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A Strained Aminoazoniatricyclene Species: Result of an Intramolecular Stabilization of a Cyclopropaniminium Ion by an Amino Moiety

Matthias Dotzauer, Wolfgang Eisfeld, Elmar Vilsmaier,* Karin Fröhlich,
Uwe Bergsträsser, and Claus Tetzlaff

Fachbereich Chemie der Universität Kaiserslautern, D-67663 Kaiserslautern, Germany

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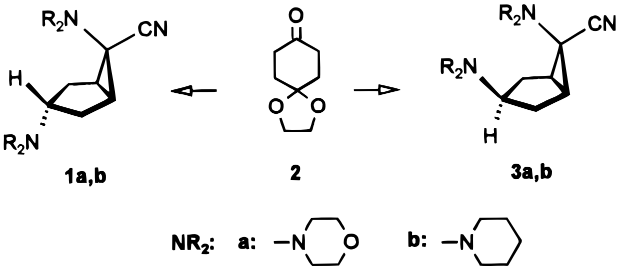
Ab initio calculations of the cationic intermediates of a cyclopropane-forming process of 1,4-diamino-6-chlorocyclohexene precursors predict the 3α-aminobicyclohexane-6-iminium ion **6c** to be more stable than its 3*β*-isomer **7c**. The latter, however, stabilizes itself by intramolecular cyclization leading to aminoazoniatricyclene species **9c**. The aminocyclohexenyl cation **8c** proved to have no minimum on both the MP2 and the MP4(SDTQ) potential energy surfaces. Optimization of species **8c** causes a ring closure reaction to give iminium analogues **6c** or **7c**. The potential energy curve of this transformation **6c** → **8c** → **7c** was calculated. Experimentally, solvolysis of chloro enamine isomers **4a** and **5a** was studied as a simple access to these cationic intermediates: 3α-amino 6-iminium ion **6a** leading to 3α-amino 6-semiaminal **12** is generated exclusively from trans chloro enamine **4a** and as main intermediate (67%) from cis chloro enamine **5a**. In the latter case, aminoazonia compound **9a** is formed as a byproduct (33%) which decomposes in water to give 3*β*-amino 6-semiaminal **13** via 3*β*-amino 6-iminium ion **7a**. Aminoazoniatricyclene species **9a** is obtained as stable tetrafluoroborate in acetonitrile or dichloromethane by reaction of chloro enamine isomers **4a** or **5a** with $AgBF_4^-$. ^1H and ^{13}C NMR spectral and X-ray structural data are given for this strained tricyclic system **9a**.

Introduction

Diaminobicyclohexanecarbonitrile diastereomers **1a**,**b** and **3a**,**b** could be synthesized with high stereoselectivity from cyclohexanone derivative **2** by two five-step sequences.[1] Identical chemical transformations were used; the sequence of the steps, however, caused the stereodifferentiation of the syntheses (see Scheme 1).

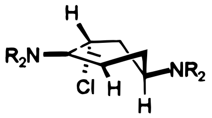
Scheme 1



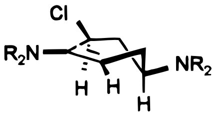
The way from **2** to **1a** included the reaction of chloro enamine stereoisomers **4a**/**5a** as a 7:3 mixture with cyanide in acetonitrile−water (9:1). A detailed study showed that this procedure provided **1a** with 85% diastereoselectivity.[2]

This result was interpreted as the consequence of an easier formation of a 3α-bicyclohexane-6-iminium species **6a** with respect to its 3*β*-isomer **7a**; aminoallyl cation **8a**, thereby, should be passed on the way from **5a** to **6a**.

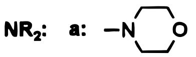
For a better understanding of these reactions, we studied the analogous ionic species **6c**, **7c**, and **8c** by ab initio calculations. These theoretical investigations should give an insight into the energetic situation of the various possible reaction paths starting from chloro enamines **4a** and **5a**. Additionally, the solvolysis of chloro enamine isomers **4a** and **5a** was investigated as a simple method for the generation of cationic intermediates **6a**, **7a**, and **8a**. The results of these studies are reported in this paper.

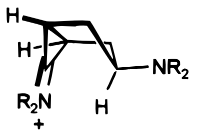


4a

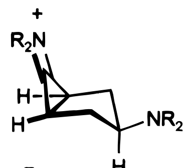


5a

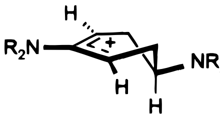




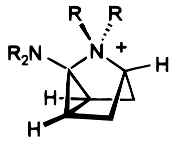
6a,c



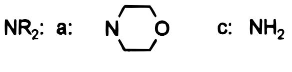
7a,c



8a,c



9a,c



Computational Methods

Calculations were performed for parent structures **6c**−**9c** in which the morpholino groups were replaced by NH_2 moieties. All geometries were fully optimized in C_s or C_1 symmetry using the Gaussian 92 and Gaussian 94 program packages.[3a,b] The 6-31+G* basis set was applied in order to account for potential long-range interactions (e.g., nitrogen

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⊗ Abstract published in *Advance ACS Abstracts,* November 1, 1996.

