Organic Chemistry

Non-Planar Structures of Sterically Overcrowded Trialkylamines
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Dedicated to Professor Wolfgang Kirmse on the occasion of his 90th birthday

Abstract: Several amines with three bulky alkyl groups at the nitrogen atom, which exceed the steric crowding of trisopropylamine significantly, were synthesized, mainly by treating N-chlorodialkylamines with Grignard reagents. In six cases, namely tert-butyldiisopropylamine, 1-adamantyl-tert-butyldiisopropylamine, di-1-adamantylamines with an additional N-cyclohexyl or N-exo-2-norbonyl substituent, as well as 2,2,6,6-tetramethylpiperidine derivatives with N-cyclohexyl or N-neopentyl groups, appropriate single crystals were generated that enabled X-ray diffraction studies and analysis of the molecular structures. The four noncyclic amines adopt triskele-like conformations, and the sum of the three C–N–C angles is always in the range of 351.1° to 352.4°. Consequently, these amines proved to be structurally significantly flatter than trialkylamines without steric congestion, which is also signalized by the smaller heights of the NC3 pyramids (0.241–0.259 Å). There is no clear correlation between the heights of these pyramids and the degree of the steric crowding in the new amines, presumably because steric repulsion is partly compensated by dispersion interaction. In the cases of the two heterocyclic amines, the steric stress is smaller, and the molecular structures include quite different conformations. Quantum chemical calculations led to precise gas-phase structures of the sterically crowded trialkylamines exhibiting heights of the NC3 pyramids and preferred molecular conformers which are similar to those resulting from the X-ray studies.

Introduction

The amine entity belongs to the most important functional groups in chemistry.[1] Quite distinct classes of amines are in the center of interest depending on the different properties and the respective fields of application. Tertiary and secondary amines with sterically demanding alkyl substituents, such as Hünig’s base 1,[2] and 2,2,6,6-tetramethylpiperidine (2),[3] play a major role as Brensted bases with low nucleophilicity or as precursors of persistent nitroxyl radicals, like 3,[4] which are used for spin labeling tools (Figure 1).[5] Many heterocyclic compounds of type 4 and free radicals derived from these piperidines serve as polymerization inhibitors and photostabilizers, well known as hindered amine light stabilizers (HALS).[6] Similar substances were recently introduced as base in frustrated Lewis pairs.[7] Furthermore, amines with bulky alkyl groups were studied in view of their pharmacological activity.[8] Finally, some sterically hindered amines have come into industrial use in gas-treating processes.[9]

In academia, other features than applications, such as new records of steric congestion[10] and molecular structures of trialkylamines, are often in the focus of attention. Especially, the question whether amines with three bulky alkyl groups will adopt a planar instead of the pyramidal nitrogen atom to mini-

Figure 1. Sterically hindered amine derivatives with wide ranges of applications.
mize the interaction of the amine substituents, has held a cer-
tain fascination for chemists. This question was mainly inves-
tigated by analyzing triisopropylamine (5) since other repre-
sentatives with significantly higher steric distress were not ac-
cessible up to quite recently (Figure 2). Based on the results of
electron diffraction studies, 5 should be very nearly planar
about nitrogen with a value for the C–N–C bond angle of
119.2(3)°. Thus, a sum of the angles at the nitrogen atom of
357.6° was detected, which is quite close to 360°, an indica-
tion of a planar structure. However, in temperature
single-crystal X-ray diffraction of 5 led to the C–N–C angle of
116.2(1)° and a sum of angles of 348.6°; thus a height of the
NC₃ pyramid (nitrogen at the top) of 0.27–0.29 Å (depending
on temperature) was determined. The latter value is more than
a half of the corresponding height in triethylamine (6), which amounts to 0.467 Å. In the solid state, the molecule of 5
obviously adopts a somewhat flatter pyramid instead of a
planar structure, and this is significantly different to the cor-
responding results of the gas-phase electron diffraction.
It might be argued that crystal field effects are possibly responsible for the non-planar molecular structure of 5 in a crystallized solid.

Herein, we describe the synthesis of several trialkylamines,
which include significantly higher steric crowding than 5. In the six cases of amines 8a and 8e–i, generation of single crys-
tals and X-ray diffraction were successful to analyze the mole-
cular structures. Based on these results, quantum chemical cal-
culations led to precise gas-phase structures of the title com-
ounds.

