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Left/right handedness assignment to chiral tetrahedral AB_4 structures

Dina Yogev-Einot,[a,b,c] Mark Pinsky[a,d] and David Avnir[a,b,*]

[a]*Institute of Chemistry, The Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[b]*The Lise Meitner Minerva Center for Computational Quantum Chemistry, The Hebrew University of Jerusalem, Jerusalem 91904, Israel*
[c]*Department of Chemistry, The Open University of Israel, Raanana 43107, Israel*
[d]*Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem 91904, Israel*

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Abstract—Chiral tetrahedral AB_4 molecules or molecular fragments, where A and B are atoms, are common, yet handedness assignment rules for these species, to the best of our knowledge, do not exist. We propose a simple set of rules for such an assignment and apply it to many chiral molecules; to a chiral crystal—quartz—identifying preservation of handedness across its phase transition; and to a large random population of chiral AB_4 structures. The concept of handedness-labelling is discussed by presenting a second alternative for labelling.

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1. Introduction

While the common image of tetrahedral AB_4 species is that they are achiral (because of molecules such as CH_4, CCl_4, etc.) the largely unnoticed reality is that the majority of tetracoordinated molecules or molecular fragments are chiral.[1] The main origins of this chirality are the facts that it is quite rare to find perfect tetrahedricity of AB_4 (in crystals, in the adsorbed state, in amorphous materials, in clusters and so on), and that this distortion from ideality, much more often than not, is such that the resulting structure has no mirror plane (or an S_n symmetry element). Collected in the first two columns of Table 1 are some examples of common tetrahedral structures, which although not recognized as such, are chiral. One can identify chirality either qualitatively by inspection of the structure and its coordinates, or quantitatively, by measuring the degree of chirality (third column;[2–4] zero on this scale is achirality). Examples of genuine AB_4 achiral structures of course exist, and are collected at the bottom of the table for the sake of providing the full picture.

Since the chirality of solids is a prime parameter in heterogeneous catalysis,[8] in chromatographic separations[9] and in optics[10]—to mention just few key applications—the question of the associated handedness, emerges. To the best of our knowledge, there are no official, IUPAC-accepted rules for assigning left- or right-handedness to AB_4 elementary building blocks, where A and B are atoms.[11] It is perhaps of relevance to mention here that handedness rules have been proposed for some related cases, none of which are applicable, however, for the simple AB_4 case. These include the rules for chiral octahedral six-coordinated complexes,[11] tris-bidentate octahedral complexes, $A(B–B)_3$,[12] that can be applied in principle to bidentate $A(B–B)_2$ systems,[13] the Cahn–Ingold–Prelog (CIP) rules for conformational chirality of $A(C–X)_4$,[14,15] helical rules which require the existence and identification of a C_2 symmetry axis,[16–18] and perhaps also the rules for spiro compounds, where one considers the central atom.[14,19]

Herein we report a simple set of rules for handedness assignment of tetrahedral chiral AB_4 structures. We recall that labelling an object as 'left' or 'right' is arbitrary; in chemistry and physics it has simply been a matter of agreed convention. Therefore, when one approaches the handedness-labelling of a family of objects, which is not covered by existing labelling methods, due to the arbitrariness of the problem, all options are open. However, we have decided to develop a labelling method, which is as close as possible in its rational to the labelling rules, which are currently used for four-coordinated structures, namely,

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[*] Corresponding author. Tel.: +972 2658 5332; fax: +972 2652 0099; e-mail: david@chem.ch.huji.ac.il

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Table 1. Common chiral tetrahedral AB_4 structures

