

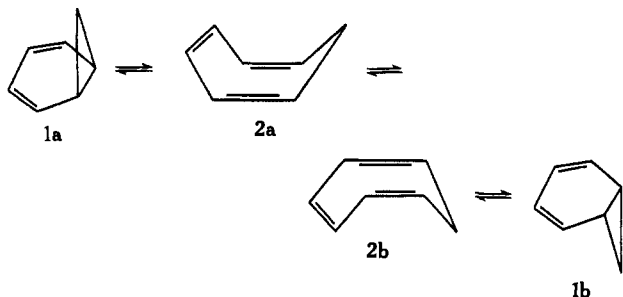
Nitrogen Analogs of Cycloheptatrienes and Norcaradienes. A Nuclear Magnetic Resonance Study of Their Thermodynamic and Kinetic Properties^{1,2}

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Contribution from the Institut für Organische Chemie, Universität München, 8 Munich, Germany, the Fachbereich Chemie, Universität Regensburg, 84 Regensburg, Germany, and the Department of Chemistry and Radiation Laboratory,⁷ University of Notre Dame, Notre Dame, Indiana 46556. Received August 24, 1971

Abstract: The static nmr parameters of a series of substituted monoaza (class A) and diaza (class B) analogs of the cycloheptatriene–norcaradiene system, accessible through a general and versatile Diels–Alder cycloaddition of cyclopropenes to 1,2,4-triazines and 1,2,4,5-tetrazines, conclusively establish that compounds in class A exist predominantly as monocyclic 4*H*-azepines, whereas those in class B energetically prefer the bicyclic 3,4-diazanorcaradiene structure. The causes of this crossover in thermodynamic stability are discussed. The compounds are found to undergo diastereotopomerizations or isomerizations at rates commensurate with the nmr time scale, attributable to ring reversal in class A and to a combination of valence-isomerization and ring-reversal processes in class B. Three representative examples, exhibiting ABC \rightleftharpoons ACB, A₂BC \rightleftharpoons A₂CB, and ABCD \rightleftharpoons ABDC type proton spectra, are analyzed quantitatively by dynamic nmr spectroscopy, the analyses providing experimental demonstrations of the superiority of dynamic nmr studies on complex spin systems to those on simple ones. The accurate rate data thus obtained, taken together with estimated free energies of activation for related compounds, permit an assessment of the shape of the potential barriers and of the factors influencing the barrier heights.

The intriguing variability of the norcaradiene–cycloheptatriene system has enticed numerous investigators to choose it as a convenient model framework for thermodynamic and kinetic studies.⁸ Norcaradiene itself has never been detected in the parent hydrocarbon, but the equilibrium $1 \rightleftharpoons 2$ can be shifted



toward the bicyclic form **1** by judicious substitution, especially at the 7 position,^{9–11} by double-bond fixation of the butadiene segment of **1** enforced by annelation

to benzenoid rings,⁸ or by bridging across the 1,6 positions.⁸ The nature of the substituent effects at the 7 position on the thermodynamics of the system remained puzzling for some time,⁹ but is now reasonably well understood.¹² On the dynamic side the valence isomerization $1 \rightleftharpoons 2$,¹³ the ring reversal $2a \rightleftharpoons 2b$,¹⁴ and the net topomerization¹⁵ $1a \rightleftharpoons 1b$ ¹⁶ have all been studied on suitable derivatives. The possibility of placing unequal substituents in the 7 position discloses an additional thermodynamic and kinetic versatility of the system.^{13a,14c,d,17}

This chemical playground can be further expanded by modifying the carbon framework itself with heteroatoms. In the benzene oxide–oxepin system^{18,19} both forms could sometimes be detected at equilibrium, offering the opportunity for a kinetic analysis of the valence isomerization,²⁰ whereas the corresponding nitrogen analogs seem to show a stronger preference for the monocyclic structure.^{21,22} On the other hand, deriva-

(1) Preliminary communication: D. A. Kleier, G. Binsch, A. Steigel, and J. Sauer, *J. Amer. Chem. Soc.*, **92**, 3787 (1970).

(2) Taken in part from the Ph.D. dissertations of A. S., University of Regensburg, 1971, and of D. A. K., University of Notre Dame, 1970.

(3) University of Munich and University of Regensburg.

(4) University of Notre Dame.

(5) National Science Foundation Predoctoral Fellow, 1969–1970.

(6) Alfred P. Sloan Research Fellow.

(7) The Radiation Laboratory is operated by the University of Notre Dame under contract with the U. S. Atomic Energy Commission. This is AEC Document No. COO-38-800.

(8) For a review see G. Maier, *Angew. Chem.*, **79**, 446 (1967); *Angew. Chem., Int. Ed. Engl.*, **6**, 402 (1967).

(9) E. Ciganek, *J. Amer. Chem. Soc.*, **89**, 1454, 1458 (1967).

(10) T. Mukai, H. Kubota, and T. Toda, *Tetrahedron Lett.*, 3581 (1967); J. A. Berson, P. W. Grubb, R. A. Clark, D. R. Hartter, and M. R. Wilcott, III, *J. Amer. Chem. Soc.*, **89**, 4076 (1967); J. A. Berson, D. R. Hartter, H. Klinger, and P. W. Grubb, *J. Org. Chem.*, **33**, 1669 (1968); T. Toda, M. Nitta, and T. Mukai, *Tetrahedron Lett.*, 4401 (1969).

(11) D. Schönleber, *Angew. Chem.*, **81**, 83 (1969); *Angew. Chem., Int. Ed. Engl.*, **8**, 76 (1969); M. Jones, *Angew. Chem.*, **81**, 83 (1969); *Angew. Chem., Int. Ed. Engl.*, **8**, 76 (1969); D. Schönleber, *Chem. Ber.*, **102**, 1789 (1969).

(12) (a) R. Hoffmann, *Tetrahedron Lett.*, 2907 (1970); (b) H. Günther, *ibid.*, 5173 (1970).

(13) (a) E. Ciganek, *J. Amer. Chem. Soc.*, **87**, 1149 (1965). (b) M. Görlitz and H. Günther, *Tetrahedron*, **25**, 4467 (1969).

(14) (a) F. A. L. Anet, *J. Amer. Chem. Soc.*, **86**, 458 (1964); (b) F. R. Jensen and L. A. Smith, *ibid.*, **86**, 956 (1964); (c) W. E. Heyd and C. A. Cupas, *ibid.*, **91**, 1559 (1969); (d) C. H. Bushweller, M. Sharpe and S. J. Weininger, *Tetrahedron Lett.*, 453 (1970).

(15) For a definition of this term, see G. Binsch, E. L. Eliel, and H. Kessler, *Angew. Chem.*, **83**, 618 (1971); *Angew. Chem., Int. Ed. Engl.*, **10**, 570 (1971).

(16) H. J. Reich, E. Ciganek, and J. D. Roberts, *J. Amer. Chem. Soc.*, **92**, 5166 (1970).

(17) H. Günther, M. Görlitz, and H.-H. Hinrichs, *Tetrahedron*, **24**, 5665 (1968), and references therein.

(18) For a review see E. Vogel and H. Günther, *Angew. Chem.*, **79**, 429 (1967); *Angew. Chem., Int. Ed. Engl.*, **6**, 385 (1967).

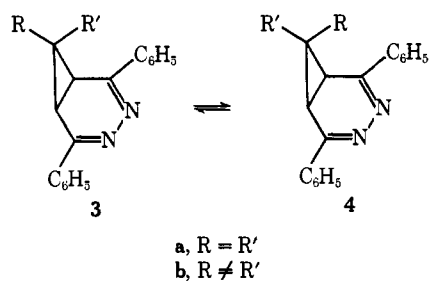
(19) H. Prinzbach and P. Vogel, *Helv. Chim. Acta*, **52**, 396 (1969).

(20) H. Günther, *Tetrahedron Lett.*, 4085 (1965); H. Günther, R. Schubart, and E. Vogel, *Z. Naturforsch.*, **B**, **22**, 25 (1967).

(21) For a review see L. A. Paquette, *Angew. Chem.*, **83**, 11 (1971); *Angew. Chem., Int. Ed. Engl.*, **10**, 11 (1971).

