rameters are not tightly constrained, the zero-time correction obtained below is uncertain to ~25 ms ($C_6H_5I^+$) or 10 ms ($C_6H_5Br^+$)).

Since both eq 3 and eq A1 have the same exponential behavior, the zero point of t in eq 3 may be adjusted so that eq 3 provides an equally good representation of the data. The simple description of eq 3 is properly corrected by taking the value of t to be the time from the end of the IR irradiation to a point 30 ms ($C_6H_5I^+$) or 10 ms ($C_6H_5Br^+$) before the midpoint of the visible pulse.

The treatment above is still deficient in one respect: the use of dissociation rate constants k_{dA} and k_{dB} presupposes that the A and B populations of ions photodissociate by a time-independent process, as in simple one-photon dissociation. However, the A ions (and possibly the B ions) are actually believed to dissociate by a sequential two-photon process that cannot be described exactly by a simple dissociation rate constant. A more elaborate treatment to account for this would be unwarranted on the basis of the present data, and we simply state our expectation that no major error is introduced by neglecting this effect.

Registry No. Iodobenzene radical cation, 38406-85-8; bromobenzene radical cation, 55450-33-4.

Stereodynamics of Diethylmethylamine and Triethylamine

C. Hackett Bushweller,*[1] Stephen H. Fleischman,*[1] Gilbert L. Grady,[1] Paul McGoff,[1] Christopher D. Rithner,[1] Michael R. Whalon,[1] John G. Brennan,[2] Richard P. Marcantonio,[2] and Raymond P. Domingue[1]

Contribution from the Departments of Chemistry, University of Vermont, Burlington, Vermont 05405, and State University of New York, Albany, New York 12222.
Received April 13, 1982

Abstract: Diethylmethylamine is the simplest acyclic trialkylamine that possesses the requisite symmetry that allows, in principle, the direct observation of both nitrogen inversion and isolated nitrogen–carbon bond rotation using ^1H dynamic nuclear magnetic resonance (DNMR) spectroscopy. DNMR studies of diethylmethylamine and two deuterated derivatives complemented by empirical force-field calculations reveal a comprehensive picture of the stereodynamics of this representative acyclic trialkylamine. The DNMR studies show clear evidence for pyramidal inversion at nitrogen. In addition to nitrogen inversion, the results also speak for several "families" of rotamers for diethylmethylamine that undergo very rapid, DNMR-invisible *intra*family conformational exchange via isolated N–CH_2 rotation while also undergoing higher barrier DNMR-visible *inter*family exchange also via isolated N–CH_2 rotation. The DNMR-visible N–CH_2 rotation processes involve CCH_3/N-alkyl eclipsing in the transition state while the DNMR-invisible processes involve CCH_3/lone pair eclipsing. Although the symmetry of triethylamine precludes the DNMR-observation of nitrogen inversion, ^1H DNMR evidence for restricted N–CH_2 rotation and empirical force-field calculations reveal stereodynamics for triethylamine that are highly analogous to diethylmethylamine.

There has been much previous interest in the stereodynamics of acyclic and cyclic amines. The effects of π-bonding, electronegativity, ring strain, and other structural parameters on the nitrogen inversion barrier seem to be well established.[3] However, there are *two* rate processes associated with the nitrogen atom of a trialkylamine. One of these processes is indeed pyramidal inversion, and the other is isolated rotation about the nitrogen–carbon bonds. If one is to address the inversion/rotation dichotomy incisively in such amines, information regarding inversion barriers, rotation barriers, and conformational preferences is essential. In light of the huge effort devoted to studies of nitrogen inversion,[3] there is a surprising paucity of information regarding isolated nitrogen–carbon bond rotation and rotamer preferences in simple acyclic trialkylamines.[4] Although ^1H dynamic nuclear magnetic resonance (DNMR) studies in our laboratory provided some insight into both inversion and rotation processes in a number of *tert*-butylamine and isopropylamine derivatives, such crowded molecules may not be representative of simpler acyclic trialkylamines.[5]

Diethylmethylamine is the simplest acyclic trialkylamine that possesses the requisite symmetry that allows, in principle, the direct observation of both nitrogen inversion and *isolated* nitrogen–carbon bond rotation (i.e., *no* concomitant inversion) using the ^1H DNMR method *provided* the inversion barrier is higher than the barrier for isolated rotation about the nitrogen–carbon bonds.[5] A next higher homologue, triethylamine, possesses symmetry that renders nitrogen inversion DNMR-invisible but allows, in principle, the detection of isolated nitrogen–carbon bond rotation. This paper reports the results of ^1H DNMR studies of the stereodynamics of diethylmethylamine, triethylamine, and selectively deuterated derivatives complemented by empirical force-field (EFF) calculations. For each of these two amines, the evidence suggests the existence of several "families" of rotamers that undergo very rapid,

(1) University of Vermont.
(2) State University of New York.
(3) (a) Rauk, A.; Allen, L. C.; Mislow, K. *Angew. Chem., Int. Ed. Engl.* **1970**, *9*, 400. (b) Lehn, J. M. *Fortschr. Chem. Forsch.* **1970**, *15*, 311. (c) Lambert, J. B. *Top. Stereochem.* **1971**, *6*, 19. (d) Bushweller, C. H.; O'Neil, J. W. *J. Am. Chem. Soc.* **1970**, *92*, 2159. (e) Bushweller, C. H.; O'Neil, J. W.; Bilofsky, H. S. *Tetrahedron* **1972**, *28*, 2697. (f) Bushweller, C. H.; Lourandos, M. Z.; Brunelle, J. A. *J. Am. Chem. Soc.* **1974**, *96*, 1591.
(4) (a) Lide, D. R., Jr.; Mann, D. E. *J. Chem. Phys.* **1958**, *28*, 572. (b) Kumar, K. *Chem. Phys. Lett.* **1971**, *9*, 504. (c) Crocker, C.; Goggin, P. L. *J. Chem. Soc., Dalton Trans.* **1978**, 388. (d) Profeta, S., Jr., Ph.D. Dissertation, University of Georgia, 1978.
(5) (a) Bushweller, C. H.; Anderson, W. G.; Stevenson, P. E.; Burkey, D. L.; O'Neil, J. W. *J. Am. Chem. Soc.* **1974**, *96*, 3892. (b) Bushweller, C. H.; Anderson, W. G.; Stevenson, P. E.; O'Neil, J. W. *Ibid.* **1975**, *97*, 4338. (c) Bushweller, C. H.; Wang, C. Y.; Reny, J.; Lourandos, M. Z. *Ibid.* **1977**, *99*, 3938.
(6) This work was presented in part at "A Conversation in the Discipline: Stereodynamics of Molecular Systems", State University of New York, Albany, New York, April 23–24, 1979. See: Bushweller, C. H.; Laurenzi, B. J.; Brennan, J. G.; Goldberg, M. J.; Marcantonio, R. P. "Stereodynamics of Molecular Systems"; Sarma, R. H., Ed.; Pergamon Press: New York, 1979; pp 113–129.

0002-7863/82/1504-6224$01.25/0

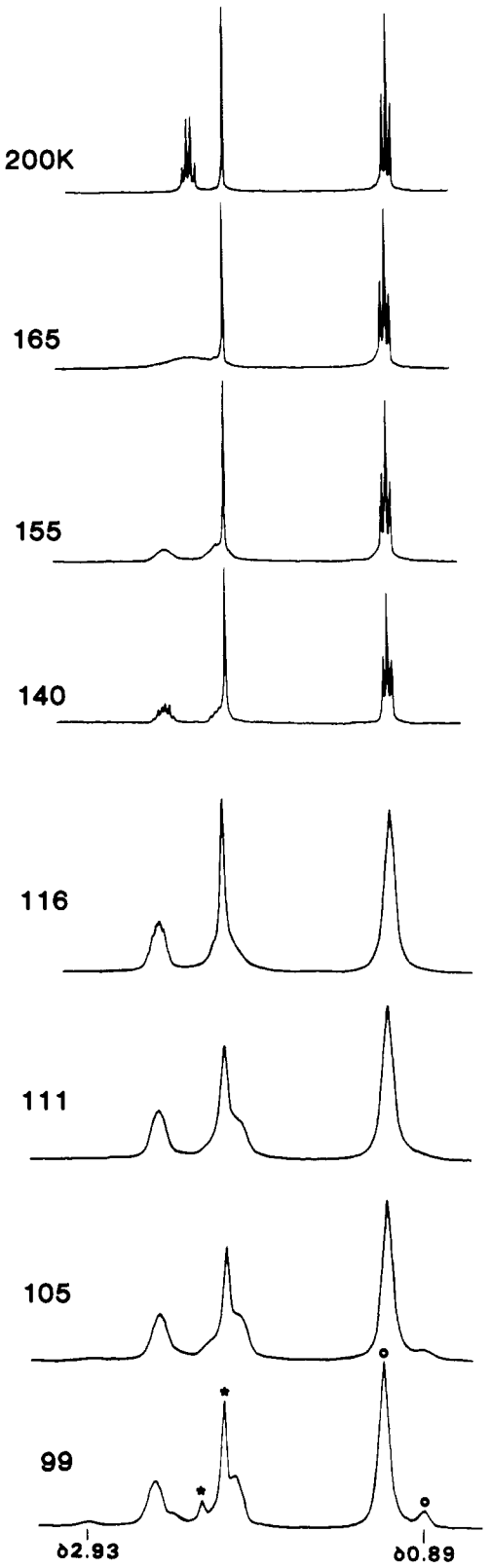


Figure 1. ^{1}H DNMR spectra (270 MHz) of diethylmethylamine (3% v/v in $CBrF_3$). All chemical shifts are referenced to Me_4Si.

DNMR-invisible *intra*family exchange via isolated N–CH_2 rotation while also undergoing higher barrier, DNMR-visible *inter*family equilibrations.[6]

Results and Discussion

The ^{1}H NMR spectrum (270 MHz) of diethylmethylamine (3% v/v in $CBrF_3$) at 200 K consists of an A_2X_3 spectrum (δ_A 2.32, δ_X 1.06, $^3J_{AX}$ = 7.0 Hz; Me_4Si reference) for the NC_2H_5 groups and a singlet (δ 2.10) for NCH_3 (Figure 1). Over the temperature

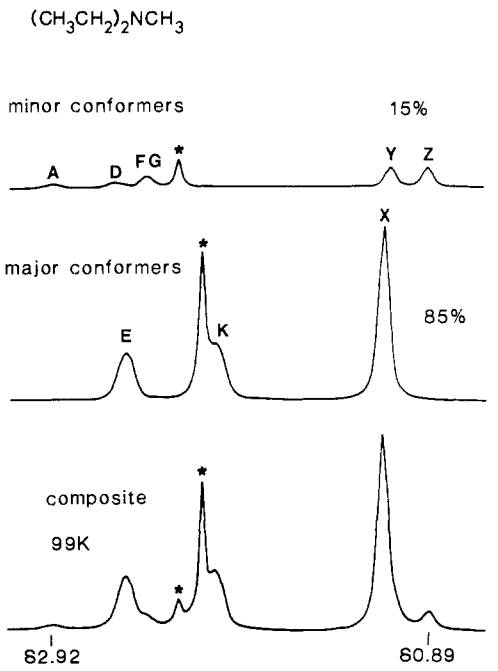


Figure 2. Theoretical decomposition of the ^{1}H NMR spectrum (270 MHz) of diethylmethylamine at 99 K (also see Figure 1). The asterisks indicate the positions of the NCH_3 singlets.

range from 170 to 140 K, the NCH_2 resonance decoalesces and at 140 K is sharpened into the AB portion of an ABX_3 spectrum (δ_A 2.47, δ_B 2.12, δ_X 1.06, $^2J_{AB}$ = −13.8 Hz, $^3J_{AX}$ = $^3J_{BX}$ = 7.0 Hz). The NCH_3 and CCH_3 resonances undergo no decoalescence over the 170 to 140 K temperature range. Using a standard rationale, we assigned this decoalescence for the NCH_2 resonance to slowing *nitrogen inversion*.[5] At 140 K, the diastereotopic protons on a given NCH_2 moiety are interchanging via inversion at a rate that is slow on the ^{1}H NMR time scale, and two different resonances are observed. All isolated rotations are still fast on the NMR time scale at 140 K. From an ABX_3 to BAX_3 DNMR simulation model, the $\Delta G^{\ddagger}$ for inversion is 7.9 ± 0.4 kcal/mol at 160 K.[7]

