

# Pericyclic Synthesis and Study of Select $\pi$ Frames

Apostolos G. Anastassiou

Department of Chemistry, Syracuse University, Syracuse, New York 13210

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During the first two decades following Hückel's formulation of the " $4n + 2$ " rule of "aromaticity",<sup>1</sup> relatively little was accomplished experimentally in the area of annulene synthesis. It was, in fact, not until the turn of the 1950–1960 decade that major experimental advances in the area began to appear, primarily because of two significant and largely unrelated developments, (i) the formulation by Sondheimer of a general method of synthesis based on the oxidative coupling of terminal diacetylenes<sup>2</sup> and (ii) the discovery of NMR spectroscopy by the practicing organic chemist. Shortly thereafter, synthetic methodology in the area was further advanced by the use of pericyclic<sup>3</sup> bond reorganization; a striking example is Schröder's two-step synthesis of bullvalene<sup>4a</sup> and [16]annulene<sup>4b</sup> from common cyclooctatetraene.<sup>1</sup> The mid-1960's witnessed Woodward and Hoffmann's explicitly formulated recognition of the control that orbital symmetry exerts on many chemical transformations, leading to the derivation of a set of "symmetry rules"<sup>3</sup> which provided the theoretically inclined organic chemist with the necessary foundation upon which to develop synthetic pericyclization.

A fundamental advantage that pericyclic synthesis offers over other methods is that it is practicable at low temperatures and in the absence of potentially destructive reagents. It is, in other words, a method of synthesis that is uniquely suited to the construction of sensitive molecules. The early recognition of the synthetic advantages offered by tactically conceived pericyclization is perhaps best exemplified by van Tamelen's pioneering work on the photosynthesis of the coveted  $10\pi$  monocycle, cyclodecapentaene, from transfused 9,10-dihydronaphthalene.<sup>5</sup>

Our own work dealing with the synthesis and study of select  $\pi$  frames has necessitated heavy use of preparative pericyclization. A few years ago we reviewed<sup>6</sup> early portions of our research in the area, i.e., those pertaining to the construction of the heteronin frame in one photoinduced retroelectrocyclic step from the 9-hetero[6.1.0]triene skeleton. In this Account we describe some of our most recent findings in the field, which appropriately demonstrate the unique synthetic attributes of properly designed pericyclization.

## A $C_4H_4$ Homologation Leading to Benzannelated Heteronins and Hetero[13]annulenes

Among nonbenzenoid aromatics, intramolecular comparison with benzene in terms of  $\pi$ -electron delocalization is normally judged to be a revealing but harsh

criterion of a molecule's "aromatic" character. The obvious significance of such comparison in the case of the cyclononatetraenyl anion and aza[9]annulene (azonine) prompted us to examine the  $\pi$ -electron response of these systems to benzannelation. In order to circumvent any synthetic complication which might arise from the potential sensitivity of these benzannulenes we designed a pericyclic synthesis (Scheme I) based on information recently gained in our laboratories from a mechanistic study,<sup>7,8</sup> namely that exposure of thermally activated **1** to dienone **4** leads to a pair of diastereomeric cycloadducts (one shown in **5**) containing a nine-membered ring. Replacement, in this scheme, of dienone **4** with  $\alpha$ -pyrone (**6**) followed by pyrolytic extrusion of  $CO_2$  from the resulting lactones **7a,b** led to the key *unsubstituted* bicyclo[7.4.0]pentaenes **8a**<sup>9</sup> and **8b**.<sup>10</sup> In turn, these substances were readily converted to the desired benzannulenes **9a**<sup>9</sup> and **9b**<sup>10</sup> on exposure to *o*-chloranil. With the general benzannelated frame **9** in hand we turned attention to the preparation of members containing loosely held, readily delocalizable, lone pairs, i.e., compounds with high affinity for  $10\pi$ -electron delocalization in the nine-membered portion of the bicycle. To this end, we prepared parent benzazonine **10** by nucleophilic removal of the acetyl appendage from **9b**, and conjugate base **11** by base-induced deprotonation of **10**. Somewhat surprisingly, examination of **10** and **11** by NMR revealed the presence of benzopolyeneic frames consisting of largely localized nine-membered rings.<sup>11</sup> By contrast, the benzocyclononatetraenyl anion **12**, prepared from **9a** via base-promoted deprotonation, proved to be extensively delocalized and strongly diatropic (aromatic) by NMR.<sup>12</sup>

Unexpectedly, both anions, **11** and **12**, were found to undergo *cis*  $\rightarrow$  *trans* isomerization on warming, **12** yielding **13** [ $\Delta G^\ddagger(56^\circ C) = 26.2$  kcal/mol] with preservation of aromaticity<sup>13</sup> and **11** leading to **14** [ $\Delta G^\ddagger(0^\circ C) = 19.8$  kcal/mol] with acquisition of "aromatic" char-

(1) (a) E. Hückel, *Z. Phys.*, **70**, 204 (1931); (b) *ibid.*, **76**, 628 (1932).

(2) For a recent review on the subject, see F. Sondheimer, *Acc. Chem. Res.*, **5**, 81 (1972).

(3) For a definition of the term, see R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry", Academic Press, New York, N.Y., 1970.

(4) (a) G. Schröder, *Chem. Ber.*, **97**, 3140 (1964); (b) G. Schröder and J. F. M. Oth, *Tetrahedron Lett.*, 4083 (1966).

(5) For a lucid description of this and related cases of synthetic pericyclization, see E. E. van Tamelen, *Acc. Chem. Res.*, **5**, 186 (1972).

(6) A. G. Anastassiou, *Acc. Chem. Res.*, **5**, 281 (1972).

