DOI: 10.1002/ejoc.200900474

Conformational Analysis and Optical Rotation of Carene β-Amino Alcohols: A DFT Study

Krzysztof Z. Łączkowski[a,b] and Angelika Baranowska*[a,b]

Dedicated to Professor Marek Zaidlewicz on the occasion of his 70th birthday

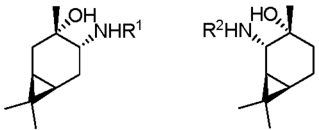
Keywords: Amino alcohols / Density functional calculations / Conformational analysis / Optical rotation

Four carene β-amino alcohols are subject of conformational analysis and optical rotation calculations carried out by using density functional theory with the hybrid B3LYP functional and aug-cc-pVDZ basis set. Despite relatively small values of the experimental optical rotations and conformational flexibility of these systems, the correct sign for the specific rotation was predicted for three of studied cases.

(© Wiley-VCH Verlag GmbH & Co. KGaA, 69451 Weinheim, Germany, 2009)

Introduction

β-Amino alcohols are widely used as auxiliaries and catalysts and provide excellent enantioselectivity in a variety of organic reactions, for example, in the enantioselective reduction of prochiral ketones,[1a,1b] the Diels–Alder reaction,[2a,2b] the addition of diethylzinc to benzaldehyde,[3] and other reactions.[4a–4h] Among them, terpene β-amino alcohols, which can be easily derived from naturally occurring optically pure terpenes, in many cases proved to be very efficient catalysts and to provide high enantioselective excess values.[1–4] Though terpene β-amino alcohols have been subject to numerous experimental studies, carene *cis*-β-amino alcohols have been reported only recently.[5] The first method of synthesis of *cis*-β-amino alcohols from (+)-3-carene was developed by Krzemiński.[5a,5b] Lately, an independent shorter method for the synthesis of terpene β-amino alcohols and *N*-methylamino alcohols, among them amino alcohols **1**–**4** (Figure 1), was developed in our group.[5c,5d]



1, R^1 = H ; **3**, R^2 = H
2, R^1 = CH_3 ; **4**, R^2 = CH_3

Figure 1. β-Amino alcohols **1**–**4** derived from (+)-3- and (+)-2-carene.

In the asymmetric synthesis of organic compounds, the determination of absolute configuration (AC) of the product is a crucial step. The most straightforward method used to determine the AC is X-ray analysis; however, this method needs a monocrystal of the studied compound. In most of the cases, additional reactions must be carried out to obtain a crystalline derivative, which thus increases both the total time and the cost of the synthetic process. The possibility of determining the AC through comparison of calculated specific optical rotation (OR) values with the experimental data would thus be an attractive alternative to X-ray analysis.

In this paper we focus on the conformational analysis and specific optical rotation calculations of (+)-3- and (+)-2-carene *cis*-β-amino alcohols **1** and **3**, and their *N*-methyl derivatives **2** and **4**, whose ACs were recently confirmed by using X-ray analysis.[5c] To the best of our knowledge, this is the first computational study of specific rotation of β-amino alcohols. Molecules under investigation are conformationally flexible and thus represent a computationally demanding group of systems.

Several studies of OR of conformationally flexible molecules are reported in literature.[6] The TDDFT[7a–7c] approximation with the B3LYP functional[7d] and the aug-cc-pVDZ basis set[7e] allowed for correct determination of AC of many of the studied systems. Accounting for the solvent effect through the polarizable continuum model (PCM)[8] was shown to improve the agreement between the theoretical and experimental results in the case of comparison with the data from measurement carried out in methanol.[6b,6c] Conformational flexibility of amino alcohols **1**–

---

[a] Department of Chemistry, Nicolaus Copernicus University,
7 Gagarin St., 87-100 Toruń, Poland
[b] Department of Chemistry, University of Santiago de Compostela,
15706 Santiago de Compostela, Spain
Fax: +34-981-595-012
E-mail: angelikasabina.baranowska@usc.es

© 2009 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

4 makes them an ideal test case for further evaluation of reliability of standard TDDFT/B3LYP specific rotation calculation.

