On the Mechanism of Adamantane Rearrangements

Sir:

Lewis acid catalyzed isomerizations are highly successful methods for the preparation of adamantane, diamantane, and diamonoid molecules.[1,2] The number of possible reaction pathways is remarkably large; in no case has a mechanism been fully elucidated.

The difficulties involved are illustrated by the rearrangement of tricyclodecanes to adamantane. By assuming that only 1,2-alkyl shifts allow skeletal change and by excluding highly strained structures and primary cation intermediates, Whitlock and Siefken[3] constructed a rearrangement graph (Figure 1) showing the interrelationships between $C_{10}H_{16}$ isomers. At least 2897 pathways for the conversion of tetrahydrodicylcopentadiene (**2**) to adamantane (**1**) are possible.

Careful study has failed to reveal any $C_{10}H_{16}$ intermedites during the rearrangement of **2** to **1**.[1,4,4a] Other experimental approaches have only provided suggestive mechanistic information.[1,2a,3,4] Methyl groups have been used as labels, but such substituents may bias the reaction toward certain pathways.[2b,4] All tricyclodecane isomers studied to date (**3**,[5] **4**,[3] **5**,[6] and **6**[7] in Figure 1) have been found to rearrange to adamantane, but this merely reveals that more than one pathway may be followed.

We report here a general approach to the study of such complex processes. Molecular mechanics[8] provides a reasonably reliable method of calculating the

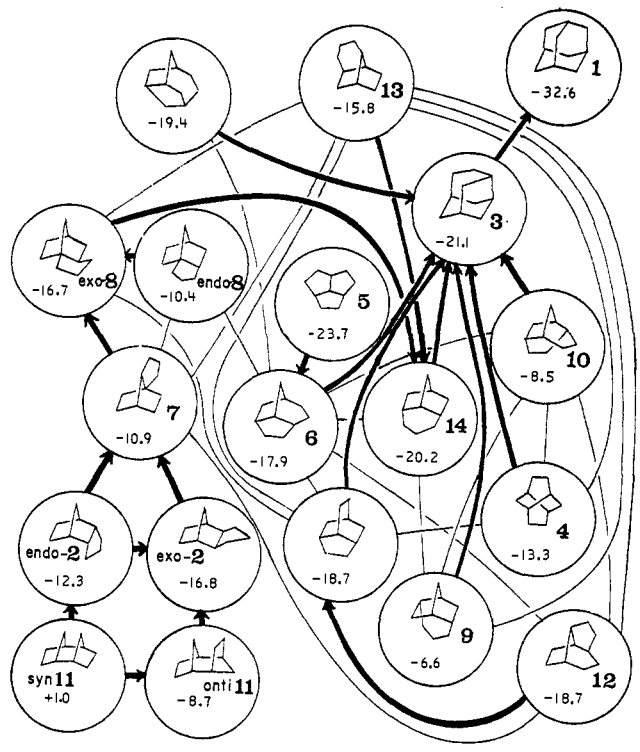
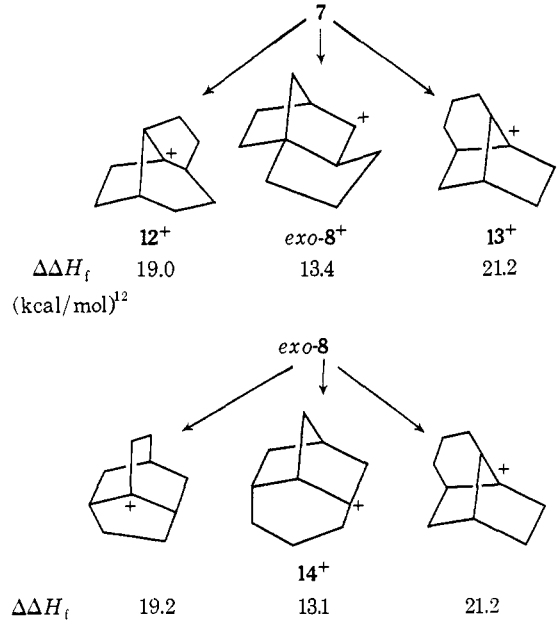