(22) H. Prinzbach, D. Stusche, and R. Kitzing, *Angew. Chem.*, **82**, 393 (1970); *Angew. Chem., Int. Ed. Engl.*, **9**, 377 (1970).

tives of the 3,4-diaza system, first described by Maier,⁸ exhibit a pronounced tendency to exist as 3,4-diazanorcaradienes. Maier and Heep²³ were also the first to report variable-temperature nmr evidence for topomerizations of the type **3a** \rightleftharpoons **4a** or endo-exo isomeriza-



tions of the type **3b** \rightleftharpoons **4b**, inferring the monocyclic forms as transient intermediates in these processes. Unfortunately, the temperature necessary to bring about a complete time-averaging of the nmr signals was inconveniently high for a precise analysis by nmr line-shape methods²⁴ and the investigation was also hampered by the onset of irreversible isomerizations. In view of the great activity in this field it is perhaps somewhat surprising that no system has so far been encountered in which both the valence isomerization and the ring reversal could be studied simultaneously. Until such a molecule becomes known, a detailed dynamic investigation of topomerizations of the type **1a** \rightleftharpoons **1b** probably offers the best chances to learn something about the interplay of factors controlling the physical properties of the total system.

Recently, a versatile method for the synthesis of a large variety of substituted diazanorcaradienes²⁵ and azepines²⁶ has been developed in one of the authors' laboratories. A computationally feasible procedure for the rigorous analysis of complicated exchange-broadened nmr spectra has concurrently become available.²⁷ Since the new compounds showed characteristic rate phenomena in a particularly convenient range for nmr line-shape studies and since several spin systems exhibited the ideal degree of complexity for an experimental verification of the claims made on the basis of theory,²⁷ it seemed desirable to subject some of the spectra to a detailed static and dynamic analysis. We here report the results and conclusions of our joint venture.

Results

The general scheme (Chart I) for the convenient preparation of nitrogen analogs of the norcaradiene-cycloheptatriene system employed in this work is founded on an extrapolation of the previously known²⁸ reactivity of 1,2,4,5-tetrazines in Diels-Alder reactions, to cyclopropenes as dienophiles and to 1,2,4-triazines as diene components. Of the numerous compounds

(23) G. Maier and U. Heep, *Chem. Ber.*, **101**, 1371 (1968).

(24) For a review see G. Binsch, *Top. Stereochem.*, **3**, 97 (1968).

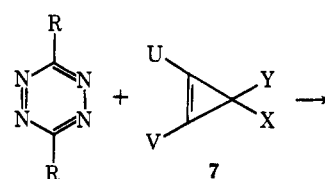
(25) J. Sauer and G. Heinrichs, *Tetrahedron Lett.*, 4979 (1966); G. Heinrichs, H. Krapf, B. Schröder, A. Steigel, T. Troll, and J. Sauer, *ibid.*, 1617 (1970); see also M. A. Battiste and T. J. Barton, *ibid.*, 1227 (1967).

(26) W. Dittmar, J. Sauer, and A. Steigel, *ibid.*, 5171 (1969).

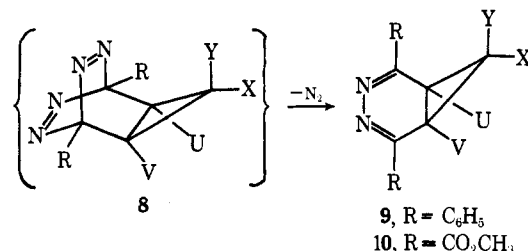
(27) G. Binsch, *J. Amer. Chem. Soc.*, **91**, 1304 (1969); D. A. Kleier and G. Binsch, *J. Magn. Resonance*, **3**, 146 (1970).

(28) (a) R. A. Carboni and R. V. Lindsey, Jr., *J. Amer. Chem. Soc.*, **81**, 4342 (1959); (b) M. Avram, I. G. Dinulescu, E. Marica, and C. D. Nenitzescu, *Chem. Ber.*, **95**, 2248 (1962); (c) J. Sauer, A. Mielert, D. Lang, and D. Peter, *ibid.*, **98**, 1435 (1965).

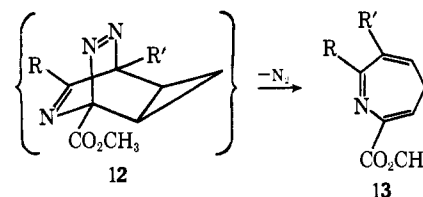
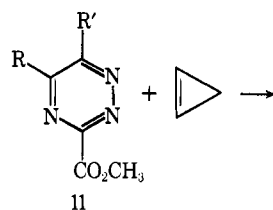
Chart I



5, R = C₆H₅
6, R = CO₂CH₃



a, U = V = X = Y = H
b, U = CH₃; V = X = Y = H
c, U = V = Y = H; X = CH₃
d, U = V = CH₃; X = Y = H
e, U = V = H; X = Y = CH₃



a, R = R' = C₆H₅
b, R = R' = CO₂CH₃
c, R = C₆H₅; R' = H

thus prepared^{25,26} those whose nmr spectra are of particular interest are included in Chart I. The diazanorcaradienes **9a**, **c**, and **d** had been obtained *via* a more laborious route by Maier.²⁹ Compounds **9e** and **10d** have not yet been synthesized; they appear in Chart I only for the sake of economy in notation.

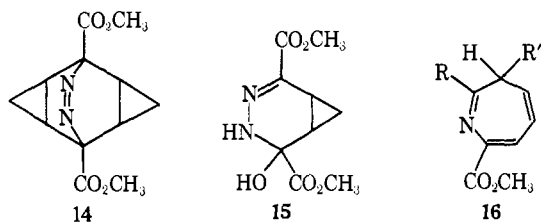
Under the reaction conditions employed, which involved mixing of the components in inert solvents at room temperature, the primary Diels-Alder adducts **8** and **12** smoothly eliminate nitrogen and could therefore not be isolated, but their intermediacy may be inferred from kinetic evidence.^{28c} The derivatives **10** proved to be highly reactive compounds, which easily add another molecule of cyclopropene to yield products of the type **14**.³⁰ It is therefore essential that the reactions with **6** be carried out in nonpolar solvents such as ether, where the low solubility of **10** prevents their further reaction with the dienophiles **7**.

(29) G. Maier, *ibid.*, **98**, 2438, 2446 (1965).

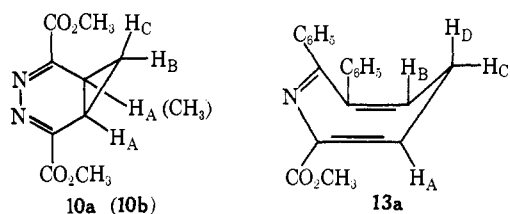
(30) W. Dittmar, G. Heinrichs, A. Steigel, T. Troll, and J. Sauer, *Tetrahedron Lett.*, 1623 (1970).

Table I. Chemical Shifts at 60 MHz Downfield from Internal TMS and Coupling Constants for the Labeled Protons of **10a,b** and **13a** in CDCl₃ Solution

Compd no.	Concn, <i>M</i>	Temp, °C	Static parameters, Hz									
			ν_A	ν_B	ν_C	ν_D	J_{AB}	J_{AC}	J_{AD}	J_{BC}	J_{BD}	J_{CD}
10a	0.40	-25.1	183.07 ±0.06	136.60 ±0.06	-1.62 ±0.06		8.92 ±0.07	4.75 ±0.07		-3.85 ±0.08		
10b	0.57	-32.8	162.13 ±0.02	123.29 ±0.02	4.96 ±0.03		9.51 ±0.03	5.18 ±0.04		-4.19 ±0.04		
13a	0.32	-26.7	396.89 ±0.05	381.88 ±0.05	176.81 ±0.06	129.21 ±0.05	-0.01 ±0.07	8.00 ±0.08	6.01 ±0.07	7.74 ±0.08	6.96 ±0.07	-13.01 ±0.08



Of the other chemical properties of the new compounds only the following two are of interest in the context of the present paper. (1) Several of the diazonorcaradienes **9** and **10** easily react with hydrogen cyanide, alcohols, and water to form 1:1 adducts. The derivatives **10** are in fact so hygroscopic as to be some-



times accompanied by hydrates of the type **15**. Unfortunately, these hydrates could not always be fully removed by recrystallizations and occasionally interfered somewhat with the nmr measurements. (2) The 3,4-diazonorcaradienes **9** and **10** as well as the 4*H*-azepines **13** are prone to undergo irreversible rearrangements or decompositions at elevated temperatures, which in some cases have been identified as being due to hydrogen migrations. The 4*H*-azepines **13** may be converted to the 3*H*-azepines **16** on a preparative scale by heating in refluxing pyridine.²⁶ Only one representative example of **14** and **15** is described in the Experimental Section; further details will be published elsewhere.

The sharp low-temperature nmr subspectra pertaining to the labeled protons in **10a**, **10b**, and **13a** have been subjected to a rigorous static analysis. The least-squares values of the chemical shift and coupling parameters at one particular temperature are presented in Table I and their temperature dependence is displayed in Figure 1. The quality of the agreement between the total experimental line shapes at low temperature and the corresponding computed spectra may be gleaned from a comparison of the topmost left with the topmost right curves in Figures 2-4. Chemical shifts of the remaining protons in **10a**, **10b**, and **13a** and nmr data for the other new compounds, obtained by approximate first-order analyses, are given in the Experimental Section.

