Nitrogen Analogs of 1,6-Methano[12]annulene. Effect on Valence Tautomerism of the Locus of Aza Substitution[1]

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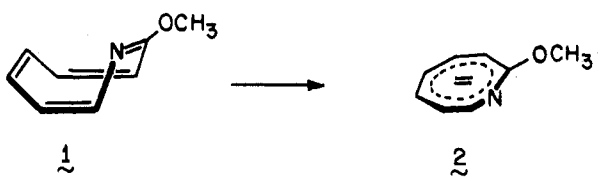
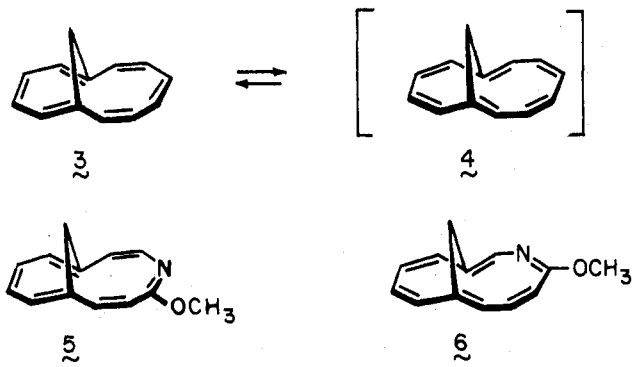
Beckmann rearrangement of 4,9-methano[11]annulenone oxime with tosyl chloride in pyridine and subsequent direct methanolysis leads to azaannulene **5** in 90% yield. The oxime of 3,8-methano[11]annulenone rearranges only with difficulty to give β-lactam **13**. The valence isomeric lactam **14** cannot be detected at temperatures up to 110°. The contrasting behavior of **8** and **13** and the question of heavy thermodynamic weighting in the direction of the bridged cycloheptatriene form are discussed. It is concluded that planar bridged cycloheptatriene derivatives are more stable because of lessened strain and electronic delocalization of the neutral homoaromatic type. The electrochemical reduction of **5** reveals that multielectron (2ϵ) discharge occurs, but that the resulting dianion is highly reactive or unstable (cyclic voltammetry data). Alkali metal reductions performed in liquid ammonia support the surprising instability of dianion **18**. Dihydro products **19** and **20** were formed upon quenching.

To date, studies of the consequences of ring nitrogen substitution for trigonal carbon on the chemical properties of $4n$-π monocyclic polyolefins have been limited to the azocine group.[2,3] Although such π-equivalent heterocycles as **1** are true polyolefins, alkali metal reduction affords the very stable planar 10-π-electron dianions **2** which are endowed with substantial aromatic character.[4] Electrochemical measurements have shown that reductions under these conditions occur by direct two-electron transfer and that azocinyl dianions are not reoxidized until the potential is scanned 1 V anodic of the initial reduction wave.[5] The properties of multielectron addition and resistance to oxidation are not shared by cyclooctatetraene and its derivatives. The azocines are endowed with a sufficient number of unique chemical features that systematic investigation of higher homologs of this ring system appeared desirable.



1 **2**

This paper, therefore, describes a study of the aza analogs **5** and **6** of 1,6-methano[12]annulene (**3**). The compan-

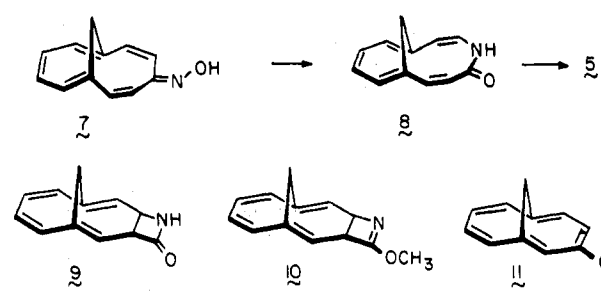


3 **4**

5 **6**

ion study by Vogel of the parent hydrocarbon[6] has shown the bridged annulene to be highly puckered, to exist essentially exclusively as valence tautomer **3** having the cycloheptatriene part structure, and to possess a paramagnetic ring current. Positioning of the imidate group as in **5** should permit the π-electron array which is energetically favored in **3**. In **6**,[7] however, maintenance of the imidate function should lead to bond fixation in the less stable electronic arrangement. Consequently, these isomeric heterocycles were expected to focus attention upon those electronic features peculiar to the [12]annulene model. Efforts to prepare **6** have failed in the final step, but the study has provided experimental information concerning the interrelationship of the locus of the nitrogen atom (as amide and imidate groups) and the preferred direction of valency tautomerism.

Synthetic Considerations. The approach to **5** involved ring expansion of 4,9-methano[11]annulenone.[8] This ketone was converted to its oxime **7** by refluxing with hydroxylamine hydrochloride and pyridine in ethanol solution. Beckmann rearrangement of **7** proved to be exceptionally facile, stirring with a twofold excess of tosyl chloride in pyridine at room temperature for 3 hr being adequate to provide good yields of **8** after hydrolysis. The ir spectrum



7 **8** **5**

9 **10** **11**

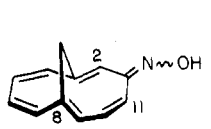
of this lactam shows intense absorptions at 3300, 2920, and 1675 cm^{-1}. Its ^1H NMR features a multiplet at δ 5.8–7.0 of area 9 due to the perimeter hydrogens and the >NH group and broadened doublets (J = 14 Hz) at 3.1 and 2.1 for the pair of bridge protons. The spectrum revealed no evidence for the presence of β-lactam isomer **9**, in marked contrast to the recognized predominance of 7-azabicyclo[4.2.0]octatrien-8-ones in equilibrium with their ring-opened monocyclic counterparts.[3e]

In the presence of trimethyloxonium fluoroborate, **8** was converted to **5** (60%) with concomitant formation of considerable polymer. Subsequently, it was recognized that attempted formation of the fluoroborate and perchlorate salts of **5** also led to decomposition. Since attempted ring expansion of oxime **7** with phosphorus pentachloride or polyphosphoric acid afforded only polymer, the lability of these polyenes to acidic media was made clearly evident. These difficulties could be totally bypassed by allowing oxime **7** to react with tosyl chloride in pyridine followed by direct methanolysis to give **5** in 90% yield.

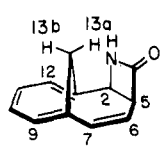
Azaannulene **5** is an air-stable, bright orange solid showing intense imidate absorption in the infrared at 1670 cm^{-1} and an ultraviolet maximum at 257 nm (ϵ 40,000). Its ^1H NMR spectrum consists of the expected olefinic pattern showing seven of the eight olefinic protons as a series of

multiplets at δ 5.85–6.60, H_2 appearing at higher field (5.08, broadened d, J = 10 Hz) owing to its unique position β to the nitrogen atom.[3] The bridgehead methylene protons are seen as widely separated doublets (J = 12 Hz) at δ 5.34 and 1.64, their mutual spin interaction having been unequivocally established by double-resonance experiments. As in the case of **8**, no spectroscopic evidence was obtained to suggest that **5** is in tautomeric equilibrium with **10** or its norcaradiene valence tautomer. Given that low levels of **10** could be present in <2% concentration and thereby escape spectral detection, then exposure to a strong base would be expected to produce nitrile **11**, much in the same way that **1** is converted to benzonitrile.[3d] However, **5** proved to be totally inert to the action of potassium *tert*-butoxide in refluxing tetrahydrofuran (8 hr) or dimethylformamide at 25° (16 hr). It would appear, therefore, that **10** is not present. Furthermore, the inability of **5** to undergo cycloaddition with *N*-phenylmaleimide (threefold excess, refluxing xylene, 30 hr) or dimethyl acetylenedicarboxylate (40-fold excess, refluxing toluene, 24 hr) attests to the unimportance of the norcaradiene isomer.