R_{2}N
R_{3}

Figure 2. Pyramidal structures of amines 5 and 6 in the solid state.

Results and Discussion

Synthesis of the amines

We mainly prepared tertiary amines 8, in which steric distress
surpasses that of the standard compound 5 distinctly, by treating
N-chlorodialkylamines 7 with Grignard reagents in the presence
of a major excess of tetramethylethylenediamine (TMEDA). The
substrates 7 were easily available by chlorination of the cor-
sponding secondary amines with the help of N-chlorosuccinimide.
Okay yields of the alkylation products 8 were achieved as depicted in Table 1, however, in some cases, alternative methods led to better yields of the de-
sired amines. For example, target compound 8a was also ac-
cessible by transforming formamide 9 into the respective
chloroiminium chloride with the aid of oxalyl chloride, followed
by the reaction with two equivalents of methylmagnesium bromide (Scheme 1). Furthermore, in situ generation of 1-adam-
tantyl triflate by exposure of bromide 10 to silver triflate

Table 1. Synthesis of tertiary amines 8 from N-chlorodialkylamines 7.

| R₁ | R₂ | R₃ | Yield of 8 [%] |
|----|----|----|-------------|
| a  | t-Bu | i-Pr | 35 |
| b  | t-Bu | t-Bu | 23 |
| c  | t-Bu | t-amyl | 19 |
| d  | t-amyl | t-amyl | 26 |
| e  | t-Bu | 1-adamantyl | 24 |
| f  | 1-adamantyl | 1-adamantyl | 25 |
| g  | 1-adamantyl | 1-adamantyl | 16 |
| h  | CMe₃CH₂C(OCH₂CH₂O)CH₂CMe₂ | CyMgCl | 18 |
| i  | CMe₃CH₂C(OCH₂CH₂O)CH₂CMe₂ | t-BuCH₂MgBr | 23 |
| j  | CMe₃C(CH₂CMe₂ | t-BuCl₂MgBr | 35 |

[a] Isolated yields. [b] 2-exo-Norbornyl Grignard reagent.

Scheme 1. Synthesis of amines 8a and 8e by using alternative methods.

and subsequent treatment with tert-butylisopropylamine yielded
the desired product 8e. In the case of 8a,b,d,j, the title compounds proved to be color-
less liquids at room temperature, whereas highly viscous li-
uids or waxy solids were obtained in other cases, and crystal-
line solids resulted by handling of 8e–h in methanol at differ-
ent temperatures. Owing to the low melting points and the
tendency to form plastic/disordered crystals, the crystallization
and subsequent data collection as well as structure solution
and refinement were very challenging for the compounds 8a,
8e, 8f, 8g, 8h, and 8i. Unfortunately, all attempts to obtain
crystals which were suitable for structure determination with
atomic resolution failed for compounds 8b, 8c, 8d, and the
known model compound tri-tert-butylmethanol. The structure
solution and refinement were performed using the pro-
grams SHELXS, SHELXT or Superflp (for structure solu-
tion) and SHELXL (for refinement) embedded in Olex2.
Thus, single-crystal X-ray studies were successful for 8a and
the five amines 8e–i, some crystallographic details are given in
Table 2 (comprehensive data).
Table 2. Some crystallographic details of amines 8a and 8e–f18,24,25.