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Table 1. HF/6-31+G*, MP2/6-31+G*, and MP4(SDTQ)/6-31G* Total Energies (au), Zero-Point Energies (ZPE, kcal/mol), and Relative Energies Including Zero-Point Correction (kcal/mol) of Cationic Intermediates 6c, 7c, 8c, and 9c and of Transition States of the Reactions 8c → 6c, 8c → 7c, and 7c → 9c

compd	HF/6-31+G* (au)	ZPE[a] (kcal/mol)	E_{rel}[b] (kcal/mol)	MP2//HF[c] (au)	E_{rel}[b] (kcal/mol)	MP2//MP2[c] (au)	E_{rel}[b] (kcal/mol)	MP4//MP2[d] (au)	E_{rel}[b] (kcal/mol)
6c	−342.23808	102.18	19.6	−343.33060	27.5	−343.33398	26.8	−343.42367	25.2
7c	−342.23447	102.20	21.9	−343.32584	30.6	−343.32872	30.1	−343.41857	28.4
8c	−342.23481	100.45	19.9	−343.31600	35.0				
9c	−342.27284	104.41	0.0	−343.37805	0.0	−343.38025	0.0	−343.467231	0.0
8c → **6c**	−342.22720	100.94	25.2	−343.32538	29.6				
8c → **7c**	−342.21851	101.06	30.7	−343.31695	35.0				
7c → **9c**	−342.23423	102.25	22.1	−343.32527	31.0	−343.32801	30.6		

[a] Zero-point energy scaled by a factor[5] of 0.89. [b] Relative energies corrected for zero-point vibration using scaled zero-point energies from frequency calculations at HF/6-31+G* level of theory. [c] 6-31+G* basis set is used in all cases. [d] 6-31G* basis set is used for the MP4 single-point-calculations.

lone pairs) by the use of diffuse functions at all heavy atoms.[4a−c] The cations were preoptimized at HF/3-21G* level of theory followed by refinement of the geometries at HF/6-31+G* and MP2/6-31+G* levels. The same method without MP2-optimization was used for transition states **8c** → **6c** and **8c** → **7c**, which correspond to the ring closure of allyl cation **8c** leading to bicyclohexane structures **6c** and **7c**, respectively.

Frequency calculations were performed for all stationary points, and the structures were proved as real minima and transition states by zero and one imaginary frequencies, respectively. Zero-point energies (ZPE) derived from the frequency calculations were scaled by the factor[5] of 0.89 and added to the relative energies. In the case of allyl cation **8c**, optimization in C_s symmetry resulted in two imaginary frequencies, and removal of the symmetry restriction was required to locate a real minimum in C_1 symmetry. Single-point-calculations at MP2/6-31+G* level were carried out using the HF/6-31+G* geometries for further improvement of the energies. Partially contradictory results of the single points with respect to the Hartree−Fock (HF) calculations prompted us to reoptimize all minima at MP2/6-31+G* level of theory (vide infra). The reliability of these energies finally was improved by MP4(SDTQ)/6-31G* single point calculations using the MP2-optimized structures. Unfortunately, our computation facilities limited us to the use of the 6-31G* basis set for MP4 calculations. We approximated the MP4/6-31+G* energies by calculating the increments between MP2/6-31G* and MP4/6-31G* total energies and adding these to the MP2/6-31+G* results.

Results and Discussion

Ab Initio Calculations. Calculations at the HF/6-31+G* level showed relatively small differences in energy for the cationic intermediates **6c**, **7c**, and **8c**; **6c** in the boat conformation, thereby, turned out to be more stable than **7c** in a chair conformation by approximately 2 kcal/mol (Table 1). No minimum was found for **7c** in a boat conformation; all efforts to minimize such a structure resulted in bond formation between the amino group at C(3) and the iminium cation at C(6) to give azoniatricyclene species **9c**. A very small activation barrier of 0.2 kcal/mol was determined for the reaction **7c** → **9c**. This transition state still shows chair-like geometry as established by the dihedral angle α of the planes C1−C2−C4−C5 and C2−C3−C4 of 10.9° (**7c**, $\alpha = 36.5°$); it corresponds, therefore, to the inversion of the chair conformation of **7c**. This is clearly confirmed by calculations at the parent bicyclo[3.1.0]hexane which gave a comparable value for the inversion of the chair conformation to the more stable boat conformer.[6] No further activation barrier was found for the C6−N3 bond formation. Ammonium ion **9c** is predicted to be about 22 kcal/mol lower in energy than its precursor **7c** and turns out to be the global minimum of the investigated system. Different energies were found for the transition states of the two possible ring closure reactions of the aminoallyl cation **8c**. The way to 3α-iminium ion **6c** should require distinctly less energy ($\Delta E = 5.3$ kcal/mol) than the formation of 3β-iminium ion **7c** ($\Delta E = 10.8$ kcal/mol).

The situation of allyl cation **8c** within these cationic intermediates changed completely upon MP2/6-31+G* single-point-calculations leading to similar energetic values for cation **8c** and for transition state **8c** → **7c**. Subsequent reoptimization of structures **6c**−**9c** at MP2/6-31+G* level of theory resulted in no minimum for allyl cation **8c**. All attempts for optimization of this geometry led to formation of cyclopropaniminium structure **6c**. Again, azoniatricyclene **9c** was established as the most stable of the cationic species and was predicted to be more stable by 26.8 and 30.1 kcal/mol with respect to iminium ions **6c** and **7c**, respectively. The activation barrier for formation of **9c** from **7c** again was found to be very small (0.5 kcal/mol, see also ref 6b).

The applicability of the MP2 method for these cationic systems was underlined by MP4(SDTQ)/6-31G* single-point-calculations on the MP2-optimized geometries. The difference in energy between azoniatricyclene species **9c** and the iminium structures **6c** and **7c** decreased by only 1.6 and 1.7 kcal/mol, respectively.