The oxime of 3,8-methano[11]annulenone (**12**) was synthesized from the corresponding ketone, which was obtained from reduction of 11-chloro-3,8-methano[11]annulenone.[9] In this instance the yields of oxime were not high, a maximum of 30% being realized in pyridine solution at room temperature for 48 hr. Unlike its symmetrical counterpart, the tosylate of **12** did not readily undergo the Beckmann rearrangement. For example, decomposition was encountered when this oxime tosylate was stirred at 0–25° in methanol–pyridine or water–acetone–pyridine solvent systems. However, prior removal of the pyridine in vacuo and subsequent solvolysis in an aqueous dioxane medium containing sodium acetate did give lactam product in 35% yield. When the less nucleophilic base 2,6-lutidine replaced sodium acetate under these conditions, the optimal yield for conversion to **13** (55%) was realized.



12



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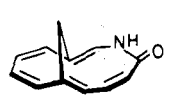

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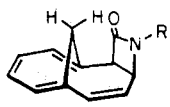
Noteworthy spectral features of **13** are the intense ir signals at 3418 and 1764 cm^{-1} and a parent molecular ion at m/e 185.0843 indicative of a β-lactam structure of molecular formula $C_{12}H_{11}NO$. In striking contrast to the behavior of **8**, where the base peak is the molecular ion, **13** exhibits a weak molecular ion and a base peak at m/e 142 (M − 43, loss of [CONH] ·). This type of fragmentation conforms to the usual behavior of β-lactams.[10]

Spin decoupling studies elucidated the gross structural features of **13** and the magnitude of the coupling constants $J_{2,5}$ = 5.0, $J_{5,6}$ = 7.0, $J_{6,7}$ = 12.0, and $J_{13a,13b}$ = 11.5 Hz. The syn stereochemical assignment was derived by pseudocontact shifting of the ^1H NMR spectrum with $Eu(fod)_3$.[11] The relevant ΔEu values[12] are H_2, −6.80; H_3, −11.66; H_5, −18.09; H_6, −11.68; H_7, −5.03; H_9, H_{12}, −2.72; H_{10}, H_{11}, −1.41; H_{13a}, −8.83; H_{13b}, −3.17. Since the lanthanide shift reagent complexes principally to the oxygen atom, the enhanced downfield shifting of both H_5 and H_{13a} requires that H_5 be α to the amide carbonyl and the methano bridge be syn to the β-lactam ring. That H_2 appears as a doublet coupled only to H_5 necessitates that the β-lactam ring be oriented as shown rather than in the reverse sense. This finding implicates C_2 as the vinyl carbon in **12** (in the form of the tosylate derivative) with the greater capability for migration to nitrogen, perhaps because of the stereochemistry prevailing in the crystalline oxime isomer employed.

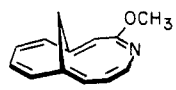
Despite the fact that **13** probably arises by ring closure of initially formed lactam **14**, no evidence for the reversal of this process could be gained by ^1H NMR studies at temperatures up to 110°. Nor was there any indication that the anti isomer of **13** was present during any of these experiments.

All attempts to effect the O-methylation of **13** resulted in decomposition with formation of noncharacterizable oils. Surprisingly, even the action of trimethyloxonium fluoroborate[10,13] and methyl fluorosulfonate,[14] two of the most powerful sources of methyl cation, were not successful in providing the desired imino ether. Efforts to generate the ring-expanded imino chloride and tosylate likewise failed.

Speculation then centered about the isomeric structure **15a** as a possible precursor to the π electronically related azaannulene **16**. The earlier observation that methano-



15a, R = H
b, R = SO_2Cl



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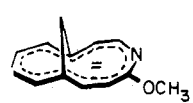
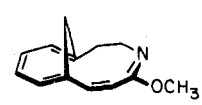
17a, R = H
b, R = Br
c, R = $CONH_2$
d, R = CN
e, R = COOH

[10]annulene reacts with bromine at −78° with formation of an addition product capable of dehydrobromination to give **17b**[15] seemingly points to preferential electrophilic attack at C_2 in this system. This suggested that [2 + 2] cycloaddition of chlorosulfonyl isocyanate (CSI) to **17a** might proceed so as to produce **15b**. Treatment of **17a** with CSI at −78° gave only very small quantities of a product possessing absorption at 1805 cm^{-1} as revealed by direct infrared analysis of the reaction mixture. Warming of the solution to −15° caused disappearance of this band with simultaneous appearance of an intense new carbonyl peak at 1700 cm^{-1}. Hydrolysis with alkaline sodium sulfite[16] and chromatography on Florisil furnished only amide **17c** and nitrile **17d**, which were prepared independently from the known carboxylic acid **17e**.[15] Evidently, the driving force of electronic delocalization in the cyclodecapentaene ring facilitates proton transfer from C_2 to nitrogen in the initial zwitterion. If **15b** is involved as an intermediate of kinetic consequence, its heterolytic ring opening at the C–N bond would generate the same dipolar species.

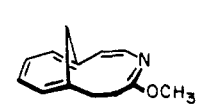
Electrochemical Reduction of 5. The $4n$-π-electronic nature of **5** is perhaps most clearly revealed by its ^1H NMR spectrum, which provides evidence for the presence of localized π bonds and adoption of a conformation which deviates significantly from planarity. In contrast, the dianion of **5** comprises a $(4n + 2)$-π-electron system and might consequently exhibit extended delocalization and "aromatic" character as denoted by **18**. Introduction of a pair of elec-



18



19



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trons into the π network of **5** is expected to carry with it the requirement for attainment of a more nearly planar conformation as well. Because of the intrinsic capability of electrochemical techniques for providing diagnostic information on such questions, the polarographic reduction of **5** was examined initially. Polarographic reduction of **5** (10^{-4} M) was conducted at a dropping mercury electrode in dry,

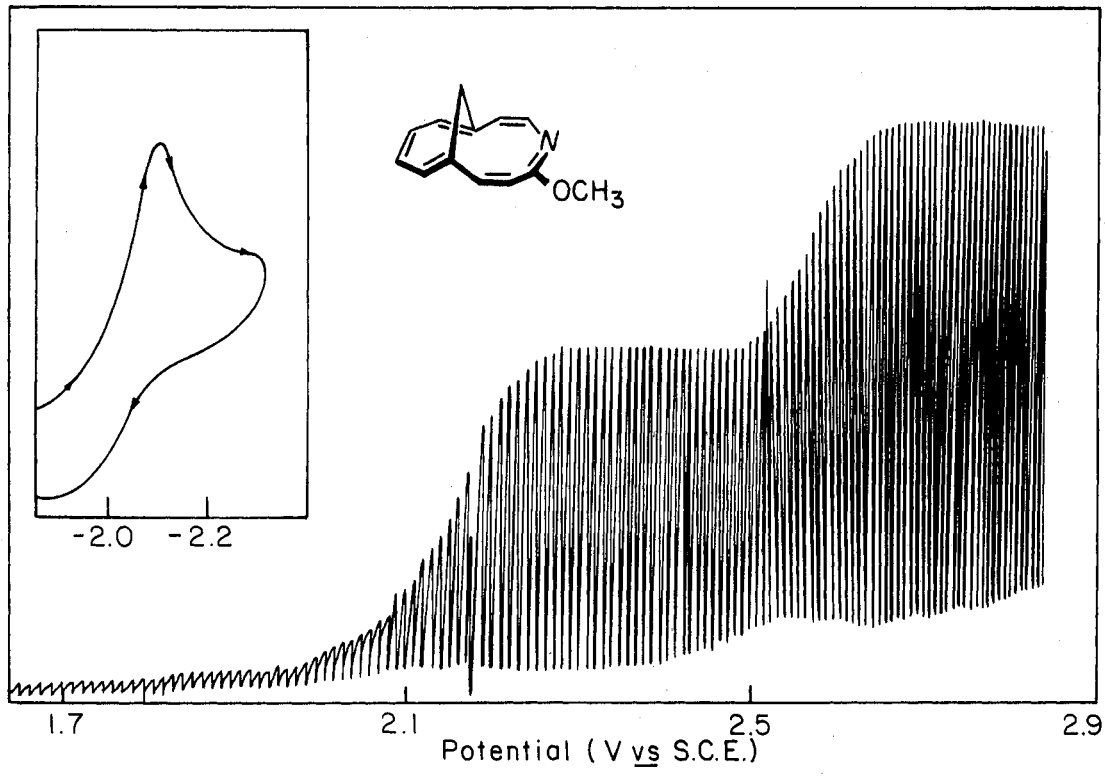


Figure 1. Polarography of 1.15×10^{-4} *M* **5** in anhydrous THF, 0.2 *M* TBAP. Inset shows cyclic voltammetry of this sample at a scan rate of 200 mV/sec.

