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COMPUTATION OF N-C-N SYSTEMS: THEORY VS. EXPERIMENT[1]

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Abstract. *In sequel to a previous recent study[4], methylenediamine (MDA) was calculated by higher level ab initio methods namely 6-31G* and MP3//6-31G* levels. The influence of polarization functions on the calculated pyramidality of nitrogen and on the magnitude of the anomeric effect is discussed. At the same time, a structural-statistical study was performed on molecules containing the N-C-N moiety retrieved from the Cambridge Structural Database (CSD). Both methods complement and improve results from the previous study. Special attention was given to the tertiary amine case and the N-C-N bond angle for which new MM2 parameters are put forward. These are mainly based on ab initio calculations of N,N-dimethylmethylenediamine and tetramethylmethylenediamine and on a comparative study of C-N bond lengths in primary, secondary and tertiary amines.*

INTRODUCTION

We have pursued in recent years an approach to probe the stereoelectronic features of X-C-Y systems and refined a tool for predicting them. We combined MO-*ab initio* calculations with structural statistical analysis, to parameterize the MM2 force field for such molecules. After having first dealt with O-C-O systems[2,3] and before the recent treatment of the O-C-N grouping[5], we have published a study on stereoelectronics in N-C-N systems[4]. The work was based on 3-21G//3-21G *ab initio* calculations on small model molecules, and indicated that the *anomeric effect* in N-C-N systems is smaller than that in O-C-O systems at the same level (1.6 kcal/mol vs. 3.9 kcal/mol) but that its structural manifestations are borne out as expected[4].

The *anomeric effect* has been subject of extensive study during the last two decades[6]. Its most known manifestation is that an electronegative substituent at the anomeric carbon of, say, a pyranose ring prefers the axial (**1**) rather than the equatorial (**2**) conformation. In time it was generalized to any R-X-C-Y-R' system (X,Y electronegative heteroatoms) and defined as the tendency of the above moiety to assume *gauche* (**3**) rather than *anti* (**4**) conformations around the X-C and C-Y bonds[6-8].

The occurrence of an *anomeric effect* in a system influences its properties as follows:[1-4,8] (i) structure e.g., shorter or longer anomeric bonds and larger anomeric bond angles; (ii) energy i.e., greater stability of *gauche* (axial) forms over *anti* (equatorial) ones; (iii) reactivity i.e., variation of rates of attack at or around the anomeric center, all those as a function of geometry.

The most accepted explanation of the effect[6,7] invokes a stabilizing interaction between a lone pair situated on X and an antiperiplanar σ^* orbital of the adjacent C-Y bond (**5**), or in valence bond terms, double bond - no bond resonance (**5**↔**5'**)[6-8], best described as "negative hyperconjugation".[13]

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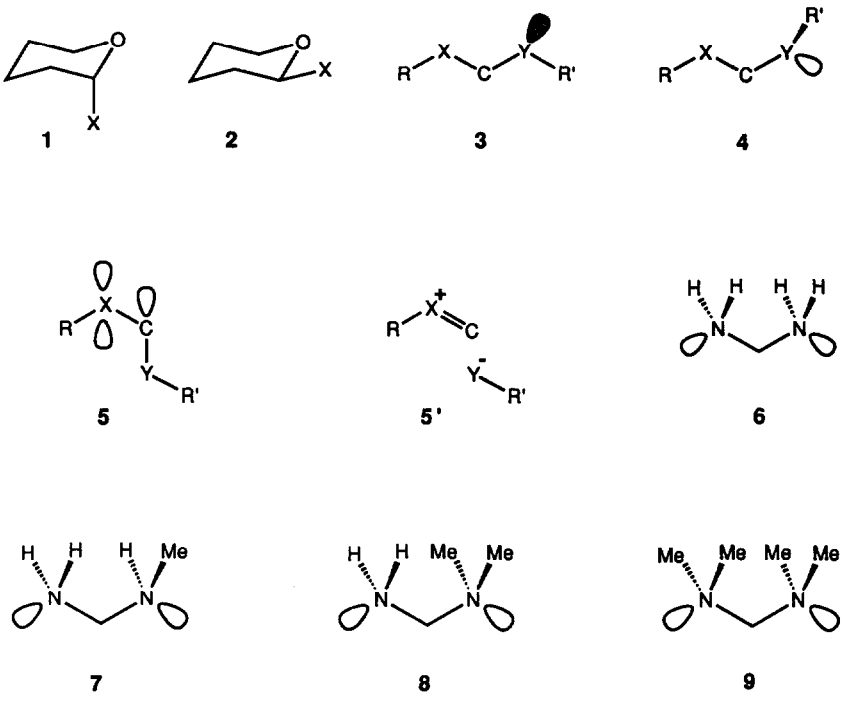


The current work is motivated by three main factors: (i) the absence of reliable experimental geometrical parameters for the N-C-N system in the previous study[4]; (ii) the need to cross-check the performance of the 3-21G basis set with respect to the N-C-N system, in particular, its ability to describe the pyramidality of the N atoms and the possibilities for H...N non bonded interactions; (iii) the lack of *ab initio* results for tertiary N-C-N moieties.

Therefore, we performed and describe here the results of a structural-statistical analysis of X-ray diffraction data for molecules containing the N-C-N moiety along with high level *ab initio* results for MDA (**6**) using large polarized basis sets (6-31G*, 6-31G**) and post HF methods (MP3). In addition to that we carried out 3-21G *ab initio* calculations for N,N-dimethylmethylenediamine (NNDMMDA) (**8**) and tetramethylmethylenediamine (TMMDA) (**9**); similar ones for methylenediamine (MDA) (**6**) and N-methylmethylenediamine (NMMDA) (**7**) were available from the previous study[4].

