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X-ray structure and conformational study of tris(2-(dimethylamino)phenyl)methanol: Roles of hydrogen bond in conformational conversions of molecules



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HIGHLIGHTS

- Tris(2-(dimethylamino) phenyl)methanol was synthesized and characterized.
- The X-ray crystal structure of the 2syn/1-anti conformer is reported.
- Variable-temperature ¹H NMR studies indicate four conformers in solution.
- Intra-molecular hydrogen bond affects inter-conversions between conformers.
- Mechanisms of intra- and interconformational conversions are proposed.

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G R A P H I C A L A B S T R A C T

Roles of hydrogen bond in conformational conversions of tris(2-(dimethylamino)phenyl)methanol: synthesis, X-ray structure and conformational study by variable-temperature ¹H NMR spectroscopy.



ABSTRACT

Tris(2-(dimethylamino)phenyl)methanol, $(2-(Me)_2N-C_6H_4)_3COH$, was synthesized and characterized by using NMR, EA and ESI-MS. Single crystal of the 2-syn/1-anti conformer of the tertiary alcohol was obtained and analyzed by X-ray diffraction. The variable-temperature ¹H NMR experiments reveal that, in solution, the tertiary alcohol is an equilibrium mixture of four conformers, all-syn, 2-syn/1-anti, 1-syn/ 2-anti and all-anti. The results show that hydrogen bond plays an important role in both intra- and inter-conformational conversions of molecules. The intra-conformational conversions within specific conformers are just helical changes. The inter-conformational conversions between conformers occurred via one-ring flip process.

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Introduction

The stereochemistry of triarylmethanes (TAMs) and structurally related compounds have attracted much attention since the publications by Kurkland et al. in the middle 1970's. [1-3]. In the



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early 1980's, Mislow and co-workers had demonstrated that TAMs molecules undergo conformational changes through restricted and correlated rotations of their attached aryl groups [4–7]. It was now generally accepted that the enantiomerization of TAMs molecules can principally involve eight pathways (Fig. 1), one zero-ring, three one-ring, three two-ring and one three-ring flip paths [3,4,8]. For these multi-blade propeller molecules, the lowest energy (threshold) rotating mechanism can be one-ring flip [9,10], two-ring flip [5,11,12] or n-ring flip [13]. The choice of rotating mechanism should depend on the contributions of the steric effect of the attached aryl groups [14].

Recently, Hey-Hawkins' group have described the synthesis and properties of ortho-amino substituted arylmethanol derivatives $(2-(R_1)_2N-C_6H_4-C(R_2)_2OH, R_1 = Me, Et, R_2 = Ph, Cy;)$. The common feature of these tertiary alcohols is that they form the intramolecular hydrogen bond $(O-H\cdots N(alkyl)_2)$ [15]. Pozharskii's group has reported the synthesis and properties of triarylmethanol derivatives (TAMols) bearing one or two 1,8-bis(dimethylamino)-naphthalen-2-yl arms [16]. ¹H NMR studies of these TAMols shown the proton of their hydroxyl groups would induce the temperature-driven tandem configuration inversion of the both nitrogen atoms via intermolecular hydrogen bond [17].

These recent researches imply that TAMols bearing three ortho-dialkylamino substituted aryl arms would have interesting stereochemistry. A simple example is tris(2-(dimethy-lamino)phenyl)methanol, which had been prepared and reported by Bayer a century ago [18]. Comparing with tris(4-(dimethy-lamino)phenyl)methanol (crystal violet base) [18,19], studies on this compound is rare, despite a long history of discovery. In this work, this tertiary alcohol was synthesized and studied as a model of this kind of compounds.

Experimental

General remarks

All necessary manipulations involving air- and moisturesensitive compounds were performed by standard Schlenk techniques under nitrogen atmosphere in vacuum-line. *n*-Hexane and N, N-dimethylaniline were thoroughly dried over phosphorus pentoxide and CaH₂, respectively. N¹,N¹,N²,N²-tetramethylethane-1,2diamine (TMEDA) was dried with molecular sieve 4 Å and distilled before use. Ethyl carbonochloridate and *n*-butyllithium were purchased from Aldrich. Other commercially available reagents were purchased and used as received. ¹H NMR and ¹³C NMR spectra were recorded on Bruker Avance III 400 and 600 MHz NMR spectrometers. Element Analysis was determined with Thermo Scientific Flash 2000 Organic Elemental Analyzer. Infrared (IR) spectrum was measured on a Bruker's VERTEX 70 Series Fourier transform infrared (FTIR) spectrometer.

Tris(2-(dimethylamino)phenyl)methanol

Under ice-water bath cooling, 4.7 mL (42.5 mmol) ethyl carbonochloridate was added drop-wise into the stirring solution of (2-(dimethylamino)phenyl)lithium, which was used as prepared by the reaction of 16.2 mL (128 mmol) N,N-dimethylaniline with 45 mL *n*-butyllithium (2.89 M, dissolved in TMEDA/*n*-hexane (21.5 mL/120 mL)) [20-22]. The mixture was gradually warmed to room temperature, stirred overnight and then terminated with ethanol (95%, 5 mL). After solvents evaporated under reduced pressure, the residues were dissolved in 50 mL dichloromethane. The obtained dichloromethane solution was washed times with water, dried with anhydrous MgSO₄, and then filtered. After evaporating dichloromethane under reduced pressure, the crude product was finally obtained as a colorless viscous liquid which crystallize slowly to form centimeter crystals in a few months later. The uncrystallized liquid fraction was poured out and the remaining crystals were washed times with cold *n*-hexane (yield: 5.48 g, ~33%). EA for C25H31N3O: Calculated: C, 77.08, H, 8.02, N, 10.79; Flash EA: C, 77.08, H, 8.05, N, 10.77; ¹H NMR (CDCl₃, 25 °C) δppm (m, J(Hz), xH, assignment): a). SSS conformer: 2.79 (s, 18H, Methyl), 6.66 (d, 3H, 15.7, Ar-3-H), 7.15 (t, 3H, 15.5, Ar-5-H), 7.44 (t, 3H, 14.8, Ar-4-H), 7.66 (d, 3H, 15.9, Ar-6-H), 14.82 (s, ¹H, OH, -50 °C); b). SSA and SAA conformers: 2.26(18H, s), 7.01(dt, 12.3, 2.9, 3H, Ar-5-H), 7.22 (dd, 3H, 18.8, 2.9 Ar-3-H), 7.22 (dt, 22.6, 2.8, 3H, Ar-4-H), 7.27 (dd, 8.1, 1.6, 3H, Ar-6-H), 9.709 (s, ¹H, OH); c.) AAA conformer: 1.97 (Methyl, s, -50 °C). ^{13}C NMR $\delta(ppm,\ \text{CDCl}_3,\ 25\ ^{\circ}\text{C})\text{:}$ SSA and SAA conformers: 45.93(C_{Me}), 83.46(C_{OH}), 123.48(C3), 123.71(C4), 127.69(C5), 131.21(C6), 143.61(C1), 153.13(C2); Other conformers: not detected; m/e (ESI-MS):389.9(389.2 + H), 372.2(389.9 - OH); IR data (KBr pellets, v/cm⁻¹): 3380(s., O-H), 3053 and 3014 (s., C-H, Ar), 2968/2936 and 2816/2777 (s., C-H, asy. and sy., Me),