The compound	The analyzed AB_4 species	Degree of chirality	Handedness[a]	Ref. code of CCDC[b]
Pentakis(acetonitrile-*N*)-chloro-aluminium bis(tetrachloro-iron(iii))	$FeCl_4$	0.2739	Right	ACNALC02
Bis((h^5-1-*t*-butyl-2-methyl-1,2-azaborolinyl)-(h^6-toluene)-iron) tetrabromo-iron	$FeBr_4$	0.0142	Right	DEBWIQ
3-(2-Diethylammonium-ethoxy)-1,2-benzisothiazole tetrachlorocuprate	$CuCl_4$	0.0122	Left	AEBZTZ
Bis(2-methylpyridinium) tetrabromo-copper(ii)	$CuBr_4$	0.0002	Left	BACHOD
(a-(N^2-2-Aminoethylamidino)alaninato)-chloro-ethylenediamine-cobalt(iii) tetrachloro-zinc(ii)	$ZnCl_4$	0.0464	Left	AECACO
Bis(bis(h^5-cyclopentadienyl)-rhenium) tetrabromo cobalt	$CoBr_4$	0.6515	Right	DIFWOE
Bis(2-aminophenyltriphenylphosphonium) tetrachloro-nickelate(ii)	$NiCl_4$	0.0113	Right	YABYUV
Cyanomethyl-tris(2,4,6-trimethylphenyl)-phosphonium tetraiodo-mercury(ii)	HgI_4	0.3373	Left	CNPSHG
6,14-Diacetylmonodethiosirodesmin PL chloroform solvate	CCl_4	0.0953	Left	CAMNUZ
(*E*)-2,3-Dichloro-4-(*p*-tolylsulfonylimino)-3,4-dihydro-1(2*H*)-naphthalenone carbon tetrachloride solvate	CCl_4	0.0892	Right	QETSOX
Catena(tetraethoxyphosphonium nonachloro-di-tellurium(iv))	PO_4 ($P(OCC)_4$)	0.0010	Right	JOJNIF
Tetrakis(ethylenediammonium) ammonium tetraphosphato-aluminium	PO_4 ($Al(PO_4)_4$)	0.0012	Left	JUFZAL
Tetrakis(hydroxydimethylsilyl)methane	CSi_4 ($C(SiC_2O)_4$)	0.0135	Right	GIBKOR
Tetrakis(phenylsilyl)methane	CSi_4 ($C(SiH_2Ph)_4$)	0.0097	Left	SETWUJ
Silicon dioxide, low-quartz	SiO_4	0.0007	Left	Will[5]
Germanium oxide, low-temperature quartz-type	GeO_4	0.0211	Left	Glinnemann[6]
Bis(tetramethylammonium) tetrabromo-zinc(ii)	$ZnBr_4$	0.0000	Achiral	CEKLOT
Ethylenediammonium tetrachlorocobalt(ii) chloride	$CoCl_4$	0.0000	Achiral	ENAMCC10
Tetrakis(ethylenediammonium) ammonium tetraphosphato-aluminium	AlO_4 ($Al(PO_4)_4$)	0.0000	Achiral	JUFZAL

[a] The triangles method (Section 2).

[b] From the Cambridge Crystallographic Data Centre (CCDC).[7]

the CIP rules. Herein we shall make another proposition, not only for the sake of showing the freedom of choice, but also because the comparison of the two methods illuminated some interesting features of the general problem of handedness assignment. Finally, as for the CIP rules, the set of rules for tetrahedral chiral AB_4 structures focuses on the substituents only, namely, on the B_4 pyramid.[21]

2. Results and discussion

2.1. Handedness assignment rules for chiral AB_4 species: the triangles method

1. Given an AB_4 species, view the B_4 pyramid (Fig. 1a).
2. Calculate the perimeter length of the four triangle faces (shaded blue) of the pyramid (Fig. 1a–d).
3. Take the triangle with the largest perimeter and place it on the page plane, with the fourth substituent behind the page (Fig. 1d).
4. Determine the direction from the longest edge to the shortest one (Fig. 1f; here we follow the CIP hierarchy, which begins with the 'largest').
5. If that direction is clockwise (which is the case in this example) then AB_4 is labelled as a right-handed tetrahedron, R^0; a counterclockwise direction (Fig. 1e) is a left-handed AB_4, S^0. Figure 1e and f shows a pair of enantiomers.

