benzaldehyde, 0.23, 0.22; p-(dimethylaminoacetophenone, 0.08, 0.08. Additional spots appeared from the reaction mixture with R_f values of 0.02, 0.05, 0.12, 0.32, and 0.47, which were not identified.

Light Emmission Measurements. The apparatus and techniques used to measure light emission were previously described.[1e,14c,36] For the present measurements, an electrically heated thermostated aluminum block was used in place of the water bath. The o-dichlorobenzene solvent with or without additives (3.00 mL) was thermostated in a 1-cm stoppered cell at 140 °C and injected with 50 μL of a peroxide solution. The cell was rapidly removed, shaken, and returned to the instrument. The output from the PMT was traced on a strip-chart recorder, and the area was integrated with a planimeter. The system was calibrated with tetramethyl-1,2-dioxetane and DBA, where α_T = 36% is assumed.

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Registry No. 1, 83026-53-3; 2, 83026-54-4; 3, 28047-94-1; 4, 5338-94-3; 5, 2124-31-4; 2-[4-(dimethylamino)phenyl]-2-propanol, 83026-55-5; *tert*-butyl hydroperoxide, 75-91-2; α-phenylethyl alcohol, 98-85-1.

Arylation and Heteroarylation of Photochemically Generated Purinyl Radicals[1]

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Neutral purinyl radicals are new transient intermediates in nucleic acid chemistry. Photolysis of 9-substituted 6-iodopurines with ultraviolet light provides an excellent method for generating purin-6-yl radicals (or caged radical pairs), through homolysis of the weak carbon–iodine bond. The intermediacy of these radicals can be inferred from ESR data. When photolysis is carried out in the presence of benzene, the nascent purinyl radicals (or radical pairs) are intercepted and the corresponding 9-substituted 6-arylpurine is isolated. Heteroaromatic arylations also are possible. Thus, photolysis in the presence of *N*-methylpyrrole results in the formation of 9-substituted 6-(*N*-methylpyrr-2-yl)purine. Furan and thiophene derivatives also undergo photoarylation. The products are consistent with the preferred sites for radical attack upon these heteroaromatics. Reaction with diphenyl disulfide results in the formation of the corresponding purinyl thioether.

We have reported recently the use of a diazotization/deamination procedure for the conversion of 6-aminopurine precursors to various 6-halogenated purines.[2] This deamination procedure was utilized for the direct synthesis of the antibiotic nebularine, from readily available adenosine.[3] These reactions apparently proceed via diazotization of the 6-amino group to form unstable intermediate diazonium salts or azo compounds which decompose homolytically under the reaction conditions to generate purinyl radicals. We have discovered that 9-substituted purin-6-yl radicals or corresponding radical pairs can be relatively cleanly generated by the photolysis of 6-iodopurines. This paper reports on the generation and specific arylation and heteroarylation of transient purinyl radicals.

Direct attachment of aryl groups to the purine ring has not been reported to occur in nature. Few 6-arylpurines have been synthesized, although 6-phenylpurine and some *N*-alkyl derivatives have been prepared.[4,5] 6-(3-Methylpyrrol-1-yl)purine, a methylpyrrole attached to purine through the pyrrole nitrogen at position 6, has been prepared from zeatin.[6] Synthetic 2-arylpurines,[7] which have been evaluated as coronary vasodilators, as well as 8-phenylpurines,[8] are also known. The only literature method for direct 6-arylation of purines is nucleophilic displacement of chlorine from 6-chloropurines by phenyllithium. The 6-arylpurines, especially those possessing heterocyclic substituents in the 6-position, bear a structural resemblance to cytokinins such as kinetin and its riboside,[9] although the aminomethylene spacer group is absent in the arylpurines. Synthetic aryl and heteroaryl purines also may be useful as biochemical probes for the study of enzyme-catalyzed reactions.

Results and Discussion

The preparation of biaryls via photolysis of iodo aromatics such as iodobenzene has been the subject of a number of investigations.[10,11] These reactions proceed via homolysis of the weak aryl carbon–iodine bond.[12] Phenyl radicals generated in heteroaromatic solvents such as furan, thiophene, and pyrrole afford modest yields of phenyl-substituted heterocyclic products.[13,14] Preferred sites for radical attack on various heteroaromatics have been experimentally determined.[15] Photoarylations in which a heteroaryl iodide is employed generally proceed as for iodobenzene.[16-18] When shorter wavelength UV light is