RESULTS AND DISCUSSION

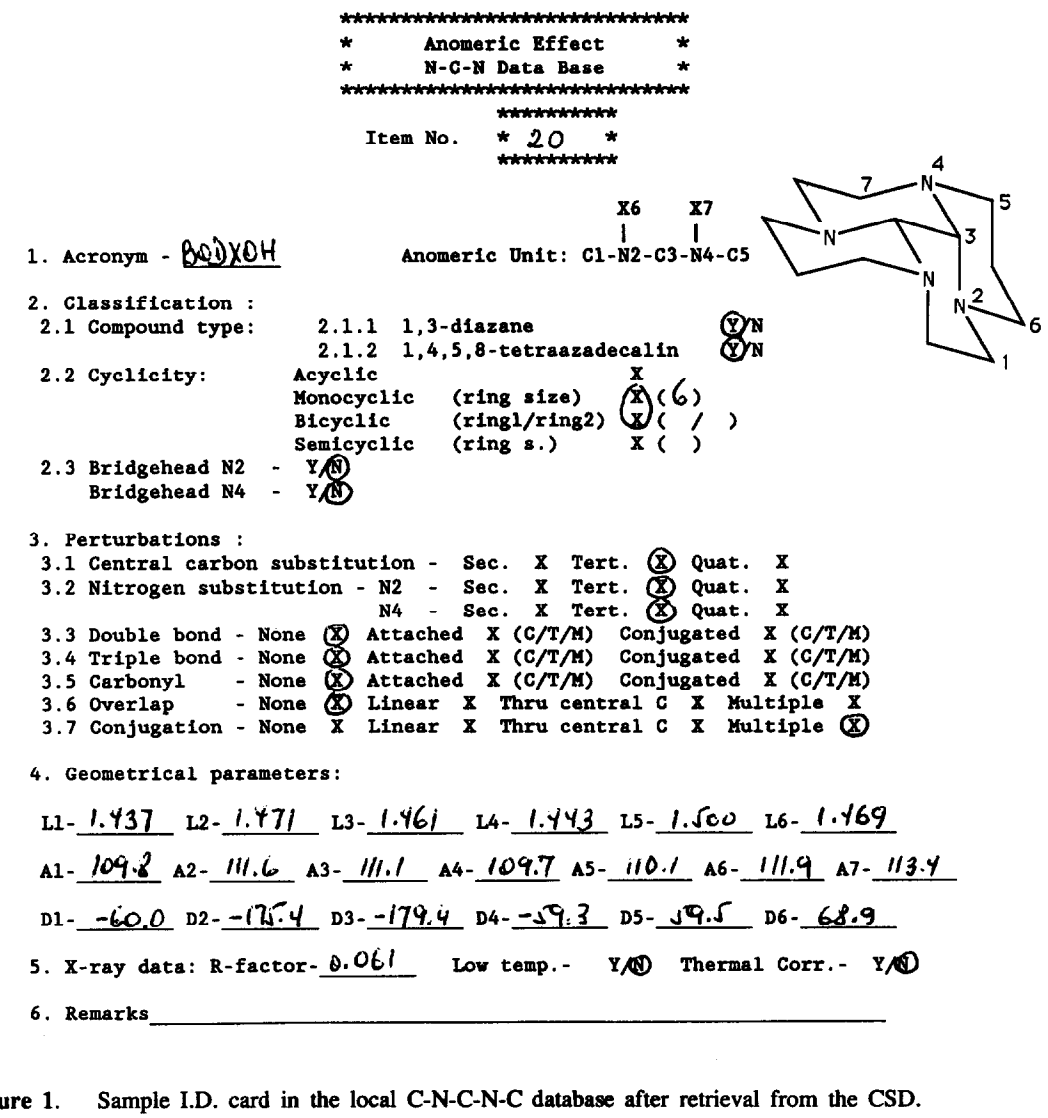
Structural analysis

Reliable structural parameters as often obtained from crystallographic analysis are good probes for the *anomeric effect*[6] and correlate well with the conformation of the anomeric moiety[1,3,5]. Hence, structures containing the R-N-C-N-R' moiety were retrieved from the Cambridge Structural Database (CSD, January 1990 edition)[9]. They were then subjected to a classifying and purging procedure. Structures

having at least one of the following features were removed from the data base:

1. R factor > 0.1
2. Double bond/Triple bond/Carbonyl attached to the anomeric unit.
3. Heteroatom connected to the anomeric unit.
4. Charged quaternary nitrogen in the anomeric unit.
5. Metal ion present in the molecule.

The resulting "pure" data set contained 214 entries, each of which was recorded on a specially designed card (Figure 1).



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**********************************
*      Anomeric Effect           *
*      N-C-N Data Base           *
**********************************
                 **********
  Item No.       * 20   *
                 **********

                                                    X6    X7
                                                    |     |
1. Acronym - BADXOH          Anomeric Unit: C1-N2-C3-N4-C5

2. Classification :
 2.1 Compound type:     2.1.1  1,3-diazane                    (Y)/N
                        2.1.2  1,4,5,8-tetraazadecalin        (Y)/N
 2.2 Cyclicity:       Acyclic                          X
                      Monocyclic   (ring size)        (X) (6)
                      Bicyclic     (ring1/ring2)      (X) (  /  )
                      Semicyclic   (ring s.)          X   (  )
 2.3 Bridgehead N2  - Y/(N)
     Bridgehead N4  - Y/(N)

3. Perturbations :
 3.1 Central carbon substitution -  Sec.  X  Tert. (X)  Quat.  X
 3.2 Nitrogen substitution - N2  -  Sec.  X  Tert. (X)  Quat.  X
                              N4  -  Sec.  X  Tert. (X)  Quat.  X
 3.3 Double bond - None (X) Attached  X (C/T/M)  Conjugated  X (C/T/M)
 3.4 Triple bond - None (X) Attached  X (C/T/M)  Conjugated  X (C/T/M)
 3.5 Carbonyl    - None (X) Attached  X (C/T/M)  Conjugated  X (C/T/M)
 3.6 Overlap     - None (X) Linear    X  Thru central C  X  Multiple  X
 3.7 Conjugation - None  X  Linear    X  Thru central C  X  Multiple (X)

4. Geometrical parameters:

L1- 1.437  L2- 1.471  L3- 1.461  L4- 1.443  L5- 1.500  L6- 1.469

A1- 109.8  A2- 111.6  A3- 111.1  A4- 109.7  A5- 110.1  A6- 111.9  A7- 113.4

D1- -60.0  D2- -176.4  D3- -179.4  D4- -59.3  D5- 59.5  D6- 68.9

5. X-ray data: R-factor- 0.061   Low temp.- Y/(N)  Thermal Corr.- Y/(N)

6. Remarks_____
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Figure 1. Sample I.D. card in the local C-N-C-N-C database after retrieval from the CSD.

