SYNTHESIS OF NOVEL HETEROCYCLIC CLEFTS DERIVED FROM TETRACYCLO[6.3.0.0^{4,11}.0^{5,9}]UNDECANE-3,6-DIONE AND TRICYCLO-[6.3.0.0^{2,6}]UNDECANE-3,11-DIONE†

Makhluf J. Haddadin*§, Yanjun Wang, Svetlana Frenkel, Simon G. Bott*, Lei Yang, Paul S. Braterman, * Carol Carvallo, and Alan P. Marchand*

Department of Chemistry, University of North Texas, Denton, TX 76203-0068, U. S. A.

William H. Watson*, Ram P. Kashyap, Mariusz Krawiec, and Susan A. Bourne

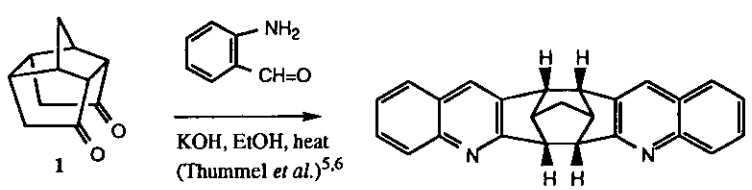
Department of Chemistry, Texas Christian University, Box 32908, Ft. Worth, TX 76129, U. S. A.

Abstract- New molecular clefts (**6a-6c**), (**9a**), and (**9b**) have been prepared *via* base promoted reactions of 3,6-diaryl-1,2,4,5-tetrazines with tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-3,6-dione (**1**) and with tricyclo[6.3.0.0^{2,6}]undecane-3,11-dione (**10**), respectively. Compounds of this type are of interest as a potential new class of host molecules for use in host-guest complexation studies (i.e., inclusion phenomena and molecular recognition). The results obtained *via* studies of the solution electrochemistry of systems (**6a-6c**), (**9a**), and (**9b**) afforded no evidence for the existence of any significant electronic interaction between opposing "arms" in these molecular clefts.

INTRODUCTION

As part of a continuing program which is concerned with the synthesis and chemistry of novel polycyclic cage compounds,[1,2] we recently reported the synthesis of several new molecular clefts (e.g., **2** and **3**, see Scheme 1).[3,4] Similarly, Thummel and coworkers reported that a quinoline-containing heterocyclic molecular cleft, (i.e., "orthocyclophane" **4**), could be synthesized via Frieldländer condensation of *ortho*-aminobenzaldehyde with tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane-3,6-dione (1) (Scheme 1).[5,6] We now report the synthesis of a series of novel molecular clefts via base promoted reactions of **1** and of tricyclo[6.3.0.0^{2,6}]undecane-3,11-dione with 3,6-diaryl-1,2,4,5-tetrazines. These new clefts are of interest as a potential new class of host molecules for the study of host-guest interactions (i.e., inclusion phenomena and molecular recognition).

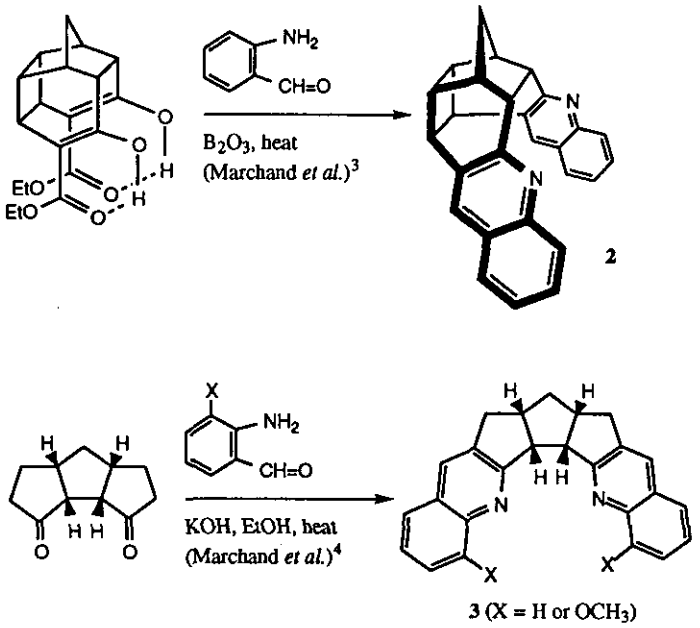
Scheme 1



1 4

†Dedicated to Professor Alan R. Katritzky on the occasion of his 65th birthday.
§On sabbatical leave from the American University of Beirut, 1990-1991.

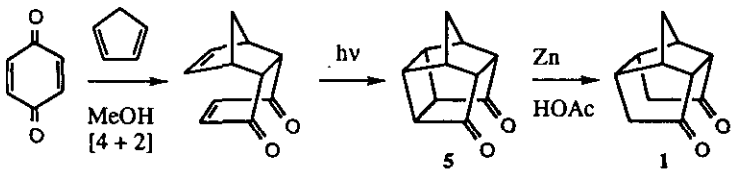
Scheme 1 (continued)



RESULTS AND DISCUSSION

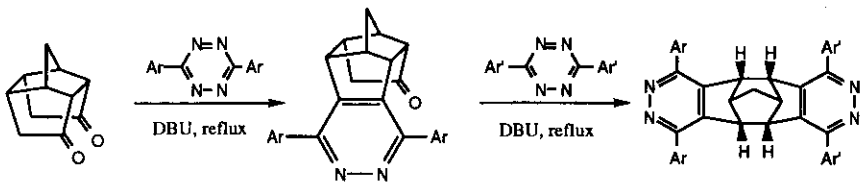
The starting material (**1**) can be prepared in high yield steps *via* zinc-promoted reduction[7] of pentacyclo-[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane-8,11-dione (**5**) (see Scheme 2).[8,9] Our approach for synthesizing new molecular

Scheme 2



clefts, shown in Scheme 3, is based on a report by Haddadin and co-workers[10a] that ketone enolates function as electron-rich dienophiles in inverse electron demand Diels-Alder reactions with electron-poor dienes, e.g., 3,6-diaryl-1,2,4,5-tetrazines.[10b] Thus, a variety of molecular clefts have been synthesized by using this method, e.g., **6a** (mp 336.0-337.5 °C), **6b** (mp 335-336 °C), and **6c** (this material was obtained with $CHCl_3$ included as solvate in the crystal lattice, molecular formula $C_{37}H_{26}N_6 \cdot CHCl_3$, mp 287-288 °C). The structure of each of these compounds was established unequivocally by application of X-ray crystallographic methods; structure drawings of **6a**, **6b**, and **6c** appear in Figure 1.