oxygen-free tetrahydrofuran solution containing 0.2 *M* tetra-*n*-butylammonium perchlorate as background electrolyte. Two non-Nernstian waves were seen with half-wave potentials of −2.18 and −2.58 V vs. SCE (Figure 1). The respective diffusion current constants, $I = i_d/(C^\circ m^{2/3}t^{1/6})$, were measured to be 5.3 and 4.2 × 10^2 $\mu A m M^{-1} g^{-2/3} t^{1/2}$, indicative of greater than one-electron transfer at each step. Comparison with the *I* values measured for cyclooctatetraene and 2-methoxyazocine showed the first wave to be an overall two-electron process. The second wave is a fractional one (1–2 electrons), the source of which is believed to be one or more dihydro products which may arise by in situ Hofmann elimination involving the background electrolyte.[17]

In an effort to test this assumption, the 11,12-dihydro derivative **19** was also electrolytically reduced under identical conditions. A one-electron wave was observed at −2.50 V, the features of which compared very favorably to those seen with **5**. A postwave was also in evidence, appearing at very negative potential (−2.84 V) just prior to discharge of solvent. Addition of small quantities of **5** to the cell containing **19** did, however, not produce an additive effect on the wave attributable to initial reduction of **19**.

Introduction of water into the tetrahydrofuran solution of **5** increased the height of the two-electron wave by 10%. Significantly, the two waves did not coalesce and the half-wave potentials remained essentially invariant, indicating that radical anion $\mathbf{5}\cdot^-$ is short lived and that further reduction to **18** occurs in a fast step prior to significant protonation.[5] The net observable polarographic result is multielectron discharge, now recognized as a rather general feature of π-equivalent nitrogen-containing polyolefins.

In anhydrous acetonitrile (AN) as solvent, the reducibility of **5** was made more facile ($E_{1/2}$ = −1.82 V, Table I). The overall irreversibility of the two-electron reductions in the two solvent systems was verified by cyclic voltammetry. At scan speeds up to 500 mV/sec, no anodic current appears (see, for example, inset of Figure 1) in agreement with the earlier assumption that the reactive intermediate so produced is rapidly consumed under these conditions. This behavior contrasts with the previously reported electrochemical properties of various simple 2-methoxyazocines and 6-methoxydibenz[*b*,*f*]azocine.[5] Should the species generated under these conditions be dianion **18**, the data require that it possess a high level of reactivity. Chemical verification of this conclusion is given below.

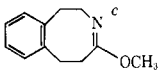
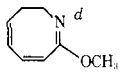
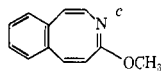
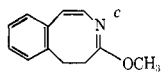
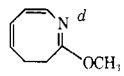
Comparison of $E_{1/2}$ values indicates that **5** is reduced 0.1 V more readily than 3,8-dimethyl-2-methoxyazocine but with greater difficulty (by 0.24 V) than the parent system. The behavior of **5** contrasts expectedly with that reported recently for hydrocarbon **3**[18] which, much like cyclooctatetraene, undergoes stepwise reversible one-electron reduction, presumably via the intermediate radical anion. Unfortunately, the solvent system employed for **3** differs from those utilized in this study; a more precise comparison is thereby precluded.

Table I
Electrochemical Data

Polyene	Solvent	$E_{1/2}$, V vs. SCE	*n* overall
Cyclooctatetraene[b]	THF	−1.96	1
		−2.16	1
	AN	−1.87	1
2-Methoxyazocine[c]	THF	−1.94	2
3,8-Dimethyl-2-methoxyazocine[c]	THF	−2.28	2
3[d]	DMF	−1.51	1
		−1.72	1
5	THF	−2.18	2
	AN	−1.82	2
19	THF	−2.50	1

[a] Derived from the relationship $n_{app} = I_{unk}(n_{COT}/I_{COT})$, except for **3**. [b] Data taken from ref 17a. [c] Data taken from ref 5b. [d] Data taken from ref 18.

Table II
Summary of ^{1}H NMR Chemical Shift Data for Certain Protons of Various Imino Ethers ($CDCl_3$ Solution, 60 MHz, δ Values)

Compd	$H_{\alpha N}$[a]	$H_{\beta N}$[a]	$H_{\alpha OCH_3}$[b]	$H_{\beta OCH_3}$[b]	Uv data
	3.60–4.00		2.53–3.30		
	3.78–4.10	2.38–2.80	5.40	6.30	λ_{max} (isooctane) 246 nm (ϵ 3860)
19	3.70–4.10	2.60–3.05	5.50	6.35	λ_{max} (C_2H_5OH) 236 nm (ϵ 20,000) and 312 (7900)
	6.67	5.87	6.02	6.82	
	6.68	5.73	2.60–3.25		
	6.36	5.10	2.56		λ_{max} (isooctane) 263 nm (ϵ 4900)
20	6.25	5.52	1.6–2.95		λ_{max} (C_2H_5OH) 237 nm (ϵ 18,000) and 325 (8640)

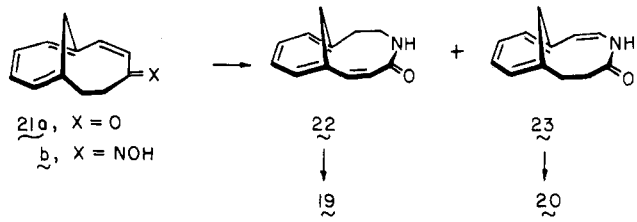
[a] The symbols αN and βN refer to those protons positioned α and β, respectively, relative to nitrogen. [b] Symbolism is used to designate those protons situated α and β to the methoxyl group. [c] Data taken from ref 3f. [d] Data taken from ref 4b.

Alkali Metal Reduction of 5. All of the chemical reductions were conducted in rigorously purified dry solvents on freshly sublimed samples of **5**. Rather unexpectedly, treatment of **5** with 2.15 g-atoms of potassium metal in ammonia–tetrahydrofuran (9:1) for 50 min at −78° returned 80% of unreacted imino ether. Extension of the reaction period to 8 hr and enhancement of the level of potassium to 8.3 g-atoms resulted in 2% recovery of **5**. In addition, a mixture of **19** (24%) and **20** (18%) was now obtained. The actual amounts of **19** and **20** varied due to the incidence of polymerization. To illustrate, when the identical reduction was performed at the reflux temperature of ammonia (−33°) for 30 min (2.7–3.2 g-atomic equiv of potassium), there could be isolated only 8–10% of **20**. Under these conditions, a rapid color change from red-orange to dull brown was evident and deposition of polymer began to occur after 20 min. Quenching of these solutions with a proton source produced no color change.

In the most favorable circumstances, a rather large excess of potassium (ca. 9 equiv) and rather long reaction times (9–10 hr) at −78° were required. To minimize possible decomposition during work-up, ice water and ether were simultaneously introduced, and organic layer was separated, and the product was subjected directly to silica gel chromatography.

Structures **19** and **20** were deduced from their respective uv and ^{1}H NMR features as gauged by comparison with spectra of known compounds (Table II). Both dihydro derivatives show a characteristic pair of doublets in the vinyl region; for **19**, the mutual splitting of these signals (due to H_3 and H_4) is 13 Hz, while that for **20** (attributable to H_{11}, H_{12}) is of diminished magnitude (10 Hz). The latter value seemingly is typical for the -CH=CHN=C(OCH_3)- unit.[3,4]

As further proof, **19** and **20** were independently synthesized from bicyclo[5.4.1]dodeca-2,7,9,11-tetraen-4-one (**21a**) by Beckmann rearrangement of its oxime (**21b**) through use of tosyl chloride in pyridine. Under these conditions, the dihydro lactams **22** and **23** were produced in a



5:1 ratio, a result anticipated from the recognized greater migratory aptitude of the trigonal carbon in related α,β-unsaturated oximes.[19] Subsequent to their chromatographic separation, these lactams were individually treated with trimethyloxonium fluoroborate to give **19** and **20**, respectively. The identity of these imino ethers with those isolated previously served specifically to remove from consideration other possible isomers in which the integrity of the bridged cycloheptatriene ring had been destroyed by protonation.

