J. Org. Chem. **1986**, *51*, 3169–3176 **3169**

Hz, 1 H), 3.83–3.72 (m, 3 H), 2.44 (s, 6 H), 2.08–1.83 (m, 10 H), 1.68 (s, 3 H), 1.58 (s, 6 H), 1.33 (s, 3 H), 1.17 (s, 3 H); IR 2920, 1735, 1655, 1595, 1495, 1440, 1380, 1305, 1240, 1140, 1090, 1045, 900, 820, 750, 665 cm^{-1}. Anal. Calcd for $C_{34}H_{46}O_4S_2$: C, 70.06; H, 7.95. Found: C, 69.17; H, 7.92.

B. With Lithium Iodide and Sodium Cyanide. A solution of **4a** (211 mg, 0.33 mmol), lithium iodide trihydrate (580 mg), and sodium cyanide (32 mg) in 5 mL of DMF was stirred at 120 °C for 20 h, after which no starting material could be observed by TLC. The solution was worked up as described above, and purification afforded **4b** (101 mg, 0.19 mmol, 58% yield).

C. With Tetramethylammonium Acetate. A solution of **4a** (211 mg, 0.33 mmol) and tetramethylammonium acetate (386 mg) in 3 mL of HMPA was stirred at 95 °C for 7 h. The mixture was worked up as described above, affording 91 mg of **4b** (0.17 mmol, 47% yield).

Demethoxycarbonylation of 9,17-Dicarbomethoxy-3,7,11,15,19,23-hexamethyl-1,9,17-tris(*p*-tolylsulfonyl)-2,6,10,14,18,22-tetracosahexaene (4c). A solution of **4c**[12] (122 mg, 0.12 mmol), PATP (45 mg, 0.4 mmol), and cesium carbonate (50 mg) in 3 mL of DMF was stirred at 85 °C for 5 h. The mixture was poured into water (20 mL) and extracted with ether (3 × 10 mL). The combined extracts were washed twice with 1 M HCl (5 mL), water, and brine and dried over $MgSO_4$. The solvent was removed under reduced pressure to yield 95 mg of pale yellow oil, which was found (by TLC and NMR) to be pure **4d** (0.11 mmol, 92% yield): NMR 7.83–7.63 (m, 6 H), 7.40–7.23 (m, 6 H), 5.25–4.82 (m, 6 H), 3.95–3.72 (m, 4 H), 2.44 (s, 3 H), 2.43 (s, 6 H), 2.07–1.77 (m, 16 H), 1.68 (s, 3 H), 1.58 (s, 6 H), 1.50 (s, 6 H), 1.33 (s, 3 H), 1.20 (s, 3 H); IR 2920, 1660, 1595, 1495, 1440, 1380, 1305, 1240, 1180, 1140, 1090, 1025, 910, 820, 735, 670 cm^{-1}. Anal. Calcd for $C_{51}H_{68}O_6S_3$: C, 70.15; H, 7.85. Found: C, 68.78; H, 7.85.

Acknowledgment. We thank the Schmidt Foundation for Applied Research for their generous financial support.

Registry No. **3a**, 102779-87-3; **3b**, 102745-41-5; **4a**, 102779-88-4; **4b**, 68690-58-4; **4c**, 102745-40-4; **4d**, 66958-23-4; Cs_2CO_3, 534-17-8; 4-aminothiophenol, 1193-02-8; ubiquinone-10, 303-98-0; methyl 2-benzyl-3-oxobutanoate, 3666-82-8; dimethyl dibenzylpropanedioate, 3666-83-9; ethyl 2-benzyl-3-oxobutanoate, 620-79-1; methyl α-cyanobenzenepropanoate, 57519-78-5; ethyl α-cyanobenzenepropanoate, 6731-58-4; methyl α-tosylbenzenepropanoate, 94143-11-0; dimethyl benzylpropanedioate, 49769-78-0; 4-phenyl-2-butanone, 2550-26-7; 3-benzyl-4-phenyl-2-butanone, 3506-88-5; benzenepropanenitrile, 645-59-0; phenethyl *p*-tolyl sulfone, 19719-87-0; 3-phenylpropanoic acid, 501-52-0; methyl 3-phenylpropanoate, 103-25-3.

Electron Transfer in the Decomposition of Hexaalkylhydrazine Dications

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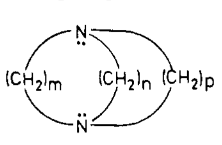
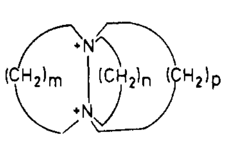
Received April 22, 1986

Rearrangements of hexaalkylhydrazine dications [$R_3N^+N^+R_3$] to α-amino ammonium cations [$R_3N^+CHR'NR_2$] derived by Hofmann-like degradation (loss of an α proton and NN bond cleavage to give an amino immonium cation, followed by addition of the amino group to the $C{=}N^+$ bond) are investigated. Tricyclic dications $\mathbf{6}^{2+}$ and $\mathbf{10}^{2+}$ give $\mathbf{14}^+$ and $\mathbf{8}^+$, respectively, showing high selectivity for hydrogen loss from the methylenes in the bicyclo[2.2.2]octyl rings which can have CH bonds aligned with the NN bond over the three other types of methylene groups as well as the methyl group. Selectivity for hydrogen loss from the methyl and methylene carbons of the bicyclic dication $\mathbf{3}^{2+}$ proves to be sensitive to the reaction conditions. $NC\mathit{H}_3/NC\mathit{H}_2$ attack ratios from 4 to 10 were observed for carbonate and chloride in acetonitrile (chloride in water failed to react), but a ratio of about 1 was observed for iodide in both acetonitrile and water. It is argued that iodide decomposes the dications by an electron-transfer mechanism in which the key step is hydrogen atom abstraction from the 3e-σ-bonded cation radical. This is consistent with the observed even higher selectivity to HC,NN bond alignment than occurs for base attack on the dication.

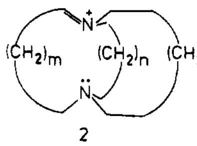
Alder and co-workers have intensively studied the chemistry of medium-ring tricyclic diamines **1**[*mnp*], which they have shown to have very unusual electron- and proton-transfer properties.[1] Most notably for this work, **1**[333] and **1**[444] are oxidized to cation radicals having three electron σ bonds and to tetracyclic diazoniapropellane dications $\mathbf{1}^{2+}$. Their first route to these compounds grew out of work on alkylation of 1,8-diaminonaphthalene with 1,3-dibromopropane[2] and involved bicyclo-bis-alkylation of bicyclic hydrazines to bridgehead diazoniapropellanes $\mathbf{1}^{2+}$, which were reduced to the diamines. This route has been used to prepare **1**[332], **1**[333], **1**[433], **1**[433], and **1**[444].[3-5] Other members of the **1**[*mnp*] series have been prepared by reduction of α-amino ammonium ions generated from bicyclic amidines and α,ω-dihaloalkanes (used for **1**[433], **1**[432], and **1**[633])[6] and by reaction of ω-chloroalkanals with cyclic medium-ring diamines (11 examples).[7] Not surprisingly, $\mathbf{1}^{2+}$ is sensitive



1[mnp]



1^{2+}



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(1) For a review, see: Alder, R. W.; Sessions, R. B. *Chemistry of Amino, Nitroso, and Nitro Compounds and their Derivatives*, Shvo, Y., Ed.; J. Wiley and Sons: New York, 1982; Part 2, Chapter 18, pp 782–804.

(2) (a) Alder, R. W.; Goode, N. C.; King, T. J.; Mellor, J. M.; Miller, D. W. *J. Chem. Soc., Chem. Commun.* **1976**, 173. (b) Alder, R. W.; Gill, R.; Goode, N. C. *Ibid.* **1976**, 973.

(3) Alder, R. W.; Sessions, R. B.; Mellor, J. M.; Rawlins, M. F. *J. Chem. Soc., Chem. Commun.* **1977**, 747.

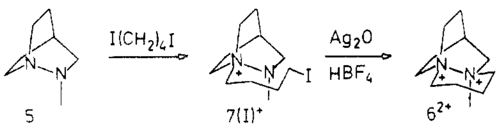
(4) Alder, R. W.; Sessions, R. B. *J. Am. Chem. Soc.* **1979**, *101*, 3651.

(5) Alder, R. W.; Sessions, R. B.; Bennett, A. J.; Moss, R. E. *J. Chem. Soc., Perkin Trans. 1* **1982**, 603.