The static parameters extracted from the low-temperature subspectra of **10a** and **13a** are characterized by four distinctive features, each of which provides in

itself sufficient evidence for the 3,4-diazonorcaradiene structure of **10a** and for the 4*H*-azepine structure of **13a**. (1) The chemical shifts of the labeled protons of **10a** are typical for hydrogen atoms attached to saturated carbon, whereas of those in **13a**, two lie in the olefinic range.³¹ (2) The magnitudes and relative signs of the geminal coupling constants clearly indicate a cyclopropane ring in **10a** and an allylic methylene group in **13a**. (3) The protons B and C in **10a** resonate at significantly higher fields than their counterparts C and D in **13a**. In particular, the high upfield shift of proton C in **10a** demands the presence of a geometrical constraint that forces this hydrogen atom into the strong diamagnetic shielding region of a π -electron system. (4) The values of the vicinal coupling constants in **10a** are consistent with the spacial relationships between hydrogen atoms attached to a three-membered carbocyclic ring, whereas those in **13a** indicate different dihedral angles. Naturally, not all of these features are encountered in some of the more highly substituted derivatives, but sufficient nmr information was always available for an unambiguous structural assignment. All the new compounds in the series **9** and **10** show low-temperature nmr spectra consistent only with the 3,4-diazonorcaradiene structure, the corresponding monocyclic forms remaining undetectable by nmr at all temperatures. Conversely, all the nmr signals in the series **13** must be attributed to 4*H*-azepines, no contamination with the corresponding bicyclic forms being noticeable.

The low-temperature nmr spectrum of the new compound **10c** showed an additional element of complexity, analogous to that already described by Maier²⁹ for **9c**, in that the methyl group at position 7 gives rise to two doublets at δ 1.52 ($J = 6.0$ Hz) and 0.54 ($J = 6.1$ Hz) in the approximate intensity ratio of 65:35 at -30° , with correspondingly more complicated patterns for the other protons which were not analyzed in detail. It is clear that **10c** represents an equilibrium mixture of two isomers, the characteristic methyl shifts identifying the more populous one as that having the methyl group in the exo position.

The nmr spectra attributable to the rigid 3,4-diazonorcaradiene structures for **9** and **10** and to the tub-shaped 4*H*-azepine framework for **13** exhibit reversible line-broadening effects as a function of temperature and converge toward sharp spectra with fewer lines at the high-temperature extremes. The magnitudes of the time-averaged static parameters require that the line broadening be caused by an exchange of ligands at the 7 position in **9**, **10**, and **13**, which corresponds to endo-

(31) The assignment of the two olefinic chemical shifts to protons A and B in **13a** was chosen arbitrarily; a reversal of this assignment would be without consequence for the arguments of the present paper.

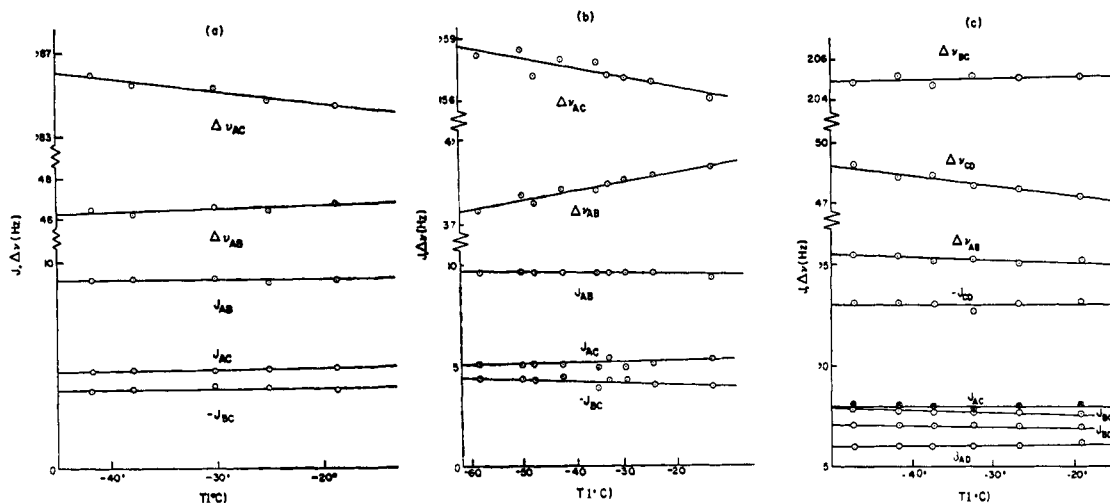


Figure 1. Temperature dependence of the static nmr parameters of 10a (a), 10b (b), and 13a (c).

exo isomerizations for 9c^{23,29} and 10c and to diastereotopomerizations¹⁵ or enantiomerizations in the other cases. The linear least-squares functions used for approximating the temperature dependence of the static parameters of 10a, 10b, and 13a below the onset of exchange broadening (Figure 1) predicted the measured time-averaged values of all chemical shifts and coupling constants in these compounds within experimental error, thus adding support to the validity of the linear extrapolation procedure employed for calculating the necessary static information in the temperature range where it is not directly obtainable from the spectra.³² Rate constants were determined from a visual comparison of the experimental exchange-broadened spectra with line shapes generated with the computer programs DNMR3³³ for 10a and DNMR2³⁴ for 10b and 13a; representative examples are shown in Figures 2–4. Since part of the strongly exchange-broadened subspectrum of 10b happens to be buried in the tail of a nonexchanging methyl group, the latter was included in the calculation (Figure 3). The impurity lines in the experimental spectra of Figures 2 and 3 were shown to be attributable to the corresponding hydrates. The impurity signal in the aliphatic proton region of Figure 4 is of unknown origin. Arrhenius plots (Figures 5–7) and Eyring plots yielded the activation parameters listed in Table II. The application of well-known approximate procedures^{24,35} gave estimates of the free energies of activation at the coalescence temperatures for the other compounds. These values, together with those reported by Maier and Heep,²³ are collected in Table III.

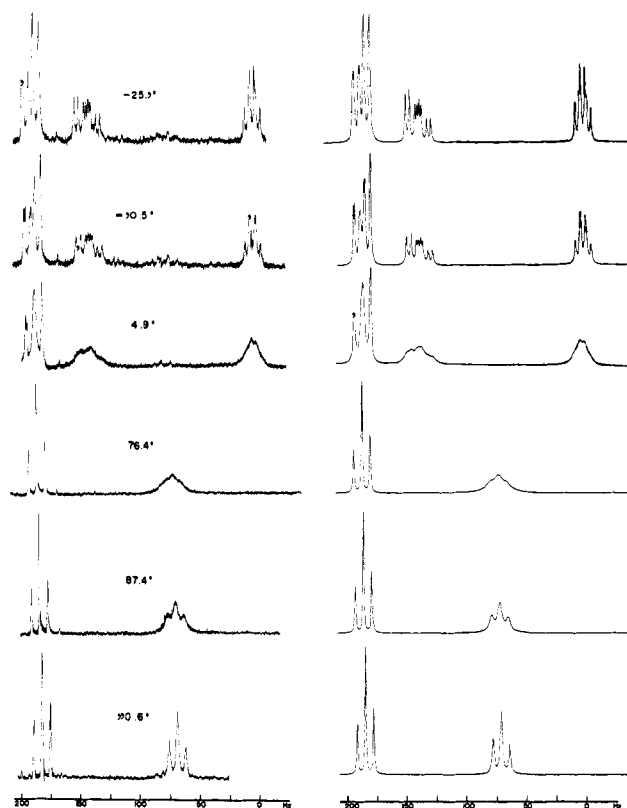
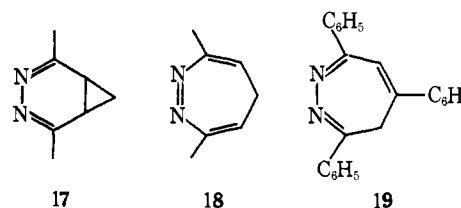


Figure 2. Experimental (left) and computed (right) A₂BC ⇌ A₂CB dnmr spectra of 10a.

Discussion

On the basis of the analytical sensitivity of proton nmr spectroscopy one must conclude that the bicyclic form 17 of 9 and 10 is more stable than the monocyclic



form 18 by at least 3 kcal/mol and that the quantity

(32) In principle, such static information could be obtained indirectly by performing a least-squares dynamic calculation on the total line shape, in which the chemical shifts and coupling constants are also treated as independent variables. In practice, the mathematical and computational obstacles of such an approach for cases as complex as the present ones have not yet been overcome.