Achirality will appear, for instance, as two identical triangles, only with opposite directionality. As with all labelling conventions, here too there must be cases where the object is chiral, but handedness cannot be assigned by the selected

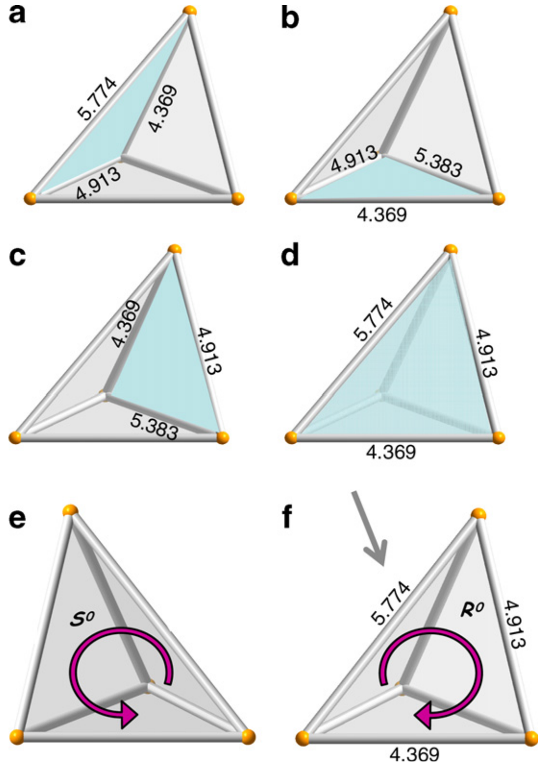

Figure 1. Handedness assignment rules for chiral AB_4 species—the triangles method: Calculate the perimeter lengths for each of the four triangle faces (a–d, shaded blue), select the triangle with the largest perimeter and place it in the page plane (d). If the direction, from the longest edge to the shortest one is clockwise, as in (d)—see (f)—then AB_4 is labelled as a right-handed tetrahedron, R^0; a counterclockwise direction (e) is a left-handed tetrahedron, S^0.

convention. Such chiral objects are said to have latent handedness (or non-handedness).[22] Examples, including the CIP rules and the helix rules, have been discussed before.[22,23] For our set of rules latent handedness will appear, for instance, in the case of two triangles of equal perimeter composed of a different combination of edge lengths, rotating in opposite directions.

2.2. An alternative: handedness assignment of AB_4 based on torsion angle

As noted in Section 1, it is interesting to select and compare with an alternative labelling method. For this purpose we relied on another IUPAC recommended method, which is based on the torsion angle within the molecule, as explained in Figure 2.[15,16] According to this method, the P or M (plus or minus) or Δ/Λ (clockwise, right-handed or anticlockwise, left-handed) labels are determined by the directionality of the torsion angle between two bonds: close to the viewer (1–2 in Fig. 2) and distant from the viewer (3–4 in the figure). Based on this approach, an alternative set of rules for the handedness assignment of AB_4 is as follows (Fig. 3):

1. Given an AB_4 species, view the three pairs of the non-connected edges of the B_4 pyramid (Fig. 3a; three pairs of different colours).
2. For each of the pairs, project one edge on top of the other along the line that connects their middles, as shown in Figure 3b–d. (It does not matter which of the two edges is put in the back).
3. Three torsional angles form, from which select the smallest angle (Fig. 3c[24]).
4. Determine the directionality of that angle from the edge that is close to you to the one at the back. If clockwise, it is a right-handed AB_4 species (the case shown in Fig. 3e) and if anticlockwise, it is a left-handed species (Fig. 3f).