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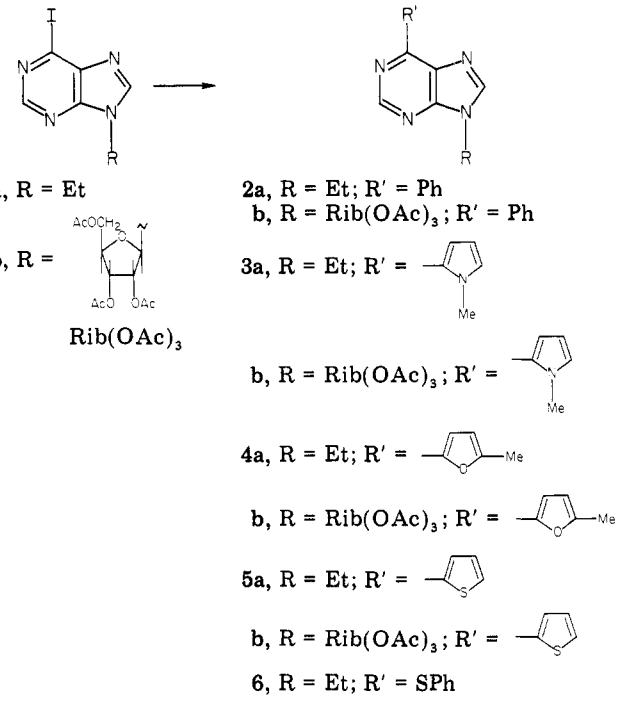
excluded by the use of appropriate filters, no rearrangement of arylated products is observed.[11,16] Reports where both the radical source and the substrate are heteroaromatics are rare.[19-21]

Photoarylation of purine was initially examined with the photolysis of 6-iodo-9-ethylpurine (**1a**) in dry, nitrogen-purged benzene. When ultraviolet radiation was supplied in a Rayonet photolysis apparatus by mercury lamps with the principal wavelength of 2537 Å, the reaction required 24 h. Much shorter reaction times (6 h) are required when a Hanovia 450-W mercury lamp (with Vycor filter) is used. Following removal of solvent and separation on silica gel plates, 6-phenyl-9-ethylpurine (**2a**) was obtained in 54% yield as colorless rods from hexane; mp 61 °C. The phenylpurine was identified by its mass spectrum (m/z 224, M^+), its ^1H and ^{13}C NMR resonances, and its UV data (290.5 nm, ϵ 1.8×10^4). The bathochromic shift observed in the UV spectrum is consistent with extension of conjugation through the phenyl group. Results similar to that observed for **1a** were obtained with the corresponding nucleoside **1b**.



Extension of this photoinduced reaction to the heteroaromatic solvents described in this paper was limited by three requirements. Such solvents must exist as liquids in the temperature range of the photolysis assembly. The solvents and their products must be photolytically stable under the reaction conditions. Such solvents must exhibit selectivity in radical reactions.

When **1a** was allowed to react with freshly distilled, dry, nitrogen-purged *N*-methylpyrrole in a Hanovia apparatus with irradiation from a Vycor-sleeved 450-W mercury lamp for 8 h, 6-(*N*-methylpyrr-2-yl)-9-ethylpurine (**3a**) was isolated in 54% yield as colorless plates (heptane); mp 93 °C. That substitution had occurred at the α-position of the pyrrole ring was evidenced by the chemical shifts, multiplicities, and coupling constants of the ^1H NMR resonances and by the off-resonance ^{13}C data of the pyrrole ring in the product. In the ^1H NMR spectrum, H-3 appeared as a doublet of doublets at δ 7.83 with $J_{3,4}$ = 3.7 Hz and $J_{3,5}$ = 1.9 Hz. The downfield shift of this proton from 6.11 ppm in *N*-methylpyrrole is similar to the observed downfield shift of the ortho (α) protons of the phenyl group in **2a** and **2b**. The observed coupling constants, particularly $J_{3,4}$, are characteristic of 2-substituted pyrroles.[22] The UV spectrum of **3a** showed absorption at 239 nm (ϵ 9.7×10^3), a broad band at 269 nm (ϵ 3.2×10^3), and an intense absorption at 343.5 nm (ϵ 3.0×10^4) indicative of conjugation of the pyrrole moiety to the purine ring. The protected nucleoside **1b** underwent facile heteroarylation to the product **3b**.

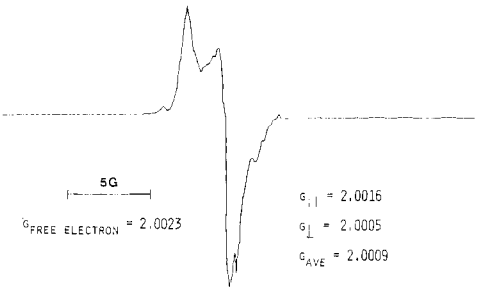


Figure 1. ESR spectrum of photoirradiated 6-iodo-9-ethylpurine in benzene at 77 K.

Under conditions of photolysis, **1a** reacted with 2-methylfuran as the solvent to give 6-(5-methylfur-2-yl)-9-ethylpurine (**4a**) in 52% yield. The position of substitution on the furan ring could be deduced from its NMR data, specifically its ^1H NMR spectrum. The proton on carbon 3 (H-3) of the furan system appeared as a clean doublet at δ 7.83 with $J_{3,4}$ = 3.3 Hz. The observed coupling constant is typical of $J_{3,4}$ for substituted furans.[22] The downfield shift of this proton is consistent with substitution of the purinyl moiety at carbon 2. Further substantiation of this assignment was evident in the chemical shift (δ 6.30) and multiplicity (doublet of doublets, $J_{4,3}$ = 3.3 Hz, $J_{allylic}$ = 1.0 Hz) of H-4. No other substitution pattern could be accommodated by the ^1H NMR spectral data. As in the case of **3a**, a bathochromic shift of the purine ring absorption was evident in the UV spectrum of **4a**. The nucleoside **1b** gave similar results.