(33) D. A. Kleier and G. Binsch, "DNMR3: A Computer Program for the Calculation of Complex Exchange-Broadened NMR Spectra, Modified Version for Spin Systems Exhibiting Magnetic Equivalence or Symmetry," Program 165, Quantum Chemistry Program Exchange, Indiana University, 1970.

(34) G. Binsch and D. A. Kleier, "The Computation of Complex Exchange-Broadened NMR Spectra," Program 140, Quantum Chemistry Program Exchange, Indiana University, 1969.

(35) H. G. Schmid, H. Friebohn, S. Kabuss, and R. Mecke, *Spectrochim. Acta*, **22**, 623 (1966); A. Mannschreck, G. Rissmann, F. Vögtle, and D. Wild, *Chem. Ber.*, **100**, 335 (1967); A. Mannschreck, R. Radeglia, E. Gründemann, and R. Ohme, *ibid.*, **100**, 1778 (1967).

Table II. Arrhenius and Eyring Parameters for the Diastereotopomerization of **10a** and the Enantiomerizations of **10b** and **13a**

Compd	Temp range, deg	Activation parameters			
		E_a , kcal/mol	Log A , sec $^{-1}$	ΔH^\ddagger , kcal/mol	ΔS^\ddagger , eu
10a	121	15.30 \pm 0.11	13.02 \pm 0.07	14.67 \pm 0.11	-0.61 \pm 0.34
10b	115	14.63 \pm 0.12	12.84 \pm 0.08	14.01 \pm 0.13	-1.88 \pm 0.43
13a	93	14.53 \pm 0.16	12.56 \pm 0.12	13.93 \pm 0.17	-3.09 \pm 0.55

$\Delta G^\circ = (G^\circ_{17} - G^\circ_{18}) - (G^\circ_2 - G^\circ_{18})$ is therefore larger than 6 kcal/mol. This crossover in thermodynamic

whereas the bond energy of a nitrogen-nitrogen double bond is smaller by about 50 kcal/mol,³⁶ a fact that also

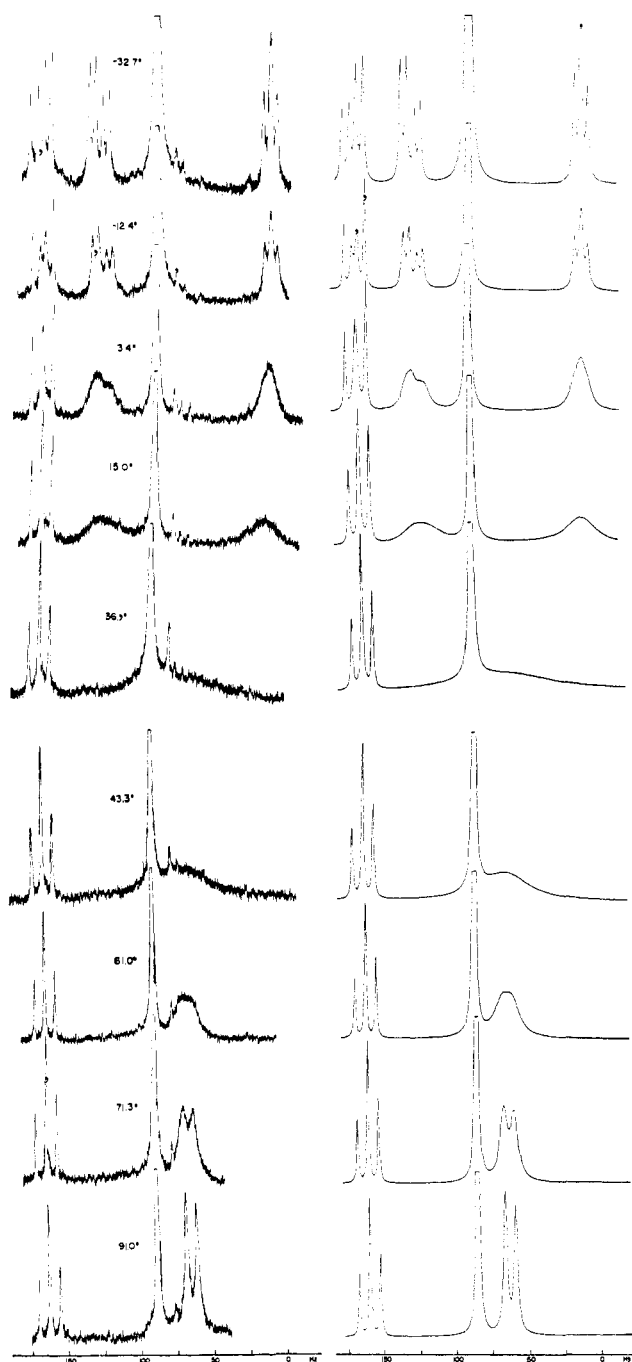


Figure 3. Experimental (left) and computed (right) ABC \rightleftharpoons ACB dnmr spectra of **10b**.

stability can easily be accounted for if one remembers that the average bond energies of carbon-carbon and carbon-nitrogen double bonds are virtually the same,

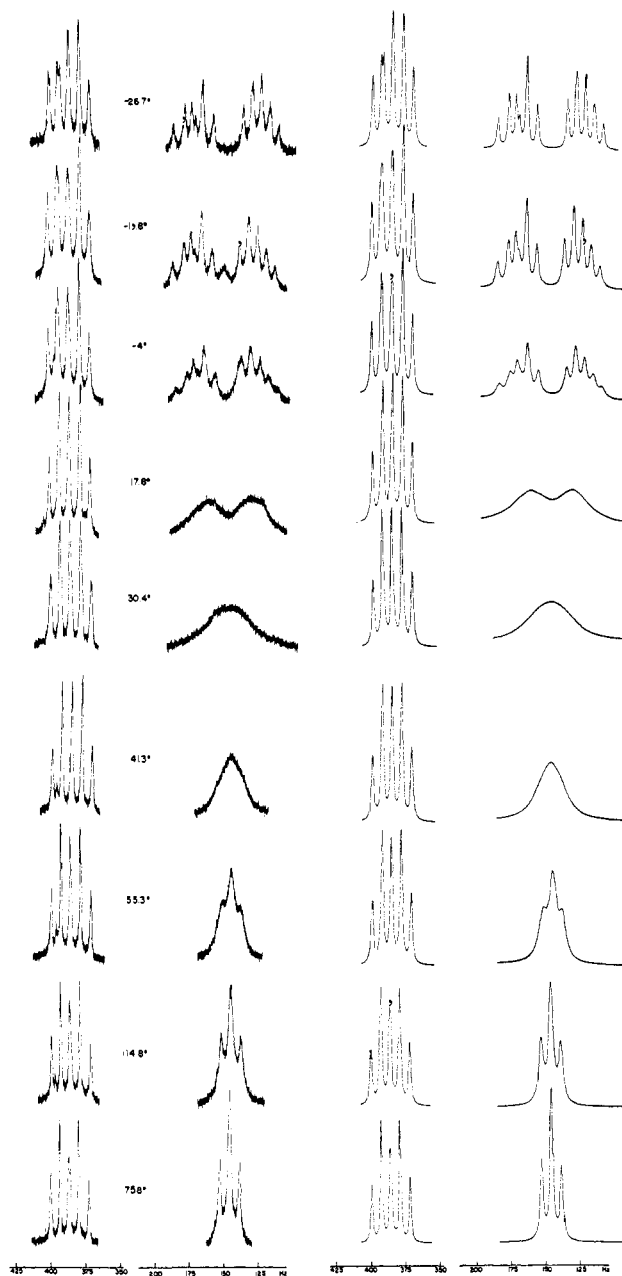
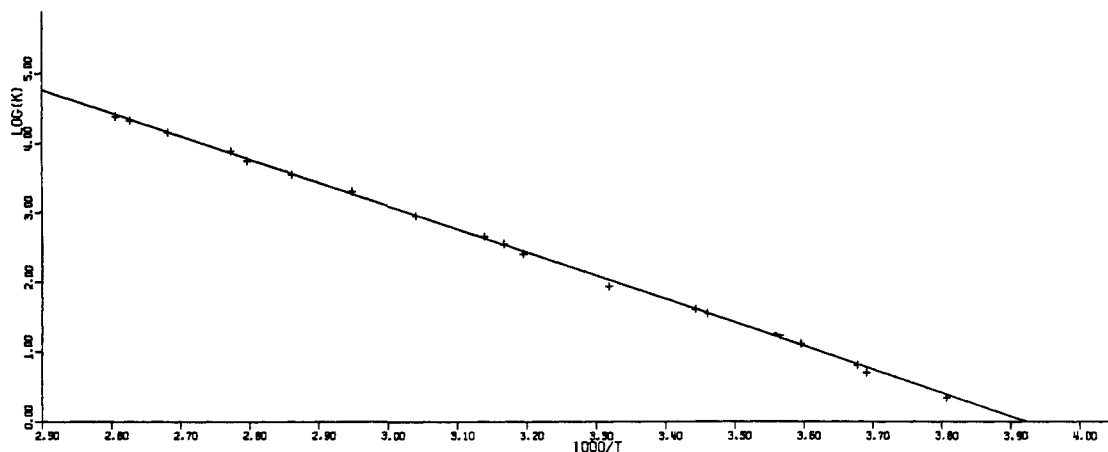
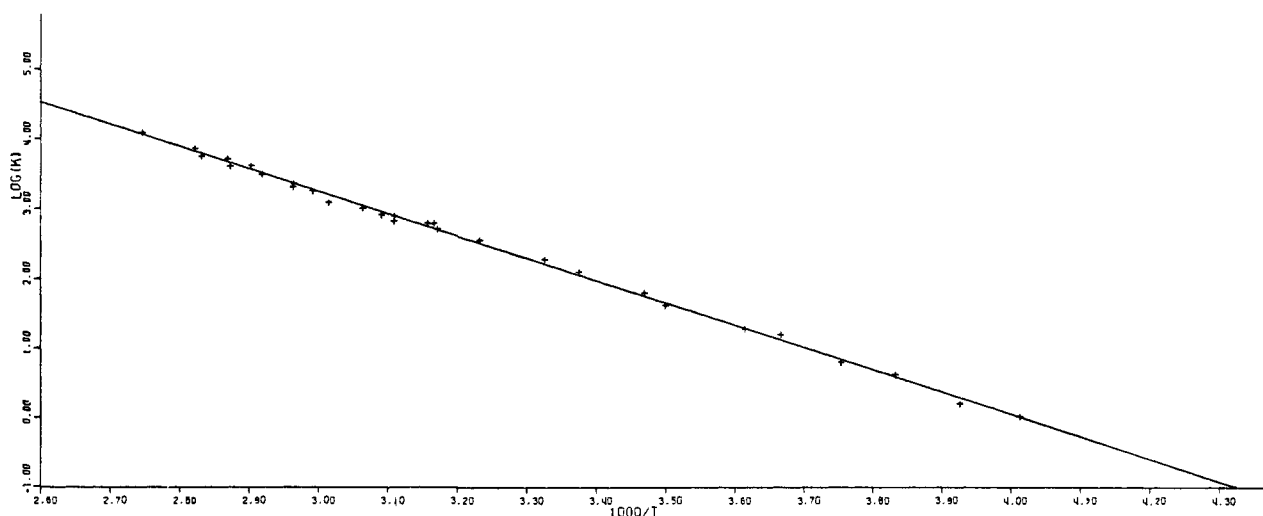