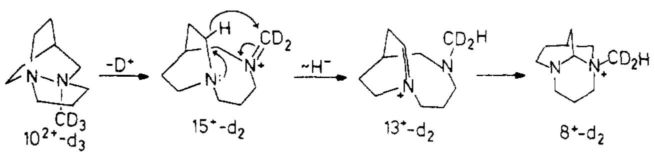
(6) Alder, R. W.; Sessions, R. B. *Tetrahedron Lett.* **1982**, *23*, 121.

0022-3263/86/1951-3169$01.50/0

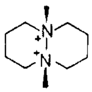
Scheme I



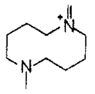
Scheme II



to base, undergoing a special case of Hofmann fragmentation. Deprotonation occurs α to nitrogen with NN bond cleavage generating **2** as an undetected intermediate, which can close by internal trapping to a tetracyclic α-amino ammonium salt[4] or be trapped by external nucleophiles.[8] Alder, Grob, and co-workers have contrasted the behavior of several examples of 1^{2+} with that of *cis*-dimethyldiazadecalin 3^{2+}.[8] While unsymmetrical examples of 1^{2+} gave products arising from loss of a proton at more than one α-carbon, all of the products observed from 3^{2+} were derived from immonium ion 4^+, which is formed by deprotonation of the methyl group.



3^{2+}

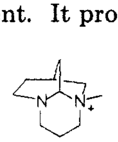


4^+

We recently reported using Alder's successive bis-alkylation conditions to convert 2-methyl-1,2-diazabicyclo[2.2.2]octane (**5**) to dication 6^{2+} according to Scheme I[9] and its reductive NN cleavage to neutral **6**. This paper describes the preparation of the lower homologue of 6^{2+}, which has a trimethylene bridge between N_1 and N_2 of **5**, and the rearrangement chemistry of these dications. These rearrangements proved to be more complicated than we expected and led us to carry out a reinvestigation of the behavior of 3^{2+}.

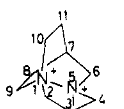
Results: Rearrangement of 6^{2+} and 10^{2+} to α-Amino Ammonium Salts

Diiodobutane is unconveniently reactive for the preparation[9] of $7(X)^+$, and we report the details of a preparation substituting dibromobutane, which gives cleaner 6^{2+}, in the experimental Section. Alder and co-workers have pointed out that five-membered ring closure is enough faster than six-membered ring closure to make attempted monoalkylations of hydrazines with dihalopropanes fail and instead give bis-alkylation to dications under conditions where the dications decompose. This proves to be the case for alkylation of **5** with 1,3-diiodopropane. Under the same conditions that gave $7(I)^+$ with 1,4-diiodobutane, no analogous monoalkylated material was produced upon treatment of **5** with 1,3-diiodopropane. Instead, the reaction mixture turns red, and the major product is a salt which shows a single proton as a doublet at δ 5.25 in its NMR spectrum and thus appeared to be an α-amino ammonium salt.[4,6-8] Analysis of its 500-MHz ^1H NMR spectrum with the aid of extensive decoupling experiments showed this material to have an ammonium methyl group and $(CH_2)_3$ and $CH_2CH_2CH(CH_2CH)CH_2$ fragments to be present. It proved to be 8^+ based on spectral data and chemical transformation, as described below. Authentic monoalkylated **5** was obtained by the method of Alder and co-workers,[5] employing 3-bromopropanol to produce $9(OH)^+$, which was closed in fluoroboric acid to dication salt $10^{2+}(BF_4^-)_2$. Reduction of 8^+I^- with LAH or sodium in liquid ammonia gave the same product as reduction of $10^{2+}(BF_4^-)_2$ with sodium in liquid ammonia. This product proved to be 5-methyl-1,5-diazabicyclo[5.2.2]undecane **11**, constituting a chemical proof of the carbon connectivity of 8^+. When the reaction of **5** with 1,3-diiodopropane was followed by NMR, we did observe formation of $9(I)^+$, accompanied by what appears to be a small amount of its N_2 alkylated isomer 12^+, but no other compounds were observed except $5H^+$ and 8^+. We presume from the structure of 8^+ that its immediate precursor is immonium cation 13^+, and it seems reasonable that this cation closes to 8^+ too rapidly for it to build up to a concentration detectable by NMR under our conditions. We hypothesized at the time that $9(I)^+$ closed to 10^{2+}, which did not build up because it is deprotonated under the reaction conditions too rapidly. We isolated 8^+I^- in 47% yield based upon **5**, as well as some protonated **5**, which is surprisingly efficient considering that **5** and its alkylated forms are the only bases available for deprotonation under the conditions employed. Authentic $10^{2+}(BF_4^-)_2$ is observed to slowly but very cleanly rearrange to $8^+BF_4^-$ upon standing in acetonitrile (presumably containing adventitious base), and the reaction is more rapid upon addition of amine bases or potassium carbonate. The same rearrangement occurs with $6^{2+}(BF_4^-)_2$, for 14^+ is produced in high yield upon treatment with potassium carbonate in acetonitrile.

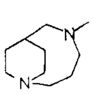


8^+

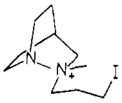
$9(X)^+$



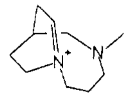
10^{2+}



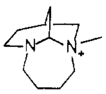
11



12^+



13^+



14^+

Results and Discussion: Methyl vs. Methylene Deprotonation

We were surprised to see efficient rearrangement of 10^{2+} to 8^+ and 6^{2+} to 14^+ because 3^{2+} gave only products derived from methyl proton loss upon treatment with base.[8] As Alder and co-workers pointed out, a preference for Hofmann orientation can hardly be considered surprising, and it seemed entirely possible[10] that intramolecular hydride transfer as shown in Scheme II might be the reason for seeing only products derived from apparent methylene proton loss. The bicyclic structure appears to hold 15^+ in good position for internal hydride transfer to give 13^+, in contrast to the monocyclic analogue 4^+, the immonium salt produced from 3^{2+}, for which no products from methylene hydrogen loss were reported. Adequate precident for such an intramolecular hydride transfer does appear to exist.[11-13]

However, the deuterium-labeling experiment shown in Scheme II demonstrated that hydride transfer does not

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[7] Alder, R. W.; Eastment, P.; Moss, R. E.; Sessions, R. B.; Stringfellow, M. A. *Tetrahedron Lett.* **1982**, *23*, 4184.

[8] Alder, R. W.; Sessions, R. B.; Gmunder, J. O, Grob, C. A. *J. Chem. Soc., Perkin Trans. 1* **1984**, 411.

[9] Nelsen, S. F.; Gannett, P. M. *J. Am. Chem. Soc.* **1982**, *104*, 4700.

[10] Prof. Dr. E. Winterfeld first made this suggestion to us.

[11] (a) Deno, N. C.; Peterson, H. J.; Saines, G. S. *Chem. Rev.* **1960**, *60*, 7. (b) Prelog, V.% Tranham, J. G. *Molecular Rearrangements*; deMayo, P., Ed., Interscience Pub.: New York, 1963; p 593.

[12] Chin-You, N.; MacLean, D. B.; Prakash, A.; Calvo, C., *Can. J. Chem.* **1971**, *49*, 3240.

[13] ten Broeke, J.; Douglas, A. W.; Grabowski, E. J. J. *J. Org. Chem.* **1976**, *41*, 3159.

occur. Hydride transfer would introduce protium at the methyl group to give 8^+-d_2. We were able to detect no incorporation of protium at the methyl group of the 8^+ formed by ^{1}H-, ^{2}H-, or ^{1}H-decoupled ^{13}C NMR. We conclude that the hydride transfer of Scheme II is not significant under these conditions and hence that there really is a significant selectivity for loss of a proton from C_9 and/or C_{10} in preference to both the methyl group and the three other α-methylene carbons (C_2, C_4, C_6). The antiperiplanar arrangement of hydrogens on C_9 and C_{10} with the N^+-N^+ bond seems likely to be involved in the activation of these positions, although it seemed strange that the NCH_2/NCH_3 selectivity for 10^{2+} and 6^{2+} were so much higher than that for 3^{2+}.

