# Thiol−Thione Tautomerism in Thioformic Acid: Importance of Specific Solvent Interactions

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Attempts have been made to resolve a discrepancy in the recent literature concerning the thiol−thione tautomerism of monothioformic acid. Whereas Kato et al. (*J. Am. Chem. Soc.* **1996**, *118*, 1262) reported that the thione acid [RC(=S)OH] exists predominantly in polar solvents at very low temperatures, Jemmis et al. (*J. Phys. Chem. A* **1997**, *101*, 7389) found, from ab initio calculations including continuum treatments of the solvent effect, that the thione forms HC(=S)OH and $CH_3C(=S)OH$ are less predominant, irrespective of the solvent polarity. However, both groups of authors have suggested specific solvation as a possible reason for the discrepancy and called for further studies. Indeed, the present work points out that specific interactions between polar and aprotic solvent molecules such as dimethyl ether and tetrahydrofuran and H atoms of the carboxylic function, giving strong hydrogen bonded O−H···O complexes, are likely to tip the balance in favor of the thione acids. This fact is supported by calculations carried out using ab initio molecular orbital methods [HF, MP2, CCSD(T)] and density functional theory (B3LYP) with the 6-31G** and 6-311++G** basis sets. The results presented here show that the continuum solvent effect does not significantly modify the gas phase thermodynamic stability. In addition, the stability of the cyclic dimeric forms has been examined, suggesting the thiol form is still the most stable, although the greatest stabilization occurs in the thione form. Overall, hydrogen-bonded interactions in O−H···O complexes are stronger than in S−H···O complexes and thus play a crucial role in stabilizing the thione isomers. Specific solute−solvent interactions appear to play a key role in the thiol−thione equilibrium and need to be considered in similar cases.

## Introduction

Proton exchange in ketones, amides, peptides, and proteins is of fundamental importance in the reactivity of organic, heterocyclic, and biochemical compounds as well as in enzymatic catalysis and spontaneous mutation.[1] Systems such as vinyl alcohol−acetaldehyde and 2-hydroxypyridine−2-pyridone are among the most studied models for the prototypic tautomerism shown in eq 1, in which X and Y involve a variety of heteroatoms.[2,3]

(1)

Numerous earlier studies[4] concluded that the equilibrium (eq 1), involving formally a 1,3-shift of the hydrogen, strongly depends on the environment. Thus, the predominant form in solution could be different from that in the gas phase or in the crystalline state. Tautomerism of thiocarboxylic acids where X, Y = O, S in eq 1, has been studied on a number of occasions in part due to the important role that the −C(=O)S− and −C(=S)O− functionals play in the catalytic activities of enzymes such as cysteine or serine proteases.[5] It may be useful here to give a brief overview of the results available for monomeric thioformic acid (referred to hereafter as MTFA), the simplest thiol−thione tautomeric system. UV, IR, and proton NMR spectra[6] indicated that MTFA exists preferentially in the thiol form [HC(=O)-SH]. A subsequent microwave study[7] also suggested the thiol form to be the most stable and revealed in addition its presence in both syn and anti conformers. The syn−anti isomerization has further been established by IR[8,9] and NMR[10] spectroscopic studies. From a theoretical point of view, several studies[11−20] on MTFA using ab initio MO calculations confirmed the predominance of the thiol acid in the gas phase. In general, it appears that the syn thiol is the more stable conformer; the relative abundance is roughly 1:3 in the gas phase at room temperature in favor of the syn thiol form. The barrier to rotation amounts to 40 kJ/mol and is shown to be strongly affected by the solvent effect (in $CD_2Cl_2$ solutions).[9,10]

Regarding the effect of the medium on the tautomeric equilibrium (eq 1), Kato and co-workers[21] have recently deduced, on the basis of IR and NMR spectra, a reversed stability ordering in substituted compounds. Whereas Kato et al.[21] reported that the thione acid [RC(=S)OH] exists predominantly in polar solvents at very low temperatures, Jemmis and co-workers[19] found from ab initio calculations, including continuum treatments of the solvent, that the thione forms HC(=S)OH and $CH_3C(=S)OH$ are less predominant irrespective of the solvent polarity. The latter authors[19] found that solvents with various dielectric constants up to $\epsilon = 35.9$ are not effective on the thermodynamic stabilities, in contrast with earlier experimental observations.[21]