With inversion slow on the NMR time scale at 140 K, any further decoalescence below 140 K can be assigned with confidence to slowing isolated rotation. Indeed, the most likely isolated rotation to be observed is rotation about the N–CH_2 bonds. For a large number of related amines, we have never achieved the necessary conditions (i.e., low enough temperatures and viable solvent systems) to observe a decoalescence due to isolated C–CH_3 or N–CH_3 bond rotation.[5] In these relatively flexible systems, it is apparent that the C–CH_3 and N–CH_3 rotation barriers are low enough (e.g., <5 kcal/mol) to be DNMR-invisible.[8]

At temperatures below 140 K, the spectrum of diethylmethylamine does in fact undergo a second decoalescence (Figure 1). The most obvious changes involve a splitting of the CCH_3 resonance into two peaks of unequal intensity (see circles on the 99 K spectrum of Figure 1) and a similar decoalescence for the NCH_3 signal (see asterisks on the 99 K spectrum). In addition, the NCH_2 resonances also decoalesce. The observation of different CCH_3 resonances, different NCH_3 resonances, and more than two NCH_2 resonances at 99 K allows a confident assignment of this second decoalescence to *isolated rotation about the N–CH_2 bonds*. A theoretical simulation of the 99 K experimental spectrum is presented as the "composite" spectrum of Figure 2. The composite

(7) The DNMR line shape simulation program used is a substantially revised version of DNMR3 written by Kleier and Binsch (Kleier, D. A.; Binsch, G. Quantum Chemistry Program Exchange, Indiana University, Program 165). Our local revisions are described by Bushweller et al. (Bushweller, C. H.; Bhat, G.; Letendre, L. J.; Brunelle, J. A.; Bilofsky, H. S.; Ruben, H.; Templeton, D. H.; Zalkin, A. *J. Am. Chem. Soc.* **1975**, *97*, 65).

(8) Restricted methyl rotation can be DNMR visible in highly crowded, *rigid* systems. See: Nakamura, M.; Ōki, M.; Nakanishi, H. *J. Am. Chem. Soc.* **1973**, *95*, 7169.

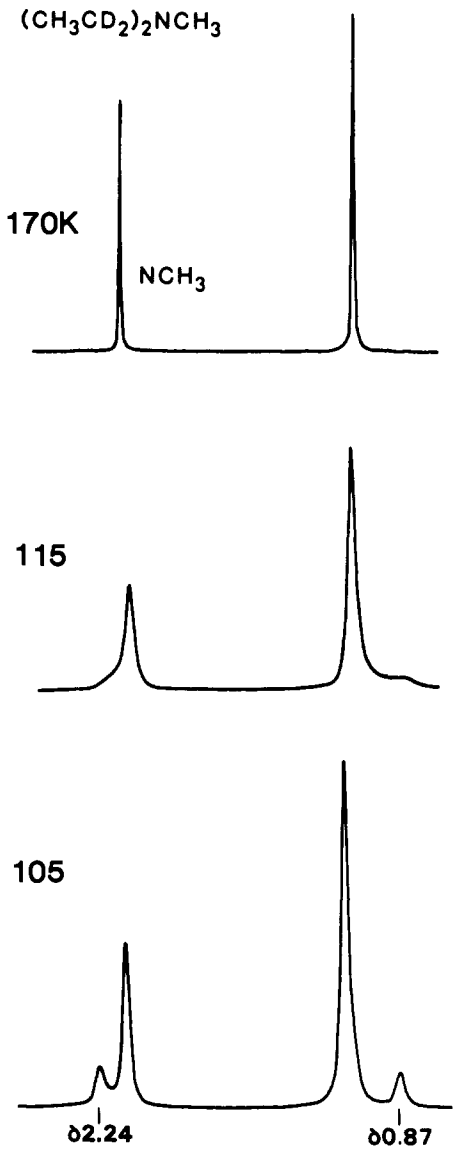


Figure 3. ^{1}H DNMR spectra (270 MHz) of $(CH_3CD_2)_2NCH_3$ (**1**: 2% v/v in $CBrF_3$).

spectrum results from the superposition of two unequally populated subspectra. The minor subspectrum at the top of Figure 2 accounts for 15% of the area of the composite spectrum and consists of an ADY_3 spectrum (δ_A 2.92, δ_D 2.56, δ_Y 1.06, $^2J_{AD} = -14.0$ Hz, $^3J_{AY} = {}^3J_{DY} = 7.0$ Hz) and an FGZ_3 spectrum (δ_F 2.40, δ_G 2.34, δ_Z 0.86, $^2J_{FG} = -14.0$ Hz, $^3J_{FZ} = {}^3J_{GZ} = 7.0$ Hz) for the NC_2H_5 groups with an NCH_3 singlet at δ 2.24 (see asterisk). The NCH_3 and CCH_3 resonances are accurately simulated, respectively, as three homotopic protons; i.e., both N–CH_3 and C–CH_3 rotations are fast on the NMR time scale at 99 K. The area ratios of the ADY_3 spectrum to the FGZ_3 spectrum to the NCH_3 singlet are 5:5:3, suggesting that this subspectrum corresponds to one type of molecular geometry.

The major subspectrum (85%) in the middle of Figure 2 consists of an EKX_3 spectrum (δ_E 2.51, δ_K 2.02, δ_X 1.11, $^2J_{EK} = -12.0$ Hz, $^3J_{EX} = {}^3J_{KX} = 7.0$ Hz) for the NC_2H_5 groups and an NCH_3 singlet (δ 2.12; see asterisk). The area ratio of the EKX_3 spectrum to the NCH_3 singlet is 10:3, suggesting again that this subspectrum reflects one type of molecular geometry albeit different from the minor species. It is noteworthy that the major subspectrum apparently reflects greater molecular symmetry than the minor subspectrum.

While the spectrum of diethylmethylamine at 99 K shows the presence of at least two molecular geometries, the spectrum is obscured by subspectral overlap due to vicinal proton–proton coupling ($^3J_{HH}$) and very short T_2 values at such low temperatures.

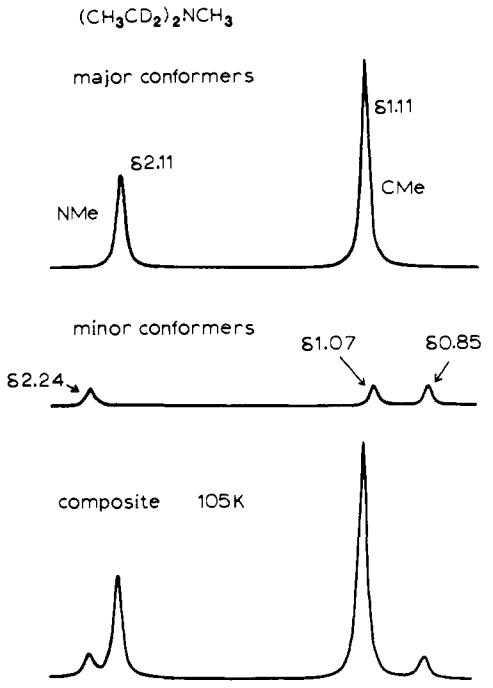


Figure 4. Theoretical decomposition of the ^{1}H NMR spectrum of $(CH_3CD_2)_2NCH_3$ (**1**) at 105 K (also see Figure 3).

In order to alleviate this problem, we examined the ^{1}H DNMR spectra (270 MHz) of $(CH_3CD_2)_2NCH_3$ (**1**; 2% v/v in $CBrF_3$).

1: $(CH_3CD_2)_2NCH_3$

2: $(CD_3CH_2)_2NCH_3$

Below 150 K, efficient ^{2}H quadrupolar relaxation decouples deuterons from protons and all vicinal spin–spin coupling is removed.[9] The substitution of protons by deuterons will also lead presumably to less efficient proton spin–spin relaxation in **1** and sharper lines at low temperatures.[10] It should be noted that the deuteration of the methylene groups renders nitrogen inversion DNMR-invisible for **1**. The spectra of **1** are illustrated in Figure 3. At 105 K, the NCH_3 signal has decoalesced into two singlets at δ 2.24 and 2.13 with a respective area ratio of 15:85, in good agreement with the spectrum of $(CH_3CH_2)_2NCH_3$ at 99 K (Figure 2). The CCH_3 groups of **1** at 105 K show two resolved signals with an area ratio of about 92:8. A computer-assisted decomposition of the spectrum of **1** at 105 K reveals two subspectra (Figure 4). The minor subspectrum (15%) consists of an NCH_3 singlet (δ 2.24) and *two* CCH_3 singlets at δ 1.07 and 0.85. The peak areas of these three singlets are all equal. The major subspectrum (85%) of **1** consists of an NCH_3 peak (δ 2.11) and *one* CCH_3 singlet (δ 1.11) with a respective area ratio of 1:2.

These data begin to reveal the nature of preferred geometries for diethylmethylamine. From well-established chemical shift trends,[5] a CCH_3 group has a ^{1}H NMR chemical shift at δ 1.10 ± 0.05 if gauche to the nitrogen lone pair and δ 0.85 ± 0.05 if anti to the lone pair; i.e., the anti methyl is upfield from the gauche methyl. From a consideration of Figures 2 and 4, it is apparent that the minor subspectra of $(CH_3CH_2)_2NCH_3$ and $(CH_3CD_2)_2NCH_3$ suggest an equal distribution of CCH_3 groups between positions gauche and anti to the nitrogen lone pair while the major subspectra speak for an exclusive preference of the CCH_3 groups for positions gauche to the lone pair. Any proposed molecular geometries must be consistent with these observations.

In order to provide a more conclusive picture of the stereodynamics of diethylmethylamine, we examined the ^{1}H DNMR spectra (270 MHz) of $(CD_3CH_2)_2NCH_3$ (**2**; 2% v/v in $CBrF_3$). For **2**, vicinal proton–proton spin–spin coupling is removed and

(9) Beall, H.; Bushweller, C. H. *Chem. Rev.* **1973**, *73*, 465.
(10) Mantsch, H. H.; Saito, H.; Smith, I. C. P. *Prog. Nucl. Magn. Reson. Spectrosc.* **1977**, *11*, 211.

