valine methyl ester dissolved in 2.0 ml of tetrahydrofuran. The value of this solution was −1.259 indicating there was not any significant racemization.

N-Carbobenzoxy-S-benzyl-L-Cysteinylglycine p-Nitrophenyl Ester.—Glycine *p*-nitrophenyl ester hydrobromide (0.277 g, 0.001 mmol) was dissolved in dimethylformamide (2 ml) and tetrahydrofuran (20 ml) was added, followed by the addition of N-carbobenzoxy-S-benzyl-L-cysteine pentafluorophenyl ester (0.511 g, 0.001 mmol). The solution was cooled to −10°, and triethylamine (0.14 ml, 0.001 mol) was added. After 10 min at −10° and 20 min at room temperature, the mixture was filtered. Ethyl acetate (25 ml) was added to the filtrate, and the solution washed with saturated sodium chloride. The dried solution was evaporated and the residue triturated with ether. Filtration gave 0.364 g (70%) of a crude product, mp 150–153°. This material was dissolved in 20 ml of hot methanol and tetrahydrofuran mixture (1:1) and diluted with an equal volume of ether. On cooling a small amount of white solid separated which was discarded. The filtrate on dilution with an excess of hexane afforded the desired dipeptide, 0.260 g, mp 158–159°, $[\alpha]^{22}\text{D}$ −26.85 (*c* 2, tetrahydrofuran).

Anal. Calcd for $C_{26}H_{25}N_3SO_7$: C, 59.65; H, 4.81; N, 8.02. Found: C, 59.30; H, 4.88; N, 8.29.

Registry No.—N-Carbobenzoxydihydroalanine pentachlorophenyl ester, 24164-70-3; N-carbobenzoxydehydroalanine *p*-nitrophenyl ester, 24164-71-4; N-carbobenzoxy-S-benzyl-L-cysteine pentabromophenyl ester, 24164-49-6; N-carbobenzoxy-S-benzyl-2,4,6-tribromophenyl ester, 24164-39-4; N-carbobenzo-S-benzyl-2,4,5-trichlorophenyl ester, 24164-40-7; N-carbobenzoxy-S-benzyl-2,4-dinitrophenyl ester, 23180-03-2; N-carbobenzoxy-S-benzyl-2,6-dinitrophenyl ester, 24164-42-9; N-carbobenzoxy-S-benzylthiobenzyl ester, 24164-43-0; (±)-N-carbobenzoxy-S-benzylcysteinepentachlorophenyl ester, 24164-44-1; (±)-N-carbobenzoxy-S-benzylcysteine thiobenzyl ester, 24164-45-2; N-carbobenzoxy-S-benzylcysteine thiobenzyl ester hydrazide, 24164-46-3; N-carbobenzoxy-S-benzyl-L-cysteinyl pentafluorophenyl ester valine methyl ester dipeptide, 24215-87-0; N-carbobenzoxy-S-benzyl-L-cysteinylglycine *p*-nitrophenyl ester, 7669-99-0.

Acknowledgment.—This work was supported by grants from the National Institutes of Health (GM No. 06579 and 08795). We wish to thank Professor H. Horan for the infrared spectra.

The Rotational Barrier in 1,8-Diarylnaphthalenes[1a]

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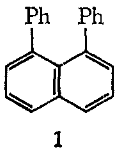
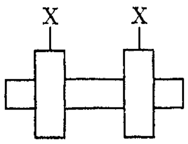
Received November 26, 1969

A series of 1-phenyl-8-(3-substituted phenyl)naphthalenes, **5–8**, have been synthesized to examine the question of the ease of rotation of the aryl rings in 1,8-diarylnaphthalenes. Although a number of 1,8-diphenylnaphthalenes with substituents in the phenyl rings exhibit temperature-dependent nmr spectra, the spectra are normally too complex for simple interpretation. However, the nonequivalence of the methyl signals in the low-temperature nmr spectrum of the derivative **8a** with a *meta* 2-hydroxy-2-propyl substituent provides unambiguous evidence for the rotation of the substituted phenyl ring in this substance. The free energy of activation ($\Delta G^{\ddagger}$) for this rotation is calculated to be 16 kcal/mol at 25°.

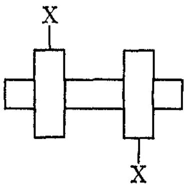
Various evidence[2,3] indicates the favored conformation of 1,8-diphenylnaphthalene (**1**) to be one in which the two phenyl rings are parallel to one another and perpendicular to the plane of the naphthalene ring as illustrated by a top view of the molecule in structure **2**. Consideration of the dimensions of such molecules as discerned from molecular models and the limited X-ray crystallographic data available[2] suggests the existence of a substantial energy barrier to rotation of the phenyl rings and led us to expect that *cis* (**2a**) and *trans* (**2b**) isomers of 1,8-di(*ortho*- or *meta*-substituted phenyl)naphthalenes might be isolated. In fact, we were completely unsuccessful in this attempt and instead isolated a series of di-*meta*-substituted compounds as single crystalline substances.[3] Nmr and dipole moment data obtained from certain of these compounds suggested that equilibration of the two geometrical isomers **2a** ⇌ **2b** may be relatively rapid in solution with an energy barrier to rotation on the order of 10 kcal/mol. Since this energy barrier seemed unusually low and the interpretation of our data for these disubstituted compounds (**2**) was not unambiguous, we have sought more convincing evidence about this rotation barrier. This paper describes the preparation of a series of monosubstituted diphenylnaphthalenes (Scheme I) and appropriate nmr measurements which clearly demonstrate the rotation of the substituted phenyl ring in solution at 25°.