Figure 4. Experimental (left) and computed (right) ABCD \rightleftharpoons ABDC dnmr spectra of **13a**.

manifests itself in the well-known tendency of 1-pyrazolines to tautomerize to 2-pyrazolines. Indeed,

(36) See, for instance, D. J. Royer, "Bonding Theory," McGraw-Hill, New York, N. Y., 1986, p 184. There is unfortunately a great deal of uncertainty in the bond energies involving nitrogen. Our calculations are based on the following average values (kcal/mol): C-C, 83; C=C, 146.4; C-N, 72; C=N, 145; N-N, 40; N=N, 92.

Figure 5. Arrhenius plot for the topomerization of **10a**.Figure 6. Arrhenius plot for the enantiomerization of **10b**.

the molecule **19**, in which the monocyclic form does not suffer from the strong energetic disadvantage of a nitrogen–nitrogen double bond, is reported³⁷ to be a 2,3-diazacycloheptatriene. Taking values of bond ener-

the literature³⁸ is correct, it appears that **17** should be more stable than **18** by an amount at least equal to that by which **2** is thought to be more stable than **1**, or more likely by a somewhat larger amount. The energetic

Table III. Coalescence Temperatures and Free Energies of Activation for Isomerizations or Topomerizations of **9**, **10**, and **13**

Compd	T_c , °C	ΔG^\ddagger , kcal/mol	Compd	T_c , °C	ΔG^\ddagger , kcal/mol
9a ^a	170–180	$>20.9 \pm 0.3$	10c	55 ± 5	16.6 ± 0.5^c
9b	170–175	20.8 ± 0.6	10e	66 ± 5	16.7 ± 0.3
9c ^{a,b}	183 ± 1	23.1 ± 0.7	13b	-40 ± 5	11.2 ± 0.5
9d ^a	104 ± 5	18.5 ± 1.0	13c	<-60	$<10^e$

^a Reference 23. ^b Average value for the endo–exo and exo–endo isomerizations;²³ the rate of this isomerization was also followed²⁹ by conventional kinetic techniques, yielding activation parameters indistinguishable from the line-shape value within experimental error. ^c Exo–endo isomerization. ^d Endo–exo isomerization. ^e Significant broadening was observed at -60° , but no frozen spectra were recorded. The estimated upper limit for ΔG^\ddagger rests on the assumption of a chemical shift difference between the exchanging protons similar to that in **13b**.

gies also for the other bonds from a variety of sources one estimates³⁶ $\Delta E = (E_1 - E_{17}) - (E_2 - E_{18})$ to be somewhere in the vicinity of 30 kcal/mol. Thus, if the estimate of 11 ± 4 kcal/mol for the energy difference between cycloheptatriene and norcaradiene quoted in

(37) O. Buchardt, C. L. Pedersen, U. Svanholm, A. M. Duffield, and A. T. Balaban, *Acta Chem. Scand.*, **23**, 3125 (1969).

preference for the monocyclic form in **13** can also be rationalized on the basis of bond energies; since the most strongly destabilizing structural element of **18** is absent in both forms of **13**, it is not surprising to find that the situation is qualitatively the same as that in

(38) J. A. Berson and M. R. Willcott, III, *J. Amer. Chem. Soc.*, **88**, 2494 (1966).

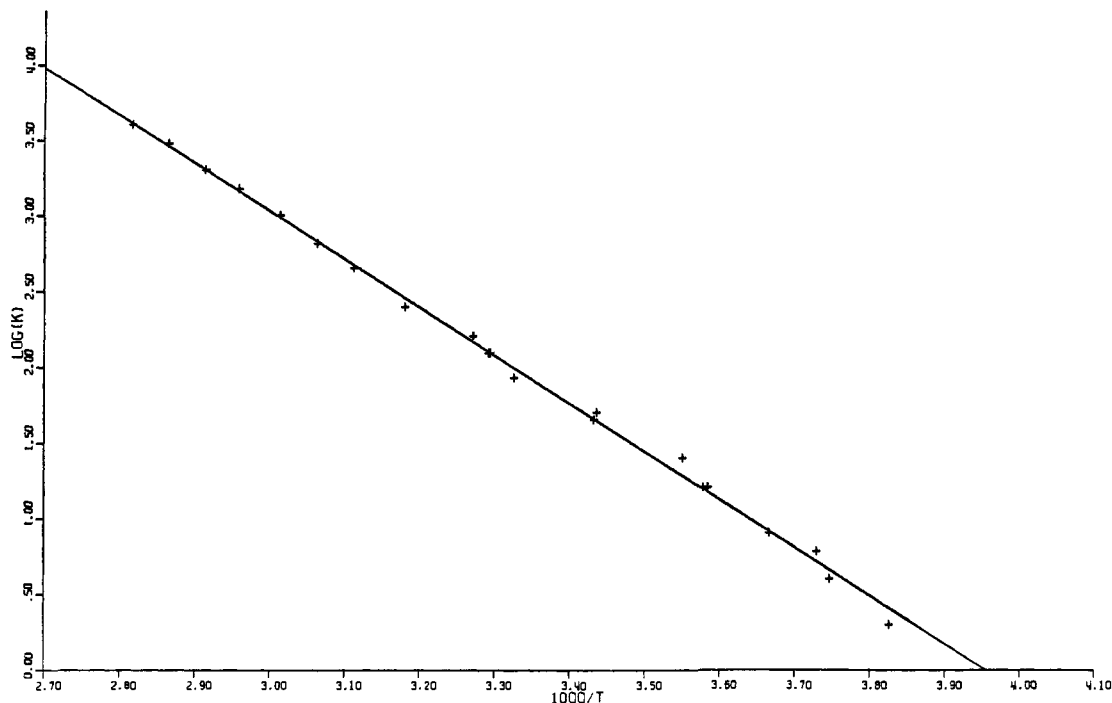


Figure 7. Arrhenius plot for the enantiomerization of **13a**.

cycloheptatriene itself. Undoubtedly, there are other factors in **9**, **10**, and **13** that modify the thermodynamics of the systems, but since the equilibria are so strongly biased they cannot be studied directly. We shall later demonstrate, however, that our interpretation of the dynamics provides some tentative indirect information about the relative ground-state stabilities of the variously substituted derivatives.