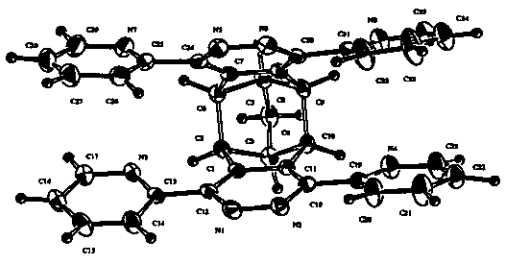
Scheme 3



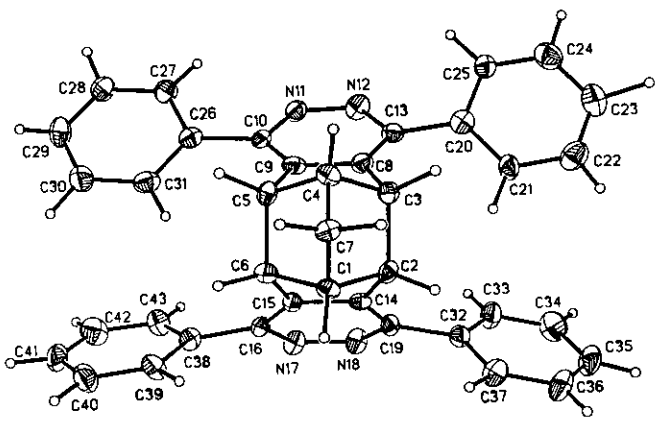
1

7a: Ar = 2-pyridyl
7b: Ar = phenyl

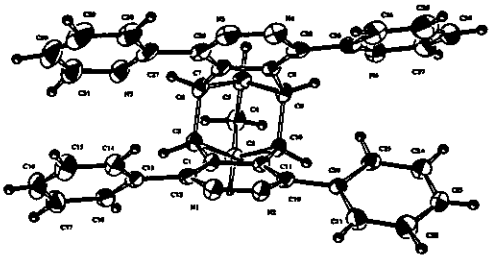
6a: Ar = Ar' = 2-pyridyl
6b: Ar = Ar' =Ph
6c: Ar = 2-pyridyl, Ar' = Ph



6a



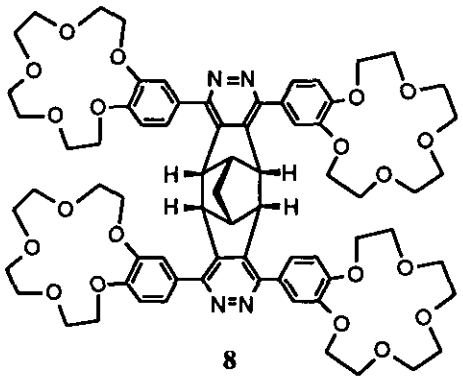
6b



6c

Figure 1. X-ray structure drawings of **6a, 6b, and 6c**

Recently, we utilized the methodology shown in Scheme 3 to produce a "tetra-crowned cleft" (**8**) in which benzo-15-crown-5 units are fixed at each end of the cleft in such a manner as to result in a paired array of two "sets" of two spatially proximate crown ether moieties.[11] It was demonstrated that the crown ether moieties in each of the two sets in **8** interact cooperatively with guest alkali metal cations, thereby rendering **8** capable of highly selective K^+ ion complexation (*via* a series of picrate extraction experiments) and of K^+ ion transport across a liquid membrane.[11]



8

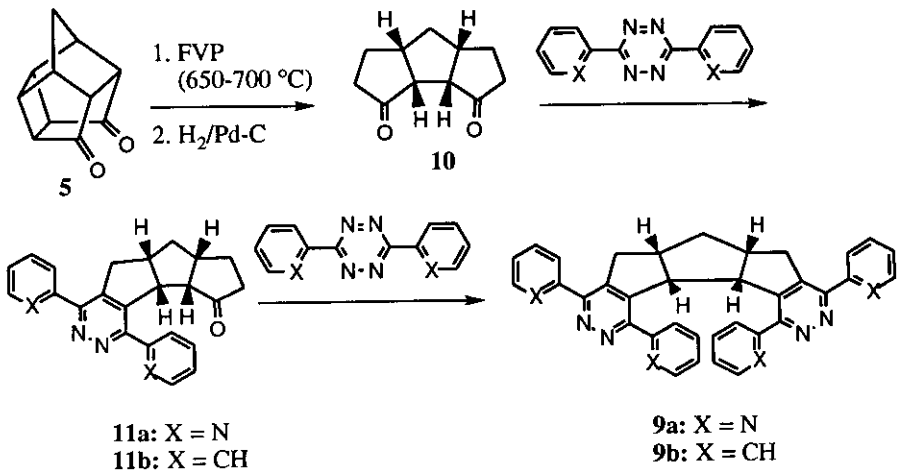
As part of the present study, two additional molecular clefts, **9a** and **9b**, have been prepared by using the route shown in Scheme 4. X-Ray structure drawings of **9a** and **9b** appear in Figure 4. Tricyclo[6.3.0.$0^{2,6}$]undecane-3,11-dione (**10**), which provides the template upon which clefts (**9a**) and (**9b**) are constructed, can be prepared conveniently and in high yield *via* a two-step sequence by starting with cage diketone (**5**).[12] Other tricyclo-[6.3.0.$0^{2,6}$]undecane derived molecular clefts which are closely related to **9a** and **9b** have been reported recently by our group[3,4,13] and by others.[14]

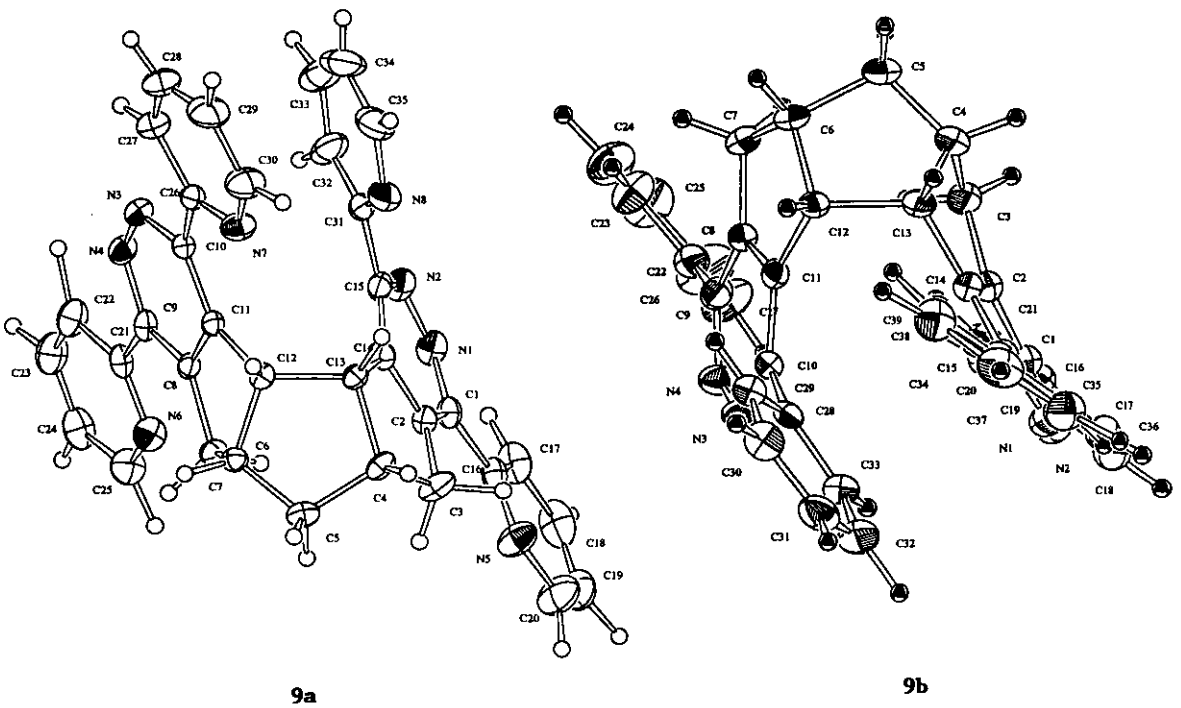
X-RAY STRUCTURAL FEATURES OF 6a-6c, 9a, AND 9b