| 8a     | 8e     | 8f     | 8g     | 8h     | 8i     |
|--------|--------|--------|--------|--------|--------|
| Empirical formula | C9H11N | C9H11N | C9H11N | C9H11N | C9H11N |
| Formula weight | 158.22 | 249.43 | 252.57 | 379.61 | 281.43 |
| Temperature [K] | 100.00 | 100.00 | 100.00 | 100.00 | 99.97 |
| Crystal system | monoclinic | monoclinic | monoclinic | monoclinic | monoclinic |
| Space group | P21/c | P21/c | P21/c | P21/c | P21/c |
| a [Å] | 6.3045(10) | 18.776(5) | 16.4655(10) | 6.4480(1) | 14.812(7) |
| b [Å] | 11.2957(17) | 6.4752(18) | 6.4635(10) | 16.6531(7) | 8.785(4) |
| c [Å] | 15.212(12) | 24.315(6) | 19.8240(2) | 10.1718(6) | 6.285(3) |
| V [Å³] | 1072.9(3) | 2956.2(14) | 2058.03(4) | 1047.35(10) | 790.3(6) |
| Z | 4 | 4 | 4 | 2 | 2 |
| μ [mm⁻¹] | 1.092 | 1.121 | 1.186 | 1.204 | 1.183 |
| F(000) | 360.0 | 1120.0 | 816.0 | 420 | 312.0 |
| Crystal size [mm³] | 0.711 x 0.216 x 0.086 | 0.168 x 0.129 x 0.074 | 0.155 x 0.046 x 0.029 | 0.404 x 0.403 x 0.24 | 0.5 x 0.5 x 0.5 |
| λ [Å] | 0.71073 | 0.71073 | 1.51484 | 0.71073 | 0.71073 |
| 2θ range for data collection [°] | 4.506 to 62.936 | 1.674 to 50.816 | 6.330 to 160.578 | 9.066 to 136.488 | 5.44 to 62.98 |
| Index ranges | –2 ≤ h ≤ 8 | –22 ≤ h ≤ 22 | –20 ≤ h ≤ 20 | –6 ≤ h ≤ 7 | –21 ≤ h ≤ 20 |
| | –16 ≤ k ≤ 15 | –7 ≤ k ≤ 7 | –8 ≤ k ≤ 7 | –20 ≤ k ≤ 20 | –12 ≤ k ≤ 12 |
| | –21 ≤ l ≤ 22 | –29 ≤ l ≤ 29 | –25 ≤ l ≤ 25 | –12 ≤ l ≤ 12 | –9 ≤ l ≤ 8 |
| | 12.400 | 33.220 | 23.2051 | 3721 | 4638 |
| | 5434 | 4545 | 4451 | 3721 | 7297 |
| | 0.0248 | 0.0607 | 0.0756 | 0.0959 | 0.0686 |
| | 0.0215 | 0.0075 | 0.0128 | 0.0367 | 0.0478 |
| | 5434/0/192 | 4545/0/409 | 3721/1/254 | 1297/182/171 | 7051/0/357 |
| | 0.0556 | 0.0878 | 0.1447 | 0.1044 | 0.0756 |
| | 0.0495 | 0.0756 | 0.1447 | 0.0756 | 0.0495 |
| | 0.0371 | 0.0128 | 0.1447 | 0.0128 | 0.0371 |
| | 5434/0/336 | 4545/0/409 | 3721/1/254 | 1297/182/171 | 7051/0/357 |
| | 1.048 | 0.104 | 0.104 | 0.104 | 0.104 |
| | 1.060 | 0.24 | 0.24 | 0.24 | 0.24 |
| | 1.026 | 0.24 | 0.24 | 0.24 | 0.24 |
| | 0.104 | 0.075 | 0.075 | 0.075 | 0.075 |
| | 0.24 | 0.075 | 0.075 | 0.075 | 0.075 |
| | 0.24 | 0.075 | 0.075 | 0.075 | 0.075 |

The molecular structure of amine 8a in the single crystal shows a triskele-like conformation with three arms around the nitrogen atom (N1-C1-C4, N1-C5-H5), and N1-C8-H8, see Figure 3), which obviously enables optimal packing of the bulky alkyl groups. Similar triskele-like conformations were also detected in the case of the three other nonyclic amines 8e, 8f, and 8g (Figure 4). These preferred conformations can be characterized by selected, roughly antiperiplanar torsion angles as depicted in Table 3. When the C–N bond lengths of 8a are compared with those of the sterically more stressed amines 8e, 8f, and 8g, slightly greater values are found in the latter cases, even for C–N bonds connecting the same alkyl group with nitrogen; for example, 8b-N in 8a leads to a bond length of 1.4786(10) Å, whereas 8e revealed 1.491(3) Å. The greatest C–N distances were always experimentally observed for the nitrogen-attached 1-adamantanyl units (1.50–1.52 Å). The C–N bond angles ranged from 109.7 to 123.2° (Table 3). As expected, a small angle was detected for the IPrN–N–IPr group in 8a [113.17(6)°], while the greatest angle value resulted for amine 8f, in which the nitrogen is bridging two 1-adamantyl moieties. However, two quite different C–N–C angles were found in single amines even if the nitrogen is connected with a pair of the same alkyl groups. For example, the molecular structure of 8f includes two C1-adamantyl–N–C1-cyclohexyl angles of 109.70(13)° and 119.49(13)°; in the case of the smaller angle, the HI(C1)–C1