Four conformations of the basic N-C-N unit were considered and defined (Figure 2): *aa*, $ag^{\pm}$, $g^{\pm}g^{\pm}$, and $g^{\pm}g^{\mp}$†. The entire set is shown in 3D-histogram form in Figure 3 in which the abundance of each conformation is taken as a qualitative indication of its relative stability. Further analysis of the data revealed a large number of overlapping anomeric units. This may influence anomeric structural parameters due to cross-hyperconjugation[3]. These structures were thus eliminated leaving a total of 34 entries in three populated groups: *aa*, $ag^{\pm}$, and $g^{\pm}g^{\pm}$. The data were rechecked for severe steric constraints resulting in a lean but reliable data set. A side effect of the described process is the exclusion of primary and secondary amines leaving structures containing only tertiary N atoms (except two cases with secondary N atoms left in the *ag* group). Results are presented in Table 1 along with a scheme of the structural moiety and parameters of interest. Starting with the energy criterion as indicated by relative abundance (Figure 3: *aa*-137 entries, $ag^{\pm}$-41 entries, $g^{\pm}g^{\mp}$-11 entries, $g^{\pm}g^{\pm}$-3 entries), the lp-N-C-N dihedral angle overwhelmingly prefers the *anti* rather than the *gauche* orientation (180 vs. 70 cases respectively). The *aa* group is the largest one (138 entries) followed by the $ag^{\pm}$ group (42 entries) while both the $g^{\pm}g^{\pm}$ and $g^{\pm}g^{\mp}$ groups are small (3 and 11 cases respectively). This is in good agreement with the calculated results obtained for MDA itself (*aa*=0.00 kcal/mol; $ag^{\pm}$=1.63 kcal/mol; $g^{\pm}g^{\pm}$=2.71 kcal/mol; $g^{\pm}g^{\mp}$=8.26 kcal/mol at 3-21G level). The particular small population of the $g^{\pm}g^{\pm}$ group, can be attributed to the lack of primary and secondary nitrogens which may be stabilized by H-bond type interactions which play a significant role in MDA[4].

The small final data base (Table 1) prevents the performance of any meaningful statistical analysis. In the relatively large $ag^{\pm}$ group (20 entries) the expected structural trends are actually observed: L2 (1.475Å) is larger than L3 (1.460Å) and the pyramidality†† of N2 is smaller than that of N4 (338.8° vs. 332.4° respectively) all in accord with one anomeric interaction. For example, in 10b,10c-cis-3a,5a,8a,10a-tetraazaperhydropyrene (**10**)[10] which belongs to this group, L2=1.461Å < L3=1.471Å. Also, both A1 and A4 are larger than A3 and A6 (111.9° and 111.5° vs. 109.7° and 109.8° respectively) in accord with one anomeric interaction (cf. Table 1 for definition of structural parameters). However, the differences from the data of other conformers are small and may lead to overinterpretations. It appears that this is due to the small stereoelectronic effect in N-C-N (as compared to O-C-O and O-C-N) and the observation of structural trends is obstructed by both the lack of sufficient strainless structures containing the N-C-N moiety and by steric effects which mask the weak n_N- $\sigma^*_{C\text{-}N}$ anomeric interaction.

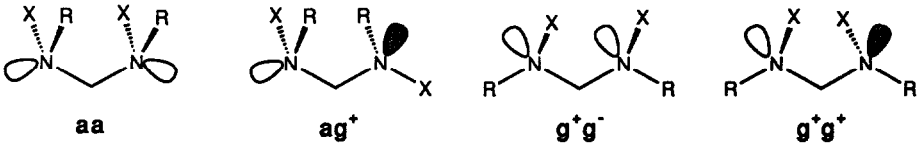


Figure 2. 4 conformers of the basic R-N-C-N-R' anomeric unit. Definitions are made through two dihedral angles: D1=lp-N-C-N and D2=N-C-N-lp, a=anti=±160-180°; g=gauche=±30-90°, R = C; X = C or H†.

† The four conformers are defined on the sequence lp-N-C-N-lp to avoid ambiguity and in accord with our[4] and others[13,17] previous studies. The location of the Nlp is determined according to the following procedure: 3 unit vectors are drawn from the nitrogen atom along its 3 bonds. The lp is located along the negative direction of the vector sum of these 3 vectors.