To resolve such a discrepancy, an attempt has been made to take another look at the problem by considering a more active aspect of the solvent effect. As a matter of fact, in many cases[22−24] the solvent should not be regarded as a passive continuum having only a global electrostatic influence on the solute; solvent molecules may be able to intervene in the chemical transformation as coreactants and/or catalysts. In this

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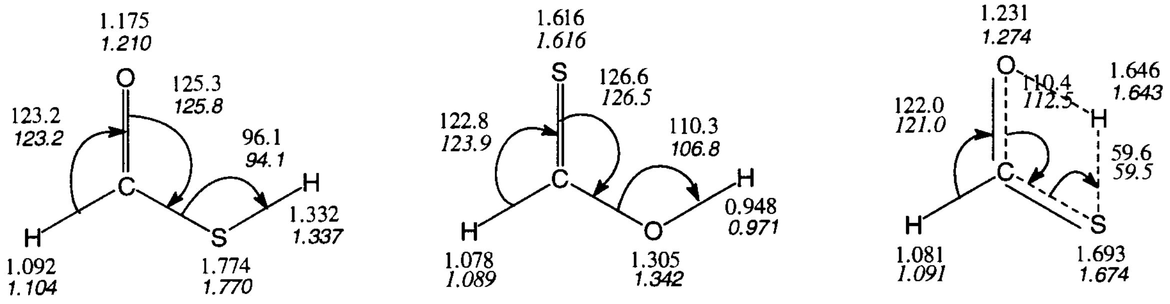


(1) (2) (3)

**Figure 1.** Optimized geometries in the gas phase. The entries are HF and *MP2* in italics, all with the 6-311++G** basis set.

regard, Kato et al.[21] have already suggested that the higher stability of the thione acids arises from a stronger interaction between an O−H bond and the polar solvent molecules, but this fact was not investigated any further. In the theoretical treatment of Jemmis et al.[19] the authors have in fact not considered the solute−solvent specific interactions. However, they have noticed the discrepancy and again suggested that the hydrogen bond interactions between HC(X)YH and the polar molecules of the solvent may control the thermodynamic equilibrium of these chalcogenoformic acid derivatives.[14]

Therefore, in the present work, particular attention has been paid to the specific interactions between the thiocarboxylic functions and polar solvent molecules. When the solvent was regarded as an active participant in the reaction, it was found that these specific interactions indeed play an important role in the thiol−thione tautomerism. Moreover, the stability of the cyclic and alternative dimeric forms has also been examined, indicating that without specific solvation the thiol remains the more stable form.

## Methods of Calculation

All quantum chemical calculations were performed using the Gaussian 94[25] suite of programs. In the gas phase, we distinguish MTFA monomer and its complexed structures with dimethyl ether as well as its cyclic and alternative dimers. For molecular orbital calculations on monomer structures, the methods considered include second-order perturbation theory (MP2), quadratic configuration interaction [QCISD(T)], and coupled-cluster theory [CCSD(T)] in conjunction with the 6-31G** and 6-311++G** basis sets. Density functional calculations were also carried out on the monomers using the hybrid B3LYP functional for exchange and correlation, together with the basis sets mentioned above. The calculations on the structures complexed with dimethyl ether were performed at both HF and MP2 levels with the 6-311++G** basis set. The electronic energies of the dimers were obtained from calculations at the HF, MP2, and B3LYP (for cyclic dimers) levels of theory using both mentioned basis sets on geometries fully optimized at the corresponding levels. The analytic harmonic vibrational frequency calculations were done to characterize the nature of stationary points on the potential energy surface and also to estimate the zero-point vibrational energies (ZPEs).

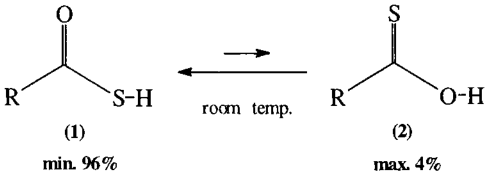
After the tautomeric equilibrium in the gas phase was studied, the effect of the solvent on the structure and the relative stabilities at the tautomeric equilibrium has been analyzed. Both active and passive solvent effects were considered. Active solvent effects are approached by using a microscopic model. The purpose is to quantify the specific interactions between both solute and solvent molecules. We have therefore constructed a supermolecule, built of the gas phase monomer structure together with a solvent molecule, and performed quantum chemical calculations on this supermolecule. We have considered dimethyl ether ($CH_3OCH_3$) as a model to mimic tetrahydrofuran (THF), which was effectively employed in the experiment of Kato et al.[21] Passive solvent effects are subsequently treated by a macroscopic continuum model that describes mainly the electrostatic influence of the bulk solvent on a solute. The solvent is thus approached by a homogeneous continuum, characterized by its dielectric constant $\epsilon$. The solute is placed in a cavity, imbedded in the continuum. In the present work, the simple self-consistent reaction field method (SCRF) has been used to model the global influence of the solvent. Note that throughout this paper, relative energies and ZPE are given in kilojoules per mole, bond lengths in ångstroms, and bond angles in degrees.