Fig. 1. The rotational (flip) mechanisms for the Ar₃ZX systems [4].

1593,1572,1483 and 1443 (s., C—C, ring), overlapped (*deform.*, C—H, *asy.* and *sy.*, Me), 1358 (*deform.*, O—H), overlapped (s., C—N, Ar and Me), 1094 (s., C—O), 762 (*wag.*, C—H, Ar and *deform.*, ring).

X-ray diffraction measurements

The crystal data were collected on a Bruker SMART APEX II CCD diffractometer. The crystal structure was solved using direct methods and refined by full-matrix least-squares procedures on F2 with SHELXL-2014/7 [23]. Crystal data and structure refinement details are summarized in Table 1. Relevant data of the selected bond length (Å) and angles (°) were summarized in Table 2.

Results and discussion

TAMols were usually prepared by using aryl magnesium compounds through multi-step reactions [18]. The synthetic routes of the present work were shown in Scheme 1. It can be conveniently prepared through the reaction of ethyl carbonochloridate with (2-(dimethylamino)phenyl)lithium, which was previously prepared by the reaction of N,N-dimethylaniline with *n*-butyllithium/ TMEDA in *n*-hexane [20–22]. The crude product was finally obtained as a viscous liquid, which crystallize slowly to centimeter crystals in a few months later. Single crystals, suitable for X-ray diffraction studies, were obtained by layering methanol solution of the tertiary alcohol onto deionized water (4:1).

According to the orientations of the three dimethylaminophenyl arms with respective to a reference plane (defined by the three carbon atoms attached to the central carbon), the tertiary alcohol can have four possible conformers, including all-syn(SSS), 2-syn/1-anti(SSA), 1-syn/2-anti(SAA) and all-anti(AAA). However, despite efforts made to obtain that of the other conformers, only the single crystals of the SSA conformer were obtained (Fig. 2).

X-ray analysis reveals that the structural motif of the obtained SSA crystal is an intermolecular hydrogen bonded dimer of two enantiomeric molecules. The basic geometry (distances and angles) around the central carbon atom and the attached hydroxyl group is within the range of typical values recorded for analogous TAMols [15–17]. The interatomic distance (Å) of C(1)–C(2) (1.558(2)) is slightly larger than that of C(1)–C(8) (1.544(2)) and C(1)–C(14)(1.540(2)), indicating that there are steric repulsion between the dimethylamino group of anti-arm and the inner edges of benzene rings of two syn-arms. Structural features of SSA conformer can still be classified as a helical arrangement, despite a smaller dihedral angle of 11.84° between the O(1)–C(1)–C(2) plane and the benzene ring plane of anti-arm. The corresponding dihedral angles observed for the two syn-arms are respectively 43.89° (O-H---N binding syn-arm) and 68.47°. These two angles are slightly larger than the dihedral angles of 37.46° and 65.42° recorded for analogous TAMols bearing two 1,8-di(dimethylamino)-2-naphthyl (syn-)arms [17]. The dihedral angle between the two benzene ring planes of the syn-arms is 66.48°. Correspondingly, the two dihedral angles between the benzene ring plane of anti-arm and that of two syn-arms are respectively 85.64° and 86.35° (O–H---N binding syn-arm), approximately perpendicular. The dihedral angle between the C(20)—N(1)—C(21) plane and the benzene ring plane of anti-arm is 89.41°, nearly perpendicular. The corresponding dihedral angles observed in the two syn-arms are respectively 76.58° and 83.89° (O-H---N binding syn-arm). These dihedral angles indicate the three aryl arms and their attached dimethylamino groups have some flexibility to fit the molecular conformation.

Conformational studies of the tertiary alcohol in solution were carried out by using the variable-temperature ¹H NMR. Results

Table 1

Crystal data and structure refinement for tris(2-(dimethylamino)phenyl)methanol.

Empirical formula	C ₂₅ H ₃₁ N ₃ O
Formula weight	389.53
Temperature (K)	296(2)
Wavelength (Å)	0.71073
Crystal size (mm ³)	$0.32\times0.21\times0.18$
Crystal system	Monoclinic
Space group	$P2_1/c$
a (Å)	8.8799(9)
b (Å)	24.205(2)
c (Å)	11.0329(11)
α (°)	90
β(°)	106.5150(10)
γ (°)	90
Volume (Å ³)	2273.5(4)
Ζ	4
Calculated density (Mg/m ³)	1.138
Absorption coefficient (mm ⁻¹)	0.070
F(000)	840
θ range for data collection (°)	2.39-25.50
Limiting indices	$-10 \leqslant h \leqslant 10$
	$-29 \leqslant k \leqslant 29$
	$-12 \leqslant l \leqslant 13$
Reflections collected/unique	15,190/4223 [<i>R</i> (int) = 0.0348]
Completeness to θ = 25.50	99.6%
Absorption correction	None
Max. and min. transmission	0.9875 and 0.9779
Refinement method	Full-matrix least-squares on F ²
Data/restraints/parameters	4223/0/269
Goodness-of-fit on F^2	1.019
Final R indices $[I > 2\sigma(I)]$	$R_1 = 0.0461$
	$wR_2 = 0.1083$
R indices (all data)	$R_1 = 0.0797$
	$wR_2 = 0.1266$
Largest diff. peak and hole ($e Å^{-3}$)	0.116 and -0.144

show that in chloroform-d, the tertiary alcohol is an equilibrium mixture, which are mainly composed of one conformer (Fig. S2.). The 2d NMR spectra, HSQC, HMBC, COSY and NOESY, had been done to analysis these conformers (Fig. S3–S6). However, except the main conformer, the other minor conformers are difficult to be identified because of their low populations. The NMR observations indicate that in addition to temperature, hydrogen bond should play a role in the inter-conversions between conformers.