Definitions and Computational Details

Optical rotation $[\alpha]^\lambda$ of conformationally flexible enantiomer 1 is defined as[6a]

$$[\alpha]^\lambda = \frac{ee(\varepsilon_1)}{100}\sum_{i=1}^{N} X_i[\alpha]_i^\lambda \qquad (1)$$

where $ee(\varepsilon_1)$ denotes the enantiomeric excess of enantiomer 1 in the mixture and $[\alpha]_i^\lambda$ is the optical rotation of conformer i. Symbol X_i represents the fractional population of conformer i and can be obtained according to Boltzmann statistics as[6c]

$$X_i = \frac{\exp(-\Delta_i E/kT)}{\sum_{i=1}^{N}\exp(-\Delta_i E/kT)} \qquad (2)$$

where $\Delta_i E$ denotes the relative energy of conformer i, k is the Boltzmann constant, and T is the temperature. The summation in Equations (1) and (2) runs over all (N) stable conformers of enantiomer 1.

The specific rotation calculations are routinely performed by using the TDDFT[7a–7c] approximation. The TDDFT, based on the extension of the first Hohenberg–Kohn (HK) theorem to the case of the time-dependent systems, is a generalization of the stationary DFT and allows investigating the time-dependent properties of molecules. The generalized first HK theorem states that the time-dependent electron density is uniquely defined by the time-dependent external potential. Time evolution of the system is characterized by the time-dependent Schrödinger equation and the many-body problem is solved upon assuming, analogously to the case of stationary DFT, that the electrons are noninteracting particles. In the cases of relatively small external potentials the problem of the complete solution of the time-dependent Kohn–Sham equation is avoided by the use of the response theory.[7c]

The choice of the basis set for any ab initio or (TD)DFT calculation is to a large extent the result of a compromise between accuracy and feasibility of the calculation. In the case of optical rotation calculations the fact that the size of the system is usually large makes the use of possibly small basis set mandatory. In contrast, the basis set used in the specific rotation calculations must include both polarization and diffuse functions to correctly describe the system interacting with the external electromagnetic field. The aug-cc-pVDZ basis set is well recognized to be a reasonable choice for TDDFT/B3LYP calculations of specific rotation of large systems.[6,9] The use of the larger aug-cc-pVTZ basis set in order to improve the quality of the results would lead to a dramatic increase in computing time, especially for large (and flexible) systems.

Because it has been found that even small changes in the set of optimized geometrical parameters may cause substantial changes in the final OR value,[10] the basis set and the level of theory used at the stage of geometrical parameters optimization need to be chosen carefully.

The first step of the present investigation was the optimization of the geometrical parameters of studied amino alcohols **1**–**4**. One starting point was chosen for molecules **1** and **3**, and two independent starting points for molecules **2** and **4**, corresponding to the inversion of the configuration on the nitrogen atom. To confirm that the optimized structures correspond to the real minima, the corresponding vibrational frequencies were calculated. Additionally, for molecules **1** and **3** two other optimization starting points corresponding to different deformations of the ring were chosen, leading to the same optimized structures and thus confirming that terpene rings present in the molecules are relatively rigid.

For all optimized geometries we performed potential energy scans, changing values of two dihedral angles corresponding to the rotation of the OH group (in molecules **1**–**4**) and either an NH_2 (in molecules **1** and **3**) or $NHCH_3$ (in molecules **2** and **4**) group. The dihedral angles were changed by 30° in each step, which gave a total of 144 points of potential energy surfaces for molecules **1** and **3** and 288 points for molecules **2** and **4**. The structures corresponding to the minima of the surfaces (five for molecules **1** and **3** and eight for molecules **2** and **4**) were chosen as starting points for the geometrical parameters optimization. Analysis of potential energies, bond lengths, and bond angles of optimized structures was performed to recognize different stable conformers. Five stable conformers were found for molecules **1** and **3** and six for molecules **2** and **4**. Vibrational frequencies were calculated for all optimized structures. Finally, the specific rotation calculations were carried out for all stable conformers of molecules **1**–**4**.