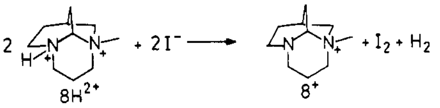
Results and Discussion: Reactions of $R_6N_2^{2+}$ with Iodide

Our first realization that the rearrangements of 10^{2+} and 6^{2+} to α-amino ammonium salts were not necessarily simple base-catalyzed processes came when we tried to exchange the BF_4^- counterion for I^- to check the chemical shifts observed when **5** was treated with 1,3-diiodopropane. We found that KI in D_2O also catalyzes the rearrangements of both dications. These reactions are not fast, requiring about a day for completion at room temperature. The initial products appear from their proton NMR spectra to be the HI salts of the α-amino ammonium cation iodides, which were converted by potassium carbonate to the iodides, which were isolated and characterized. The reaction mixtures of the iodide-catalyzed rearrangements turn brown, presumably because some I_2/I_3^- is formed, but ^{1}H NMR spectra of the crude reaction mixtures indicate very clean conversion of the dications to the α-amino ammonium cations. The rearrangements proved not to require a full equivalent of iodide to go to completion, although they are quite slow with less iodide. Treatment of $10^{2+}(BF_4^-)_2$ in D_2O with 0.2 mol of KI per mol of 10^{2+} showed 50% conversion to protonated 8^+ after 2.5 days and 90% after 8 days, and no starting material was detected after 17 days.

Because iodide in water is an extremely feeble base, we suspected that the most likely mechanism for the iodide-catalyzed rearrangement involved initial electron transfer. Cyclic voltammetry shows that the hexaalkylhydrazine dications are easily reduced, but only very distended, irreversible, and electrode-dependent waves were observed, precluding obtaining accurate thermodynamic information on the reductions. At room temperature in acetonitrile which is 0.1 M in tetra-*n*-butylammonium perchlorate, 0.2 V/s scan rate at platinum, we saw reduction current passed negative of about 0 V vs. SCE and peak potentials at −0.1 and −1.5 V for 10^{2+}. Under these conditions 6^{2+} passes reduction current negative of +0.1 and −1.5 V.[9]

Evidence for formation of 3e-σ-bonded cation radicals upon reduction of the tricyclic dications was obtained by working at the faster timescale of pulse radiolysis, using reduction by solvated electrons in water containing 0.1 M *tert*-butyl alcohol (to scavange the hydroxyl radicals produced by the pulse of radiation). We observed the very broad visible absorption expected for the 3e-σ-bonded cation radicals, λ_{max} 490 ± 10 nm for 10^+, 500 ± 10 nm for 6^+, to be compared with the 470 nm observed for 3^+.[14] Disappointingly, but in agreement with the electrochemistry, the extra two-carbon bridge connecting the nitrogens of 10^+ and 6^+ compared to 3^+ does not lead to a significantly longer lifetime for these species.

Scheme III



Treatment of 10^{2+} with *n*-Bu_4NI in CD_3CN leads to far more rapid reaction than in water and a white precipitate immediately forms. We identify this precipitate as protonated 8^+, $8H^{2+}$, on the basis of its IR spectrum and because stirring with carbonate produces 8^+. Interestingly, this white solid is unstable in acetonitrile, darkening and producing the NMR spectrum of unprotonated 8^+ upon standing. We can only presume that iodide is reducing hydrogen from $8H^{2+}$, as shown in Scheme III.

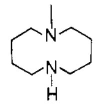
Although it is certainly less clear that electron transfer would have to be involved in rearranging 10^{2+} to $8H^{2+}$ in acetonitrile, where iodide is a significantly stronger base than in water, where it is a very weak base, we point out that the electron transfer is also expected to be significantly faster in acetonitrile than in water, so that the rearrangement being much faster is consistent with either proton or electron transfer.

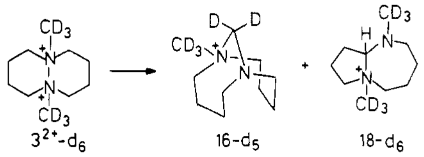
Results and Discussion: Reinvestigation of 3^{2+} Decompositions

Having shown that 10^{2+} does not undergo detectable methyl group deprotonation under our conditions, we turned to the puzzling question of why 3^{2+} shows such different selectivity. Alder and co-workers[8] reported that treatment of the difluoroborate with K_2CO_3/D_2O gave an 80:20 mixture of **16** (internal trapping of 4^+):**17** (from hydrolysis of 4^+) as analyzed by ^{13}C NMR, without observation of other products. The ratio of **16**:**17** was reported to be pH-dependent, but once formed, **15** did not convert to **16** upon standing in solution for 2 weeks, suggesting that hydroxide trapped 4^+ to ultimately give **17**. In agreement with the result of Alder and co-workers, stirring $3^{2+}(BF_4^-)_2$ with 1 molar equiv of Na_2CO_3 in D_2O for 4 days gave a solution showing ^{1}H NMR signals for **16** and a minor product we presume to be **17** and no signals attributable to products from α-methylene deprotonation.

We discovered that the situation is more complicated than this during experiments with 3^{2+}-d_6. When 1 molar equiv of K_2CO_3 is added to 3^{2+}-d_6 in D_2O, a precipitate of


16


17



KBF_4 forms immediately. If this flocculant material is centrifuged to the bottom of the tube and the NMR spectrum run within 10 min, a triplet at δ 5.02 is observed, which we assign to that on the bridgehead carbon of **18**-d_6, derived from methylene group deprotonation. This product is present in significant amount, although it is somewhat difficult to quantitate. All the other $C_\alpha H$ signals of both **16**-d_6 and **18**-d_5 come between δ 2.7 and 3.3 (8 H and 6 H, respectively), and integration of the single H at δ 5.02 relative to this region gave a **16**-d_5:**18**-d_6 ratio of about 2:1. Examination of the same sample after 3 days showed essentially no signal at δ 5.02, and it appeared to

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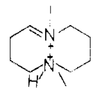
[14] Nelsen, S. F.; Alder, R. W.; Sessions, R. B.; Asmus, K.-D.; Hiller, K.-O.; Gobl, M. *J. Am. Chem. Soc.* **1980**, *102*, 1429.

be rather cleanly **16**-d_5. We conclude that **18** hydrolyzes slowly, to products which do not have signals which are obvious in the presence of **16**; more than one product may well be formed.

Returning to the undeuterated system, **18** is definitely initially detectable by ^1H NMR, although it is only present in small amount and hydrolyzes as the solutions stand. The amounts of material formed were quantitated by integration of the **16** CH_2 bridge singlet and the **18** bridgehead H triplet relative to methanol contained in a capillary tube inserted into the sample tube and integrated relative to starting material before carbonate was added. After 10 min, about 10–14% $\mathbf{3}^{2+}$ remained, and overlap of its peaks with the isolated signals of **16** precluded accurate integrations, but **18** could be quantitated, and about 10% was present. After 45 min, under 5% $\mathbf{3}^{2+}$ remained, and 84% **16** and 8% **18** were detected by integration, while after 24 h, the amount of **16** was 77% and no **18** could be detected. Although methylene hydrogen loss is slower than methyl hydrogen loss from $\mathbf{3}^{2+}$, the difference in their reactivity is small enough that incorporating a primary deuterium isotope effect slowing methyl hydrogen loss causes about one-third of the product to arise by methylene hydrogen loss.

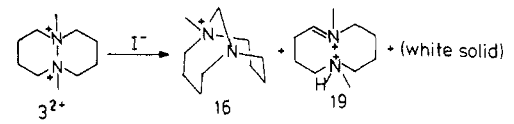
Because hydrolysis of **18** to undetected products is clearly causing the **16**:**18** ratio to increase with time and not accurately reflect the ratio of NCH_3:NCH_2 attack, we also examined the reaction of $\mathbf{3}^{2+}$ with K_2CO_3 in CD_3CN, hoping to slow down the hydrolysis. We found the time for completion of the reaction with K_2CO_3 in CD_3CN to be rather unreproducable, presumably caused by variable amounts of water in the acetonitrile, and the reaction was rather slow, probably because of the low solubility of the carbonate. Protonated immonium salt **19** was observed to build up when the the solutions were not stirred, indicating that the NCH_2 deprotonation product is decomposing the dication competatively with its closure to **18**. In a quantitated run using K_2CO_3 in acetonitrile without stirring, and taking special precautions to preclude water, the ratio of NCH_3/NCH_2 products (**16**/**18**) after dication had disappeared was ~4/1, and a methanol capillary tube internal standard showed 96% of the starting material accounted for. After several days of standing, the **16**/**18** ratio was observed to increase to ~6/1, and internal standards (methanol capillary and *p*-dibromobenzene added to the sample) showed only 80% of the starting material accounted for. We believe that traces of water had hydrolyzed **18** to undetected products.