1



2a



2b

The synthetic route (Scheme I) followed our earlier pattern[3] in which the unsaturated ketone **3** was converted to a diene **4** which was dehydrogenated to the diarylnaphthalene **5**. This aryl chloride **5** was converted to the cyanide **6** with CuCN in HMP[4] and then hydrolyzed to the acid **7a**. This acid **7a** (pK^*_{MCS} = 7.04)[5] is slightly less acidic than the corresponding monoarylnaphthalene derivative **9a** (pK^*_{MCS} = 6.50–6.56)[3,5] possibly reflecting the increased steric hindrance to solvation of the carboxylate anion from acid **7a**.

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(1) (a) This research has been supported by Public Health Service Grant 1-R01-CA10933 from the National Cancer Institute; (b) National Institutes of Health Predoctoral Fellow, 1968–1970.

(2) For a review, see V. Balasubramaniyan, *Chem. Rev.*, **66**, 567 (1966).

(3) (a) H. O. House and R. W. Bashe, II, *J. Org. Chem.*, **30**, 2942 (1965); **32**, 784 (1967). (b) H. O. House, R. W. Magin, and H. W. Thompson, *ibid.*, **28**, 2403 (1963), and references therein.

(4) H. O. House and W. F. Fischer, Jr., *ibid.*, **34**, 3626 (1969).

(5) The values pK^*_{MCS} are the apparent pK_a values in a mixture of 20% water and 80% Methyl Cellosolve: W. Simon, *Angew. Chem., Int. Ed. Engl.*, **3**, 661 (1964).

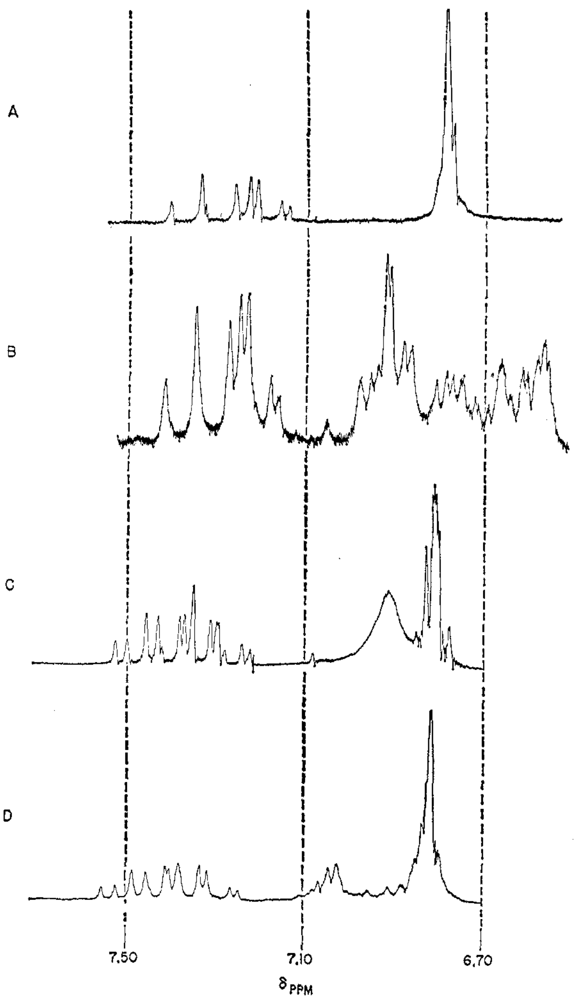
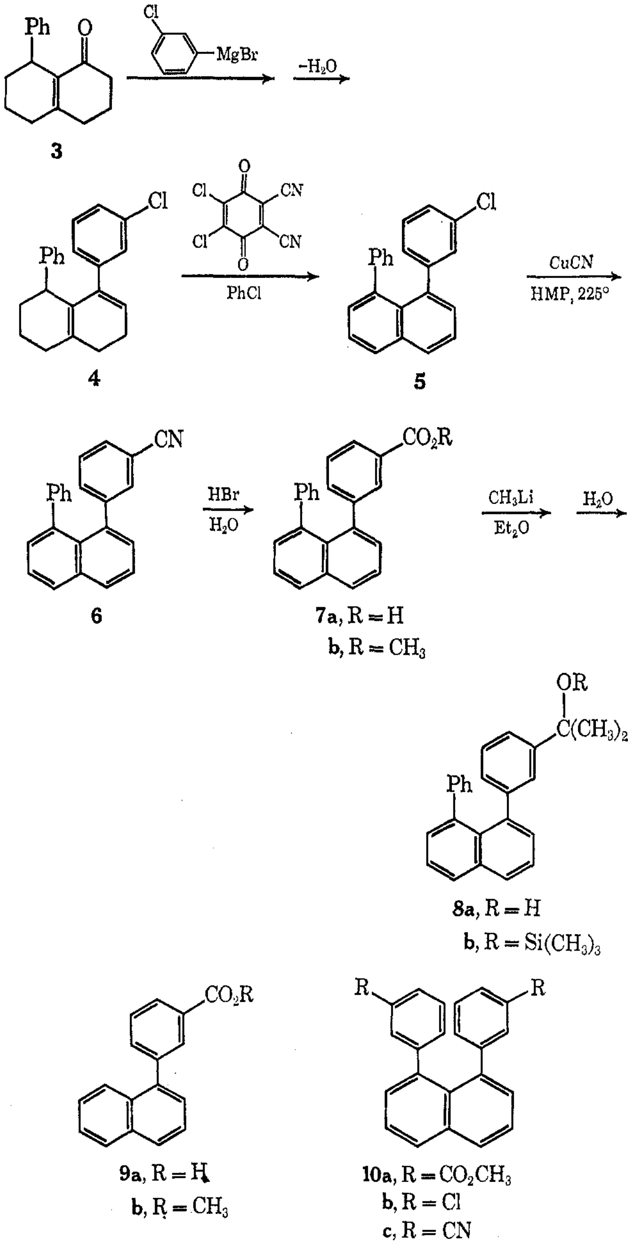