(7) A. G. Anastassiou and R. C. Griffith, *J. Am. Chem. Soc.*, **93**, 3083 (1971).

(8) A. G. Anastassiou, R. L. Elliott, H. Wright, and J. Clardy, *J. Org. Chem.*, **38**, 1951 (1973).

(9) A. G. Anastassiou, S. S. Libsch, and R. C. Griffith, *Tetrahedron Lett.*, 3103 (1973).

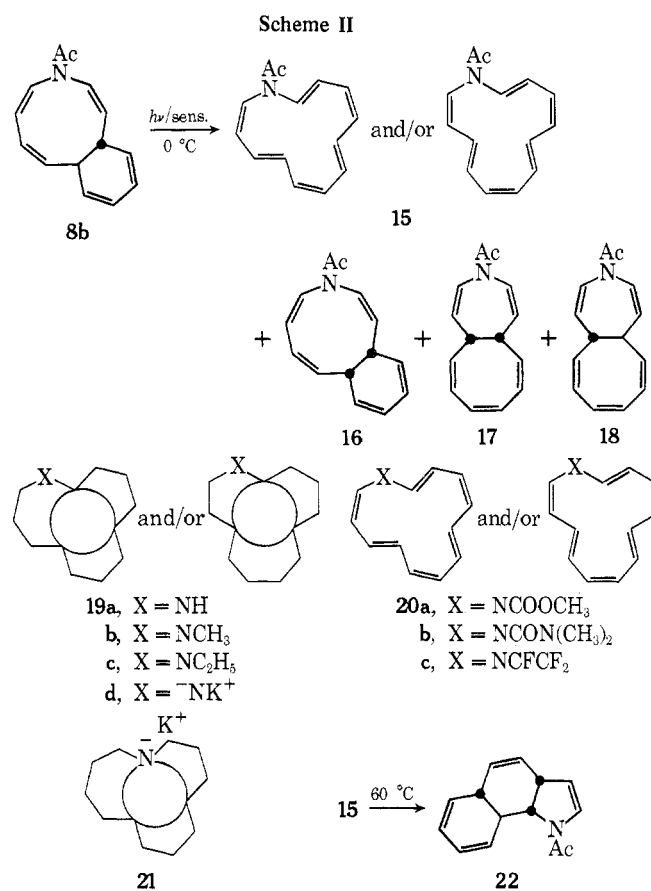
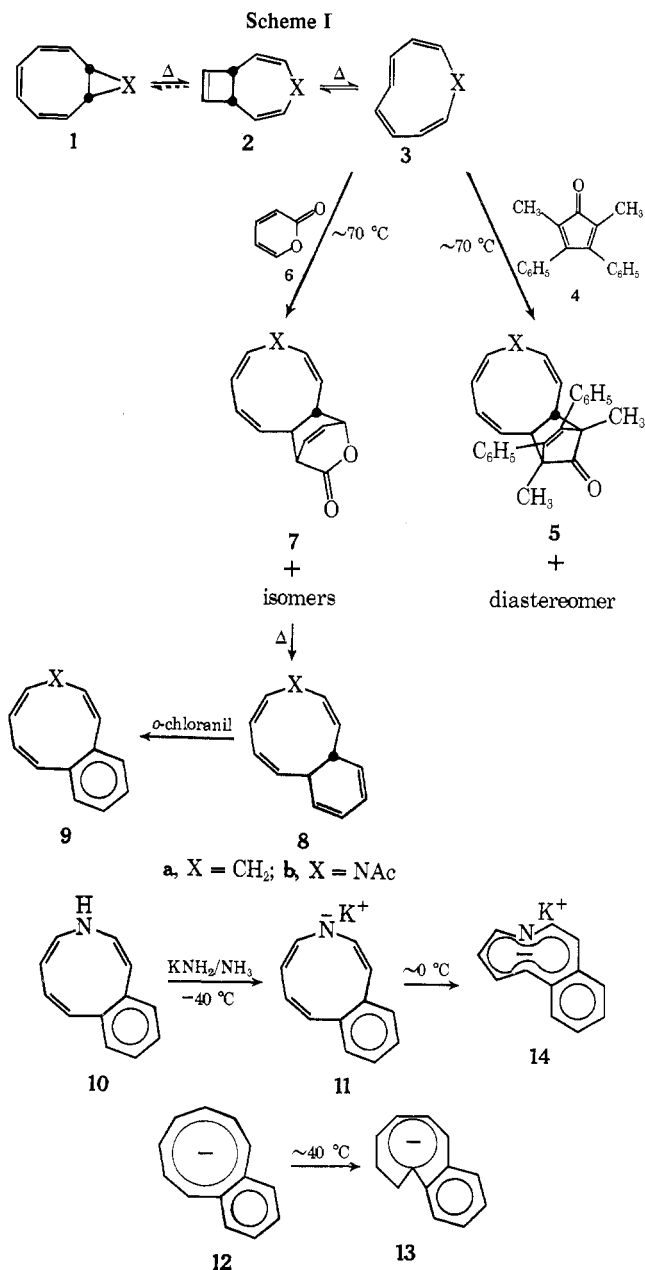
(10) A. G. Anastassiou, E. Reichmanis, and R. L. Elliott, *Tetrahedron Lett.*, 3805 (1973).

(11) A. G. Anastassiou and E. Reichmanis, *Angew. Chem.*, **86**, 410 (1974).

(12) A. G. Anastassiou and R. C. Griffith, *J. Am. Chem. Soc.*, **96**, 611 (1974).

(13) A. G. Anastassiou and E. Reichmanis, *Angew. Chem.*, **86**, 784 (1974).