A comparison of X-ray structural data indicates that the 2-pyridyl-substituted pyridazines may be more suitable for forming clefts as compared with the corresponding phenyl-substituted pyridazines. Thus, the pyridyl groups and the pyridazine rings in these compounds are able to achieve a nearly coplanar arrangement in which the pyridine and pyridazine nitrogen atoms are mutually *trans*. This arrangement minimizes steric interactions; the results of molecular mechanics (PCMODEL)[15] calculations indicate a deviation from coplanarity of only 12.4 °, while the average experimental value for **6a** and **6c** is 14.9 °.

The corresponding phenyl-substituted pyridazines exhibit severe steric interactions between the *ortho*-phenyl hydrogen atoms and the cyclopentanoid ring which is fused to the pyridazine moiety. Molecular mechanics calculations predict an interplanar angle of 41.8 °; the average experimental value of this angle for **6b** and **6c** is 37.6 °. The C(1)-C(12)-C(13) type angle (see structure drawing of **6a**, Figure 1) is calculated to be 125.1 ° for

Scheme 4





9a **9b**

Figure 2. X-ray structure drawings of **9a** and **9b**

pyridyl and 124.2 ° for phenyl substituted pyridazines; the average observed values for these two angles are 125.7 ° and 124.6 °, respectively.

Compound (**6a**), a pyridyl-containing cleft, is calculated to contain 5.6 kcal/mol less strain energy than the corresponding phenyl-substituted cleft (**6b**). Rotation of the pyridyl group in such a manner as to bring the pyridyl and pyridazine ring nitrogens into close proximity (i.e., *cisoid*) results in a structure which is 5.9 kcal/mol less stable than the corresponding structure in which the pyridyl rings are rotated in such a way as to move these two nitrogen atoms as far apart as possible (i.e., *transoid*).

In solid (**6a**), three of the four pyridyl groups are nearly parallel, while the fourth group makes an angle of *ca.* 15 ° with the other three. In **6c**, one phenyl group is almost parallel with the two pyridyl groups, while in **6b**, the phenyl rings display large interplanar angles with respect to the pyridazine rings. The pyridazine-pyridazine N···N distances in compounds (**6a**) and (**6c**) range from 4.473 Å to 4.608 Å, while in **6b** (i.e., the most "highly twisted" cleft), this separation is increased to an average value of 5.048 Å. While the pyridazine-pyridazine internuclear distance has increased in **6b** *vis-à-vis* that in **6a** and **6c**, this cleft-widening effect occurs simply in response to the cross-cleft steric interactions that occur between opposing phenyl substitutents (the overall result of which is to effectively obstruct the cavity within the molecular cleft).

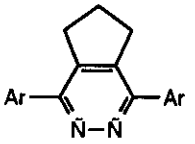
In **9a**, three of the four pyridyl groups are nearly coplanar with their respective attached pyridazine moiety; the interplanar angles vary from 4.2 (6) ° to 8.5 (6) °. The fourth pyridyl group is twisted out of the plane defined by the attached pyridazine ring by 35.0 (6) °. In **9b**, three of the phenyl groups are twisted out of the plane defined by the attached pyridazine ring by 35.4 (5) ° to 49.5 (5) °, while the fourth phenyl group deviates from planarity with its attached pyridazine moiety by only 8.5 (5) °. These results are consistent with observations made previously for **6a-6c** (*vide supra*). Deviations from aryl group coplanarity in **9b** result primarily from nonbonded interactions that involve the *ortho* ring C-H bonds in the phenyl substituents. There is no correlation between the length of the carbon-carbon bond and the interplanar angle between the pyridazine ring and attached pyridyl or phenyl groups in **9a** and **9b**, respectively.

As can be seen upon inspection of Figure 2, the two substituted pyridazine systems in **9a** form a tapered cleft whose dimensions are defined by the saturated carbocyclic cis,cisoid,cis tricycloundecane backbone in conjunction with the attached planar heterocyclic "arms". It is anticipated that the existence of significant intermolecular host-guest interactions should lead to rotation of the derivatized pyridyl groups, thereby enhancing the molecular recognition process. It is further expected that slight conformational changes in the central five-membered ring in the tricycloundecane backbone will produce a significant effect upon the dimensions of the molecular cleft. Molecular mechanics (MM3)[16] calculations accurately reproduce the geometry of **9a** and thus should be of assistance in assessing which derivatives are likely to be most suitable for complex formation with specific guest molecules.

ELECTROCHEMICAL STUDIES

In an effort to determine whether there might be any unusual face-to-face electronic interactions between opposing "arms" in molecular clefts (**6**) and (**9**), studies of their solution electrochemistry (cyclic voltammety)

were undertaken. For comparison, two reference compounds, (**12a**) and (**12b**) (structures shown below), were included in both studies. Each of these compounds serves as a model for one isolated "arm" of a molecular cleft.



12a: Ar = 2-pyridyl
12b: Ar = phenyl

Electrochemical data, shown in Table 1, were collected in dimethylformamide (DMF) solvent and, in selected cases, also in acetonitrile. For studies in DMF solvent, we find that several of the compounds that contain the bis(2'-pyridyl)pyridazine ring system [i.e., **6a**, **7a**, **9a**, **11a**, **12a**, and 2,6-di(2'-pyridyl)-1,2,4,5-tetrazine] display a reversible or electrochemically quasi-reversible one-electron reduction at *ca.* -2.23 V (relative to ferrocene/ferrocenium). We associate this reduction with $\pi(10)$, the LUMO of this aromatic system.