Plots of cations **6c**, **7c**, and **9c** are shown in Figure 1. Atomic distances of the cyclopropaniminum unit in **6c** and **7c** from calculations at different levels of theory are given in Table 2. Selected atomic distances of **9c** are listed in Table 5. The contradictory predictions about

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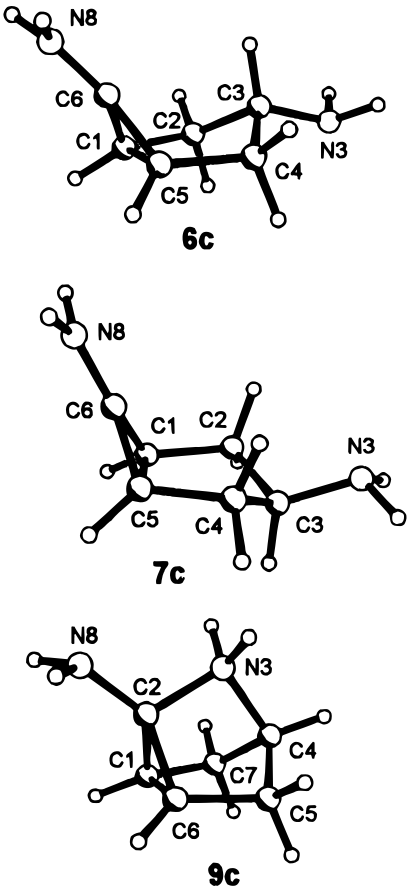


6c

7c

9c

Figure 1. Structures of cations **6c**, **7c**, and **9c** from ab initio calculations at the MP2/6-31+G* level of theory. Numbering of atoms corresponds to the usual counting in the parent systems.

Table 2. Atomic Distances of the Cyclopropaniminium Unit in Cations 6c and 7c from ab Initio Calculations at MP2/6-31+G* Level of Theory. HF/6-31+G* Values in Parantheses and HF/3-21G* Values in Brackets

	atomic distances (Å) of the cyclopropaniminium unit		
cation	N−C	C(1−-C(6) (C(5)−C(6)	C(1)−C(5)
6c	1.291	1.437	1.610
	(1.270)	(1.445)	(1.550)
	[1.264]	[1.463]	[1.547]
7c	1.286	1.441	1.578
	(1.268)	(1.444)	(1.543)
	[1.263]	[1.458]	[1.548]

the status of allyl cation **8c** required a more detailed study of the potential energy curve of the interconversion of the species **6c** and **7c** via **8c**. The energy of cationic species on the way from **7c** → **8c** → **6c**, therefore, was calculated as a function of the dihedral angle Θ between the C1−C2−C4−C5 and the C1−C5−C6 plane. The fixed angle Θ was varied stepwise between 110° and 245°. The geometry was restricted to C_s-symmetry. All other internal coordinates were optimized at MP2/6-31+G* level of theory which gave the HF and MP2 energies. Additionally, single-point-calculations were performed at MP4/6-31G* level of theory. The MP2-optimized iminium ions **6c** and **7c** afforded dihedral angles Θ of 244.0° and 112.3°, respectively. Aminoallyl cation **8c** was expected to appear at Θ = 180°. The obtained potential energy curves are graphically displayed in Figure 2; the numerical data are given in Table 3.

Table 3. Relative Energies and C1−C5 Distance of the Cationic Species on the Way from 7c → 8c → 6c as a Function of Dihedral Angle Θ between the C1−C2−C4−C5 and the C1−C5−C6 Plane. HF, MP2, and MP4 Energies for Selected MP2-Optimized Structures

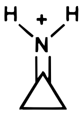
dihedral angle (Θ, deg)	C1−C5 distance (Å)	HF//MP2[a] (E_{rel},[c] kcal/mol)	MP2//MP2[a] (E_{rel},[c] kcal/mol)	MP4//MP2[b] (E_{rel},[c] kcal/mol)
244.0	1.610	0.00[d]	0.00[e]	0.00[f]
240	1.642	1.11	0.28	
230	1.818	5.67	2.67	
220	2.114	5.82	4.29	4.32
210	2.244	4.35	4.94	
200	2.318	3.54	5.68	4.67
190	2.360	2.95	6.40	
180	2.380	3.11	7.04	5.76
170	2.376	4.07	7.67	
160	2.350	6.07	8.28	7.14
150	2.286	8.94	8.68	7.85
140	2.158	11.42	8.85	8.66
130	1.772	10.20	7.46	8.04
120	1.618	3.93	4.24	4.43
112.3	1.578	1.71	3.30	3.20

[a] 6-31+G* basis set is used. [b] 6-31G* basis set is used for MP4 (SDTQ) single-point calculations. [c] Relative energy without correction for zero-point vibrational energy. [d] Absolute value: −342.33403 au. [e] Absolute value: −343.33398 au. [f] Absolute value: −343.42367 au.

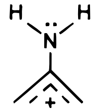
The calculated values in Table 3 do not include zero-point-energy correction from frequency calculations at each point due to our limited computation capacity. The dependence of zero-point energy from the dihedral angle Θ, however, is described in a sufficient approximation by the zero-point-energy values of the HF calculations of the species **6c**, **7c**, and **8c** and the transition states **6c** → **8c** and **7c** → **8c**. These results and the determined corresponding Θ values were used for construction of a representative curve of relative zero-point energies of the investigated system which is added to each potential energy curve in Figure 2.

Figure 2 shows that HF calculations on the one hand and MP2 and MP4 calculations on the other hand result in completely different potential energy curves. As expected, two maxima and three minima were found at the HF level. The HF minimum at Θ ≈ 190° corresponds to allyl cation **8c**. The passing of the allyl cation structure **8c** is also reflected by the evolution of the C1−C5 distance (Table 3). But this minimum and the maximum for the transition **6c** → **8c** disappeared in the MP2 and MP4 curves; the remaining maximum near 140° is comparable with that of the HF transition **7c** → **8c**. The potential energy curves clearly show that both diffuse basis functions and the MP4 level of theory reduce the relative energy of the minimum energy pathway and the transition state, while the relative energies of the minima **6c** and **7c** are barely affected. Hence, we have strong evidence that **8c** cannot be an existing intermediate. This would be in agreement with the absence of any trapping products of aminoallyl cation **8a** with nucleophiles (vide infra).