All attempts to generate dianion **18** for the purpose of spectroscopic detection met with serious difficulties because of rapid decomposition or polymerization. Thus, exposure of **5** to 2 equiv of potassium in ND_3 at −78° in an NMR tube on a vacuum line[20] resulted in formation of a deep red color just prior to becoming black. Only broad ^{1}H NMR signals were seen during and after this color change. When a solution of **5** (1.5–50 mg) in THF-d_8 contained in an NMR tube under nitrogen was brought into contact with a potassium mirror at −78°, gradual decomposition set in. No meaningful new peaks were seen to develop. Experiments with low concentrations of **5** were made with pulse Fourier transform techniques, but no spectral evidence for **18** could be secured.

The factors preventing observation of **18** are not yet known.[21] If this result is due to the inherent instability of **18**, the lack of aromatic character would contrast noticeably with the properties of azocinyl dianions[3,22] and the dianions of **3** and 1,7-methano[12]annulene,[18] which show diamagnetic ring currents.

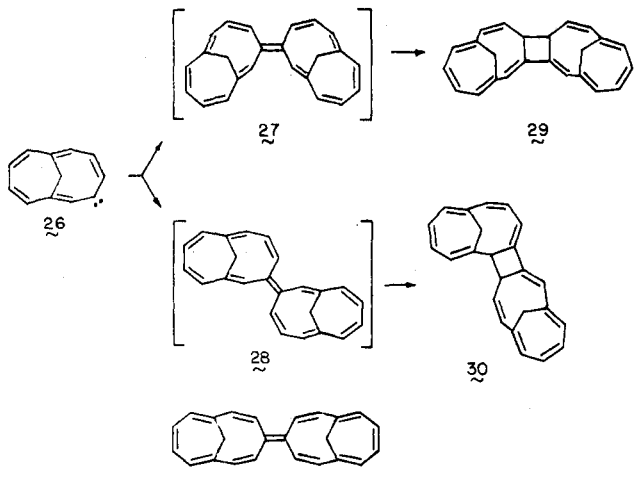
Discussion

The identification of hydrocarbon **3** and its π-equivalent heterocyclic congener **5** as bridged [12]annulenes devoid of an observable capability for π bond shift isomerization points up the greater thermodynamic stability of those valence isomers which contain a bridged cycloheptatriene unit. Although it has been justifiably argued that the absence of the 1,6-dimethylenecyclohepta-2,4-diene form **4** is due to its greater strain,[6] we are currently of the opinion that this energetic discrepancy arises in part from electronic considerations as well.

The thermodynamic relationship between the dihydroazocinone **24** and its β-lactam valence isomer **25** is recognized to be weighted heavily (97.6%) in favor of **25** at 60°.[3e]

24 **25**

The amide function clearly plays a very different role than an imino ether moiety, since in the latter event the medium ring structure (e.g., **1**) is overwhelmingly adopted. Speculation has centered upon the improved electrostatic and π conjugative situation in **25** as the source of its lower free energy.[3e] On this basis, the rapid disrotatory closure of **14** to **13** is fully expected, although the apparent irreversibility of this change is somewhat surprising at first glance. In these terms, the reluctance of **8** to undergo intramolecular cyclization with formation of β-lactam **9** is still more anomalous, at least until an added structural feature is recognized. Should the instability of the yet elusive lactams **9** and **14** be further increased because of the necessity to incorporate a 1,6-dimethylenecyclohepa-2,4-diene unit, then the added disparity in ground-state energy would demonstrate itself in the manner observed experimentally. Valence isomerization *away from* such bridged annulenes seems to be an entirely general phenomenon. For example, the dimeric [11]annulenes **27** and **28** believed to arise from dimerization of carbene **26** undergo irreversible electrocyclic ring closure to give divinylcyclobutanes **29** and **30**.



27 **29**

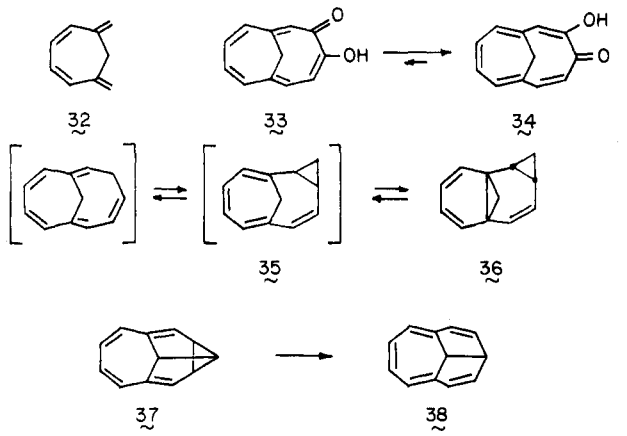
26

28 **30**

31

Jones has attributed this propensity for cyclization to "a gain in homoaromaticity".[23] In contrast, fulvalene **31** resulting from the dimerization of 4,9-methano[11]annulenylidene is entirely stable,[24] no bond shift isomerization being required to avoid 1,6-dimethylenecycloheptadiene part structures in this instance.

Despite the independent existence of parent hydrocarbon **32**,[25] the instability which this tetraene unit brings to bridged annulenes is reflected further in the dominance of **34** over **33** (spectroscopically nondetectable),[26] a simple prototropic shift otherwise separating these 10-π-electron tropolone analogs, and the preference of **35** to exist in tetracyclic form **36** which contains, inter alia, two cyclopropane rings.[9,27] This latter phenomenon may be compared



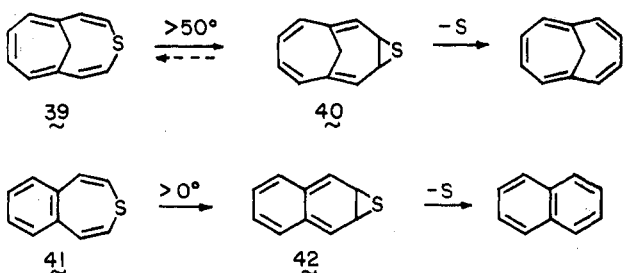
32 **33** **34**

35 **36**

37 **38**

with recent work showing that pentaene **38** far outweighs tautomer **37** in thermodynamic stability.[28,29]

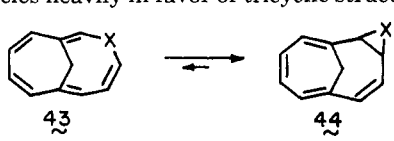
A like assessment of the π-electronic structure of bridged heteroannulenes such as **39** has shown tricyclic valence tautomer **40** to be destabilized to an extent which renders negligible the equilibrium concentration of the latter.[30] That a small equilibrium concentration of **40** is attainable is suggested by the demonstrated propensity of the system to extrude sulfur above 50°. It is noteworthy, however, that 4,5-benzothiepin (**41**) loses sulfur at approximately 0°.[26a] Thus, even though the latter compound must become *o*-quinonoid with loss of benzenoid character (cf. **42**), its reactivity exceeds that of **39**, which likely undergoes such cheletropic transformation via **40**.



39 **40**

41 **42**

As an extension of this analysis, we would predict that the unknown heteroannulene class **43** will exhibit equilibrium tendencies heavily in favor of tricyclic structure **44**. The



43 **44**

close relationship of **44** to β-lactam **13** requires no further comment.