Table 1. Electrochemical data[a]

Compound	$(E_c + E_a)/2$ (V)	E_a-E_c (mV)	Compound	$(E_c + E_a)/2$ (V)	E_a-E_c (mV)
6a	-2.24	60	**9a**	-2.45[b,c]	
6b	-1.33	240	**11a**	-2.24	70
	-2.48	90			
			12a	-2.22	70
6c	-1.46[b,c]			-2.31[d]	100
	-2.22	60			
			e	-1.25	70
7a	-2.23	84			

[a] Data at room temperature vs ferrocene/ferrocenium under same conditions. [b] E_c value. [c] Irreversible. [d] Data obtained for compound in acetonitrile solution. [e] 3,6-Di-(2'-pyridyl)-1,2,4,5-tetrazine.

In model compound (**12b**), no reduction wave could be obtained down to -2.88 V in acetonitrile and to -2.48 V in DMF. To the extent that differences in reduction potential can be equated with differences in one-electron

energies, we infer that $\pi(10)$ lies at least 0.5 eV higher in energy in the bis(phenyl)pyridazine system than does $\pi(10)$ in the corresponding bis(2'-pyridyl) derivatives.[17]

An interesting feature of the data in Table 1 is that both **6b** and **6c** (but not the corresponding model compound, **12b**) show irreversible reductions at *ca.* -1.4 V. Another, closely related molecule (**7b**) which (like **6b**, **6c**, and **12b**) also contains the 2,5-diphenylpyridazine moiety, could not be studied due to low solubility in either DMF or acetonitrile. This irreversible reduction behavior appears to be a feature which is associated spe-cifically with those molecules that contain the bis(phenyl)pyridazine [but not the bis(2'-pyridyl)pyridazine)] functionality. The results of detailed spectroscopic and spectroelectrochemical studies on these and related compounds will be reported elsewhere.

SUMMARY AND CONCLUSIONS

We have successfully synthesized and have fully characterized five new heterocyclic molecular clefts (**6a-6c**), (**9a**), and (**9b**). In each case, the assigned structure has been verified unequivocally *via* application of single X-ray crystallographic methods (see Figures 1 and 2). Further studies of **6a-6c** and of related heterocyclic clefts that are designed to explore the utility of these systems for selective complexation of metal ions and for ion transport through liquid membranes are underway in our laboratory.

In addition, solution electrochemical (cyclic voltammetry) studies were pursued in an effort to determine the importance of "electronic communication" between opposing "arms" of molecular clefts (**6a-6c**), (**9a**), and (**9b**). The results of these studies suggest that an intramolecular interaction of this type is probably not operative in our systems.

EXPERIMENTAL SECTION

Melting points are uncorrected. Electronic spectra were collected on a Perkin Elmer Lambda 9 UV-VIS-NIR Spectrometer. Acetonitrile (hplc grade) was used as obtained from the Aldrich Chemical Company.

6,7-[3',6'-Di-(2''-pyridyl)-4',5'-pyridazino]tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecan-2-one (7a). A solution of **1** (1.76 g, 10 mmol) and 3,6-dipyridyl-1,2,4,5-tetrazine[18] (2.4 g, 10.2 mmol) in dry THF (50 ml) was heated under argon to reflux temperature. To this solution was added dropwise with stirring 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU, 3.5 ml, excess), and the resulting violet solution was refluxed until the color of the reaction mixture faded to yellow (*ca.* 2-3 h). The reaction mixture was allowed to cool to ambient temperature and then was concentrated *in vacuo*. Methanol (7 ml) was added to the residue, whereupon a yellow solid precipitated. This solid was collected by suction filtration, and the residue was washed with MeOH (2 x 5 ml) and then was air-dried. The resulting solid was recrystallized from CH_2Cl_2-MeOH, thereby affording pure **7a** (2.8 g, 77%) as a pale yellow microcrystalline solid: mp 233.5-234.0 °C; ir (KBr) 2944 (w), 1732 (s,), 1577 (m), 1562 (m), 1372 (s), 788 (w), 738 cm^{-1} (w); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 243 (1.7), 288 nm (2.5); ^{1}H Nmr ($CDCl_3$) δ 1.57 (AB, J_{AB} = 19.1 Hz, 1 H), 1.97-2.20 (m, 3 H), 2.82 (br d, J = 10.9 Hz, 1 H), 2.96-3.02 (m, 2 H), 3.29 (s, 1 H), 4.08 (br d, J = 10.4 Hz, 1 H), 4.48 (br d, J = 10.9 Hz, 1 H), 7.26-7.33 (m, 2 H), 7.78-7.87 (m, 2 H), 8.53-8.73 (m, 4

H); ^{13}C Nmr ($CDCl_3$) δ 34.78 (t), 40.27 (d), 42.77 (t), 48.78 (d), 50.70 (d), 50.83 (d), 56.85 (d), 58.43 (d), 122.82 (d), 122.93 (d), 123.68 (d), 123.73 (d), 136.56 (d), 136.64 (d), 147.96 (s), 148.12 (s), 148.98 (d), 149.08 (d), 153.99 (s), 154.46 (s), 155.05 (s, 2C), 218.31 (s); Anal. Calcd for $C_{23}H_{18}N_4O$: C, 75.41; H, 4.92. Found: C, 75.58; H, 5.20.

6,7-[3',6'-Diphenyl-4',5'-pyridazino]tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecan-2-one (7b). A solution of **1** (880 mg, 5.0 mmol) and 5% methanolic KOH (1 ml) in THF (20 ml) was heated to reflux temperature. To the resulting deep violet solution was added dropwise with stirring a hot solution of 3,6-diphenyl-1,2,4,5-tetrazine[19] (1.17 g, 5.0 mmol) in THF (30 ml). The color of the reaction mixture faded immediately, with concomitant evolution of N_2 gas. The reaction mixture was allowed to cool to ambient temperature and then was concentrated *in vacuo*. Methanol (10 ml) was added to the residue, whereupon a colorless solid precipitated. This solid was collected by suction filtration, and the residue was air-dried to afford crude **7b** (1.40 g, 75%). The crude product was recrystallized from EtOAc-CH_2Cl_2, thereby affording pure **7b** as a colorless microcrystalline solid: mp 201-202 °C; ir (KBr) 2959 (m), 1731 (s), 1371 (s), 773 (m), 698 (s), 691 cm^{-1} (s); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 269 nm (2.8); ^{1}H Nmr ($CDCl_3$) δ 1.82 (*AB*, J_{AB} = 18.8 Hz, 1H); 2.02 [br d(*AB*), *J* = 16.0, 10.0 Hz, 2 H], 2.43 [br d(*AB*), *J* = 19.0, 6.7 Hz, 1 H], 2.87-2.92 (m, 1 H), 2.98-3.20 (m, 2 H), 3.29 (br s, 1 H), 3.40-3.51 (m, 2 H), 5.70-7.70 (m, 6 H), 7.82-8.10 (m, 4 H); ^{13}C Nmr ($CDCl_3$) δ 35.33 (t), 40.47 (d), 43.09 (d), 49.43 (d), 51.31 (d), 51.51 (d), 57.48 (d), 61.23 (d), 128.63 (d), 129.04 (d), 129.14 (d), 129.27 (d), 129.80 (d), 129.98 (d), 136.61 (s), 136.66 (s), 145.58 (s), 145.90 (s), 155.59 (s), 155.78 (s), 217.41 (s). Anal. Calcd for $C_{25}H_{20}N_2O$: C, 82.39; H, 5.53. Found: C, 82.56; H, 5.75.

