

First Experimental Evidence of an Intramolecular H Bond between Aliphatic CI and Aromatic C–H

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Supporting Information

ABSTRACT: The first example of an intramolecular H bond between aliphatic Cl and aromatic C–H was observed in the crystal of C_2 -symmetric (4*R*,5*R*)-4,5-bis(diphenylchloromethyl)-1,3,2-dioxathiolane 2-oxide. In this case one Cl atom is engaged in H-bonding with two *ortho*-C–H groups in the axial and equatorial phenyl planes, with the recorded distances of 2.562 Å and 2.804 Å, respectively. The observed angle for C_a–H–Cl is 108.41° and that for C_q–H–Cl is 96.53°.



Understanding the nature of chemical bonding is of the most fundamental importance in chemistry.¹ Our ability to describe and predict the reactivity and chemical and physical properties of molecules and chemical compounds is a derivative of what we know about chemical bonding. Therefore, any new data, refining and widening the frontiers of our knowledge of chemical bonding, are of paramount importance in the theoretical and practical aspects of current science of chemistry.²

The hydrogen bond, a bond bridging two electronegative atoms by a hydrogen atom, plays a very important role in biology,³ material science,⁴ and chemistry.⁵ In the past nearly 80 years, investigations of hydrogen bonds have yielded a great wealth of knowledge about various types and forms of hydrogen bonding phenomena.⁶ However, the most studied examples dealt with the $X-H\cdots Y$ (X, Y = O, N, S) type of relatively strong H-bonds, playing a significant role in biology. On the other hand, other types of rather weak H-bonds,⁷ involving, for instance, the C-Hbond as a H-bond donor, have been substantially much less studied. Thus, the $C-H\cdots E$ type of weak H-bond (E = electronegative atoms except for carbon), since it was proposed by Glasstone in 1937,8 is still one of the most long-standing contentions in organic chemistry. Taylor and Kennard most definitely presented two basic crystallographic characteristics of the weak $C-H \cdots E$ (E = O, N, Cl) H-bond based on systematic investigation of neutron diffraction crystal structures in 1982.9 In particular, the distance between the proton and the acceptor atom is shorter than the sum of their van der Waals radii, and the donor-proton-acceptor angle in a H-bond must be at least 90°.

Since their seminal work, a great number of compounds possessing C-H···E (E = O, N, S, F, Cl, Br, I, etc.) H-bonds have been discovered. One of the rare examples is the C-H···Cl H-bond, for which most of the reported examples (intra- and intermolecular) involve anionic Cl⁻¹⁰ Examples of the H-bond between C-H and covalent Cl are even rarer, and all involve Cl bonded to an aromatic ring.¹¹ In these cases, the corresponding H-bond is facilitated by the flat geometry of the aromatic ring and the unshielded steric position of the Cl atom. Thus, to the best of our knowledge, a particular case of a C-H···Cl H-bond involving an aliphatic Cl atom has never been reported.

In the course of our work on the chemistry of chiral 1,1,4,4tetrasubstituted butanetetraol¹² and its application for studying self-disproportionation of enantiomers *via* achiral chromatography,¹³ sublimation,¹⁴ as well as heterocomplexation crystallization,¹⁵ we designed and synthesized a C_2 chiral cyclic sulfite ester (4*R*,5*R*)-4,5-bis(diphenylchloromethyl)-1,3,2-dioxathiolane 2-oxide (2) via the reaction of (2*R*,3*R*)-1,1,4,4-tetraphenylbutanetetraol¹⁶ (3) with SOCl₂ (Scheme 1), and we found that selective 2,3-cyclosulfitation of (2*R*,3*R*)-3 preferentially occurred to form (4*R*,5*R*)-4,5-bis(diphenylhydroxymethyl)-1,3,2-dioxathiolane 2-oxide (4). Sequentially, the resulting (4*R*,5*R*)-4 was chlorinated step by step to furnish (4*R*,5*R*)-2. (4*R*,5*R*)-2 was dissolved in hot ethanol and then slowly cooled to afford single

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Scheme 1. Synthesis of (4R,5R)-2



Figure 1. Crystal structure of (4*R*,5*R*)-2 with numbering scheme.