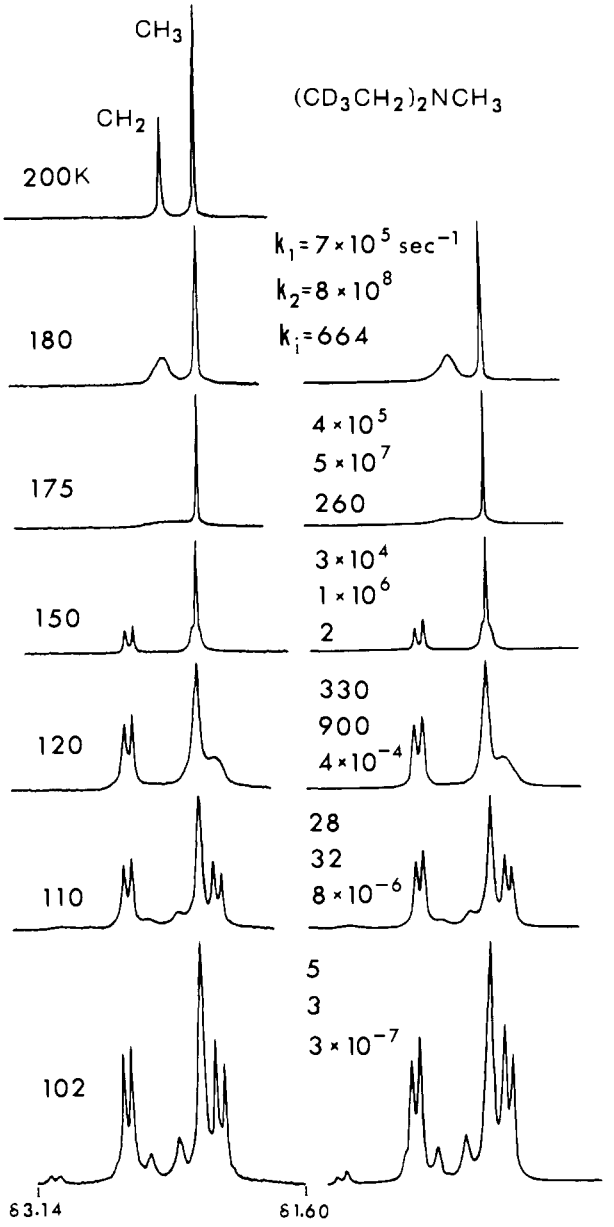


Figure 5. Experimental ^1H DNMR spectra (270 MHz) of $(CD_3CH_2)_2NCH_3$ (**2**; 2% v/v in $CBrF_3$) in the left column and theoretical DNMR simulations in the right column. k_i is the first-order rate constant for inversion at nitrogen. k_1 is the rotation rate constant for conversion from a family of minor conformers to a family of major conformers. k_2 is the rotation rate constant for direct interfamily exchange among families of minor rotamers.

nitrogen inversion is now DNMR-visible. The chemical shifts of the methylene protons at slow exchange should provide valuable information regarding the orientation of the methylene protons with respect to the lone pair.[11]

The experimental spectra of **2** are shown in the left column of Figure 5. The spectra were run without ^2H irradiation, and small proton–deuteron vicinal spin–spin coupling leads to a differential broadening of the NCH_2 resonance at 200 K. However, at about 150 K, and at progressively lower temperatures, deuterium quadrupolar relaxation effectively decouples the NCH_2 protons from deuterons.[9] The decoalescence of the NCH_2 signal into a single AB spectrum (δ_A 2.47, δ_B 2.09, $^2J_{AB}$ = −13.0 Hz) at 150 K is assigned to slowing inversion ($\Delta G^\ddagger$ = 7.9 ± 0.4 kcal/mol at 160 K; also see Figure 1). The second decoalescence below 150 K (Figure 5) is then assigned to slowing isolated N–CH_2 bond

(11) Lambert, J. B.; Keske, R. G.; Carhart, R. E.; Jovanovich, A. P. *J. Am. Chem. Soc.* **1967**, *89*, 3761.

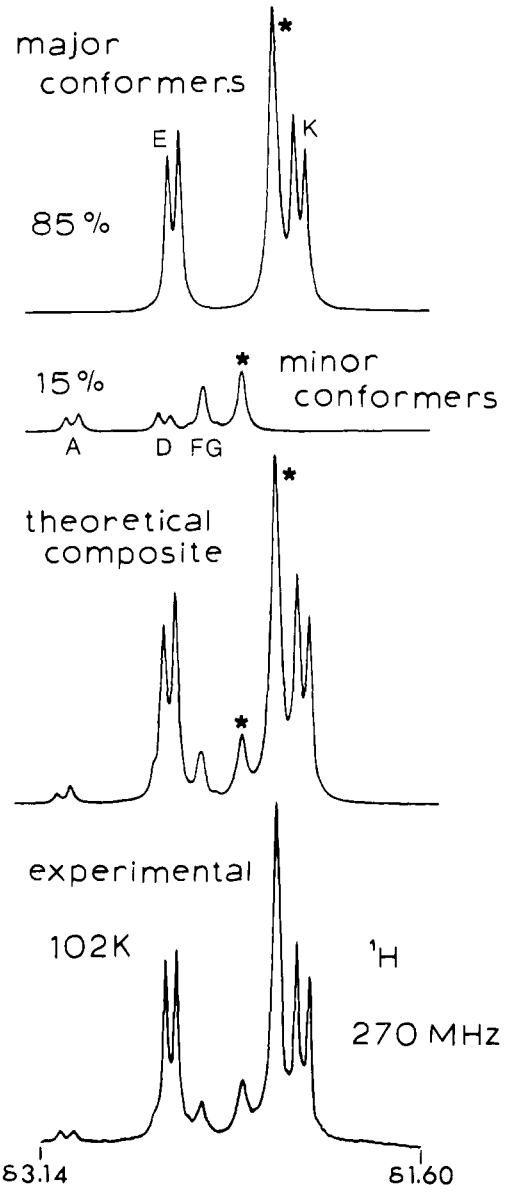


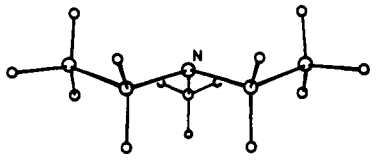
Figure 6. Theoretical decomposition of the ^1H NMR spectrum (270 MHz) of $(CD_3CH_2)_2NCH_3$ (**2**) at 102 K (also see Figure 5). The asterisks indicate the positions of the NCH_3 singlets.

rotation (also see Figure 1). It is gratifying that the spectrum of **2** at 102 K (Figure 5) is much more clearly defined than the spectrum of diethylmethylamine at 99 K (Figure 1).

The spectrum of **2** at 102 K is composed of two subspectra (Figure 6). The major subspectrum that accounts for 85% of the area of the composite spectrum is shown at the top of Figure 6. It consists of an NCH_3 singlet (δ 2.12; see asterisk) and an EK spectrum for the NCH_2 groups (δ_E 2.53, δ_K 2.01, $^2J_{EK}$ = −12.0 Hz). The area ratio of the EK spectrum to the singlet is 4:3. The minor subspectrum (15%; Figure 6) is composed of an NCH_3 singlet (δ 2.25; see asterisk), an AD spectrum (δ_A 2.92, δ_D 2.56, $^2J_{AD}$ = −14.0 Hz), and a closely spaced FG spectrum (δ_F 2.41, δ_G 2.39, $^2J_{FG}$ = −14.0 Hz) for the NCH_2 groups. The respective relative areas of the NCH_3 singlet and the AD and FG spectra are 3, 2, and 2.

The single EK spin system in the major subspectrum of **2** suggests C_s symmetry for the conformer(s) involved. The two methylene protons on a given NCH_2 moiety are diastereotopic, but the two *separate sets* of diastereotopic NCH_2 protons are apparently enantiotopic; i.e., they can be reflected through a mirror plane, thus giving a single EK spectrum. In addition, the major subspectrum for **1** suggests that in the dominant conformer(s) all CCH_3 groups are gauche to the lone pair. Upon consideration

of these data, a reasonable choice of major conformer for diethylmethylamine is the **GG** form, which does in fact possess C_s



GG

C_S symmetry

symmetry. For the purpose of naming the various conformers of diethylmethylamine, the letter **G** defines a CCH_3 group that is gauche to both the lone pair and the NCH_3 group, **G'** defines a CCH_3 group that is gauche to the lone pair and the other NC_2H_5 group, and **A** defines a CCH_3 group anti to the lone pair.

However, assignment of the major subspectrum of diethylmethylamine exclusively to the **GG** conformer is problematical in light of the relatively small $\Delta\delta_{EK}$ value (0.52 ppm) for **2**. In the **GG** conformer, one methylene proton on each methylene group is anti to the lone pair and the other is gauche. From well-established chemical shift trends in other trialkylamines, the chemical shift difference between gauche and anti protons for an NCH_2 group is 1.05 ± 0.10 ppm.[5a,11] If the major subspectrum of diethylmethylamine reflected an exclusive preference for the **GG** geometry, indications are that the $\Delta\delta_{EK}$ value would be much larger.

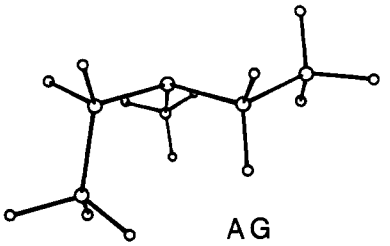
In performing a DNMR experiment, decoalescence to a set of two signals that differ in chemical shift by a value much smaller than that predicted from legitimate models suggests that the spectrum is subject to some conformational exchange that is *still rapid* on the NMR time scale. Thus, while we observe a clear-cut decoalescence attributable to restricted $N-CH_2$ rotation, it is apparent that other processes remain rapid on the NMR time scale even at 102 K. It appears that the **GG** rotamer may be interconverting very rapidly with other rotamers of different symmetry (e.g., GG' or G'G) at 102 K.

The minor subspectrum of **1** shows an equal distribution of CCH_3 groups between positions anti and gauche to the lone pair and one NCH_3 resonance (Figure 4). The minor subspectrum of **2** shows four different NCH_2 chemical shifts (Figure 6), i.e., four diastereotopic NCH_2 protons, which of course suggests C_1 symmetry. On the basis of these data, one reasonable choice of conformer would be the **AG** form. One might anticipate a closely spaced FG spectrum for the anti NCH_2CD_3 group of the **AG** rotamer (Figure 6), but the small $\Delta\delta_{AD}$ value (0.36 ppm) once again suggests averaging for the other NCH_2CD_3 moiety even at 102 K.

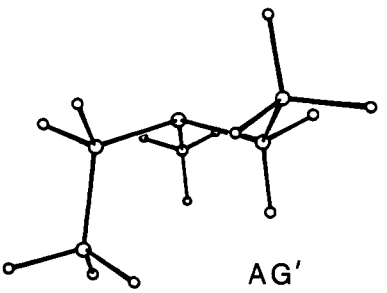
Indeed, a consideration of models suggests that the **GG** and **GG'** (or enantiomeric **G'G**) conformers should have comparable stabilities. The **AG** (or enantiomeric **GA**) and **AG'** (or enantiomeric **G'A**) conformers should also have similar energies. Thus, intuition suggests that four different molecular geometries are reasonable, even though only *two* subspectra are observed at about 100 K (Figures 2, 4, and 6).

In order to shed light on this apparent discrepancy, we performed some empirical force-field (EFF) calculations using Allinger's 1980 MM2 force-field which is parameterized for pyramidal trivalent nitrogen.[4d,12] This program optimizes van der Waals, torsional, bond angle bending, bond stretching, stretching–bending, and dipole–dipole energy terms for each molecular geometry and searches for energy minima with a modified Newton–Raphson minimization scheme. The program is capable of generating energy surfaces for intramolecular conformational exchange.

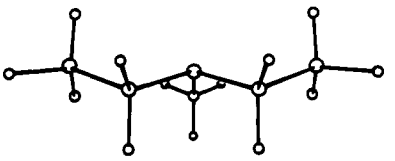
In order to establish more unequivocally the $\Delta\delta$ value for NCH_2 protons gauche and anti to the lone pair in an *acyclic* trialkylamine,



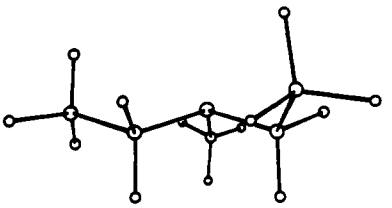
AG



AG'

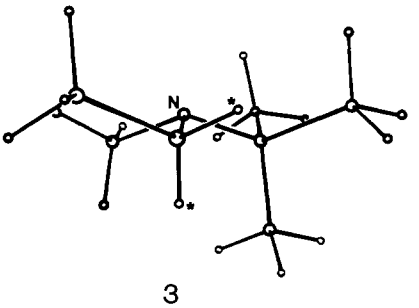


GG



GG'

we performed MM2 calculations for *tert*-butylmethylethylamine that indicated that **3** and its enantiomeric invertomer are the stable



3

conformers. An approximate 120° clockwise or counterclockwise $N-CH_2$ rotation starting from **3** produces geometries that are energy minima but possess serious 1,5-interactions. These geometries are calculated to be at least 3 kcal/mol higher in energy than **3**; i.e., the MM2 method predicts *one NMR-detectable geometry*. Thus, one would expect that under conditions of slow inversion, the NMR spectrum of the diastereotopic NCH_2 protons of the deuterated derivative $(t\text{-}C_4H_9)(CH_3)N(CH_2CD_3)$ (**4**) will

4: $(t\text{-}C_4H_9)(CH_3)N(CH_2CD_3)$

not be subject to any rotameric averaging and would indeed reflect

(12) Allinger, N. L.; Yuh, Y. H. Quantum Chemistry Program Exchange, Indiana University, 1980, Program 395.