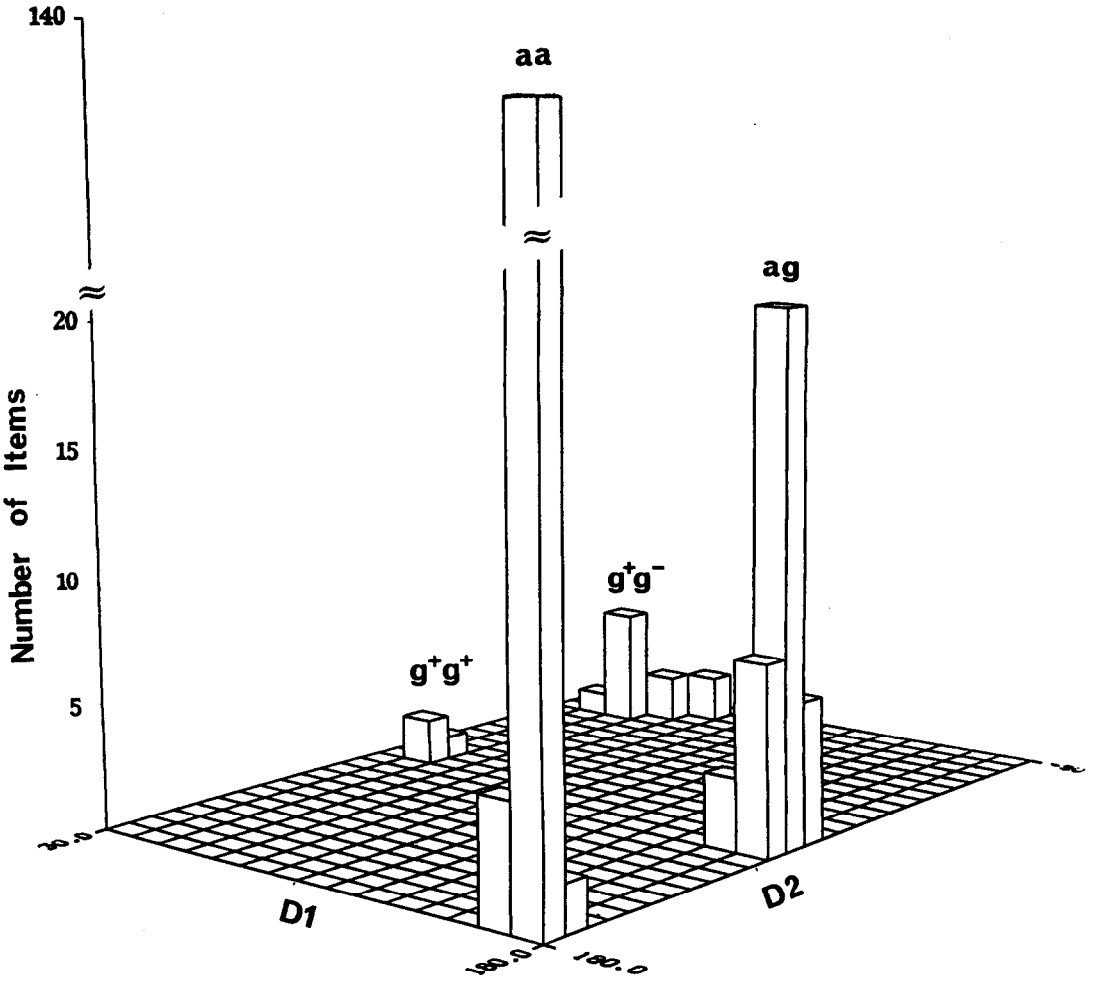
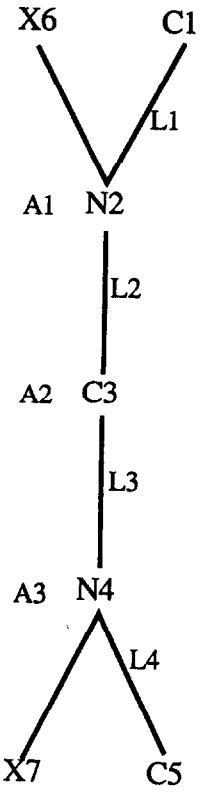


Figure 3. 3D Histogram of 193 structures containing the R-N-C-N-R moiety after suitable purging and "normalization" to one enantiomer in each case. Occurrence is shown as function of the two dihedral angles in the anomeric unit: D1=lp-N-C-N; D2=N-C-N-lp.

Table 1. Mean values of bond lengths (L, Å), bond angles (A, deg.) and dihedral angles (D, deg.) and their standard deviations (σ) in the various conformations of C1-N2-C3-N4-C5 containing structures retrieved from the CSD, after removal of cases deviating in more than 3σ from the mean values (cf. on the right scheme of the C1-N2(X6)-C3-N4(X7)-C5 anomeric unit,[a] where X may be any nonelectronegative atom).

		aa	$ag^{\pm}$	$g^{\pm}g^{\mp}$ [b]
	Entries	5	20	5
L	C1-N2	1.476	1.472	1.466
	σ	0.008	0.011	0.007
	N2-C3	1.479	1.460	1.462
	σ	0.009	0.008	0.007
	C3-N4	1.475	1.473	1.468
	σ	0.016	0.010	0.029
	N4-C5	1.487	1.476	1.470
	σ	0.018	0.015	0.009
	N2-X6	1.480	1.477	1.462
	σ	0.013	0.015	0.013
	N4-X7	1.490	1.464	1.468
	σ	0.010	0.012	0.004
A	C1-N2-C3	110.0	110.8	110.8
	σ	1.6	2.0	0.7
	N2-C3-N4	113.0	112.1	110.0
	σ	2.4	0.9	0.9
	C3-N4-C5	108.1	110.4	111.1
	σ	2.0	1.6	2.2
	X6-N2-C3	109.4	110.3	107.2
	σ	1.0	2.3	2.3
	C1-N2-X6	109.0	112.7	111.5
	σ	0.7	2.1	2.5
	X7-N4-C3	109.0	110.9	109.9
	σ	1.6	2.1	2.0
	C5-N4-X7	111.4	111.0	110.5
	σ	2.9	1.9	0.7
D	lp-N2-C3-N4	178.3	176.4	56.5
	σ	2.0	1.8	4.8
	N2-C3-N4-lp	178.7	56.1	57.1
	σ	2.3	4.4	2.1
	C1-N2-C3-N4	59.0	62.7	61.4
	σ	2.0	4.6	3.3
	N2-C3-N4-C5	61.6	62.5	61.9
	σ	2.6	3.7	2.1
	X6-N2-C3-N4	60.8	62.8	176.6
	σ	2.3	4.8	4.9
	N2-C3-N4-X7	59.7	173.5	176.1
	σ	1.7	6.3	3.6
	Pyramidality[††]:			
	N2:	328.5	338.8	329.6
	N4:	328.5	331.9	331.6



a L=bonds, A=bond angles, D=dihedral angles. L1=C1-N2, L2=N2-C3, L3=C3-N4, L4=N4-C5, L5=N
A1=C1-N2-C3, A2=N2-C3-N4, A3=C3-N4-C5, A4=X6-N2-C3, A5=C1-N2-X6, A6=X7-N4-C3, A7=C5-N4-X7,
D1=lp-N2-C3-N4, D2=N2-C3-N4-lp, D3=C1-N2-C3-N4, D4=N2-C3-N4-C5, D5=X6-N2-C3-N4, D6=N2-C3-N
b The conformations are in accord with the definitions made in Figure 2 and footnote †.