19

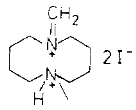
The ratios of NCH_3/NCH_2 deprotonation using K_2CO_3 as the base added are obviously different in water (about 10/1) and in acetonitrile (4/1). Part of the reason may be that we cannot measure the amount of **18** formed in water accurately because it hydrolyzes too rapidly, but the bases reacting with the dication may well be different in the two solvents as well because of the difference in carbonate solubility. Our results show that the difference between NCH_3 and NCH_2 reactivity of $\mathbf{3}^{2+}$ is not as great as previously thought, which makes the considerably lower ratios observed for the tricyclic dication less surprising. The tricyclic compounds have more hindrance to attack at their methyl groups, which should lower the ratio.

Scheme IV

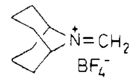


Reaction of $\mathbf{3}^{2+}$ with iodide in CD_3CN gives attack ratio considerably different than those reported above in reactions with carbonate. When a 0.04 M solution of $\mathbf{3}^{2+}(BF_4^-)_2$ in CD_3CN is treated with 1 molar equiv of a 0.4 M solution of n-Bu_4NI in CD_3CN, the solution immediately turns yellow and a flocculant white precipitate forms throughout the solution. This white precipitate dissolves over a period of hours, as the solution darkens to a deep red. The NMR spectrum of this red solution shows **16** and a compound we identify as protonated immonium salt **19** (see Scheme IV). It exhibits *N*-methyl signals at δ 3.68 (=NRMe) and 2.75 (R_2N^+HMe, d, J = 5 Hz), an immonium vinyl H at 8.37 (J = 7.9 Hz) coupled to a 2 H multiplet at 2.4 (=C-HCH_2), and single hydrogen multiplets at 4.20 and 3.95 (=NCH_2); the corresponding spectrum from $\mathbf{3}^{2+}$-d_6 lacked the *N*-methyl signals and showed noticably sharper lines for the δ 8.37 triplet. The ratio of **16**/**19** is ~1, and integration relative to the n-Bu_4N^+ signals showed that the yields were high, about 50% each. Stirring solutions containing **19** with potassium carbonate leads to several products, including **18**; we presume that the complex products arise from hydrolysis of enamines derived from **19**.

If the white solid initially produced is centrifuged to the bottom of the NMR tube and the spectrum run before it dissolves and the solution turns red, the ratio of **16**:**19** is significantly smaller, about 1:1.2, indicating that this solid is a precursor to **16**. Its insolubility prevented our obtaining an NMR spectrum, but the IR spectrum of this material (KBr disk) showed a strong, broad N^+–H stretch at 2200–2600 cm^{-1} and only weak, very broad absorptions in the $C{=}N^+$ region, peaking about 1650 cm^{-1}. We argue that this solid cannot be the protonated immonium precursor of **16**, **20**, because this IR spectrum is very different from that shown by an authentic $R_2N^+{=}CH_2$ species **21** (sharp $N^+{=}CH_2$ stretch at 3150, sharp $N^+{=}C$ stretch at 1690, and very strong, sharp $={CH_2}$ wag at 910 cm^{-1} [15,16]). We assign it instead to protonated **16**, $\mathbf{16H}^{2+}$. The ratio of methyl:methylene hydrogen loss in reaction of $\mathbf{3}^{2+}$ is significantly different when carbonate causes the decomposition (ratio over 3.5:1) than when iodide is the reagent (ratio about 1:1).



20



21

16H²⁺

Iodide in water also decomposes $\mathbf{3}^{2+}$. Treatment of dication solutions in D_2O with KI causes an immediate yellow coloration; the solution turns orange within a few minutes and a precipitate of KBF_4 appears. Decomposition of $\mathbf{3}^{2+}$ is complete in 24 h, giving a rather complex product mixture which has not been quantitatively analyzed. In addition to **16**, products showing triplets of equal intensity at δ 4.95 and 5.08 and methyl singlets which overlap at δ 2.58 are produced; we suspect, but have not proven, that these are water adducts of the immonium salt **19**. From their chemical shift and triplet multiplicity, these products are only reasonably derived by NCH_2 hydrogen loss from the dication. The integration ratio of the 2 H singlet of **16** to the sum of the two triplets was determined

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(15) Nelsen, S. F.; Kessel, C. R.; Brien, D. J. *J. Am. Chem. Soc.* **1980**, *102*, 702.

(16) PhD. Thesis of C. R. Kessel, University of Wisconsin, 1980, p 304.

Table I. Approximate Initial Ratio of Products from NCH_3:NCH_2 Loss in the Decomposition of 3^{2+}

reagent	solvent	ratio
K_2CO_3	D_2O	10
KCl	D_2O	no reaction
KI	D_2O	~1[a]
K_2CO_3	CD_3CN	4
Et_4NCl	CD_2CN	3.8
n-Bu_4NI	CD_3CN	1

[a] The structures of products appearing to derive from NCH_2 loss were not determined, but the ratio appeared to be slightly under 1.

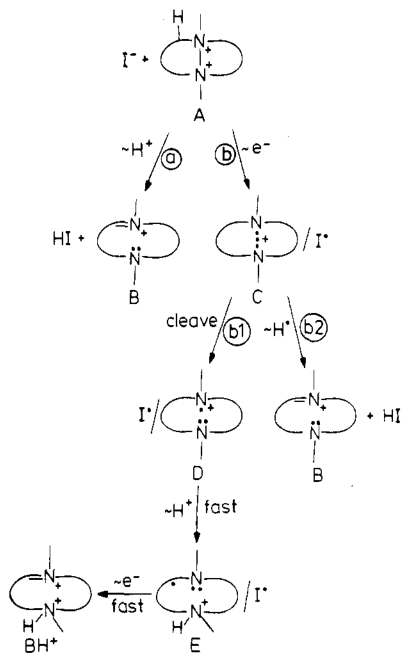
to be about 1:1.2, which we suggest is our best measure of the ratio of methyl to methylene hydrogen loss in the dication in this reaction. The demethylated compound **17** derived from hydrolysis of **16** was found upon basic workup of these reaction mixtures, and small amounts of protonated **17** have been crystallized out.

In contrast to the behavior of 3^{2+} when treated with iodide in water, chloride causes no significant decomposition in 24 h at concentrations where complete decomposition is observed with iodide, or even upon treatment with twice as much KCl for 48 h. Reaction with Et_4NCl in CD_3CN does lead to decomposition, and quantitation by integration relative to the Et_4N^+ signals gave initial yields of 63% **16**, 21% **19**, as well as solid $\mathbf{16H^{2+}}$, which could not be integrated. Assuming that the 16% of material missing from the NMR integration is $\mathbf{16H^{2+}}$, the ratio of NCH_3/NCH_2 attack products is 3.8, within experimental error of what was observed in the K_2CO_3/CD_3CN experiment.

The plethora of NMR peaks for each product of 3^{2+} decomposition and their instability upon standing makes quantitation of the product mixtures rather inaccurate. Nevertheless, it is clear that the ratio of products derived from hydrogen loss at the NCH_3 to those derived from loss at the NCH_2 positions is quite different when carbonate and iodide are the reagents, and that chloride decomposes the dication in CD_3CN to give about the same ratio as carbonate, but does not decompose it in water (see Table I). We previously reported[9] that 3^{2+} differs substantially from the tricyclic hexaalkylhydrazine dications in that no reduction current is observed in its cyclic voltammogram near 0–0.5 V vs. SCE, but only a broad reduction wave peaking at −1.4 V. This is not correct, and we presumably had decomposed the sample of 3^{2+} used for the previously reported cyclic voltammogram. The cyclic voltammogram of authentic 3^{2+} shows an irreversible reduction wave peaking at +0.12 V vs. SCE (0.2 V/s scan rate in acetonitrile containing 0.1 M tetra-*n*-butylammonium perchlorate, at Pt). 3^{2+} actually shows its irreversible reduction wave positive of ("easier than") those of the tricyclic dications.