Figure 1. Tricyclodecane graph (based on ref 3).

stabilities of molecules.[9,10] The calculated heats of formation of the tricyclodecanes, listed under the structural formulas in Figure 1, indicate the relative stabilities of the various isomers. Even at this lowest level of approximation, considerable mechanistic insight is gained. The first step, **2** → **7**, is endothermic, but all subsequent steps leading to **1** can be exothermic. The formation of **7** may thus act as the rate determining step, and this suggests why intermediates are difficult to detect in the rearrangement of **2** to **1**. Other



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(4a) NOTE ADDED IN PROOF. By working with an active catalyst at 25°, Dr. M. A. McKervey has now succeeded in isolating an as yet unidentified intermediate (private communication).

(5) D. Lenoir and P. v. R. Schleyer, *Chem. Commun.*, 941 (1970).

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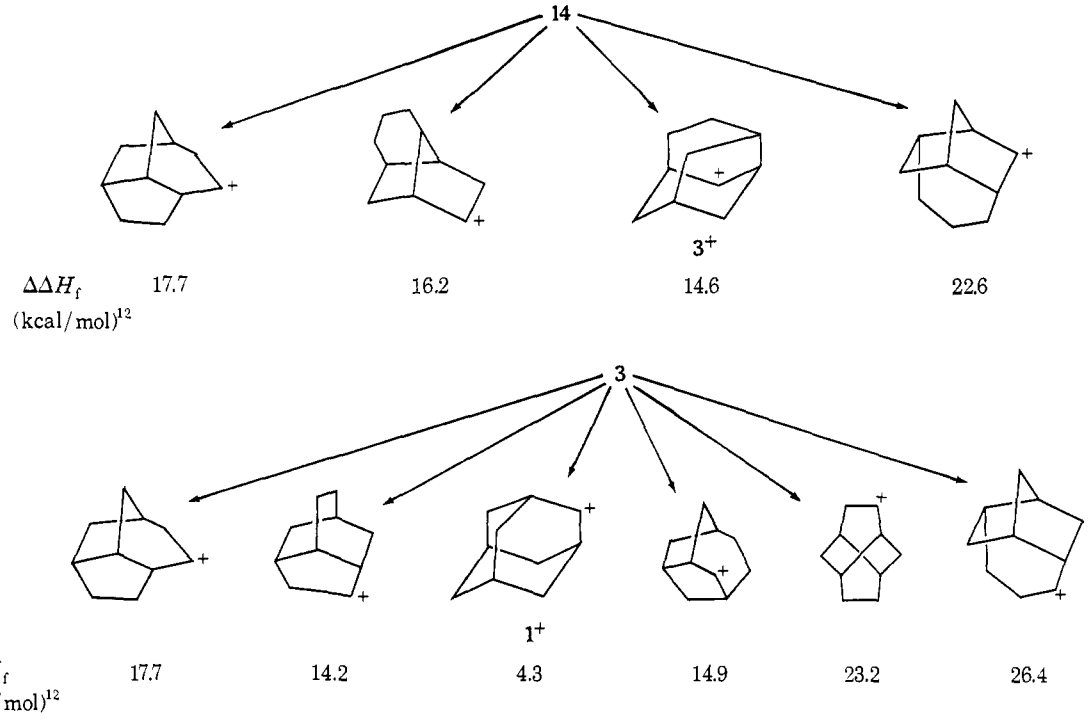
(8) Review: J. E. Williams, P. J. Stang, and P. v. R. Schleyer, *Annu. Rev. Phys. Chem.*, **19**, 531 (1968); N. L. Allinger, M. T. Tribble, M. A. Miller, and D. N. Wertz, *J. Amer. Chem. Soc.*, **93**, 1637 (1971).

(9) Calculations were carried out based on a force field described by E. M. Engler, J. D. Andose, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, in press (*cf.* ref 11g).

(10) E. M. Engler, Ph.D. Thesis, Princeton University, 1973.