Ab initio calculations

We had previously calculated MDA at 3-21G//3-21G level[4] and a parameterization scheme for the *anomeric effect* in N-C-N systems was developed and introduced into Allinger's MM2-80 force field[4,11]. In sequel to that and as promised there[4] we proceeded to cross-check and improve on the approach, especially in what concerns N-pyramidality††, C-N bonds in tertiary amines and the N-C-N bond angle. Three different sets of calculations were designed and applied to MDA in its four conformations (Fig. 2, R=X=H and Table 2), according to the following rationale:

1. The inclusion of polarization functions at 6-31G*//6-31G* level[12] may provide a better description of the nitrogen's lp. It has been pointed out already that the 3-21G basis set underestimates N pyramidality[13]. This is intimately connected to the magnitude of the anomeric interaction via its influence on the n_N- $\sigma^*_{C\text{-}N}$ energy gap. We have therefore calculated the H-N-H bond angle in amonia at 3-21G level and found it to be 112.4°. A comparison with 6-31G* and experimental results indicate indeed, that the polarized basis set is in a much better accord with the experimental values (6-31G*: 107.2°; exp.: 106.7°)[14].
2. Large polarized basis sets are known to cause severe bond shortening[14,15]. Electron correlation can offset this[15]. Hence, MP3//6-31G* calculations were performed on all conformers with optimization of the C-N bond lengths and N-C-N bond angle.
3. In order to obtain a better description of interactions involving H atoms, 6-31G**//6-31G** calculations were performed as well.

The results in Table 2 show that the same trend in relative stability is obtained at all levels. The smaller energy difference between the conformers obtained with the polarized basis set may be attributed to an increase in the nitrogen pyramidality leading to a decreased *p* character of the lp's. At the same time severe C-N bond shortening was indeed observed. Electron correlation offset these two phenomena, bringing both the energy but especially the bond lengths into close agreement with 3-21G results and with common chemical knowledge. The N-C-N bond angle is relatively insensitive to the use of polarization functions.

Using the 6-31G** basis set, no additional stabilization of conformers having geometries suitable for interactions involving H atoms is observed. Based on these results, we therefore conclude that the 3-21G level was, in fact, adequate for treating N-C-N systems.

In this framework of the structural manifestations of the *anomeric effect*,[3] we would like to point out two additional aspects:

1. C-H bond lengths - At all levels there exists a correlation between the number of lp antiperiplanar to a C-H bond and its length[16].
2. Nitrogen pyramidality†† - Higher level calculations bring about a generally higher nitrogen pyramidality. However, a very small difference is observed, if at all, between the different conformations of MDA. The only clear manifestation of this kind is observed in the *ag* conformer where N1 is somewhat more pyramidal than N3. This may indicate, not as expected but as observed

††Nitrogen's pyramidality is defined here as the sum of the 3 valence angles around the nitrogen.[13] As the sum increases, the pyramidality decreases and the p character of the nitrogen lone pair increases.

Table 2. Selected structural parameters for MDA calculated at 3-21G, 6-31G*, 6-31G**, and MP3/6-31G* levels#. Numbers in parentheses indicated the number of lp's antiperiplanar to C-H bonds. Relative energies (Erel) in kcal/mol; bond lengths (L) in A; bond angles (A), dihedral angles (D), and pyramidalities in degrees.

	aa	$ag^{\pm}$	$g^{\pm}g^{\pm}$	$g^{\pm}g^{\mp}$
3-21G//3-21G				
Erel	0.00	1.63	2.71	8.26
L(N1-C2)	1.466	1.458	1.461	1.464
L(C2-N3)	1.466	1.471	1.461	1.464
L(C2-H6)	1.080(1)	1.086(1)	1.089(1)	1.081(0)
L(C2-H7)	1.080(1)	1.081(0)	1.089(1)	1.096(2)
A(N1-C2-N3)	118.4	113.4	106.9	110.4
Pyramidality:				
N1	340.3	335.7	339.9	340.0
N3	340.4	341.3	339.9	340.1
6-31G*//6-31G*				
Erel	0.00	0.43	0.71	5.20
L(N1-C2)	1.450	1.441	1.446	1.449
L(C2-N3)	1.450	1.457	1.446	1.449
L(C2-H6)	1.082(1)	1.089(1)	1.090(1)	1.083(0)
L(C2-H7)	1.080(1)	1.081(0)	1.090(1)	1.097(2)
A(N1-C2-N3)	118.6	113.3	107.6	109.7
Pyramidality:				
N1	329.9	327.3	329.0	327.4
N3	329.9	328.9	329.2	327.4

	aa	$ag^{\pm}$	$g^{\pm}g^{\pm}$	$g^{\pm}g^{\mp}$
6-31G**//6-31G**				
Erel	0.00	0.47	0.81	5.14
L(N1-C2)	1.449	1.440	1.445	1.448
L(C2-N3)	1.449	1.455	1.444	1.448
L(C2-H6)	1.084(1)	1.090(1)	1.092(1)	1.085(0)
L(C2-H7)	1.084(1)	1.084(0)	1.092(1)	1.098(2)
A(N1-C2-N3)	118.6	113.4	107.8	109.8
Pyramidality:				
N1	330.8	328.1	330.0	328.3
N3	330.8	329.6	330.1	328.3
MP3/6-31G*				
Erel	0.00	0.55	1.13	5.70
L(N1-C2)	1.460	1.450	1.456	1.460
L(C2-N3)	1.460	1.468	1.457	1.460
A(N1-C2-N3)	119.0	113.2	107.0	109.3

#The only parameters optimized at MP3/6-31G* are L(N1-C2), L(C2-N3) and A(N1-C2-N3). Therefore, they are the only ones presented.

once before[17], that the participation of a nitrogen's lp in an anomeric interaction is accompanied by an increased N pyramidality.

