Articles

Polar Effects in Free-Radical Reactions. Homolytic Heteroaromatic Substitutions by Alkyl Bromides

Francesco Minisci,* Francesca Fontana,* Giuseppe Pianese, and Yong Ming Yan

Dipartimento di Chimica del Politecnico, piazza Leonardo da Vinci 32, 20133 Milano, Italy

Received March 10, 1993

Alkyl bromides have been utilized for the first time as radical sources for heteroaromatic substitution. A variety of procedures was revealed to be successful for bromine abstraction: Bu_3SnH with AIBN, $(Me_3Si)_3SiH$ with AIBN, PhSiH, Ph_2SiH_2, or Et_3SiH associated with peroxides (H_2O_2, t-BuOOH, $(t\text{-BuO})_2$, $(t\text{-BuOOCO})_2$, $(PhCOO)_2$). The importance of the polar effects is discussed.

Recently,[1] we developed simple and selective sources of alkyl radicals from alkyl iodides for synthetic purposes. They are based on iodine abstraction from alkyl iodides by aryl or methyl radicals. Aryl radicals were generated by acyl peroxides[1a,b] or by diazonium salts,[1b,c] whereas methyl radicals were produced by a variety of simple sources (DMSO + H_2O_2,[1d,e,f] MeCOMe + H_2O_2,[1d,g] t-BuOOH,[1h] t-BuOOBu-t,[1h] MeCOOOCOMe,[1i] MeCOOH + $S_2O_8^{2-}$,[1i] t-BuOOCOOCOOBu-t).

Such reactions are not suitable for alkyl bromides because bromine abstraction by aryl or methyl radicals is slower than iodine abstraction, and therefore the reaction is not selective in this case, as hydrogen abstraction from C–H bonds or addition to double bonds or to aromatic rings become competitive processes. This difference in behavior would appear to be due more to a different mechanism of atom transfer than to the bond strengths: bromine transfer is characterized by a classical transition state (eq 2), while iodine abstraction would be characterized by a much faster and more selective addition–elimination mechanism[1e,f,2] (eq 3).

$$RI + {}^{\bullet}Ar\ (Me^{\bullet}) \rightarrow R^{\bullet} + ArI\ (MeI) \qquad (1)$$

$$RBr + {}^{\bullet}X \rightarrow [R\cdot\cdot X\cdot\cdot Br]^{\ddagger} \rightarrow R^{\bullet} + BrX \qquad (2)$$

$$RI + X^{\bullet} \rightleftharpoons R\text{–}\dot{I}\text{–}X \rightarrow R^{\bullet} + IX \qquad (3)$$

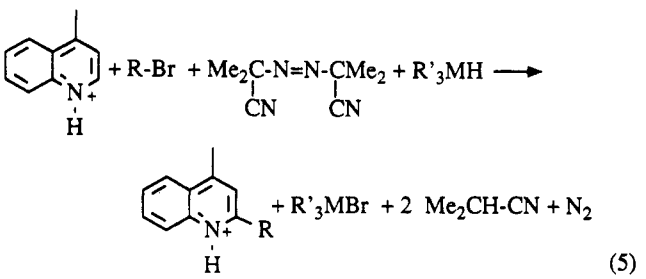
In order to utilize alkyl bromides as sources of alkyl radicals useful for homolytic aromatic substitutions, we have taken advantage of the well-known[3] high rate of bromine abstraction by tin and silicon radicals (eq 4). Thus, we utilized Bu_3SnH, $(Me_3Si)_3SiH$, Ph_2SiH_2, $PhSiH_3$, and Et_3SiH as sources of tin and silicon radicals.

$$R\text{-}Br + {}^{\bullet}M\text{<} \longrightarrow {}^{\bullet}R + Br\text{-}M\text{<} \qquad (4)$$

M = Sn or Si
$k = 10^8\text{–}10^9\ M^{-1}s^{-1}$

Results

Tributyltin hydride. Bu_3SnH reacts in refluxing acetonitrile with alkyl bromides and stoichiometric amounts of azobisisobutyronitrile (AIBN) in the presence of protonated lepidine to give the selective substitution in position 2 (eq 5). The Bu_3SnH solution was dropped in



$$+ R\text{-}Br + Me_2C(CN)\text{-}N{=}N\text{-}C(CN)Me_2 + R'_3MH \longrightarrow$$

$$+ R'_3MBr + 2\ Me_2CH\text{-}CN + N_2 \qquad (5)$$

M = Sn, Si R' = *n*-Bu, Me_3Si

the reaction mixture in order to keep its stationary concentration low. The results with a primary, a secondary, and a tertiary alkyl bromide are reported in Table I.