Apostolos G. Anastassiou received his undergraduate training at the American University of Beirut and his Ph.D. degree from Yale University in 1963. He then joined Du Pont's Central Research Department. Since 1966 he has held a faculty position with the Chemistry Department at Syracuse University where he directs work dealing with the synthesis and study of theoretically significant molecules and the study of molecular rearrangements and electron-deficient intermediates.



acter!<sup>14</sup> Bearing in mind that the parent cyclonona-tetraenyl anion experiences the reverse process, trans  $\rightarrow$  cis, on warming,<sup>15</sup> one is forced into the conclusion that the cis  $\rightarrow$  trans isomerization observed with anions 11 and 12 is activated as a means of alleviating strain. This strain, which is not due to any skeletal factors but rather to nonbonded H-H repulsion about the ring juncture of the all-cis frame, seriously reduces the molecule's ability to flatten and thus realize its "aromatic" potential. Passage from 12 to 13 and from 11 to 14 results in the removal of one such set of H-H repulsions and enables the molecule to flatten and hence to delocalize its  $\pi$  electrons.

Exposure of the synthetically versatile azabicyclic 8b to light instead of an oxidant leads to the aza[13]annulene shown in 15 (ca. 30% yield) together with three new bicyclic isomers, 16, 17, and 18<sup>16</sup> (Scheme II). In an ef-

fort to assess the effect of N-substitution on the possible development of  $\pi$  delocalization in a 13-membered "4n + 2" $\pi$  heteromonocyclic frame, acetamide 15 was subjected to N-substituent exchange by consecutive exposure to strong base and an appropriate electrophile. The resulting substances are depicted in 19 and 20. In turn, parent amine 19a was converted to its conjugate base 19d on treatment with potassium mirror at  $-80$  °C.<sup>17</sup>

Careful examination by <sup>1</sup>H NMR of the substances thus produced led to their classification into two distinct classes, with 19 showing clear signs of diatropism (aromaticity) and 20 (as well as 15) entirely lacking in this respect.<sup>17</sup> Not unexpectedly, representative members of the two classes of aza[13]annulene differ in their response to thermal activation. One thus finds that parent amine 19a does not respond to prolonged thermal treatment at 56 °C, whereas acetamide 15 readily yields a tricyclic isomer tentatively formulated as 22.<sup>18</sup> In light of these observations we were surprised to find that the most extensively diatropic member of the "aromatic" group, 19d [<sup>2</sup>H ( $\tau$  1.6), <sup>13</sup>C ( $\tau$  12.5)], rapidly isomerizes to 21 (a compound synthesized by Schröder et al.<sup>19</sup>) when warmed to 0 °C. Obviously this transformation cannot be attributed to  $\pi$  instability, for it occurs with overall preservation of monocyclic character. In fact, bearing in mind that (i) the 19d to 21 process transforms the heteroannulene's skeleton from cctct to cctccc,<sup>20</sup>

(16) A. G. Anastassiou and R. L. Elliott, *J. Am. Chem. Soc.*, **96**, 5257 (1974).

(17) A. G. Anastassiou, R. L. Elliott, and E. Reichmanis, *J. Am. Chem. Soc.*, **96**, 7823 (1974).

(18) Unpublished results by R. L. Elliott.

(19) (a) G. Schröder, G. Frank, H. Röttele, and J. F. M. Oth, *Angew. Chem.*, **86**, 237 (1974); (b) G. Frank and G. Schröder, *Chem. Ber.*, **108**, 3736 (1975).

(20) For a description of the convention employed in the choice of double-bond sequence, see ref. 8.

(14) A. G. Anastassiou and E. Reichmanis, *J. Chem. Soc., Chem. Commun.*, 149 (1975).

(15) G. Boche, D. Martens, and W. Danzer, *Angew. Chem.*, **81**, 1003 (1969). For more recent information on the matter, see G. Boche and A. Bieberbach, *Tetrahedron Lett.*, 1021 (1976).

i.e., a net change of a single formal double bond from trans to cis, and (ii) geometrical isomerization in an annulene is energetically possible only in the event of extensive  $\pi$  delocalization, one must conclude that the observed transformation is reflective not of  $\pi$  instability but rather of well-developed  $\pi$  delocalization in **19d**. Why then does **19d** isomerize at all? The only rational answer is relief of "inner"-proton crowding, a quick count revealing the presence of three such protons in **19d** and only two in **21**.

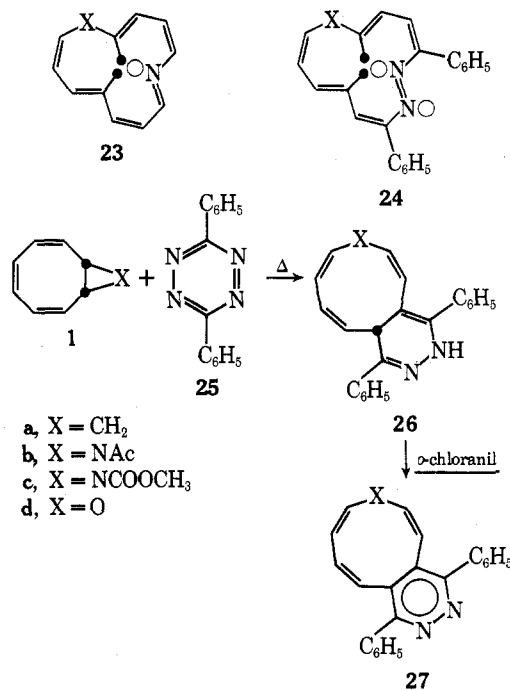
In summary, we note that the results described in this section offer clear demonstration of the powerful influence that (i) lone-pair availability (compare **11** to **12** and **19** to **20**) and (ii) nonbonded H-H repulsion, be it peripheral (compare **11** to **14** and **12** to **13**) or central (compare **19d** to **21**), exert on the development of "aromatic" character in medium-large cyclic  $\pi$  ribbons.