The finding that allyl cation **8c** does not have an equilibrium structure at the MP2 and MP4 level, differs



10



11

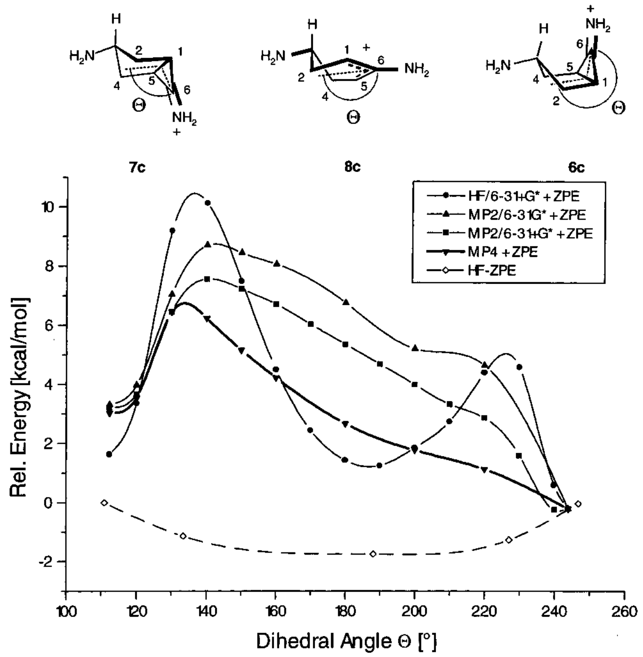
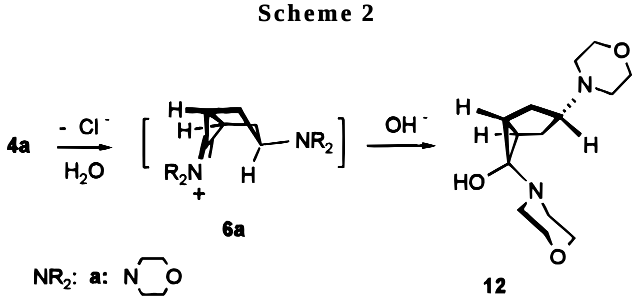


Figure 2. Energies of the cationic species on the way from **7c** → **8c** → **6c** as a function of dihedral angle between the C1–C2–C4–C5 and the C1–C5–C6 plane. HF, MP2, and MP4 energies for selected MP2-optimized structures including zero-point energy.

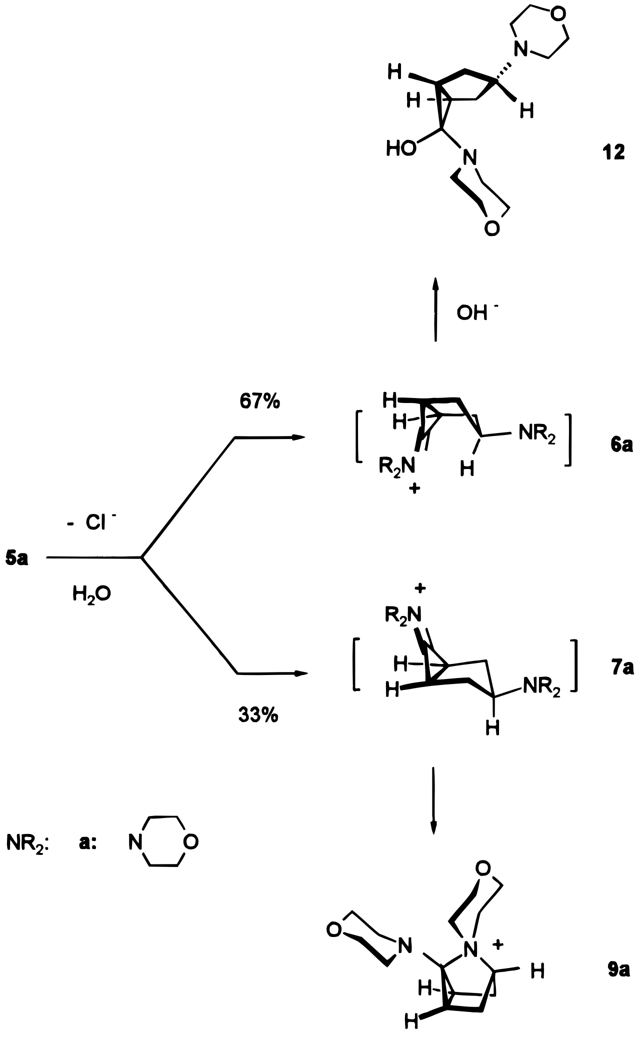
strongly from the reports about ab initio[7–9] or semiempirical[10] calculations for the parent systems **10** and **11** in which both cations were predicted as having energetic minima on the potential energy surface. Cyclopropaniminium ion **10**, thereby, turned out to be the more stable species in all cases [**10**/**11** ΔE (kcal/mol), 33.4,[7] 23.4,[8] 20.8,[9] 24.4 (AM1)[10] and 17.7 (MNDO)[10]]. In the most recent publication,[9] energies of cations **10** and **11** were calculated on HF/3-21G, HF/6-31G*, MP2/6-31G*, and even MP4/6-31G* levels of theory, but only the HF/3-21G level was used for geometry optimization. We could demonstrate in the meantime[11] that using a higher level for optimization of geometry gives no minimum for the aminoallyl cation **11**. More extensive calculations about this topic are in progress and will be published separately.[11]