Tris(trimethylsilyl)silane (TTMSS). $(Me_3Si)_3SiH$ reacts with alkyl bromides and protonated lepidine under the same conditions used for Bu_3SnH to give the same substitution (eq 5). The results are reported in Table II.

Monophenyl-, Diphenyl- and Triethylsilanes. Several radical sources were utilized. **(i) Acetone and H_2O_2.** Ph_2SiH_2 and Et_3SiH react with alkyl bromides in refluxing acetone and H_2O_2 in the presence of protonated heteroaromatic bases to give the selective alkylation of the heterocyclic ring (eq 6). The results with a variety of heteroaromatic bases are reported in Table III.

(ii) *tert*-Butyl Hydroperoxide. Ph_2SiH_2 and t-BuOOH react in acetonitrile with cyclohexyl bromide in the presence of protonated lepidine and a catalytic amount of Fe(III) salt, according to eq 7.

(1) (a) Minisci, F.; Tortelli, V.; Vismara, E.; Castaldi, G. *Tetrahedron Lett.* **1984**, *25*, 3897. (b) Minisci, F.; Vismara, E.; Fontana, F.; Morini, G.; Serravalle, M.; Giordano, C. *J. Org. Chem.* **1986**, *51*, 4411. (c) Citterio, A.; Minisci, F. *J. Org. Chem.* **1982**, *47*, 1759. (d) Fontana, F.; Minisci, F.; Vismara, E. *Tetrahedron Lett.* **1988**, *29*, 1975. (e) Minisci, F.; Vismara, E.; Fontana, F. *J. Org. Chem.* **1989**, *54*, 5224. (f) Minisci, F.; Coppa, F.; Fontana, F.; Pianese, G.; Zhao, L. *J. Org. Chem.* **1992**, *57*, 3929. (g) Coppa, F.; Fontana, F.; Minisci, F.; Nogueira Barbosa, M. C.; Vismara, E. *Tetrahedron* **1991**, *47*, 7343. (h) Fontana, F.; Minisci, F.; Nogueira Barbosa, M. C.; Vismara, E. *Acta Chem. Scand.* **1989**, *43*, 995. (i) Minisci, F.; Vismara, E.; Fontana, F. *Heterocycles* **1989**, *28*, 489.

(2) Minisci, F. *Sulfur-Centered Reactive Intermediates in Chemistry and Biology*; Chatgilialoglu, C., Asmus, K. D., Eds.; Plenum Press: New York, 1990; pp 303–317.

(3) Chatgilialoglu, C.; Ingold, K. U.; Scaiano, J. C. *J. Am. Chem. Soc.* **1982**, *104*, 5123.

0022-3263/93/1958-4207$04.00/0

Table I. Alkylation of Position 2 of Lepidine by Alkyl Bromides, Bu_3SnH, and AIBN

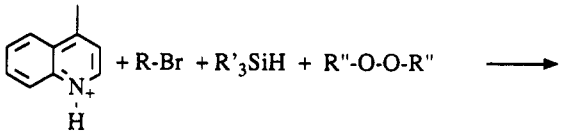
alkyl bromide	conversn (%)	yield[a] (%)
n-hexyl	34	42
cyclohexyl	41	95
tert-butyl	44	100

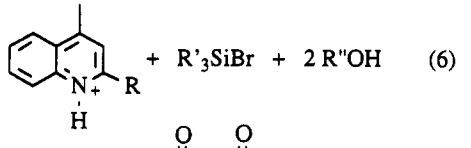
[a] Based on the converted heterocyclic base.

Table II. Alkylation of Position 2 of Lepidine by Alkyl Bromides, TTMSS, and AIBN

alkyl bromide	conversn (%)	yield[a] (%)
n-hexyl	43	71
cyclohexyl	54	94
tert-butyl	87	100

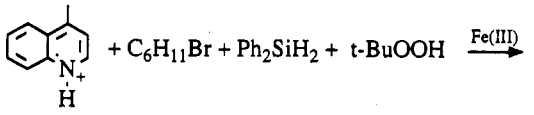
[a] Based on the converted heterocyclic base.