Figure 2. Intramolecular $C-H\cdots Cl$ and $C-H\cdots O$ weak H bonds in a crystal of (4R,SR)-**2**. For clarity, only one set of data were labeled per weak H bond.

crystals suitable for X-ray crystallographic analysis.¹⁷ The crystal structure of (4R,5R)-2 is shown in Figure 1. The crystallographic data reveal that there are four molecules of (4R,5R)-2 in a unit cell. (4R,5R)-2 belongs to a typical orthorhombic system, with space group C222(1) but possesses several very complicated intramolecular and intermolecular H-bond networks.

Figure 2 depicts the intramolecular C-H···Cl and C-H···O (the 1,3,2-dioxathiolane ring) H-bonds in the crystal of (4R,5R)-2. It may be seen from Figure 2 that the distances from the Cl to *ortho*-C-H groups in the axial and equatorial phenyl planes are 2.562 Å and 2.804 Å, respectively, with the bond angles 108.41° for C_a-H-Cl and 96.53° for C_q-H-Cl, indicating that the chlorines at the aliphatic quaternary carbons participate in the



Figure 3. Intermolecular $C-H \cdots O$ H-bonds in a crystal of (4R,5R)-2. For clarity, the bond angle of the $C-H \cdots O$ and the $H \cdots O$ distance were separately written.

formation of a $C-H_{a}$ · · · Cl H-bond,¹⁸ and the bond intensity in the first case is higher. This is the first example of a clear intramolecular H-bond between the aliphatic chlorine and the C-H bond. While the distance-angle characteristics⁹ obtained for compound (4R,5R)-2 are undoubtedly pointing to the presence of a $C-H\cdots Cl-C$ hydrogen bond, we decided still to seek additional noncrystallographic evidence. In particular, in light of a conclusion made by Thallapally and Nangia¹⁹ on a rather difficult distinction between true C-H···Cl hydrogen bonds and merely van der Waals interactions, based only on crystal structure analysis, we decided to study the IR spectra of compound (4R,5R)-2. It is well-known that absorption of a C-Cl bond in IR spectra is found at a broad region of 800- 600 cm^{-1} , and most commonly at 750–700 cm^{-1.20} In the IR spectra of compound (4R,5R)-2, there is a strong absorption at the lower-than-usual wavenumber region of 615 cm⁻¹, corresponding to the C-Cl bond. One may agree that this result is in full agreement with the theoretical prediction, considering that in the case of the $C-H\cdots Cl-C$ hydrogen bond the charge density on the Cl atom is decreased as well as the strength of the C-Cl bond, resulting in IR absorption of the C-Cl bond shifted toward the low wavenumber region. Thus, the observed absorption of the C-Cl bond in the IR spectra of compound (4R,5R)-2 serves as additional, noncrystallographic evidence for the C-H···Cl-C hydrogen bond. The formation of C-H···Cl H-bonds would result in weakening of the C-H bond and strengthening of the Cl-C bond. Thus, it is estimated that both the stability of the C-Cl bond as well as the reactivity of the C-H bond are increased. This result perhaps can be a helpful guide in the design of a new type of catalysts for selective activation of aromatic C-H bonds.

In addition, it was also observed that the distance between another *ortho*-C–H of the equatorial phenyls and the oxygen of the 1,3,2-dioxathiolane ring is 2.493 Å, with bond angle 108.92°, indicating the existence of another intramolecular C–H_o···O (in the five-membered ring) H-bond. The above facts reveal that the aromatic *ortho*-C–H bonds can participate in the formation of the different types of intramolecular H-bonds.

Intermolecular C–H···O H-bonds also exist in the crystal of (4R,5R)-2. As seen in Figure 3, the distance from the oxygen of the S=O bond in one molecule of (4R,5R)-2 to the *meta*-C-H in the equatorial phenyl planes in the adjacent two molecules of (4R,5R)-2 is 2.59 Å, with a 159.57° angle; meanwhile, the same distance and angle exist between the *meta*-C–H in the equatorial



Figure 4. Molecular assmbly of crystalline (4R,5R)-2.



Figure 5. Electrostatic repulsive interactions in a crystal of (4R,5R)-2.

phenyl planes in (4R,5R)-2 and the oxygen of the S=O bond in the adjacent (4R,5R)-2 molecules. It quite agrees with the character of an intermolecular weak H-bond C-H···O (sulfinyl group).¹⁸ Thus, the (4R,5R)-2 molecules are self-assembling into an infinite, layered framework along the *c* axis through intermolecular C-H_m···O bonds (Figure 4).