Discussion: Deprotonation vs. Electron Transfer in $R_6N_2^{2+}$ Decomposition

Scheme V



Scheme V summarizes some mechanistic possibilities for the reactions under discussion, using an idealized hexaalkylhydrazine dication having only one labile α hydrogen, A, and iodide as the reagent. Initiation could be by proton transfer, pulling off the labile hydrogen to give immonium salt B (path a) or by electron transfer, giving the 3e-σ-bonded cation C and an iodine atom (path b). Because iodide is such a weak base in water, we suggest that the fact that it catalyzes $R_6N_2^{2+}$ decomposition at all suggests that electron transfer may well occur, as does the failure of chloride to initiate decomposition. Iodide is a considerably better reducing agent than chloride, and their formal potentials for one-electron oxidation have been estimated at 0.96 and 1.86 V vs. SCE, respectively.[17] The fact that both partners of the presumed electron transfer only give irreversible cyclic voltammograms because of product instability precludes quantitative discussion of the endothermicity of the electron transfer, but iodide oxidizes to iodine and the tricyclic dications reduce irreversibly at potentials which are not separated by more than a few hundred millivolts, so electron transfer is likely not to be prohibitively endothermic. Alder and Sessions[18] have shown that the remarkably slow electron transfer between **1**[444] and $\mathbf{1}[444]^{2+}$ is catalyzed by iodide, which presumably involves electron transfer from iodide to the dication, providing additional evidence that iodide can reduce hexaalkylhydrazine dications. The significant change in selectivity observed for 3^{2+} reaction with carbonate and iodide in water also suggests to us that different intermediates are involved. The fact that amine bases (such as the products) doubtless also decompose the dications, presumably by path a, would lead to real difficulty in establishing what this ratio actually is for "pure iodide" reaction.

We had *initially* thought that path b would proceed to products via the reactions of path b1, involving 3e-σ-bond cleavage of C to amminium cation D, very rapid internal proton transfer to give α-amino radical E, and back-electron-transfer to produce BH^+.[14] The oxidation of E to BH^+ would certainly be very rapid; examples of α-amino radicals with alkyl group substitution which allow measurement of formal reduction potential by cyclic voltammetry[15] have $E^{\circ\prime}$ negative of −1.5, and whatever easily reduced species was available would be forced to accept the electron; we showed the iodine atom in Scheme V, but dication or even protons could also assume this role. We no longer think that path b1 is a reasonable possibility for the reaction. One thing that seems inconsistent with path b1 is that although the protonated immonium ion derived from NCH_2 attack, **19**, is a major product of iodide decomposition of 3^{2+}, its NCH_3 attack analogue **20** was never seen, the only product we found being closure product **16**. Path b1 produces both **19** and **20** without the intermediacy of

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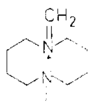
(17) Eberson, L. *Adv. Phys. Org. Chem.* **1982**, *18*, 79.

(18) Alder, R. W.; Sessions, R. B. *J. Am. Chem. Soc.* **1979**, *101*, 3651.

their unprotonated forms, such as **22**, which we would



22

expect would be required for closure to **16**. It is also embarassing for path b1 that no methyl group attack was found upon decomposition of $\mathbf{10}^{2+}$, because this requires postulating that the 3e-σ bond breaks to exclusively end up with the lone pair on the methylated nitrogen; this seems to us rather unlikely.

Recent work by Alder, Bonafacic, and Asmus[19] provides important kinetic evidence against path b1 which is quite independent of the above considerations. They have demonstrated that 3e-σ-bonded hexaalkylhydrazine cation radicals react very rapidly with a wide range of free radicals by hydrogen atom abstraction. The usually quite unreactive thiyl radical *t*-BuS· reacts with the long-lived pericyclic example of C, $\mathbf{1}[444]^+$ with a second-order rate constant of $3.2(3) \times 10^9$ M^{-1} s^{-1}, and even $I_2^{\cdot-}$ has a rate constant exceeding 10^8. Such large rate constants for attack of rather unreactive radicals upon $\mathbf{1}[444]^+$ presumably are caused by unusually weak C(α)–H bonds. Interaction of the C(α)–H bond with the half-filled σ^* orbital of the NN bond apparently is responsible for this unusual reactivity.

Electron transfer from I$^-$ to $\mathbf{3}^{2+}$ would produce a $\mathbf{3}^+$,I· pair in solution. Because the rate constant expected for hydrogen atom transfer within this pair is on the order of 10^9 or greater for favorably aligned C(α)–H bonds (those nearly parallel with the 3e-σ bond axis), hydrogen atom transfer ought to compete with diffusion of these species apart. The three-electron σ bond strength in $R_6N_2^+$ species has been estimated at about 14 kcal/mol both by consideration of the gas-phase bond dissociation energies of examples of **1** and their mono bridgehead aza analogues[20] and from the observed solution lifetime of $\mathbf{3}^+$, measured by pulse radiolysis to be about 5 ms, corresponding to a pH-independent first-order process.[14] Kinetic considerations, then, suggest that path b1 cannot be expected to lead to product formation in competition with path b2. Pathways a and b2 are expected to show the same anti attack selectivity (removal of hydrogen anti to the NN bond) for reagents attacking the tricyclic dications, so determination of this stereochemistry would not help distinguish these pathways. We find path b2 very attractive for rationalizing the principal experimental observation, a significant decrease in the CH_3:CH_2 attack ratio when I$^-$ replaces CO_3^{2-} as the reagent. Two-electron processes such as the Grob fragmentation[21] have been known for years to have a strong requirement for H–C, C–X antiperiplanar alignment, so an even stronger requirement for such an alignment (which is necessary to explain the decrease in ratio) seemed quite difficult to explain. We suggest, however, that an even stronger requirement for alignment is reasonable for the 3e-σ-bonded cation radical, which has a half-filled σ^* orbital interacting with the CH bond and a significantly longer NN bond length,[22] than for the dication, in which the σ^* orbital is empty. The σ,σ^* splitting is significantly smaller in the 3e-σ-bonded cation radical, so the NN(σ^*),CH(σ) energy gap should be significantly smaller, leading to larger mixing and hence more CH bond weakening than in the dication. It now seems quite likely that the iodide-catalyzed rearrangement of $\mathbf{6}^{2+}$ and $\mathbf{10}^{2+}$ to α-amino ammonium cations, which not only shows high selectivity for methylene group deprotonation over methyl group deprotonation but also exhibits a high selectivity between different methylene groups of the dication, is a result of an electron-transfer reaction mechanism. The implications of path b1 vs. b2 for intermolecular reactions are discussed separately.[23]

Experimental Section

***cis*-1,6-(Hexadeuteriodimethyl)-1,6-diazoniabicyclo[4.4.0]dodecane Bis(tetrafluoroborate) ($\mathbf{3}^{2+}$-$\boldsymbol{d}_6$).** A solution of bis(deuteriomethyl)hexahydropyridazine obtained by $LiAlD_4$ reduction of the bis(ethyl carbamate) (0.305 g, 2.54 mmol) was treated with 1,4-dibromopropane (3.52 g, 16.3 mmol) and the mixture heated at 47 °C for 1 h. The white solid mass was broken up under anhydrous ether and washed with five 20-mL portions of ether via cannula. After evacuation to remove the last traces of ether, the monoalkylated compound was a white powder weighing 0.575 g (1.6 mmol, 64%). This material was dissolved in 3 mL of 60% aqueous HBF_4 and added dropwise to a stirred solution of 0.374 g (1.6 mmol) of $AgBF_4$ in 2.8 mL of 60% HBF_4. After stirring at room temperature 3 h, the silver salts were filtered off through a fine glass frit and rinsed with 1.5 mL of 60% HBF_4. A 20:30 EtOH/Et_2O mixture was added to the filtrate dropwise until no more solid seemed to be forming (ca. 50 mL), and the precipitate was filtered, rinsed with ether, and dried under vacuum to give the product as a white powder, 0.463 g (1.3 mmol, 83%): ^{1}H NMR (CD_3CN) δ 4.70 (t, 2 H), 4.30 (t, 2 H), 3.96 (d, 2 H), 3.73 (d, 2 H), 2.45–2.0 (m, 8 H); (D_2O) 4.84 (td [J = 13.4, 3.3 Hz]), 4.40 (td), 4.05 (d), 3.84 (d), 2.5–1.95 (m).

2-Methyl-1,2-diazabicyclo[2.2.2]octane (5). A modified Eschweiler–Clarke methylation[24] is presently used. A total of 3 mL of 88% formic acid was cooled to 0 °C and added to a 25-mL, round-bottomed flask containing 2.22 g (19.8 mmol) of 1,2-diazabicyclo[2.2.2]octane,[25] under a nitrogen atmosphere. Immediately after dissolution, 2.0 g of 37% formaldehyde was added all at once, and the mixture was heated and bubbled vigorously. The flask was heated on a steambath for 4 h and cooled to room temperature, and 25 mL of water and enough KOH were added to make the solution strongly basic. Extraction with 10 × 25 mL portions of pentane, drying with K_2CO_3, and distillation gave 2.41 g (19.1 mmol, 96%) of **5** as a colorless oil, bp (17 torr) 66 °C.