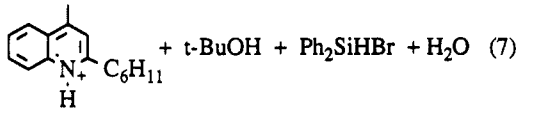




(6)

R" = H, *t*-Bu, *t*-BuO-C(=O)-, Ph-C(=O)-





(7)

(iii) Di-*tert*-butyl Peroxide, *tert*-Butyl Peroxyoxalate, and Benzoyl Peroxide. Thermal decomposition of $(t\text{-BuO})_2$, $(t\text{-BuOOCO})_2$, or $(PhCOO)_2$ in the presence of an alkyl bromide, Ph_2SiH_2, $PhSiH_3$, or Et_3SiH and a protonated heteroaromatic base leads to the selective alkylation of the heterocyclic ring according to eq 6. The best results were obtained with *tert*-butyl peroxyoxalate; they are reported in Table IV.

Discussion

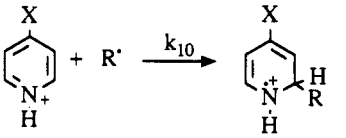
Tributyltin Hydride. Bu_3SnH rapidly reacts with carbon-centered radicals to generate tin radicals[4] (eq 8).

$$Bu_3SnH + {}^{\bullet}R \xrightarrow{k_8} Bu_3Sn^{\bullet} + RH \qquad (8)$$
$$k_8 \approx 10^6\ M^{-1}\ s^{-1}$$

On the other hand, $Bu_3Sn^{\bullet}$ radical rapidly reacts with alkyl bromides[3] to generate alkyl radicals in a chain process (eq 9). Two main problems arise in the attempt to use radical

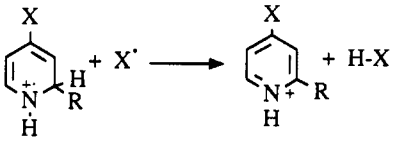
$$Bu_3Sn^{\bullet} + RBr \xrightarrow{k_9} Bu_3SnBr + R^{\bullet} \qquad (9)$$
$$k_9 \approx 10^8\ M^{-1}s^{-1}$$

$R^{\bullet}$ from eq 9 for the aromatic substitution; the first one concerns the competition of eq 8. Thus, only aromatic substrates, whose reaction rates with alkyl radicals are of the same order of magnitude or faster than Bu_3SnH (eq 10) are suitable for this homolytic substitution. This is the case for protonated heteroaromatic bases with nucleophilic alkyl radicals[1i] (alkyl radicals without electron-withdrawing groups directly bonded to the free-radical center) (eq 10). The second problem is related to the

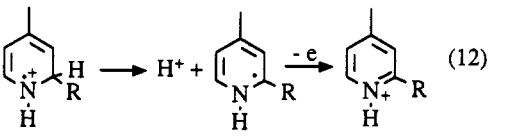


(10)

$k_{10} \sim 10^5$-$10^8\ M^{-1}s^{-1}$



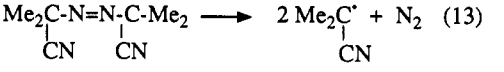
(11)



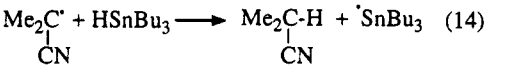
(12)

rearomatization of the radical adduct, which cannot take place by a chain process with Bu_3SnH but could occur either through hydrogen abstraction from an intermediate radical (eq 11) or by an electron-transfer oxidation (eq 12).

The first problem was solved by keeping a low stationary concentration of Bu_3SnH through slow addition during the reaction. Attempts to use oxidizing conditions suitable for eq 12 failed because oxidation of the tin hydride or of the $Bu_3Sn^{\bullet}$ radical competes with the aromatic substitution. Thus, we considered the possibility of rearomatization according to eq 11 by using stoichiometric amounts of AIBN as the initial source of radicals (eq 13). Polar



(13)



(14)

effects determine the success of the substitution because the α-cyanoisopropyl radical has a somewhat electrophilic character, due to the proximity of the cyano group to the radical center, so that it does not react with protonated heteroaromatic bases, while it abstracts hydrogen from Bu_3SnH (eq 14).