Heteroarylation of thiophene by photolysis of 1 in the presence of this sulfur-containing heterocycle as the solvent gave **5** with substitution occurring at the α-position of the thiophene ring. Assignment of structure was made from spectral data.

Previous studies of radical attack upon pyrrole and furan derivatives show that both exhibit high regioselectivity of reaction at the 2-position.[15] Reportedly for thiophene, several percent of the 3-isomer forms along with the predominant 2 isomer. In our reactions, only one product was observed in all cases, for both the nucleosides and ethyl derivatives. Spectroscopic data of the products were consistent with the locus of attack being at the α- rather than the less favorable β-position.

The radical nature of the photoarylation reaction was further demonstrated by ESR spectroscopy. A benzene solution of 9-ethyl-6-iodopurine in a quartz ESR tube was degassed under vacuum in several freeze–thaw cycles. The sealed tube was irradiated at 25 °C with a mercury lamp (2537 Å) and rapidly cooled in liquid nitrogen. The ESR

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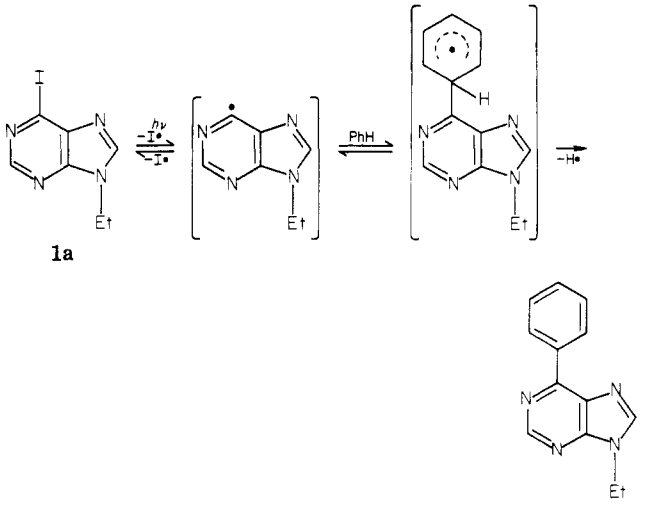
Scheme I. Mechanism of Photoarylation of 6-Iodo-9-ethylpurine in Benzene



spectrum of this sample obtained at 77 K is shown in Figure 1. The shape of the spectrum suggests that the radical(s) possess(es) considerable structural asymmetry. The resonance ($g_{\parallel}$ = 2.0016, $g_{\perp}$ = 2.0005, g_{av} = 2.0009) corresponds to an aromatic free radical. Complete brief thawing of the frozen sample followed by recooling to 77 K caused the ESR signal to disappear completely. A mechanistic explanation accommodated by the results of this experiment is shown in Scheme I. An alternative explanation that invokes the intermediacy of solvent-caged radical pairs is consistent also with the ESR data.[23]

That nascent purinyl radicals (either free or caged) were indeed being intercepted by aromatic and heteroaromatic substrates was further supported by another experiment, i.e. reaction with disulfide linkages. Displacement reactions in which aryl radicals attack a sulfur of weak disulfide linkages to give aryl thioethers and thienyl radicals are well-known.[24,25] The reaction between photochemically generated purinyl radicals and diphenyl disulfide was examined by photolysis of 6-iodo-9-ethylpurine in DMF solution at 3500 Å. The longer wavelength light was used because the ultraviolet absorption of the solvent is appreciable below 3000 Å. The photochemically induced displacement results in the formation of 6-(phenylthio)-9-ethylpurine.

Neutral purinyl radicals are new intermediates in nucleic acid chemistry.[2] This report presents one example of the utility of such transient species in the modification of nucleic acid bases.

Experimental Section

Irradiation was accomplished in a Hanovia 450-W mercury photolysis apparatus or in a Rayonet photochemical reactor.

Melting points were determined on a Thomas-Hoover capillary melting point apparatus and are uncorrected. Nuclear magnetic resonance spectra employing tetramethylsilane as the internal standard were recorded on JEOL Model FX90Q and Bruker Model HX90E Pulse Fourier transform spectrometers. Electron spin resonance spectra were recorded on a Varian V-4500 X-band spectrometer. Mass spectra were obtained on a Hewlett-Packard 5985 GC/MS system. The ultraviolet spectra were recorded on a Varian-Cary Model 219 spectrophotometer. Elemental analyses were performed by the University of Iowa Microanalytical Service or by Galbraith Laboratories, Knoxville, TN. *N*-Methylpyrrole and 2-methylfuran (Aldrich) were distilled prior to use; thiophene (Aldrich), benzene, heptane, and dimethyl sulfoxide (MCB Omnisolv) were used without further purification. Preparative layer chromatography employed EM silica gel PF_{254} plates, activated for 3 h at 135 °C.