To clarify the roles of the hydrogen bond, models of four possible conformers were established and calculated by using CS ChemBio3D software (Ver., 14.0) and the attached programs. The MM94 calculations suggest that the trigonal pyramidal configuration is more favorable for the nitrogen atoms of dimethylamino groups (Fig. 3. first row). The minimized conformational energy of SSA1 model is 125.945 kcal/mol, which is lower than that of the other conformers, 129.812 (SSS₁), 130.852 (SAA₁) and 145.076 (AAA₁) kcal/mol. For the models with syn-arms (SSS₁, SSA₁ and SAA₁), the inward lone-pair elections of the nitrogen atoms on their syn-arms were also suggested to form hydrogen bonds with the central hydroxyl group. However, the MM2 force field calculations indicate that the lone-pair electrons of their nitrogen atoms would like to conjugate with the attached benzene rings (Fig. 3. second row). This conjugating status would increase the steric hindrance between aromatic arms, and therefore to some extent hinder the ring-flips of them. Therefore, the decisive factor stabilizing the different conformers was thought to be the dimethylamino groups. The minimized conformational energies of models calculated by the MM2 method are respectively 90.1697 (SSS₂), 95.9137 (SSA₂), 100.7246 (SAA₂) and 105.4372 (AAA₂) kcal/mol. Each of them is correspondingly smaller than that calculated by MM94 method.

Comparing MM94 models with the corresponding MM2 models, it was found that the formation of the intramolecular hydrogen

 Table 2

 Selected bond length (Å) and angles (°) for tris(2-(dimethylamino)phenyl)methanol.