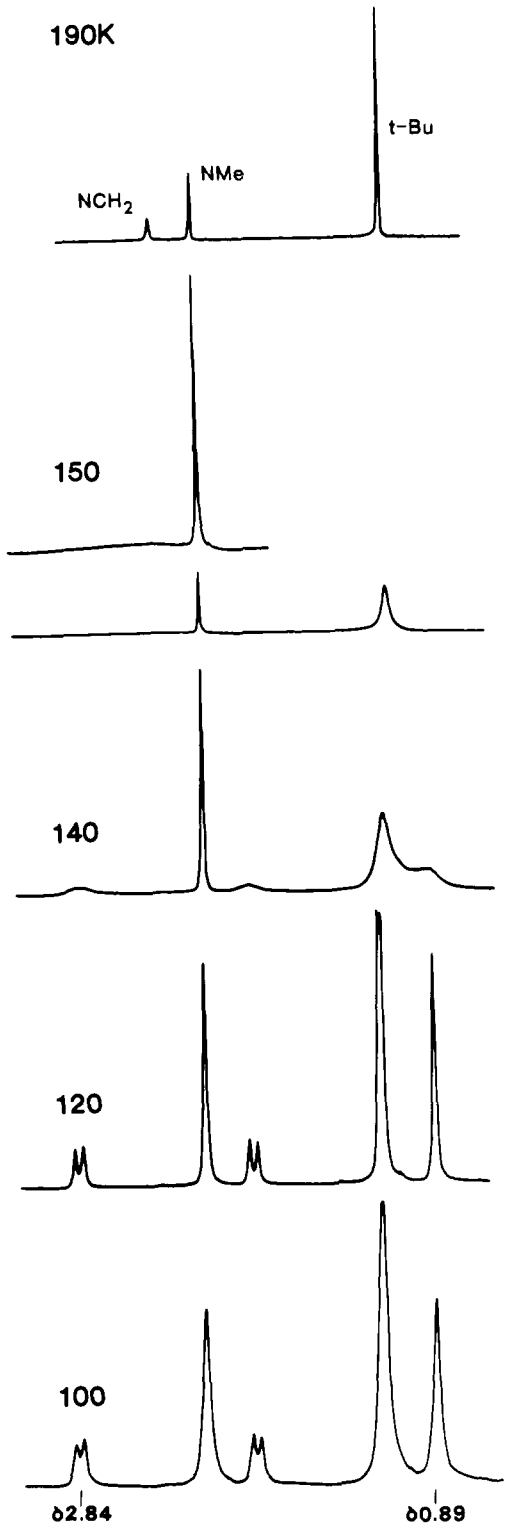


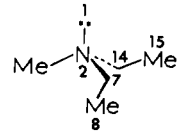
Figure 7. ^{1}H DNMR spectra (270 MHz) of (t-C_4H_9)(CH_3)N(CH_2CD_3) (**4**; 2% v/v in $CBrF_3$).

the actual $\Delta\delta$ value between protons located anti and gauche to the lone pair (see asterisked protons on structure **3**). Indeed, the NCH_2 signal for **4** is decoalesced at 130 K into a single AM spectrum (δ_A 2.85, δ_M 1.88, $^2J_{AM}$ = −13.0 Hz) due to slowing inversion.[5] More importantly, the AM spectrum undergoes *no further decoalescence* all the way down to 100 K (Figure 7). This indicates the presence of *one* NMR-detectable species consistent with the MM2 calculations. The $\Delta\delta_{AM}$ value (0.97 ppm) is in excellent agreement with other NCH_2 chemical shift model systems.[11] Thus, our concern regarding the small NCH_2 $\Delta\delta$ values for **2** at 102 K seems justified.

The decoalescence observed for the t-C_4H_9 signal of **4** (Figure 7) reflects the slowing of a correlated *tert*-butyl rotation/nitrogen inversion process that is addressed in detail in another paper.[5a] The previous work[5a] was done on a relatively low sensitivity, continuous wave 60-MHz NMR system and is corroborated by these more recent studies on a highly sensitive, pulsed FT 270-MHz NMR system.

In addition, we performed a check of the MM2 method with respect to N–C bond rotation barriers. For all the rotation barrier calculations in this paper, we employed the dihedral angle driver method rather than the restricted motion method.[12] In some instances, a slightly higher calculated energy can result if the driver method is used.[13] The MM2 method gives a rotation barrier of 4.7 kcal/mol for trimethylamine as compared to an experimental barrier of 4.4 kcal/mol.[4a]

We then turned to detailed MM2 calculations for diethylmethylamine. A 5000-point optimized energy surface was computed as a function of two dihedral angles in diethylmethylamine. With the lone pair labeled as position number 1, the two pertinent dihedral angles are 1–2–7–8 and 1–2–14–15, as defined in structure **5**. The results of these calculations are shown as an



5

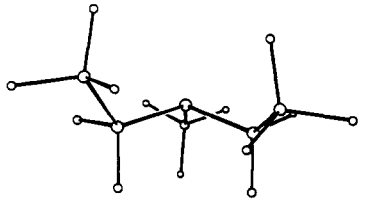
energy contour map (Figure 8). The energy separation between adjacent contours is set at 1 kcal/mol. Energy minima correspond to specific conformations for diethylmethylamine, and these are labeled in bold black letters. Energy maxima, i.e., energy peaks or "mountain tops", are labeled with solid red circles, and saddle points are labeled as solid green circles. These calculations indicate several important trends regarding the stereodynamics of diethylmethylamine.

With regard to conformational preference, optimized MM2 calculations in the region of each energy minimum indicate the **GG′** (or **G′G**) rotamer to be most stable. MM2 predicts almost perfect staggering along all the C–C and N–C bonds. The dihedral angle between the **G** C–CH_3 and N–CH_3 bonds is 57° with the C–CH_3 group tilted away from the lone pair. The **G′** C–CH_3/N–CH_3 dihedral angle is 175°, with C–CH_3 tilted toward the lone pair. The CNC bond angles are 111°. The **GG** rotamer is computed to be very slightly higher in energy (+0.05 kcal/mol) than the **GG′** form. In the **GG** form, both C–CH_3/N–CH_3 dihedral angles are 61° with CNC bond angles of 111°. These calculations corroborate our conclusions from a consideration of models that the **GG** and **GG′** conformations should have very comparable stabilities.

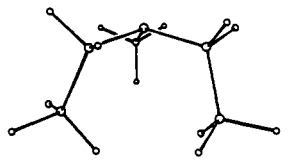
The **AG′** rotamer is MM2 computed to be 0.47 kcal/mol higher in energy than **GG′**. For the **AG′** form, the dihedral angle between the **A** C–CH_3 and N–CH_3 bonds is 67° and between the **G′** C–CH_3 and N–CH_3 is 177°, and the CNC bond angles are 110–111°. The **AG** rotamer is 0.66 kcal/mol above **GG′**, with an **A** C–CH_3/N–CH_3 dihedral angle of 63°, a **G** C–CH_3/N–CH_3 dihedral angle of 62° (C–CH_3 tilted toward lone pair), and CNC bond angles of 111°.

Those geometries that have severe 1,5-interactions such as the **G′G′** and **AA** forms are computed to be 2.96 and 3.82 kcal/mol, respectively, higher in energy than **GG′**. Indeed, the MM2-optimized **G′G′** and **AA** structures do not have C_s symmetry but have the two C–CH_3 bonds skewed with respect to each other, presumably leading to an optimization of 1,5-interactions The broad energy minima shown for the **G′G′** and **AA** rotamers in Figure 8 may reflect low-barrier N–CH_2 torsional motions that are not resolved on this particular energy surface. A compilation of relative MM2 energies of the various conformers of diethylmethylamine can be found in Table I.

(13) Profeta, S., Jr., personal communication. Burkert, U.; Allinger, N. L. *J. Comput. Chem.* **1982**, *3*, 40.



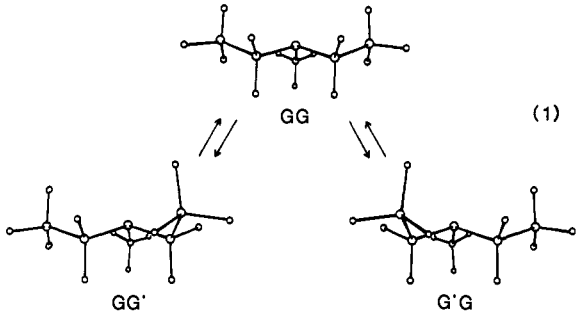
G'G'



AA

Thus, the MM2 calculations indicate that four geometries of diethylmethylamine (**GG'**, **GG**, **AG'**, **AG**) should be present in concentrations high enough to be NMR-detectable. But, once again, only *two* subspectra are observed at about 100 K (Figures 2, 4, 6). MM2 calculations of rotation barriers shed light on this apparent discrepancy.

An optimized MM2 calculation of the **GG** to **GG'** (or **GG** to **G'G**) rotation barrier via that itinerary in which CCH_3 eclipses the lone pair (eq 1) gives a value of 4.4 kcal/mol. The actual

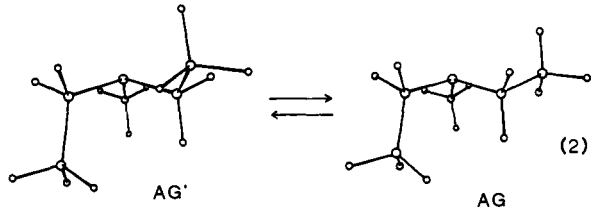


GG (1)

GG' G'G

rotation barrier may in fact be lower than 4.4 kcal/mol (vide supra), but this computed value is still below the lower barrier limit for DNMR detection in our laboratory (~5 kcal/mol). Therefore, a **GG'** to **GG** to **G'G** rotational exchange (eq 1) that occurs via CCH_3/lone pair eclipsing will be DNMR-invisible. If the equilibrations in eq 1 are fast on the NMR time scale at 100 K, the effective, time-averaged symmetry of this system is C_s. We assign the major subspectrum of **2** (Figure 6) to this family of three rapidly exchanging rotamers (eq 1) which will indeed give just *one* subspectrum at 100 K as observed.

Similarly, the MM2-calculated rotation barrier for an **AG'** to **AG** (or **G'A** to **GA**) conversion (eq 2) via a CCH_3/lone pair



AG' AG (2)

eclipsing is 4.5 kcal/mol, which is of course also below our lower DNMR limit and would lead to a fast process on the NMR time scale even at 100 K. The time-averaged symmetry for a rapidly exchanging **AG'** to **AG** system is C_1 and would lead to the observation of four different NCH_2 chemical shifts, as observed in the minor subspectrum of **2** (Figure 6). Thus, we assign the minor subspectrum of **2** to **AG'/AG** and enantiomeric **G'A/GA** families of rotamers that respectively will give only one subspectrum due to rapid *intra*family exchange (eq 2).

Rapid intrafamily exchange in either eq 1 or eq 2 would also explain the small $\Delta\delta$ values observed for the NCH_2 protons at 100 K.