6-Phenyl-9-ethylpurine (2a). To 250 mL dry N_2-purged benzene was added 0.222 g (0.810 mmol) of 6-iodo-9-ethylpurine (**1a**). The solid dissolved on stirring, and the solution was transferred to the Pyrex immersion well of a quartz photochemical reactor. The system was flushed with nitrogen, and photolysis was carried out by employing a 450-W mercury UV source with a Vycor glass sleeve filter. The photoarylation was followed by UV spectral methods, and after 6 h the reaction was stopped. The solvent was removed under reduced pressure, and the residue was chromatographed on silica gel plates. The two principal bands that resulted from development of the plates with 1:10 ethanol–ethyl acetate occurred at R_f 0.47 and 0.59. The band at R_f 0.47 corresponded to unreacted **1a** (0.044 g, 0.16 mmol, 32.0%). After elution, the band at R_f 0.59 afforded 0.060 g (0.268 mmol, 53.6%) of **2a** as an amorphous solid. Recrystallization from Skellysolve B gave colorless tufts: mp 60.5–61 °C; ^{13}C NMR ($CDCl_3$) δ 14.9, 38.4, 128.1, 129.3, 130.4, 130.4, 135.3, 143.2, 151.8, 151.8, 154.3; ^{1}H NMR ($CDCl_3$) δ 1.59 (t, 3 H), 4.362 (q, 2 H), 8.12 (s, 1 H), 9.03 (s, 1 H), 7.5–7.6 and 8.7–8.8 (m, 5 H); UV (EtOH) λ_{max} 290.5 nm (ϵ 1.8 × 10^4), 278, 312 nm (sh); mass spectrum, *m/z* (relative intensity) 225 (21.4), 224 (M^+, 100.0), 196 ($M^+ - C_2H_4$, 89.3), 195 (28.6), 169 (41.7), 142 (14.3), 78 (10.7).

Anal. Calcd for $C_{13}H_{12}N_4$: C, 69.6; H, 5.3; N, 25.0. Found: C, 69.9; H, 5.2; N, 25.0.

6-(*N*-Methylpyrr-2-yl)-9-ethylpurine (3a). To 52 mL of distilled, dry *N*-methylpyrrole was added 0.301 g (1.10 mmol) of **1a**. The solution was thoroughly purged with nitrogen and photolyzed as described for **2a**. After 8 h, the reaction was discontinued, and the solvent was removed. The brown-black residue was chromatographed on silica gel with 1:10 ethanol–ethyl acetate as the developer. Where practicable, the reaction products were handled under a stream of nitrogen to minimize oxidation. The band at R_f = 0.63 was eluted to give 0.134 g (0.593 mmol, 53.9%) of **3a** as a tawny solid which was recrystallized from heptane to afford colorless plates: mp 93–93.5 °C; ^{13}C NMR ($CDcl_3$) δ 14.9, 38.2, 37.8, 108.4, 119.0, 126.7, 128.7, 128.8, 142.1, 149.2, 150.5, 151.0; ^{1}H NMR ($CDCl_3$) δ 1.56 (t, 3 H), 4.20 (s, 3 H), 4.31 (q, 2 H), 6.30 (dd, 1 H), 6.86 (t, 1 H), 7.85 (dd, 1 H), 8.01 (s, 1 H), 8.83 (s, 1 H); UV (EtOH) λ_{max} 239 nm (ϵ 9.7 × 10^3), 269 (3.2 × 10^3), 343.5 (3.0 × 10^4); mass spectrum, *m/z* (relative intensity) 228 (9.7), 227 (M^+, 74.0), 226 (100.0), 198 (Pur C_2H_5, 38.7), 186 (25.8), 149 (Pur, 41.9), 97 (16.1), 71 (22.6).

Anal. Calcd for $C_{12}H_{13}N_5$: C, 63.4; H, 5.8; N, 30.8. Found: C, 63.2; H, 5.9; N, 30.7.

6-(5-Methylfur-2-yl)-9-ethylpurine (4a). To 55 mL dry N_2-purged 2-methylfuran was added 0.278 g (1.01 mmol) of **1a**. The mixture was transferred to the Hanovia photochemical reactor, stirred, flushed with N_2 and photolyzed as for **2a**. After 9 h, the reaction was discontinued. Removal of solvent and silica gel chromatography (1:10 ethanol/ethyl acetate) gave 0.065 g (0.237 mmol, 24%) of recovered starting material, **1a**, and 0.120 g (0.519 mmol, 52%) of **4a**, as an off-white waxy solid. Recrystallization from heptane gave colorless needles: mp 156–157 °C; ^{13}C NMR ($CDCl_3$) δ 14.1, 15.4, 38.9, 109.5, 119.6, 128.1, 143.6, 145.9, 147.9, 151.6, 152.5, 156.6; ^{1}H NMR ($CDCl_3$) δ 1.57 (t, 3 H), 2.51 (s, 3 H), 4.33 (q, 2 H), 6.30 (dd, 1 H), 7.83 (d, 1 H), 8.09 (s, 1 H), 8.94 (s, 1 H); UV (EtOH) λ_{max} 230 nm (ϵ 9.7 × 10^3), 280 (2.0 × 10), 328.5 (2.6 × 10^4), 339 (2.6 × 10^4); mass spectrum, *m/z* (relative intensity) 229 (11.3), 228 (M^+, 79.0), 213 (8.1), 200 (Pur C_2H_5 + H, 32.3), 185 (27.4), 149 (Pur-het + H, 75.8), 83 (MeFurH$^+$, 59.7), 69 (FurH$^+$, 100.0).