## Results and Discussion

All of the MTFA structures considered in this paper are in their syn conformation because the latter are more stable than the corresponding anti conformers, and moreover, they have the right nuclear position for the tautomeric rearrangement (Figure 1). We are mainly concerned with the portion of the potential energy surface containing two minima (the tautomeric thiol and thione forms), as well as the transition structure connecting them by a 1,3-H shift.

**(A) Unimolecular Rearrangement.** The process involving the MTFA monomer has been repeatedly investigated and abundantly commented on in earlier studies.[11−14] Here we mention briefly the main results obtained in this work.

*(A1) Gas Phase 1,3-H Shift.* Relative energies (REs) of both isomeric forms as well as the barrier height of the 1,3-H shift, calculated at different levels of theory, are given in Table 1. For the sake of simplicity in the presentation, the total and zero-point energies are omitted. Note that ZPE corrections are included in the RE values. All methods (HF, post-HF, and DFT) give a similar trend, showing that the thiol form **(1)** is ~20 kJ/mol more stable than the thione form (**2**). This is in agreement with experimental observations[9] in the gas phase as shown in eq 2 and with numerous earlier theoretical studies. It seems that



(2)

the stability of the tautomeric forms is determined by their bond energies as well as by the degree of electron delocalization. As the double bonding between carbon and oxygen is energetically

**TABLE 1: Relative Energies (in Kilojoules per Mole) Including ZPE[a] Corrections for both Thiol and Thione Forms as Well as the Transition Structure Connecting Them**

| method[b] | basis set | HCOSH (thiol) | HCSOH (thione) | TS |
|---|---|---|---|---|
| HF$_{(opt)}$ | 6-31G** | 0 | 16 | 190 |
| B3LYP$_{(opt)}$ | 6-31G** | 0 | 13 | 127 |
| MP2$_{(opt)}$ | 6-31G** | 0 | 13 | 131 |
| QCISD$_{(opt)}$ | 6-31G** | 0 | 16 | 147 |
| HF$_{(opt)}$ | 6-311++G** | 0 | 24 | 193 |
| B3LYP$_{(a)}$ | 6-311++G** | 0 | 19 | 134 |
| MP2$_{(opt)}$ | 6-311++G** | 0 | 20 | 132 |
| MP4sdtq$_{(b)}$ | 6-311++G** | 0 | 25 | 135 |
| QCISD(T)$_{(b)}$ | 6-311++G** | 0 | 22 | 138 |
| CCSD$_{(opt)}$ | 6-311++G** | 0 | 23 | 151 |
| CCSD(T)$_{(c)}$ | 6-311++G** | 0 | 21 | 139 |

[a] ZPEs scaled by 0.9 at the HF level and by 0.963 at the B3LYP level. [b] (opt), based on geometry optimized at the level indicated; (a), based on B3LYP/6-31G** geometry; (b), based on MP2/6-311++G** geometry; (c), based on CCSD/6-311++G** geometry.

**TABLE 2: Overview of Dielectric Constants at Different Temperatures**

| solvent | temp °C | dielectric constant $\epsilon$ |
|---|---|---|
| water | 20 | 80.4[a] |
|  | 25 | 78.5[a] |
| dimethyl ether | −120 | 12.0[b] |
|  | 20 | 7.9[b] |
|  | 25 | 5.0[a] |
| tetrahydrofuran (THF) | 1 | 8.9[c] |
|  | 20 | 8.2[c] |
|  | 40 | 7.6[c] |

[a] Weast, R. C. *Handbook of Chemistry and Physics*; CRC Press: Boca Raton, FL, 1989−1990. [b] Wong, M. W.; Frisch, M. J.; Wiberg, K. B. *J. Am. Chem. Soc.* **1991**, *113*, 4776; **1992**, *114*, 523, 1645. [c] Hill, N. E. *Proc. R. Soc. London* **1957**, *A240*, 101.