### Further Pericyclic Homologations

In theory, modification of an annulene by the introduction of  $sp^2$  nitrogen in place of a CH group should not significantly influence the  $\pi$  energetics of the hypothetical planar system. On the other hand, in medium-large systems such as the aza[13]annulenes, where "inner"-hydrogen repulsions pose a serious and sometimes insurmountable problem in the attainment of planarity, replacement of an inwardly directed, sterically demanding, CH unit by a largely innocuous and possibly H-attractive lone pair (compare **20** with **23**) would, no doubt, lead to significant reduction of "incavity" crowding with consequent enhancement in the molecule's affinity to "flatten". The net outcome of such a seemingly minor structural change would then be to *sterically* facilitate  $\pi$ -electron delocalization and, in cases where " $4n + 2$ "- $\pi$  electrons are involved, enhance overall stability.

With these thoughts in mind and because of recently gained experience in the pericyclic synthesis of aza[13]-annulene, we modified the earlier synthetic procedure by effecting cycloadditive coupling between **1a-d** and diphenyltetrazine **25**<sup>21</sup> instead of  $\alpha$ -pyrone (**6**). This led to the desired bicyclo[7.4.0]pentadienes **26a-d**<sup>22-24</sup> which, in turn, were readily converted to the novel pyridazino derivatives **27a-d** on mild treatment with *o*-chloranil. These substances are good models for the purpose of direct comparison between pyridazine and azonine or the cyclononatetraenyl anion in terms of  $\pi$ -electron mobility. In addition, they are well suited for assessing the magnitude of H-Ph "peri" interaction relative to its more conventional H-H variant. Examination of select members of **27** along these lines is currently under way in our laboratories.

Besides its synthetic utility in the ultimate pericyclic construction of the general frame shown in **24**, the coupling between **1** and **25** carries interesting mechanistic implications as it is believed to represent the first bona fide example of direct<sup>25</sup> thermal cycloaddition onto the [6.1.0] frame of **1**.<sup>23,24</sup>



The pericyclic procedures developed in our laboratories for the construction of hetero [9]- and [13]annulenes and by Schröder et al. for the synthesis of similarly unrestricted<sup>26</sup> hetero [13]-<sup>20,27</sup> and [17]annulenes<sup>28,29</sup> utilize cyclooctatetraene as the basic building unit and a homologation sequence strictly designed to increase skeletal size by four-carbon blocks. As a result, the applicability of this method in its present design is strictly limited to the synthesis of  $(4n + 1)$ -membered, " $4n + 2$ "- $\pi$  heteroannulenes. In fact, there is, as of this writing, no method available for the construction of medium-large or large unrestricted<sup>26</sup>  $(4n - 1)$ -membered, " $4n$ "- $\pi$  heteromonocycles.<sup>30</sup>

In theory, it should be possible to apply the  $C_4$  homologation procedure to one or more of the known heteropins (**28**; X = O, NCOOEt, NCN etc.)<sup>31</sup> and thus eventually synthesize larger members of the family. In practice, one finds this not to be possible without further modification, because the relatively unstrained double bonds of the buckled heteropin frame are unreactive toward  $\alpha$ -pyrone. In light of this complication it became necessary to operate on the substantially more strained double bonds of the bicyclic photoisomers<sup>31</sup> of **28** (**29a** and **29b**) and thus generate the desired  $C_{10}H_{10}X$  molecules, in tricyclic form (**30a,b**<sup>32-34</sup> and **31**<sup>32</sup>). Not

(21) For reports on the use of symmetrical tetrazines in cycloaddition, see: (a) J. Sauer and G. Heinrichs *Tetrahedron Lett.*, 4979 (1966); (b) P. L. Watson and R. N. Warrener, *Aust. J. Chem.*, 26, 1725 (1973).

(22) A. G. Anastassiou and S. J. Girgenti, *Angew. Chem.*, 87, 842 (1975).

(23) A. G. Anastassiou and E. Reichmanis, *J. Chem. Soc., Chem. Commun.*, 313 (1976).

(24) Unpublished results obtained in these laboratories by Dr. R. Schaefer.

(25) The term "uniparticulate" was originally coined by Paquette et al. to describe the reaction between *cis*-bicyclo[6.1.0]nona-2,4,6-triene (**1a**) and TCNE (L. A. Paquette, M. J. Broadhurst, L. K. Read, and J. Clardy, *J. Am. Chem. Soc.*, 95, 4639 (1973)) or chlorosulfonyl isocyanate (CSI) (L. A. Paquette, M. J. Broadhurst, C. Lee, and J. Clardy, *ibid.*, 95, 4647 (1973)). For more recent information and a basically different view, see: (a) G. Boche, H. Weber, and J. Benz, *Angew. Chem.*, 86, 238 (1974); (b) J. E. Baldwin and D. B. Bryan, *J. Am. Chem. Soc.*, 96, 319 (1974).

(26) The term is employed here to distinguish from annelated, dehydro, and bridged members of the family.

(27) W. Henne, G. Plinke, and G. Schröder, *Chem. Ber.*, 108, 3753 (1975).