Before discussing the chemical implications of the kinetic results we should like to comment on the unique features of the rate studies themselves. As indicated in Table II, rate data could be obtained over a much larger temperature range than usually accessible by nmr line-shape measurements, for three interrelated reasons. (1) By virtue of the spin-spin interaction between the exchanging and nonexchanging nuclei the spectra are relatively complex at both the low- and high-temperature extremes; in particular, they do not degenerate into a single line in the fast-exchange limit. In the temperature ranges where the fine structure disappears or reappears the spectra are still quite sensitive to small changes in the rate constants. This is in distinct contrast to the situation encountered with two collapsing singlets or with an $AB \rightleftharpoons BA$ exchange problem, to which the spectra of **10a**, **10b**, and **13a** could be reduced by replacing the nonexchanging protons with deuterium nuclei, where the sensitivity of the line shapes is high in the immediate vicinity of the coalescence point, but diminishes rapidly toward both temperature extremes. It is for this reason that reliable values of the free energies of activation at the coalescence point can be obtained from simple spectra without difficulty, the application of crude approximate formulas to low-quality spectra being entirely adequate for this purpose, but that the vast majority of the Arrhenius and Eyring parameters reported in the earlier literature,²⁴ which depend critically on the temperature extremes, presents such a dismal picture that some authors have in despera-

tion even gone so far as to question the validity of the theory. The intrinsic advantages of dnmr studies on reasonably complex spin systems are now beginning to be realized by many workers; the recent papers by a group of Swedish authors³⁹ being especially noteworthy for their outstanding quality. (2) The exchanging protons in **10a**, **10b**, and **13a** are separated by a relatively large chemical shift difference at low temperature, especially in **10a** (Figure 2). This fact alone ensures that the line shapes respond to the rate of exchange over a large temperature range, but by the same token the line width changes at the extremes remain sensitive to spurious effects such as field inhomogeneities and relaxation over a large temperature range as well. It is easy to show theoretically that the fine structure caused by spin-spin coupling depends more critically on the rate of exchange than on these spurious effects. Thus it is the combination of a large chemical shift difference between the exchanging nuclei with the complexity of the spectra at the extremes that is most important from a quantitative point of view. (3) In dnmr calculations one needs to know the line width in the absence of exchange, usually expressed by an effective transverse relaxation time T_2^{eff} . This parameter has an almost negligible effect on the calculations for the broad lines around the coalescence point, but is of critical importance at the extremes, where the exchange broadening becomes comparable to the effective natural line width. We have previously shown^{27,40} that the total information content of an nmr spectrum can be condensed into two complex vectors, **Q** and **S**, and that the real elements of the spectral vector **Q** may be taken to represent the widths of the lines and the imaginary elements of the shape vector **S** their deviation from Lorentzian absorption

(39) K. I. Dahlqvist and S. Forsén, *J. Phys. Chem.*, **73**, 4124 (1969); T. Drakenberg and S. Forsén, *ibid.*, **74**, 1 (1970); K. I. Dahlqvist and S. Forsén, *J. Magn. Resonance*, **2**, 61 (1970).

(40) G. Binsch, *Mol. Phys.*, **15**, 469 (1968).

shape. If one finds an imaginary element of **S** close to zero in a trial calculation and a corresponding real element of **Q** essentially equal to $-1/T_2^{\text{eff}}$, one has thereby identified a line that is not noticeably affected by the exchange rate. Such lines could be found in the spectra of **10a**, **10b**, and **13a** throughout the entire temperature ranges, thus always providing direct numerical information on T_2^{eff} in the absence of exchange; in other words, the spectra carry their own built-in line-width calibrations.

The essential importance of a large temperature range in dnmr determinations of Arrhenius and Eyring parameters emerges from an error analysis of the Arrhenius equation, which yields the following approximate expression for the relative error of the activation energy E_a

$$\left(\frac{\sigma_{E_a}}{E_a}\right)^2 \approx \frac{2T^2}{(\Delta T)^2} \left(\frac{\sigma_T}{T}\right)^2 + 2\left(\frac{1}{\Delta(\ln k)}\right)^2 \left(\frac{\sigma_k}{k}\right)^2$$

If the measurements are carried out at a temperature around 300°K and cover a range ΔT of 10°, a typical statistical error of 1° (0.3%)⁴¹ causes an error of 14% in the activation energy, and a typical error of 5% in the rate constant introduces an error of 10% in E_a , the combined error then being 17%. Increasing the temperature range to 100° reduces all error contributions to E_a by a factor of approximately 10. In reading the current literature one is tempted to conclude that in spite of the triviality of the problem the true error situation in dnmr spectroscopy is not fully appreciated, there being a great deal of loose talk about statistical errors not being meaningful.

The Arrhenius plots of Figures 5–7 only give an impression of the precision of the fit to a straight line, but the numbers of Table II were obtained from an error propagation treatment. There remains one unsatisfactory feature, however. Whereas the average standard deviation of the temperatures could be calculated objectively and was found to be 0.23° for the total body of measurements, a value that applies essentially uniformly over the total temperature range and therefore only affects the precision of the linear fit, the errors in the rate constants vary considerably but had to be estimated visually from trial line-shape calculations. The only way to eliminate this subjective element would be by a least-squares fit to the total line shape, and such a procedure, as already mentioned,³² is not yet available.

In view of the total body of information on the norcadiene-cycloheptatriene system it seems reasonable to postulate that the observed topomerizations or enantiomerizations of **9** and **10** proceed in two reversible steps, a valence isomerization of the diazanorcardiene to the monocyclic diazacycloheptatriene followed by ring reversal of the latter. If both steps are discrete the general shape of the energy profile could conceivably be either of type A or B of Figure 8; a concerted mechanism would only be consistent with the general shape B and would require that the subsidiary energy maxima degenerate to shoulders (dashed line in B of Figure 8). For deciding between the possibilities A and B of Figure 8 the activation entropies of Table II provide the most interesting piece of information. Molecule **10a** contains a plane of symmetry, and this plane is retained throughout the reaction coordi-

(41) This value may easily be exceeded if the temperature is measured outside the sample tube.

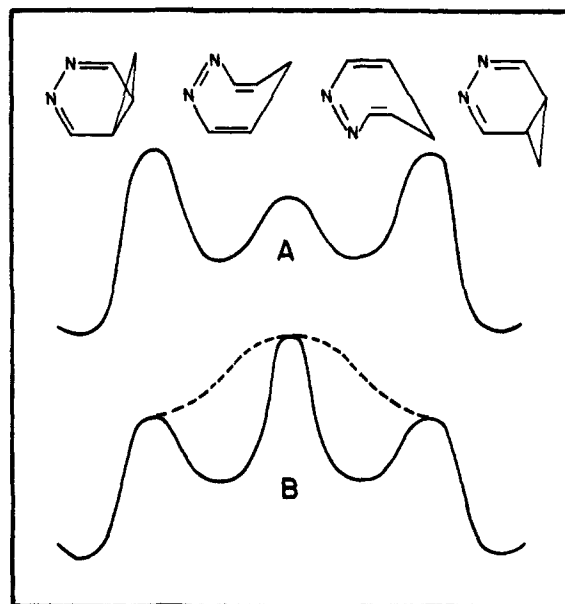
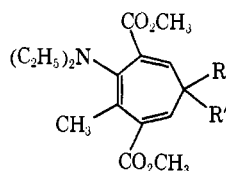


Figure 8. Possible general shapes of energy profiles for the diazanorcardiene-diazacycloheptatriene system.

nate; its entropy of activation is found to be close to zero. The substituted derivative **10b**, however, is chiral in the ground state and should therefore have an entropy of mixing equal to $R \ln 2 = 1.38$ eu. The transition state of the valence isomerization is still chiral, and if this transition state is rate determining (profile A of Figure 8), there does not seem to be a compelling reason why ΔS^\ddagger of **10b** should differ very much from that of **10a**. However, the transition state of the ring reversal is presumably planar and therefore achiral, and if this transition state is rate determining (profile B of Figure 8), then ΔS^\ddagger of **10b** is expected to be more negative than that of **10a** by approximately 1.4 eu, which seems to be in better agreement with the numbers actually observed. By an analogous argument, the activation entropy for the ring reversal of the chiral tub-shaped 4*H*-azepine **13a** might also be expected to be significantly negative. We certainly cannot claim that this reasoning proves the shape B of the potential, for quite apart from the error situation the issue is clouded by our insufficient theoretical understanding of small activation entropies and the virtual nonexistence of reliable experimental numbers for low-barrier rate processes in solution, but the conclusion seems to be in agreement with that drawn by Reich, Ciganek, and Roberts¹⁶ and also allows an internally consistent interpretation of the barrier heights to be discussed presently.