Figure 1.—Nmr spectra (100 MHz) of the aryl and high-field (4 H) naphthyl regions for (A) the dichloro derivative **10b** in $Cl_2C{=}CCl_2$ at 119°; (B) the dichloro derivative **10b** in $Cl_2C{=}CCl_2$ at −25°; (C) the monochloro derivative **5** in $CDCl_3$ at 50°; (D) the monochloro derivative **5** in $CDCl_3$ at −7°.

In earlier work[3] the nmr O–Me singlet for the diester **10a** was observed to broaden and then split into a closely spaced doublet as solutions of the diester were cooled below 20°. Further indications of conformational changes have now been found in the comparison of room temperature and lower temperature nmr spectra of the aryl derivatives **1**, **5**, **7b**, and **10b**. Figure 1 illustrates several of these spectra at relatively low and high temperatures for the monochloro and dichloro derivatives **5** and **10b**. Although the lower field region (δ 7.0–7.5, the four higher field naphthyl CH) of the spectra undergo only minor variations, the patterns observed in the higher field region (δ 6.5–7.0, phenyl or *m*-chlorophenyl CH) are strikingly dependent on temperature. Similar, although less pronounced, changes are seen for the absorption of phenyl protons in the 100-MHz spectrum of 1,8-diphenylnaphthalene in the temperature range +56 to −18.5°. The nmr spectrum of the monoester **7b** exhibited only a single methoxyl peak throughout the temperature range from −5 to +65°. This observation suggests that the doublet for the methoxy groups observed in the nmr spectrum of the diester **10c** at temperatures below 10° is probably attributable to conformations **2a** and **2b** and not to conformations involving rotation of the carbomethoxy groups with respect to the phenyl ring.

SCHEME I



3

4

5

6

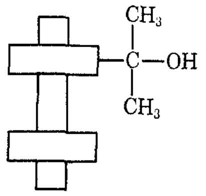
7a, R = H
b, R = CH_3

8a, R = H
b, R = $Si(CH_3)_3$

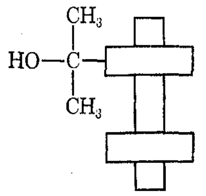
9a, R = H
b, R = CH_3

10a, R = CO_2CH_3
b, R = Cl
c, R = CN

Although these variations in nmr pattern with temperature were indicative of the slowing down of some sort of conformational change, the complexity of the absorption patterns in 60- and 100-MHz spectra made a detailed interpretation difficult. For this reason the dimethylcarbinol **8a** was synthesized with the expectation that two different nmr C–Me signals would be seen if the grouping $Me_2C(OH)$– was bound to an asymmetric environment such as the *meta* position of a nonrotating phenyl ring in 1,8-diphenylnaphthalene as in structure **11a**. If the ring to which the group was bonded were able to rotate rapidly, the resulting racemization process **11a** ⇄ **11b** would average the

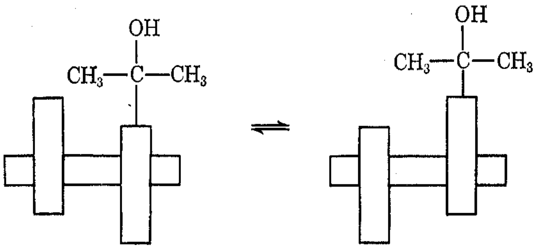


11a



11b

positions of two nmr C–Me signals to give a single line. As illustrated in Figure 2, precisely this behavior is observed in spectra measured at various temperatures. This observation requires rotation of the substituted phenyl ring and is not compatible with other conformational changes such as the distorted conformations illustrated in structures **12** which would not racemize the molecule.