Figure 3. Molecular structure of amine 8a as determined from the crystal structure analysis; the triskele-like conformation is emphasized by red color. The ellipsoids are shown at the 50% probability level.23
Some molecular details of amines endo and exo, and an equilibrating, and another set of bond angles at nitrogen with another set of the corresponding torsion angles. In the cases of the noncyclic amines 8a, 8e, and 8f, 8g, this result may lead to the assumption that there is a limit in the height of NC3 pyramids, which cannot be significantly smaller than 0.24 Å even in the case of sterically overcrowded trialkylamines.

Since product 8g was prepared from -2-norbornyl group was also thinkable. Thus, the X-ray crystal structure analysis confirmed now the exo-2-norborynol structure of 8g, which was previously assigned by NMR spectroscopy. Recently, two non-equivalent rotamers of 8e were detected in a 5:1 ratio using high resolution NMR methods. Because this amine bears three different bulky alkyl groups, it obviously is able to adopt two distinct triskele-like conformations in solution. The main rotamer in solution corresponds to the molecular structure of 8e in the single crystal.

| Table 3. Some molecular details of amines 8a and 8e-i resulting from X-ray studies.\[16, 28\] |
| --- | --- | --- | --- | --- | --- |
| C–N bond lengths [Å] | 8e[\(a\)] | 8f | 8g | 8h | 8i[\(b\)] |
| C1-N1-C5-H(C5) | 1.496(10) | 1.516(3) | 1.499(2) | 1.501(7) | 1.492(4) |
| C5-N1-C11-H(C11) | 1.4757(10) | 1.491(3) | 1.500(2) | 1.508(6) | 1.486(3) |
| C7-N1-C17-H(C17) | 1.4739(10) | 1.481(3) | 1.518(2) | 1.484(7) | 1.485(3) |
| C9-N1-C19-H(C19) | 1.4740(10) | 1.487(3) | 1.503(2) | 1.487(4) | 1.493(2) |
| Bond angles at nitrogen [\(\text{°}\)] | | | | | |
| C1-N1-C5-H(C5) | 122.77(6) | 122.86(17) | 119.49(13) | 120.8(4) | 116.0(7) |
| C5-N1-C11-H(C11) | 115.60(6) | 110.57(15) | 109.70(13) | 111.1(4) | 119.2(2) |
| C11-N1-C17-H(C17) | 113.17(6) | 117.71(18) | 123.17(13) | 120.4(4) | 120.6(7) |
| C7-N1-C17-H(C17) | 351.54 | 351.14 | 352.36 | 352.3 | 350.4 |
| C9-N1-C19-H(C19) | 0.2537(3) | 0.2588(19) | 0.2410(18) | 0.243(5) | 0.268(3) |
| Height of the NC3 pyramid (nitrogen at the top) [Å] | | | | | |
| 8a | 0.2537(3) | 0.2588(19) | 0.2410(18) | 0.243(5) | 0.268(3) |
| 8e | 0.2585(19) | 0.2585(19) | 0.2410(18) | 0.243(5) | 0.268(3) |
| Selected torsion angles [\(\text{°}\)] | \(\widehat{C}1-N1-C7-C9\) | \(\widehat{C}1-N1-C6-C9\) | \(\widehat{C}1-N1-C12-C11\) | \(\widehat{C}1-N1-C11-C15\) | \(\widehat{C}1-N1-C11-C12\) |
| C1-N1-C7-C9 | 165.5(7) | 162.65(1) | 162.65(1) | 162.65(1) | 162.65(1) |
| C1-N1-C6-C9 | 171.0(6) | 171.0(6) | 171.0(6) | 171.0(6) | 171.0(6) |
| C1-N1-C12-C11 | 179.30(15) | 179.30(15) | 179.30(15) | 179.30(15) | 179.30(15) |
| C1-N1-C11-C15 | 164.8(12) | 164.8(12) | 164.8(12) | 164.8(12) | 164.8(12) |
| C1-N1-C11-C12 | 169.08(13) | 169.08(13) | 169.08(13) | 169.08(13) | 169.08(13) |
| C1-N1-C12-C11 | 164.0(12) | 164.0(12) | 164.0(12) | 164.0(12) | 164.0(12) |
| C1-N1-C11-C15 | 168.20(14) | 168.20(14) | 168.20(14) | 168.20(14) | 168.20(14) |
| C1-N1-C12-C11 | 166.20(14) | 166.20(14) | 166.20(14) | 166.20(14) | 166.20(14) |
| C1-N1-C11-C15 | 173.7(4) | 173.7(4) | 173.7(4) | 173.7(4) | 173.7(4) |
| C1-N1-C12-C11 | 170.6(7) | 170.6(7) | 170.6(7) | 170.6(7) | 170.6(7) |