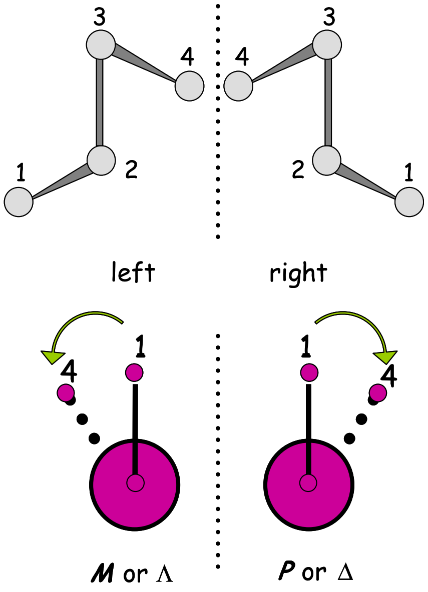

Figure 2. The IUPAC M/P or Δ/Λ—torsion-angle rules: In a chain of atoms, 1–4, the dihedral angle between the 1–3 plane and the 2–4 plane determines the handedness, as shown.

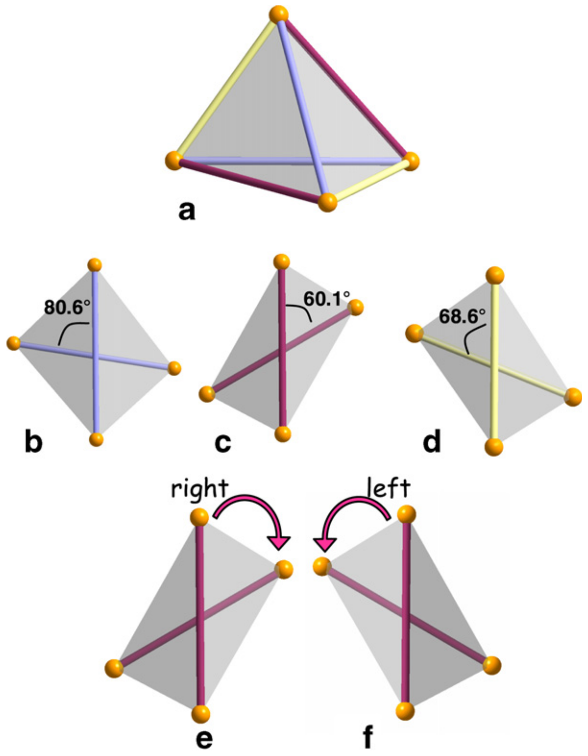

Figure 3. Handedness assignment for chiral AB_4—the torsion-angle method: The pyramid (a) has three pairs of non-connected edges (three pairs of colours). Determine the three torsional angles of the non-connected edges (b–d). Select the smallest angle (c) and determine the directionality of that angle from the edge that is close to you to the one at the back (e). If clockwise, it is a right-handed AB_4 species (e), and if anticlockwise, it is a left-handed species (f).

The structure is a perfect tetrahedron if all three angles are equal to 90° and achiral if there are at least two equal dihedral angles in opposite directionalities.

2.3. Testing and applying the handedness-labels

2.3.1. Testing the labelling methods. Before applying the R^0 or S^0 labels to real molecules, the method was tested on some models, and compared to the alternative labelling method, as follows: Three pairs of AB_4 structures were prepared, with either C_s (this achiral structure was chosen as a blank-test), or C_2 or C_1 (chiral) symmetries, as shown in Figure 4. Table 2 summarizes the absolute configuration for each structure by each of the two methods. It can be seen first, that the two methods identify the achirality correctly, and that mirror images of each of the chiral structures indeed give the opposite handedness assignment. It is also seen that the two methods, according to Table 2, give opposite handedness; since handedness labelling is arbitrary, there is no reason to expect that the two methods will give the same handedness. A real example for such a situation is the GeO_4 tetrahedron (Fig. 5) of germania at high pressure.[25,26] This tetrahedron is left-handed (S^0) by the triangles method, but right-handed by the torsion-angle method.

2.3.2. Testing the labelling method on a large population. Next we tested the reliability of the R^0–S^0 method

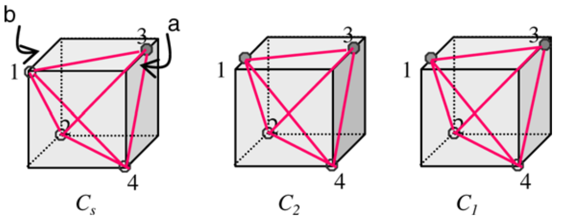

Figure 4. Distorted tetrahedra. The distortions were carried out as follows: The distortion to C_s was affected by changing the position of point 3 on edge (a); to C_2 by moving points 1 and 3 the same distance on edges (a) and (b); and to C_1 same as for C_2, but with different distances of motion.