Anal. Calcd for $C_{12}H_{12}N_4O$: C, 63.2; H, 5.3; N, 24.6. Found: C, 63.0; H, 5.3; N, 24.6.

6-(Thien-2-yl)-9-ethylpurine (5a). To 60 mL dry N_2-purged thiophene was added 0.211 g (0.77 mmol) of **1a**. The solution was transferred to the Hanovia photochemical reactor and treated as for **2a** for a total of 9.5 h. Removal of solvent gave a brown syrup which was chromatographed on silica gel with 1:10 ethanol–ethyl acetate as the developer. The band at R_f 0.57 upon elution yielded **5a** as an oil which solidified on standing (0.069

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g, 0.30 mmol, 39.0%). Recrystallization of this from heptane gave spiny colorless needles: mp 75–77 °C; ^{13}C NMR ($CDCl_3$) δ 15.4, 40.0, 128.7, 130.8, 131.5, 132.6, 139.9, 143.9, 150.0, 151.8, 152.3; ^{1}H NMR ($CDCl_3$) δ 1.58 (t, 3 H), 4.34 (q, 2 H), 7.27 (dd, 1 H), 7.61 (dd, 1 H), 8.11 (s, 1 H), 8.67 (dd, 1 H), 8.89 (s, 1 H); UV (EtOH) λ_{max} 226.5 nm (ε 8.4 × 10^3), 271 (6.2 × 10^3), 324 (2.0 × 10^4), 337 (sh); mass spectrum, *m/z* (relative intensity) 232 (^{34}SM$^+$, 0.6), 231 (1.5), 230 (^{32}SM$^+$, 8.5), 202 (M$^+$ – C_2H_4, 11.2), 149 (Et-PurH$^+$, 7.9), 97 (10.5), 85 (11.2), 32 (84.6), 31 (100.0).

Anal. Calcd for $C_{11}H_{10}N_4S$: C, 57.5; H, 4.4; N, 24.3. Found: C, 57.3; H, 4.3; N, 23.4.

6-Phenyl-9β-(2′,3′,5′-tri-*O*-acetyl-D-ribofuranosyl)purine (2b). A solution of 0.272 g (0.54 mmol) of **1b**[2] in dry benzene (250 mL) was purged with nitrogen and photolyzed as described for **2a**. The progress of reaction was monitored by thin-layer chromatography on silica gel. After 7 h, when no further changes in TLC were observed, the reaction mixture was concentrated under reduced pressure. The orange residue was chromatographed. Three developments with 7:200 2-propanol–dichloromethane gave two significant bands. After elution by 1:9 methanol–dichloromethane, the principal band at R_f 0.5 gave 0.146 g (0.295 mmol, 54.6%) of **2b** as a colorless oil: ^{13}C NMR ($CDCl_3$) δ 20.1, 20.2, 20.4, 62.8, 70.4, 72.8, 80.1, 86.2, 128.4, 129.6, 130.9, 131.4, 135.1, 142.41, 152.4, 155.1, 169.1, 169.3, 170.0; ^{1}H NMR ($CDCl_3$) δ 2.08 (s, 3 H), 2.13 (s, 3 H), 2.15 (s, 3 H), 4.45 (s, 3 H), 5.75 (t, 1 H), 6.03 (t, 1 H), 6.31 (d, 1 H), 8.31 (s, 1 H), 9.03 (s, 1 H), 7.5–7.6, 8.7–8.8 (m, 5 H); UV (EtOH) λ_{max} 290 nm (ε 2.0 × 10^4) 274, 308 (sh); mass spectrum, *m/z* (relative intensity) 455 (1.5), 454 (M$^+$, 4.7), 395 (M$^+$ – C_3H_7O, 20.8), 259 (sugar, 14.1), 225 (Pur + CH_2O, 20.8), 198 (12.9), 197 (90.9), 196 (16.5), 170 (26.4), 139 (100.0), 97 (59.6), 43 (79.0).

Anal. Calcd for $C_{22}H_{22}N_4O_7$: C, 58.2; H, 4.9; N, 12.3. Found: C, 57.6; H, 4.9; N, 12.4.

The band at R_f 0.62 upon elution afforded only a trace of starting material.