In our assessment, the remarkable thermodynamic stability of bridged cycloheptatriene structures relative to their 1,6-dimethylenecycloheptadiene counterparts is ascribable to some degree to strain effects and in part to electronic influences. The implication which the latter consid-

eration carries is that the cycloheptatriene ring is capable to some degree of homoaromatic interaction (the more planar the more so). Since neutral homoaromaticity[28] is involved, the effect cannot realistically be as pronounced as it is in an ionic species,[31] e.g., the homotropylium ion, where minimization of charge concentration further enhances (markedly) electronic delocalization. Admittedly, the effect must be a more delicate one. Although a detailed discussion of this point is deferred to a later paper, the **45** ⇄ **46** equilibrium serves to illustrate the relevant issue. Discovery of the existence of **45** and **46** as separate structural entities was construed to mean that there could be no energy minimum between these valence tautomers.[32] The homobenzene possibility was thereby considered eliminated. However, it does not seem to have been considered that either (or both) structure could be stabilized by homoaromatic interaction in its own right.

45 **46**

Experimental Section

Melting points are corrected and boiling points are uncorrected. Proton magnetic resonance spectra were obtained on Varian A-60A, Varian HA-100, and Jeolco MH-100 spectrometers; apparent splittings are given in all cases. Infrared spectra were determined on a Perkin-Elmer Model 137 instrument. Mass spectra were recorded on an AEI-MS9 spectrometer at an ionization potential of 70 eV. Elemental analyses were performed by the Scandinavian Microanalytical Laboratory, Herlev, Denmark. Preparative VPC work was done on a Varian Aerograph A90-P3 instrument equipped with a thermal conductivity detector.

4,9-Methano[11]annulenone Oxime (7). A solution of 510 mg (3.0 mmol) of 4,9-methano[11]annulenone[8] and 315 mg (4.5 mmol) of hydroxylamine hydrochloride in a 1:1 mixture of pyridine and ethanol (6 ml) was refluxed for 3 hr under nitrogen. The cooled reaction mixture was partitioned between water (100 ml) and methylene chloride (100 ml) and the organic phase was separated, dried, and concentrated. The residue was recrystallized from ethanol (8 ml) to give 420 mg (77%) of **7**, mp 190–193° (lit.[8] mp 197–198°). This material was used without further purification.

1-Aza-1,2-dihydro-5,10-methano[12]annulen-2-one (8). A solution of **7** (0.50 g, 2.7 mmol) and tosyl chloride (1.0 g, 5.3 mmol) in 20 ml of pyridine was stirred at 0° for 30 min and at room temperature for 3 hr. The deep orange solution soon became black in color. The dark reaction mixture was diluted with methylene chloride and water and the organic phase was washed with saturated sodium bicarbonate solution and water. This solution was dried and evaporated to afford a black solid, chromatography of which on silica gel (elution with 10% ether–benzene) furnished a yellow solid. Recrystallization from methylene chloride–hexane gave 350 mg (70%) of **8**: mp 148–149°; ν_{max} ($CHCl_3$) 3300, 2920, and 1675 cm^{-1}; λ_{max} (C_2H_5OH) 257 nm (ϵ 40,000); δ_{TMS} ($CDCl_3$) 5.8–7.0 (m, 9, olefinic and >NH), 3.1 (br d, J = 14 Hz, bridgehead proton), and 2.1 (br d, J = 14 Hz, bridgehead proton).

Anal. Calcd for $C_{12}H_{11}NO$: C, 77.81; H, 5.99; N, 7.56. Found: C, 77.73; H, 5.97; N, 7.49.

1-Aza-2-methoxy-5,10-methano[12]annulene (5). Procedure A. A solution of lactam **8** (370 mg, 2.0 mmol) and trimethyloxonium fluoroborate (326 mg, 2.2 mmol) in 10 ml of methylene chloride was stirred under nitrogen for 5.5 hr. The solution was neutralized with sodium bicarbonate (400 mg) in 10 ml of water. The mixture was partitioned between methylene chloride and water and the organic phase was dried and evaporated to produce a red-orange solid. Purification by silica gel chromatography (elution with 50% hexane–benzene) gave 270 mg (68%) of pure orange crystals: mp 68–70°; ν_{max} ($CHCl_3$) 3003, 1675, 1600, 1432, 1400, and 1210 cm^{-1}; δ_{TMS} ($CDCl_3$) 5.85–6.55 (m, 7, olefinic), 5.34 (d, J = 12 Hz, bridgehead proton), 5.08 (d, J = 10 Hz, H_{11}), 3.76 (s, methoxyl), and 1.64 (d, J = 12 Hz, bridgehead proton). Double irradiation at δ 1.64 caused the signal at δ 5.34 to collapse to a singlet.

Anal. Calcd for $C_{13}H_{13}NO$: C, 78.36; H, 6.58; N, 7.03. Found: C, 78.34; H, 6.64; N, 6.84.

Procedure B. A solution of oxime **7** (100 mg, 0.54 mmol) and tosyl chloride (200 mg, 1.05 mmol) in 3 ml of pyridine was stirred under nitrogen for 15 min at 0° and then for 3.5 hr at 25°. Methanol (4 ml) was added and the resulting black solution was kept at room temperature for 30 min. Water (100 ml) and methylene chloride (100 ml) were added and the organic phase was worked up as before to give 98 mg (90%) of **5** after sublimation.

3,8-Methano[11]annulenone Oxime (12). A solution of 3,8-methano[11]annulenone[9] (380 mg, 2.2 mmol) and hydroxylamine hydrochloride (184 mg, 2.6 mmol) in 1:1 pyridine–ethanol (4 ml) was stirred at room temperature for 48 hr under nitrogen. Work-up in the predescribed manner left a red oil. Chromatography on silica gel (elution with 10% ethyl acetate in methylene chloride) and recrystallization from pentane afforded 150 mg (30%) of **12** as a red solid: mp 148–149°; ν_{max} (neat) (on oily mixture of isomers) 3200, 1620, and 1595 cm^{-1}; δ_{TMS} ($CDCl_3$) 7.0 (br s, –OH), 5.76–6.68 (m, 8, olefinic), 3.97 (d, J = 12 Hz, bridgehead proton), and 2.86 (d, J = 12 Hz, bridgehead proton); calcd m/e 185.0840, found 185.0843.

Anal. Calcd for $C_{12}H_{11}NO$: C, 77.81; H, 5.99; N, 7.56. Found: C, 77.72; H, 6.17; N, 7.27.

Ring Expansion of 12. A solution of oxime **12** (84 mg, 0.45 mmol) in 2 ml of pyridine cooled to 0° was treated with tosyl chloride (95 mg, 0.50 mmol) and stirred for 55 min under nitrogen. The reaction mixture was poured into methylene chloride and water and the aqueous layer was extracted twice with additional CH_2Cl_2. The combined organic phases were dried, evaporated, and removed of residual pyridine at 0.05 mm. When free of pyridine, the oxime tosylate is stable for several days in a freezer.

The unpurified tosylate (170 mg) was dissolved in a mixture of dioxane (3 ml), water (3 ml), and 2,6-lutidine (100 mg) and stirred under nitrogen at room temperature for 3 hr. Work-up as predescribed gave crude product which was purified by silica gel chromatography (elution with 50% ether–pentane). There was obtained 60 mg of β-lactam **13** which after recrystallization from ether–pentane had mp 124–126° (47 mg, 55%); ν_{max} ($CHCl_3$) 3418 and 1764 cm^{-1}; λ_{max} (C_2H_5OH) 226 nm (ϵ 31,000) and 284 (4480); for ^1H NMR data see text.

Anal. Calcd for $C_{12}H_{11}NO$: C, 77.81; H, 5.99. Found: C, 77.36; H, 6.10.