Table 2. Handedness labels of the AB_4 structures of Figure 3 by the two conventions

Structure	The triangles method	The torsion-angle method
C_s	Achiral	Achiral
C_s-mirror image	Achiral	Achiral
C_2	R^0 (right)	Left
C_2-mirror image	S^0 (left)	Right
C_1	R^0 (right)	Left
C_1-mirror image	S^0 (left)	Right

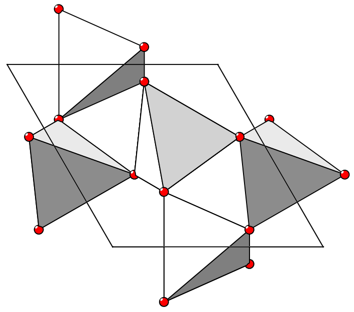

Figure 5. The unit cell (projected through the c-axis) of α-quartz-germania, GeO_2, where all of the GeO_4 linked tetrahedra have the same structure and are chiral. The handedness of each tetrahedron is left (S^0) by the triangles method, but right by the torsion-angle method.

by analyzing a large population of 10,000 arbitrarily distorted AB_4 structures (where, in order to bear some resemblance to real structures, the distortions were limited to angles in the range of 80–140° and bond lengths were randomly varied within 10% of the original length). The underlying assumptions were, first, that the probability that any of the resulting AB_4 structures will still have a mirror symmetry (and therefore be achiral) is very low; and second, that about half of the resulting chiral structures should be left-handed, and the other portion right-handed, namely, the population should be approximately racemic; indeed, within ±0.5%, this was the observation (4975 and 5025 right- and left-handed structures, respectively). To ascertain that the ±0.5% deviation from pure racemicity reflects only the finite population taken (and not inherent errors), we also evaluated the % of left-handedness for each consecutive 1000 structures, and it is seen that the percentage fluctuates around the 50.0% line (Fig. 6).[27]

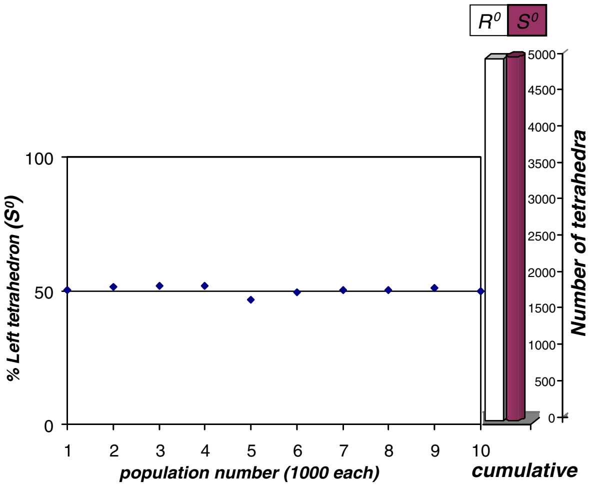

Figure 6. Right bars: The distribution between left-handedness (S^0) and right-handedness (S^0) in 10,000 randomly distorted tetrahedra. The graph shows the fluctuation in the % of S^0 around 50% for each of the 10 batches of 1000 tetrahedra.

2.3.3. Attaching handedness labels in Table 1. After carrying out all of these tests, we applied the R^0–S^0 method on the entries in Table 1, and provide their handedness for each case, based on the reported crystallographic data in the CCDC[7] and ICSD[28] data bases. No problems were encountered in these determinations, which can also be done automatically: a simple program is available from the authors.