We used the DFT/B3LYP/aug-cc-pVDZ level of theory for the optimization of geometrical parameters of all considered systems as well as for the potential energy scans. Calculations of the vibrational frequencies were carried out by using the same level of approximation. The specific rotation calculations were carried out at the TDDFT/B3LYP/aug-cc-pVDZ level of approximation. The London atomic orbitals (LAOs)[11] were employed in the OR calculations to ensure the origin independence of the results. The total OR values were obtained by using Equation (1). We neglected the solvent and the vibrational effects in all calculations.

The optimization of the geometrical parameters and vibrational frequency calculations were carried out by using the Gaussian 03 program.[12] Specific optical rotations were calculated with the Dalton 2.0 program.[13] All OR results are reported in $10^{-1}\,^\circ\,\mathrm{cm}^2\,\mathrm{g}^{-1}$ referred to as OR-units.

Results and Discussion

Geometrical Parameters Optimization

Optimized conformers of **1**–**4** are presented in Figures 2, 3, 4, and 5 and labeled with letters **A**–**E** for molecules **1** and **3** and letters **A**–**F** for molecules **2** and **4**. In all cases, the letter **A** denotes the most stable conformer and the potential energy of conformers grows in the series **A** < **B** < **C** < **D** < **E** for molecules **1** and **3** and in the order **A** < **B** < **C** < **D** < **E** < **F** for molecules **2** and **4**.

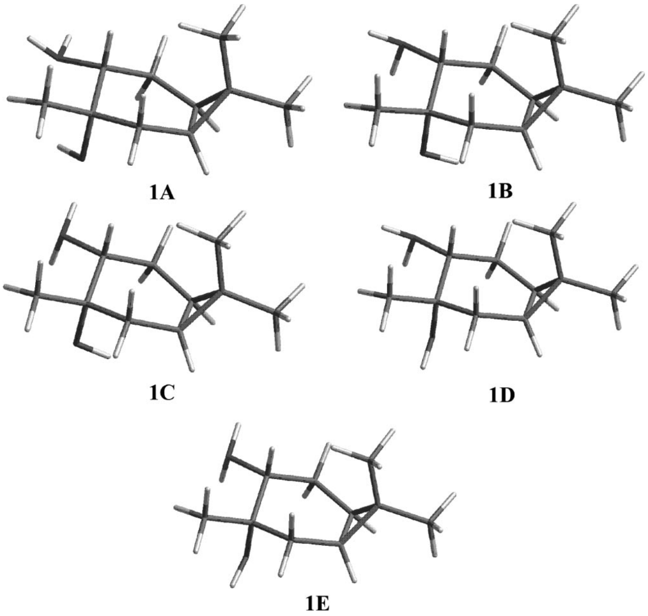

1A **1B** **1C** **1D** **1E**

Figure 2. Optimized conformers **1A**–**1E** of β-amino alcohol **1**.

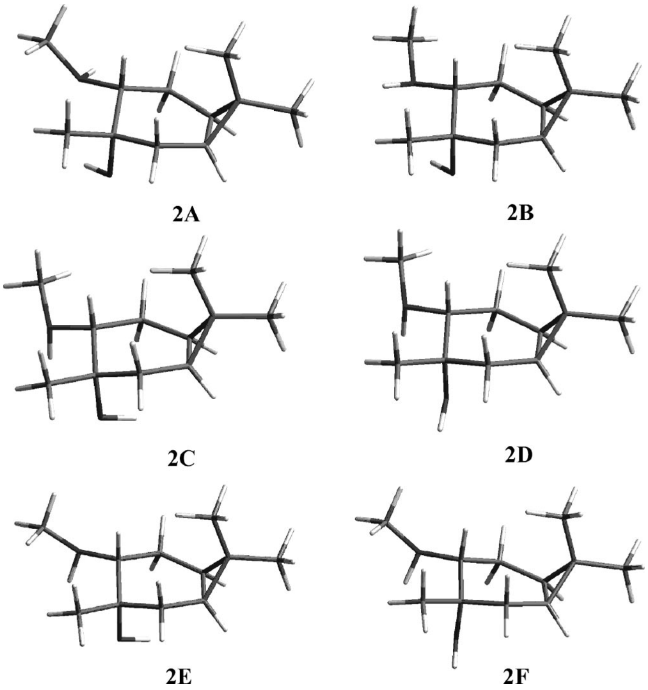

2A **2B** **2C** **2D** **2E** **2F**

Figure 3. Optimized conformers **2A**–**2F** of β-amino alcohol **2**.

