Structural studies on Mannich bases of 2-Hydroxy-3,4,5,6-tetrachlorobenzene. An UV, IR, NMR and DFT study. A mini-review☆

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ABSTRACT

Mannich bases of 2-Hydroxy-3,4,5,6-tetrachlorobenzene are chosen as an exemplary case for tautomeric Mannich bases. Molecular structures are calculated. OH stretching frequencies are rationalized based on DFT calculations. Intrinsic deuterium isotope effects on ^{13}C chemical shifts in the M-form are estimated based on OH bond lengths. The observed deuterium isotope effects on ^{13}C chemical shifts are demonstrated to be largely of equilibrium type except at ambient temperatures.

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1. Introduction

Mannich bases (MB) play an important role in hydrogen bond research as a model for non-resonance intramolecular hydrogen bonds that show tautomerism. The controlling factors for proton transfer in tautomeric systems are particularly interesting. Tautomerism can be studied by UV, IR and isotope effects on chemical shifts in solution often supported by density functional theory (DFT) calculations. A key system is provided by the Mannich bases of 3,4,5,6-tetrachlorophenol (those formed with dimethylamine or diethylamine are in the following abbreviated Cl_4MBdm (**1**) or Cl_4MBde (**2**), respectively). Excellent reviews by Koll and Wolschann [1–3] and Sobczyk [4,5] exist in which this system is considered.

Quantum chemical calculations are especially useful for tautomeric systems with fast interconversion as both tautomers usually cannot be isolated. DFT calculations may therefore provide information about structures, NMR chemical shifts and IR vibrations of both tautomers.

2. Results and discussion

2.1. Structure

Cl_4MBdm (**1**) can exist in two tautomeric forms as seen in Fig. 1. This is also true for Cl_4MBde (**2**). The calculated structure of the molecular form (M-form) of (**1**) is seen in Fig. 2; a distinct feature is the twist of the OH group out of the aromatic ring plane, as seen in the view to the left.

In case of the proton transfer form (PT-form) X-ray structures shows the presence of a dimer in the solid state [4]. For the 3,4,6-trichloro compound (**4**) a dimer has been demonstrated at low temperature in a freon solution [6] and one may assume this will also be the case for the tetrachloro compound in solution.

2.2. UV spectroscopy

The UV spectrum of Cl_4MBde (**2**) at different temperatures is given in Fig. 3 [7].

It is clearly seen that a new species is appearing at low temperature. This is assigned to the PT-form [5]. The red shift is consistent with the formation of a moiety containing a phenolate group as seen by titration of a Mannich base [8].

2.3. Infrared spectroscopy

A very large collection of IR spectra of MB was investigated with emphasis on the OH stretching vibrations (νOH). The νOH bands
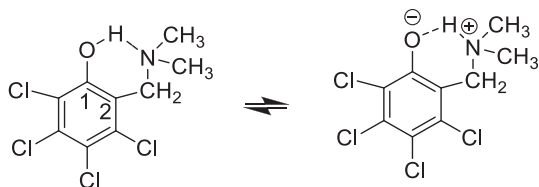

Fig. 1. Structure of Cl₄MBdm (**1**) including tautomerism.
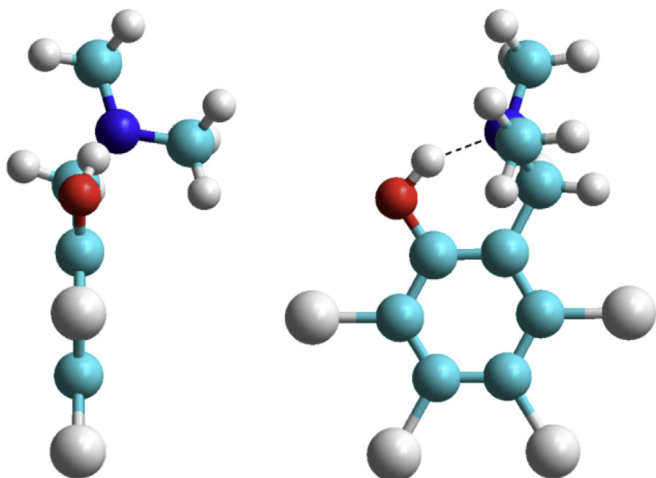

Fig. 2. Calculated structure of the molecular form of Cl₄MBdm (**1**) seen from two different angles.
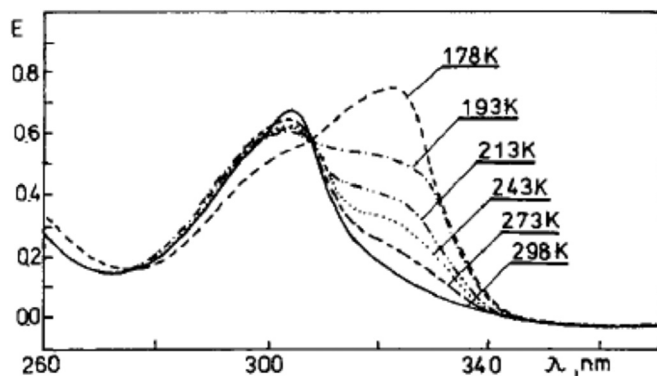