The tributyltin radical rapidly abstracts a bromine atom according to eq 4, thus generating a nucleophilic alkyl radical, which can then react either with Bu_3SnH (eq 8) in a chain process or with a protonated heteroaromatic base; the rate constants, k_8 and k_{10}, are of the same order of magnitude,[1i] so that addition to the heterocyclic ring prevails if a higher concentration of the heteroaromatic base is kept in the reaction medium compared to that of Bu_3SnH. The radical adduct with the heterocyclic ring (eq 10) is a stabilized cyclohexadienyl-type radical, which can reach a stationary concentration suitable for inter-

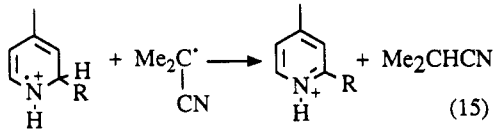
(4) Chatgilialoglu, C.; Ingold, K. U.; Scaiano, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 7739.
(5) Minisci, F.; Fontana, F.; Vismara, E. *J. Heterocycl. Chem.* **1990**, *27*, 79.

Table III. Alkylation of Heteroaromatic Bases by Alkyl Bromides, Silanes, and H_2O_2

heterocyclic base	alkyl bromide	silane	orientation (%)	conversn (%)	yield[a] (%)
quinoline	n-hexyl	Ph_2SiH_2	2 (64), 4 (36)	28	52
quinoline	cyclohexyl	Ph_2SiH_2	2 (56), 4 (44)	57	96
quinoline	cyclohexyl	$PhSiH_3$	2 (54), 4 (46)	61	98
quinoline	cyclohexyl	Et_3SiH	2 (56), 4 (44)	38	92
quinoline	*tert*-butyl	Ph_2SiH_2	2	67	86
quinoline	*tert*-butyl	$PhSiH_3$	2	70	93
lepidine	n-hexyl	Ph_2SiH_2	2	37	45
lepidine	cyclohexyl	Ph_2SiH_2	2	50	83
lepidine	cyclohexyl	$PhSiH_3$	2	42	82
lepidine	cyclohexyl	Et_3SiH	2	38	91
lepidine	*tert*-butyl	Et_3SiH	2	15	95
lepidine	*tert*-butyl	Ph_2SiH_2	2	44	76
quinaldine	cyclohexyl	Ph_2SiH_2	4	53	74
quinaldine	cyclohexyl	$PhSiH_3$	4	62	86
quinaldine	cyclohexyl	Et_3SiH	4	28	91
4-cyanopyridine	cyclohexyl	Ph_2SiH_2	2 (86), 2,6 (14)	71	72
benzothiazole	cyclohexyl	Ph_2SiH_2	2	64	39

[a] Based on the converted heteroaromatic base.

cepting an α-cyanoisopropyl radical, leading to the substitution product (eq 15).



(15)

Tris(trimethylsilyl)silane (TTMSS). $(Me_3Si)_3SiH$ has been reported[6] to be preferable to Bu_3SnH, since its use avoids the need for a special workup procedure; moreover, TTMSS and its silicon-containing byproducts are less toxic than the corresponding tin compounds.

Under the same conditions utilized with Bu_3SnH, TTMSS gave a quite similar reaction (eq 5). The results are somewhat better than those obtained by Bu_3SnH; this can be related to the fact that hydrogen abstraction from TTMSS by alkyl radicals (eq 16) is slower by 1 order of

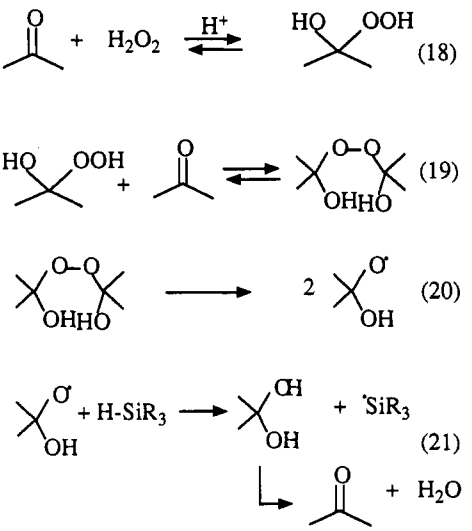
$$R^{\bullet} + HSi(SiMe_3)_3 \xrightarrow{k_{16}} RH + {}^{\bullet}Si(SiMe_3)_3 \qquad (16)$$
$$k_{16} \approx 10^5\ M^{-1}s^{-1}$$

magnitude than the abstraction from Bu_3SnH (eq 8). Thus, the competition of eq 16 is less important than that of eq 8.