$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8 ()	0 ()		5,
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(1)-O(1)	1.431(2)	C(1)-C(14)	1.540(2)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(1)-C(8)	1.544(2)	C(1)-C(2)	1.558(2)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(2)-C(7)	1.392(2)	C(2)—C(3)	1.399(2)
$\begin{array}{cccccc} C(4)-C(5) & 1.369(3) & C(5)-C(6) & 1.369(3) \\ C(6)-C(7) & 1.384(3) & C(8)-C(13) & 1.390(2) \\ C(8)-C(9) & 1.407(3) & C(9)-C(10) & 1.394(3) \\ C(9)-N(2) & 1.434(2) & C(10)-C(11) & 1.367(3) \\ C(11)-C(12) & 1.374(3) & C(12)-C(13) & 1.386(3) \\ C(14)-C(15) & 1.391(2) & C(14)-C(19) & 1.395(2) \\ C(15)-C(16) & 1.395(3) & C(15)-N(3) & 1.453(2) \\ C(16)-C(17) & 1.368(3) & C(17)-C(18) & 1.376(3) \\ C(18)-C(19) & 1.369(3) & C(20)-N(1) & 1.459(2) \\ C(21)-N(1) & 1.454(2) & C(22)-N(2) & 1.462(3) \\ C(23)-N(2) & 1.452(3) & C(24)-N(3) & 1.468(3) \\ C(25)-N(3) & 1.468(3) & O(1)-C(1)-C(14) & 109.7(1) \\ O(1)-C(1)-C(2) & 108.7(1) & C(14)-C(1)-C(8) & 115.0(1) \\ O(1)-C(1)-C(2) & 108.7(1) & C(14)-C(1)-C(2) & 109.7(1) \\ C(8)-C(1)-C(2) & 110.8(1) & C(7)-C(2)-C(3) & 117.5(2) \\ C(7)-C(2)-C(1) & 118.2(2) & C(3)-C(2)-C(1) & 124.3(2) \\ C(4)-C(3)-C(2) & 119.6(2) & C(5)-C(4)-C(3) & 121.9(2) \\ C(4)-C(3)-C(2) & 119.6(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(13)-C(8)-C(1) & 122.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(10)-C(9) & 112.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(10)-C(11)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(17)-C(20) & 111.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ C(3)-N(2)-C(23) & 114.2(2) & C(25)-N(3)-C(24) & 111.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)$	C(3)-C(4)	1.391(3)	C(3)—N(1)	1.439(2)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(4)—C(5)	1.369(3)	C(5)—C(6)	1.369(3)
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C(6)—C(7)	1.384(3)	C(8)-C(13)	1.390(2)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(8)—C(9)	1.407(3)	C(9)—C(10)	1.394(3)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(9)—N(2)	1.434(2)	C(10)-C(11)	1.367(3)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(11)-C(12)	1.374(3)	C(12)-C(13)	1.386(3)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(14)-C(15)	1.391(2)	C(14)-C(19)	1.395(2)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	C(15)-C(16)	1.395(3)	C(15)—N(3)	1.453(2)
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C(16)-C(17)	1.368(3)	C(17)-C(18)	1.376(3)
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C(18)-C(19)	1.369(3)	C(20)—N(1)	1.459(2)
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C(21)—N(1)	1.454(2)	C(22)—N(2)	1.462(3)
$\begin{array}{cccccc} C(25)-N(3) & 1.468(3) & O(1)-C(1)-C(14) & 109.7(1) \\ O(1)-C(1)-C(8) & 102.6(1) & C(14)-C(1)-C(8) & 115.0(1) \\ O(1)-C(1)-C(2) & 108.7(1) & C(14)-C(1)-C(2) & 109.7(1) \\ C(8)-C(1)-C(2) & 110.8(1) & C(7)-C(2)-C(3) & 117.5(2) \\ C(7)-C(2)-C(1) & 118.2(2) & C(3)-C(2)-C(1) & 124.3(2) \\ C(4)-C(3)-C(2) & 119.6(2) & C(4)-C(3)-N(1) & 119.5(2) \\ C(2)-C(3)-N(1) & 120.9(2) & C(5)-C(4)-C(3) & 121.9(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(17)-C(18) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(24) & 111.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(23)—N(2)	1.452(3)	C(24)—N(3)	1.468(3)
$\begin{array}{ccccccc} O(1)-C(1)-C(8) & 102.6(1) & C(14)-C(1)-C(8) & 115.0(1) \\ O(1)-C(1)-C(2) & 108.7(1) & C(14)-C(1)-C(2) & 109.7(1) \\ C(8)-C(1)-C(2) & 110.8(1) & C(7)-C(2)-C(3) & 117.5(2) \\ C(7)-C(2)-C(1) & 118.2(2) & C(3)-C(2)-C(1) & 124.3(2) \\ C(4)-C(3)-C(2) & 119.6(2) & C(4)-C(3)-N(1) & 119.5(2) \\ C(2)-C(3)-N(1) & 120.9(2) & C(5)-C(4)-C(3) & 121.9(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(25)—N(3)	1.468(3)	O(1)-C(1)-C(14)	109.7(1)
$\begin{array}{cccccccc} O(1)-C(1)-C(2) & 108.7(1) & C(14)-C(1)-C(2) & 109.7(1) \\ C(8)-C(1)-C(2) & 110.8(1) & C(7)-C(2)-C(3) & 117.5(2) \\ C(7)-C(2)-C(1) & 118.2(2) & C(3)-C(2)-C(1) & 124.3(2) \\ C(4)-C(3)-C(2) & 119.6(2) & C(4)-C(3) & 121.9(2) \\ C(2)-C(3)-N(1) & 120.9(2) & C(5)-C(4)-C(3) & 121.9(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	O(1)-C(1)-C(8)	102.6(1)	C(14)-C(1)-C(8)	115.0(1)
$\begin{array}{llllllllllllllllllllllllllllllllllll$	O(1)-C(1)-C(2)	108.7(1)	C(14)-C(1)-C(2)	109.7(1)
$\begin{array}{cccccc} C(7)-C(2)-C(1) & 118.2(2) & C(3)-C(2)-C(1) & 124.3(2) \\ C(4)-C(3)-C(2) & 119.6(2) & C(4)-C(3)-N(1) & 119.5(2) \\ C(2)-C(3)-N(1) & 120.9(2) & C(5)-C(4)-C(3) & 121.9(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(1)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(8) - C(1) - C(2)	110.8(1)	C(7)-C(2)-C(3)	117.5(2)
$\begin{array}{ccccc} C(4)-C(3)-C(2) & 119.6(2) & C(4)-C(3)-N(1) & 119.5(2) \\ C(2)-C(3)-N(1) & 120.9(2) & C(5)-C(4)-C(3) & 121.9(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(13)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(20) & 111.3(2) \\ C(3)-N(1)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(7)-C(2)-C(1)	118.2(2)	C(3) - C(2) - C(1)	124.3(2)
$\begin{array}{ccccc} C(2)-C(3)-N(1) & 120.9(2) & C(5)-C(4)-C(3) & 121.9(2) \\ C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.0(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(23)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(4) - C(3) - C(2)	119.6(2)	C(4) - C(3) - N(1)	119.5(2)
$\begin{array}{ccccc} C(4)-C(5)-C(6) & 119.0(2) & C(5)-C(6)-C(7) & 120.1(2) \\ C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(23)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(2) - C(3) - N(1)	120.9(2)	C(5)-C(4)-C(3)	121.9(2)
$\begin{array}{ccccc} C(6)-C(7)-C(2) & 121.9(2) & C(13)-C(8)-C(9) & 117.4(2) \\ C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(17)-C(18) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(4) - C(5) - C(6)	119.0(2)	C(5)-C(6)-C(7)	120.1(2)
$\begin{array}{cccccc} C(13)-C(8)-C(1) & 120.5(2) & C(9)-C(8)-C(1) & 121.9(2) \\ C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(17)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(6) - C(7) - C(2)	121.9(2)	C(13)-C(8)-C(9)	117.4(2)
$\begin{array}{ccccc} C(10)-C(9)-C(8) & 118.9(2) & C(10)-C(9)-N(2) & 120.4(2) \\ C(8)-C(9)-N(2) & 120.7(2) & C(11)-C(10)-C(9) & 122.5(2) \\ C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(13)-C(8)-C(1)	120.5(2)	C(9) - C(8) - C(1)	121.9(2)
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C(10)-C(9)-C(8)	118.9(2)	C(10)-C(9)-N(2)	120.4(2)
$\begin{array}{ccccc} C(10)-C(11)-C(12) & 119.3(2) & C(11)-C(12)-C(13) & 119.1(2) \\ C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(8) - C(9) - N(2)	120.7(2)	C(11)-C(10)-C(9)	122.5(2)
$\begin{array}{ccccc} C(12)-C(13)-C(8) & 122.8(2) & C(15)-C(14)-C(19) & 117.5(2) \\ C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(10)-C(11)-C(12)	119.3(2)	C(11)-C(12)-C(13)	119.1(2)
$\begin{array}{ccccc} C(15)-C(14)-C(1) & 121.1(2) & C(19)-C(14)-C(1) & 121.3(2) \\ C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(12)-C(13)-C(8)	122.8(2)	C(15)-C(14)-C(19)	117.5(2)
$\begin{array}{cccc} C(14)-C(15)-C(16) & 120.1(2) & C(14)-C(15)-N(3) & 120.0(2) \\ C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(15)-C(14)-C(1)	121.1(2)	C(19) - C(14) - C(1)	121.3(2)
$\begin{array}{cccc} C(16)-C(15)-N(3) & 119.9(2) & C(17)-C(16)-C(15) & 120.8(2) \\ C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \\ \end{array}$	C(14)-C(15)-C(16)	120.1(2)	C(14)-C(15)-N(3)	120.0(2)
$\begin{array}{cccc} C(16)-C(17)-C(18) & 119.8(2) & C(19)-C(18)-C(17) & 119.8(2) \\ C(18)-C(19)-C(14) & 122.0(2) & C(3)-N(1)-C(21) & 114.3(2) \\ C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \end{array}$	C(16)-C(15)-N(3)	119.9(2)	C(17)-C(16)-C(15)	120.8(2)
$\begin{array}{llllllllllllllllllllllllllllllllllll$	C(16)-C(17)-C(18)	119.8(2)	C(19)-C(18)-C(17)	119.8(2)
$\begin{array}{cccc} C(3)-N(1)-C(20) & 112.4(2) & C(21)-N(1)-C(20) & 111.3(2) \\ C(23)-N(2)-C(22) & 110.9(2) & C(15)-N(3)-C(25) & 112.5(2) \\ C(9)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \end{array}$	C(18) - C(19) - C(14)	122.0(2)	C(3) - N(1) - C(21)	114.3(2)
$\begin{array}{cccc} C(23) - N(2) - C(22) & 110.9(2) & C(15) - N(3) - C(25) & 112.5(2) \\ C(9) - N(2) - C(23) & 114.2(2) & C(9) - N(2) - C(22) & 114.9(2) \\ C(15) - N(3) - C(24) & 112.4(2) & C(25) - N(3) - C(24) & 111.9(2) \end{array}$	C(3)-N(1)-C(20)	112.4(2)	C(21)-N(1)-C(20)	111.3(2)
$\begin{array}{ccc} C(9)-N(2)-C(23) & 114.2(2) & C(9)-N(2)-C(22) & 114.9(2) \\ C(15)-N(3)-C(24) & 112.4(2) & C(25)-N(3)-C(24) & 111.9(2) \end{array}$	C(23)—N(2)—C(22)	110.9(2)	C(15)—N(3)—C(25)	112.5(2)
C(15)-N(3)-C(24) 112.4(2) $C(25)-N(3)-C(24)$ 111.9(2)	C(9)–N(2)–C(23)	114.2(2)	C(9)—N(2)—C(22)	114.9(2)
	C(15)—N(3)—C(24)	112.4(2)	C(25)—N(3)—C(24)	111.9(2)