12a **12b**

The observed variation in C–Me signals with temperature (Figure 2, B, C, and D) was simulated (Figure 2, E, F, and G) with a computer program[6] to allow determination of the pre-exchange lifetimes, τ, at various temperatures. From these the activation energy, $\Delta G^{\ddagger}$, for rotation of the *substituted* phenyl ring in the carbinol **8a** was calculated to be 16 kcal/mol at 25°. With a rotation barrier this low our failure to isolate the *cis* and *trans* isomers **2a** and **2b** in our earlier study[3a] becomes understandable.

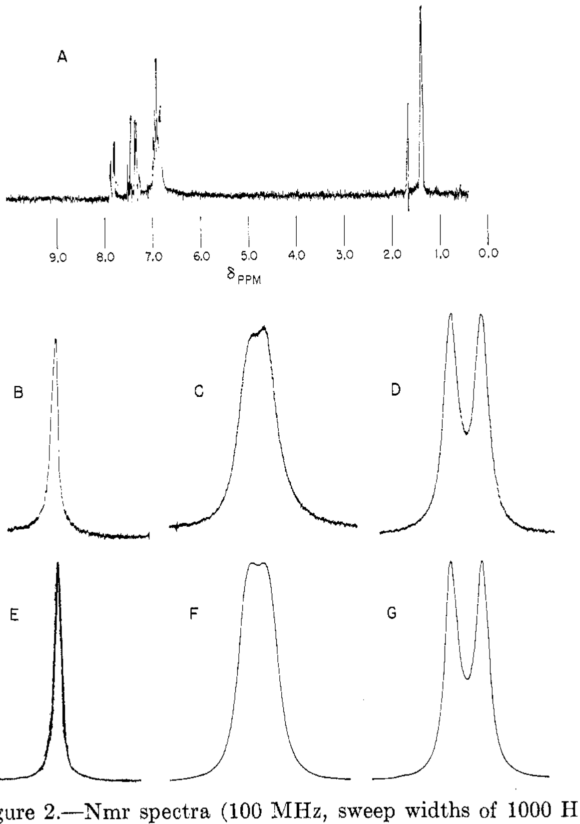


Figure 2.—Nmr spectra (100 MHz, sweep widths of 1000 Hz for A and 50 Hz for B–G) of the dimethylcarbonol **8a** in $CDCl_3$: (A) complete spectrum at 27°, (B) observed C-methyl peak at 65.2°; (C) observed C-methyl peak at 27.6°; (D) observed C-methyl peaks at 10.0°; curves E, F, and G are computer simulated spectra corresponding to observed spectra B, C, and D with τ values of 0.006, 0.155, and 0.500 sec. The peak separation in the slow exchange limit is 3.5 Hz.

Experimental Section[7]

Preparation of the Diene 4.—A solution of 155 mmol of *m*-chlorophenylmagnesium bromide[3a] in 234 ml of Et_2O was treated with a solution of 28.37 g (127 mmol) of the previously described[3a,8] conjugated ketone **3** (mp 74.2–75.3°) in 100 ml of Et_2O. After the resulting mixture had been stirred at 25° for 21 hr, aqueous NH_4Cl was added. The combined Et_2O layer and the Et_2O extract of the aqueous phase were washed with aqueous $NaHCO_3$, dried, and concentrated to leave 33.19 g of the crude alcohol intermediate as a yellow liquid: ir (CCl_4) 3575 cm^{-1} (OH); nmr (CCl_4) δ 6.7–7.2 (9 H, m, aryl CH), 3.0–3.2 (1 H, m, benzylic CH), and 1.4–2.4 (12 H, m, aliphatic CH). A solution of the crude alcohol in 400 ml of Ac_2O was refluxed for 24 hr and then concentrated under reduced pressure. After a solution of the residual liquid in Et_2O had been washed with aqueous $NaHCO_3$, dried, and concentrated, the crude diene **4** remained as 29.39 g of yellow liquid. Chromatography (silica gel) separated 11.50 g of the diene as a colorless liquid fraction (eluted with 4:1 v/v hexane–benzene) which was crystallized from hexane to separate 7.57 g (18.6%) of the pure diene **4** as colorless prisms: mp 81–82°; ir (CCl_4) no OH or C=O in the 3- or 6-μ regions; uv (95% EtOH) 261 mμ (br, ϵ 12,400);[9] nmr (CCl_4) δ 6.2–7.4 (9 H, m, aryl CH), 5.4 (1 H, m, vinyl CH), 3.45 (1 H, m, benzylic CH), and 1.3–2.5 (10 H, m, aliphatic CH); mass spectrum, *m/e* (relative intensity), 322 (8), 321 (36), 320 (25), 319 (100), 216 (27), 167 (24), 141 (36), 99 (50), 91 (29), 57 (72), 56 (58), 43 (55), 42 (34), and 41 (61).