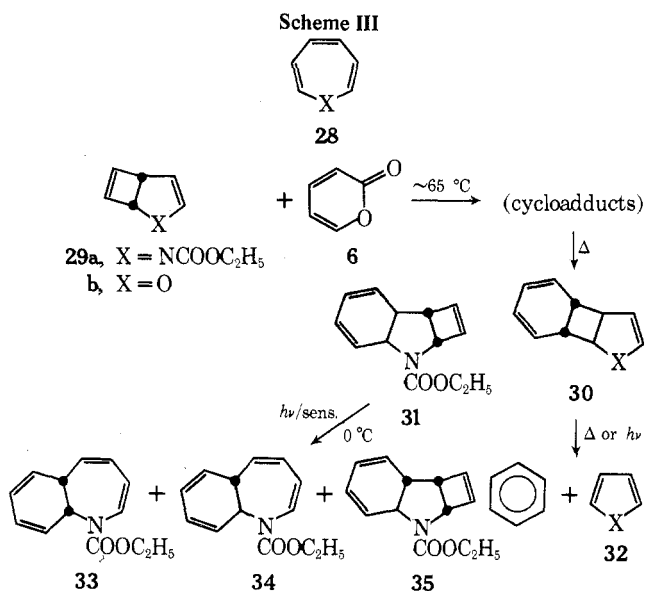
(28) G. Schröder, G. Heil, H. Röttele, and J. F. M. Oth, *Angew. Chem.*, 84, 474 (1972).

(29) G. Schröder, G. Plinke, and J. F. M. Oth, *Angew. Chem.*, 84, 472 (1972).

(30) For a recent enumeration of known "restricted" " $4n$ "- $\pi$  heteromonocycles, see F. Sondheimer, *Chimia*, 28, 163 (1974).

(31) For an extensive review on the subject, see L. A. Paquette in "Non-benzenoid Aromatics", Vol. I, J. P. Snyder, Ed., Academic Press, 1969, pp 249-310.

(32) Unpublished results by E. Reichmanis.



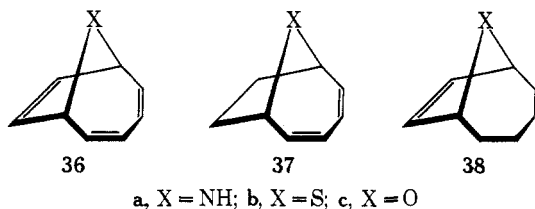
unexpectedly, **30** which may be formally regarded as a cycloadduct of benzene and **32**, cannot be utilized as an intermediate in the synthetic scheme, for it readily fragments on exposure to either light or mild heat. The situation with the alternate tricyclic, **31**, is basically different, since exposure to light here leads to rapid isomerization into **33**, **34**, and **35**<sup>32</sup> (Scheme III).

With the first stage of this synthetic project, that dealing with the C<sub>4</sub> homologation process, adequately completed, attention in our laboratories is now being focused on the more challenging task of converting one or more of the C<sub>10</sub>H<sub>10</sub>NCOOEt isomers, now available, into the desired 11-membered frame.

### The 9-Heteronona[4.2.1]trienes

The bridged heterocycle depicted in **36** is formally related to its isomeric heteronona by transfer of the heteroatom from main frame to bridge. The net outcome of this hypothetical relocation is to: (i) entirely eliminate two of the molecule's p-π centers, (ii) divide the π frame into three formally independent units and (iii) significantly enhance skeletal rigidity. In other words, what one has in **36** is a model ideally structured for studying the possible participation of a heteroatomic lone pair in nonbonded interaction.

The general skeleton **36** is now available for the three basic heteroatoms, nitrogen (**36a**),<sup>35</sup> sulfur (**36b**),<sup>36</sup> and oxygen (**36c**).<sup>37,38</sup> Other heteroatomic variants of the



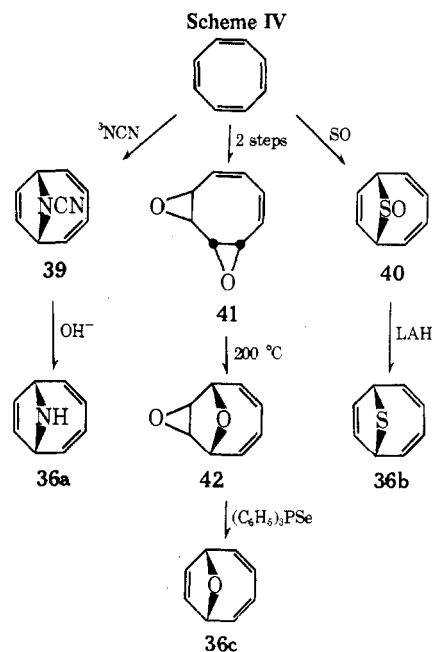
(33) Unpublished results by S. J. Girgenti.

(34) The all-cis (syn) counterpart of **31b** was recently prepared from photoinduced cycloaddition of furan onto benzene: J. Berridge, D. Bryce-Smith, A. Gilbert, and T. S. Cantrell, *J. Chem. Soc., Chem. Commun.*, 611 (1975), and references therein.

(35) (a) A. G. Anastassiou, *J. Am. Chem. Soc.*, **87**, 5512 (1965); (b) A. G. Anastassiou and R. P. Cellura, *J. Org. Chem.*, **37**, 3126 (1972).

(36) (a) A. G. Anastassiou and B. Chao, *Chem. Commun.*, 979 (1971); (b) A. G. Anastassiou, J. C. Wetzel, and B. Chao, *J. Am. Chem. Soc.*, **97**, 1124 (1975).

(37) A. G. Anastassiou, *Pure Appl. Chem.*, **44**, 691 (1975). For experimental detail see ref 46.



system with X = PC<sub>6</sub>H<sub>5</sub> or POC<sub>6</sub>H<sub>5</sub>,<sup>39</sup> are also known, but we shall here limit our coverage to the three basic members **36a-c**. These were synthesized in our laboratories and were properly analyzed for purposes of direct comparison.