bond can hold up one syn-arm to a specific orientation (Fig. 3, first row). And as a result, one benzene ring of three aromatic arms could take a more perpendicular status with respect to the reference plane. This perpendicular status of one benzene ring can empty space for the other two benzene rings, especially for the one with a smaller dihedral angle to the reference plane, to accomplish the ring-flip process (Fig. 3, first row). Therefore, the formation of intro-molecular hydrogen bond was thought to be critically necessary for the inter-conversions between conformers. In the dissolving process, the MM94 (crystal) molecules of SSA conformer can change to the MM94 molecules of the other conformers via inter-conformational conversions through one-ring flip process. However, they would be also likely change to the corresponding molecules of themselves with MM2 model character, because



Scheme 1. Synthesis of Tris(2-(dimethylamino)phenyl)methanol.

of lower conformational energies. Despite the similarity of MM94 SSA₁ model to its solid structure, the realtime configuration of specific conformers in solution should be similar but different with the calculated static models (MM94 and MM2). Molecules of each specific conformers were thought to equilibrium between their MM94 and MM2 models, along with the configuration changes of its three nitrogen atoms (induced by the formation of an intramolecular hydrogen bond). However, driven by the formation of the intromolecular hydrogen bond and the steric hindrance among the substituents, it is difficult to clarify to the direction of these intra-conformational equilibria (Fig. 3, green colored).

The above calculations indicate that the strong signals in spectra can be assigned to the SSA conformer. However, the influences of hydrogen bond formation on the chemical shifts of methyl and aromatic protons should not to be neglected, because hydrogen binding was generally regarded to be dominant over that of the geometric differences [16,17]. If the constant states of SSA conformer in solution are the molecules with the MM94 model character, the protons of the binding syn-arm and the protons of the other two arms should give different chemical shift values. Therefore, there must have exchanges meet the requirements of protons' chemical equivalence.

To interpret the considerations, the possible equilibria of the intra-conformational changes of SSA conformer were examined with the consideration of the hydrogen bond influences and on the basis of the ring flip mechanism (Scheme 2). The results of the conformational analysis reveal that to satisfy the equal probability requirement, SSA conformer should have twelve states. It is self-evident that the interconversions between the enantiomeric pair need to break the specific conformational states. Therefore, the twelve states of SSA conformer should separately belong to two equilibrium cycles of six each [24].

The both equilibrium cycles of SSA conformers include basically two intra-conformational change process (Scheme 2), protonbonded (PB) helical changes (also to be arm exchanges) and proton-induced (PI) helical changes (also to be donor exchanges). The **PB** helical changes of SSA conformer are virtually two-ring flip conversions, which need the other two non-binding arms synchronously rotating through the reference plane. Therefore, the PB helical changes of SSA conformer were thought to be high barrier conversions, which are less possible to occur. While, the PI helical changes of the SSA conformer are low barrier conversions following zero-ring flip pathway, which did not need any ring rotating through the reference plane. The intra-conformational analysis of SSA conformer shows that the nitrogen atoms of its' two syn-arms have more opportunities to form hydrogen bond with the hydroxyl proton than that of anti-arms. The above analysis also indicates that the intra-conformational changes of SSA conformer itself cannot meet the requirements of protons' chemical equivalence. This prompts us to examine conformational states of the other conformers and the conversions among all the conformers.

In spectra (Figs. S2 and 4), the signal at around 2.79 ppm was assigned to methyl protons of the SSS conformer. Although weak, the four aromatic signals of the SSS conformer can be clearly identified in the spectra (Figs. S2 and 4). According to the chemical shift values and the splitting patterns, these four ¹H proton signals can be respectively assigned to the Ar-*x*-H protons of this specific conformer. The hydroxyl proton signal of this conformer can be observed at around 14.7–14.9 ppm, only in low temperature spectra obtained at around below $-50 \,^{\circ}\text{C}$ (Fig. 4). The integral ratios of this set of signals (Methyl/Ar-*x*-H/OH) is very close to 18/3/1, indicating the correlation of them.