For molecules **1** and **3**, conformer **A**, and for **2** and **4** conformers **A** and **B** seem to possess a week intramolecular hydrogen bond, which explains the fact that they are much more stable than other conformers of these systems. This is consistent with earlier observation by de Carvalho et al.[14] of forming an intramolecular hydrogen bond in a camphor-based γ-amino alcohol.

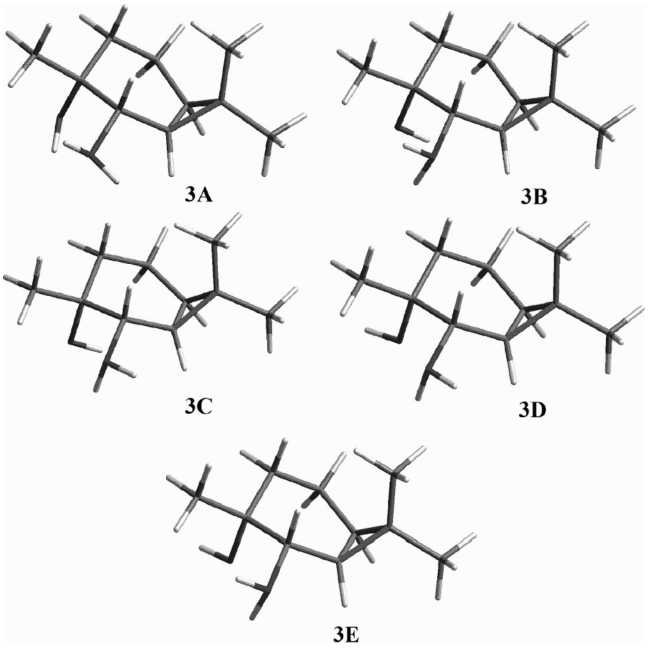

3A **3B** **3C** **3D** **3E**

Figure 4. Optimized conformers **3A**–**3E** of β-amino alcohol **3**.

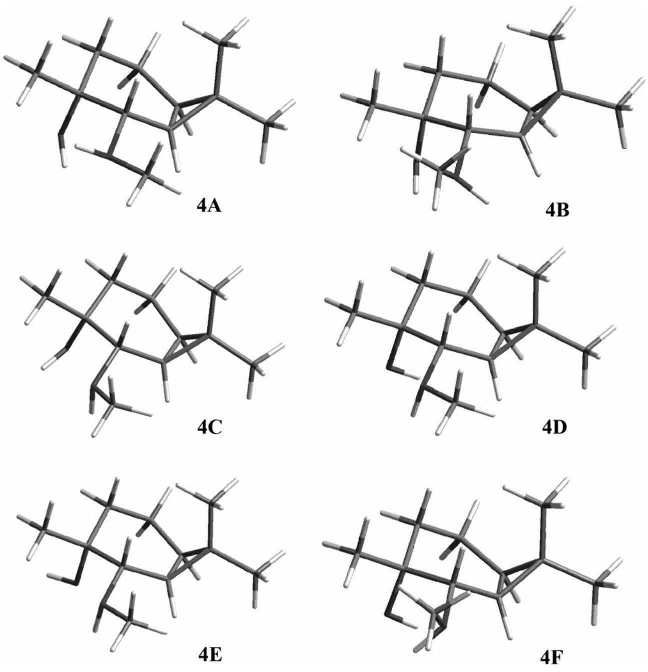

4A **4B** **4C** **4D** **4E** **4F**

Figure 5. Optimized conformers **4A**–**4F** of β-amino alcohol **4**.