Brief scrutiny of Scheme IV reveals heavy use of pericyclic transformation in the construction of **36**. Synthesis of the basic frame of **36a** and **36b** is thus seen to entail simple one-step cheletropy between cyclooctatetraene and triplet NCN or SO, whereas **36c** was built by a multistep sequence whose key step is a thermal bond shift converting one of the two oxirane units of **41** into the 1,4-oxide bridge of **42**.<sup>40</sup>

The π system of **36** was examined with the use of two spectroscopic methods, photoelectron (PE)<sup>41</sup> and <sup>13</sup>C NMR, both of which possess well documented ability to sense nonbonded effects. The PES method accomplishes this with an assessment of the degree and direction of key energy changes resulting from nonbonded interaction between two or more of the molecule's upper occupied levels, while <sup>13</sup>C NMR allows one to make sensitive estimates of crucial changes in electronic distribution and, quite often, in molecular geometry.

Comparison of **36** with its partially saturated relatives **37a-c**,<sup>35b,36b,42</sup> and **38a-c**,<sup>36b,42,43</sup> by means of either PES or <sup>13</sup>C NMR established the presence of an interacting lone pair whose influence drops substantially with increasing electronegativity (N to O) and, to a smaller degree, size (N to S). In brief, the PES information allows one to reach the following conclusions about the system: (i) the lone pair in **36a**<sup>44</sup> is responsible for the development of rather extensive bicycloconjugation, i.e., closed-loop interaction between all three of the

(38) R. Aumann and H. Aeverbeck, *J. Organomet. Chem.*, **85**, C4 (1975).

(39) T. J. Katz, J. C. Carnahan, G. M. Clarke, and N. Acton, *J. Am. Chem. Soc.*, **92**, 734 (1970).

(40) A. G. Anastassiou and E. Reichmanis, *J. Org. Chem.*, **38**, 2421 (1973).

(41) The photoelectron spectroscopic work was carried out in collaboration with Professor A. Schweig and his group. All spectroscopic determinations were made at Marburg, Germany.

(42) N. Heap, G. H. Green, and G. H. Witham, *J. Chem. Soc. C*, **160** (1969).

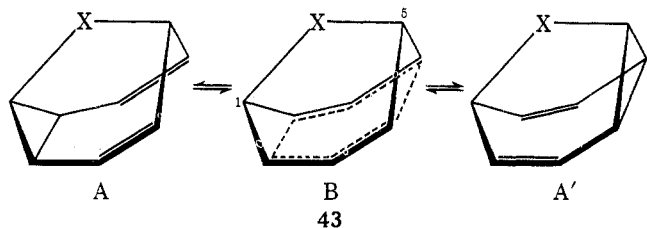
(43) A. G. Anastassiou and H. Yamamoto, *J. Chem. Soc., Chem. Commun.*, 840 (1973).

(44) H. Schmidt, A. Schweig, A. G. Anastassiou, and H. Yamamoto, *J. Chem. Soc., Chem. Commun.*, 218 (1974).

formally isolated  $\pi(p)$  units of the molecule, and (ii) the lone pair in **36b**<sup>45</sup> and, to a smaller extent, in **36c**<sup>46</sup> merely gives rise to localized interaction (*homoconjugation*?) with the neighboring ethylene. Similar characteristics were exposed by the <sup>13</sup>C NMR criterion.<sup>47</sup> Specifically, one observes a uniformly consistent upfield shift of the two-carbon ethylenic resonance on passing from **38** to **36**—12.1 ppm for X = O, 12.4 ppm for X = NCN, 13.9 ppm for X = S, and 14.9 ppm for X = NH. In terms of origin, these rather substantial shifts may be regarded as products of two largely independent contributions, (i) increased electron density and (ii) enhanced skeletal strain; the magnitude of  $J_{^{13}\text{C}-\text{H}}$  uniformly increases by ca. 5 Hz on passing from **38** to **36**. Judging from the constancy of  $\Delta J_{^{13}\text{C}-\text{H}}$  one may reasonably dismiss the strain factor in a direct comparison between the four heterotrienes, **36a–c** and **39**. In other words, any differences in chemical shift obtained from such a comparison may be attributed to changes in lone-pair-induced electron density over and above those encountered in **38**. While admittedly small, the chemical shift differences thus obtained, -1 ppm (NH  $\rightarrow$  S), -2.5 ppm (NH  $\rightarrow$  NCN), -2.8 ppm (NH  $\rightarrow$  O), are unquestionably meaningful. The emerging trend which is consistent with that derived earlier from PES information on **36** shows that lone-pair involvement in nonbonded interaction decreases in the order NH > S > O. What one has here is a situation which appears to strictly parallel that observed in the heteronins.

### The 9-Heterobarbaralanes

Possibly the most interesting property of a molecule such as **43** is its condition of rapid flux resulting from interconversion of two isoenergetic forms, A and A', by way of a potentially "aromatic" (six-electron) transition state. Of paramount significance in this connection is the intriguing but as yet unrealized possibility that the system may, under certain conditions,<sup>48</sup> become associated with a transition state B which is more stable than the valence isomeric forms A and A' and thus develop "aromatic" character. Our attention in this problem was concentrated primarily on heterobarbaralanes, such as **43**, with X = heteroatom, which are



ideally structured for a study of the effect that lone-pair availability might have on the rate of molecular flux and hence on the relative stability of key form B.

As seen in Scheme V, the basic 9-heterobarbaralane frame was constructed in a single photoinduced pericyclic step from **36**.<sup>49,50</sup> Formamide **43b** and urethane

(45) C. Müller, A. Schweig, A. G. Anastassiou, and J. C. Wetzel, *Tetrahedron*, **30**, 4089 (1974).

(46) H. Schmidt, A. Schweig, A. G. Anastassiou, and J. C. Wetzel, *Tetrahedron*, **32**, 2239 (1976).