Anal. Calcd for $C_{22}H_{21}Cl$: C, 82.35; H, 6.60; Cl, 11.05. Found: C, 82.08; H, 6.67; Cl, 11.35.

Preparation of the *m*-Chloro Derivative 5.—A solution of 1.00 g (3.12 mmol) of the diene **4** and 2.20 g (9.7 mmol) of 2,3-dichloro-5,6-dicyanobenzoquinone in 45 ml of PhCl was refluxed for 22 hr under N_2 and then was concentrated under reduced pressure. After the residue had been extracted with three portions of boiling hexane, the combined hexane solutions were filtered through 50 g of alumina (activity grade II) and then concentrated, to leave 1.10 g of the crude chloride **5** as a colorless liquid. The product **5** crystallized from hexane as 397 mg (40%) of white needles, mp 88.6–89.9°. Sublimation (112° and 0.1 mm) afforded the pure chloride **5**: mp 89–90°; ir (CCl_4) no OH or C=O in the 3- or 6-μ regions; uv (95% EtOH) 235 mμ (ϵ 49,400), and 300 (11,800);[10] nmr (CCl_4) δ 6.8–8.1 (m, aryl CH) (for variations with temperature, see Figure 1); mass spectrum, *m/e* (relative intensity) 316 (21), 314 (60), 132 (33), 104 (31), 103 (29), 44 (100), and 43 (56).

Anal. Calcd for $C_{22}H_{15}Cl$: C, 83.93; H, 4.80; Cl, 11.26. Found: C, 83.77; H, 4.97; Cl, 11.39.

Preparation of the Nitrile 6.—A solution of 5.19 g (16.5 mmol) of the chloride **5** and 14.8 g (165 mmol) of CuCN in 21 ml of hexamethylphosphoramide was heated to 225° under an N_2 atmosphere for 2.5 hr and then cooled and poured into aqueous NaCN. The benzene extract of the mixture was washed successively with H_2O, aqueous HCl, aqueous $NaHCO_3$, H_2O, and aqueous NaCl, and then dried and concentrated. The residual yellow solid (5.52 g) was fractionally crystallized from hexane to separate 4.35 g (86%) of fractions of the crude nitrile **6** melting within the range 89.5–112.5°.

Recrystallization of the crude nitrile **6** from hexane afforded samples melting within the range 112–115° which contained

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[6] J. B. Lisle, B. S. Thesis, Massachusetts Institute of Technology, June 1968.

[7] All melting points are corrected and all boiling points are uncorrected. Unless otherwise stated, magnesium sulfate was employed as a drying agent. The infrared spectra were determined with a Perkin-Elmer Model 237 infrared recording spectrophotometer fitted with a grating. The ultraviolet spectra were determined with a Cary recording spectrophotometer, Model 14. The nmr spectra were determined with a Varian Model A-60, T-60, or HA-100 nmr spectrometer. The chemical-shift values are expressed either in Hz or δ values (ppm) relative to a tetramethylsilane or hexamethyldisiloxane internal standard. The mass spectra were obtained with Hitachi (Perkin-Elmer) mass spectrometer. All reactions involving strong bases or organometallic intermediates were performed under a nitrogen atmosphere.

[8] H. O. House and H. W. Thompson, *J. Org. Chem.*, **28**, 360 (1963).

[9] The analogous di-*m*-chlorophenyl diene[3a] has an ultraviolet maximum at 258 mμ (ϵ 11,100). As noted elsewhere,[3a] we believe these uv data are more consistent with a 2-aryl-1,3-butadiene chromophore rather than a 1-aryl-1,3-butadiene derivative.

[10] The corresponding uv data for the other 1,8-diarylnaphthalenes are 235.5 mμ (ϵ 54,500) and 300 (11,500) for **1**,[3b] and 234 mμ (ϵ 58,400) and 300 (21,500) for **10b**.[3a]

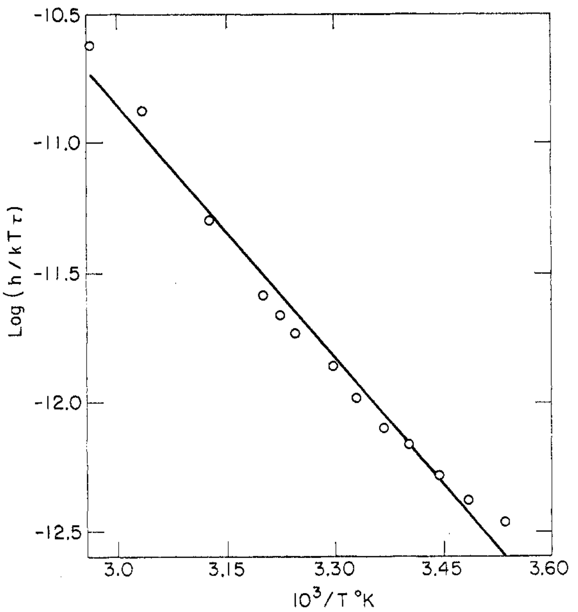

Figure 3.—Plot of log ($h/kT\tau$) as a function of $1/T$ for the dimethylcarbinol **8a** in $CDCl_3$. The slope of this line is $-\Delta H^{\ddagger}/2.303R$.