Specific Rotation Results

Theoretical optical rotation results for molecules **1**–**4** are presented in Tables 1, 2, 3, and 4 and compared with the experimental results obtained for amino alcohols of >99%*ee* in the chloroform solutions. The total theoretical and the experimental OR sign differ only in the case of molecule **1**. The absolute value of predicted specific rotation of system **3** compares acceptably well with the experiment; however, in the case of systems **1** and **2** the theoretical absolute value of OR is almost twice as large as the experimental

© 2009 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

one. Also, for system **4** the difference between the theoretical and experimental results is substantial. The very good agreement of the theoretical and experimental OR values for molecule **3** may to some extent be fortuitous.

Table 1. Relative energies $\Delta_i E$ [kcal mol^{-1}], optical rotations $[\alpha]_i^{\mathrm{D}}$, fractional populations X_i [%], and weighted optical rotations $X_i[\alpha]_i^{\mathrm{D}}$ of conformers **1A**–**1E**, and total specific rotation $[\alpha]^{\mathrm{D}}$ of molecule **1**.

Conformer	$\Delta_i E$	$[\alpha]_i^{\mathrm{D}}$	X_i [%]	$X_i[\alpha]_i^{\mathrm{D}}$
1A	0.0000	–33.19	79.83	–26.49
1B	1.1144	31.82	12.16	3.87
1C	1.7734	–47.30	3.99	–1.89
1D	2.1478	43.83	2.12	0.93
1E	2.2136	–29.02	1.90	–0.55
$[\alpha]^{\mathrm{D}}$ (theor.)				–24.13
$[\alpha]^{\mathrm{D}}$ (exp.)				12.5[a]

[a] Experimental result recorded in $CHCl_3$ at room temperature with c = 3.2 g/100 mL.[5c]

Table 2. Relative energies $\Delta_i E$ [kcal mol^{-1}], optical rotations $[\alpha]_i^{\mathrm{D}}$, fractional populations X_i [%], and weighted optical rotations $X_i[\alpha]_i^{\mathrm{D}}$ of conformers **2A**–**2F**, and total specific rotation $[\alpha]^{\mathrm{D}}$ of molecule **2**.

Conformer	$\Delta_i E$	$[\alpha]_i^{\mathrm{D}}$	X_i [%]	$X_i[\alpha]_i^{\mathrm{D}}$
2A	0.0000	–47.98	45.16	–21.67
2B	0.0979	–93.66	38.28	–35.85
2C	0.9159	–31.10	9.62	–2.99
2D	1.3891	–18.52	4.33	–0.80
2E	1.7715	12.59	2.27	0.29
2F	2.9056	21.64	0.33	0.07
$[\alpha]^{\mathrm{D}}$ (theor.)				–60.96
$[\alpha]^{\mathrm{D}}$ (exp.)				–29.9[a]

[a] Experimental result recorded in $CHCl_3$ at room temperature for c = 2.5 g/100 mL.[5c]

Table 3. Relative energies $\Delta_i E$ [kcal mol^{-1}], optical rotations $[\alpha]_i^{\mathrm{D}}$, fractional populations X_i [%], and weighted optical rotations $X_i[\alpha]_i^{\mathrm{D}}$ of conformers **3A**–**3E**, and total specific rotation $[\alpha]^{\mathrm{D}}$ of molecule **3**.

Conformer	$\Delta_i E$	$[\alpha]_i^{\mathrm{D}}$	X_i [%]	$X_i[\alpha]_i^{\mathrm{D}}$
3A	0.0000	–2.28	91.24	–2.08
3B	1.7901	–66.38	4.44	–2.95
3C	2.1967	–5.19	2.23	–0.12
3D	2.5331	–33.55	1.27	–0.42
3E	2.7850	–94.26	0.83	–0.78
$[\alpha]^{\mathrm{D}}$ (theor.)				–6.35
$[\alpha]^{\mathrm{D}}$ (exp.)				–8.4[a]

[a] Experimental result recorded in $CHCl_3$ at room temperature for c = 2.7 g/100 mL.[5c]

Table 4. Relative energies $\Delta_i E$ [kcal mol^{-1}], optical rotations $[\alpha]_i^{\mathrm{D}}$, fractional populations X_i [%], and weighted optical rotations $X_i[\alpha]_i^{\mathrm{D}}$ of conformers **4A**–**4F**, and total specific rotation $[\alpha]^{\mathrm{D}}$ of molecule **4**.