(47) Unpublished results by E. Reichmanis.

(48) For a theoretical analysis of the situation, see: (a) R. Hoffmann and W.-D. Stohrer, *J. Am. Chem. Soc.*, **93**, 6941 (1971); (b) M. J. S. Dewar and D. H. Lo, *ibid.*, **93**, 7201 (1971).

(49) A. G. Anastassiou and B. Chao, *J. Chem. Soc., Chem. Commun.*, 277 (1972).

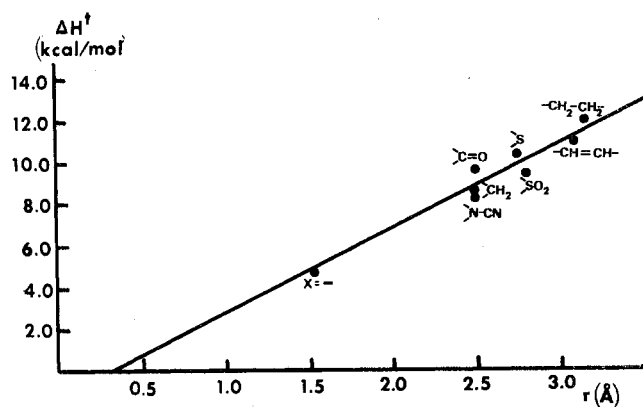
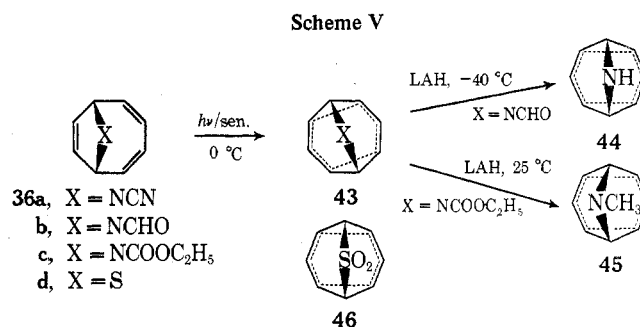


Figure 1. Plot of experimentally determined  $\Delta H^\ddagger$  values for the degenerate rearrangement of bridged homotropilidines **43** vs. C(1)–C(5) internuclear separation.



**43d** were then reductively converted to amine **44** and methylamine **45**, respectively.<sup>51</sup> As expected all the heterobarbaralanes depicted in Scheme V were found to exist in a state of rapid flux at ambient temperature. Proper assessment of the influence exerted by the heteroatomic bridge on the energy of the key transition state B in terms of both effective electronegativity and size was made by conducting variable-temperature NMR studies on amine **44**,<sup>51</sup> cyanamide **43a**,<sup>49</sup> sulfide **43c**,<sup>50</sup> and sulfone **46**.<sup>52</sup> Analysis of the information thus secured revealed, rather surprisingly, that the rate of flux in a 9-heterobarbaralane depends heavily on bridge size but is largely insensitive to lone-pair availability.<sup>53</sup>  $\Delta G^\ddagger(-110^\circ\text{C}) = 7.7$  kcal/mol for **44** and **43a**, and  $\Delta G^\ddagger(-58^\circ\text{C}) = 9.6$  kcal/mol for **43d** and **46**.

The important energetic control that bridge size exerts on the rate of flux of a 9-heterobarbaralane suggests that the C(1)–C(5) internuclear separation must be a crucial factor. In fact, one discovers this to be a general characteristic of bridged homotropilidines and not to be limited to the hetero-bridged variants examined in our laboratories. Specifically, a plot of  $\Delta H^\ddagger$  (a reliable measure of transition-state energetics) vs.  $r[\text{C}(1)\text{--}\text{C}(5)]$  (measured from Dreiding molecular models) for a variety of bridged homotropilidines rewards one with the *good* straight line depicted in Figure 1.<sup>53</sup> It is also interesting to note in connection with this linear plot that, at  $\Delta H^\ddagger = 0$ , the energy turning point between classical,  $E(A) < E(B)$ , and "aromatic,"  $E(B) < E(A)$ , character, the line intercepts the abscissa at the unrealistically

(50) A. G. Anastassiou, A. E. Winston, and E. Reichmanis, *J. Chem. Soc., Chem. Commun.*, 779 (1973).

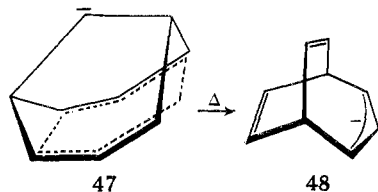
(51) A. G. Anastassiou, E. Reichmanis, and A. E. Winston, *Angew. Chem.*, **88**, 382 (1976).

(52) L. A. Paquette, U. Jacobsson, and M. Oku, *J. Chem. Soc., Chem. Commun.*, 115 (1975).

(53) A. G. Anastassiou, E. Reichmanis, and J. C. Wetzel, *Tetrahedron Lett.*, 1651 (1975).

short distance of 0.32 Å. This finding of course suggests the need for major *electronic* perturbation<sup>48</sup> if the key energy imbalance  $\Delta H^\ddagger < 0$  is ever to be realized.

Another characteristic of the  $\pi$ -excessive 9-heterobarbaralanes is that they are iso- $\pi$ -electronic with the corresponding carbanion, the 9-barbaralyl anion **47** whose highly symmetric  $D_{3h}$  form was recently theorized to be unstable because of the presence of a doubly degenerate, partially occupied set of HFMO's.<sup>54</sup> The predicted instability of **47** has since been convincingly demonstrated in the laboratory<sup>55</sup> as well, insofar as all attempts at generating this species invariably result in skeletal rearrangement to **48**.