Therefore, the SSS conformer should also be composed of the two propeller enantiomers (Scheme 3). Taking SSS conformation, the hydroxyl proton would induce the lone-pair electrons of all



Fig. 2. Crystal structure of SSA conformer with thermal ellipsoids at 30% probability level. Selected (bond) distances (Å) and (torsion) angles (deg): O(1)-H(1) 0.820(1), N(3)-H(1) 1.978(2), C(23)-H(23c) 0.960(2), H(23c)-O(1) 2.397(1), O(1)-H(1)-N(3) 143.3(1), O(1)-H(23c)-C(23) 127.7(1), O(1)-C(1)-C(2)-C(7) 12.5(2), O(1)-C(1)-C(3)-C(9) 65.4(2), O(1)-C(1)-C(1)-C(1)+C(1) 45.4(2).



Fig. 3. Conformational models of tris(2-(dimethylamino)phenyl)methanol and assumed equilibria among conformers (models).

the nitrogen atoms orienting inward to facilitate the formation of the intramolecular hydrogen bond [15–17]. The binding competition of the three dimethylamino groups to hydroxyl proton, the so called "proton sponge" effect [16,17,25,26], would result

in the formation of "dynamic" hydrogen bond. The formed dynamic hydrogen bond, as well as the steric hindrance among substituents, would to some extend, restrict the rotational freedom of the aniline moieties and maintain the stability of the SSS



Scheme 2. Two assumed equilibria cycles of SSA conformer (For clarity, N-methyl groups were omitted, and hydrogen bonds (O-H---N) were expressed as O---N).

conformation. As observed, the signals of this conformer can still be recognized in high temperature spectra, according to their varying trends with temperature (Fig. S2.).

The helical change between propellers of SSS conformer can follow the zero-ring flip pathway, which did not need any benzene ring rotating through the reference plane. It can be accomplished by synchronizing the switching of the hydroxyl proton, the adjustments of the dimethylamino groups and the unidirectional rotations of aryl arms (Scheme 3.). The derivative time-averaged conformation of C3 symmetry was thought to be consistent with the ¹H NMR observations. With the temperature increasing, the gradually broadening of the methyl resonance should be caused by the increase of molecular thermal motion ability. With the temperature decreasing, the gradually broadening of the methyl resonance should indicate the slowdown of proton switching (helical change). Similarly, the gradual emergence of the hydroxyl proton resonance should be an evidence that the hydroxyl proton becomes stuck to a specific nitrogen atom at low temperature. The separated distribution of its aryl signals was thought to be the time-averaged influence of switching hydroxyl proton on the chemical shifts of aromatic protons. The SSS conformer reaches its highest proportion at around -10 °C with a ratio of 8.88/100, calculated by the integrated area of its methyl signals with respective to that of the strong methyl signals at around 2.26 ppm. As indicated by the sharp methyl signals, the helical change of SSS conformer was regarded to be a fast low barrier process at around room temperature. The above considerations and observations indicate that SSS conformer itself can meet the requirement of protons' chemical equivalence.

Due to the fast helical change, the three syn-arms of SSS conformer were thought to have the equal opportunities of flipping, which results in the easy formation of SSA conformer. As a comparison, the generation of SSS conformer from SSA conformer was thought to be a slow process, which needs the benzene ring flip of the only anti-arm of SSA conformer (Fig. 3 red¹ colored). To accomplish the conversion, the **PI** helical change of SSA conformer



Fig. 4. Full spectra of tris(2-(dimethylamino)phenyl)methanol at low temperature and aromatic region of SSS conformer at 25 °C (Chloroform-d).

is necessary, because of the large steric hindrance between the binding sys-arm and the only anti-arm. A competition to the ring flip of the only anti-arm is the ring flip of the newborn non-binding synarm (after **PI** helical change of SSA conformer). The latter ring flip, generating SAA conformer, was thought to be more liable to occur than the former, because of a smaller steric hindrance.

The presence of SAA comfomer remains an enigma, since it was not directly observed. Similar to SSA conformer, conformational analysis show that SAA conformer should also have twelve states, which separately belong to two equilibrium cycles of six each (Scheme 4). The two equilibrium cycles of SAA conformers also include two intra-conformational change process, proton-bonded (**PB**) helical changes (just helical conversions) and hydrogenbond-blocked (**HBB**) helical changes (including both donor and

¹ For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

Scheme 3. Assumed conformational changes and time-averaged conformation of **SSS** conformer It was generally agreed that TAMs exist as racemic mixtures of M- and P-propeller structures [8].

arm exchanges). The **PB** helical changes of SAA conformer are lowbarrier intra-conformational conversions following zero-ring flip pathway. However, the **HBB** helical changes of SAA conformer could occur only if the hydrogen-bond barrier and the two-ring flip barrier are crossed simultaneously.

The intra-conformational analysis shows that in SAA conformational states, the nitrogen atom of the only syn-arm has more opportunities to form hydrogen bond with the hydroxyl proton than that of the other two anti-arms. The intra-conformational analysis also shows that the **PI** process of SSA conformer should be more fast than the **HBB** process of SAA conformer. The two considerations reveal a significant difference between the overall donor (N) exchange rates between SSA and SAA conformers, indicating that the time-averaged chemical shifts of their attached protons should also be different. The above analysis show that only intra-conformational changes cannot meet the requirement of chemical equivalence and, the inter-conversions between the both conformers should be considered as factors.

The inter-conformational conversions via two-ring flip process, SSS \leftrightarrow SAA and SSA \leftrightarrow AAA, were thought to be unlikely to occur, because of a relatively high transition state barrier. As already mentioned, the interconversions between the enantiomeric pair of SSA and SAA conformers all need to break the specific conformational states of individual conformer. If not considering these inter-conformational conversions between SSA conformer and SAA conformer, there should be a big difference in probabilities that their nitrogen atoms of syn-arms and anti-arms to form hydrogen bonds with the hydroxyl proton. The interconversions of the enantiomeric pair of the SSA and SAA conformers can be accomplished via two one-ring flip process, respectively through SSS and AAA conformational states. While, the conversions between twelve conformational states of SSA conformer and that of SAA conformer (Scheme 2 and 4), each to each, only need one one-ring flip process (Fig. 3, equilibrium black colored). The conversion from SSA conformer to SAA conformer can be easily accomplished through the one-ring flip of the non-binding syn-arm. Or else, this conversion can also be accomplished through a PI helical change of SSA conformer, and then a subsequent ring flip of the newborn non-binding syn-arm. That indicates that PI helical changes would afford equal opportunities for the two syn-arms of SSA conformer to flip. Similarly, the conversion from SAA conformer to SSA conformer can be accomplished through one-ring flip of one of two anti-arms. The **PB** helical changes of SAA conformer would also promise the two anti-arms equal opportunities to flip. Therefore, it was regarded that the inter-conformational conversions between the SSA and SAA conformers, a one-ring flip process, would control the overall arm exchanges rates of them both. And as a result, these would ultimately surpass or flatten the difference in donor exchange rates between them, indicating that they will behave like one conformer. The strong resonances in the spectra were once thought to be correlated only with SSA conformer. However, this easy assignment is obviously inconsistent with the above analysis that the arm exchanges rates of inter-conformational process (one-ring flip, SSA \leftrightarrow SAA) are faster than that of the intra-conformational process (two-ring flip, the PB process of SSA and the HBB process of SAA). That is to say, on the basis of combined considerations of both intra- and inter-conformational changes, we would like to believe that protons of SAA conformer should also have contributions to these strong signals.