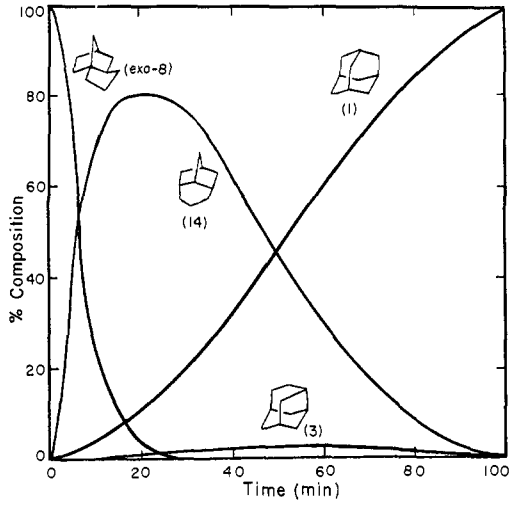


Figure 2. Aluminum bromide isomerization of *exo*-1,2-trimethylenenorbornane (*exo*-**8**) to adamantane (**1**).

high-energy structures, such as *endo*-**8**, **9**, **10**, and **11**, can be eliminated from the graph with confidence; **5** and **11** are mechanistic dead ends.

The presumed carbonium ion intermediates provide the highest level of approximation presently attainable, since no way has yet been devised for calculating the energies of transition states reliably for structures of this size. Although strain calculations have not been widely tested in secondary cations, such calculations have proven to give remarkably good estimates of tertiary reactivities.[11]

Figure 1 suggests that rearrangement from **7** might proceed favorably to give *exo*-**8**, **12**, or **13**. However, the calculated relative carbonium ion enthalpies[11,12] indicate that rearrangement *via* *exo*-**8**$^+$ is strongly favored; **12**$^+$ and **13**$^+$ possess strained bridgehead cations. Similarly, *exo*-**8** should give **14**$^+$ preferentially. Both at the hydrocarbon and at the carbocation level, the remaining steps should be **14** → **3** → **1**. The most favorable pathway from tetrahydrodicyclopentadiene (*endo*-**2**) to adamantane (**1**) on the basis of this analysis is **2** → **7** → *exo*-**8** → **14** → **3** → **1**. On the basis of suggestive experimental evidence, Whitlock and Siefken also chose this same pathway as appearing most favorable.[3,13]

We have tested this proposed route experimentally. To avoid the energetic "bottleneck," **7**, rearrangement of *exo*-**8**[14] was effected with 1:1 $AlBr_3$ in CS_2 at −10°. The conditions to produce **1** from *exo*-**8** are much milder than those necessary from **2**; *exo*-**8** gives **1** in minutes at 25°, while **2** requires refluxing for considerably longer times.[2a,4] Further, following the isomerization of *exo*-**8** by glc revealed the presence of two intermediates (Figure 2). The first of these was identified as tricyclo[5.2.1.$0^{2,6}$]decane

(11) (a) G. J. Gleicher and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **89**, 582 (1967); (b) P. v. R. Schleyer, P. R. Isele, and R. C. Bingham, *J. Org. Chem.*, **33**, 1239 (1968); (c) R. C. Bingham, W. F. Sliwinski, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **92**, 3471 (1970); (d) R. C. Bingham and P. v. R. Schleyer, *ibid.*, **93**, 3189 (1971); (e) R. C. Bingham and P. v. R. Schleyer, *Tetrahedron Lett.*, 27 (1971); (f) A. Karim, M. A. McKervey, E. M. Engler, and P. v. R. Schleyer, *ibid.*, 3987 (1971); (g) J. L. Fry, E. M. Engler, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **94**, 4628 (1972).