Monophenyl-, Diphenyl- and Triethylsilanes. $PhSiH_3$, Ph_2SiH, and Et_3SiH are much cheaper than TTMSS and Bu_3SnH, but the SiH bond strengths are significantly higher (BDE for Et_3SiH, $PhSiH_3$, $(Me_3Si)_3SiH$, and Bu_3SnH are, respectively, 90.1, 88.2, 79.0, and 74.0 kcal/mol),[7] which do not allow hydrogen abstraction by the α-cyanoisopropyl radical; therefore, the procedure above discussed for Bu_3SnH and TTMSS is not suitable for these silanes. Thus, we developed new procedures which take advantage of the fact that oxygen-centered radicals rapidly and selectively abstract hydrogen atoms from silanes[7] (eq 17). The thermal decomposition of hydrogen peroxide in

$$Et_3Si\text{-}H + t\text{-}BuO^{\bullet} \xrightarrow{k_{17}} Et_3Si^{\bullet} + t\text{-}BuOH \qquad (17)$$
$$k_{17} \approx 5.7 \times 10^6\ M^{-1}\ s^{-1}$$

refluxing acetone is a very simple and cheap source of oxygen-centered radicals, which has been developed in this laboratory. Since H_2O_2 does not undergo homolysis under these mild conditions, we explain the formation of silyl radicals by eqs 18–21. Silyl radicals abstract bromine



atoms very rapidly from alkyl bromides (eq 22). The

$$RBr + {}^{\bullet}SiEt_3 \xrightarrow{k_{22}} {}^{\bullet}R + BrSiEt_3 \qquad (22)$$
$$k_{22} = 10^8\text{–}10^9\ M^{-1}s^{-1}$$

addition of the alkyl radicals to the heterocyclic ring and the subsequent oxidation of the radical adduct occurs according to the general mechanism of the heterocyclic substitution under oxidizing conditions.[1i,5] The main inconvenience of the procedure is related to the slow homolysis of the acetone peroxide (eq 20); this can be reflected in a low selectivity with the less reactive alkyl bromides and the more oxidizable heteroaromatic bases, such as benzothiazole (Table III).

The use of other classical sources of oxygen-centered radicals, such as t-BuOOH (eq 23), $(t\text{-}BuO)_2$ (eq 24), $(t\text{-}BuOOCO)_2$ (eq 25), and $(PhCOO)_2$ (eq 24) was successful; *tert*-butyl peroxyoxalate gave the higher selectivity. This could be explained by the milder experimental conditions, which limit the competitive β-fission of the oxygen-centered radicals, a more significant byprocess at higher temperatures. Again, polar effects are mainly responsible for the success of the heteroaromatic substitution because

(6) Chatgilialoglu, C. *Acc. Chem. Res.* **1992**, *25*, 188.
(7) Kanabus-Kaminska, M.; Hawari, J. A.; Griller, D.; Chatgilialoglu, C. *J. Am. Chem. Soc.* **1987**, *109*, 5267.

$$t\text{-BuOOH} + \text{Fe(III)} \longrightarrow t\text{-BuO}^{\cdot} + \text{H}^{+} + \left[\text{Fe}=\text{O}\right] \quad (23)$$

$$\text{ROOR} \longrightarrow 2\,\text{RO}^{\cdot} \quad (24)$$

R = t-Bu, PhCO

$$(t\text{-BuOOCO})_2 \longrightarrow 2\,\text{t-BuO}^{\cdot} + 2\,\text{CO}_2 \quad (25)$$