**TABLE 3: Relative Energies of the Stationary Points in the Thiol−Thione Interconversion without and with Specific Interactions of Dimethyl Ether, both in Gas Phase and Surrounded by a Solvent Continuum Modeled by an SCRF Method (Kilojoules per Mole, Including ZPE[a] Corrections)**

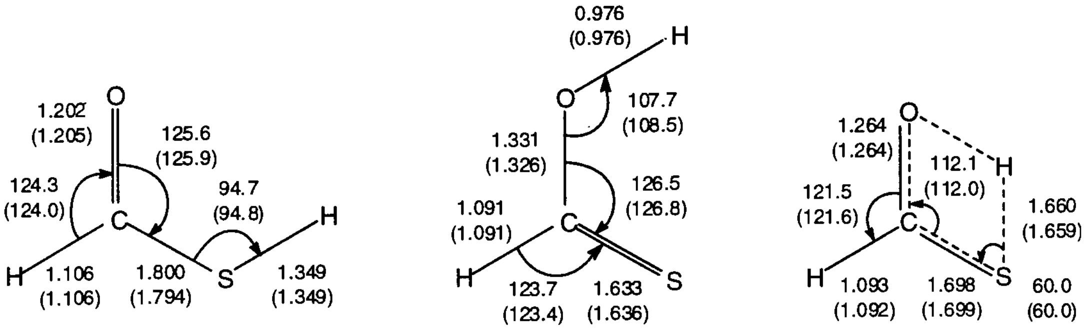
| method[b] |  | gas phase $\epsilon = 1$ | solvent $a_0$[c] | solvent $\epsilon = 5$ | solvent $\epsilon = 10$ | solvent $\epsilon = 80$ |
|---|---|---|---|---|---|---|
|  | Unimolecular Rearrangement |  |  |  |  |  |
| HF/6-31G** | HCOSH **(1)** | 0 | 3.35 | 0 | 0 | 0 |
|  | HCSOH **(2)** | 16 | 3.54 | 15 | 14 | 14 |
|  | TS | 190 | 3.43 | 191 | 191 | 191 |
| B3LYP/6-31G** | HCOSH **(1)** | 0 | 3.35 | 0 | 0 | 0 |
|  | HCSOH **(2)** | 13 | 3.43 | 12 | 12 | 12 |
|  | TS | 127 | 3.46 | 127 | 127 | 128 |
| MP2/6-311++G** | HCOSH **(1)** | 0 | 3.38 | 0 | 0 | 0 |
|  | HCSOH **(2)** | 20 | 3.43 | 20 | 21 | 21 |
|  | TS | 132 | 3.49 | 132 | 133 | 133 |
|  | Rearrangement with Specific Interactions of Dimethyl Ether |  |  |  |  |  |
| HF/6-31G**$_{(opt)}$ | thiol−$(CH_3)_2O$ **(I)** | 0 | 4.21 | 0 | 0 | 0 |
|  | thione−$(CH_3)_2O$ **(II)** | −2 | 4.31 | −3 | −4 | −4 |
|  | ts−$(CH_3)_2O$ **(III)** | 196 | 4.15 | 195 | 195 | 195 |
| HF/6-311++G**$_{(opt)}$ | thiol−$(CH_3)_2O$ **(I)** | 0 | 4.32 | 0 | 0 | 0 |
|  | thione−$(CH_3)_2O$ **(II)** | 7 | 4.19 | 5 | 5 | 4 |
|  | ts−$(CH_3)_2O$ **(III)** | 197 | 4.19 | 197 | 197 | 197 |
| MP2/6-311++G**$_{(a)}$ | thiol−$(CH_3)_2O$ **(I)** | 0 | 4.32 | 0 | 0 | 0 |
|  | thione−$(CH_3)_2O$ **(II)** | −2 | 4.19 | −4 | −5 | −5 |
|  | ts−$(CH_3)_2O$ **(III)** | 138 | 4.19 | 138 | 138 | 139 |

[a] ZPEs scaled by 0.9 at the HF level and by 0.963 at the B3LYP level. [b] (opt), based on geometry optimized at this level; (a), based on HF/6-311++G** geometry. [c] Radius of spherical cavity (in ångstroms).

more favorable than the one between carbon and sulfur, **1** is stabilized by ∼42 kJ/mol relative to **2**. This difference, however, is offset by the larger resonance energy of the thione form (**2**). The barrier height for the 1,3-H shift amounts to ∼140 kJ/mol with respect to the thiol form. It is worth noting that the results derived from the DFT/B3LYP treatment are quite close to high-level post-HF methods such as QCISD(T) or CCSD(T).