6-(*N*-Methylpyrr-2-yl)-9β-(2′,3′,5′-tri-*O*-acetyl-D-ribofuranosyl)purine (3b). To 50 mL of dry, distilled, N_2-purged *N*-methylpyrrole was added 0.218 g (0.433 mmol) of **1b**, and the solution was photolyzed as described for **2b**. The solution darkened during irradiation. After 11 h the reaction was stopped, and the solvent was removed on a rotary evaporator. The brown syrup remaining was chromatographed on silica gel by employing 1:50 2-propanol–dichloromethane as the developer. Two developments were required. Where practicable, the reaction products were handled under nitrogen; the mixture darkened at room temperature in air. Upon elution with 1:9 methanol–dichloromethane 0.140 g (0.306 mmol, 70.7%) of **3b**, the chief product (R_f 0.32), was obtained as a pale beige oil which darkens on exposure to air: ^{13}C NMR ($CDCl_3$) δ 20.4, 20.5, 20.8, 38.3, 63.2, 70.8, 78.6, 80.3, 86.2, 109.1, 119.9, 127.0, 129.5, 129.8, 141.2, 150.2, 150.8, 152.0, 169.4, 169.6, 170.3; ^{1}H NMR ($CDCl_3$) δ 2.07 (s, 3 H), 2.13 (s, 3 H), 2.14 (s, 3 H), 4.19 (s, 3 H), 4.42 (s, 3 H), 5.70 (t, 1 H), 6.00 (t, 1 H), 6.29 (d, 1 H), 6.33 (dd, 1 H), 6.90 (t, 1 H), 7.87 (dd, 1 H), 8.16 (s, 1 H), 8.82 (s, 1 H); UV (EtOH) λ_{max} 242 nm (ε 9.7 × 10^3), 268 (2.9 × 10^3), 332 (sh), 345 (2.9 × 10^4); mass spectrum, *m/z* (relative intensity) 459 (0.7), 458 (3.7), 457 (M$^+$, 15.0), 259 (sugar, 2.5), 228 (Pur + CH_2O, 5.9), 200 (15.5), 199 (41.5), 198 (Pur, 100.0), 183 (1.5), 157 (5.3), 139 (37.6), 97 (26.8), 43 (39.9).

Anal. Calcd for $C_{21}H_{23}N_5O_7 \cdot H_2O$: C, 53.0; H, 5.3; N, 14.7. Found: C, 52.7; H, 5.1; N, 14.2.

6-(5-Methylfur-2-yl)-9β-(2′,3′,5′-tri-*O*-acetyl-D-ribofuranosyl)purine (4b). To 20 mL of dry, N_2-purged 2-methylfuran was added 0.338 g 0.67 mmol) of **1b**. The nearly colorless solution was stirred and transferred to a quartz photolysis tube in a Rayonet photochemical reactor fitted with 2537-Å mercury lamps. The solution was purged with nitrogen for 10 min and then irradiated. The solution slowly turned brown. Lost solvent (~5 mL) was replenished after 16 h. After 23 h the irradiation was discontinued, and the solvent was removed under reduced pressure. The resulting tan gum was chromatographed on silica gel with 1:50 2-propanol–dichloromethane, to give a broad band at R_f 0.25 which was rechromatographed on silica gel with neat ethyl acetate as the developing solvent. The band at R_f 0.75 was starting material (0.062 g, 0.123 mmol, 18.3%). The band at R_f 0.70 yielded 0.156 g (0.340 mmol, 50.7%) of **4b** as a colorless oil: ^{13}C NMR ($CDCl_3$) δ 14.2, 20.4, 20.6, 20.8, 63.1, 70.7, 78.6, 80.4, 86.4, 109.7, 120.3, 128.1, 142.4, 146.4, 147.6, 151.3, 153.0, 157.0, 169.4, 169.6, 170.4; ^{1}H NMR ($CDCl_3$) δ 2.08 (s, 3 H), 2.12 (s, 3 H), 2.16 (s, 3 H), 2.52 (s, 3 H), 4.44 (s, 3 H), 5.74 (t, 1 H), 6.00 (t, 1 H), 6.28 (d, 1 H), 6.28 (d, 1 H), 7.85 (d, 1 H), 8.24 (s, 1 H), 8.94 (s, 1 H); UV (EtOH) λ_{max} 230 nm (ε 9.5 × 10^3), 270 (3.5 × 10^3), 329.5 (2.8 × 10^4), 339 (2.8 × 10^4); mass spectrum, *m/z* (relative intensity) 460 (1.0), 459 (3.6), 458 (M$^+$, 15.0), 259 (sugar, 9.0), 229 (Pur + CH_2O, 24.2); 201 (54.5), 200 (PurH, 82.5), 185 (200 – CH_3, 11.6), 171 (15.9), 157 (17.5), 139 (100.0), 97 (70.5), 43 (86.6).

Anal. Calcd for $C_{21}H_{22}N_4O_8 \cdot H_2O$: C, 52.9; H, 5.1; N, 11.7. Found: C, 53.3; H, 4.9; N, 11.2.

