.

$$\ln k - \ln A = E_a/RT \quad (6)$$

$$\ln A = \ln (ekT/h) + \Delta S^*/R \quad (7)$$

Least squares plots of ln k vs. $1/T$ for rearrangement of **6a–c** were linear.

Crossover Experiment. A mixture of **6b** and **6c** (0.5 g of each) was dissolved in dioxane and heated at reflux (100 °C) for 3 h (over 3 half-lives of **6c**). The solvent was stripped off, and the resulting residue was analyzed by thin-layer chromatography and showed only two spots corresponding to **7b** and **7c**: R_f (25% benzene–75% petroleum ether 80–100 °C) of **7b**, 0.953; R_f of **7c**, 0.869; authentic **7b**, R_f 0.957; authentic **7c**, R_f 0.871.

Registry No. **5a**, 6574-15-8; **5b**, 10389-51-2; **5c**, 15822-77-2; **5d**, 5320-98-9; **5e**, 15822-71-6; **5f**, 15822-78-3; **5g**, 78019-75-7; **5h**, 78019-76-8; **5i**, 78019-77-9; **5j**, 78019-78-0; **6a**, 40832-54-0; **6a**·HCl, 78019-79-1; **6b**, 40832-53-9; **6b** picrate, 78019-80-4; **6b**·HCl, 78019-81-5; **6c**, 54399-43-8; **6c**·HCl, 78019-82-6; **6d**, 78019-83-7; **6d** picrate, 78019-84-8; **6e**, 78019-85-9; **6e**·HCl, 78019-86-0; **6f**, 78019-87-1; **6f**·HCl, 78019-88-2; **6g**, 78019-89-3; **6g**·HCl, 78019-90-6; **6h**, 78019-91-7; **6h**·HCl, 78019-92-8; **6i**, 78019-93-9; **6i**·HCl, 78019-94-0; **6j**, 78019-95-1; **6j**·HCl, 78019-96-2; **7a**, 78039-75-5; **7b**, 78019-97-3; **7c**, 78019-98-4; **7d**, 78019-99-5; **7e**, 78020-00-5; **7f**, 78020-01-6; **7g**, 78020-02-7; **7h**, 78039-76-6; **7i**, 78020-03-8; **7j**, 78039-77-7; piperidine, 110-89-4; morpholine, 110-91-8; 2-methylpiperidine, 109-05-7; 3-methylpiperidine, 626-56-2; 4-methylpiperidine, 626-58-4; *p*-nitrofluorobenzene, 350-46-9; *o*-nitrofluorobenzene, 1493-27-2.

Thiol–Oxygen Cooxidation Reactions of Cyclopentene, *cis*- and *trans*-But-2-ene, Norbornene, and Norbornadiene

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Thiol–oxygen cooxidation (TOCO) of olefins, followed by reduction of the initially formed hydroperoxides with triphenylphosphine, affords β-hydroxy sulfides in moderate to good yields. The structures of the major products from *cis*- and *trans*-but-2-ene and from cyclopentene indicate that coupling of the intermediate β-thioalkyl radicals with oxygen occurs mainly anti to the sulfur substituent but proceeds too slowly to compete effectively with internal rotation about the C_α–C_β bond. TOCO reactions of aromatic thiols with norbornene involve preferential exo addition of arylthio radicals to the double bond followed by coupling with oxygen in both exo and endo modes; the exo/endo ratio is sensitive to the nature of the thiol. TOCO reactions of norbornadiene afford, inter alia, hydroxy sulfides containing the tricyclene nucleus.

Thiol–oxygen cooxidation (TOCO) reactions[1,2] of olefins and reactive arenes afford convenient and efficient routes to hydroperoxy sulfides or hydroperoxy thioesters and compounds derived therefrom such as hydroxy sulfoxides,[2] aryl thioethers and thioesters,[3] and dihydroarene bis(thioethers).[3] Notable features of TOCO reactions, which can be applied to the preparation of useful synthons,[4-6] are their susceptibility to initiation by free-radical precursors, their propensity to rapidly afford high yields of products, and their relative freedom from side reactions.

These and other features of TOCO reactions are consistent with the free-radical mechanism first enunciated by Kharasch.[7] It involves three chain-propagation steps. In the first (eq 1), addition of thiyl radicals proceeds regioselectively at the less substituted terminus of an olefinic bond, or, in the case of arenes, to a position of high free valence.[3] The regioselectivity of the addition is consistent both with the steric effects of substituents on radical reactions[8,9] and with their expected polar effects[9] on attack by electrophilic species.[10] Rate constants for step 1 are available from studies of free-radical additions of thiols and olefins;[11] typical values of k_1 lie in the range 10^4–10^7 M^{-1} s^{-1}. Recent determinations[12] give values of 2.7 × 10^5 and 2 × 10^8 s^{-1} for k_{-1} in reactions involving elimination of BuS· and PhS· respectively[13] (eq 1-3).

The second propagation step (eq 2) is expected to be very fast. Although rate constants have not been precisely

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