The barrier to ring reversal in **13a** is found to be about twice as large as the free energy of activation for the corresponding process in cycloheptatriene,^{11a,b} but comparison with the data in Table III demonstrates that this increase cannot be attributed entirely to an inherent property of the 4*H*-azepine ring system. A substantial part of the barrier is apparently caused by a steric inhibition of resonance in the planar transition state, in which the vicinal phenyl substituents cannot simultaneously adopt a coplanar arrangement with the π system of the ring, an effect less important in **13b** and absent in **13c**. In general agreement with this contention, the free energy of activation for the ring reversal of 2-anilino-3*H*-azepine, where steric effects are

also expected to be unimportant, is reported⁴² to be 10.2 kcal/mol. The high ΔG^\ddagger value of 17.3 kcal/mol measured³⁷ for **19**, on the other hand, is undoubtedly due to the nature of the ring system itself, since the planar transition state cannot avoid an energetically unfavorable partial nitrogen–nitrogen double bond. Preliminary results⁴³ in the series **20–22** indicate that



- 20**, R = R' = H
21, R = H; R' = CH₃
22, R = R' = CH₃

7-methyl substituents only slightly facilitate ring reversal, confirming a surmise already mentioned in the literature,¹⁶ but the effect is so small that one cannot be certain of its reality on the basis of approximate calculations.

The most remarkable aspect of the topomerization or isomerization barriers of the 3,4-diazanorcaradienes (Tables II and III) is the 6 kcal/mol increase observed on replacing the 2,5-ester substituents with phenyl groups. This feature would be difficult to understand on the basis of profile A of Figure 8, for one would rather expect that the transition state of the valence isomerization should profit energetically from conjugation to a similar extent as the ground state, but seems to be consistent with profile B of Figure 8. The following arguments can be adduced in support of the hypothesis that the relative thermodynamic stabilities of the 3,4-diazanorcaradienes themselves are mainly responsible for the total observed barriers. (1) In the unsubstituted benzene oxide–oxepin system the two forms are of almost equal stability,¹⁸ but no monocyclic form could be detected¹⁹ in the 2,5-diphenyl-3,4-dicarbomethoxy⁴⁴ derivative and no bicyclic form in the 2,3,4,5-tetra-carbomethoxy derivative.⁴⁵ (2) The relative thermodynamic stability of the bicyclic form in the benzene oxide–oxepin system decreases in going from the unsubstituted to the 1-methyl- and 1,6-dimethyl-substituted derivatives,¹⁸ whereas the barrier to the valence isomerization seems to remain unaffected.^{18, 20} The data in Tables II and III indicate that the 3,4-diazanorcaradiene topomerization or enantiomerization barriers parallel the thermodynamic sequence in the oxygen analogs and not the kinetics of the valence isomerization. (3) On the basis of MO arguments analogous to those presented by Hoffmann^{12a} and Günther^{12b} one might expect that methyl substituents in the 7 position stabilize the bicyclic forms. Thus the barrier increase observed for **9c**, **10c**, and **10e** also seems to be consistent with the above hypothesis. In conclusion, we believe that the kinetic studies of the present paper have also furnished semiquantitative information about thermodynamic properties that are experimentally inaccessible from direct investigations of equilibria.^{45a}

(42) A. Mannschreck, G. Rissmann, F. Vögtle, and D. Wild, *Chem. Ber.*, **100**, 335 (1967).

(43) A. Steigel and J. Sauer, unpublished.

(44) For convenience, we use the cycloheptatriene numbering system throughout.

(45) H. Prinzbach, P. Vogel, and W. Auge, *Chimia*, **21**, 469 (1967).

Experimental Section

Nmr Measurements. Solutions of the samples in CDCl₃ were placed in precision nmr tubes (Wilmad) and degassed by three freeze–thaw cycles, after which the tubes were sealed under reduced pressure. Nmr spectra were recorded on precalibrated chart paper, using a Varian A-60A spectrometer equipped with a variable-temperature probe. The calibration was checked periodically with an audiofrequency side-band generator. Temperatures were measured by recording the nmr signals of a thermometer liquid, contained in a sealed capillary (0.05 mm i.d.) within the sample solution, immediately before and immediately after recording a spectrum. If the two temperatures differed by more than 0.5°, the spectrum was discarded and rerun. The thermometer liquid consisted of an equimolar mixture of ethylene glycol and perdeuteriomethanol, to which 0.03% by volume of concentrated hydrochloric acid had been added. The chemical shifts of the thermometer liquid were cross-calibrated against van Geet's curves⁴⁶ by concurrently recording the nmr signals of a pair of capillaries in the same nmr tube partially filled with CDCl₃, one member of the pair containing acidified methanol⁴⁶ or acidified ethylene glycol.⁴⁶ The Teflon plugs recommended by Forsén and coworkers³⁹ for holding the capillaries in the center of the nmr tube were found to be dispensable if the capillaries extended 4 ± 1 mm above the level of the surrounding liquid in the nmr tube; under these conditions the capillaries automatically adjusted themselves in the center at a spinning rate of 50 rpm.

Calculations. The low-temperature nmr spectra were analyzed using a slightly modified version of the iterative computer program LAOCN3⁴⁷ and the temperature-dependent static parameters thus obtained were computer-fitted to straight lines. The static parameters in the exchange-broadened region were computed from extrapolations of these lines. The line-width parameter T_2^{eff} was calculated from the widths at half-height of lines not affected by the exchange rate (*vide supra*). Trial spectral and shape vectors were calculated on a Univac 1107 computer using the programs DNMR2³⁴ and DNMR3,³³ making use of the punch option. Line shapes were generated on a Univac 418 computer using a plotting program that accepted the punched-card output of DNMR2 and DNMR3 as input and also allowed the superposition of the nonexchanging methyl singlet for **10b**. Rate constants were determined from a visual comparison of experimental spectra with computed trial line shapes and their errors estimated on the basis of a subjective judgment on the sensitivity of the fit to changes in the rate constant. An average value for the standard deviation of the temperatures was computed for a series of k spectra from temperatures T_j^b and T_j^f , measured before and after recording a spectrum j , using the formula⁴⁸ $\sigma^2 = (2k)^{-1} \sum (T_j^f - T_j^b)^2$.

Arrhenius and Eyring parameters and their errors were calculated using a computer program based on standard error propagation formulas for linear least-squares functions.⁴⁹

2,5-Dicarbomethoxy-3,4-diazanorcaradiene (10a). A slow stream of gaseous cyclopropene (**7a**), generated according to the general procedure of Closs and Krantz,⁵⁰ was passed through a stirred suspension of 2.58 g (13.0 mmol) of **6**^{28b,c} in 60 ml of dry ether for 5 hr at room temperature, yielding 2.17 g (79%) of **10a** as a yellow precipitate: mp 123°dec; nmr (CDCl₃) δ 3.97 (s, 6) and A₂BC pattern at –25.1° (see Table I); ir (KBr) 3100, 1730, 1710, 1525 cm⁻¹.

Anal. Calcd for C₉H₁₀N₂O₄: C, 51.42; H, 4.80; N, 13.33. Found: C, 51.43; H, 4.96; N, 13.06.

The crude material obtained on evaporation of the ether solution was shown by nmr to consist mainly of the 1:2 adduct of **6** and **7a** (*vide infra*).

Reaction of 10a with Cyclopropene. A solution of 210 mg (1.00 mmol) of **10a** in 5 ml of dry chloroform was added to 1 ml of

(45a) NOTE ADDED IN PROOF. The methyl substituent effects obtained *directly* from equilibrium measurements in the barbaralyl system (J. C. Barborak, S. Chari, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **93**, 5275 (1971)), are in quantitative agreement with the numbers determined *indirectly* in the present paper, thus adding support to the contention that the differences in the 3,4-diazanorcaradiene barrier heights are governed by ground-state effects.

(46) A. L. van Geet, *Anal. Chem.*, **40**, 2227 (1968); **42**, 679 (1970).

(47) A. A. Bothner-By and S. Castellano, "LAOCN3," Program 111, Quantum Chemistry Program Exchange, Indiana University, 1967.

(48) E. B. Wilson, "An Introduction to Scientific Research," McGraw-Hill, New York, N. Y., 1952, p 245.