\[a\] A second molecule in the asymmetric unit leads to another set of C–N bond lengths with 1.497(3), 1.497(3), and 1.501(3) Å and another set of bond angles at nitrogen with 122.11(7), 110.00(16), and 119.70(17)° as well as another set of the corresponding torsion angles.\[16\] \[b\] A second molecule in the asymmetric unit leads to another set of C–N bond lengths with 1.475(2), 1.490(2), and 1.499(2) Å and another set of bond angles at nitrogen with 114.16(12), 113.56(13), and 116.65(12)° as well as another set of the corresponding torsion angles.\[14\]
In the molecular structures of the heterocyclic amines 8h and 8i, determined by the X-ray crystal structure analysis, the piperidine rings and also the cyclohexane ring of 8h adopt chair conformations (Figure 5). The amino group at the cyclohexane moiety of 8h is in an equatorial position, and the same is true for the cyclohexyl and the neopentyl groups at the piperidine units of 8h and 8i, respectively. These equatorial positions are confirmed by roughly antiperiplanar torsion angles as depicted in Table 3. However, the conformations of the exocyclic substituents at the nitrogen atoms are quite different: Whereas H(C1) of the cyclohexyl group points to C7 and the angles C1-N1-C7 [110.6(7)°] and C1-N1-C11 [120.4(4)°] are rather distinct in 8h, the molecular structure of 8i is more symmetric with similar angles C1-N1-C6 [113.96(12)°] and C1-N1-C12 [114.15(12)°] as well as similar absolute values of the torsion angles C2-C1-N1-C6 [111.14(16)°] and C2-C1-N1-C12 [−111.44(16)°]; furthermore, torsion angle N1-C1-C2-C4 [4(7)°] is very small.

Although amine 8h bears a secondary and two tertiary alkyl groups at the nitrogen, the steric stress is smaller than that of 8e, 8f, and 8g because of the piperidine ring structure, which connects both tertiary alkyl moieties in 8h. Consequently, the sum of the three angles at the nitrogen atom of 8h is slightly smaller and the height of the NC₃ pyramid is somewhat greater than the corresponding values of amine 8a that includes two secondary and only a single tertiary alkyl group at nitrogen (Table 3). In the case of the compound 8i with a primary alkyl unit at the piperidine N-atom, the sum of the three C–N–C angles proves to be significantly smaller than that of trisopropylamine (5); and the height of the NC₃ pyramid is considerably greater than that of 5.

We do not believe that crystal field effects are responsible for the non-planar molecular structures of our sterically overcrowded trialkylamines. In order to confirm this assumption, structural characterization of these amines in the gas phase, based on high-quality quantum chemical calculations, will be helpful.

Quantum chemical calculations

In order to elucidate the effect of crystallization further, we did detailed calculations on all the species in the gas as well as the solid crystalline phase. Furthermore, we computed other similar compounds with smaller alkyl groups. Finally, we did a conformational search of all the systems 8a–8j, in order to see if the conformer in the periodic crystal indeed corresponds to the minimum structure found in the gas phase.

The effect of different generalized gradient approximation (GGA) density functionals is also tested. In Table 4, we compare the experimental crystal structures to the experimental one and its gas phase structures.

Since different GGA functionals, like BLYP, PBE, and even the average of our computed methods yield very similar results, we do not believe that these will change when using another, different method. The computed crystal structures have a lower height of the NC₃ pyramid than the experimental ones, probably due to temperature and zero-point effects on the cell volume. And whereas the height is even lower in the gas phase of the less crowded compounds 8a, 8e, and 8h, it becomes larger for the gas phase of 8f, 8g, and 8i. Still, all of the reported heights are in the range of 0.225–0.350 Å, indicating that this is the value to be expected for such compounds.