We analyzed the behavior of anomeric N-C bond length (L) vs. N pyramidality (ΣA)[††] and came up with the following relationship: for $\Sigma A < 330^{\circ}$, L = 1.473Å; for $330^{\circ} < \Sigma A < 335^{\circ}$, L = 1.465Å; for $\Sigma A > 335^{\circ}$, L = 1.459Å. In addition, we have computed, at 6-31G* level, the transition state for N inversion in the *ag* conformer of MDA by planarizing the "anti" nitrogen atom. The characteristics of the obtained structure are the followings: $L(C\text{-}N_{planar})$ = 1.421Å and Erel = 5.95 kcal/mol. These values are to be compared with the corresponding ones for the "normal" ag conformer ($L(C\text{-}N_{anti})$ = 1.441Å; Erel = 0.39 kcal/mol).

The two manifestations of the anomeric effect are in apparent conflict here: the energy of the species with lower pyramidality is higher, notwithstanding the attainment of a better *anomeric effect*, as manifest in the typical behavior of the structural parameters. This phenomenon has been observed also in the recent comprehensive treatment by Reed and Schleyer[13] of $F_nAH_mNH_2$ systems.

This apparent contradiction is eventually understood if one considers the two opposed effects: the better n_p - σ^* overlap achieved by a p type orbital in a planar NR_2 geometry, but at the high cost of rehybridization (planarization) energy.

Force field parameterization†††

The adaptation of the parameterization scheme for the *anomeric effect* in N-C-N moieties which has been developed for the MM2-80 force field[4,11] to MMP2-87[11b] demanded some changes mainly due to differences between the two versions. In order to minimize interference with the normal operation of the program, these changes are activated only when anomeric units are concerned:

1. Non-directional H-bonds of MMP2-87 were substituted by directional ones, designed to account for intramolecular H...N interactions when primary or secondary N atoms are found within an anomeric unit. (MM2-80 took no account of H-bonds). These include N-H...N and weak NCH...N interactions.

Table 3. MMP2-87 modified parameters

Torsional parameters

Angle	V1	V2	V3
N-C-N-C	0.00	-0.80	1.10
N-C-N-lp	1.80	1.00	-0.20
N-C-N-H	-0.20	-0.40	0.50
H-C-N-C	0.00	0.00	0.70

"VDW" parameters

Type	ε	r*
(N)-lp...H-(N)	0.35	2.50
(N)-lp...H-(C-X)	0.70	2.70

Anomeric parameters (bonds)

k = 0.0060 C = 2.30 d = -0.0180
a = 0.0286 b = 0.0070

Anomeric parameters (N-C-N)

θ_0 = 118.5° ks = 1.045 k = 7.50

Table 4. Selected structural parameters for N,N-dimethylmethylenediamine (NNDMMDA) and N,N,N',N'-tetramethylmethylenediamine (TMMDA) calculated at 3-21G level. The g^+g^- conformer of NNDMMDA has converged to g^-g^-. Relative energies (Erel) in kcal/mol; bond lengths (L) in Å; bond angles (A) and dihedral angles (D) in degrees.

		NNDMMDA			TMMDA		
		aa	*ag*	g^+g^+			g^+g^+
	Erel	0.00	1.27	2.14		(N1-C2)	1.458
	(N1-C2)	1.461	1.452	1.459		(C2-N3)	1.458
	(C2-N3)	1.465	1.472	1.460		(N1-C4)	1.463
L	(N3-C4)	1.464	1.465	1.463	L	(N1-C5)	1.465
	(N3-C5)	1.464	1.464	1.465		(N3-C6)	1.463
	(N1-C2-N3)	118.0	114.5	109.2		(N3-C7)	1.465
A	(C2-N3-C4)	114.4	112.9	113.6		(N1-C2-N3)	110.4
	(C2-N3-C5)	114.4	113.8	113.5		(C4-N1-C2)	113.9
	(N1-C2-N3-C4)	66.8	166.3	167.1	A	(C5-N1-C2)	113.1
D	(N1-C2-N3-C5)	-66.0	-63.4	-61.7		(C2-N3-C6)	113.9
						(C2-N3-C7)	113.1
						(C4-N1-C2-N3)	165.9
						(C5-N1-C2-N3)	-63.5
					D	(C6-N3-C2-N1)	165.9
						(C7-N3-C2-N1)	-63.5

††† The parameterization scheme for MMP2-87 is similar to that already developed for MM2-80. Hence, only modifications are discussed. The reader may wish to consult reference 4 for a complete description of the parameterization process.

2. Electronegativity corrections for N-C-N bonds were circumvented. The entire treatment of these bonds is done via the anomeric parameters (no electronegativity corrections were available in MM2-80).

In addition, torsional parameters, anomeric parameters and H-bond parameters were slightly modified to account for the somewhat different environment obtained in the 87 version. The modified parameters are presented in Table 3.

Two structural features deserve, in our opinion, special attention and were therefore treated during the modification process:

1. Tertiary amines - *Ab initio* calculations have demonstrated the gradual decrease in C-N bond lengths when going from primary to secondary and to tertiary amines[18]. However, inclusion of a tertiary amine in an anomeric unit may lead to complications. In order to study this point, we have performed 3-21G//3-21G calculations on 4 conformers of N,N-dimethylmethylenediamine (**8**) as well as on the g^+g^+ conformer of N,N,N',N'-tetramethylmethylenediamine (**9**). The latter is the only conformer of this molecule observed experimentally[19]. Results are given in Table 4 and indicate that for all conformers of NNDMMDA (including g^+g^+ where no anomeric interactions are present) the C-N bonds of the tertiary nitrogen are **longer** than that of the primary nitrogen. The C-N bonds obtained for TMMDA largely match those of the "tertiary" part of the g^+g^+ conformer of NNDMMDA. In both cases the inner C-N bonds are shorter than the outer ones. It seems that in this case, anomeric interactions, steric interactions and C-X bond shortening known to appear when several electronegative atoms are connected to the same carbon[3,20] add up to level off the trends observed in the ordinary CH_3NH_2, $(CH_3)_2NH$, $(CH_3)_3N$ series[21]. Moreover, a statistical analysis of C-N bond lengths in primary, secondary and tertiary amines retrieved from the CSD revealed only negligible differences (Table 5).