6-(Thien-2-yl)-9β-(2′,3′,5′-tri-*O*-acetyl-D-ribofuranosyl)-purine (5b). To 60 mL dry N_2-purged thiophene was added 0.190 g (0.38 mmol) of **1b**. The solution was photolyzed in the Hanovia photochemical reactor as described for **2b**. After 8.5 h the reaction was stopped, and the solvent was removed. The resulting malodorous brown material was taken up in 2–3 mL of 1:9 methanol–dichloromethane and chromatographed on silica gel with 1:50 2-propanol–dichloromethane as the developing solvent. The principal band at R_f 0.45 upon elution and removal of solvent in vacuo afforded 0.094 g (0.204 mmol, 53.8%) of **5b** as a foam: ^{13}C NMR ($CDCl_3$) δ 20.4, 20.5, 20.8, 63.1, 70.7, 73.1, 80.5, 86.4, 128.8, 130.9, 131.1, 133.0, 139.7, 142.5, 150.7, 151.6, 152.8, 169.3, 169.6, 170.3; ^{1}H NMR ($CDCl_3$) δ 2.09 (s, 3 H), 2.13 (s, 3 H), 2.16 (s, 3 H), 4.44 (s, 3 H), 5.70 (t, 1 H), 6.00 (t, 1 H), 6.28 (d, 1 H), 7.26 (dd, 1 H), 7.63 (dd, 1 H), 8.26 (s, 1 H), 8.66 (dd, 1 H), 8.89 (s, 1 H); UV (EtOH) λ_{max} 225 nm (ε 8.3 × 10^3), 270 (6.2 × 10^3), 322.5 (2.1 × 10^4), 335 (sh); mass spectrum, *m/z* (relative intensity) 460 (7.9), 402 (5.7), 259 (20.0), 203 (Pur + 2 H, 56.6), 202 (32.9), 157 (20.1), 149 (60.8), 139 (98.7), 97 (100.0).

Anal. Calcd for $C_{20}H_{20}N_4O_7S \cdot 2H_2O$: C, 48.4; H, 4.9; N, 11.3. Found: C, 48.3; H, 4.7; N, 10.8.

6-(Phenylthio)-9-ethylpurine (6). To 0.236 g (0.861 mmol) of **1a** dissolved in 15 mL of dry *N,N*-dimethylformamide was added 0.262 g (1.20 mmol) of diphenyl disulfide (Aldrich Chemical Co.). The solution was purged with N_2 and irradiated in a Rayonet photochemical reactor by employing a 3500-Å mercury source for 19.5 h, at which point no further change was visible by TLC of reaction aliquots. The solvent was removed in vacuo at 85 °C. The residue was separated by preparative layer chromatography on silica gel with 1:10 ethanol–ethyl acetate as the developer. The bands were eluted with 10% MeOH in CH_2Cl_2. The band at R_f 0.44 gave 0.146 g (0.533 mmol, 61.9%) of the starting purine **1a**. The band at R_f 0.68 afforded upon elution 0.036 g (0.141 mmol, 16.4%, 43.0% conversion) of **6**, the title compound, as buff crystals which were dried in vacuo: mp 106–108 °C; ^{13}C NMR δ Me_4Si ($CDCl_3$) 15.4, 39.1, 127.5, 129.2, 129.4, 130.9, 135.5, 142.6, 148.9, 152.1, 160.5; ^{1}H NMR δ Me_4Si ($CDCl_3$) 1.55 (t, 3 H), 4.31 (q, 2 H), 7.35–7.75 (m, 5 H), 8.01 (s, 1 H), 8.62 (s, 1 H); UV (EtOH) λ_{max} 289.5 nm (ε 1.73 × 10^4); mass spectrum, *m/z* (relative intensity) 256 (M$^+$, 50.0), 255 (100), 241 (M$^+$ – CH_3, 24.0), 227 (M$^+$ – C_2H_5, 24.0), 162 (60.0), 147 (M$^+$ – PhS, 70.0), 129 (80.0), 119 (Pur$^+$ – H, 36.7), 93 (33.3), 71 (70.0), 57 (26.7).

Anal. Calcd for $C_{13}H_{12}N_4S$: C, 60.9; H, 4.7; N, 21.9. Found: C, 60.7; H, 4.8; N, 21.2.

6-Iodo-9-ethylpurine (1a). Method A. From 9-Ethyladenine. A stirred mixture of 0.815 g (5.00 mmol) of 9-ethyladenine[2] and 8 mL of diiodomethane was treated at 70 °C under nitrogen with 5.4 mL (40.00 mmol) of *n*-pentyl nitrite. The reaction was continued for 3 h, the solvent was removed on a rotary evaporator at 85 °C, and the residue was taken up in CH_2Cl_2. This solution was treated with aqueous sodium sulfite. The organic layer was dried with Na_2SO_4, concentrated, and chromatographed on silica gel with 1:9 methanol–dichloromethane as the developing solvent. The band at R_f 0.19 upon elution yielded 0.145 g of unreacted 9-ethyladenine (0.89 mmol, 17.8%). The band at R_f 0.55 gave 0.49 g (1.79 mmol, 35.8%) of **1a** as a yellow solid which crystallized from heptane as pale yellow plates: mp 141–143 °C (lit.[2] mp 141–143 °C).

Method B. From 6-Iodopurine. To 2.00 g (8.14 mmol) of 6-iodopurine and 1.22 g (9.00 mmol) of K_2CO_3 was added 80 mL of dry dimethyl sulfoxide followed by 1.28 mL (16.30 mmol) of iodoethane. The mixture was protected from moisture and stirred at 35 °C for 2.5 h. It was then chilled in an ice–water bath, and 48 mL of water was slowly added. The resulting solution was extracted with three 40-mL portions of ether and four 40-mL

portions of toluene. The organics were combined, dried (Na_2SO_4), and chromatographed on silica gel with 1:9 methanol–dichloromethane as the developing solvent. The principal band at R_f 0.72 afforded after elution 1.22 g (4.45 mmol, 54.7%) of solid **1a** which recrystallized from heptane as pale yellow crystals: mp 144–145 °C (lit.[2] mp 141–143 °C); UV (EtOH) λ_{max} 276.5 nm (ϵ 1.2 × 10^4).