Less hindered trialkylamines, such as trimethylamine, usually exhibit larger NC₃ heights. For triethylamine (6) and tripropylamine, different conformers will of course give different values for the heights. This is illustrated in Table 5, where the pyramidal NC₃ height can also vary widely between 0.3 and 0.45 Å. In order to discuss not only the pyramidal heights, but also the

### Table 4. Effect of different methods and the environment on the molecular structures 8a, 8e, 8f, 8g, 8h, and 8i on the height of the NC₃ pyramid (nitrogen at the top) in Å.

|       | exp. | DFT average | BLYP + D3 | PBE + D3 | RPBE + D3 |
|-------|------|-------------|-----------|----------|-----------|
|       |      | crystal     | gas       | crystal   | gas       |
| 8a    | 0.254| 0.243       | 0.230     | 0.245    | 0.230     |
| 8e    | 0.259| 0.254       | 0.242     | 0.258    | 0.241     |
| 8f    | 0.241| 0.226       | 0.247     | 0.223    | 0.248     |
| 8g    | 0.243| 0.234       | 0.236     | 0.232    | 0.237     |
| 8h    | 0.268| 0.253       | 0.243     | 0.254    | 0.239     |
| 8i    | 0.341| 0.318       | 0.329     | 0.316    | 0.325     |

[a] Average of the BLYP + D3, optB88-vdW, PBE + D3, PBE + TS, RPBE + D3 and vdw-DF2 GGA functionals.

### Table 5. Different gas phase conformers of tertiary amines R₃N with their pyramidal NC₃ heights in Å using BLYP + D3/TZVPPD. The energy differences to the lowest conformer are given in kJ mol⁻¹.

| R     | methyl | ethyl | n-propyl | isopropyl |
|-------|--------|-------|----------|-----------|
|       | Energy | Energy | Energy   | Energy    |
| 1     | 0.430  | 0.424 | 0.411    | 0.411     |
| 2     | 2.1    | 1.9   | 4.15     | 15.3      |
| 3     | 3.2    | 3.2   | 0.419    | 15.7      |
| 4     | 7.5    | 4.4   | 0.373    | 25.9      |
| 5     | 4.6    | 3.70  | 0.287    | 0.287     |
energies needed to make the molecule more planar, we enforced the NC₃ substructure to be in one plane; we set the dihedral angles to zero regarding all CNC planes and reoptimized the minimum configurations. Although this is not necessarily the transition state on the potential energy surface since all side groups will have to invert as well, it yields an estimate of the umbrella motion for the minimum structure to become planar. For trimethylamine, the B3LYP\(^{[26]}\) + D3/TZVPPD\(^{[27]}\) barrier is rather high with as much as 31.2 kJ mol\(^{-1}\), whereas it is lowered to 15 kJ mol\(^{-1}\) for triethylamine and 15.9 kJ mol\(^{-1}\) for tri-n-propylamine. The optimized B3LYP/TZVPPD structures without dispersion yield 29.1, 17.9, and 15.2 kJ mol\(^{-1}\), respectively, implying that the barrier for trimethylamine and tripropylamine are somewhat lowered by van der Waals interactions, whereas for triethylamine, it is larger.

Trisopropylamine (5), which has been previously mentioned and investigated more than 20 years ago, is a particular interesting case: A similar analysis between the planar and the non-planar structure in the gas phase of this compound yields an extremely low inversion barrier of only 2.4 kJ mol\(^{-1}\) and a pyramidal height of only 0.200 Å for B3LYP + D3/TZVPPD. Whereas basis set limit CCSD(T)\(^{[16]}\) increases this barrier to 4.8–5.3 kJ mol\(^{-1}\) depending on the geometry used, the zero-point energy contribution lowers the barrier by 3.0 kJ mol\(^{-1}\). Thus, including the zero-point energy contribution and using more accurate post-Hartree–Fock methods, we would end up around 1.8–2.3 kJ mol\(^{-1}\) energy difference between the planar and the non-planar structure. The transition state has an extremely small imaginary frequency of 88 cm\(^{-1}\) when using B3LYP + D3, which is about 13 kJ mol\(^{-1}\).