The internal steric hindrance between the three anti-arms were thought to be the only factor which stabilizes AAA conformer and distinguishes itself from the other conformers. AAA conformer was thought to be thermodynamically unstable because of a high internal energy. Logically, this conformer can only be generated from SSA conformer. The conversion needs firstly the breaking of intra-molecular hydrogen bond of SAA conformer, then following the ring flip of the only syn-arm (Fig. 3. blue colored). And therefore, it should be a minor conformer. The resonances of the hydroxyl and aryl protons of the AAA conformer might be too weak to be visible or be overlapped by the resonances of the other conformers (Fig. 4 and S1.). However, in the high field region of spectra (Fig. S2a), the emerging signal, which presents firstly as a sharp shoulder peak, then grows up gradually to a separate peak and finally vanished with temperature increasing, can be assigned to the methyl protons of this specific conformer. The variation trend of the methyl resonance was thought to be consistent with the opposing effects of the increased temperature on the thermal stability and the dynamic generation of this specific conformer. The broadened methyl signals in high temperature spectra should indicate the configuration changes of nitrogen atoms (between trigonal pyramidal and planar), which is caused by the increase of the molecular thermal motion ability. With the temperature decreasing, the sharp trend of its methyl signal should indicate a frozen conformation of C3 symmetry. The helical conversions of AAA conformer were thought, at least in low temperature condition, to be difficult because of the large steric hindrance and the low thermal motion ability. With temperature increasing, AAA conformer reaches its highest proportion at around -30 °C with a ratio of 3.80/100, calculated by the integrated area of its methyl signals with respective to that of the strong methyl signals at around 2.26 ppm.

Additional variable-temperature ¹H NMR experiments, from -60 to 60 °C, were carried out in methanol-d4 (Fig. S7). The variation trends of conformers in methanol are similar to that in chloroform (Fig. S2), except the absence of AAA conformer. Calculation results show that the steric hindrance among the groups, as well as thus produced the inward orientation of the lonely pair of nitrogen atoms, counts against the tertiary alcohol to form the N···H–OCH₃ inter-molecular hydrogen bonds with methanol (solvent). Instead, methanol would like to form intermolecular hydrogen bonds with the hydroxyl group of the tertiary alcohol (Fig. 5). Comparing with the calculation results of the preceding models (Fig. 3, first row), the relative smaller energies of the present models in Fig. 5, 119.746 (SSS₃), 116.128 (SSA₃), 122.119 (SAA₃) and 137.472 (AAA₃) kcal/mol, should indicate more stable conformations. At the same temperature, the line width of the methyl signal of SSS conformer in methanol is broader than that





Scheme 4. Two assumed equilibria cycles of SAA conformer (For clarity, N-methyl groups were omitted and hydrogen bonds (O-H---N) were expressed as O---N).



Fig. 5. Conformational models of tris(2-(dimethylamino)phenyl)methanol in methanol.

in chloroform. The binding solvent molecule was thought to increase the steric hindrance. And therefore, the broadened methyl signal at low temperature (-50-60 °C) should indicate the slowdown of the helical changes of SSS conformer (Fig. S7a). With temperature increasing, the broadened and weakened methyl signal of SSS conformer should indicate the increase of the molecular thermal motion ability and the strength reduction of the intermolecular hydrogen bond. The above observations should indicate that the formation of inter-molecular hydrogen bond, as a disturbing factor, might to some extent hinder the helical changes of SSS conformer and, as well as that of the other conformers (Fig. 5). According to the calculation results, the stronger signals can still be assigned to the SSA and SAA conformers. However, due to the same reasons in chloroform, it is difficult to clarify the contributions of SAA conformer to the strong signals. The variation trend of their methyl signal is similar to that of the SSS conformer. With the variation of temperature, it was also found that the varying intensity of their methyl signal in methanol is larger than that in chloroform (Fig. S2). Their four aromatic signals showed a more separate distribution in low temperature spectra (Fig. S7b), different with the crowded distribution in chloroform (Fig. S2b). These observations should indicate that the formation of inter-molecular hydrogen bond increase the interface of the intra-molecular hydrogen bond to methyl groups and benzene rings. With temperature decreasing, the shifting trend of the Ar-3-H signal to low field is nearly stopped (with respect to that of the other aromatic protons and comparing with that observed in chloroform, Fig. S7b). From the conjugate relations, Ar-3-H protons are more close to the nitrogen atoms than the other aromatic protons. Therefore, the observation should indicate that the influence of intra-molecular hydrogen bonds to the Ar-3-H protons is stronger than to the other aromatic protons. This observation should also indicate that in addition to the decrease of thermal motion ability, the strength of intramolecular hydrogen bond can also be increased by the formation of inter-molecular hydrogen bond. Moreover, with temperature decreasing to -50 °C (Fig. S7b), the signal of Ar-3-H protons was found to become broadened with respect to that of the other aromatic protons, indicating the slowdown of the conversion between SSA and SAA conformers. The above observations and considerations suggest that in methanol, both the steric hindrance between groups and the strength of intra-molecular hydrogen bond increased with temperature decreasing, due to the formation of inter-molecular hydrogen bond. Considering the conversion from SAA conformer to AAA conformer is the only one which needs the breaking of intra-molecular hydrogen bond, it is reasonable to accept the absence of AAA conformer in methanol.