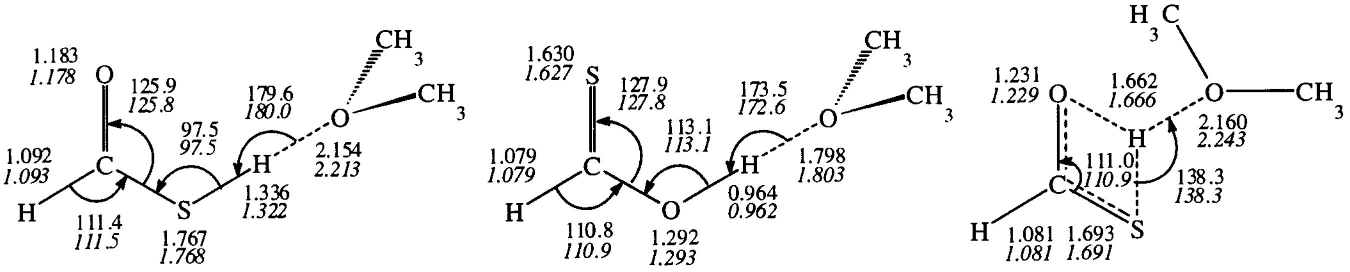
*(A2) Continuum Effect on Relative Stability and 1,3-H Shift Barrier Height.* To estimate the electrostatic influence of the solvent on the solute behavior, an SCRF method has been used.[26] The main reason for the choice of this model is to simplify the theoretical treatment and to avoid the practical restrictions in using the microscopic model (involving a restricted number of solvent molecules) due to our limited computational resources. In the SCRF model, the solute is placed in a spherical cavity immersed in a continuum with a dielectric constant $\epsilon$. A polarization in the molecule will induce a polarization in the medium, and the electric field applied to the solute by the polarized solvent will in turn interact with the molecular multipole to lead to net stabilization. A disadvantage of this model is that the spherical cavity is not always realistic. Moreover, only dipolar moments of the electronic distribution of the solute are taken into account. Nevertheless, this method seems to be a good guide in indicating trends.[26] To understand the effect of the dielectric medium on the intramolecular, tautomeric equilibrium, we have considered different dielectric constants having values of 80, 10, and 5. From Table 2, it can be seen that these values are temperature dependent, increasing for a solvent when the temperature decreases. The chosen values correspond to those of water and dimethyl ether as solvents. The dielectric constant of dimethyl ether is similar to that of THF. It seems that dimethyl ether is a realistic model for THF, which is a common solvent for organic molecules, from both viewpoints of dielectric constants and electronic structures. The only parameters necessary for an SCRF calculation are the dielectric constant and the radius of the spherical cavity in which the solute is placed. The radius is estimated by means of the solute molar volume. The SCRF energy calculations and optimizations were performed at both HF and B3LYP levels using the 6-31G** basis set. Due to the lack of analytical gradients, the geometry could not be optimized in solvent at the MP2 level of theory; therefore, only single-point SCRF calculations were performed on the MP2 gas phase geometries using the 6-311++G** basis set. The results reported in Table 3 show that there is practically no change either in REs or in barrier height with respect to the gaseous phase situation. The effect of the electrostatic interactions between solute and solvent continuum is negligible. These conclusions are in agreement with the ones reported by Jemmis et al.[19] in their theoretical study of the tautomeric rearrangements of a larger sample of mono- and dichalcogenide analogues of formic acid.

*(A3) Geometries of the Monomer Structures.* As mentioned above, geometrical parameters of the monomer structures were determined using the MP2, QCISD, CCSD, and B3LYP methods along with the d,p-polarized 6-31G** basis set. The B3LYP method appears to provide the values closest to the CCSD ones. Figure 2 shows the B3LYP/6-31G** geometries of the monomeric structures calculated in the gas phase and in a solvent continuum by means of an SCRF method ($\epsilon = 80$, polar solvent). Usually, the electrostatic influence of the polarized solvent modifies the electron distribution in the solute structure and thereby its geometry. However, it turns out that the electrostatic, or the so-called "passive", solvent effects are negligible. The molecular geometry of the structure under consideration, either the minimum or the transition structure



**(1)** **(2)** **(3)**

**Figure 2.** Optimized geometries calculated in the gas phase, as well as surrounded by a solvent continuum ($\epsilon = 80$) using the SCRF method. The entries are B3LYP and (SCRF−B3LYP), all with the 6-31G** basis set.