2,3:6,7-Bis[3',6'-di-(2"-pyridyl)-4',5'-pyridazino]tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane (6a). To a warm solution of **7a** (60 mg, 0.16 mmol) and 3,6-dipyridyl-1,2,4,5-tetrazine[18] (42 mg, 0.18 mmol) in dry toluene (20 ml) under argon was added DBU (1.0 ml, excess), and the resulting solution was refluxed with stirring for 9 h. The reaction mixture was allowed to cool to ambient temperature and then was concentrated *in vacuo*. Methanol (5 ml) was added to the residue, whereupon a yellow solid precipitated. This solid was collected by suction filtration, and the residue was washed with MeOH (2 x 5 ml) and then air-dried. The resulting solid was recrystallized from EtOAc-CH_2Cl_2, thereby affording pure **6a** (56 mg, 61%) as a pale yellow microcrystalline solid: mp 336.0-337.5 °C (decomp.); ir (KBr) 2915 (w), 1577 (m), 1563 (m), 1464 (m), 1422 (m), 1374 (s), 790 (s), 736 cm^{-1} (s); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 247 (3.6), 285 nm (5.1); ^{1}H Nmr ($CDCl_3$) δ 2.25 (s, 2 H), 3.74 (s, 2 H), 4.66 (t, *J* = 1.9 Hz, 4 H), 7.00-7.08 (dt, *J* = 7.8, 1.8 Hz, 4 H), 7.41-7.52 (ddd, *J* = 7.5, 4.8, 1.1 Hz, 4 H), 7.96 (d, *J* = 8.0 Hz, 4 H), 8.20-8.24 (br d, *J* = 4.8 Hz, 4 H); ^{13}C Nmr ($CDCl_3$) δ 34.40 (t), 50.03 (d), 62.17 (d), 122.64 (d), 123.07 (d), 136.14 (d), 148.09 (d), 149.15 (s), 153.70 (s), 155.17 (s); Anal. Calcd for $C_{35}H_{24}N_8$: C, 75.54, H, 4.32; Found: C, 75.50, H, 4.60.

2,3:6,7-Bis[3',6'-diphenyl-4',5'-pyridazino]tetracyclo[6.3.0.0^{4,11}.0^{5,9}]undecane (6b). To a refluxing solution of **1** (1.76 g, 10 mmol) and 3,6-diphenyl-1,2,4,5-tetrazine[19] (4.68 g, 20 mmol) in THF (100 ml) was added dropwise with stirring 5% methanolic KOH (2 ml). The reaction proceeded with immediate evolution of N_2 gas. Within minutes, the initial violet color of the reaction mixture was discharged. The resulting light tan solution

was concentrated *in vacuo*, and MeOH (20 ml) was added to the residue, whereupon a white precipitate was formed. The precipitate was collected by suction filtration and air-dried. The product, crude **6b** (5.3 g, 97%), mp 325-330 °C (decomp.), was recrystallized from EtOAc-CH_2Cl_2, thereby affording pure **6b**: mp 335-336 °C; ir (KBr) 3035 (w), 2965 (m), 1542 (m), 1485 (m), 1443 (m), 1436 (m), 1372 (s), 1358 (s), 1020 (m), 760 (s), 689 cm^{-1} (s); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 262 nm (5.2); ^1H Nmr ($CDCl_3$) δ 2.14 (s, 2 H), 3.75 (s, 2 H), 3.83-3.82-3.84 (m, 4 H), 7.13-7.24 (m, 8 H), 7.28-7.38 (m, 4 H), 7.41-7.48 (m, 8 H); ^{13}C Nmr ($CDCl_3$) δ 34.21 (t), 49.55 (d), 64.18 (d), 128.47 (d), 128.84 (d), 128.93 (d), 135.91 (s), 145.67 (s), 154.64 (s). Anal. Calcd for $C_{39}H_{28}N_4$: C, 84.76; H, 5.11. Found: C, 85.04; H, 5.25.

2,3-[3',6'-Di-(2"-pyridyl)-4',5'-pyridazino]:6,7-[3"',6"'-diphenyl-4"',5"'-pyridazino]tetracyclo[6.3.0.$0^{4,11}.0^{5,9}$]undecane (6c). To a solution of **7a** (500 mg, 1.37 mmol) in warm THF (80 ml) was added 3,6-diphenyl-1,2,4,5-tetrazine[19] (320 mg, 1.37 mmol) and 5% methanolic KOH (1.5 ml). The resulting mixture was refluxed for 12 h and then allowed to cool to ambient temperature. The reaction mixture was concentrated *in vacuo*, and MeOH (10 ml) was added to the residue, whereupon a solid precipitated from solution. The precipitate was collected by suction filtration, and the residue was washed with MeOH (3 x 5 ml), thereby affording crude **6c** (544 mg, 72%). Recrystallization of this material from EtOAc-CH_2Cl_2 afforded pure **6c**: mp 288.5-289.5 °C; ir (KBr) 2965 (w), 1577 (w), 1563 (w), 1464 (w), 1373 (s), 787 (m), 766 (m), 698 (s), 647 cm^{-1} (m); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 254 (3.8), 278 nm (4.0); ^1H Nmr ($CDCl_3$) δ 2.25 (s, 2 H), 3.76 (t, J = 4.3 Hz, 2 H), 3.91 (dd, J = 9.7, 3.5 Hz, 2 H), 4.84 (dd, J = 9.8, 3.7 Hz, 2 H), 7.05-7.25 (m, 8 H), 7.39 (br d, J = 7.0 Hz, 4 H), 7.69 (dddd, J = 7.9, 7.8, 1.9, 0.9 Hz, 2 H), 8.26-8.31 (m, 2 H), 8.36-8.42 (m, 2 H); ^{13}C Nmr ($CDCl_3$) d 34.82 (t), 50.20 (d), 50.45 (d), 63.15 (d), 64.11 (d), 123.60 (d, 2 C), 124.25 (d, 2 C), 128.45 (d), 128.77 (d), 128.83 (d), 136.86 (s), 136.98 (d), 146.87 (s), 148.87 (d), 149.01 (s), 153.62 (s), 155.23 (s), 155.33 (s); Crystals of the material thereby obtained contained CH_2Cl_2 as solvate. Anal. Calcd for $C_{37}H_{26}N_6 \cdot CH_2Cl_2$: C, 71.36; H, 4.41, Found: C, 71.49; H, 4.36.