When neglecting dispersion, the value of 2.4 kJ mol\(^{-1}\) decreases the B3LYP barrier by 1.4 kJ mol\(^{-1}\) to 1.0 kJ mol\(^{-1}\). Since in a molecular crystal, the dispersion is more uniform than for a single molecule, this decrease may explain that we obtain an almost planar structure with an height of 0.03 Å, rather independent on the functional used when reoptimizing the solid crystal structure of this compound which has been reported as disordered with a pyramidal height of 0.291 Å\(^{[14]}\).

Interestingly, the calculations provide exactly the opposite results than experiment, in which the gas phase structure was determined to be planar\(^{[10]}\), whereas the crystal structure was non-planar: For the gas phase, this is likely due to the extremely flat potential energy surface around the minimum structure. For the solid phase, we were not able to discern the exact cause of this discrepancy between experiment and theory: It is not the thermal and zero-point expansion of the cell volume, as larger cell volumes yield similar planar structures. The culprit for these differences are either the underestimation of DFT for these differences are either the underestimation of DFT or thermal motions which are not easily described by and modelled by theory.

Continuing with compounds 8a–8j synthesized, a similar analysis like in Table 5 is performed in Table 6, whereas an analysis of 8g and 8i only gives one conformer within a given energy range of 30 kJ mol\(^{-1}\). It is important to note that in all cases, the lowest energy structure of the gas phase is the one also found in the crystalline phase, see Figures 3, Figure 4, and Figure 6 with structures of 8a, 8e, 8f, and 8g. Perhaps contrary to initial intuition, the barriers to planarity and the pyramidal NC₃ heights increase again after being rather small for compound 8a. This is an effect to the van der Waals interactions of the large, bulky groups, which attract each other: When optimizing all structures without extra dispersion, using just B3LYP/TZVPPD (without D3 correction), all barriers of the more bulky compounds 8a–8j investigated are lowered and all pyramidal heights are consequently lowered.

In general, the conformational structure seems to have a very large effect on the planarity. For example, compound 8e has one almost planar structure when being in a conformer which is about 13 kJ mol\(^{-1}\) above the gas phase minimum structure, and 8f one conformer which is about 10 kJ mol\(^{-1}\) above the gas phase minimum. In case a crystal structure could trap one of these conformers in a polymorph, we would obtain an NC₃ height close to zero. Overall, this effect thus shows structures (in the gas phase) in a much wider range.
than the different crystal structures of the synthesized compounds, ranging between 0.08 and 0.33 Å for the NC₃ heights.

Conclusions

In summary, the molecular structures of our sterically overcrowded trialkylamines, which do not include any π system or hetero atom in proximity to the nitrogen atom, proved to be pyramidal with NC₃ heights that are significantly smaller than those of simple species such as trimethylamine or triethylamine. Tertiary amines with heteroatom functionalities in the α or β positions were previously investigated, also by using X-ray studies, and led to nearly planar molecular structures, which were explained by orbital interaction effects.[10] In our cases of trialkylamines, steric effects alone obviously cannot enforce complete planarization of the amine nitrogen. Crystal field effects are not responsible for the non-planar structures of such trialkylamines because characterization in the gas phase, based on high-quality quantum chemical calculations, led to structural results which are similar to those of single-crystal X-ray diffraction analysis. On the one hand, van der Waals interactions of the bulky alkyl groups are a plausible explanation that even record-breaking steric stress cannot enforce complete planarization of the nitrogen atom. On the other hand, dispersion[20] plays also a role in the molecular structures of the title compounds.

As shown by our X-ray studies as well as quantum chemical calculations for the molecules in the gas phase, the noncyclic amines 8a and 8e-g adopt triskel-like conformations, which can be utilized to interpret the corresponding temperature-dependent high-resolution NMR spectra. The same is true for the quite different conformations of the heterocyclic amines 8h and 8i. Currently, we are investigating rotation processes within these amines with the help of dynamic NMR spectroscopy. Furthermore, we are trying to prepare tertiary amines with even more steric crowding, for example, open-chain tri-tert-alkylamines, by oxidative ring opening of unsaturated 2,2,6,6-tetramethylpiperidines and 2,2,5,5-tetramethylpyrrolidines.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: amines · molecular structures · quantum chemistry · steric hindrance · X-ray diffraction

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