**(I)** **(II)** **(III)**

**Figure 3.** Selected optimized geometries calculated at the HF level of MTFA complexed with dimethyl ether. The entries are 6-31G** basis set and *6-311++G*** basis set in italics.

(TS) for the 1,3-H shift, change only marginally even in highly polar solvent.

**(B) MTFA Structures Complexed with Dimethyl Ether.** In a polar solvent such as dimethyl ether, hydrogen-bonded interactions usually occur between the solvent and solute molecules. These interactions are called here specific solvent interactions. A crucial question is to which extent the thiol−thione forms can be stabilized by specific interactions and thereby which consequences are seen in the tautomeric equilibrium (eq 1). As stated above, specific solvent interactions were simulated by a simple microscopic discrete model considering a supermolecule built of a solute and an interacting solvent molcule. The optimized supermolecules are given in Figure 3. Because the hydrogen-bonded interactions also induce a change in the charge distribution, the influence of the continuum on the relative stability of the complexed structures was considered as well. First, calculations were performed at the HF level using the 6-31G** and 6-311++G** basis set. These calculations confirm the necessity of diffuse functions for a correct description of hydrogen bonds. Therefore, MP2 calculations were subsequently done using the larger 6-311++G** basis set.

*(B1) Relative Energies.* The REs of both tautomeric forms and TS complexed with dimethyl ether given in Table 3 point out that, in the gas phase, both complexed forms become similarly stable. The reason for a stabilization of the thione isomer is the stronger specific interaction in the O−H···O complex (**II**) in comparison with that in the S−H···O (**I**). As a consequence, the stabilization energy in the thione complex (**II**) is ~20 kJ/mol higher than in the thiol complex (**I**), as can be seen from Table 3. Concerning the transition structure for the 1,3-H shift, despite extensive attempts, we were not able to locate a true TS using full geometry optimization. The structure (**III**) could only be located with a fixed SHO angle. The purpose for such a constraint is to obtain a quantitative evaluation of the stabilization on the TS. After all, no large stabilization seems to occur upon complexation. Within the constraint, the activation energy is in fact increased by ~6 kJ/mol relative to the thiol form (Figure 4). If the continuum solvent effect is taken into account, it is found that the electrostatic interactions further enforce the relative stability of the thione form (**II**). The latter becomes now 5 kJ/mol more stable than the thiol form (Table 3). This is qualitatively in agreement with the experimental observation of Kato et al.[21]

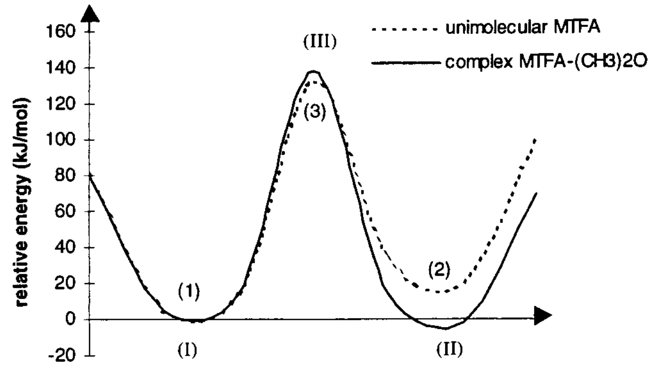
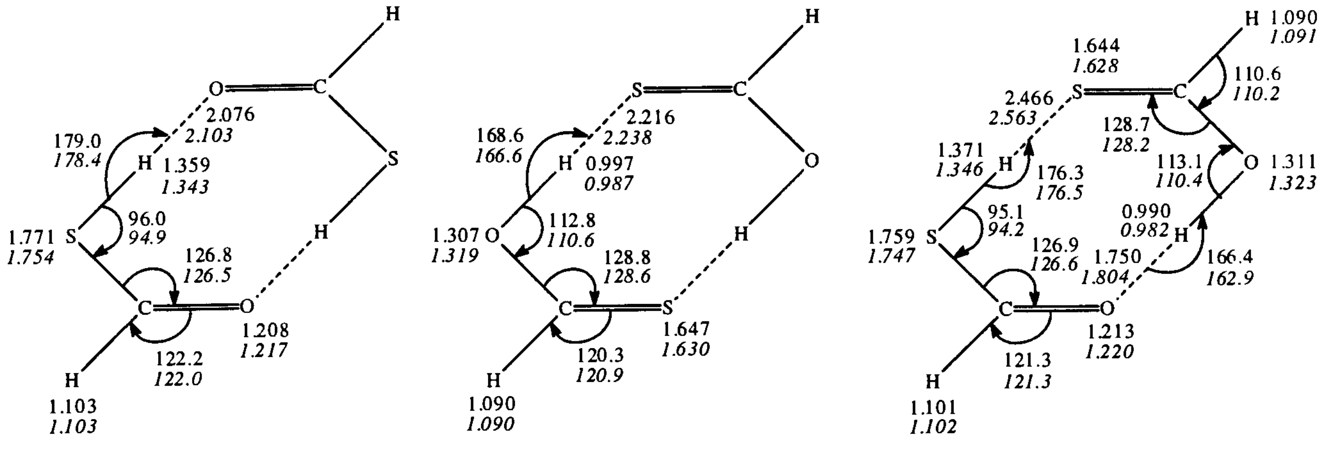