Conformer	$\Delta_i E$	$[\alpha]_i^{\mathrm{D}}$	X_i [%]	$X_i[\alpha]_i^{\mathrm{D}}$
4A	0.0000	74.59	43.42	32.39
4B	0.3897	–17.70	22.49	–3.98
4C	0.6689	85.04	14.04	11.94
4D	0.7572	68.41	12.10	8.27
4E	1.0629	43.76	7.22	3.16
4F	2.4220	–52.87	0.73	–0.39
$[\alpha]^{\mathrm{D}}$ (theor.)				51.40
$[\alpha]^{\mathrm{D}}$ (exp.)				36.4[a]

[a] Experimental result recorded in $CHCl_3$ at room temperature for c = 2.15 g/100 mL.[5c]

For molecules **1**, **2**, and **4** the individual contributions to the total OR differ in sign, which causes their partial cancelation, and thus makes the sign of the total OR sensitive to the choice of fractional populations, that is, to the accuracy of the approximation used for their evaluation. However, large changes in the fractional populations would be necessary to significantly improve the agreement of the theoretical results with the experimental values, especially in the case of molecules **1** and **2**. For molecule **1**, lowest-energy conformer **1A** strongly dominates (almost 80% of the population). The stabilization of conformer **1B** by as much as 0.6 kcal mol^{-1} would change the value of the total OR to about –14.3 OR-units, and even if **1B** was stabilized by 1 kcal mol^{-1} the sign of the total OR would remain negative. The sign of the total OR would change if **1B** was the most stable conformer and **1A** was at least about 0.1 kcal mol^{-1} less stable than **1B** (leaving the relative energies of other conformers unchanged); however, it does not seem to be possible that conformer **1B** is more stable than **1A**, which possesses an intramolecular hydrogen bond. For molecule **2**, conformers **2A** and **2B** constitute over 80% of the whole population. The destabilization of conformer **2B** by as much as 0.6 kcal mol^{-1} would lead to an OR value equal to –50.4 OR-units, but still the theoretical result would be far from the experimental value. The opposite-sign conformers **2E** and **2F** have very high relative energies, and thus large changes in $\Delta_i E$ would be necessary to significantly enlarge their fractional populations and improve the agreement of the total theoretical OR with the experimental result. Molecule **4** is more sensitive to changes in the relative energy values, and stabilization of **4B** by 0.3 kcal mol^{-1} would lead to a total OR of about 42.5 OR-units. The observed disagreement of the theoretical and experimental specific rotations may also to some extent result from neglecting the vibrational effects[15] in the calculations.

It is not clear why for molecule **1** the predicted OR sign is in disagreement with the experimental result, whereas for the three other systems, very similar to **1**, theoretical predictions agree in sign with the experiment. It is possible that accounting for solvent effects in the OR calculations could improve the agreement between the theoretical and experimental results. However, the experimental data correspond to measurements carried out in chloroform, which does not form hydrogen bonds with the solute, and thus, the solvent interacts only weakly with the solute molecules.[6a,6b] It seems that neglecting these interactions cannot be the only factor leading to an incorrect sign of theoretical OR for **1**.

Another possible reason for the failure of the present approach for molecule **1** can be the fact that a still too small or insufficiently diffuse basis set was used in the calculations. The available literature results show that although in some of the studied cases replacement of the aug-cc-pVDZ set with the aug-cc-pVTZ set does not cause a substantial change in the value of the calculated specific rotation, in other cases the difference is significant[15d] and even a change in sign of the resulting specific rotation is observed.[9a,10] Attempts were made to perform test single-point energy calculations for the conformers of molecule **1** with the aug-cc-pVTZ set, but convergence problems were encountered. However, it has to be stressed that even if the convergence problems did not occur, the use of the aug-cc-pVTZ basis set (with a total of 989 functions for this system) in the TDDFT OR calculations for molecule **1** instead of the aug-cc-pVDZ set (with 447 functions for this system) would lead to a dramatic increase in computing times. Thus, although the quality of the results would be improved with the larger set, it is very difficult to use the aug-cc-pVTZ set in regular calculations for systems larger than those having a few so-called heavy atoms. Diffuse and flexible but at the same time possibly small basis set for the calculation of the specific rotation would be highly desired.