(glpc analysis, silicone gum SE-52) the nitrile **6** (retention time *ca.* 25 min) accompanied by *ca.* 3% of the starting chloride **5** (retention time 12.8 min). A collected (glpc) sample of the nitrile was recrystallized from hexane to separate the pure nitrile **6** as white prisms, mp 127.5–128.5°. After sublimation (140° and 0.1 mm), the nitrile melted at 128–129°: ir ($CHCl_3$) 2225 cm^{-1} (C≡N); uv max (95% EtOH) 229 mμ (ε 47,900) and 301 (10,600); nmr ($CDCl_3$) δ 7.3–8.2 (6 H, m, naphthyl CH) and 6.7–7.3 (9 H, m, phenyl CH); mass spectrum, *m/e* (relative intensity) 306 (25), 305 (100, M^+), 304 (18), 203 (11), 202 (9), 149 (9), and 138 (8).

Anal. Calcd for $C_{23}H_{15}N$: C, 90.46; H, 4.95; N, 4.59. Found: C, 90.56; H, 4.85; N, 4.24.

Preparation of the Acid Derivative 7.—A mixture of 5.36 g (16.6 mmol) of the nitrile **6** and 50 ml of aqueous 48% HBr was refluxed for 16 hr and then concentrated under reduced pressure. A solution of the residue in Et_2O was extracted with aqueous Na_2CO_3, and the combined aqueous solutions were acidified (HCl) and extracted with Et_2O. The latter Et_2O solution was dried and concentrated to leave 2.13 g of crude acid as a yellow solid. The neutral material (2.89 g) from this hydrolysis was refluxed with a mixture of 30 ml of aqueous 48% HBr and 50 ml of HOAc for an additional 48 hr and then subjected to the same work-up procedure to separate 0.95 g of crude acid. The combined acidic products were recrystallized from a hexane–EtOAc mixture to separate 2.14 g (38%) of the acid **7a** as a pale yellow solid, mp 224.6–226°. Further purification involving partitioning between Et_2O and aqueous Na_2CO_3, acidification, and recrystallization gave the pure acid as white prisms: mp 225–226.5°; ir (KBr pellet) 1685 cm^{-1} (br, carboxyl C=O); uv (95% EtOH) 232 mμ (ε 53,800) and 301 (11,800); nmr [$(CD_3)_2SO$] δ 6.8–8.4 (m, aryl CH).

Anal. Calcd for $C_{23}H_{16}O_2$: C, 85.16; H, 4.97. Found: C, 84.93; H, 5.07.

The pK^*_{MCS} value[5] for the acid **7a** at 25° was 7.04 compared with a value of 6.56[3a] for the acid **9a**. A 1.25-g (3.85 mmol) sample of the acid **7a** was esterified with excess ethereal CH_2N_2. The crude neutral product, 1.245 g of yellow oil, was crystallized from MeOH to give 1.04 g (81%) of the ester **7b** as white prisms: mp 84.5–85.7° (recrystallization raised the melting point to 86.1–87.1°); ir (CCl_4) 1725 cm^{-1} (conjugated ester C=O); uv (95% EtOH) 231 mμ (ε 52,000) and 300 (11,200); nmr ($CDCl_3$) δ 6.7–8.0 (15 H, m, aryl CH) and 3.75 (3 H, s, OCH_3); mass spectrum, *m/e* (relative intensity) 338 (100), 279 (18), 252 (19), 138 (25), and 126 (18).

Anal. Calcd for $C_{24}H_{18}O_2$: C, 85.18; H, 5.36. Found: C, 84.97; H, 5.47.

Preparation of the Dimethylcarbinol 8a.—A solution of 502 mg (1.48 mmol) of the ester **7b** in 15 ml of Et_2O was added to 25 ml of an ethereal solution containing 3.97 mmol of MeLi. The mixture was stirred at 25–30° for 45 min and then mixed with aqueous NH_4Cl. The Et_2O layer and the Et_2O extract of the aqueous phase were combined, washed with aqueous $NaHCO_3$, dried, and concentrated. After considerable effort the residual oil (501 mg) was successfully crystallized from hexane at Dry Ice temperatures to separate 265 mg (53%) of the carbinol **8a** as white needles: mp 97.6–98.6°; ir (CCl_4) 3560 and 3590 cm^{-1} (OH); uv max (95% EtOH) 236 mμ (ε 51,700) and 301 (11,300); nmr ($CDCl_3$) δ 6.7–8.1 (15 H, aryl CH), 1.62 (1 H, s, OH), and 1.40 (6 H, s, CCH_3).