Solvolysis of Chloro Enamines 4a and 5a. Solvolysis of **4a** or **5a** in NaOD/D_2O occurred very quickly as indicated by the absence of any chloro enamine signals in immediately measured ^{1}H NMR spectra. The ^{13}C NMR spectrum of the reaction mixture of trans chloro enamine **4a** showed the formation of only one product which was identified as 3α-amino 6α-semiaminal **12** (See Scheme 2). Small impurities (less than 5%) could be detected beside derivative **12** as the main product by following the solvolysis of **4a** by ^{1}H NMR spectroscopy. Cis chloro enamine **5a** as starting material produced mainly 3α-amino 6α-semiaminal **12** in addition to a second compound (ratio 2:1) (See Scheme 3). 3α-Amino 6α-semiaminal **12** was removed by extraction with dichloromethane. The remaining intermediate product in the aqueous solution could be established as 2-amino-3-azoniatricyclene species **9a** by the ^{1}H (at 0 °C) and ^{13}C NMR spectra (−35 °C, addition of CD_3OD). It decomposed at 0 °C within 12 h, providing one product which proved to be 3β-amino 6α-semiaminal **13**.

Scheme 2



Scheme 3



The results of the ab initio calculations predict an access to 3-azoniatricyclene **9a** if cations **6a** or **7a** could be generated in the absence of a nucleophile. And indeed, derivative **9a**·BF_4^- was obtained by addition of silver tetrafluoroborate to a solution of either trans chloro

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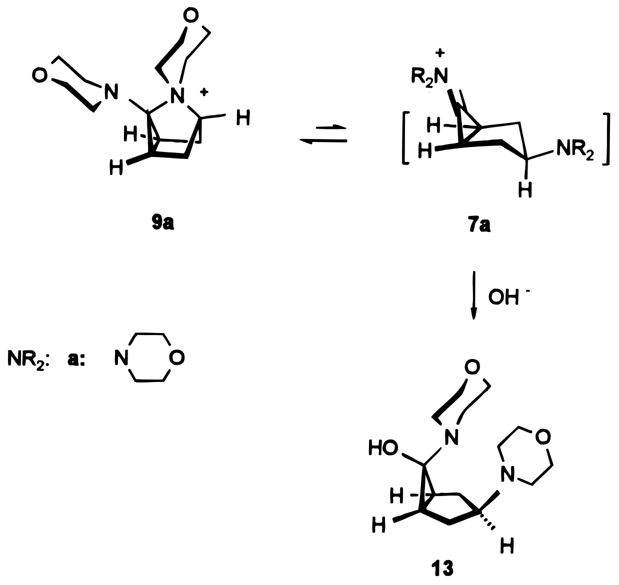
Scheme 4



Scheme 5

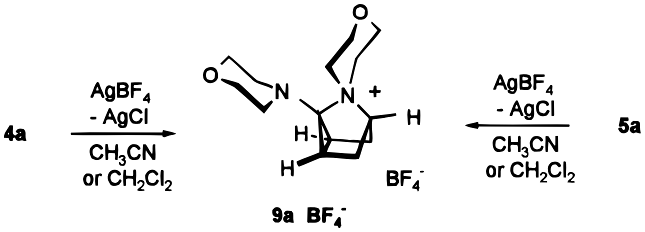


Table 4. NMR Data of the Cationic Intermediate 9a from Cis Chloro Enamine 5a upon Solvolysis (δ values in ppm, *J* in Hz, D_2O, CH_2Cl_2 as standard)[a]

structural unit	^{13}C NMR δ (m,[b] $^1J_{CH}$)	^1H NMR δ (m[b])
carbocyclic unit		
C(1)−H, C(6)−H	16.2 (d, 184)	2.13 (s[c])
C(5)−H, C(7)−H	29.8 (t, 135)	1.80 (H_A[d])
		2.19 (H_B[d])
C(4)−H	58.5 (d, 166)	4.37 (s[e])
C(2)	74.3 (s)	
morpholinium unit		
NCH_2	49.3 (t, 144)	3.02 (H_A[f])
		3.36 (H_B[f,g])
OCH_2	61.4 (t, 143)	3.79 (H_X[f,g])
		3.89 (H_Y[f])
morpholino unit		
NCH_2	50.9 (t, 137)	2.62 (H_A[h,i])
		2.76 (H_B[h,j])
OCH_2	66.8 (t, 144)	3.64 (H_X[h,k])
		3.70 (H_Y[h,l])

[a] ^1H NMR: 400.135 MHz, CH_2Cl_2 δ 5.30 ppm. ^{13}C NMR: 100.61 MHz, CH_2Cl_2 δ 53.8 ppm. [b] Multiplicity. [c] $J < 1.5$ due to half-width of the signal. [d] AB system, $^2J_{HH} = 13.4$. [e] $J < 2.5$ due to half-width of the signal. [f] ABXY system, $^2J_{HH} = 12.7$. [g] $^3J_{HH} = 12.7$. [h] ABXY system. [i] $^2J_{HH} = 13.3$, $^3J_{HH} = 10.8$. [j] $^2J_{HH} = 13.3$. [k] $^2J_{HH} = 10.8$, $^3J_{HH} = 10.8$. [l] $^2J_{HH} = 10.8$.

enamine **4a** or cis chloro enamine **5a** in acetonitrile at −20 °C. The resulting ammonium tetrafluoroborate **9a**·BF_4^- was stable for a longer period in acetonitrile in the absence of water (See Scheme 5).