(49) See, for instance, W. E. Deming, "Statistical Adjustment of Data," Wiley, New York, N. Y., 1943, Chapters IV, IX, and X.

(50) G. L. Closs and K. D. Krantz, *J. Org. Chem.*, **31**, 638 (1966).

liquid cyclopropene and the solution stirred at room temperature for 15 min. On evaporation to dryness 250 mg (100%) of **14** was obtained as a microcrystalline material: colorless needles (methanol); mp 161–162° dec; nmr (CDCl₃) δ 3.96 (s, 6), 1.93 (dd, *J* = 3.7 and 7.4 Hz, 4), 0.56 (9, *J* ≈ 7.2 Hz, 2), 0.13 (dt, *J* = 3.7 and 6.8 Hz, 2). The simplicity of the nmr spectrum indicates a highly symmetrical structure.

Anal. Calcd for C₁₂H₁₄N₂O₄: C, 57.59; H, 5.64; N, 11.22. Found: C, 57.62; H, 5.76; N, 11.32.

Reaction of 10a with Water. When 2 drops of water was added to a slurry of 210 mg (1.00 mmol) of **10a** in 2 ml of dioxane, the yellow solid rapidly dissolved on shaking, resulting in a colorless solution, from which **15** was isolated in quantitative yield: colorless prisms (ethyl acetate); mp 132–133° dec; ir (KBr) 3300 (OH, NH), 1735, 1707, 1610 cm⁻¹; nmr (pyridine-*d*₅) δ 7.2 (broad singlet, 1), 3.79 (s, 3), 3.73 (s, 3), 2.5 (m, 2), 1.5 and 1.15 (AB part of an ABCD pattern).

Anal. Calcd for C₉H₁₂N₂O₅: C, 47.37; H, 5.30; N, 12.28. Found: C, 47.37; H, 5.28; N, 12.14.

1-Methyl-2,5-dicarbomethoxy-3,4-diazanocaradiene (10b). Reaction of 1-methylcyclopropene with **6** in the manner described for the preparation of **10a** produced **10b** in 60% yield: mp 77–79° dec; ir (KBr) 3095, 1750, 1725, 1530 cm⁻¹; nmr (CDCl₃) δ 3.96 (s, 6) 1.49 (s, 3), ABC pattern at –32.8° (see Table I).

Anal. Calcd for C₁₀H₁₂N₂O₄: C, 53.57; H, 5.39; N, 12.50. Found: C, 53.40; H, 5.46; N, 12.46.

7-Methyl-2,5-dicarbomethoxy-3,4-diazanocaradiene (10c). Prepared in 75% yield from **6** and 3-methylcyclopropene: mp 113–115° dec; ir (KBr) 1735, 1710 cm⁻¹; nmr (CDCl₃) δ 3.99 (s, 6) and broad signals in the range from δ 3.0 to 0.5 at room temperature; at –30° two sharp doublets were discernible at δ 1.52 and 0.54 in the approximate intensity ratio of 65:35, superimposed on a complex pattern; a value for Δ*G*[‡] was calculated at 55°, using formulas described in the literature.^{35,51}

Anal. Calcd for C₁₀H₁₂N₂O₄: C, 53.57; H, 5.39; N, 12.50. Found: C, 53.59; H, 5.28; N, 12.29.

7,7-Dimethyl-2,5-dicarbomethoxy-3,4-diazanocaradiene (10e) was prepared in 59% yield from **6** and 3,3-dimethylcyclopropene: mp 98–100°; ir (KBr) 1740, 1710 cm⁻¹; nmr (CDCl₃) δ 3.96 (s, 6), 2.88 (s, 2), at –20° two singlets of relative intensity 3 at δ 1.55 and 0.59, which coalesced at 66°.

(51) A. Jaeschke, H. Muensch, H. G. Schmid, H. Friebohn, and A. Mannschreck, *J. Mol. Spectrosc.*, **31**, 14 (1969).

Anal. Calcd for C₁₁H₁₄N₂O₄: C, 55.45; H, 5.92; N, 11.76. Found: C, 55.07; H, 5.85; N, 11.74.

1-Methyl-2,5-diphenyl-3,4-diazanocaradiene (9b). To a solution of 1-methylcyclopropene, generated from 4 g (0.1 mol) of sodium amide and 10.0 g (0.11 mol) of methallyl chloride, in 5 ml of chloroform was added **5**⁵² in 100-mg portions. After each addition the solution was shaken until the yellow color had disappeared; 3.0 g (12.7 mmol) of **5** could thus be brought to react. The solvent was removed under reduced pressure and the remaining oil crystallized from ethyl acetate–petroleum ether to yield 3.28 g (99%) of **9b**: mp 100–102°; nmr (CDCl₃) δ 8.2–7.3 (m, 10), 1.34 (s, 3), ABC pattern with δ_A 2.30, δ_B 1.94, δ_C 0.53.

Anal. Calcd for C₁₈H₁₈N₂: C, 83.04; H, 6.20; N, 10.76. Found: C, 83.33; H, 6.38; N, 10.57.

2-Carbomethoxy-6,7-diphenyl-4H-azepine (13a). A gaseous stream of cyclopropene was passed through a stirred suspension of 1.46 g (5.0 mmol) of **11a**^{28,53} in 20 ml of dry ether for 15 min, after which time a homogeneous solution resulted. The oil remaining after removal of the solvent yielded 1.40 g (92%) of **13a** upon crystallization from methanol: mp 75–79°; ir (KBr) 1715 cm⁻¹; nmr (CDCl₃) δ 8–7 (m, 10), 3.85 (s, 3), ABXY pattern at –26.7° (see Table I).

Anal. Calcd for C₂₀H₁₇NO₂: C, 79.18; H, 5.65; N, 4.62. Found: C, 79.29; H, 5.73; N, 4.71.

2,6,7-Tricarbomethoxy-4H-azepine (13b) was prepared in analogy to **13a** from **11b**²⁸ in 77% yield: mp 94–95°; ir (KBr) 1730, 1705, 1620, 1575 cm⁻¹; nmr (CDCl₃) δ 7.06 (t, 1), 6.55 (t, 1), 3.94 (s, 3), 3.85 (s, 3), 3.75 (s, 3), 2.57 (t, 2).

Anal. Calcd for C₁₂H₁₃NO₆: C, 53.93; H, 4.90; N, 5.24. Found: C, 53.82; H, 5.07; N, 5.25.

2-Carbomethoxy-7-phenyl-4H-azepine (13c) was prepared in analogy to **13a** from **11c**⁵⁴ in 82% yield: mp 61–62°; ir (KBr) 1710, 1620, 1595 cm⁻¹; nmr (CDCl₃) δ 8.2–7.3 (m, 5), 6.37 (dt, *J* = 0.7 and 7.1 Hz, 1), 6.35 (d, *J* = 9.9 Hz, 1), 6.05 (ddt, *J* = 0.7, 9.9, and 6.6 Hz, 1), 3.80 (s, 3), 2.33 (t, *J* = 6.9 Hz, 2).

Anal. Calcd for C₁₄H₁₃NO₂: C, 73.99; H, 5.77; N, 6.16. Found: C, 73.88; H, 5.72; N, 6.42.

(52) M. O. Abdel-Rahman, M. A. Kira, and M. N. Tolba, *Tetrahedron Lett.*, 3871 (1968); R. Huisgen, J. Sauer, and M. Seidel, *Justus Liebigs Ann. Chem.*, **654**, 146 (1962).

(53) P. Schmidt and J. Druey, *Helv. Chim. Acta*, **38**, 1562 (1955).

(54) A. Steigel and J. Sauer, *Tetrahedron Lett.*, 3357 (1970).

Activation Energy Requirements in Hydrogen Abstractions. Quantitative Description of the Causes in Terms of Bond Energies and Infrared Frequencies

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Abstract: The energy of the three-body system in the transition state for hydrogen abstraction reactions can be obtained by the combination of three Morse curves. The calculated energies of activation are accurate to better than 1 kcal/mol for Δ*H* < ±15 kcal/mol. Forty reactions of wide variety are treated successfully. Examples are given for the use of the method in assigning bond dissociation energies from energies of activation. The method describes the “polar effect” quantitatively. It is found that the energy of activation primarily serves to overcome anti-bonding between the terminal groups in the transition state. In addition to bond strengths, bond lengths and vibrational stretching frequencies are found to affect the energy of activation significantly.

The empirical Arrhenius expression (eq 1) has been found to provide a reasonably accurate description of the temperature dependence of rate

$$k = Ae^{-E_a/RT} \quad (1)$$

constants over wide temperature ranges. More theoretical approaches, such as collision models, transition-state theory, and thermodynamic and detailed quantum mechanical theory, lead to expressions of essentially the same form. The *a priori* calculation