Further examination of the crystallographic data showed that in (4R,5R)-2 the distance between Cl and the oxygen of the S=O bond is 3.328 Å, and the distances from the sulfur to the Cl_a and Cl_{1a} are 3.151 and 3.588 Å, respectively, meaning that there is an effective electrostatic repulsive interaction between the chlorine atoms and the atoms of the S=O group. Furthermore, interaction of Cl_a with the O of the S=O is stronger than that between the sulfur and either Cl (Figure 5). The electrostatic repulsive interactions change the space distribution of the substituted groups and increase the symmetry of the molecule, resulting also in a change of the bond lengths and bond angles in the ring.

As seen from Figures 1–5, the sulfur atom is located above the two equatorial phenyl planes and in the opposite direction to both the perpendicular phenyl planes. Therefore, the steric effect of the phenyl groups at C(4) and C(5) on the S=O bond is insignificant. On the other hand, Cl_{α} and $Cl_{1\alpha}$ are located above the two equatorial phenyl planes and, thus, almost symmetrically arranged on the two sides of the 1,3,2-dioxathiolane ring. Furthermore, both Cl atoms not only hinder the 1,3,2-dioxathiolane ring but also engaged in electrostatic repulsive interactions, making an additional effect on the reactivity of the



Scheme 2. (4R,5R)-2 Was Oxidized into the Corresponding

Sulfate Ester by Air O₂

five-membered ring. Therefore, (4R,5R)-2 is a more stable cyclic sulfite ester than its cyclic sulfite ester analogues, such as (4R,5R)-4-diphenylchloromethyl-5-diphenylhydroxymethyl-1,3, 2-dioxathiolane 2-oxide and (4R,5R)-4,5-bis(diphenylhydroxymethyl)-1,3,2-dioxathiolane 2-oxide as well as 2,3-ketone-protected chloro-substituted TADDOLs (where the C–Cl bond was readily broken by MeOH merely by simple crystallization from MeOH).²¹ In fact, it has been observed that (4R,5R)-2 does not undergo ring-opening and cleavage of the C–Cl bond in 2 M NaOH at room temperature, and it is easily oxidized by the oxygen in air into the corresponding sulfate ester (Scheme 2).

In summary, a molecule possessing an intramolecular H-bond between the Cl atom, bonded to an aliphatic carbon, and an aromatic C—H has been discovered for the first time in a C_2 chiral cyclic sulfite ester, (4R,5R)-4,5-bis(diphenylchloromethyl)-1,3,2-dioxathiolane 2-oxide [(4R,5R)-2]. In this molecule, there also is another type of intramolecular H-bond C—H···O (the dioxathiolane ring) as well as electrostatic repulsive interactions between the Cl atoms and the S=O group. Combination of these intramolecular H-bonds and electrostatic interactions may result in very unusual reactivity of compound 2, which is currently under investigation and will be reported in due course.

ASSOCIATED CONTENT

Supporting Information. The preparative procedure, spectra, and CIF data for (4*R*,5*R*)-**2**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(17) Final atomic coordinates of the crystal for (4*R*,5*R*)-2, along with lists of anisotropic thermal parameters, hydrogen coordinates, bond lengths, and bond angles, have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. 759035. Data can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, U.K. (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.cn; web: http//www.ccdc.cam.ac.uk).

(18) The van der Waals radii for C, H, O, and Cl are 1.72, 1.10, 1.40, and 1.80 Å (Pauling, L. *The nature of the chemical bond*), respectively. In (4*R*,5*R*)-2, the distances between the Cl and the *ortho*-H's of the axial and equatorial phenyl planes are 2.562 Å and 2.804 Å, respectively, being shorter than the sum (2.90 Å) of the van der Waals radii for H and Cl. On the other hand, the angles for C_a —H—Cl and C_q —H—Cl are 108.41° and 96.53°, respectively. These data are true of the two basic crystallographic characteristics of the C—H···E weak H-bond presented by Taylor and Kennard.⁹ Similar crystallographic characteristics of the intramolecular C—H_o···O (the 1,3,2-dioxathiolane ring) and intermolecular C—H_m···O (the S=O) weak H bonds were also observed.

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