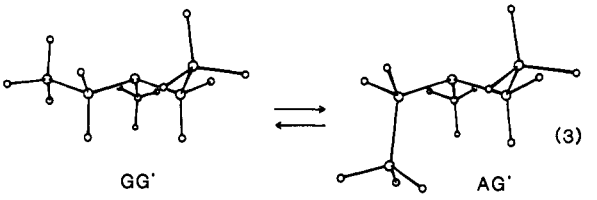
Table I. Relative Energies of the Various Conformers of Diethylmethylamine Computed with the 1980 MM2 Force Field[4d,12]

conformer	rel energy, kcal/mol
GG'	0.00
GG	0.05
AG'	0.47
AG	0.66
G'G'	2.96
AA	3.82

Table II. Rotation Barriers about the $N-CH_2$ Bonds in Diethylmethylamine with the 1980 MM2 Force Field[4d,12]

process	eclipsing in the transition state	barrier, kcal/mol
GG to GG'	CCH_3/lone pair	4.4
AG' to AG	CCH_3/lone pair	4.5
GG' to AG'	CCH_3/NCH_3	6.0

In contrast, the MM2 rotation barrier for a **GG'** to **AG'** process during which CCH_3 eclipses NCH_3 (eq 3) is a DNMR-visible

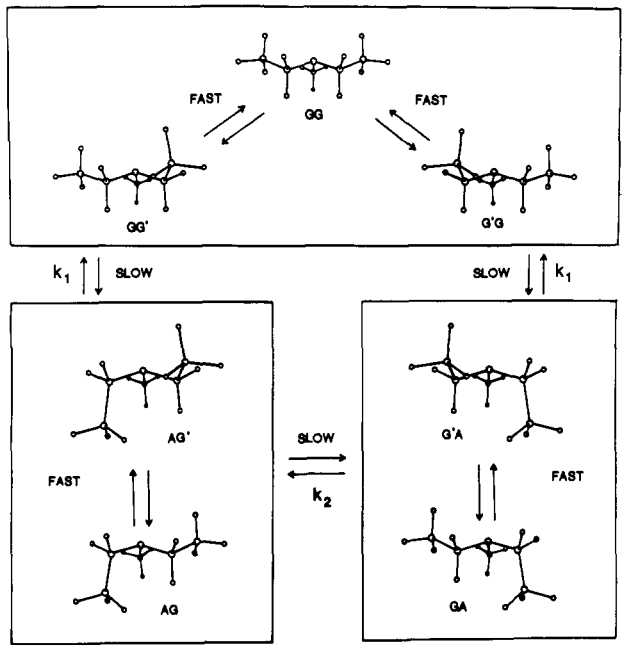


GG' AG' (3)

6.0 kcal/mol and should be a good estimate of the barrier separating **GG'/GG/G'G** and **AG'/AG** families of rotamers. Thus, it is apparent that the decoalescence observed for **2** from 140 to 102 K is due at least in part to slowing this *inter*family process. A compilation of selected MM2 rotation barriers for diethylmethylamine may be found in Table II.

From these MM2 calculations, certain trends emerge. If rotation about an $N-CH_2$ bond in diethylmethylamine occurs via a CCH_3/lone pair eclipsing, this process has a barrier too low (~4.4 kcal/mol) to be DNMR-visible, at least in our laboratory. If $N-CH_2$ rotation occurs via a CCH_3/N–alkyl eclipsing, this process has a barrier of about 6 kcal/mol and is DNMR-visible. For one set of invertomers of diethylmethylamine, all these various exchanges among NMR-detectable rotamers are illustrated in eq 4. Rotameric interconversions *within* each of the boxes of eq 4 are fast on the DNMR time scale at 100 K; i.e., they involve CCH_3/lone pair eclipsings. Transformation of a rotamer in one box to a rotamer in another box involves at least one CCH_3/N–alkyl eclipsing in each instance and is presumably slow on the DNMR time scale at 100 K. This situation provides a kinetic definition for three families of rotamers respectively contained within the three boxes of eq 4. The time-averaged symmetry of the **GG'/GG/G'G** family is C_s and of the **AG/AG'** or **GA/G'A** family is C_1. The NMR spectra of the **AG/AG'** and **GA/G'A** families are identical, but it should be noted that an **AG/AG'** to **GA/G'A** interfamily equilibration interchanges the environments of CCH_3 groups and NCH_2 protons. Thus, for symmetry and barrier reasons, this interfamily process is in principle DNMR-visible, as are the **AG/AG'** to **GG'/GG/G'G** and **GA/G'A** to **GG'/GG/G'G** interfamily processes (eq 4).

With these ideas in mind, it is appropriate to consider the results of the theoretical simulations of the spectra of **2** in Figure 5. The conceptual approach to devising as simple a DNMR simulation model as possible incorporated the idea of "sitting" on one NCH_2 moiety and following its travels around eq 4. For accurate simulations of the NCH_2 spectra from 200 to 102 K, it was necessary to employ six configurations of two nuclei each. Three of these two-spin systems adequately simulate the AD, EK, and FG spectra at 102 K (Figure 6). Under conditions of slow inversion (i.e., below 150 K), these three spin systems simulate adequately the



ONE SET OF INVERTOMERS (4)

DNMR-visible N–CH_2 rotation processes in eq 4. However, above 150 K, inversion eventually effects complete interchange of all the environments of the NCH_2 protons. In order to account for this, it is necessary to add three more two-spin configurations to the ultimate DNMR model, i.e., DA, KE, and GF. These six two-spin systems (AD, DA, EK, KE, FG, GF) are adequate to simulate all DNMR-observable inversion and N–CH_2 rotation processes for **2**.

Below 150 K (Figure 5), the inversion process no longer contributes to the DNMR line shape, and the diastereotopic nature of the NCH_2 protons is clearly evident. Indeed, there are a limited number of allowed chemical shift interchanges due to restricted N–CH_2 rotation; i.e., total interchange does not occur. The specific chemical shift interchanges required for accurate simulations of the NCH_2 spectra below 150 K are indicated by the double-headed arrows of Figure 9.

The DNMR spectra of the NCH_3 group were simulated with a simple two-site exchange and were superimposed on the NCH_2 spectra.

Thus, k_i in Figure 5 refers to the composite rate constant for inversion between the two complete sets of invertomers. Very small values of k_i at very low temperatures were obtained by extrapolation from higher temperatures where k_i still affected the DNMR line shape. The rate constant k_1 is for conversion of an **AG/AG'** or **GA/G'A** family to the **GG'/GG/G'G** family of rotamers, and k_2 is for the **AG/AG'** to **GA/G'A** interfamily process. Very large values of k_1 and k_2 at higher temperatures were obtained by extrapolation from lower temperatures. Obviously, the rate constants for *intra*family exchange cannot be determined by DNMR.

From DNMR line-shape analysis, the $\Delta G^{\ddagger}$ value for conversion of a **GG'/GG/G'G** family to an **AG/AG'** family of rotamers (eq 4) is 5.9 ± 0.4 kcal/mol at 120 K. These rotation processes involve CCH_3/N-alkyl eclipsings, and the experimental $\Delta G^{\ddagger}$ value compares favorably with the MM2 barrier of 6.0 kcal/mol for the **GG'** to **AG'** process. From the DNMR spectra, the $\Delta G^{\ddagger}$ value for **AG/AG'** to **GA/G'A** interfamily exchange is 5.2 ± 0.4 kcal/mol at 120 K. A consideration of the energy contour map (Figure 8) suggests that an **AG/AG'** to **GA/G'A** process that does not proceed via a **GG'/GG/G'G** family occurs most logically via an **AA** form. The MM2 barriers for an **AG** to **AA** process and for an **AG'** to **AA** conversion are 8.1 and 5.9 kcal/mol, respectively. Both of these MM2 barriers suggest DNMR-visibility, but the 5.9 kcal/mol value is more in line with the observed $\Delta G^{\ddagger}$ value of 5.2 kcal/mol and seems to favor the **AG'** to **AA** itinerary.

In light of the internal consistency between the DNMR spectral results and the MM2 calculations presented above and the rather comprehensive picture of the stereodynamics of diethylmethylamine that has emerged, it is interesting to return to the energy contour map in Figure 8. It is clear that there is a mirror plane that is perpendicular to the energy surface and that extends from the lower right corner to the upper left corner of the contour map. The mirror plane of the contour map is coincident with the time-averaged or actual molecular mirror plane of each of a number of the conformers of diethylmethylamine (i.e., **AA**, **G'G'**, **GG**). Immediately flanking the mirror plane of the contour map are conformers of C_1 symmetry. Reflection of the **G'G** rotamer through the contour map mirror plane produces the enantiomeric **GG'** form, reflection of **GA** produces the enantiomeric **AG**, and reflection of **G'A** produces the enantiomeric **AG'**. It is also evident from the energy contour map that, to a very good first approximation, the preferred route for rotamer interconversion involves rotation about *one* N–CH_2 bond at a time. There is no evidence for preferred correlated rotations about two N–CH_2 bonds. Those N–CH_2 bond rotations that involve a CCH_3/N-alkyl eclipsing are DNMR-visible and those that involve a CCH_3/lone pair eclipsing are DNMR-invisible.

The rather comprehensive stereodynamics defined above for diethylmethylamine should be relevant to a simple homologue, i.e., triethylamine. The nitrogen inversion barrier in triethylamine will be similar to that in diethylmethylamine. Thus, in the situation where the nitrogen inversion barrier in triethylamine is higher than the isolated N–CH_2 rotation barriers, the nitrogen inversion process will be DNMR-invisible for symmetry reasons.[5] However, certain of the N–CH_2 isolated rotation processes in triethylamine are, in principle, DNMR-visible and should have barriers comparable to the analogous processes in diethylmethylamine. Indeed, as will be shown below, triethylamine and two deuterated derivatives undergo *one* DNMR decoalescence over the same temperature range where isolated N–CH_2 rotation in diethylmethylamine slows on the NMR time scale.

The ^1H NMR spectrum (270 MHz) of triethylamine (2% v/v in $CBrF_3$) at 170 K shows a typical A_2X_3 spectrum (δ_A 2.48, δ_X 1.00, $^3J_{AX}$ = 7.0 Hz), as illustrated in Figure 10. At temperatures below 140 K, the spectrum broadens, undergoes one decoalescence, albeit complex, and sharpens into the "slow-exchange" spectrum at 97 K (Figure 10). The 97 K spectrum is simulated accurately via superposition of two subspectra. The major subspectrum (94%) consists of A_2Z_3 (δ_A 2.77, δ_Z 0.76, $^3J_{AZ}$ = 6.0 Hz) and CEX_3 (δ_C 2.50, δ_E 2.36, δ_X 1.10, $^3J_{CX}$ = $^3J_{EX}$ = 6.0 Hz, $^2J_{CE}$ = −12.0 Hz) spin systems. The CEX_3:A_2Z_3 area ratio is 2:1 (Figure 11). The minor subspectrum is an F_2Y_3 spin system (δ_F 2.25, δ_Y 1.07, $^3J_{FY}$ = 6.0 Hz). The δ_X and δ_Y values speak for methyl groups gauche to the lone pair while the δ_Z value indicates methyl groups anti to the lone pair. In light of the results obtained for diethylmethylamine (vide supra), this decoalescence may be assigned with confidence to restricted N–CH_2 rotation.

The DNMR behavior of the methyl protons of triethylamine (Figure 10) is corroborated by an examination of the ^1H DNMR spectra of $(CH_3CD_2)_3N$ (**6**; 2% v/v in $CBrF_3$). The methyl singlet

6: $(CH_3CD_2)_3N$

7: $(CD_3CH_2)_3N$

of **6** at 170 K decoalesces at lower temperatures into two resolved singlets centered at δ 1.10 and 0.77 (Figure 12) with a peak area ratio of about 2.2:1.0 at 100 K. A theoretical decomposition of the 100 K spectrum reveals two subspectra. The major subspectrum (94%) consists of two singlets at δ 1.10 and 0.76 with a respective area ratio of 2:1. The minor subspectrum (6%) is simulated as *one* singlet at δ 1.07 that is buried under the large singlet at δ 1.10 (see Figure 13). Thus, these chemical shift values indicate that the major conformers of triethylamine have twice as many methyl groups gauche to the lone pair as anti, and the minor conformers appear to have all methyls gauche to the lone pair.