Conclusion

In summary, tris(2-(dimethylamino)phenyl)methanol has been synthesized and characterized. X-ray structure of SSA conformer reveals that the 2-dimethylaminophenyl arms and their attached dimethylamino groups have some flexibility to fit the molecular conformation. Variable-temperature ¹H NMR experiments confirmed that, in solution, the tertiary alcohol is an equilibrium mixture of the four conformers, SSS, SSA, SAA and AAA. Calculation results show that SSA conformer is the one with smallest conformational energy. And in solution, the tertiary alcohol mainly exists as SSA conformer. Calculation results indicate that the intro-molecular hydrogen bond can hold up one aromatic arm in a perpendicular orientation with respect to the reference plane. This perpendicular status facilitates the benzene ring flip of the non-binding aromatic arms, especially the one with a smaller dihedral angle with respect to the reference plane. The interconversions between conformers were regarded mainly though the one-ring flip pathway, instead of two-ring flip pathway. While, the intra-conformational conversions for individual conformers are just helical conversions, which occurred by following a zero-ring flip pathway. The SSS conformer undergoes a fast helical change, which derived a time-averaged conformation of C3 symmetry at around room temperature. The steric hindrance is the only factor stabilizing the AAA conformer, which exhibits a frozen conformation of C3 symmetry at low temperature. The overall arm and donor (N) exchanges of both SSA and SAA conformers were found to be controlled by the one-ring flip conversions between them. And as a result, the both conformers behave like one conformer, which gives same chemical shifts.

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Appendix A. Supplementary material

Crystallographic data for the structure reported in this paper has been deposited with the Cambridge Crystallographic Center, CCDC No 1002962. (Copies of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, fax: +44 1223 336 033, e-mail: deposit@ ccdc.cam.ac.uk or http://www.ccdc.cam.ac.uk). The following ZIP file contains the MOL files of models of conformers and the spectra files referred to in this article.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.molstruc.2015.03. 009.

References

- [1] A.K. Colter, I.I. Schuster, R.J. Kurkland, J. Am. Chem. Soc. 87 (10) (1965) 2278-2279.
- [2] R.J. Kurkland, I.I. Schuster, A.K. Colter, J. Am. Chem. Soc. 87 (10) (1965) 2279– 2281.
- [3] I.I. Schuster, A.K. Colter, R.J. Kurkland, J. Am. Chem. Soc. 90 (17) (1968) 4679–4687.
- [4] D. Gust, K. Mislow, J. Am. Chem. Soc. 95 (5) (1973) 1535–1547.
- [5] P. Finocchiaro, D. Gust, K. Mislow, J. Am. Chem. Soc. 96 (7) (1974) 2165-2167.
- [6] P. Finocchiaro, D. Gust, K. Mislow, J. Am. Chem. Soc. 96 (10) (1974) 3205–3213.
- [7] M.R. Kates, J.D. Andose, P. Finocchiaro, D. Gust, K. Mislow, J. Am. Chem. Soc. 97 (7) (1975) 1772–1778.
 [8] V. Mislow, A. Chure, Bus. 6 (1) (1976) 262–22.
- [8] K. Mislow, Acc. Chem. Res. 9 (1) (1976) 26–33.
- [9] S. Ito, N. Morita, T. Asao, Tetrahedron Lett. 33 (1992) 6669–6672.
- [10] S. Ito, N. Morita, T. Asao, Bull. Chem. Soc. Jpn. 68 (1995) 1409-1436.
- [11] B. Driesschaert, R. Robiette, C.S. Le Duff, L. Collard, K. Robeyns, B. Gallez, J. Marchand-Brynaert, Eur. J. Org. Chem. 2012 (33) (2012) 6517–6525.
- [12] V.M. Tormyshev, A.M. Genaev, G.E. Sal'nikov, O.Yu. Rogozhnikova, T.I. Troitskaya, D.V. Trukhin, V.I. Mamatyuk, D.S. Fadeev, H.J. Halpern, Eur. J. Org. Chem. 2012 (3) (2012) 623–629.
- [13] S. Brydges, M.J. McGlinchey, J. Org. Chem. 67 (22) (2002) 7688-7698.
- [14] S. Ito, N. Morita, T. Asao, Bull. Chem. Soc. Jpn. 68 (1995) 2639-2648.
- [15] H.T. Al-Masri, J. Sieler, P. Lönnecke, S. Blaurock, K. Domasevitchb, E. Hey-Hawkins, Tetrahedron 60 (2004) 333–339.
- [16] A.F. Pozharskii, A.V. Degtyarev, O.V. Ryabtsova, V.A. Ozeryanskii, M.E. Kletskii, Z.A. Starikova, L. Sobczyk, A. Filarowski, J. Org. Chem. 72 (2007) 3006–3019.
- [17] A.F. Pozharskii, A.V. Degtyarev, V.A. Ozeryanskii, O.V. Ryabtsova, Z.A. Starikova, G.S. Borodkin, J. Org. Chem. 75 (2010) 4706–4715.
- [18] Adolf von Baeyer, Justus Liebigs, Annalen der Chemie 354 (2) (1907) 152-204.
- [19] M. Rebek, M.K. Semlitisch, Mh. Chem. 92 (1961) 214–218.
- [20] P. Stanetty, I.K. Rodler, B. Krumpak, J. Prakt. Chem./Chem. -Ztg. 336 (1994) 333-339.
- [21] M.A. Nichols, P.G. Williard, J. Am. Chem. Soc. 115 (1993) 1568-1572.
- [22] J.-K. Zhang, P.-C.h. Wang, X.-W. Wang, L. Wang, J.-C. Chen, Zh.-W. Zheng, Y.-P. Niu, J. Organomet. Chem. 696 (23) (2011) 3697–3702.
- [23] G.M. Sheldrick, Acta Cryst. A64 (2008) 112-122.
- [24] J.F. Blount, P. Finocchiaro, D. Gust, Kurt Mlslow, J. Am. Chem. Soc. 95 (21) (1973) 7019–7029.
- [25] H.A. Staab, T. Saupe, Angew. Chem. Int. Ed. 27 (7) (1988) 865-879.
- [26] A.L. Llamas-Saiz, C. Foces-Foces, J. Elguero, J. Mol. Struct. 328 (1994) 297–323.