This information from NMR spectroscopy allowed a synthesis of both semiaminals **12** and **13** with high diastereoselectivity using a mixture of chloro enamine stereoisomers **4a**/**5a** (available in a 7:3 ratio)[2] as starting material. Solvolysis of the mixture of **4a**/**5a** and extraction of formed semiaminal with dichloromethane prior to the decomposition of the stable intermediate **9a** (from **5**) gave pure 3α-semiaminal **12** in 62% yield (theoretical amount 90%). Reaction of **4a**/**5a** with silver tetrafluoroborate in dichloromethane and subsequent addition of an aqueous sodium hydroxide solution, on the other hand, provided pure 3*β*-semiaminal **13** in 48% yield (See Scheme 4 and 5). Additionally, strained aminoazoniatricyclene tetrafluoroborate **9a**·BF_4^- could be obtained in solution in acetonitrile without considerable decomposition.

Structure of Semiaminals 12 and 13. 6*β*-Configuration of both **12** and **13** followed from the hindrance of dynamics of one morpholine (ABXY system in the ^1H NMR[1,2,12–15]). 3α-Configuration of **12** could be deduced from the typical signals of the C(3)−H unit [^1H NMR ($CDCl_3$) $\delta = 3.02$, $^3J_{AM} = {}^3J_{AN} = 7.7$ Hz; ^{13}C NMR (D_2O) $\delta = 66.6$ (d, $^1J_{CH} = 142$ Hz), ($CDCl_3$) $\delta = 67.2$ (d); boat conformation[1,2,12,16,17]]. The analogous signals of **13** indicated the presence of a 3*β*-configuration and a chair conformation [C(3)−H, ^1H NMR ($CDCl_3$) δ 3.09, $^3J_{AM} = 10.7$ Hz; $^3J_{AN} = 7.9$ Hz; ^{13}C NMR (D_2O) δ 74.8 (d), $^1J_{CH} = 134$ Hz[1,2,12,16,17]].

Structure of 2-Amino-3-azoniatricyclene 9a. ^1H and ^{13}C NMR spectral data (Table 4) indicate the presence of a plane of symmetry in **9a**. The concordance of ^1H and ^{13}C NMR signals was determined by a CH-COSY experiment. Increased $^1J_{CH}$ coupling constants for C(1)−H/C(6)−H (e.g., $^1J_{CH} = 175$ Hz in nortricyclene[18]) and C(4)−H and N(CH_2) of one morpholine moiety and high-field shifting of C(1)/C(6), C(4) (typical for nortricyclene[19]), and of one morpholine OCH_2 group (typical for *β*-positions of ammonium ions[20]) are remarkable in the ^{13}C NMR spectrum. The absence of a vicinal coupling for the hydrogen atoms of the carbocyclic unit in the ^1H NMR spectrum is not surprising [only small $^3J_{HH}$ coupling constants ($J \approx 1.5$ Hz)[21] in nortricyclene]. ^1H NMR shifts of both morpholino moieties are quite different; ABXY-type ^1H NMR signals are observed for both morpholino moieties. This is not understandable since an ABXY system is expected only for the morpholinium unit. The other morpholine system in the exo-position, however, should appear as AA′XX′ signal pattern.[2,12–15]

Remaining doubts about the structure of **9a** due to the atypical ABXY-type ^1H NMR signals for the exo-morpholine could be removed by an X-ray crystallographic analysis of the corresponding tetrafluoroborate. Figure 3 shows the plot of the cation of **9a**·BF_4^-; characteristic bond lengths, bond angles, and interplanar angles are listed in Table 5.

Agreement of bond lengths of **9a**·BF_4^- (from the X-ray structural analysis) and **9c** (from ab initio calculations)

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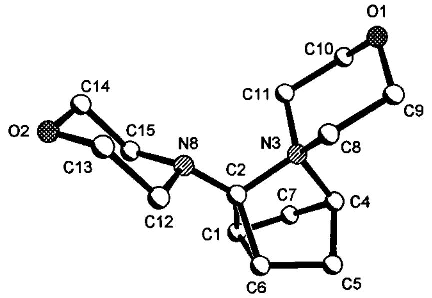
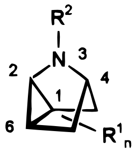


Figure 3. X-ray structure of **9a**·BF_4^-. Hydrogen atoms and the tetrafluoroborate anion were omitted for reasons of clarity.

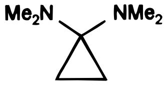
seems to be quite satisfactory in spite of different amino moieties in both derivatives (Table 5). The BF_4^- anion leads to a slight distortion of the cation **9a** and disturbs its symmetry. A relatively large difference of C(2)−N(3) and C(2)−N(8) bonds ($\Delta = 0.136$ Å) deserves attention. Quaternization of a tertiary amine generally causes an average C−N bond lengthening of only 0.04 Å.[22] The cyclopropane−N distances in diamino nitriles **1b** and **3a** were found to be betwen 1.412(1)[1] and 1.425(2) Å.[12] A C−N distance of 1.462 ± 0.013 Å was determined for the parent aminocyclopropane by microwave spectroscopy[23] (calculated C−N distance is 1.418 Å, bisected conformation; 4-31G//4-31G level[24]). The relatively short C(2)−N(8) distance in **9a**·BF_4^- (1.397 Å) may explain the unexpected hindrance of the dynamics of the exo-morpholine.