2-(Trideuteriomethyl)-1,2-diazabicyclo[2.2.2]octane (5-$\boldsymbol{d}_3$). A THF solution of 1,2-diazabicyclo[2.2.2]octane prepared from 4.0 g of its amide precursor by $LiAlH_4$ reduction was treated with 3.2 g (31.7 mmol) of triethylamine and then dropwise with 3.44 g (31.7 mmol) of ethyl chloroformate. After stirring 18 h under N_2, the triethylamine hydrochloride was filtered off and ether was added to the filtrate until no more precipitate formed. After a second filtration, solvent removal by rotary evaporation and sublimation gave 4.72 g (81%) of 2-formyl-**5**, mp 48–49 °C. A solution of 1.0 g (5.4 mmol) of this amide in 50 mL of ether was added to a suspension of 2.0 g (32.6 mmol) of $LiAlD_4$ in 50 mL of ether, and the mixture was refluxed under nitrogen for 20 h and worked up by the 1:1:3 method to give 0.67 g (96%) of **5**-d_3, which was distilled at 65 °C (ca. 12 torr) to give a clear oil showing no N-CH_3 signal in the ^{1}H NMR spectrum and having the empirical formula $C_7H_{11}D_3N_2$ by high resolution mass spectroscopy.

1-(4-Iodobutyl)-2-methyl-1-azonia-2-azabicyclo[2.2.2]octane Iodide ($\mathbf{7}$(I)$^+$I$^-$). A mixture of 1.33 g (10.6 mmol) of **5** and 6.54 g (21.1 mmol) of freshly distilled 1,4-diiodobutane in 13 mL of methanol was stirred at room temperature for 2 days and concentrated by rotary evaporation. The residue was washed with

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[19] Alder, R. W.; Bonafacić, M.; Asmus, K.-D. *J. Chem. Soc., Perkin Trans. 2*, **1986**, 227.

[20] Alder, R. W.; Arrowsmith, R. J.; Casson, A.; Sessions, R. B.; Heilbronner, E.; Kovac, B.; Huber, H.; Taagepera, M. *J. Am. Chem. Soc.* **1981**, *103*, 6137.

[21] Grob, C. A. *Angew. Chem., Int. Ed. Engl.* **1967**, *6*, 1; **1969**, *8*, 535.

[22] The NN bond length of crystalline $\mathbf{1}[444]^+$ is 2.30 Å, 0.77 Å longer than that of the dication: Alder, R. W.; Orpen, A. G; White, J. M., *J. Chem. Soc., Chem. Commun.* **1985**, 949.

[23] Nelsen, S. F.; Ippoliti, J. T. *J. Am. Chem. Soc.*, in press.

[24] (a) Moore, M. L. *Org. React. (N.Y.)* **1949**, *5*, 301. (b) Spialter, L.; Pappalardo, J. A. *The Acyclic Tertiary Amines*; McMillan: New York, 1965; p 45.

[25] Nelsen, S. F.; Gannett, P. M.; Steffeck, D. J. *J. Org. Chem.* **1980**, *45*, 3857.

ether to remove the excess diiodide, and the 3.47 g (74%) of crude **7**(I)$^{+}$I^{-} was used without purification in the next step: ^{1}H NMR (CDCl$_3$) δ 4.5–4.1 (m, 2 H), 4.1–3.6 (m, 4 H), 3.2 (m, 4 H), 2.8 (s, 3 H), 1.6–2.2 (m, 9 H).

1-(4-Bromobutyl)-2-methyl-1-azonia-2-azabicyclo[2.2.2]octane Bromide (7(Br)$^{+}$Br^{-}). A mixture of 2.71 g (12.6 mmol) of 1,4-dibromobutane and 0.35 g (2.78 mmol) of **5** in 4.5 mL of freshly distilled tetrahydrofuran was allowed to stand at room temperature 11 days and after mild heating to 35 °C for 1 day was cooled to room temperature. After addition of 15 mL of ether, solvents were decanted away through a cannula, the process was repeated 3×, and the resulting solid was dried in vaccum, giving 0.91 g (96%) of **7**(Br)$^{+}$Br^{-} as off-white needles, mp 117–119 °C: ^{1}H NMR (CDCl$_3$) δ 4.58 (m, 2 H), 3.89 (m), 3.5 (t, 2 H), 3.25 (br s, 2 H), 2.8 (s, 3 H), 2.3–1.9 (m).

6-Methyl-1,6-diazoniatricyclo[6.2.2.0^{1,6}]dodecane Bis(tetrafluoroborate) (6^{2+}(BF$_4^{-}$)$_2$). (a) From 7(I)$^{+}$I^{-}. A solution of 1.79 g of silver oxide (7.8 mmol) in 48% HB$_4$ was added to 3.4 g (7.8 mmol) of crude iodide in 25 mL of 48% HBF$_4$, the mixture was stirred 1.5 h at room temperature, and the silver salts were filtered off. The product was precipitated by addition of 30 mL of dry ethanol and 40 mL of ether, and the solid formed was washed with ether and dried in vacuo to give 1.9 g of **6**$^{2+}$(BF$_4^{-}$)$_2$ as a white powder, mp 228–230 °C dec; IR (KBr) cm^{-1} 2940, 1470, 1080; ^{1}H NMR (D$_2$O) δ 5.2–3.85 (m, 10 H), 4.05 (s, 3 H), 2.9–2.0 (m, 9 H). Anal.[26] Calcd for C$_{11}$H$_{22}$N$_2$B$_2$F$_8$: C, 37.20; H, 6.26; N, 7.91. Found: C, 37.29; H, 6.21; N, 7.97.

(b) From 7(Br)$^{+}$Br^{-}. A solution of 0.176 g (0.76 mmol) of silver oxide in 1.0 mL of 48% HBF$_4$ was added dropwise to a stirred solution of 0.26 g (0.76 mmol) of bromide in 1.0 mL of 48% HBF$_4$ and the mixture was stirred 17 h at room temperature. Filtration through a fine frit gave a clear yellow solution which was treated dropwise with a 60/40 ether/ethanol solution until the viscous yellow material which first comes out rapidly stops forming and the solution becomes cloudy. After decantation from the yellow material, the cloudy solution was treated with more ether/ethanol solution until a fine white precipitate stopped being formed. The flocculant precipitate was collected on a fine frit, washed with ether, and dried, giving 0.15 g (55%) of **6**$^{2+}$(BF$_4^{-}$)$_2$ which in contrast to the material from part is soluble in acetonitrile and was used for the work reported here.

1-(3-Hydroxypropyl)-2-methyl-1-azonia-2-azabicyclo[2.2.2]octane Bromide (9(OH)$^{+}$Br–). A solution of 0.55 g (3.97 mmol) of 3-bromo-1-propanol in 2.7 mL of acetonitrile was added slowly to a solution of 0.5 g (3.97 mmol) of **5** in 0.44 mL of acetonitrile which was cooled in an icebath, the mixture was allowed to stand at room temperature for 2 days, and 1 mL of ether was added dropwise. Within 2 h the mixture had solidified and was filtered and washed with ether under nitrogen to give 0.92 g (3.47 mmol, 87%) of alkylated **5** as colorless, hygroscopic crystals which appeared to be a 5:1 mixture of N$_1$ (**9**(OH)$^{+}$Br^{-}) and N$_2$ alkylated material and had a wide melting range of 110–138 °C: ^{1}H NMR (CD$_3$CN) δ 4.25 (br t, 1 H), 3.7 (t), 3.4–3.6 (m), 3.3 (s), 3.5 (d, 2 H), 2.7 (s, 3 H), 2.19 (m, 1 H), 1.8–2.05 (m); ^{13}C NMR (CD$_3$CN) δ 60.7 (t), 59.6 (t), 58.7 (t), 55.9 (t), 40.8 (q), 26.2 (t), 23.7 (t), 22.2 (d). Anal.[26] Calcd for C$_{10}$H$_{21}$N$_2$BrO: C, 45.29; H, 7.99; N, 10.57; Br, 30.16. Found: C, 45.07; H, 10.45; N, 10.45; Br, 30.10.