10,11-[3',6'-Di-(2"-pyridyl)-4',5'-pyridazino]tricyclo[6.3.0.$0^{2,6}$]undecan-3-one (11). To a solution of tricyclo[6.3.0.$0^{2,6}$]undecane-3,11-dione[12] (178 mg, 1.00 mmol) and 3,6-dipyridyl-1,2,4,5-tetrazine[18] (236 mg, 1.00 mmol) in THF (20 ml) was added 5% methanolic KOH solution (2.5 ml). The resulting mixture was refluxed for 2 h, at which time tlc analysis revealed that all of the starting materials had been consumed. The reaction mixture was allowed to cool to room temperature and then concentrated *in vacuo*. Methanol (7 ml) was added to the residue, whereupon a yellow solid precipitated from solution. This precipitate was collected via suction filtration, and the residue was washed with MeOH (2 x 5 ml). The residue was recrystallized from CH_2Cl_2-EtOAc, therby affording pure **11** (120 mg, 33%) as a pale yellow microcrystalline solid: mp 189-190 °C; ir (KBr) 2930 (w), 2859 (w), 1727 (s), 1577 (m), 1563 (m), 1535 (w), 1464 (m), 1415 (m), 1374 (s), 793 (s), 740 (s), 612 cm^{-1} (m); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 237 (1.7), 289 nm (2.9); ^1H Nmr ($CDCl_3$) δ 1.13-1.33 (m, 1 H), 1.61-2.55 (m, 5 H), 2.93-3.28 (m, 4 H), 3.80 (q, J = 9.9 Hz, 1 H), 5.07 (br t, J = 9.5 Hz, 1 H), 7.25-7.35 (m, 2 H), 7.80-7.92 (m, 2 H), 8.58-8.80 (m, 4 H); ^{13}C Nmr ($CDCl_3$) δ 23.03 (t), 35.03 (t), 39.42 (t), 40.14 (t), 42.59 (d), 44.24 (d), 54.72 (d), 55.74 (d), 123.20 (d), 123.24 (d), 123.33 (d), 123.44 (d), 136.34 (d), 136.37 (d),

143.45 (s), 144.15 (s), 148.03 (d), 148.33 (d), 155.03 (s) 155.97 (s), 156.02 (s), 156.72 (s), 218.55 (s). Anal. Calcd for $C_{23}H_{20}N_4O$: C, 74.98; H, 5.47. Found: C, 74.88; H, 5.32.

3,4:10,11-Bis[3',6'-Di-(2''-pyridyl)-4',5'-pyridazino]tricyclo[6.3.0.0^{2,6}]undecane (9a). To a warm solution of tricyclo[6.3.0.0^{2,6}]undecane-3,11-dione[12] (**10**, 30 mg, 0.17 mmol) and 3,6-dipyridyl-1,2,4,5-tetrazine[18] (100 mg, 0.422 mmol) in toluene (20 ml) was added DBU (1 ml, excess), and the resulting solution was refluxed for 9 h. The reaction mixture was allowed to cool to room temperature and then concentrated *in vacuo*. Methanol (3 ml) was added to the residue, whereupon a yellow solid precipitated from solution. This precipitate was collected *via* suction filtration, and the residue was washed with MeOH (2 x 5 ml). The residue, crude **9a** (37 mg, 39%), was recrystallized from CH_2Cl_2-EtOAc, therby affording pure **9a** as a pale yellow microcrystalline solid: mp 251.5-252.5 °C (decomp.); ir (KBr) 2923 (w), 2859 (w), 1577 (s), 1563 (s), 1528 (m), 1464 (s), 1422 (s), 1373 (s), 985 (w), 790 (s), 731 (s), 647 cm^{-1} (m); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 240 (3.0), 287 nm (4.7); ^{1}H Nmr ($CDCl_3$) δ 1.87 (*AB*, J_{AB} = 14.4 Hz, 1 H), 2.42-2.60 (m, 1 H), 3.09-3.34 (m, 4 H), 3.36-3.51 (m, 2 H), 5.25-5.32 (m, 2 H), 6.96-7.03 (m, 2 H), 7.28 (dt, J = 3.8, 1.2 Hz, 2 H), 7.58 (dt, J = 7.5, 1.8 Hz, 2 H), 7.79 (dt, J = 7.5, 1.8 Hz, 2 H), 7.92-7.99 (m, 2 H), 8.16-8.23 (m, 2 H), 8.38-8.44 (m, 2 H), 8.54-8.60 (m, 2 H); ^{13}C Nmr ($CDCl_3$) δ 38.27 (t), 41.01 (t), 46.96 (d), 56.35 (t), 123.16 (d), 123.61 (d), 123.95 (d), 123.98 (d), 136.80 (d), 136.90 (d), 145.74 (s), 146.30 (s), 148.47 (d), 149.17 (d), 154.92 (s), 155.48 (s), 156.10 (s), 156.15 (s). Anal. Calcd for $C_{35}H_{26}N_8$: C, 75.25; H, 4.69. Found: C, 75.49; H, 4.81.

3,4:10,11-Bis[3',6'-diphenyl-4',5'-pyridazino]tricyclo[6.3.0.0^{2,6}]undecane (9b). To a refluxing solution of **10**[12] (66 mg, 0.371 mmol) and 3,6-diphenyl-1,2,4,5-tetrazine[19] (174 mg, 0.744 mmol) in toluene (20 ml) was added 1 ml of DBU (excess). The resulting mixture was refluxed for 20 h, then cooled to room temperature, and solvent was removed *in vacuo*. Methanol (5.0 ml) was added to the residue, whereupon a yellowish solid precipitated. The precipitate was collected by filtration, and the residue was washed with MeOH (2 x 3 ml). The residue was recrystallized from CH_2Cl_2-EtOAc, thereby affording **9b** (120 mg, 58%) as a colorless microcrystalline solid: mp 248-249 °C (decomp.); ir (KBr) 2945 (w), 2925 (w), 1637 (w), 1445 (m), 1363 (s), 753 (s), 685 (s), 651 cm^{-1} (s); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 250 (sh), 269 nm (3.0); ^{1}H Nmr ($CDCl_3$) δ 2.36-2.54 (m, 2 H), 2.67 (dd, J = 5.4, 16.5 Hz, 2 H), 3.02-3.34 (m, 4 H), 4.43 (dd, J = 5.0, 2.1 Hz, 2 H), 7.17-7.25 (m, 6 H), 7.48-7.62 (m, 10 H), 7.72-7.82 (m, 4 H); ^{13}C Nmr ($CDCl_3$) δ 36.69 (t), 39.88 (t), 47.53 (d), 56.45 (d), 128.08 (d), 128.41 (d), 128.61 (d), 128.63 (d), 128.85 (d), 129.29 (d), 136.51 (s), 136.59 (s), 141.81 (s), 142.75 (s), 156.00 (s), 156.07 (s); Anal. Calcd for $C_{39}H_{30}N_4$: C, 84.45; H, 5.45. Found: C, 84.23; H, 5.64.