**Figure 4.** Relative stability of monomeric MTFA in the gas phase versus structures complexed with dimethyl ether. Calculations performed at the MP2/6-311++G** + ZPE level of theory.

*(B2) Geometries.* It seems worthwhile to consider in some detail the important changes in geometrical parameters in going from the monomer MTFA structures (Figure 2) to those complexed with dimethyl ether (Figure 3).

*(B2a) Thiol Form.* While the C=O bond length increases by 0.003 Å, both C−S and S−H bond lengths decrease by 0.006 and 0.010 Å, respectively, as a result of the S−H···O interaction. The OCS and CSH bond angles become, respectively, 0.5° and 1.4° larger.



**(1c)** **(2c)** **(1-2c)**

**Figure 5.** Selected optimized geometries of three cyclic dimer structures; **c** stands for cyclic. The entries are B3LYP and *MP2*, all with the 6-311++G** basis set.

**TABLE 4: Relative Energies of Three Cyclic Dimers of MTFA (in Kilojoules per Mole, Including ZPE[a] Corrections)**

| method | thiol dimer (**1c**) | thione dimer (**2c**) | thiol−thione dimer (**1**−**2c**) |
|---|---|---|---|
| HF/6-31G** | 0 | 18 | 4 |
| MP2/6-31G** | 0 | 17 | 6 |
| B3LYP/6-31G** | 0 | 8 | 0 |
| HF/6-311++G** | 0 | 36 | 14 |
| MP2/6-311++G** | 0 | 27 | 13 |
| B3LYP/6-311++G** | 0 | 21 | 8 |

[a] ZPEs scaled by 0.9 at the HF level, by 0.945 at the MP2 level, and by 0.963 at the B3LYP level. Geometries for all structures were fully optimized at the HF, MP2, and B3LYP levels.

**TABLE 5: Complexation Energies of Three Cyclic Dimers Considered (in Kilojoules per Mole, Including ZPE[a] Corrections)**

| method | thiol dimer (**1c**) | thione dimer (**2c**) | thiol−thione dimer (**1**−**2c**) |
|---|---|---|---|
| HF/6-31G** | −18 | −31 | −29 |
| MP2/6-31G** | −32 | −40 | −39 |
| B3LYP/6-31G** | −29 | −48 | −42 |
| HF/6-311++G** | −17 | −28 | −25 |
| MP2/6-311++G** | −27 | −42 | −35 |
| B3LYP/6-311++G** | −22 | −39 | −33 |

[a] ZPEs scaled by 0.9 at the HF level, by 0.945 at the MP2 level, and by 0.963 at the B3LYP level. Geometries for all structures were fully optimized at the HF, MP2, and B3LYP levels.

*(B2b) Thione Form.* The specific O−H···O interaction leads to an increase of 0.011 and 0.014 Å for C=S and O−H bond lengths, respectively. A decrease of 0.012 Å is calculated for the C−O bond length. The SCO and COH bond angles become, respectively, 1.2° and 2.8° larger.

*(B2c) TS Form.* As mentioned above, it is important to note that the OHS angle was kept constant (138.3°) due to the difficulty encountered in the optimization process. Although the structure shown is not a full stationary point, the energy change in this saddle region is quite small. In any case, the C−O and the C−S bond lengths seem almost unaffected. The S−H bond length increases 0.020 Å as a result of the electrostatic interaction where an OCS angle becomes 0.5° larger. The changes in geometry are somewhat greater in the thione form than in the thiol one. This supports the indication that the O−H···O interaction is stronger than the S−H···O one.