Chlorosulfonyl Isocyanate Addition to 1,6-Methano[10]annulene. A stirred solution of the annulene (1.03 g, 7.3 mmol) in 15 ml of dry methylene chloride cooled to −78° was treated under nitrogen with freshly distilled chlorosulfonyl isocyanate (1.00 g, 7.1 mmol). After 3 hr, infrared analysis indicated the presence of a weak carbonyl bond at 1850 cm^{-1}. The temperature was increased to 0° and after 7 hr an intense new carbonyl band appeared at 1700 cm^{-1} with disappearance of the peak at 1805 cm^{-1}. After an additional 12 hr at room temperature, the CSI was completely reacted. Solvent was removed in vacuo and the residue was dissolved in ether and added dropwise with stirring to a mixture of 25% sodium sulfite solution (10 ml) and ether (5 ml) cooled to 0°. Potassium hydroxide solution (10%) was added intermittently to maintain a pH of 7–8. After 15 min at room temperature the layers were separated and the aqueous layer reextracted with CH_2Cl_2 (3 × 20 ml). The dried and concentrated organic extracts were chromatographed on Florisil (pentane elution) to give a small amount of unreacted annulene. A solvent polarity increase to 10% ether in pentane afforded 130 mg (11%) of nitrile **17d** while elution with ethyl acetate led to isolation of amide **17c** (40 mg, 3%).

The nitrile was further purified by preparative vpc on a 5% SF-96 column at 165°: ν_{max} (neat) 3050, 2960, 2203, 1450, 1350, 1250, 1100, and 770 cm^{-1}; δ_{TMS} ($CDCl_3$) 7.0–7.8 (m, 7, olefinic) and −0.4 (AB pattern, J = 10 Hz, 2, bridgehead protons).

Anal. Calcd for $C_{12}H_9N$: C, 86.20; H, 5.43. Found: C, 85.96; H, 5.48.

Amide **17c** was purified either by sublimation (90°, 0.05 mm) or recrystallization from ether or methylene chloride–pentane: mp 108–109°; ν_{max} (KBr) 3340, 3160, 1640, and 1610 cm^{-1}; δ_{TMS} ($CDCl_3$) 7.85 (m, 1, proton α to carbonyl), 6.9–7.7 (m, 6), 6.38 (br s, 2, $-CONH_2$), and −0.41 (br s, 2, bridgehead); calcd m/e 185.0840, found 185.0843.

Anal. Calcd for $C_{12}H_{11}NO$: C, 77.81; H, 5.99; N, 7.56. Found: C, 77.35; H, 5.82; N, 7.49.

1,6-Methano[10]annulene-2-carboxamide (17c). A mixture of 1,6-methano[10]annulene-2-carboxylic acid (**17e**, 200 mg, 1.1 mmol), thionyl chloride (250 mg, 2.12 mmol), and benzene (10 ml) was refluxed under nitrogen for 3.5 hr. The benzene was removed in vacuo and the residue dissolved in methylene chloride was

added dropwise at −78° to dry liquid ammonia. After 3 hr, this mixture was poured onto ice and methylene chloride. The aqueous layer was extracted with methylene chloride and the combined organic phases were washed with 10% potassium hydroxide solution and water, dried, and evaporated. The yellow solid (200 mg, 100%) was recrystallized from methylene chloride–pentane to give 90 mg of **17c**, mp 107–109°, which proved to be identical by ir, ^{1}H NMR, and mixture melting point with the sample isolated above.

2-Cyano-1,6-methano[10]annulene (17d). A room-temperature solution of **17c** (94 mg, 0.51 mmol), 2,6-lutidine (200 mg, 1.9 mmol), and benzene (10 ml) was treated with thionyl chloride (180 mg, 1.5 mmol) and an immediate precipitate was observed. After 5 hr at reflux, the mixture was partitioned between water and methylene chloride. The aqueous phase was reextracted with CH_2Cl_2 (2 × 25 ml) and the combined organic layers were washed with saturated sodium bicarbonate solution and water, dried, and evaporated. The resulting red oil (100 mg) was chromatographed on Florisil (25 g) to give upon elution with 50% chloroform–pentane 48 mg (57%) of nitrile, identical in all respects with the sample isolated above.

Electrochemical Measurements. Chemicals. The tetrahydrofuran was prepared by predrying over calcium hydride and storing in vacuo over sodium–potassium alloy. The supporting electrolyte, tetra-*n*-butylammonium perchlorate (TBAP, Southwestern Analytical, Austin, Tex.), was dried by heating in vacuo at 90°. Acetonitrile was purified by distillation from phosphorus pentoxide and storage over calcium hydride.

Apparatus. The electrochemical instrumentation, cells, and procedures for achieving measurements under rigorously aprotic conditions have been previously described.[33] All measurements were made at ambient laboratory temperature, 23 ± 1°. Potentials were measured against a silver wire/0.1 *M* Ag^+ (THF) reference electrode, but are reported herein vs. the aqueous saturated calomel electrode and are not corrected for *iR* drop. The Ag/Ag^+ (0.1 *M*) reference electrode was measured to be +0.49 vs. SCE. From previous work,[5] the *iR* drop is estimated to be between 1 and 5 mV for the concentrations employed herein; the effect on the potentials is considered to be negligible.

Alkali Metal Reduction of 5. Into a dry 100-ml three-necked flask which had been fitted with a gas inlet tube, a Dry Ice condenser, a rubber septum, and a glass-encased magnetic stirring bar was placed a solution of **5** (208 mg, 1.04 mmol) in 6 ml of anhydrous tetrahydrofuran (freshly distilled from $LiAlH_4$). Liquid ammonia (55 ml) was distilled from sodium metal directly into this flask cooled to −78°. With stirring, there was introduced under a dry oxygen-free atmosphere 350 mg (9.0 mg-atoms) of potassium metal (as fine chips) during 10 min. The blue-green solution was stirred at −78° for 8 hr, whereupon 3 ml of methanol was introduced and the contents allowed to warm to room temperature. After 1 hr most of the ammonia had evaporated and the green residue was taken up in water (200 ml) and ether (3 × 100 ml). The combined organic layers were washed with water, dried, and concentrated to leave a green oil. Chromatography on silica gel (elution with 50% benzene–hexane) returned 3 mg (1.7%) of **5** and gave 50 mg (24%) of **19** and 37 mg (18%) of **20**.

In an alternative work-up procedure, the reaction mixture was quenched with methanol (2 ml) and ammonium chloride (amount equivalent to K used) at −78° followed by rapid pouring into ice water (200 ml) and ether (150 ml), immediate work-up, and chromatography.

For **19**: ν_{max} (neat) 2930, 1665, 1610, and 1210 cm^{-1}; δ_{TMS} ($CDCl_3$) 5.9–6.7 (m, 4, H_6–H_9), 6.35 and 5.50 (AB, J = 13 Hz, 2, $H_{3,4}$), 3.70–4.10 (m, 1, H_{12}), 2.60–3.05 (m, 3, H_{11} and H_{12}), 3.76 (s, 3, methoxyl), 3.24 (d with additional fine splitting, 1, H_{13a} or H_{13b}), and 1.10 (d with additional fine splitting, 1, H_{13a} or H_{13b}).

The perchlorate salt was obtained as yellow crystals, mp 194–195° (from methylene chloride–ether).

Anal. Calcd for $C_{13}H_{16}ClNO_5$: C, 51.75; H, 5.35; N, 4.64. Found: C, 52.09; H, 5.61; N, 4.46.

For **20**: ν_{max} (neat) 3010, 2950, 2860, 1670, and 1600 cm^{-1}; δ_{TMS} ($CDCl_3$) 6.0–6.7 (m, 4, H_6–H_9), 6.25 and 5.52 (AB, J = 10 Hz, 2, H_{11}, H_{12}), 3.74 (s, 3, methoxyl), 2.98 (d with additional fine coupling, J = 12 Hz, 1, H_{13a} or H_{13b}), 1.6–2.95 (m, 4, H_3, H_4), and 0.95 (d, J = 12 Hz, 1, H_{13a} or H_{13b}). Calcd for $C_{13}H_{15}NO$: *m/e* 201.1153. Found: 201.1157.

The perchlorate salt of **20** was found to decompose upon standing at room temperature.

Bicyclo[5.4.1]dodeca-2,7,9,11-tetraen-4-one Oxime (21b). A solution of ketone **21a**[9] (100 mg, 0.58 mmol) and hydroxylamine hydrochloride (70 mg, 1 mmol) in 1 ml of pyridine and 1 ml of ethanol was refluxed under nitrogen for 4 hr. Work-up in the predescribed manner left a yellow oil which was crystallized from chloroform–hexane and sublimed (100°, 0.05 mm) to give 100 mg (90%) of **21b**: mp 104–106°; ν_{max} (KBr) 3100, 1620, 1590, 1440, and 1000 cm^{-1}. Calcd for $C_{12}H_{13}NO$: *m/e* 187.0997. Found: 187.0998.