2.4. Case analysis: the handedness of the building blocks of quartz across its phase transition

We conclude this report by demonstrating its applicability to a specific problem, namely, the handedness of chiral quartz. The molecular level of chirality of this mineral is due to the 3_1 or 3_2 helices of the oxygen-connected SiO_4 tetrahedra, leading to the enantiomeric chiral space groups $P3_121$ or $P3_221$. Since the SiO_4 tetrahedra are part of a helix, they are chirally distorted as well,[29] although to a very small degree. Elsewhere we showed that the chirality of the Si-atoms tetrahedron, $SiSi_4$ [which is the $Si(OSi)_4$ unit without the oxygen atoms], which is much more pronounced,[26,29] is the smallest molecular unit of quartz, which fully represents the chirality of the whole. At 848 K quartz undergoes a phase transition from α- to β-quartz, which is still chiral, however the handedness of the space group changes across the phase transition from 3_2 (left-handed helix) in α-quartz to 6_2 (right-handed helix in the space group $P6_222$) in β-quartz. The question we address—possible only with the newly introduced R^0 or S^0 convention—is what happens to the handedness of $SiSi_4$ building-block across the phase transition. Analysis of the temperature dependent X-ray crystallographic data of Kihara[30] between 298 K and 1078 K, provides a surprising answer: despite the fact that the handedness of the space group changes across the phase transition, the handedness of $SiSi_4$ does not change (as determined by the two methods (Fig. 7a)). How can that be? As shown in Figure 7b, what does change upon the phase transition is the value

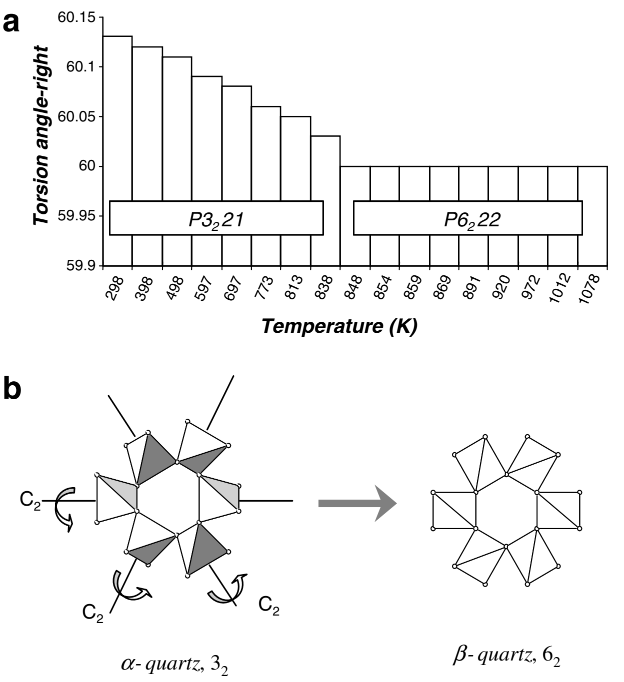

Figure 7. (a) The absolute configuration of $SiSi_4$ does not change across the phase transition, as determined by the two methods of handedness-labelling. All blocks are R^0 (cf. Fig. 6) and all torsion angles are right angles. (b) The change in the tilt-angle and space-group across the phase transition of quartz, see through the *c*-axis.

of the tilt angle (δ, defined as the angle of the C_2-rotational axis to the *a*,*b*-plane). The angle in question, is 16° in α-quartz at room temperature (Fig. 7b, left), and as the temperature increases the angle decreases, until it reaches zero for β-quartz (Fig. 7b, right), accompanied with a change in the helical space group from 3_2 (left) to 6_2 (right). This is a known paradox in quartz.[31]

3. Conclusion

In conclusion, the problem of handedness assignment to chiral AB_4 structures has been addressed. A set of rules—in the spirit of the CIP rules—has been developed, and has been demonstrated on various molecules, on a large population of artificial structures, and on the building block of quartz. Some conceptual questions, such as the ability to use more than one labelling system, and the existence of latent handedness in chiral structures have also been addressed.

Programmes: Contact author for access to programmes.

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