(12) Calculated carbonium ion energies reported here are relative to *tert*-butyl cation ($\Delta H_f°$ (calcd) = 170.4 kcal/mol) and were corrected for degree of chain branching (each β branch: 3 kcal/mol for secondary cations and 1.5 for tertiary) and for the greater electronic stability of tertiary over secondary (12 kcal/mol), and for bridging in 2-norbornyl cations (5 kcal/mol). The values of the corrections chosen were based on thermodynamic and kinetic data on cations; *cf.* D. M. Brouwer and H. Hogeveen, *Progr. Phys. Org. Chem.*, **9**, 179 (1972); F. P. Lossing and G. P. Semeluk, *Can. J. Chem.*, **48**, 955 (1970); J. L. Franklin, J. G. Dillard, H. M. Rosenstock, J. T. Herron, K. Draxl, and F. H. Field, "Ionization Potentials, Appearance Potentials, and Heats of Formation of Gaseous Positive Ions," U. S. Department of Commerce, NSRDS-NBS-26 (1969); H. Hogeveen, *Progr. Phys. Org. Chem.*, in press.

(13) Besides this 1,2-alkyl shift mechanism, a 1,3 shift of **2** to **9** followed by 1,2 shifts, **9** → **3** → **1** (ref 2a), and a 1,4 shift of **2** to **14** (ref 4) have been proposed. Such 1,3- and 1,4-carbon shifts are unlikely.

(14) Prepared by hydrogenation of 4,5-*exo*-trimethylene-2-norbornene; *cf.* E. J. Corey and R. S. Glass, *J. Amer. Chem. Soc.*, **89**, 2600 (1967).

(**14**);[15] protoadamantane (**3**)[5,16] was the second. From the relative proportions of isomers in the rearrangement of *exo*-**8**, it is possible to derive relative rate constants for each step.[17] On the basis of three separate isomerizations, rate constants relative to **3** → **1** are 0.6 for *exo*-**8** → **14** and 0.05 for **14** → **3**.

These results are consistent with the proposed pathway deduced on the basis of the molecular mechanics calculations. The darkened lines and arrows in Figure 1 represent our predictions of the most favorable pathways leading from each tricyclodecane to adamantane (**1**). We are testing these predictions experimentally in conjunction with ^{13}C labeling techniques and are employing this approach for the elucidation of other polycyclic rearrangement mechanisms.

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(15) Prepared from 2,6-trimethylenenorbornan-2-ol (ref 14) by treatment with PBr_3, followed by reduction with $LiAlH_4$ (*m/e* 136).
(16) R. M. Black and G. B. Gill, *Chem. Commun.*, 972 (1970); W. H. W. Lunn, *J. Chem. Soc. C*, 2124 (1970).
(17) K. B. Wiberg, "Physical Organic Chemistry," Wiley, New York, N. Y., 1964, pp 321–326.
(18) C.N.R.S. Postdoctoral Fellow.

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Reactions of Vinyl Ethers with Cobalamins and Cobaloximes

Sir:

Vinyl ethers were recently claimed[1] to react with Co(III) derivatives of vitamin B_{12}, *i.e.*, hydroxocobalamin, and with cobaloximes such as bromo(pyridine)cobaloxime, to yield organocobalt compounds according to eq 1. Reaction eq 1 was assumed to

$$[Co^{III}] + CH_2{=}CHOR \longrightarrow \underset{\mathbf{1}}{[Co](CH_2{=}CHOR)} \xrightarrow{OR^-} \underset{\mathbf{2}}{[Co]CH_2CH(OR)_2} \quad (1)$$