Beckmann Rearrangement of 21b. A solution of **21b** (390 mg, 2.1 mmol) in 6 ml of pyridine cooled to 0° was treated with tosyl chloride (450 mg, 2.4 mmol) and allowed to stir for 20 min at 0° and 2.5 hr at 25° before pouring into water (300 ml) and methylene chloride (4 × 100 ml). From the processed organic layers there was isolated a brown solid which was dissolved in aqueous dioxane (1:1, 18 ml) containing 300 mg of 2,6-lutidine. After 15 hr at the reflux temperature, the solution was diluted with water (200 ml) and extracted with methylene chloride (4 × 75 ml). The yellow solid (230 mg) so obtained was chromatographed on silica gel (ether elution) and furnished 30 mg of crude lactam **23** and 120 mg of isomeric lactam **22**.

Pure **22** (95 mg, 25%) was obtained by sublimation at 110–115° (0.05 mm) and recrystallization from ether–pentane: mp 147–148°; ν_{max} ($CHCl_3$) 3420, 3400, 2950, 1660, and 1640 cm^{-1}; δ_{TMS} ($CDCl_3$) 5.5–7.3 (m, 7, olefinic and >NH), 3.60 (d with additional fine splitting, J = 12.5 Hz, bridgehead), 2.2–4.3 (m, 4, methylenes), and 2.05 (d with fine splitting, J = 12.5 Hz, bridgehead); calcd *m/e* 187.0997, found 187.1000.

Anal. Calcd for $C_{12}H_{13}NO$: C, 76.97; H, 7.00; N, 7.48. Found: C, 76.59; H, 7.02; N, 7.15.

Pure **23** (22 mg, 5%) was obtained by sublimation at 100–110° (0.05 mm) followed by recrystallization from ether–pentane: mp 143–144°; ν_{max} ($CHCl_3$) 3380, 1660, and 1625 cm^{-1}; δ_{TMS} ($CDCl_3$) 6.44–6.70 (m, 2, olefinic), 5.95–6.36 (br m, 2, olefinic), 5.83 (br s, 2, olefinic), 3.12 (br d, J = 13 Hz, 1, bridgehead), and 1.6–3.0 (m, 5, bridgehead and methylenes); calcd *m/e* 187.0997, found 187.0998.

Anal. Calcd for $C_{12}H_{13}NO$: C, 76.97; H, 7.00; N, 7.48. Found: C, 76.81; H, 7.00; N, 7.44.

4-Aza-5-methoxybicyclo[6.4.1]trideca-4,6,8,10,12-pentaene (19). A solution of **22** (36 mg, 0.20 mmol) and triethyloxonium fluoroborate (46 mg, 0.30 mmol) in 2 ml of methylene chloride was stirred under nitrogen for 20 hr at room temperature. A solution of sodium bicarbonate (50 mg) in water (2 ml) was added and the mixture was partitioned between methylene chloride and water. The organic phase was washed with water, dried, and concentrated to produce **19** (40 mg, 99%) as a yellow oil which was homogeneous to vpc (6 ft × 0.25 in. 5% SE-30) and spectroscopically identical with the material isolated above.

4-Aza-5-methoxybicyclo[6.4.1]trideca-2,4,8,10,12-pentaene (20). Reaction of 22 mg (0.12 mmol) of **23** with 35.5 mg (0.24 mmol) of trimethyloxonium fluoroborate in 1.5 ml of methylene chloride as before gave 20 mg (90%) of **20**, the spectra of which were superimposable upon those of the imino ether obtained earlier.

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Registry No.—**5**, 54004-04-5; **7**, 30234-91-4; **8**, 54004-05-6; (*E*)-**12**, 54004-06-7; (*Z*)-**12**, 54004-07-8; **13**, 54004-08-9; **17a**, 2443-46-1; **17c**, 54004-09-0; **17d**, 54004-10-3; **17e**, 5873-56-3; **19**, 54004-11-4; **19** perchlorate, 54004-12-5; **20**, 54004-13-6; **20** perchlorate, 54004-14-7; **21a**, 54004-15-8; **21b**, 54004-16-9; **22**, 54004-17-0; **23**, 54004-18-1; 4,9-methano[11]annulenone, 30234-90-3; hydroxylamine hydrochloride, 5470-11-1; tosyl chloride, 98-59-9; trimethyloxonium fluoroborate, 420-37-1; 3,8-methano[11]annulenone, 40563-46-0; chlorosulfonyl isocyanate, 1189-71-5; potassium, 7440-09-7.

References and Notes

(1) Unsaturated Heterocyclic Systems. XCII. For the previous paper in this series, see L. A. Paquette, M. J. Broadhurst, C. Lee, and J. Clardy, *J. Am. Chem. Soc.*, **95**, 4647 (1973).
(2) Review: L. A. Paquette, *Angew. Chem.*, **83**, 11 (1971); *Angew. Chem., Int. Ed. Engl.*, **10**, 11 (1971).
(3) (a) L. A. Paquette and T. Kakihana, *J. Am. Chem. Soc.*, **90**, 3897 (1968); (b) L. A. Paquette and J. C. Philips, ibid., **90**, 3898 (1968); (c) L. A. Paquette, T. Kakihana, J. F. Kelly, and J. R. Malpass, *Tetrahedron Lett.*, 1455 (1969); (d) L. A. Paquette, T. Kakihana, J. F. Hansen, and J. C. Philips, *J. Am. Chem. Soc.*, **93**, 152 (1971); (e) L. A. Paquette, T. Ka-