14

$R^1_2N-CH_2-\overset{+}{N}R^2_3$

15



16

$Me_4N^+\ FSO_3^-$

17

Some compounds with 3-azanortricylene system **14** have been described in the literature;[25−28] again small vicinal coupling constants were reported.[27] The origin of **9a** is an intramolecular stabilization of bicyclic iminium ion **7a** by the morpholino moiety in the 3-position. Reactions of simple iminium ions with tertiary amines are known from the literature;[29] the resulting α-aminomethyl ammonium salts **15** were described as sensitive against moisture[29] and as giving iminium ions upon heating.[30] Alkylation of aminals was reported[30] to produce compounds of type **15**, too. In contrast to this, the immediately formed precipitate from the reaction of cyclopropanone aminal **16** with methyl fluorosulfate at −78 °C was shown to be tetramethylammonium fluorosulfate **17** instead of the expected aminocyclopropylammonium salt.[31] An example of an easy transannular cyclization in a cyclohexane by an amino moiety was described very recently.[32]

Table 5. Selected Bond Distances (Å) and Bond Angles (deg) of Aminoazoniatricyclene Species 9a·BF_4^- (X-ray Analysis) and 9c (ab initio Calculation, MP2/6-31+G* Level)

	9a·BF_4^-	**9c**
	Bond Distances (Å)	
C(1)−C(2)	1.449(3)	1.506
C(1)−C(6)	1.523(4)	1.526
C(1)−C(7)	1.504(4)	1.521
C(4)−C(5)	1.524(4)	1.533
C(4)−C(7)	1.528(4)	1.533
C(5)−C(6)	1.517(4)	1.521
C(2)−N(3)	1.533(3)	1.532
N(3)−C(4)	1.535(3)	1.515
C(2)−N(8)	1.397(3)	1.392
	Bond Angles (deg)	
N(8)C(2)N(3)	115.6(2)	115.3
C(2)N(3)C(4)	97.5(2)	99.6
C(5)C(4)C(7)	101.7(2)	103.8

Conclusion

The amino moiety in the 4-position of an 1-amino-6-chlorocyclohexene represents a "Janus-faced" stereocontrolling function. Solvolysis of such compounds **4** and **5** leads to 3α-substituted bicyclohexane derivatives **12** with high diastereoselectivity due to the preference of a boat conformation for the bicyclo[3.1.0]hexaniminium system and the anchoring effect of the 4-amino moiety. A neighboring group activity of the 4-amino moiety, however, becomes important if displacement of the chloride in **4** or **5** is forced in the absence of a nucleophile. The resulting strained aminoazoniatricyclene species **9** reacts with a nucleophile to give 3*β*-substituted bicyclohexane derivatives **13**. The "Janus-faced" stereocontrolling functionality in this system should be variable to a larger extent leading to a general principle of synthesis of substitued aminobicyclohexane stereoisomers.

Experimental Section

Solvolysis of Chloro Enamine Isomers 4a and 5a: NMR Experiments. Solvolysis of Trans Isomer 4a. Isomerically pure chloro enamine[2] **4a** (10 mg, 0.0348 mmol) was added to a solution of NaOD in D_2O (0.093 M, 0.75 mL) and shaken until a clear solution resulted which was analyzed by ^1H NMR spectroscopy. An analogous procedure was used for the sample for the ^{13}C NMR spectrum (**4a**, 60 mg, 0.209 mmol; NaOD in D_2O [0.167 M], 2.5 mL).

Solvolysis of Cis Isomer 5a. Isomerically pure chloro enamine[2] **5a** (10 mg, 0.0348 mmol) was added to an ice-cold solution of NaOD in D_2O (0.093 M, 0.75 mL) and shaken until a clear solution was obtained. The ^1H NMR spectrum indicated the formation of compounds **12** and **9a** (2:1 mixture). *N,O*-Semiaminal **12** was removed by extraction with dichloromethane (4 × 1.5 mL); the remaining aqueous layer con-

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sisted of a fairly pure solution of azoniatricyclene **9a**. The sample for the ^{13}C NMR spectrum was obtained analogously from **5a** (60 mg, 0.209 mmol), NaOD in D_2O (0.167 M, 2.0 mL), and extraction with dichloromethane (4 × 5 mL). The aqueous solution was diluted with CD_3OD (1.5 mL), and the ^{13}C NMR spectrum was recorded at −35 °C.

The decomposition of the solution of **9a** to **13** was followed by ^{1}H and ^{13}C NMR spectroscopy at room temperature. In the latter case, no CD_3OD was added to the sample.

Generation of Azoniatricyclene Species 9a in Nonaqueous Solvents: NMR Spectra. CD_3CN (0.75 mL) was added at −40 °C to a mixture of chloro enamines[1,2] **4a** and **5a** (7:3; 60 mg, 0.21 mmol) and silver tetrafluoroborate (120 mg, 0.62 mmol). Then the suspension was stirred for 2 h; during this time the temperature rose to −25 °C. The solid was removed by suction at −25 °C; ^{1}H and ^{13}C NMR spectra of the resulting solution of **9a**·BF_4^- were recorded at −25 °C.