An examination of the ^1H DNMR spectra of $(CD_3CH_2)_3N$ (**7**; 2% v/v in $CBrF_3$) provides more incisive information regarding

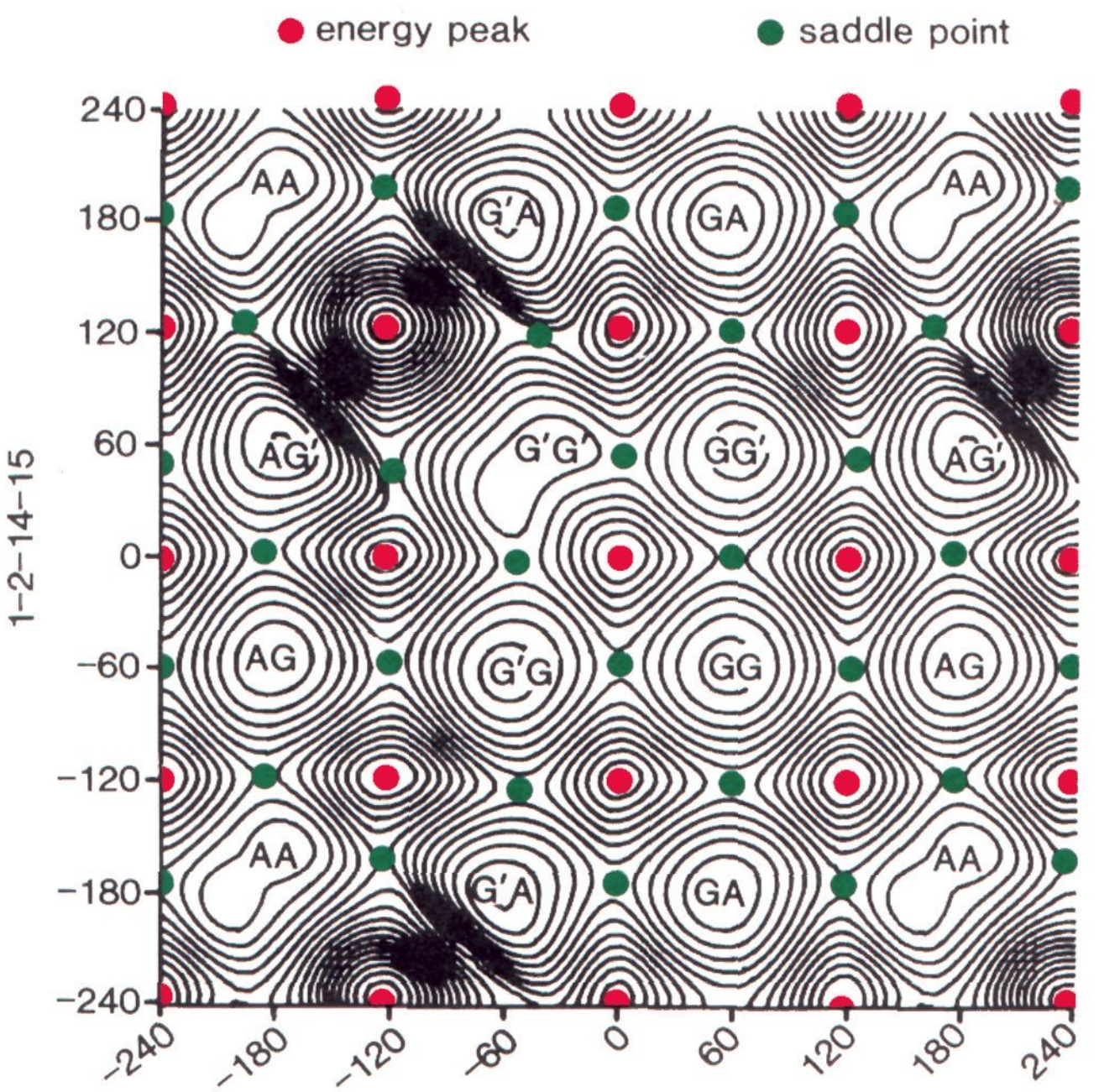


Figure 8. A 5000-point energy contour map for diethylmethylamine computed by using the 1980 MM2 force field. The two pertinent dihedral angles are defined in structure **5** and the separation between contour lines is 1.0 kcal/mol. A red dot indicates an energy peak or "mountain top" pointing toward the reader. A green dot indicates a saddle point. A pair of letters defines a particular conformation and an energy minimum.

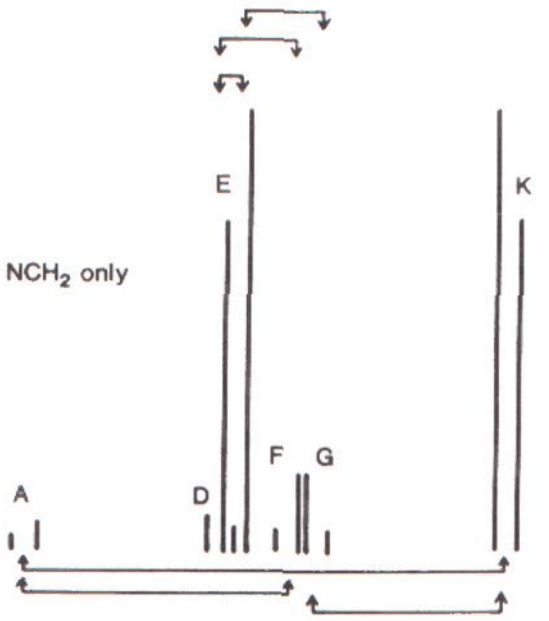


Figure 9. Schematic summary of the allowed chemical shift interchanges due to isolated rotation for the NCH_2 protons only of $(CD_3CH_2)_2NCH_3$.

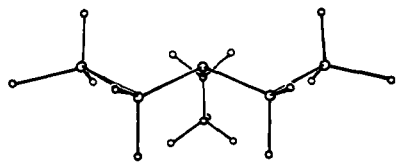
conformational preferences in triethylamine. The NCH_2 singlet of **7** at 170 K decoalesces at lower temperatures and is sharpened into a clearly defined spectrum at 105 K (Figure 14). The 105 K spectrum is decomposed theoretically into two subspectra. The major subspectrum (94%) at the top of Figure 15 consists of a singlet (or A_2 spectrum) at δ_A 2.73 and a CE spectrum (δ_C 2.50, δ_E 2.36, $^2J_{CE} = -12.0$ Hz). The A_2:CE area ratio is 1:2. The minor subspectrum (6%) consists of just one singlet (or F_2 spectrum) at δ_F 2.26.

Theoretical simulation of the DNMR spectra in Figure 14 required a chemical shift exchange model involving *direct* interchange among the peaks of the major spectrum (i.e., direct interchange among the major conformers without proceeding through the minor species), and k_1 in Figure 14 is the rate constant for these processes. The rate constant k_2 in Figure 14 refers to the conversion of major to minor conformers.

As with diethylmethylamine, the major subspectrum of triethylamine suggests C_s symmetry. The A_2 singlet in the major subspectrum of **7** (Figure 15) is associated with an ethyl group that is oriented anti to the lone pair. The chemical shift equivalence of the two methylene protons results from a static or time-averaged plane of symmetry through which these protons can be reflected. The CE spectrum apparently results from two enantiotopic sets of protons with two diastereotopic protons in each set. There is a strong analogy to the major subspectrum of **2** (Figure 6).

A conformation that has the symmetry required to be consistent with the major subspectrum in Figure 15 is the **GAG** form. The **GAG** species has two methyls gauche to the lone pair and one methyl anti and possesses the C_s symmetry that could lead to the major subspectrum in Figure 15.

However, if the CE spectrum at the top of Figure 15 is to be assigned to the two ethyl groups that are oriented gauche to the nitrogen lone pair of the **GAG** conformer, then the $\Delta\delta_{CE}$ value of

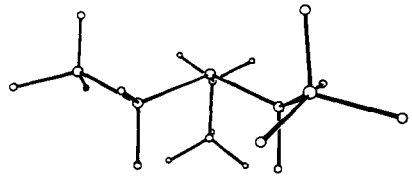


GAG

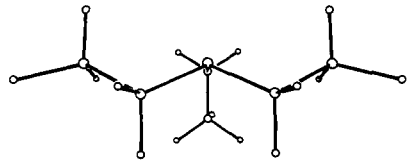
0.14 ppm is highly suspicious (vide supra). The small $\Delta\delta_{CE}$ value suggests strongly that some conformational averaging is still fast even at 105 K.

Empirical force-field calculations shed light on this situation and suggest stereodynamics for triethylamine that are highly analogous to diethylmethylamine. For purposes of naming the various conformers of triethylamine, the letter **A** denotes a methyl group oriented anti to the lone pair, **G** a methyl group gauche to the lone pair and also gauche to an **A** group, and **G′** a methyl group gauche to the lone pair and also gauche to an ethyl group that in turn has a methyl gauche to the lone pair. In a few instances, this nomenclature system does not provide a unique label for each of the many conformers, and we will provide an arbitrary designation. The reader should peruse the structural diagrams presented.

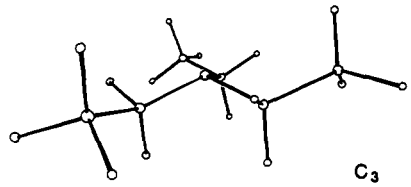
With regard to conformational preference, the MM2 calculations indicate the **G′G′G′** conformer that has C_3 symmetry to be



GAG′



GAG



G′G′G′

lowest in energy (see structures). The dihedral angle between the lone pair axis and each C–CH_3 bond is 62° with the C–CH_3 bond tilted slightly away from the lone pair and all three CNC bond angles at 111°. This conformer has perfect C_3 symmetry and has an enantiomeric form. The **GAG** conformer is computed to be only 0.01 kcal/mol higher in energy than the C_3-symmetric **G′G′G′** form. In the **GAG** conformer, the dihedral angle between the lone pair axis and each of the two **G** C–CH_3 groups is 61°. The **A** C–CH_3/lone pair dihedral angle is 180°. The CNC bond angle associated with the two **G** groups is 110° and that associated with **G** and **A** groups is 113°. The **GAG′** geometry is MM2-computed to be 0.22 kcal/mol higher in energy than the C_3 species. For the **GAG′** form, the **G** C–CH_3/lone pair dihedral angle is 54° (tilted toward lone pair), the **G′** C–CH_3/lone pair dihedral angle is 64° (tilted away from lone pair), and the **A** C–CH_3/lone pair dihedral angle is 178°. The CNC bond angle associated with the **G** and **G′** groups is 112°, with the **G** and **A** groups 111°, and with the **G′** and **A** groups 113°. For one set of nitrogen invertomers, there are of course three equivalent conformers that have **GAG** symmetry (i.e., **AGG**, **GAG**, **GGA**) and six forms that have **GAG′**

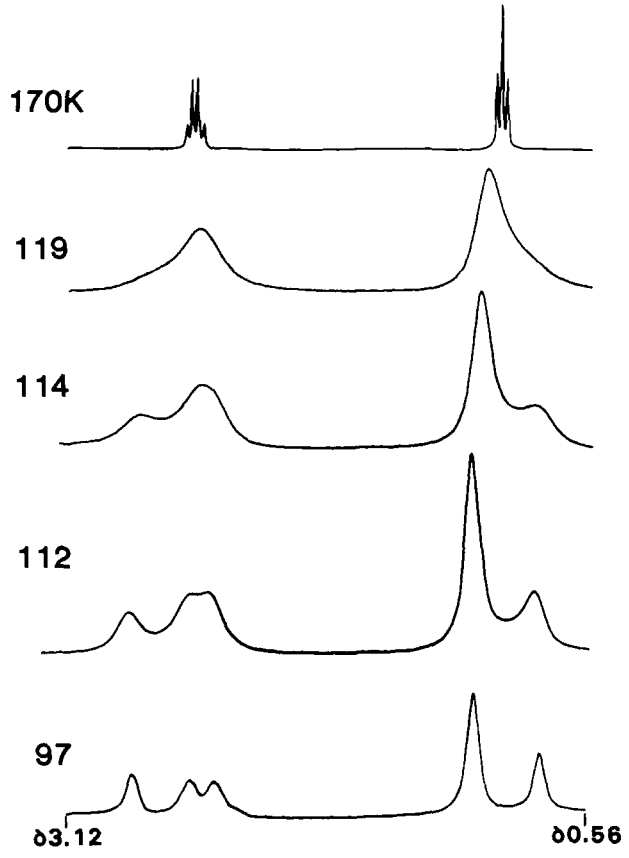


Figure 10. ^{1}H DNMR spectra (270 MHz) of triethylamine (2% v/v in $CBrF_3$).