kihana, and J. F. Kelly, *J. Org. Chem.*, **36**, 435 (1971); (f) L. A. Paquette, L. B. Anderson, J. F. Hansen, S. A. Lang, Jr., and H. Berk, *J. Am. Chem. Soc.*, **94**, 4907 (1972); (g) D. W. McNeil, M. E. Kent, E. Hedaya, P. F. D'Angelo, and P. O. Schissel, ibid., **93**, 3817 (1971).
(4) (a) L. A. Paquette, T. Kakihana, and J. F. Hansen, *Tetrahedron Lett.*, 529 (1970); (b) L. A. Paquette, J. F. Hansen, and T. Kakihana, *J. Am. Chem. Soc.*, **93**, 168 (1971); (c) L. A. Paquette and T. Kakihana, ibid., **93**, 174 (1971).
(5) (a) L. A. Paquette, J. F. Hansen, T. Kakihana, and L. B. Anderson, *Tetrahedron Lett.*, 533 (1970); (b) L. B. Anderson, J. F. Hansen, T. Kakihana, and L. A. Paquette, *J. Am. Chem. Soc.*, **93**, 161 (1971).
(6) E. Vogel, M. Mann, Y. Sakata, K. Müllen, and J. F. M. Oth, *Angew. Chem.*, **86**, 231 (1974); *Angew. Chem., Int. Ed. Engl.*, **13**, 283 (1974).
(7) The prevailing state of affairs in methoxyazabullvalene serves as a useful analogy: L. A. Paquette and T. J. Barton, *J. Am. Chem. Soc.*, **89**, 5480 (1967); L. A. Paquette, T. J. Barton, and E. B. Whipple, ibid., **89**, 5481 (1967); L. A. Paquette and G. R. Krow, ibid., **90**, 7149 (1968); L. A. Paquette and J. R. Malpass, ibid., **90**, 7151 (1968); L. A. Paquette, J. R. Malpass, G. R. Krow, and T. J. Barton, ibid., **91**, 5296 (1969); L. A. Paquette, G. R. Krow, and J. R. Malpass, ibid., **91**, 5522 (1969).
(8) W. Grimme, J. Reisdorff, W. Jünemann, and E. Vogel, *J. Am. Chem. Soc.*, **92**, 6335 (1970).
(9) E. Vogel, *Proc. XXIIIrd Int. Congr. Pure Appl. Chem.*, **1**, 275 (1971), and private communication.
(10) W. E. Volz, unpublished observations. For the response of β-lactams to thermal activation, see L. A. Paquette, M. J. Wyvratt, and G. R. Allen, Jr., *J. Am. Chem. Soc.*, **92**, 1763 (1970).
(11) R. E. Rondeau and R. E. Sievers, *J. Am. Chem. Soc.*, **93**, 1522 (1971).
(12) P. V. Demarco, T. K. Elzey, R. B. Lewis, and E. Wenkert, *J. Am. Chem. Soc.*, **92**, 5734 (1970).
(13) G. Pifferi, P. Consonni, G. Pelizza, and E. Testa, *J. Heterocycl. Chem.*, **4**, 619 (1967); D. Bormann, *Justus Liebigs Ann. Chem.*, **725**, 124 (1969).
(14) M. G. Ahmed, R. W. Alder, G. H. James, M. C. Sinnott, and M. C. Whiting, *Chem. Commun.*, 1533 (1968); R. W. Alder, *Chem. Ind. (London)*, 983 (1973).
(15) E. Vogel and W. A. Böll, *Angew. Chem.*, **76**, 784 (1964); *Angew. Chem., Int. Ed. Engl.*, **3**, 642 (1964); E. Vogel, *Chem. Soc., Spec. Publ.*, **No. 21**, 123–126 (1967).
(16) T. Durst and M. J. O'Sullivan, *J. Org. Chem.*, **35**, 2043 (1970).
(17) (a) D. R. Thielen and L. B. Anderson, *J. Am. Chem. Soc.*, **94**, 2521 (1972); (b) A. J. Fry and M. A. Mitnick, ibid., **91**, 6207 (1969); (c) A. J. Fry and R. G. Reed, ibid., **91**, 6448 (1969).
(18) J. F. M. Oth, K. Müllen, H. Königshofen, M. Mann, Y. Sakata, and E. Vogel, *Angew. Chem., Int. Ed. Engl.*, **13**, 284 (1974); *Angew. Chem.*, **86**, 232 (1974).
(19) (a) C. W. Shoppee and G. Krüger, *J. Chem. Soc.*, 3641 (1961); C. W. Shoppee, G. Krüger, and R. N. Mirrington, ibid., 1050 (1962); C. W. Shoppee, R. Lack, R. N. Mirrington, and L. R. Smith, ibid., 5868 (1965); F. Kohen, *Chem. Ind. (London)*, 1378 (1966); M. Kröner, *Chem. Ber.*, **100**, 3162 (1967); M. S. Ahmad and A. H. Siddiqui, *Aust. J. Chem.*, **21**, 1371 (1968); T. Sato, H. WaKatsuka, and K. Amano, *Tetrahedron*, **27**, 5381 (1971); Y. Tamura et al., *Chem. Pharm. Bull.*, **19**, 529 (1971); P. Catsoulacos, *Chim. Chronika*, **1**, 147 (1972); I. Fleming and R. B. Woodward, *J. Chem. Soc., Perkin Trans. 1*, 1653 (1973); Y. Tamura, H. Fujiwara, K. Sumoto, M. Ikeda, and Y. Kita, *Synthesis*, 215 (1973). (b) See also F. J. Donet and A. J. Nelson, *J. Org. Chem.*, **22**, 1107 (1957); R. H. Mazur, ibid., **26**, 1289 (1961).
(20) L. A. Paquette, S. V. Ley, R. H. Meisinger, R. K. Russell, and M. Oku, *J. Am. Chem. Soc.*, **96**, 5806 (1974); S. V. Ley and L. A. Paquette, ibid., **96**, 6670 (1974).
(21) Quenching experiments involving the use of CH_3OD were expectedly not revealing because of rapid D–H exchange with NH_3 solvent prior to proton (deuteron) transfer to the reduced species. Levels of deuterium incorporation as high as 20% were observed in **19** and **20**.
(22) G. Ewing, unpublished observations.
(23) P. H. Gebert, R. W. King, R. A. LaBar, and W. M. Jones, *J. Am. Chem. Soc.*, **95**, 2357 (1973).
(24) R. A. LaBar and W. M. Jones, *J. Am. Chem. Soc.*, **95**, 2359 (1973).
(25) G. C. Farrant and R. Feldmann, *Tetrahedron Lett.*, 4979 (1970).
(26) J. Reisdorf and E. Vogel, *Angew. Chem.*, **84**, 208 (1972); *Angew. Chem., Int. Ed. Engl.*, **11**, 218 (1972).
(27) E. Vogel, R. Feldmann, and H. Düwel, *Tetrahedron Lett.*, 1941 (1970).
(28) L. A. Paquette, R. E. Wingard, Jr., and R. K. Russell, *J. Am. Chem. Soc.*, **94**, 4739 (1972).
(29) E. Vogel, U. H. Brinker, K. Nachtkamp, J. Wassen, and K. Müllen, *Angew. Chem.*, **85**, 760 (1973); *Angew. Chem., Int. Ed. Engl.*, **12**, 758 (1973).
(30) E. Vogel, R. Feldmann, H. Düwel, H.-D. Cremer, and H. Günther, *Angew. Chem.*, **84**, 207 (1972); *Angew. Chem., Int. Ed. Engl.*, **11**, 217 (1972).
(31) Others seem to be of the opinion that the level of homoaromaticity in charged and uncharged systems should be equally pronounced.[29] It should be clear that neutral homoaromatic structures will partake of less delocalization in their ground states with the obvious result that the prevailing stabilizing contributions will be more difficultly detectable by the usual spectroscopic methods. Direct spectral comparison of neutral homoaromatic with Hückel-type aromatic systems is consequently not conveniently workable because of the large numerical gap separating the delocalization energies in these two classes of compounds.
(32) E. Ciganek, *J. Am. Chem. Soc.*, **87**, 1149 (1965).
(33) J. Mills, R. Nelson, S. Shore, and L. B. Anderson, *Anal. Chem.*, **43**, 157 (1971).

Synthesis and Photolysis of 2-Acylpyrazolidin-3-ones. A Model for the Photochemical Syntheses of 6-Azapenicillin Isomers[1]

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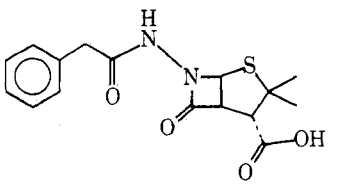
A series of 2-acyl-5,5-dimethylpyrazolidin-3-ones (**5a–e**) was prepared by two routes and shown to rearrange photochemically under a variety of conditions to *N*-acylamino-4,4-dimethylazetidin-2-ones (**9a–e**). Photolysis of the parent systems, 5,5-dimethylpyrazolidin-3-one (1), to give 1-amino-4,4-dimethylazetidin-2-one (**20**), which was acylated to give **9a**, is also discussed. A plausible reaction scheme is presented to account for the observed photochemistry.

Strong interest in the synthesis of β-lactam (azetidin-2-one) containing molecules,[2] particularly those of the penicillin and cephalosporin classes of antibiotics,[3] has continued unabated since the original discovery and structure determination of penicillin.[4] Although a large number of original syntheses of β-lactams have been reported since that period, very few of these approaches have employed either thermal[5] or photochemical[6] ring contraction steps. As a part of our approach to the synthesis of penicillin isomers containing nitrogen in the 6 position (such as I), we hope to use a photochemically induced ring contraction reaction to generate the β-lactam moiety. As a model system for such a step we have investigated the photochemistry of a series of 2-acyl-5,5-dimethylpyrazolidin-3-ones, one of which contains the side chain of penicillin G.[7] We report at this time some interesting aspects of the syntheses of these 2-acylpyrazolidin-3-ones[8] and our studies on their photochemical rearrangements to give *N*-acylamino β-lactams.



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Preparation of 2-Acyl-5,5-dimethylpyrazolidin-3-ones. After several attempts to condense acylhydrazides with 3,3-dimethylacrylic acid[9] or its ethyl ester resulted only in the isolation of 1,2-diacylhydrazides, a different approach involving functionalization of the preformed ring