5-Methyl-1,5-diazoniatricyclo[5.2.2.0^{1,5}]undecane Bis(tetrafluoroborate) (10^{2+}(BF$_4^{-}$)$_2$). A solution of 0.6 g (2.64 mmol) of **9**(OH)$^{+}$Br^{-} in 2.2 mL of 48% HBF$_4$ was allowed to stand at room temperature for 3 days and ethanol was added dropwise until the cloud point. After crystallization at −15 °C, more ethanol was added to the mixture and it was recooled. Filtration gave 0.20 g (0.585 mmol, 22% of **10**$^{2+}$(BF$_4^{-}$)$_2$ as a white powder, mp 234–236 °C dec. Concentration of the filtrate gave an additional 0.5 g of material which was crystallized from acetonitrile: ^{1}H NMR (CD$_3$CN) δ 4.51 (ddd, *J* = 13, 6.5, 6.5 Hz, 1 H), 4.32–4.11 (m, 7 NCH), 4.09–3.97 (m, 2 NCH), 3.68 (s, 3 H, Me), 2.81 (m, 2 H on C(3)), 2.56 (br s, C(7)H), 2.37–2.24 (complex, 3 H), 2.22–2.14 (complex, 1 H); ^{13}C NMR (D$_2$O) δ 71.9 (t), 66.7 (t), 61.5 (t), 61.0 (t), 57.0 (t), 54.7 (q), 22.9 (t), 22.4 (d), 21.7 (t). Anal.[26] Calcd for C$_{10}$H$_{20}$N$_2$B$_2$F$_8$: C, 35.11, H, 5.90; N, 8.20. Found: C, 33.59; H, 5.59; N, 8.28. Proton NMR shows the presence of residual acetonitrile we were unable to remove under vaccum.

1-Methyl-1-azonia-5-azatricyclo[6.2.1.0^{5,10}]undecane Iodide (8^{+}I^{-}). (a) From 5. A mixture of 7.0 g (23.8 mmol) of 1,3-diiodopropane and 1.5 g (11.9 mmol) of **5** in 38 mL of acetonitrile was allowed to stand in the dark for 48 h, and the red-orange solution poured off a bright red solid (0.27 g, shown by ^{1}H NMR to contain only a small amount of product, and a very complex mixture of other materials), and addition of ether gave more unidentified oily red precipitate. Addition of more ether gave **8**$^{+}$I^{-} as a yellow powder, 1.64 g (5.6 mmol, 47%). Most of the color could be washed out with acetonitrile (caution: the product is quite soluble), and crystals of analytical purity were obtained by vapor diffusion of ether into a saturated methylene chloride solution, mp 234 dec: °C ^{1}H NMR (CD$_3$CN, 500 MHz) δ 5.25 (d [*J* = 4 Hz], H(10)), 4.03 (m, H(2a), H(2e)), 3.86 (dd [*J* = 13, 6], H(11x)), 3.51 (br d [*J* = 12.5], H(11n)), 3.45 (ddd [*J* = 14, 10.7, 4], H(4e)), 3.25 (dt [*J* = 13.6, 6.6], H(6y)), 2.98 (m, H(4e), H(8), H(6z)), 2.55 (d, br t [*J* = 14, 5], H(9y)), 2.26 (10 line m[sepn 5], H(3a)), 1.91 (br d [*J* = 14), H(9z)), 1.74 (d-quintet [*J* = 15.4,4], H(3e)), 3.34 (s, 3 MeH); ^{13}C NMR (CDCl$_3$) δ 92.9 (d, C(9)), 65.1 (t), 60.4 (t), 53.1 (q, Me), 48,9 (t), 43.2 (t), 33.0 (d, C(7)), 32.4 (t), 32.0 (t), 16.4 (t). Anal.[26] Calcd for C$_{10}$H$_{19}$N$_2$I: C, 40.81; H, 6.51; N, 9.53; I, 43.15. Found: C, 40.66; H, 6.44; N, 9.73; I, 43.53.

(b) From 10^{2+}(BF$_4^{-}$)$_2$. A solution of 95 mg (0.278 mmol) of dication salt in 1.5 mL of D$_2$O was treated with 92.3 mg (0.556 mmol) of KI, causing a flocculant white precipitate (KBF$_4$) to form slowly. After 3 days, 38 mg (0.278 mmol) of K$_2$CO$_3$ was added to the solution, causing gas evolution (CO[2) and dissolution of the red crystals which had formed during the reaction. The water was evaporated with a stream of nitrogen, and the methylene chloride extract was crystallized by vapor diffusion of ether, giving 59 mg (72%) of **8**$^{+}$I^{-} as clear prisms, mp 249 °C dec.

5-Methyl-1,5-diazabicyclo[5.2.2]undecane (11). Solid **10**$^{2+}$(BF$_4^{-}$)$_2$ (0.94 g, 3.2 mmol) was added to a blue, stirring solution of sodium (0.22 g, 9.5 mmol) in 50 mL of liquid ammonia, and the resulting solution was refluxed 1 h under nitrogen. Methanol was added dropwise until the blue color discharged, and half the ammonia was allowed to boil off. Cautious addition of 25 mL of water gave a grey solution which was filtered through a pad of Celite, extracted with 5 × 50 mL portions of methylene chloride, and concentrated to a residue as rapidly as possible (**11** proves to decompose slowly in CH$_2$Cl$_2$). Kugelrohr distillation gave 0.34 g (2.1 mmol, 63%) of **11** as a clear oil: ^{1}H NMR δ 3.15 (m, 4 H), 3.0 (m, 2 H), 2.6 (d, 2 H), 2.45 (m, 2 H), 2.40 (s, 3 H), 2.0 (m, 1 H), 1.65 (m, 6 H); ^{13}C NMR (CDCl$_3$) δ 65.7 (t), 58.9 (t), 58.5 (t), 49.5 (q), 45.8 (t, C9,10), 31.0 (t), 28.2 (t,C8,11), 27.0 (d). Empirical formula C$_{10}$H$_{20}$N$_2$ established by high resolution mass spectroscopy.

1-Methyl-1-azonia-6-azatricyclo[7.2.1.0^{6,11}]dodecane Iodide (14^{+}I^{-}). A solution of 0.110 g (0.309 mmol) of **6**$^{2+}$(BF$_4^{-}$)$_2$ in 4 mL of D$_2$O was stirred with 0.186 g (1.12 mmol) of KI for 4 days and 0.110 g of K$_2$CO$_3$ was added, causing evolution of CO$_2$. After evaporation and vapor diffusion precipitation from CH$_2$Cl$_2$ with ether, 56 mg (59%) **14**$^{+}$I^{-} was obtained as clear, colorless crystals, mp 249 °C dec: ^{1}H NMR (CDCl$_3$) δ 5.49 (d, 1 H), 4.08–3.8 (m, 2 H), 3.57 (d, 1 H), 3.33 (s, 3 H), 2.85–3.5 (m, 5 H), 2.5 (m, 1 H), 2.22–1.73 (m 8 H); ^{13}C NMR (CDCl$_3$) δ 98.6 (d), 70.4 (t), 66.9 (t), 55.0 (t), 52.7 (q), 42.6 (t), 34.9 (d), 34.3 (t), 28.1 (t), 27.9 (t), 23.9 (t). Anal.[26] Calcd for C$_{11}$H$_{21}$N$_2$I: C, 42.85; H, 6.87; N, 9.09; I, 41.19. Found: C, 42.77; H, 6.78; N, 9.08; I, 41.24.

Decomposition Reactions of R$_6$N$_2$$^{2+}$ Followed by ^{1}H NMR. In a typical decomposition reaction in D$_2$O, 40 mg of **3**$^{2+}$(BF$_4^{-}$)$_2$ in 0.5 mL of D$_2$O was treated with 16 mg (1 molar equiv) of K$_2$CO$_3$, the white solid (KBF$_4$) was centrifuged to the bottom of the tube, and the solution was analyzed by ^{1}H NMR, integrating the triplet at δ 5.02 and the singlet at 4.4 to obtain the ratio of **18**:**16**.

In acetonitrile, 10 mg of **3**$^{2+}$(BF$_4^{-}$)$_2$ in 0.8 mL of CD$_3$CN was treated with 20 mg of K$_2$CO$_3$ (5 molar equiv), the heterogeneous mixture was stirred in a capped vial for 16 h, and the ratios of **18**:**16** were obtained by integrating the triplet at δ 5.1 relative to the singlet at 4.45. In unstirred reactions, **19** was also detected early in the reaction and was quantitated by integration of its δ 8.35 immonium hydrogen triplet. In our best quantitated run (using methanol in a capillary tube as the standard), we observed after 0.5 days 38%g remaining **3**$^{2+}$, 50% **16**, 9% **18**, and 5% **19**

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[26] Spang Microanalytical Laboratories, Eagle Harbor, MI.