proceed *via* a π complex, **1**, of the vinyl ether with the Co(III) starting materials, whose subsequent reaction with alkoxide ion was proposed to yield acetals of the corresponding formylmethylcobalt complexes **2**. A reaction of the type written in eq 1 would represent an intriguing new pathway for the synthesis of organocobalt compounds in protic media, and parallels were drawn to certain coenzyme B_{12} dependent enzymatic reactions, *i.e.*, dioldehydrase. Unfortunately, all our attempts to reproduce reaction **1** have been unsuccessful. We also failed to detect the formation of π complexes of the Co(III) complexes with vinyl ethers (R = *e.g.*, C_2H_5, eq 1). Although complexes of this type have been postulated as reactive intermediates in the solvolysis of 2-acetoxyethylcobaloximes,[2] their direct formation according to eq 1 could not be demonstrated neither by us nor by Dolphin and Silverman, using various spectroscopic and synthetic techniques. The existence of π complexes such as **1** would seem doubtful in view of the inability of the Co(III) ion to form sufficiently stable d_π–p_π bonds with organic π-electron systems. The $CH_2{=}CH$ moiety in vinyl ethers could also not be regarded as sufficiently strongly σ bonding to coordinate with the Co(III) ion in corrins or cobaloximes. Although the reaction of hydroxocobalamin with 2-hydroxyethyl vinyl ether or ethyl vinyl ether was claimed to produce mixtures of formylmethylcobalamin with the corresponding acetals of formylmethylcobalamin quantitatively,[3,4] this could not be reproduced under a variety of conditions. Upon addition of ethoxide ion or of NaOH, to a mixture of these vinyl ethers and hydroxocobalamin in ethanol or ethanol–water, only a slow formation of a Co(II)–corrin was observed which also occurred in the absence of vinyl ethers. The formation of reduced corrins from hydroxocobalamin in alkali is well known.[5] We also failed to obtain the corresponding organocobaloxime derivative by allowing bromo(pyridine)cobaloxime to react with ethyl vinyl ether in the presence of ethanol, CH_2Cl_2, and varying amounts of triethylamine; the only product isolated was pyridinecobaloxime(II).[6,7] These results demonstrate that the Co(III) starting materials cannot even be maintained in this oxidation state under the reaction conditions.

In subsequent experiments we also examined the reaction of vinyl ethers with vitamin B_{12r}, vitamin B_{12s}, and with hydridocobalamin.[8] Only the latter, generated from hydroxocobalamin by reduction with Zn in glacial acetic acid, underwent reaction, however, affording a mixture of ethylene and ethane. Initially,

(1) R. B. Silverman and D. Dolphin, *J. Amer. Chem. Soc.*, **95**, 1686 (1973).
(2) (a) B. T. Golding, H. L. Holland, U. Horn, and S. Sakrikar, *Angew. Chem., Int. Ed. Engl.*, **9**, 959 (1970); (b) R. B. Silverman, D. Dolphin, and B. M. Babior, *J. Amer. Chem. Soc.*, **94**, 4028 (1972).
(3) Formylmethylcobalamin, the corresponding cobaloximes, and their acetals were synthesized by the authors of ref 1, as well as by us,[4] utilizing conventional reductive alkylation techniques. The reported properties of the cobalamin derivatives are in slight disagreement, however. Silverman and Dolphin claim that the acetals of formylmethylcobalamin undergo simple hydrolysis to yield formylmethylcobalamin on protonation. In contrast, we observed that the acetals decompose on protonation with Co–C bond cleavage. We found no evidence for the intermediate formation of formylmethylcobalamin, which, if formed, should have been readily detectable in view of its stability in neutral and weakly acidic aqueous media.
(4) G. N. Schrauzer, W. J. Michaely, and R. J. Holland, *J. Amer. Chem. Soc.*, **95**, 2024 (1973).
(5) (a) R. Bonnett, J. R. Cannon, A. W. Johnson, and A. R. Todd, *J. Chem. Soc.*, 1158 (1957); (b) J. M. Pratt, *ibid.*, 5154 (1964); (c) R. H. Yamada, T. Kato, S. Shimizu, and S. Fukui, *Biochim. Biophys. Acta*, **117**, 13 (1966).
(6) The reducing agent in this system is apparently generated from secondary reactions between triethylamine, ethanol, and CH_2Cl_2. The reactions in this system are very complicated, and evidence for the intermediate appearance of the cobaloxime(I) nucleophile has been obtained. The latter may in turn react with the CH_2Cl_2 present to yield chloromethyl(pyridine)cobaloxime, which is known to be unstable under basic conditions.
(7) G. N. Schrauzer, A. Ribeiro, L. P. Lee, and R. K. Y. Ho, *Angew. Chem., Int. Ed. Engl.*, **10**, 807 (1971).
(8) G. N. Schrauzer and R. J. Holland, *J. Amer. Chem. Soc.*, **93**, 4060 (1971).