Simple perturbation theory requires that the destabilizing MO degeneracy predicted for **47** be lifted in a  $\pi$ -excessive 9-heterobarbaralane; furthermore, the resulting energy split must lead to net stabilization of the molecule's HFMO level which is now occupied by the lone pair. Nonetheless, this key level is still expected to lie relatively high on the molecule's energy manifold so that one might well expect to observe lone-pair-induced skeletal reorganization. In terms of lone pair availability the foregoing analysis requires that a  $\pi$ -excessive 9-heterobarbaralane become increasingly destabilized as one reduces the effective electronegativity of the bridging heteroatom. In fact, this turns out to be precisely the case. One thus finds<sup>51</sup> amine **44** and its *N*-methyl derivative **45** to possess exceedingly labile frames which may be handled only for short periods of time at subzero temperatures (the estimated half-life of **44** is 18 min at 35 °C) and which are substantially stabilized in the presence of strong acid. Consistently, one also finds such relatives as **43b** and **43c** whose lone-pair availability is greatly reduced by the attachment of a -R *N*-substituent to possess highly stable frames which entirely resist change even on prolonged heating at 100 °C. In support of this trend one also finds major stability differences between sulfide **43d**, a heat-sensitive substance ( $t_{1/2} = 36$  min., at 34 °C),<sup>56</sup> and sulfone **46**, a thermally unresponsive molecule.

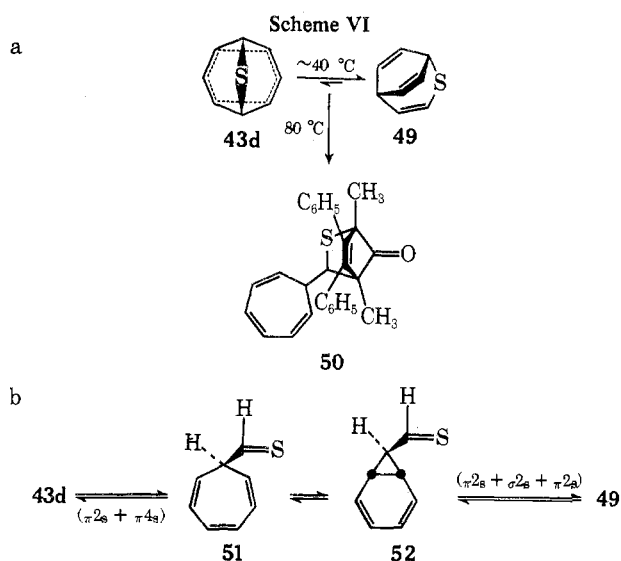
The fundamental similarity between the 9-heterobarbaralane frame and its carbanionic counterpart **47** is further accentuated by the clean thermal reorganization of 9-thiabarbaralane (**43d**) into **49**, a direct heterocyclic analog of carbanion **48**. Moreover, pericyclic trapping with dienone **6** led to the formation of cycloadduct **50**, whose structure clearly implicates thioaldehyde **51** and possibly its bicyclic variant **52**, as key intermediates in the symmetry-allowed reorganization of **43d** to **49** (see Scheme VI).<sup>56</sup>

It must be noted that the destabilizing influence that lone-pair availability exerts in the 9-heterobarbaralanes

(54) R. Hoffmann, W.-D. Stohrer, and M. J. Goldstein, *Bull. Chem. Soc. Jpn.*, **45**, 2513 (1972).

(55) M. J. Goldstein, S. Tomoda, S.-I. Murahashi, K. Hino, and I. Moritani, *J. Am. Chem. Soc.*, **97**, 3847 (1975).

(56) A. G. Anastassiou, J. C. Wetzel, and B. Chao, *J. Am. Chem. Soc.*, **98**, 6405 (1976).



is in sharp contrast to its stabilizing effect observed with the heteronins. The trend in the case of **43** is, in fact, strongly reminiscent of that observed previously with the  $8\pi$ -electron heteropins (**28**). In other words, the net influence exerted by the lone pair in **43** is qualitatively similar to that which one observes when the heteroatomic unit is directly linked to the termini of a  $6\pi$  ribbon.

### Concluding Remarks

The principal aim of this account of our group's recent research contributions to the area of novel  $\pi$  systems has been to provide the interested reader with several firsthand examples of synthetic pericyclization. Quite possibly, the use of the label "synthetic method" in connection with pericyclization will elicit objection from some of the more classical practitioners in the field. Such criticism may not, of course, be entirely without justification for as it now stands pericyclic synthesis is a procedure substantially lacking in methodology and one in which a tactically conceived multistep scheme is often controlled by what may, in many instances, be judged to be a serendipitous final step. Despite these methodological drawbacks which are, no doubt, a reflection of the procedure's infant state of tactical development, pericyclization remains strictly unrivaled in matters relating to the construction of labile substances. As a final note, it may also be worth stressing that pericyclization is the only synthetic procedure which draws directly from first principles<sup>3</sup> and as such serves to expose the theoretically suspicious empiricist to the reality and usefulness of the molecular wavefunction.

*It is always a pleasure to acknowledge the contributions of associates and particularly so when one can thank, as I do now, sincerely and without reservation. The work described in this review would certainly never have come to fruition had it not been for the truly exceptional talent and thorough dedication of five of my graduate students, Elsa Reichmanis, Robert Elliott, John Wetzel, Ronald Griffith, and Salvatore Girgenti. I also thank the National Science Foundation and the Petroleum Research Fund, administered by the American Chemical Society, whose financial backing made it all possible. Lastly, a visiting professorship at the Department of Chemistry, Princeton (Spring 1976) provided the necessary quiet atmosphere in which to write this review.*