oxygen-centered radicals are electrophilic and do not react with protonated heteroaromatic bases, but they determine, through the silyl radicals, the formation of nucleophilic carbon-centered radicals from alkyl bromides. The importance of the polar effect clearly appears also from the fact that no substitution occurs in all cases with alkyl bromides bearing electron-withdrawing groups in the α-position (e.g., $BrCH_2COOR$, $BrCH_2COR$, BrCH(R)-COOR, BrC(R)(R')COOR, $BrCH_2CN$, $BrCH(COOR)_2$, etc.). Recently, the concept of ambiphilic radical has been developed[8] for radical $\cdot CH_2COOR$ because both polar SOMO–LUMO and SOMO–HOMO interactions would lower the transition-state energy and therefore increase the rate constants for addition to alkenes with both electron-withdrawing and electron-releasing groups. This certainly is not the case for the same radicals in reactions with protonated bases and diazonium salts,[1f] in which the polar effect is the dominant factor determining reactivity with carbon-centered radicals. In these cases, the polar SOMO–LUMO interactions play a fundamental role in lowering the activation energy,[9] whereas the SOMO–HOMO interactions appear to be quite unimportant. It may be that what appears to be an ambiphilic polar character for the reaction of $\cdot CH_2COOR$ radical with alkenes actually is the result of the superimposition of polar and enthalpic effects. With protonated heteroaromatic bases and diazonium salts this superimposition would be much less significant because polar effects are much more important than enthalpic effects compared to the reaction of the same carbon-centered radicals with alkenes.

Experimental Section

General Methods. The starting materials (alkyl bromides, heteroaromatic bases, Bu_3SnH, TTMSS, $PhSiH_3$, Ph_2SiH_2, Et_3SiH, AIBN, peroxides) were obtained from commercial suppliers and used without further purification. The reaction products were analyzed by GC–MS, purified by flash chromatography on Merck silica gel 60/230–400 mesh (eluent hexane/AcOEt (90:10)), and identified by NMR and MS spectra. NMR spectra were recorded in $CDCl_3$ on Bruker AC 250 or AM 300 MHz spectrometers; MS were obtained at 70-eV on Hitachi RMU-60 or VG ZAB instruments. GC–MS analyses were obtained on a Varian Mat 112 F GC–MS spectrometer equipped with a SP2100 coated fused silica capillary column (25 m × 0.22-mm i.d.) with helium as carrier gas. Quantitative GC analyses were performed by the internal standard method on a DANI 6500 HR capillary gas chromatograph equipped with a PTV injector, a WSCOT capillary column (25 m × 0.22-mm i.d.) coated with polydimethylsiloxane (CP-Sil 5, film thickness 1 μm, FID detector, hydrogen as carrier gas, and temperature programmed from 50 to 190–250 °C at 10°/min.

Alkylation of Lepidine by Alkyl Bromides, Bu_3SnH, and AIBN. A solution of Bu_3SnH (2 mmol) and AIBN (2 mmol) in 5 mL of benzene was added dropwise over 2 h to a refluxing solution of lepidine (2 mmol), CF_3COOH (2 mmol) and alkyl bromide (5 mmol) in 10 mL of benzene. The solution was refluxed for 15 additional min and then washed with 5% aqueous NaOH and analyzed by GLC with quinoline as internal standard. The results are reported in Table I; only the position 2 on the heterocyclic ring is substituted. The pure products were identified by NMR and MS spectra.

Alkylation of Lepidine by Alkyl bromides, TTMSS, and AIBN. The reaction was carried out as above by using 2 mmol of TTMSS instead of Bu_3SnH. The results are reported in Table II.

Alkylation of Heteroaromatic Bases by Alkyl Bromides, Silanes, and H_2O_2. A solution of 2 mmol of heteroaromatic base, 6 mmol of H_2SO_4, 6 mmol of H_2O_2, 4 mmol of alkyl bromide, and 6 mmol of silane in 25 mL of acetone was refluxed for 12 h. The solution was then diluted with water, made basic with 5% aqueous NaOH, and extracted with CH_2Cl_2. The reaction products were analyzed by GLC with quinoline as internal standard. Pure products were isolated by flash chromatography. The results are reported in Table III.

Alkylation of Lepidine and Quinoline by Alkyl Bromides, Silanes, and Benzoyl Peroxide. A solution of 2 mmol of heteroaromatic base, 2 mmol of CF_3COOH, 5 mmol of alkyl bromide, 5 mmol of silane, and 2 mmol of benzoyl peroxide in 20 mL of benzene was refluxed for 4 h. The solution was then diluted with water, made basic with 5% aqueous NaOH, and extracted with CH_2Cl_2. The reaction products were analyzed by GLC. Pure products were isolated by flash chromatography. The results are reported in Table IV.