1,2-[3',6'-Di-(2''-pyridyl)-4',5'-pyridazino]cyclopentane (12a). To a refluxing solution of cyclopentanone (0.9 ml, 10 mmol, excess) and 3,6-dipyridyl-1,2,4,5-tetrazine[18] (105 mg, 0.445 mmol) in THF (20 ml) was added DBU (1.0 ml, excess). The resulting mixture was refluxed with stirring for 4 h and then allowed to cool slowly to room temperature. The reaction mixture then was concentrated *in vacuo*. To the residue was added EtOAc (5 ml) and MeOH (5 ml), and the resulting mixture was allowed to stir overnight at room temperature. A pale yellow precipitate which had formed during this period was collected *via* suction filtration. This material was recrystallized from EtOAc-CH_2Cl_2, thereby affording pure **12a** (93.5 mg, 77 %) as a pale yellow microcrystalline

solid: mp 156-157 °C (lit.[20] mp 159-161 °C); ir (KBr) 2960 (w), 2857 (w), 1585 (s), 1571 (s), 1465 (s), 1417 (s), 1372 (s), 982 (m), 783 (m), 733 cm^{-1} (m); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 229 (1.8), 286 nm (3.0); ^1H Nmr ($CDCl_3$) δ 2.14 (quintet, J = 5.1 Hz, 2 H), 3.51 (t, J = 5.1 Hz, 4 H), 7.30-7.37 (m, 2 H), 7.87 (dt, J = 5.1, 1.1 Hz, 2 H), 8.56 (d, J = 5.2 Hz, 2 H), 8.59-8.84 (m, 2 H); ^{13}C Nmr ($CDCl_3$) δ 24.21 (t), 33.42 (t), 123.3 (d), 123.6 (d), 136.6 (d), 145.7 (s), 148.8 (d), 155.2 (s), 156.1 (s); Anal. Calcd for $C_{17}H_{14}N_4$: C, 74.44; H, 5.14. Found: C, 74.25; H, 5.21.

1,2-[3',6'-Diphenyl-4',5'-pyridazino]cyclopentane (12b). To a refluxing solution of cyclopentanone (0.20 g, 2.4 mmol, excess) and 3,6-diphenyl-1,2,4,5-tetrazine[19] (160 mg, 0.68 mmol) in THF (15 ml) was added DBU (1.0 ml, excess). The resulting mixture was refluxed with stirring for 5 hr and then allowed to cool slowly to room temperature. The reaction mixture then was concentrated *in vacuo*. To the residue was added EtOAc (5 ml) and MeOH (5 ml), and the resulting mixture was allowed to stir overnight at room temperature. A colorless precipitate which had formed during this period was collected *via* suction filtration. This material was recrystallized from EtOAc-CH_2Cl_2, thereby affording pure **12b** (136 mg, 73%) as a colorless microcrystalline solid: mp 161.2-162 °C (lit. mp 132-134;[10a] mp 135-136[21]); ir (KBr) 2952 (w), 1541 (m), 1445 (m), 1370 (s), 1062 (w), 760 (s), 692 cm^{-1} (s); uv (CH_3CN) λ_{max} (ε x 10^{-4}) 266 nm (2.0); ^1H Nmr ($CDCl_3$) δ 2.13 (quintet, J = 7.4 Hz, 2 H), 3.21 (t, J = 7.4 Hz, 4 H), 7.52 (br d, J = 5.9 Hz, 6 H), 7.88-8.05 (m, 4 H); ^{13}C Nmr ($CDCl_3$) δ 25.09 (t), 33.06 (t), 128.5 (d), 128.6 (d), 129.1 (d), 137.1 (s), 142.9 (s), 156.3 (s); Anal. Calcd for $C_{19}H_{16}N_2$: C, 83.79; H, 5.92. Found: C, 84.00; H, 5.91.

X-ray Structure Determinations of 6a, 6b, 6c, 9a, and 9b. Data for a single crystal of **6b** were collected at Texas Christian University on a Nicolet R3m/μ update of a $P2_1$ diffractometer by using the ω-scan mode with a variable scan rate of 4 to 29.3 deg-min^{-1}. Data for **6a**, **6c**, **9a**, and **9b** were obtained at Texas Christian University on a Rigaku AFC6 diffractometer by using the ω-2θ mode with a constant scan rate; multiple scans were obtained for weak reflections. The structures were solved by direct methods, and the models were refined via a full-matrix least-squares procedure. A ψ-scan empirical absorption correction was applied. Crystal and refinement data for the five compounds are given in Table 2.[22]

X-ray Structure Determination of 11a. Data for a single crystal of **11a** were collected at the University of North Texas on an Enraf-Nonius CAD-4 diffractometer by using the ω-scan technique, Mo Kα radiation (λ = 0.71073 Å) and a graphite monochromator. Details of this procedure have been described elsewhere.[23] The structure was solved by using direct methods, and the model was refined via full-matrix least-squares techniques. The data were corrected for absorption by using DIFABS.[24] Hydrogen atoms were located on difference maps and then included in the model in idealized positions [U(H) = 1.3 B_{eq}(C)]. Crystal and refinement data for **11a** appear in Table 2.[22]

Electrochemical Studies. Cyclic voltammetry was performed at room temperature by using an EG&G Princeton Applied Research Potentiostat/Galvanostat, Model 273 in the manner described previously with a scan rate of 1 V-sec^{-1}.[25] Solvents employed in the electrochemical studies were either hplc grade dimethylformamide (DMF, used as obtained from the Aldrich Chemical Company) or acetonitrile (Aldrich, distilled

from P_4O_{10} immediately before use). Tetra-*n*-butylammonium hexafluorophosphate (Aldrich) was used as supporting electrolyte; this material was dried *in vacuo* for at least 2 h prior to use.