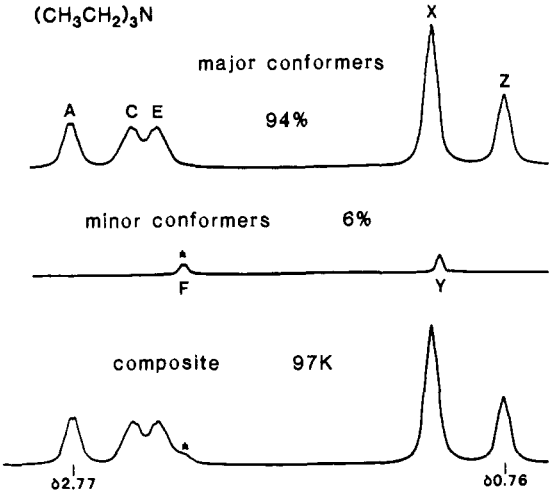


Figure 11. Theoretical decomposition of the ^{1}H NMR spectrum of triethylamine at 97 K (also see Figure 10).

Table III. Relative Energies of the Various Conformers of Triethylamine Computed with the 1980 MM2 Force Field[4d,12]

conformer	rel energy, kcal/mol
G′G′G′ (C_3 symmetry)	0.00
GAG	0.01
GAG′	0.22
G′G′G′ (C_1 symmetry)	2.94
G′AG′	3.21
AAG	3.35
AAA	7.36

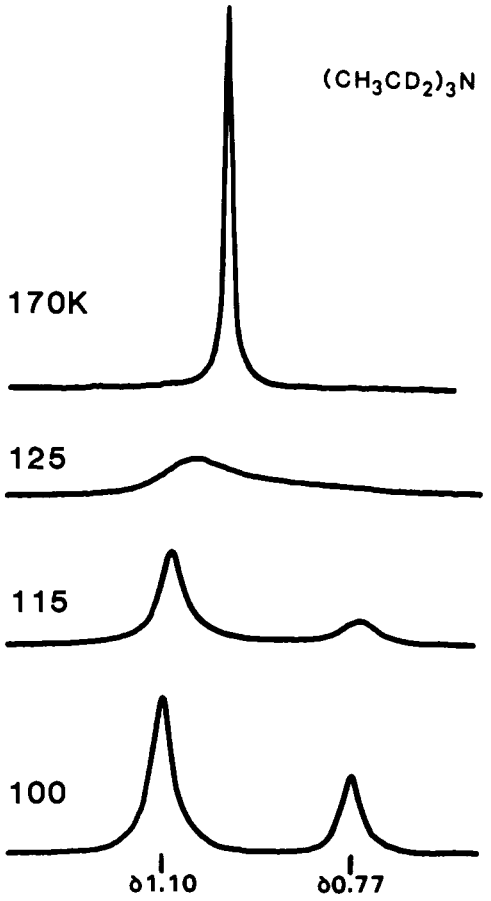


Figure 12. ^1H DNMR spectra (270 MHz) of $(CH_3CD_2)_3N$ (**6**; 2% v/v in $CBrF_3$).

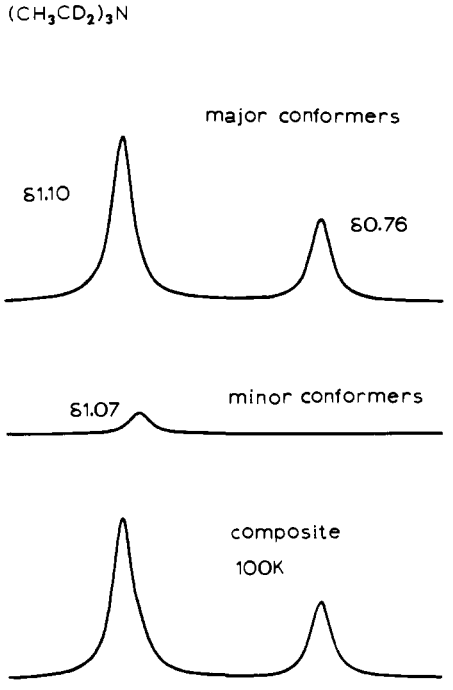


Figure 13. Theoretical decomposition of the ^1H NMR spectrum of $(CH_3CD_2)_3N$ at 100 K (also see Figure 12).

symmetry (i.e., **AGG'**, **G'AG**, **GG'A**, etc.).

Those conformers that have 1,5-interactions between two methyls are unstable. The **G'AG'**, **AAG**, **AAA**, and that specific **G'G'G'** form that has C_1 symmetry are MM2-computed to be respectively 3.21, 3.35, 7.36, and 2.94 kcal/mol in energy above the C_3 conformation. These species will not be present in concentrations high enough to be NMR-detectable. A compilation of relative MM2 rotamer energies can be found in Table III.

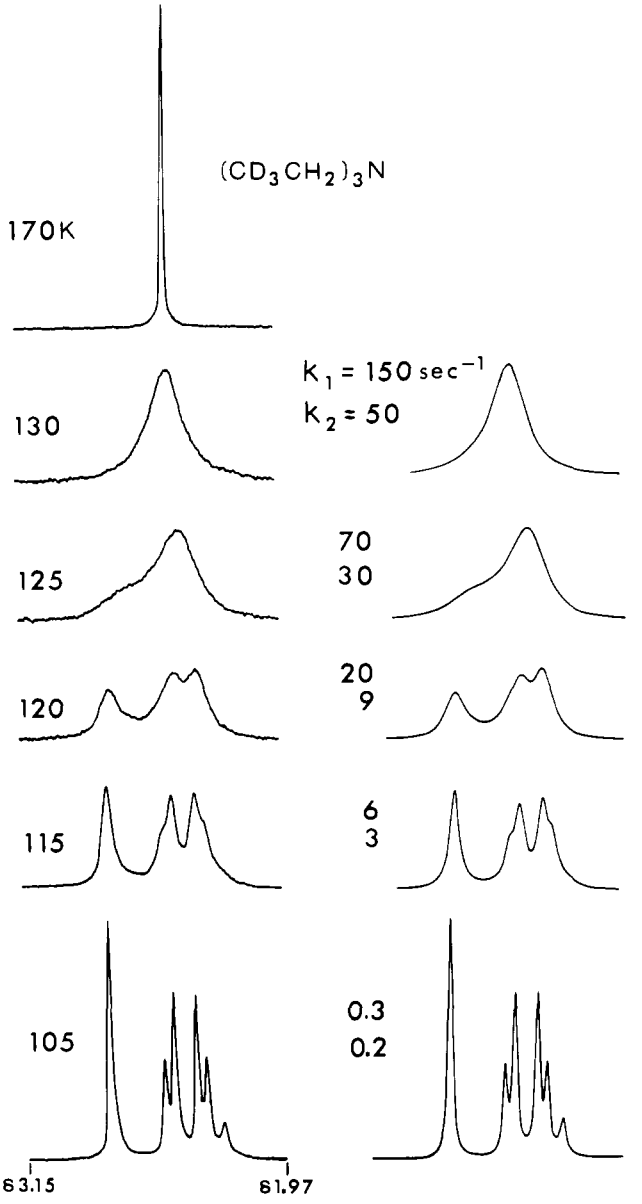
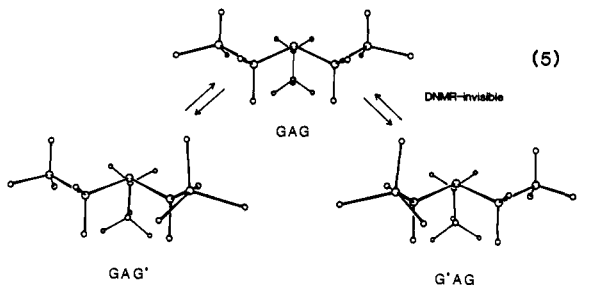


Figure 14. Experimental ^1H DNMR spectra of $(CD_3CH_2)_3N$ (**7**; 2% v/v in $CBrF_3$) in the left column and theoretical DNMR simulations in the right column. k_1 is the first-order rate constant for *direct* interchange among the major rotamers. k_2 is the rate constant for conversion of major to minor rotamers.

Thus, the MM2 calculations indicate the existence of *three* geometries for triethylamine that should be present in NMR-detectable concentrations, but only *two* subspectra are observed at 105 K (Figure 15). The situation is reminiscent of diethylmethylamine.

Indeed, conversion of a **GAG** form to **GAG'** can occur via $N-CH_2$ bond rotation involving a CCH_3/lone pair eclipsing, i.e., presumably a DNMR-invisible process at 100 K (eq 5). The



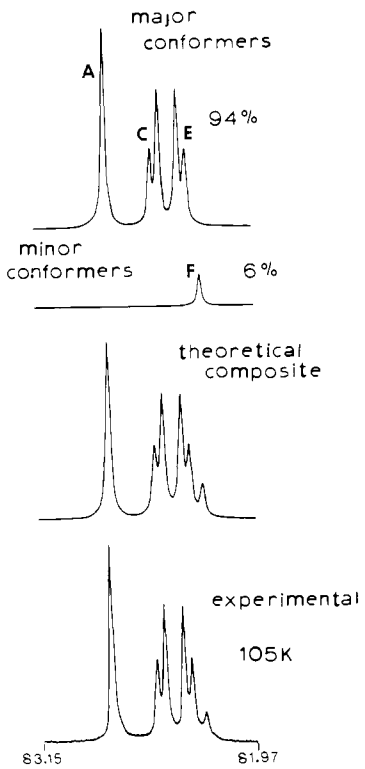


Figure 15. Theoretical decomposition of the ^1H NMR spectrum (270 MHz) of $(CD_3CH_2)_3N$ at 105 K (also see Figure 14).

Table IV. Rotation Barriers about the $N-CH_2$ Bonds in Triethylamine with the 1980 MM2 Force Field[4d,12]

process	eclipsing in the transition state	barrier, kcal/mol
GAG to GAG′	CCH_3/lone pair	4.4
GAG to AAG	CCH_3/NCH_2CH_3	5.6
G′G′G′ (C_3 symmetry) to G′G′G′ (C_1 symmetry)[a]	CCH_3/lone pair	3.9

[a] See Figure 16.

MM2-computed barrier for a **GAG** to **GAG′** process via CCH_3/lone pair eclipsing is 4.4 kcal/mol, which is indeed below our lower limit of DNMR-observation. Thus, if one ethyl group remains anti and *static* on the NMR time scale while the other two ethyl groups undergo very rapid, DNMR-invisible **G** to **G′** 120° torsions via CCH_3/lone pair eclipsing, the effective time-averaged symmetry of this **GAG′/GAG/G′AG** family of conformers is C_s (see eq 5). The stereodynamics are entirely consistent with the symmetry of the major subspectrum of **7** at 105 K (Figure 15) and the small $\Delta\delta_{CE}$ value. One can with confidence assign the major subspectrum of **7** to the **GAG′/GAG/G′AG** family of rotamers. For one set of nitrogen invertomers, there are in fact three equivalent families of major rotamers: **GAG′/GAG/G′AG**, **AGG′/AGG/AG′G**, and **GG′A/GGA/G′GA**. A compilation of selected MM2 rotation barriers can be found in Table IV.

Direct conversion from one family of major rotamers to another (i.e., *not* via the C_3 species) requires at least two CCH_3/NC_2H_5 eclipsings, i.e., presumably a DNMR-visible process. Indeed, the MM2-computed rotation barrier for the **GAG** to **AAG** process is 5.6 kcal/mol and therefore DNMR-visible. This **GAG** to **AAG** process is the rate-determining step in the **GAG** to **AAG** to **AGG′** sequence. *Direct* exchange among the peaks in the major subspectrum of **7** is required for an accurate DNMR fit (Figure 14) consistent with direct interfamily exchange among the major rotamers having a DNMR-visible barrier. The $\Delta G^{\ddagger}$ for direct exchange among the major families of rotamers from DNMR line-shape analysis is 6.0 kcal/mol at 125 K, in good agreement with the MM2 barrier.