Cyclohexylation of Lepidine by Cyclohexyl Bromide, Ph_2SiH_2, and t-BuOOH. A solution of lepidine (2 mmol), CF_3COOH (2 mmol), cyclohexyl bromide (4 mmol), Ph_2SiH_2 (5 mmol), t-BuOOH (4 mmol), and $Fe(OAc)_2OH$ (0.2 mmol) in 20 mL of acetonitrile was refluxed for 15 h. The solution was then diluted with water, made basic with 5% aqueous NaOH, and extracted with CH_2Cl_2. The reaction products were analyzed by GLC. The conversion of lepidine was 34%, and the yield of 2-cyclohexyl-4-methylquinoline, isolated by flash chromatography, based on the converted lepidine, was 54%.

Cyclohexylation of Lepidine by Cyclohexyl Bromides, Ph_2SiH_2, and $(t\text{-BuO})_2$. A solution of lepidine (2 mmol), CF_3COOH (2 mmol), cyclohexyl bromide (4 mmol), Ph_2SiH_2 (5 mmol), and $(t\text{-BuO})_2$ (4 mmol) in 20 mL of chlorobenzene was refluxed for 15 h. The solution was washed with 5% aqueous NaOH and analyzed by GLC. The conversion of lepidine was 56%, and the yield of 2-cyclohexyl-4-methylquinoline, isolated by flash chromatography, based on the converted lepidine, was 69%.

Alkylation of Lepidine and Quinoline by Alkyl Bromides, Silanes, and $(t\text{-BuOOCO})_2$. A solution of the heteroaromatic base (1 mmol), CF_3COOH (1 mmol), silane (6 mmol), alkyl bromide (4 mmol), and $(t\text{-BuOOCO})_2$ (2 mmol) in 20 mL of benzene was heated for 2 h at 50 °C. The solution was washed with 5% aqueous NaOH and analyzed by GLC. Pure products were isolated by flash chromatography. The results are reported in Table IV.

2-*tert*-Butylquinoline: NMR ($CDCl_3$) δ 1.5 (s, 9H, 3 CH_3), 7.2–8.2 (m, 6H, arom); MS *m/e* 185 (M^+); major peaks 170, 155, 125.

2-*n*-Hexylquinoline: NMR ($CDCl_3$) δ 1.0 (t, 3H, CH_3CH_2), 1.4-2.2 (m, 8H, $-(CH_2)_4-$), 2.9 (t, 2H, quin $-CH_2-$), 7.2–8.2 (m, 6H, arom); MS *m/e* 213 (M^+); major peaks 198, 184, 170, 156, 143, 129.

2-Cyclohexylquinoline: NMR ($CDCl_3$) δ 1.0–2.1 (m, 10H, $-(CH_2)_5-$), 2.8–3.3 (m, 1H, quin $-CH-$), 7.2–8.3 (m, 6H, arom); MS *m/e* 211 (M^+); major peaks 196, 182, 167, 156, 143, 129.

4-*n*-Hexylquinoline: NMR ($CDCl_3$) δ 1.0 (t, 3H, CH_3CH_2), 1.3–2.3 (m, 8H, $-(CH_2)_4-$), 2.8 (t, 2H, quin $-CH_2-$), 7.0 (d 1H, arom in pos 3), 7.3–8.3 (m, 4H, arom), 8.8 (d, 1H, arom in pos 2); MS *m/e* 213 (M^+); major peaks 198, 184, 170, 156, 143, 129.

4-Cyclohexylquinoline: NMR ($CDCl_3$) δ 1.0–2.0 (m, 10H, $-(CH_2)_4-$), 2.9 (m, 1H, quin $-CH-$), 7.1 (d, 1H, arom in pos 3),

(8) Beranek, I.; Fischer, H. *Free Radicals in Synthesis and Biology*; Minisci, F., Ed.; Kluwer Acad. Publ.: Dordrecht, 1989; pp 303–316.
(9) Minisci, F.; Citterio, A. *Advances in Free-Radical Chemistry*; Williams, G. H., Ed.; Heiden: London, 1980; Vol. 6, p 65.