Preparation of Semiaminals 12 and 13. 1α,3α,5α,6α-3,6-Dimorpholinobicyclo[3.1.0]hexan-6-ol (12). Chloro enamine[1,2] **4a**/**5a** [0.73 g, 2.55 mmol, cis−trans mixture (3:7)] was added to an aqueous sodium hydroxide solution (0.1 M, 50 mL) and stirred at 0 °C for 15 min. The resulting clear solution was extracted with dichloromethane (12 × 25 mL at 0 °C and 6 × 25 mL at 20 °C). Evaporation of the organic solvent and drying in vacuo gave crude semiaminal **12**, which was purified by extraction with ether (50 mL) in a Soxhlet apparatus. Removal of the solvent and trituration of the residue with acetonitrile−ether (1:3, 10 mL) gave colorless crystalline semiaminal **12**. Yield: 0.42 g (62%), mp 165 °C dec. ^{1}H NMR ($CDCl_3$): δ 1.65 (H_{X1}, $H_{X'1}$, 2H), 1.72 (H_N, $H_{N'}$, 2H), 1.90 (H_M, $H_{M'}$, $^2J_{MN}$ = 13.1 Hz, $^3J_{AM}$ = 7.7 Hz, $^3J_{MX}$ < 0.7 Hz, 2H), 3.02 (H_{A1}, $^3J_{AM}$ = $^3J_{AN}$ = 7.7 Hz, 1H) (AMM′NN′XX′ system), 2.35 (H_{X2}, $H_{X'2}$, 4H), 3.70 (H_{A2}, $H_{A'2}$, 4H) (AA′XX′ system), 2.58 (H_Y, 2H), 2.90 (H_{X3}, 2H), 3.53 (H_B, 2H), 3.83 (H_{A3}, 2H) (ABXY system), 2.30 (broad, 1H, OH). ^{13}C NMR (D_2O): δ 75.9 (s), 66.9 (t), 66.6 (d, $^1J_{CH}$ = 142 Hz), 65.9 (t), 51.3 (t), 47.6 (t), 30.6 (d, $^1J_{CH}$ = 165 Hz), 29.8 (t). Anal. Calcd for $C_{14}H_{24}N_2O_3$: C, 62.66; H, 9.01; N, 10.44. Found: C, 62.7; H, 9.0; N, 10.4.

1α,3*β*,5α,6α-3,6-Dimorpholinobicyclo[3.1.0]hexan-6-ol (13) from decomposition of Azoniatricyclene 9a·BF_4^-. A solution of azoniatricyclene **9a**·BF_4^- was prepared from chloro enamine[1,2] **4a**/**5a** [0.21 g, 0.73 mmol, cis−trans mixture (3:7)] and silver tetrafluoroborate (0.15 g, 0.75 mmol) in dichloromethane (25 mL) at −78 °C. Stirring was continued for 2 h, thereby allowing the temperature to rise to −50 °C. The mixture was warmed to room temperature, and the solid was removed by suction. The solvent of the filtrate was evaporated, and the residue was triturated at 0 °C with aqueous sodium hydroxide (30 mL, 0.1 M). The resulting aqueous solution of **9a**·BF_4^- was extracted with dichloromethane (10 mL) to remove byproducts. Then aqueous sodium hydroxide (6.5 mL, 2 M) was added, and the aqueous solution was stored for 2 h at rt. Semiaminal **13** was extracted with dichloromethane (6 × 50 mL) and purified by recrystallization from pentane. Yield: 0.095 g (48%), mp 136 °C. ^{1}H NMR ($CDCl_3$): δ 1.32 (H_M, $H_{M'}$, 2H), 1.59 (H_{X1}, $H_{X'1}$, 2H), 1.90 (H_N, $H_{N'}$, 2H), 3.09 (H_{A1}, $^3J_{AM}$ = 10.7 Hz; $^3J_{AN}$ = 7.9 Hz, 1H) (AMM′NN′XX′ system), 2.46 (H_{X2}, $H_{X'2}$, 4H), 3.69 (H_{A2}, $H_{A'2}$, 4H) (AA′XX′ system), 2.55 (H_Y, 2H), 2.93 (H_{X3}, 2H), 3.59 (H_B, 2H), 3.86 (H_{A3}, 2H) (ABXY system), 2.09 (s, 1H, OH). ^{13}C NMR (D_2O): δ 79.2 (s), 74.8 (d, $^1J_{CH}$ = 134 Hz), 66.8 (t), 66.5 (t), 50.5 (t), 46.7 (t), 30.0 (d, $^1J_{CH}$ = 169 Hz), 26.2 (t). Anal. Calcd for $C_{14}H_{24}N_2O_3$: C, 62.66; H, 9.01; N, 10.44. Found: C, 62.4; H, 9.0; N, 10.5.

X-Ray Crystal Structure of 2-Morpholino-3-azatricyclene-3-spiro-4′-morpholinium tetrafluoroborate 9a·BF_4^-.[33] Single crystals were obtained from a solution of **9a**·BF_4^- in acetonitrile−ether (1:1) by addition of ether by the vapor diffusion method.[34]

Crystal data: $C_{14}H_{23}BF_4N_2O_2$, fw = 338.15, mp 131 °C; monoclinic, space group C_2/c; a = 25.771(6), b = 9.601(2), and c = 15.499(3) Å; $\alpha = \gamma$ = 90° and β = 125.61(1)°; V = 3117.7(11) Å^3; eight molecules per unit cell; D_x = 1.441 g cm^{-3}; crystal size 0.42 × 0.30 × 0.15 mm.

Data collection: Diffractometer Siemens P4, temperature, 183(2) K; monochromatized Mo Kα radiation; 4172 measured reflections, 3475 independent reflections with $1.94 < \Theta < 27.50°$, $R_{(\mathrm{int})} = 0.0365$, and 2162 observed reflections with $I > 2\sigma(I)$; no absorption correction.

Structure Solution and Refinement. The structure was solved by the direct method using SHELXS-86 [35] and refined by full matrix least-squares method on F^2 using SHELXL-93.[36] All non-hydrogen atoms were refined anisotropically, and hydrogen atoms were located from difference electron density maps and refined isotropically: 300 parameters; weighting scheme $w = 1/[\sigma^2(F_o^2) + (0.015P)^2 + 2.98P]$ where $P = (F_o^2 + 2F_c^2)/3$; R1[$F^2 > 4\sigma(F^2)$] = 0.0537, wR2[F^2] = 0.1078.

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[33] The author has deposited atomic coordinates, bond lengths and angles, and thermal parameters for this structure with the Cambridge Crystallographic Data Centre. The X-ray data can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK.

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