It is worth noting that the fact that the TDDFT/B3LYP/aug-cc-pVDZ calculation allows the correct AC to be assigned for one system but fails to correctly assign the AC of other molecules that are very close in structure to the first one has been reported in literature for other systems. The widely studied case of the OR of pinenes, with the TDDFT/B3LYP/aug-cc-pVDZ level of approximation, leading to the correct sign of OR for *α*-pinene and the incorrect sign for β-pinene is one example.[9b,9c]

Conclusions

We carried out systematic conformational analysis and specific rotation calculations for carene β-amino alcohols **1**–**4**. Despite the conformational flexibility of these systems and the relatively small absolute values of their experimental specific rotations, the determined theoretical OR sign is in agreement with the experimental results in three of the studied cases, which confirms the AC determined by X-ray analysis. The present results give hope for future correct assignment of absolute configuration of other amino alcohols through careful DFT conformational analysis and TDDFT optical rotation calculations and comparison with the available experimental OR data. However, the disagreement of the theoretical and experimental OR sign observed for one of the examined systems needs further study. It is possible that a flexible and more diffuse basis set is needed for the correct theoretical assignment of absolute configuration of molecule **1**.

Acknowledgments

We acknowledge the Information & Communication Technology Centre of the Nicolaus Copernicus University, Toruń, Poland for providing computational resources.

---

[1] a) M. P. Krzemiński, A. Wojtczak, *Tetrahedron Lett.* **2005**, *46*, 8299–8302; b) D. Hobuss, A. Baro, D. Hobuss, A. Baro, S. Laschat, W. Frey, *Tetrahedron* **2008**, *64*, 1635–1640.

[2] a) S. Itsuno, K. Watanabe, T. Koizumi, K. Ito, *React. Polym.* **1995**, *24*, 219–227; b) W. A. J. Starmans, R. W. A. Walgers, L. Thijs, R. de Gelder, J. M. M. Smits, B. Zwanenburg, *Tetrahedron* **1998**, *54*, 4991–5004.

[3] C. M. Binder, A. Bautista, M. Zaidlewicz, M. P. Krzemiński, A. Oliver, B. Singaram, *J. Org. Chem.* **2009**, *74*, 2337–2343.

[4] a) B. T. Cho, M. H. Ryu, Y. S. Chun, Ch. Dauelsberg, S. Wallbaum, J. Martens, *Bull. Korean Chem. Soc.* **1994**, *15*, 53–57; b) M. P. Krzemiński, M. Zaidlewicz, *Tetrahedron: Asymmetry* **2003**, *14*, 1463–1466; c) C. E. Song, C. R. Oh, E. J. Roh, S. Lee, J. H. Choi, *Tetrahedron: Asymmetry* **1999**, *10*, 671–674; d) S. Itsuno, M. Nakano, K. Moyazaki, H. Maruda, K. Ito, *J. Chem. Soc. Perkin Trans. 1* **1985**, 2039–2044; e) Y. Akito, Y. Yoneyoshi, G. Suzukamo, *Tetrahedron Lett.* **1988**, *29*, 223–224; f) M. Masui, T. Shioiri, *Tetrahedron* **1995**, *51*, 8363–8370; g) M. Masui, T. Shiori, *Tetrahedron Lett.* **1998**, *39*, 5195–5198; h) K. Z. Łączkowski, M. M. Pakulski, M. P. Krzemiński, P. Jaisankar, M. Zaidlewicz, *Tetrahedron: Asymmetry* **2008**, *19*, 788–795.