Table IV. Alkylation of Quinoline and Lepidine by Alkyl Bromides, Silanes, and Peroxides

heteroaromatic base	alkyl bromide	silane	peroxide	orientation (%)	conversn (%)	yield[a] (%)
quinoline	*tert*-butyl	$PhSiH_2$	$(t\text{-BuOOCO})_2$	2	90	91
quinoline	*tert*-butyl	Ph_2SiH_2	$(t\text{-BuOOCO})_2$	2	70	79
quinoline	*tert*-butyl	Et_3SiH	$(t\text{-BuOOCO})_2$	2	49	68
quinoline	n-hexyl	Ph_2SiH_2	$(t\text{-BuOOCO})_2$	2 (71), 4 (29)	40	75
quinoline	*tert*-butyl	Ph_2SiH_2	$(PhCOO)_2$	2	46	82
quinoline	*tert*-butyl	$PhSiH_3$	$(PhCOO)_2$	2	54	87
quinoline	cyclohexyl	$PhSiH_3$	$(PhCOO)_2$	2 (47), 4 (53)	38	89
quinoline	cyclohexyl	Ph_2SiH_2	$(PhCOO)_2$	2 (46), 4 (54)	30	91
lepidine	cyclohexyl	Ph_2SiH_2	$(t\text{-BuOOCO})_2$	2	65	94
lepidine	cyclohexyl	$PhSiH_3$	$(t\text{-BuOOCO})_2$	2	72	92
lepidine	*tert*-butyl	$PhSiH_3$	$(t\text{-BuOOCO})_2$	2	76	90
lepidine	cyclohexyl	$PhSiH_3$	$(PhCOO)_2$	2	36	89
lepidine	cyclohexyl	Ph_2SiH_2	$(PhCOO)_2$	2	30	91
lepidine	cyclohexyl	$PhSiH_3$	$(PhCOO)_2$	2	42	86
lepidine	cyclohexyl	$PhSiH_3$	$(PhCOO)_2$	2	43	88
lepidine	*tert*-butyl	Ph_2SiH_2	t-BuOOH	2	35	48
lepidine	cyclohexyl	Ph_2SiH_2	$(t\text{-BuO})_2$	2	56	69

7.3–8.3 (m, 4H, arom), 8.7 (d, 1H, arom in pos 2); MS *m/e* 211 (M^+); major peaks 182, 168, 154, 143, 129, 115, 101.

2-*t*-Butyl-4-methylquinoline: NMR ($CDCl_3$) δ 1.5 (s, 9H, 3 CH_3), 2.7 (s, 3H, quin-CH_3), 7.3 (s, 1H, arom in pos 3), 7.4–8.2 (m, 4H, arom); MS *m/e* 199 (M^+); major peaks 184, 170, 157, 129, 115, 101, 77.

2-*n*-Hexyl-4-methylquinoline: NMR ($CDCl_3$) δ 1.0 (t, 3H, CH_3CH_2), 1.4–2.2 (m, 8H, $-(CH_2)_4-$), 2.7 (s, 3H, quin-CH_3), 2.9 (t, 2H, quin $-CH_2-$), 7.2 (s, 1H, arom in pos 3), 7.4–8.1 (m, 6H, arom); MS *m/e* 227 (M^+); major peaks 212, 197, 182, 168, 144, 129.

2-Cyclohexyl-4-methylquinoline: NMR ($CDCl_3$) δ 1.2–2.1 (m, 10H, $-(CH_2)_5-$), 2.6 (s, 3H, quin-CH_3), 2.7–3.1 (m, 1H, quin –CH–), 7.1 (m, 4H, arom); MS *m/e* 225 (M^+); major peaks 210, 196, 182, 168, 144, 129.

2-Methyl-4-cyclohexylquinoline: NMR ($CDCl_3$) δ 1.2–2.1 (m, 10H, $-(CH_2)_5-$), 2.7 (s, 3H, quin-CH_3), 2.8–3.2 (m, 1H, quin –CH–), 7.2–8.2 (m, 4H, arom); MS *m/e* 225 (M^+); major peaks 210, 196, 182, 168, 129.

2-Cyclohexyl-4-cyanopyridine: NMR ($CDCl_3$) δ 1.3–2.1 (m, 10H, $-(CH_2)_5-$), 2.7–3.0 (m, 1H, py-CH–), 7.2 (s, 1H, arom in pos 3), 7.3–7.5 (d, 1H, arom in pos 5), 8.7–8.9 (d, 1H, arom in pos 6); MS *m/e* 186 (M^+); major peaks 157, 145, 131, 118, 104.

2-Cyclohexylbenzothiazole: NMR ($CDCl_3$) δ 0.8–2.5 (m, 10H, $-(CH_2)_5-$), 2.5–3.3 (m, 1H, bzt-CH), 7.0–8.1 (m, 4H, arom); MS *m/e* 217 (M^+); major peaks 188, 162, 149, 135.