Anal. Calcd for $C_7H_7N_4I$: C, 30.6; H, 2.6; N, 20.4. Found: C, 30.6; H, 2.6; N, 20.2.

Another band at R_f 0.49 gave 0.24 g (0.88 mmol, 10.8%) of 6-iodo-7-ethylpurine which crystallized from heptane as fluffy, pale, lemon-colored crystals: mp 160–162 °C; UV (EtOH) λ_{max} 283.5 nm (ϵ 7.4 × 10^3); ^{1}H NMR ($CDCl_3$) δ 1.62 (t, 3 H), 4.62 (q, 2 H), 8.37 (s, 1 H), 8.79 (s, 1 H); mass spectrum, m/z (relative intensity) 275 (6.3), 274 (M^+, 54.2), 149 (6.9), 148 (11.1), 147 (M − I, 100.0), 119 (41.7).

Anal. Calcd for $C_7H_7N_4I$: C, 30.6; H, 2.6; N, 20.4. Found: C, 30.3; H, 2.7; N, 20.6.

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Registry No. **1a**, 74465-49-9; **1b**, 5987-74-6; **2a**, 83026-89-5; **2b**, 83026-93-1; **3a**, 83026-90-8; **3b**, 83026-94-2; **4a**, 83026-91-9; **4b**, 83026-95-3; **5a**, 83026-92-0; **5b**, 83026-96-4; **6**, 83026-97-5; benzene, 71-43-2; *N*-methylpyrrole, 96-54-8; 2-methylfuran, 534-22-5; thiophene, 110-02-1; diphenyl disulfide, 882-33-7; 9-ethyladenine, 2715-68-6; 6-iodopurine, 2545-26-8.

Mechanistic Features of Allylic Hydrogen Abstraction by Alkoxy Radicals

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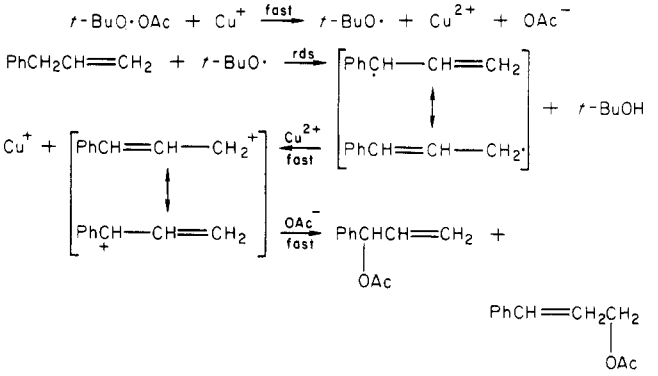
A TS‡ of angular H abstraction from allylbenzene in the course of the allylic acetoxylation reaction was previously invoked to explain a temperature-independent primary KIE; k_H/k_D = 2.90. This reaction geometry is now fully supported by the finding of inverse α-secondary deuterium isotope effects at both ends of the double bond in allylbenzene; $(k_H/k_D)_\alpha^{C_1}$ = 0.977 and $(k_H/k_D)_\alpha^{C_2}$ = 0.985. In keeping with these results an unsymmetrically structured, bridged radical intermediate, formed by the interaction of *t*-BuO· with the allylic double bond, steers the reaction course. Such a complex is recognized to be unusual since most of the verified cases of radical bridging involve heteroatom centers capable of octet expansion. A discussion is also given of the factors determining the relative influence of benzene and double bond participation in the H-abstraction reactions of allylbenzene, which possesses both of these activating functions.

The unusual stability (through resonance) of allylic radicals compared to simple alkyl radicals is often treated as the cause of the high susceptibility of allylic or benzylic hydrogen to radical abstraction.[1] Moreover, polar resonance structures are widely invoked[2,3] as the determining factors in the reactivity of benzylic and allylic hydrogen toward radical abstraction. Another reason for implicating the resonance participation of the double bond in the case of allylic H abstraction is that allylic rearrangements are common in such cases.[4,5]

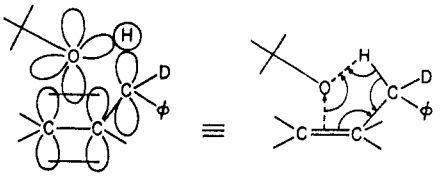
Allylic H abstraction is often the rate-determining step in many synthetically important reactions; (a) the hydroperoxidation of olefins by singlet oxygen,[6] (b) the ene reaction,[7] and (c) allylic and benzylic halogenation[8] are three common examples.

The properties of the TS‡ in H abstraction from various reaction centers has been the subject of several investigations.[2,3,9] Prior and Kniepp[9] have tested for the symmetry of the TS‡ of H abstraction from sulfur in reaction with a wide variety of free radicals by plotting the primary k_H/k_D value at 25 °C vs. the heat of reaction. This work has produced cogent evidence suggesting that the mag-

Scheme I



Scheme II. Bent TS‡ of Allylic Hydrogen Abstraction



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