Table 2. X-ray crystal and refinement data for **6a**, **6b**, **6c**, **9a**, **9b**, and **11a**

Compound	**6a**	**6b**	**6c**	**9a**	**9b**	**11a**
Formula	$C_{35}H_{24}N_8$	$C_{39}H_{28}N_4$	$C_{37}H_{26}N_6 \cdot CHCl_3$	$C_{35}H_{26}N_8$	$C_{39}H_{30}N_4$	$C_{23}H_{20}N_4O$
Formula wt.	556.6	552.7	674.0	558.6	554.7	368.4
Size (mm)	.45x.30 x.28	.30x.25x.075	.45x.33x.20	.30x.30x.35	.20x.20x.20	.22x.28x.35
Space Group	C2/c	$P2_1/n$	$P2_1/n$	$P2_1/c$	$P2_1/n$ (#14)	$P2_1/n$ (#14)
a (Å)	29.288 (7)	11.362 (8)	16.038 (2)	14.050 (2)	16.133 (4)	9.6105 (8)
b (Å)	10.398 (2)	19.282 (14)	11.613 (2)	10.713 (2)	7.976 (2)	12.754 (1)
c (Å)	20.011 (6)	12.821 (7)	17.199 (2)	18.430 (2)	22.081 (2)	19.582 (1)
α (°)	90.00	90.00	90.00	90.00	90.00	90.00
β (°)	117.10 (2)	101.79 (5)	96.800 (9)	97.08 (1)	96.24 (1)	106.880 (6)
γ (°)	90.00	90.00	90.00	90.00	90.00	90.00
V (Å^3)	5425 (4)	2750 (2)	3181 (1)	2753 (1)	2825 (1)	1864.1 (3)
Z	8	4	4	4	4	4
D_c (g-cm^{-3})	1.366	1.340	1.407	1.348	1.304	1.313
F(000)	2320	1160	1392	1168	1168	775
λ (Å)	1.54178	0.71073	1.54178	1.54178	1.54178	0.71073
μ (cm^{-1})	6.33	6.75	29.55	6.23	5.62	0.78
ω–2θ (2θ_{max})	130.2	44	130.1	130.1	157.9	44
Total refl.	5573	4323	5857	4547	8622	2548
Unique refl.	4861	3535	5643	4350	6277	2395
R_{int}	0.031	0.009	0.072	0.018	0.032	0.018
No. $I \geq 3\sigma(I)$	3119	2132	3210	2944	3411	1539
Absorp.Corr. Coeff.	0.96-1.00	0.86-0.89	0.77-1.00	0.95-1.00	0.89-1.00	0.85-1.18
Secondary Extinction Coeff. (x 10^6)	.689	1.84	2.48	.220	3.42	- -
R;wR	.052; .053	.069; .035	.061; .054	.063; .077	.064; .064	.056; .064
No. variables	485	501	531	492	509	193
$(\Delta/\sigma)_{max}$	0.01	0.018	0.01	0.01	0.01	<0.01
ρ_{min}; ρ_{max}	-0.22; 0.22	-0.30; 0.33	-0.43; 0.44	-0.38; 0.24	-0.28; 0.22	-0.32; 0.35

ACKNOWLEDGMENT

We thank the Robert A. Welch Foundation (Grant B-963 to A. P. M., B-1202 to S. G. B., B-1154 to P. S. B., and P-074 to W. H. W.) for financial support of this study.

REFERENCES

1. A. P. Marchand, 'Advances in Theoretically Interesting Molecules', Vol. 1, ed. by R. P. Thummel, JAI Press, Greenwich, CT, 1989, pp. 357-399.
2. A. P. Marchand, *SYNLETT*, 1991, 73.
3. A. P. Marchand, P. Annapurna, J. L. Flippen-Anderson, R. Gilardi, and C. George, *Tetrahedron Lett.*, 1988, **29**, 6681.
4. A. P. Marchand, P. Annapurna, R. W. Taylor, D. L. Simmons, W. H. Watson, A. Nagl, J. L. Flippen-Anderson, R. Gilardi, and C. George, *Tetrahedron*, 1990, **46**, 5077.
5. R. P. Thummel and J.-L. Lim, *Tetrahedron Lett.*, 1987, **28**, 3319.
6. J.-L. Lim, S. Chirayil, and R. P. Thummel, *J. Org. Chem.*, 1991, **56**, 1492.
7. E. Wenkert and J. E. Yoder, *J. Org. Chem.*, 1970, **35**, 2986.
8. R. C. Cookson, E. Crundwell, and J. Hudec, *Chem. Ind. (London)*, 1958, 1003.
9. A. P. Marchand and R. W. Allen, *J. Org. Chem.*, 1974, **39**, 1596.
10. (a) M. J. Haddadin, S. Firsan, and B. Nader, *J. Org. Chem.* 1979, **44**, 629. (b) D. L. Boger, *Chem. Rev.*, 1986, **86**, 781.
11. A. P. Marchand, G. M. Reddy, F. Zaragoza, R. A. Bartsch, and M. D. Eley, *Tetrahedron Lett.*,1993, **34**, 5377.
12. G. Mehta, A. Srikrishna, A. V. Reddy, and M. S. Nair, *Tetrahedron*, 1981, **37**, 4543.
13. W. H. Watson, A. Nagl, A. P. Marchand, and P. Annapurna, *Acta Crystallogr., Sect. C: Cryst. Struct. Commun.*, 1989, **C45**, 856.
14. (a) G. Mehta, C. Prabhakar, N. Padmaja, S. Ramakumar, and M. A. Viswamitra, *Tetrahedron Lett.*, 1989, **30**, 6895. (b) G. Mehta, C. Prabhakar, N. Padmaja, and M. A. Viswamitra, *J. Chem. Soc.,Perkin Trans.1*, 1992, 1747.
15. PCMODEL-386 (October, 1992) was obtained from Serena Software, Inc., P. O. Box 3076, Bloomington, IN 47402.
16. (a) N. L. Allinger, Y. H. Yuh, and J.-H. Lii, *J. Am. Chem. Soc.*,1989, **111**, 8551. (b) MM3 was obtained from Technical Utilization Corporation, 235 Glen Village Court, Powell, OH 43065.
17. The difference predicted from MOPAC calculations between $\pi(10)$ levels in **12a** and **12b** in their optimized gas-phase geometries is 0.23 eV; J. J. P. Stewart, *MOPAC. A General Molecular Orbital Package*, Version 6.0, 1990, QCPE Program No. 455.
18. (a) M. O. Abdel-Rahman, M. A. Kira, and M. N. Tolba, *Tetrahedron Lett.*, 1968, 3871. (b) J. F. Geldard and F. Lions, *J. Org. Chem.* 1965, **30**, 318.
19. K. A. Hofmann and O. Ehrhart, *Chem. Ber.*,1912, **45**, 2731.
20. M. Atfah, *J. Heterocyclic Chem.*,1989, **26**, 717.
21. D. Lang and D. Peter, *Chem. Ber.*, 1965, **98**, 1435.
22. Tables of positional parameters and their estimated standard deviations, general displacement parameter expressions, bond distances, bond angles, and torsion angles for **6a**, **6b**, **6c**, **9a**, **9b**, and **11a** (iii + 120 pages) are available upon request from the Director of the Cambridge Crystallographic Data Centre, University Chemical Laboratory, Lensfield Road, Cambridge CV2 1EW, U. K. Requests should be accompanied by the full literature citation for this article.
23. M. R. Mason, J. M. Smith, S. G. Bott, and A. R. Barron, *J. Am. Chem. Soc.*, 1993, **115**, 4971.
24. N. Walker and D. Stuart, *Acta Crystallogr., Sect. A* **1983**, *39A*, 159.
25. P. S. Braterman and J.-I. Song, *J. Org. Chem.*, 1991, **56**, 4676.

Received, 24th September, 1993