   Based on these results, the shortening factor for C-N bonds of 0.0235Å applied to tertiary amines in MM2-80 seems exaggerated. A good reproduction of *ab initio* results was obtained when a shortening factor of 0.013Å was applied to inner anomeric C-N bonds alone.

2. N-C-N angle - *Ab-initio* calculations reveal a correlation between the conformation of the lp-N-C-N-lp moiety and the N-C-N bond angle similar to that observed in O-C-O[2] and O-C-N[1] systems[22]. In all model molecules *aa*, *ag* and *gg* conformers have N-C-N angles of ca. 118°, 113°, and 109° respectively. This trend is also observed in NNDMMDA and TMMDA where inspite of steric interactions, the N-C-N bond angles of the *gg* conformers are small (109.2° and 110.4° respectively). This may indicate a dependence of this angle on electronic rather than steric interactions. In order to reproduce these results, we introduced a dependence of θ_0(N-C-N) on the

Table 5. Mean values of C-N bond lengths (Å) and their standard deviations (σ) in primary, secondary, and tertiary amines retrieved from the CSD, after removal of cases deviating in more than 3σ from the mean values.

	Primary	Secondary		Tertiary		
	N-C1	N-C1	N-C2	N-C1	N-C2	N-C3
Cases:	85	199	197	780	779	781
Mean:	1.479	1.474	1.473	1.471	1.471	1.473
σ:	0.021	0.023	0.023	0.024	0.023	0.024

Table 6. Selected structural parameters for MDA, NMMDA, NNDMMDA and TMMDA as calculated by 3-21G level and the modified MMP2-87 force field (in parentheses). Relative energy (Erel) in kcal/mol, bond lengths (L) in Å, bond angles (A) and dihedral angles (D) in degrees.

Methylenediamine (MDA)

		aa	*ag*	g^+g^+	g^+g^-
	Erel	0.00 (0.00)	1.62 (1.21)	2.70 (3.39)	8.23 (5.56)
L	(N1-C2)	1.466 (1.468)	1.459 (1.458)	1.461 (1.460)	1.464 (1.461)
L	(C2-N3)	1.466 (1.468)	1.470 (1.470)	1.461 (1.460)	1.464 (1.461)
A	(N1-C2-N3)	118.3 (117.8)	113.4 (113.6)	106.9 (107.9)	110.4 (108.7)

N-methylmethylenediamine (NMMDA)

		aa	ag^-	ag^+	g^+a	g^-g^-	g^+g^+
	Erel	0.00 (0.00)	1.23 (1.46)	1.69 (1.95)	1.50 (1.36)	2.27 (4.10)	2.48 (3.55)
	(N1-C2)	1.464 (1.469)	1.457 (1.458)	1.455 (1.458)	1.468 (1.472)	1.461 (1.464)	1.460 (1.461)
L	(C2-N3)	1.464 (1.466)	1.467 (1.469)	1.471 (1.469)	1.457 (1.456)	1.458 (1.459)	1.458 (1.459)
	(N3-C4)	1.467 (1.467)	1.465 (1.468)	1.467 (1.468)	1.470 (1.469)	1.467 (1.469)	1.464 (1.468)
	(N1-C2-N3)	118.2 (118.4)	113.8 (114.3)	113.3 (113.1)	114.4 (114.4)	108.5 (109.8)	107.5 (108.7)
A	(C2-N3-C4)	115.9 (112.3)	115.7 (112.6)	114.9 (112.4)	114.4 (114.0)	115.0 (114.2)	115.6 (112.1)
D	(N1-C2-N3-C4)	-61.9 (-61.2)	70.9 (66.9)	172.3 (175.8)	-57.8 (-66.1)	66.2 (67.1)	179.0 (-179.9)

N,N-dimethylmethylenediamine (NNDMMDA)

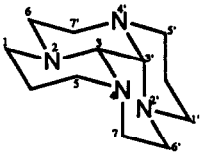
		aa	*ag*	g^+g^+
	Erel	0.00 (0.00)	1.27 (2.32)	2.14 (5.07)
	(N1-C2)	1.461 (1.470)	1.452 (1.460)	1.459 (1.466)
	(C2-N3)	1.465 (1.462)	1.472 (1.466)	1.460 (1.457)
L	(N3-C4)	1.464 (1.461)	1.465 (1.463)	1.463 (1.465)
	(N3-C5)	1.464 (1.461)	1.464 (1.462)	1.465 (1.465)
	(N1-C2-N3)	118.0 (119.2)	114.5 (114.3)	109.2 (110.1)
A	(C2-N3-C4)	114.4 (111.1)	112.9 (110.7)	113.6 (109.5)
	(C2-N3-C5)	114.4 (111.1)	113.8 (111.2)	113.5 (112.8)
	(N1-C2-N3-C4)	66.8 (61.9)	166.3 (172.5)	167.1 (171.7)
D	(N1-C2-N3-C5)	-66.0 (-62.1)	-63.4 (-64.4)	-61.7 (-65.8)

tetramethylmethylenediamine (TMMDA)

		g^+g^+
	(N1-C2)	1.458 (1.466)
	(N1-C4)	1.463 (1.466)
L	(N1-C5)	1.465 (1.466)
	(N1-C2-N3)	110.4 (114.0)
A	(C4-N1-C2)	113.9 (109.2)
	(C5-N1-C2)	113.1 (113.6)
	(C4-N1-C2-N3)	165.9 (177.2)
D	(C5-N1-C2-N3)	-63.5 (-60.4)

Table 7. Comparison of selected structural parameters as obtained from X-ray analysis and MMP2-87 calculations for molecules **10, 11, 12, and 13**. Bond lengths (L) in A, bond angles (A) and dihedral angles (D) in degrees. See formulae for atom numbering.