At this point, one must return to the fact that the MM2 method predicts the C_3-symmetric **G′G′G′** form to be the most stable

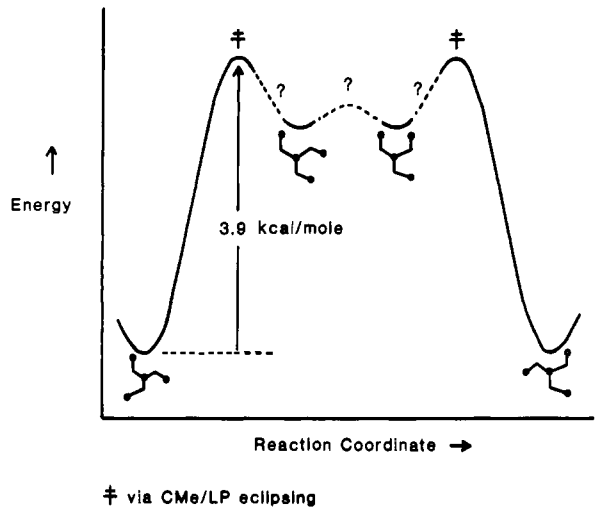
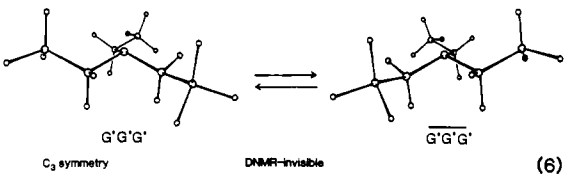


Figure 16. Energy profile for direct enantiomeric interchange via isolated $N-CH_2$ rotation between two C_3 conformers of triethylamine.

conformation. Having assigned the major NMR subspectrum of triethylamine to families of rotamers having **GAG′/GAG/G′AG** time-averaged symmetry, it is consistent to assign the minor subspectrum (i.e., the small singlet; Figure 15) to the C_3 species. However, the two methylene protons of the C_3 species are diastereotopic, and assignment of the singlet comprising the minor subspectrum of **7** at 105 K (Figure 15) is problematical until one considers the results of MM2 calculations. Conversion of one C_3 conformer to its enantiomer (eq 6) can occur via three sequential



(6)

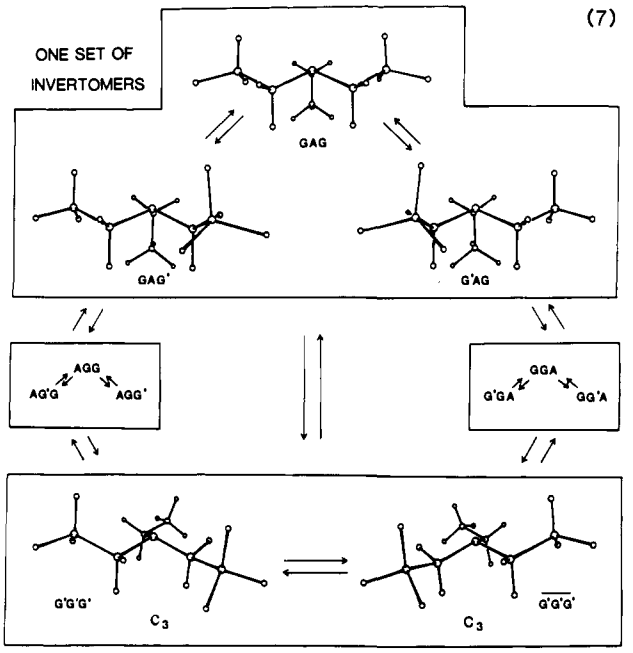
CCH_3/lone pair eclipsings illustrated in Figure 16. Figure 16 presents a view of triethylamine looking down the lone pair axis. From all the evidence presented above, these processes should be DNMR-invisible. Although the upper reaches of the energy surface for this process have not been computed in detail, it is clear that the rate-determining process is conversion of the C_3 species via a CCH_3/lone pair eclipsing to a **G′G′G′** conformer having C_1 symmetry and a repulsive 1,5-interaction (Figure 16). The MM2 barrier for this process is 3.9 kcal/mol, strongly suggesting DNMR-invisibility at 100 K. Indeed, rapid interconversion on the DNMR time scale between the enantiomeric C_3 species in eq 6 will interchange the environments of the methylene protons and give rise to the F_2 singlet observed for **7** at 105 K (Figure 15).

However, the NMR spectrum at 105 K indicates only 6% of the C_3 form, i.e., an apparent discrepancy with the MM2 calculations. There are 18 members of the rotamer families having **G′AG/GAG/GAG′** symmetries and only 4 C_3 rotamers. Thus, from at least a simple statistical point of view, there are entropy terms that favor rotamers having **G′AG/GAG/GAG′** symmetries (R ln 18) over the C_3 forms (R ln 4). At 105 K, this entropy contribution to the $\Delta G°$ value is equal to $-RT$ ln 18 + RT ln 4 or −0.3 kcal/mol. This could account in part for the observed small percentage of C_3 rotamers at 105 K. It is noteworthy that there is not as large a statistical preference for **AG/AG′** type rotamers over **GG′/GG/G′G** types in diethylmethylamine (i.e., 8 vs. 6 or 0.06 kcal/mol at 105 K) and the MM2-computed rotamer preferences agree quite well with the NMR data at 100 K.

In triethylamine, a conversion from the **GAG′** rotamer to the C_3 conformer can occur via one CCH_3/NC_2H_5 eclipsing and has an MM2 barrier of 5.9 kcal/mol; i.e., it is a DNMR-visible process. The $\Delta G^{\ddagger}$ for conversion from major to minor species from DNMR line-shape analysis (Figure 14) is 6.3 kcal/mol at 125 K, in good agreement with the MM2 barrier.

As in the case of diethylmethylamine, these results for triethylamine allow for definitions of families of rotamers based on the kinetics of conformational exchange via N–CH_2 rotation. A comprehensive equation for one set of invertomers is presented in eq 7. Those conformers within each box interconvert at rates

(7)



fast on the NMR time scale even at 100 K, and all these N–CH_2 rotations involve one or more CCH_3/lone pair eclipsings but *no* CCH_3/N–alkyl eclipsings. Proceeding from one box to another requires at least one CCH_3/N–alkyl eclipsing and involves DNMR-visible barriers (~6 kcal/mol). This situation is of course entirely analogous to diethylmethylamine.

This work provides a comprehensive picture of the rich stereodynamics of two simple but highly representative acyclic trialkylamines. Indeed, if the three alkyl groups of any acyclic trialkylamine all have straight-chain character in the region proximate to nitrogen, one might predict with confidence that the stereodynamics of the region of the amine close to nitrogen will be very similar to diethylmethylamine and triethylamine.

Experimental Section

NMR spectra were run on a Bruker 270-MHz pulsed Fourier transform NMR system at the Northeast Regional NSF-NMR Facility at Yale University and on a Bruker WM-250 pulsed Fourier transform NMR system at the University of Vermont. At very low temperatures, temperature measurement is accurate to ±4 K. For this reason, we report only $\Delta G^{\ddagger}$ values from DNMR line-shape analyses and do not report $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values which are subject to significant systematic errors. All NMR samples were prepared in precision NMR tubes on a vacuum line and degassed 3 times, and the NMR tubes were sealed.

Diethylmethylamine was purchased (Alfa Products) and purified on a 5% XE-60/25% SF-96 Chromosorb W GLPC column (20 ft by $^3/_8$ in.). ^{1}H NMR: see Figure 1.

***N*,*N*-Bis(ethyl-*1*,*1*-d_2)methylamine (1).** *N*,*N*-Diacetylmethylamine (5.0 g, 0.04 mol; Pfalz and Bauer, Inc.) was reduced with lithium aluminum deuteride (3.3 g, 0.08 mol; Stohler Isotope Chemicals, Inc.) in 60 mL of anhydrous ether. The reaction mixture was allowed to reflux for 3 h. A small but sufficient amount of 15% aqueous NaOH was added to destroy excess hydride, the ether solution was filtered, dried over anhydrous sodium sulfate, and filtered, and the bulk of the ether was removed on a spinning band distillation column. Compound **1** was purified on a 5% XE-60/25% SF-96 on Chromosorb W GLPC column (20 ft by $^3/_8$ in.). ^{1}H NMR: see Figure 3.

***N*,*N*-Bis(ethyl-*2*,*2*,*2*-d_3)methylamine (2).** Methylamine (9.3 g, 0.32 mol; Matheson Gas Products) was condensed into 100 mL of ether cooled to 195 K. The methylamine/ether solution was allowed to warm to 270 K under a dry ice/acetone condenser, and acetyl-d_3 chloride (10.0 g, 0.13 mol; Stohler Isotope Chemicals, Inc.) in 50 mL of ether was added slowly. The reaction mixture was allowed to stir for 8 h under a dry ice/acetone condenser. Solid methylamine hydrochloride was removed by filtration and the ether removed under vacuum to give 8.0 g (0.11 mol) of *N*-methylacetamide-d_3. *N*-Methylacetamide-d_3 (8.0 g, 0.11 mol) in 100 mL of anhydrous ether was reduced with lithium aluminum hydride (8.0 g, 0.21 mol) by a procedure identical with that described for compound **1** (vide supra). To the resulting ether solution of the volatile *N*-(ethyl-*2*,*2*,*2*-d_3)methylamine was added acetyl-d_3 chloride (5.0 g, 0.06 mol) and pyridine (4.7 g, 0.06 mol). The reaction mixture was allowed to stir for 18 h, the pyridinium chloride was removed by filtration, and the ether was removed under vacuum to give *N*-(ethyl-*2*,*2*,*2*-d_3)-*N*-methylacetamide-d_3, which was in turn reduced with lithium aluminum hydride (vide supra) to give an ether solution of compound **2**. Most of the ether was removed by using a spinning band distillation column, and **2** was purified on a 5% XE-60/25% SF-96 on Chromosorb W GLPC column (20 ft by $^3/_8$ in.). ^{1}H NMR: see Figure 5.

***N*-*tert*-Butyl-*N*-methyl(ethyl-*2*,*2*,*2*-d_3)amine (4)** was prepared by a procedure reported in one of our earlier papers.[5a] ^{1}H NMR: see Figure 7.

Triethylamine was purchased from Aldrich Chemical Co. and purified with a 5% XE-60/25% SF-96 on Chromosorb W GLPC column (20 ft by $^3/_8$ in.). ^{1}H NMR: see Figure 10.

Tris(ethyl-*1*,*1*-d_2)amine (6). Triacetamide was prepared with the procedure of LaLonde and Davis[14] and then reduced with lithium aluminum deuteride in anhydrous ether (vide supra). Compound **6** was purified with a 5% XE-60/25% SF-96 on Chromosorb W GLPC column (20 ft by $^3/_8$ in.). ^{1}H NMR: see Figure 12.

Tris(ethyl-*2*,*2*,*2*-d_3)amine (7). Triacetamide-d_9 was prepared by using acetyl-d_3 chloride and the procedure of LaLonde and Davis[14] and then reduced with lithium aluminum hydride in anhydrous ether by using the procedure for **6** above. ^{1}H NMR: see Figure 14.

Acknowledgment. C.H.B. is grateful to the National Science Foundation for support (Grant CHE78-21161, CHE79-26243, and CHE80-24931). We also acknowledge National Science Foundation Grant CHE79-16210 from the Chemistry Division in support of the Northeast Regional NSF-NMR Facility at Yale University. We appreciate the assistance of the University of Vermont Academic Computing Center staff in providing outstanding computational support.

Registry No. **1**, 82865-81-4; **2**, 82865-82-5; **4**, 82865-83-6; **6**, 82865-84-7; **7**, 82865-85-8; diethylmethylamine, 616-39-7; triethylamine, 121-44-8; *N*,*N*-diacetylmethylamine, 1113-68-4; methylamine, 74-89-5; acetyl-d_3 chloride, 19259-90-6; *N*-methylacetamide-d_3, 3669-69-0; *N*-(ethyl-*2*,*2*,*2*-d_3)-*N*-methylamine, 82865-86-9; *N*-(ethyl-*2*,*2*,*2*-d_3)-*N*-methylacetamide-d_3, 82865-87-0; triacetamide, 641-06-5; triacetamide-d_9, 82865-88-1.

(14) LaLonde, R. T.; Davis, C. B. *J. Org. Chem.* **1970**, *35*, 771.