(NCH_3/NCH_2 attack product ratio 3.6); after 4 days no $\mathbf{3}^{2+}$ or **19** and 77% **16**, 19% **18** (attack product ratio 4); and after 5 days 68% **16**, 12% **18** (attack product ratio 5.7, only 80% of the initial $\mathbf{3}^{2+}$ present accounted for). Analysis by adding a weighed amount of 1,4-dibromobenzene at this point gave the yields of **23**:**25** as 62:11% (5.7 ratio).

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Registry No. $\mathbf{3}^{2+}$, 73843-82-0; $\mathbf{3}^{2+}$-d_6·$2BF_4^-$, 103094-89-9; 3^{2+} (monoalkylated), 103094-90-2; **5**, 6523-29-1; **5** (amide), 1632-26-4; 2-formyl-**5**, 23014-04-2; **5**-d_3, 103094-91-3; $\mathbf{6}^{2+}$, 82415-31-4; $\mathbf{6}^{2+}$·$2BF_4^-$, 82415-32-5; **7**$(I)^+I^-$, 103094-92-4; **7**$(Br)^+Br^-$, 103094-93-5; 8^+, 103094-84-4; $\mathbf{8}^+I^-$, 103094-96-8; $\mathbf{8H}^{2+}$, 103094-85-5; **9**$(OH)^+Br^-$, 103094-94-6; $\mathbf{10}^{2+}$, 103094-82-2; $\mathbf{10}^{2+}$·$2BF_4^-$, 103094-95-7; **11**, 103094-97-9; $\mathbf{14}^+$, 103094-83-3; $\mathbf{14}^+I^-$, 103094-98-0; **16**, 90827-82-0; **18**, 103094-87-7; **19**, 103094-86-6; **21**, 73321-18-3; CO_3^{2-}, 3812-32-6; I^-, 20461-54-5; Cl^-, 16887-00-6; Et_4NCl, 56-34-8; n-Bu_4NI, 311-28-4; 1,4-diiodobutane, 628-21-7; 1,4-dibromobutane, 110-52-1; bis(deuteriomethyl)hexahydropyridazine, 26163-38-2; bis(ethyl carbamate), 4114-28-7; 1,2-diazabicyclo[2.2.2]octane, 329-94-2.

Kinetics of Thermolysis of Vinyl Azides. Empirical Rules for Formation of Azirines and Rearranged Nitriles[1]

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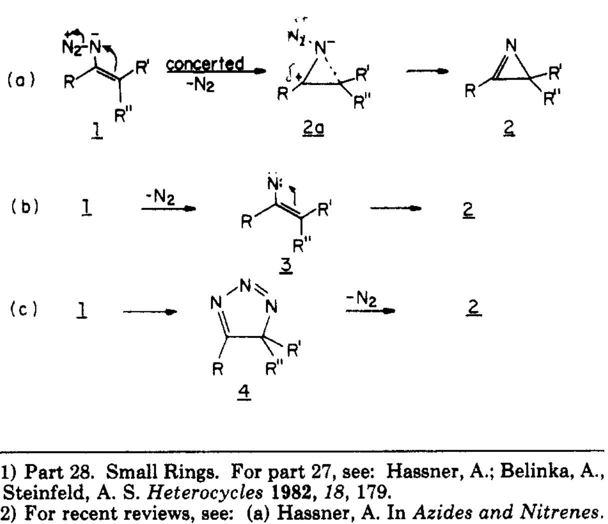
An evaluation of reported thermolyses of acyclic and cyclic vinyl azides $R(N_3)C{=}CR'$ leads to the empirical generalization that when R is aryl, alkyl, a heteroatom, or even alkoxycarbonyl, 1-azirines are usually formed upon thermolysis. When R is H or keto carbonyl (and depending on the β-substituents R′), nitriles or heterocycles are usually isolated. The kinetics of the thermolysis of α-azidostyrene (**10**) were followed by NMR, both by disappearance of **10** and appearance of azirine **11**, and are consistent with a concerted loss of nitrogen and ring closure. A reexamination of the kinetics of α-azidochalcone (**15**) thermolysis, which normally leads to rearranged nitrile **19**, revealed the intermediacy of azirine **16** which was isolated and thermolyzed. For the first time we were able to compare kinetic and thermodynamic data for vinyl azide to azirine conversion with those of azirine to nitrile rearrangement. The latter process appears to proceed via the dipolar form of a vinyl nitrene intermediate. A general scheme explaining the empirical findings is discussed.

Although thermolysis and photolysis of vinyl azides **1** to 1-azirines **2** are well established and synthetically useful reactions,[2] their mechanistic pathway has not yet been clearly established. Three major pathways have been proposed for these transformations: (a) loss of nitrogen occurring concertedly with ring formation; (b) the intermediacy of a vinyl nitrene (**3**) (presumably a singlet) which can undergo symmetry-allowed electrocyclic ring closure to **2**; (c) intramolecular [3 + 2] cycloaddition of the azido group to the double bond, followed by loss of N_2 from an intermediate triazole **4**.



Ab initio calculations[3a] for the process **1** → **4** → **2** predicted an energy of activation of 32.9 kcal/mol or 41.4 kcal/mol depending on the method used. More recent calculations[3b] favor rate-determining formation of a vinyl nitrene or a more or less concerted loss of nitrogen and indicate almost no activation energy for vinyl nitrene to azirine conversion. Attempts to clarify the mechanism of vinyl azide to azirine thermolysis have included a kinetic study by L'abbé and Mathys.[4] For the vinyl azides **1** (R = H or C=O and R′, R″ = H, Ar, ArC=O, Me), they found energies of activation (26–30 kcal/mol) and ΔS^* values (−3 to +5 eu) which are not compatible with the nitrene pathway (b), when compared to data ($E_a \sim 40$ kcal/mol, $\Delta S^* \sim +18$ eu) reported for aryl azide to arylnitrene conversion. Although path a could not be excluded, these authors favored pathway c since the kinetic data compared more favorably with those observed for pyrazoline formation from diazoalkenes.[4]

However, not all vinyl azides yield azirines upon thermolysis; in many cases[5] nitriles or heterocycles such as indoles are the reaction products (see Table I). We have critically examined a large number of reported thermolyses (usually at 35–150 °C)[6] of both cyclic and acyclic vinyl azides having a variety of substitution patterns. The reported products lead us to propose the following empirical generalizations: *Thermolyses of vinyl azides 1 to isolable*

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[1] (1) Part 28. Small Rings. For part 27, see: Hassner, A.; Belinka, A., Jr.; Steinfeld, A. S. *Heterocycles* **1982**, *18*, 179.

[2] (2) For recent reviews, see: (a) Hassner, A. In *Azides and Nitrenes. Reactivity and Utility*; Scriven, E. F. V., Ed.; Academic Press: Orlando, 1984; Chapter 2. (b) Nair, V. In *Small Ring Heterocycles*; Hassner, A., Ed.; Wiley: New York, 1983; Vol. 42, Part 1, pp 215–332. (c) Moore, H. W.; Goldish, D. M. In *The Chemistry of Functional Groups*, Suppl. D.; Patai, S., Rappoport, Z., Eds.; Wiley: New York, 1983; Chapter 8, p 321.

[3] (3) (a) Burke, L. A.; Leroy, G.; Nguyen, M. T.; Sana, M. *J. Am. Chem. Soc.* **1978**, *100*, 3668. (b) Yamabe, T.; Kaminoyama, M.; Minato, T.; Hori, K.; Isomura, K.; Taniguchi, H. Tetrahedron **1984**, *40*, 2099.

[4] (4) L'abbé, G.; Mathys, G. *J. Org. Chem.* **1974**, *39*, 1778.

[5] (5) Isomura, K.; Kobayashi, S.; Taniguchi, H. *Tetrahedron Lett.* **1968**, 3499. Isomura, K.; Okada, M.; Taniguchi, H. *Ibid.* **1969**, 4073.

[6] (6) Pyrolyses at higher temperature or in the vapor-phase may proceed through different intermediates. Similarly thermolysis of 1-azirines at higher temperatures often lead to a mixture of many products.