[5] a) M. P. Krzemiński, PL Pat. Appl. 383483, 10.04, **2007**; b) M. J. Bosiak, M. P. Krzemiński, P. Jaisankar, M. Zaidlewicz, *Tetrahedron: Asymmetry* **2008**, *19*, 956–963; c) K. Z. Łączkowski, A. Kmieciak, A. Kozakiewicz, *Tetrahedron: Asymmetry* **2009**, *20*, 1487–1492; d) (1*S*,3S,4*R*,6*R*)-4-amino-3,7,7-trimethylbicyclo-[4.1.0]heptan-3-ol (**1**), (1*S*,3*S*,4*R*,6*R*)-3,7,7-trimethyl-4-(methylamino)bicyclo[4.1.0]heptan-3-ol (**2**), (1*S*,2*S*,3*R*,6*R*)-2-amino-3,7,7-trimethylbicyclo[4.1.0]heptan-3-ol (**3**), (1*S*,2*S*,3*R*,6*R*)-3,7,7-trimethyl-2-(methylamino)bicyclo[4.1.0]heptan-3-ol (**4**).

[6] a) P. J. Stephens, F. J. Devlin, J. P. Cheeseman, M. J. Frisch, O. Bortolini, P. Besse, *Chirality* **2003**, *15*, S57–S64; b) D. Marchesan, S. Coriani, C. Forzato, P. Nitti, G. Pitacco, K. Ruud, *J. Phys. Chem. A* **2005**, *109*, 1449–1453; c) S. Coriani, A. Baranowska, L. Ferrighi, C. Forzato, D. Marchesan, P. Nitti, G. Pitacco, A. Rizzo, K. Ruud, *Chirality* **2006**, *18*, 357–369; d) M. Pecul, *Chem. Phys. Lett.* **2006**, *418*, 1–10.

[7] a) E. Runge, E. K. U. Gross, *Phys. Rev. Lett.* **1984**, *52*, 997–1000; b) E. K. U. Gross, W. Kohn, *Phys. Rev. Lett.* **1985**, *55*, 2850–2852; c) M. A. L. Marques, E. K. U. Gross, *Annu. Rev. Phys. Chem.* **2004**, *55*, 427–455; d) P. J. Stephens, F. J. Devlin, C. F. Chabalowski, M. J. Frisch, *J. Phys. Chem.* **1994**, *98*, 11623–11627; e) R. A. Kendall, T. H. Dunning Jr, R. J. Harrison, *J. Chem. Phys.* **1992**, *96*, 6796–6806.

[8] B. Mennucci, J. Tomasi, R. Cammi, J. R. Cheeseman, M. J. Frisch, F. J. Devlin, S. Gabriel, P. J. Stephens, *J. Phys. Chem. A* **2002**, *106*, 6102–6113.

[9] a) P. J. Stephens, F. J. Devlin, J. P. Cheeseman, M. J. Frisch, *J. Phys. Chem. A* **2001**, *105*, 5356–5371; b) D. M. McCann, P. J. Stephens, *J. Org. Chem.* **2006**, *71*, 6074–6098; c) T. D. Crawford, P. J. Stephens, *J. Phys. Chem. A* **2008**, *112*, 1339–1345.

[10] M. C. Tam, N. J. Russ, T. D. Crawford, *J. Chem. Phys.* **2004**, *121*, 3550–3557.

[11] F. London, *J. Phys. Radium* **1937**, *8*, 397–409.

[12] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery Jr, T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov,

G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez, J. A. Pople, *Gaussian 03*, Revision D.01, Gaussian, Inc., Wallingford, CT, **2004**.

[13] *DALTON, A Molecular Electronic Structure Program*, Release 2.0, **2005**, see http://www.kjemi.uio.no/software/dalton/dalton.html.

[14] E. M. de Carvalho, J. D. Figueroa Villar, J. S. Greco, S. Pinheiro, J. W. de M. Carneiro, *J. Mol. Struct.* **2007**, *827*, 121–125.

[15] a) K. Ruud, P. R. Taylor, P.-O. Åstrand, *Chem. Phys. Lett.* **2001**, *337*, 217–223; b) B. C. Mort, J. Autschbach, *J. Phys. Chem. A* **2005**, *109*, 8617–8623; c) J. Kongsted, T. B. Pedersen, L. Jensen, A. E. Hansen, K. V. Mikkelsen, *J. Am. Chem. Soc.* **2006**, *128*, 976–982; d) T. B. Pedersen, J. Kongsted, T. D. Crawford, K. Ruud, *J. Chem. Phys.* **2009**, *130*, 034310.

Received: May 3, 2009
Published Online: August 7, 2009