Anal. Calcd for $C_{25}H_{22}O$: C, 88.72; H, 6.55. Found: C, 89.03; H, 6.50.

In an effort to increase the separation of peaks (see Figure 2, solutions in $CDCl_3$) for the methyl signals of the carbinol **8a**, the spectrum was examined in other solvents. A comparable peak separation was observed in PhCl, and the addition of pyridine to the solution resulted in a collapse of the doublet to a broad single line. A broad single line was also observed in CD_3COCD_3. A solution of 2.18 mmol of MeLi in 1.0 ml of 1,2-dimethoxyethane (DME) was treated with 245 mg (0.728 mmol) of the ester **7b**. The resulting solution of the lithium salt of the carbinol **8a** was treated with a solution of 1.31 ml (10.0 mmol) of Me_3SiCl and 0.5 ml of Et_3N in 3.0 ml of DME which had been centrifuged to remove any Et_3NHCl. The mixture was stirred at 25° for 1 week and then partitioned between aqueous $NaHCO_3$ and pentane. The pentane solution was dried and concentrated to leave 260 mg of yellow liquid which contained (tlc on silica gel with $CHCl_3$ eluent) the silyl ether **8b** (most rapidly eluted) and a second unknown component eluted more rapidly than the alcohol **8a**. One-fourth of this material was chromatographed on silica gel to separate 51 mg of fractions [eluted with a hexane–benzene mixture (4:1 v/v)] containing the crude silyl ether **8b** as a colorless liquid: ir (CCl_4) no OH or C=O in the 3- or 6-μ regions; uv (95% EtOH) 235 mμ (ε 46,700) and 302 (10,500); nmr ($CDCl_3$) δ 6.9–7.7 (6 H, m, naphthyl CH), 6.4–6.9 (9 H, phenyl CH), 1.43 (6 H, s, CH_3C), and 0.08 (9 H, s, CH_3Si). Even at a low temperature (−20°), only a single nmr peak was seen for the two C-methyl groups. The mass spectrum exhibited the following abundant peaks: *m/e* (relative intensity) 410 (M^+, 40), 396 (35), 395 (100), 75 (19), and 73 (43).

Calculation of the Rotational Barrier.—The exchange-broadened nmr spectra were calculated and plotted with the aid of the computer program EXCNMR[6] employing the usual density matrix formalism.[11] In this study, the *measured* line width at half-height was 0.8 Hz at the high-temperature limit (65°). Based on measured values in observed spectra, the line width was assumed to vary from 0.7 to 1.0 Hz in going from 63 to 10°. The relative populations are, of course, equal, and a coupling constant, $J = 0$, was assumed between the protons on the two methyl groups. Below the coalescence temperature the line separation increased to 3.5 Hz (at 10°); this separation remained constant as the temperature was decreased to −5.6°. Below this temperature broadening of the lines became a sufficiently serious problem so that meaningful values for the peak separations could not be obtained.

Calculated and observed spectra were compared by matching line widths above coalescence and by matching peak separation and depth of "valley" as well as line widths at lower temperatures. The Arrehenius activation parameters (E_A and A) and the transition-state parameters ($\Delta S^{\ddagger}$, $\Delta H^{\ddagger}$, $\Delta G^{\ddagger}$) were calculated from the set of observed temperatures and their corresponding pre-exchange lifetimes, τ, using standard techniques.[12] In these calculations the per cent error in the values of τ was assumed to be ±5%, and the standard deviation in measuring the temperature was taken as ±0.5°. A least-squares calculation was made fitting the functions

$$F = \ln(h/kT\tau) - \Delta S^{\ddagger}/R + (\Delta H^{\ddagger}/R)(1/T)$$

where k is the Bolzmann constant, h is Planck's constant, $\Delta S^{\ddagger}$ is the entropy of activation, and $\Delta H^{\ddagger}$ is the enthalpy of activation.[13]

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(11) (a) S. Alexander, *J. Chem. Phys.*, **37**, 967, 974 (1962); **38**, 1787 (1963); **40**, 2741 (1964). (b) C. S. Johnson, Jr., *Advan. Magn. Resonance*, **1**, 33 (1965).

(12) G. Binsch, *Top. Stereochem.*, **3**, 97 (1968).

(13) These calculations were carried out using a modification of the program ACTENG, written by D. F. DeTar, and obtained from the Quantum Chemistry Program Exchange, Bloomington, Ind.