		10		**11**		**12**		**13**	
		X-ray	MMP2	X-ray	MMP2	X-ray	MMP2	X-ray	MMP2
	Inner C-N bonds								
	(N2-C3)	1.471	1.472	1.467	1.458	1.465	1.458	1.476	1.469
	(C3-N4)	1.461	1.460	1.455	1.453	1.462	1.463	1.447	1.459
L	(N2'-C3')	1.471	1.472	1.462	1.463	1.476	1.459		
	(C3'-N4')	1.461	1.460	1.465	1.458	1.458	1.469		
	Outer C-N bonds								
	(C1-N2)	1.500	1.464	1.475	1.465	1.456	1.458	1.456	1.465
	(C6-N2)	1.437	1.462	1.476	1.471	1.471	1.456	1.463	1.470
	(N4-C5)	1.543	1.462	1.471	1.464	1.478	1.474	1.470	1.465
	(N4-C7)	1.467	1.461	1.469	1.464	1.473	1.486	1.494	1.469
L	(C1'-N2')	1.500	1.464			1.478	1.474	1.482	1.465
	(C6'-N2')	1.437	1.462			1.473	1.486	1.468	1.469
	(N4'-C5')	1.443	1.462			1.465	1.458	1.473	1.465
	(N4'-C7')	1.469	1.461			1.471	1.456	1.476	1.470
	N-C-N bond angles								
	(N2-C3-N4)	111.6	114.0	109.9	110.5	110.8	114.0	113.0	115.9
	A(N2'-C3'-N4')	111.6	114.0			110.8	114.0	112.3	115.9
	C-N-C bond angles								
	(C1-N2-C3)	109.7	111.2	107.1	109.3	108.5	107.6	108.8	109.2
	(C6-N2-C3)	109.8	110.7	110.9	111.5	114.1	117.7	113.0	113.1
	(C1-N2-C6)	110.1	109.7	110.7	112.5	112.5	116.5	111.8	110.2
	(C3-N4-C5)	111.5	110.8	112.4	112.2	107.7	104.4	109.7	108.4
	(C3-N4-C7)	111.9	112.7	112.3	111.2	113.8	118.1	112.4	115.0
	(C5-N4-C7)	113.4	112.2	111.1	111.4	110.5	110.8	111.4	112.2
A	(C1'-N2'-C3')	109.7	111.2			107.7	104.4	107.4	108.4
	(C6'-N2'-C3')	109.8	110.7			113.8	118.1	110.8	115.0
	(C1'-N2'-C6')	110.1	109.7			110.5	110.8	112.9	112.2
	(C3'-N4'-C5')	111.5	110.8			108.5	107.6	109.8	109.2
	(C3'-N4'-C7')	111.9	112.7			114.1	117.7	112.0	113.1
	(C5'-N4'-C7')	113.4	112.3			112.5	116.5	109.8	110.2
	Dihedral angles								
	(C1-N2-C3-N4)	59.5	56.0	177.3	173.2	70.1	72.6	63.3	58.9
	(C6-N2-C3-N4)	-179.4	178.2	-61.8	-61.8	-163.5	-153.5	-171.9	-178.1
	(N2-C3-N4-C5)	-59.3	-55.3	-171.4	-171.1	-63.5	-66.2	-58.9	-58.2
	(N2-C3-N4-C7)	68.9	71.4	62.5	63.4	59.4	57.4	65.6	68.3
D	(C1'-N2'-C3'-N4')	59.5	56.0			63.5	66.1	-59.9	-58.2
	(C6'-N2'-C3'-N4')	-179.4	178.2			-59.4	-57.5	63.9	68.3
	(N2'-C3'-N4'-C5')	-59.3	-55.3			-70.1	-72.5	64.6	58.9
	(N2'-C3'-N4'-C7')	68.9	71.4			163.5	153.5	-173.1	-178.1



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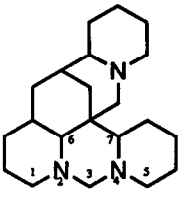

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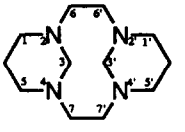

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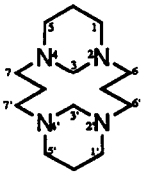

13

lp-N-C-N dihedral angles, much in the same way l_0 for the C-N bond depends on the same angles:

$$\theta_0' = \theta_0 + CORR$$

$$CORR = k/2[(\cos 2\omega_1 - 1) + (\cos 2\omega_2 - 1)]$$

where in a lp-N1-C2-N3-lp anomeric unit:

ω_1 = lp-N1-C2-N3

ω_2 = N1-C2-N3-lp

The best results were obtained when applying:

$\theta_0 = 118.5^\circ$

$k = 7.5$

Comparison of *ab initio* and MMP2-87 results obtained with the modified parameters for MDA(**6**), NMMDA (**7**) NNDMMDA (**8**) and TMMDA (**9**) is presented in Table 6.

In order to check the performances of the modified force field we have used it to calculate some of the molecules taken from the CSD. These are 10b,10c-cis-3a,5a,8a,10a-tetraazaperhydropyrene (**10**)[10], homodasycarpine (**11**)[23], 1,4,8,11-tetraazatricyclo[9.3.1.1^{4,8}]hexadecane (**12**)[24], and 1,5,9,13-tetraazatricyclo[11.3.1.1.^{5,9}] octadecane (**13**)[25]. Comparison of anomeric parameters as obtained from X-ray analysis and MMP2-87 is provided in Table 7. We reiterate that parameterization was based on *ab initio* calculations alone. Keeping this in mind, comparison between the two sets of results (MMP2-87 and X-ray geometries) is very good.

CONCLUSIONS

Following the small magnitude of the *anomeric effect* in N-C-N systems, as deduced from previous[4] and present *ab initio* energetic results, it has little effect on the structural parameters of large molecules, as evident from the study of the X-ray data base. The use of *ab initio* results as a basis for force field parameterization for N-C-N systems is, hence, justified. High level calculations including polarization functions and electron correlation support the results obtained with the 3-21G basis set. Modifications of the force field were introduced, to account for the N-C-N angle dependence on the conformation of the anomeric unit, as well as for C-N bond lengths in tertiary N-C-N nitrogens. The structural parameters thus obtained agree well with X-ray results.

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