Fig. 3. UV spectrum of Cl₄MBde (**2**) at different temperatures in CH_2Cl_2 taken from Ref. [7]. (Reproduced with permission from Elsevier).

turn out to be both broad and very intense [9]. Compounds covering both electron withdrawing and electron donating substituents were included. The OH stretching frequencies were compared to those of the corresponding complex between the phenol and the amine. A clear cut change appeared for ΔpK_a around 3. ΔpK_a is defined as the pK_a difference between that of the phenol and that of the ammonium ion (see later). IR spectra of Cl₄MBdm as well as of the deuterated species have also been investigated in matrix isolation spectra in an argon matrix. A ratio of 1.33 is found between νOH and νOD [10]. In addition, IR spectra have been recorded in *n*-butylchloride [5]. These spectra showed a broad hump from 2500 cm⁻¹ to 1600 cm⁻¹. This was suggested as being due to Zundel bands. However, a similar hump was not observed for

the 4-nitroderivative [2]. A very distinct difference is seen between IR spectra of MB in the liquid and the solid state for cases with ΔpK_a larger than 4. This difference can be attributed to the presence of the PT form in the solid [4].

Theoretical calculations of OH stretching frequencies have been performed for both the 2,4-dichloroMB and Cl₄MBdm. Although using a scaling factor of 0.95, a good fit for the B3LYP/6-31++G(d,p) model was not obtained [10] Following the suggestion of Refs. [11,12] OH stretching frequencies have been calculated using the B3LYP model [13] with the 6-31G(d) basis. As this basis set is rather small, the calculations have been checked with a larger basis set, cc-pVTZ. The B3LYP results for the compounds **1**–**11** (Table 1) with the 6-31G(d) and cc-pVTZ basis sets are found to be linearly related:

$$\nu OH(cc-pVTZ) = -83.933 + 1.0416 \cdot \nu OH(6-31G(d)) \quad \left(SD = 9.25 \text{ cm}^{-1}, \ R = 0.99787 \right)$$

The experimental OH stretching wavenumbers are plotted vs. the B3LYP/6-31G(d) results in Fig. 4 and a very good correlation is found. It must be pointed out that the calculations are performed in vacuum. However, the IR spectra are recorded in a very low dielectric medium, either in CCl₄ (**4**–**10** [9]) or in an argon matrix (**11** and **1** [10]). The equation of Fig. 4 allows a prediction of experimental OH stretching frequencies.

Looking at the calculated structure (Fig. 2) it is seen that the OH group is twisted ~15° out of the aromatic ring plane. This twist is the same using basis sets like 6-31G(d) or G-311++(d,p). A twist of this kind has led to a low OH chemical shift in e.g. 1-acetyl-2-hydroxynaphthalene and similar compounds [14]. This is not the case in the Mannich bases. Furthermore, the hydrogen bond potential is asymmetric judging from the ratio between νOH and νOD (see above). Comparing the Cl₄MB with a piperidine (**3**) or a diethylamine base (**2**), respectively, the calculated OH bond lengths B3LYP/6-31G(d) (1.0085 vs. 1.0097 Å) and the calculated stretching frequencies (3065 cm⁻¹ vs. 2968 cm⁻¹) are different. Experimentally this is demonstrated in the tri-chloroderivatives. This difference can possibly be related to differences in base strength as the pK_a values are 11.26 and 11.02, respectively, for piperidine and diethylamine. In that case the difference in OH stretching frequencies can possibly be explained by the differences in the calculated O … N distances, 2.634 vs. 2.640 Å, respectively or it can be related to the solvent reaction field [15]. Steric strain was found

Table 1
Calculated compounds.

	R	R₁	R₂	R₃	R₄
1	CH_3	Cl	Cl	Cl	Cl
2	C_2H_5	Cl	Cl	Cl	Cl
3	Piperidino	Cl	Cl	Cl	Cl
4	Ethyl	Cl	Cl	H	Cl
5	Piperidino	Cl	Cl	H	Cl
6	CH_3	H	CH_3	H	CH_3
7	Piperidino	H	Cl	H	H
8	Morpholino	H	OCH_3	H	H
9	Pyrrolidino	H	Br	H	H
10	CH_3	H	NO_2	H	H
11	CH_3	H	Cl	H	Cl
12	CH_3	H	Cl	H	H