The free energy of activation, $\Delta G^{\ddagger}$, was then calculated from the $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values at 25° with the usual relationship, $\Delta G^{\ddagger} = \Delta H^{\ddagger} - T\Delta S^{\ddagger}$. The data and calculated values were printed, and a plot was drawn (Figure 3) of log (H/kT_T) *vs.* $1/T$ where T is in degrees Kelvin. The values calculated from a series of measurements including those illustrated in Figure 2 were $\Delta G^{\ddagger} = 16.4 \pm 0.2$ kcal/mol; $\Delta H^{\ddagger} = 14.8 \pm 0.2$ kcal/mol; $\Delta S^{\ddagger} = -5.4 \pm 0.5$ eu. Because of the relatively small separation of lines (3.5 Hz in the low-temperature limit) and the tendency of the lines to broaden at lower temperatures, we believe more realistic probable limits of error for $\Delta G^{\ddagger}$ and $\Delta H^{\ddagger}$ are ±2 kcal/mol with a reasonable probability for substantial error in the value of $\Delta S^{\ddagger}$.

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Relationships between Structure, Polarography, and Electronic Spectra of 4- and 5-Substituted 2-Nitrophenols[1a]

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Polarographic oxidation potential, $E_{1/2}$(OX), and reduction potentials, $E_{1/2}$(RED), for a series of 4- and 5-substituted 2-nitrophenols have been measured in aqueous ethanol (10%) solutions buffered at pH 2.2, 4.0, 6.0, 8.0, and 9.2. Although both series appear to give polarographic waves characteristic of irreversible reactions, good correlations of $E_{1/2}$(OX) and $E_{1/2}$(RED) with the appropriate substituent constant, σ_m, σ_p, or $\sigma_p^{\pm}$, were obtained. Usually, the correlations that involved $E_{1/2}$(RED) were most satisfactory at low pH, while those that involved $E_{1/2}$(OX) were best at high pH. The correlation of the frequency of the longest wavelength maximum observed in the electronic spectrum with $E_{1/2}$(OX) or [$E_{1/2}$(OX) − $E_{1/2}$(RED)] was examined and found to be good for the 4-substituted compounds and poor for the 5-substituted ones. For the most widely divergent data, an attempt to explain the discrepancies has been made, but the investigation of other series would be desirable.

On the basis of a naive molecular orbital theory, a number of physical properties have been related to the positions of calculated energy levels of organic molecules.[2] In particular, polarographic oxidation and reduction potentials have been correlated with the calculated energy levels of the ground and first excited states, respectively,[2a] and the frequencies of certain spectral transitions have been correlated with the differences in energy between these levels.[2b]

Rather than depending upon the accuracy of such calculations for the correlation of physical and chemical properties, Simpson, Hancock, and Meyers[3a] measured the electronic spectra of some 4-substituted 2-chlorophenols in acidic and basic aqueous ethanol (5%) and initiated polarographic studies of these materials. However, only oxidation potentials could be obtained in the polarographic work. Similarly, a spectral and polarographic study[3b] of 4-substituted 2-nitroanilines was attempted but only the spectra and polarographic reduction potentials could be obtained. In this study, two series of compounds, 4- and 5-substituted 2-nitrophenols, have been examined polarographically, since these materials have a known reducible group ($-NO_2$) and a known oxidizable group (–OH or $-O^-$). The electronic spectra of these compounds were obtained previously.[4,5] It was hoped that a direct comparison of spectral frequencies and the difference between polarographic oxidation and reduction potentials would be possible for substituted 2-nitrophenols and that this comparison would be independent of the accuracy of any calculations of energy levels. Moreover, Hammett[6] relations have been used (with varying degrees of success in previous studies[3,7,8]) for the correlation of spectra and polarographic half-wave potentials with structure, and it was hoped to make more extensive comparisons of these correlations for two series of closely related compounds.

Results and Discussion

The Correlation of Oxidation and Reduction Half-Wave Potentials of 4-Substituted 2-Nitrophenols (I) and 5-Substituted 2-Nitrophenols (II) with Substituent Constants.—The oxidation and reduction half-wave potentials have been measured for the compounds of series I and II at pH 2.2, 4.0, 6.0, 8.0, and 9.2; the results are shown in Tables I and II. Spectral data and σ values for the substituents are shown in Table III.

For both series, calculations of the electron changes, n, from graphs of E(RED) *vs.* log $(i_d - i)/i$ did not give integral values for n, where E(RED) is the voltage at a point on a wave front, i_d is the diffusion current, and i is the current at a voltage E(RED). Despite this indication of irreversibility, it was assumed that corresponding electrochemical reactions were obtained in reduction, since each series satisfied certain requirements proposed by Zuman[9] for the validity of such an assumption. These requirements include a similarity of the wave heights observed which indicates that the same number of electrons are being transferred in the reduction of compounds in the same series, a similarity of the graphs of $E_{1/2}$(RED) *vs.* pH, a similarity in the

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(1) (a) Abstracted in part from the Ph.D. Dissertation of P. Y. R., Texas A & M University, May 1968. (b) To whom inquiries should be sent.

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