**(C) Dimeric Structures.** Another interesting possibility to deal with is that of the self-association of the tautomeric species. In fact, it is well-known that carboxylic acids exist in dimeric forms. In MTFA, the S−H···O, O−H···S, S−H···S, and O−H···O types of bonds could be formed and also affect the tautomeric equilibrium. To study this problem, we distinguish cyclic and alternative dimers in which each time three different associations were considered. In this way we obtain, respectively, the thiol dimer, the thione dimer, and the thiol−thione dimer.

*(C1) Cyclic Dimers.* Figure 5 displays the geometries of three possible cyclic dimers, and Tables 4 and 5 summarize their REs and complexation energies.

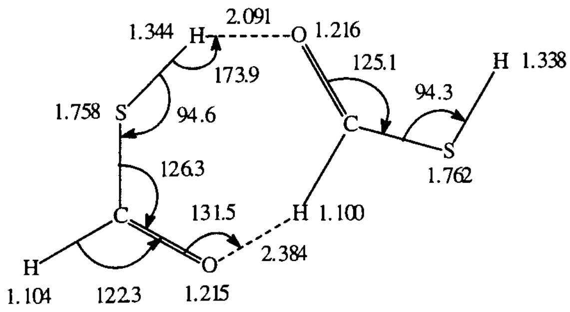
*(C1a) Relative Energies.* The results obtained at the MP2/6-311++G(d,p) + ZPE level point out that the thiol dimer (**1c**) becomes 27 kJ/mol more stable than the thione dimer (**2c**) and 13 kJ/mol more stable than the thiol−thione dimer (**1**−**2c**). This is in contrast with the stabilization energy (Table 5), which is 15 kJ/mol greater in the thione dimer (**2c**) and 8 kJ/mol greater in the thiol−thione dimer (**1**−**2c**) in comparison with that in the thiol dimer (**1c**). This is an indication that the O−H···S interactions are stronger than the S−H···O ones. Owing to intrinsic stability of the thiol form against the thione form, the thiol dimer remains by far the most stable form.

*(C1b) Geometries.* The changes in bond lengths and bond angles in going from the monomer structures (Figure 2) to the cyclic dimeric structures (Figure 5) are mentioned below.

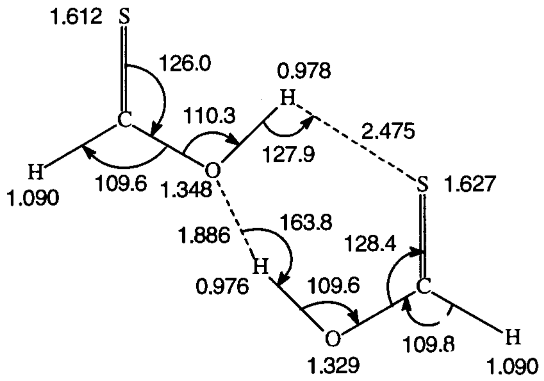
*(C1b1) Thiol Dimer (1c).* The C=O and S−H bond lengths increase by 0.007 and 0.006 Å, respectively, as a result of the S−H···O interactions. The C−S bond length decreases by 0.016 Å, and the OCS and CSH bond angles become 0.7° and 0.8° larger, respectively.

*(C1b2) Thione Dimer (2c).* By analogy with the thiol dimer, the O−H···S interaction leads to an increase in the C=S and O−H bond lengths by 0.014 and 0.016 Å, respectively. Here the C−O bond length decrease is 0.023 Å and the SCO and COH angles become, respectively, 2.1° and 3.8° larger.

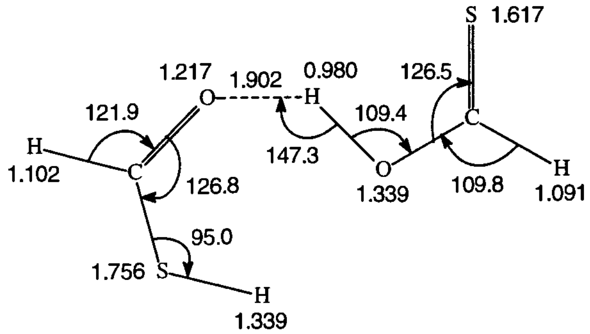
*(C1b3) Thiol−Thione Dimer (1−2c).* Here we distinguish two different monomeric forms. In the thiol form the C=O bond length increases by 0.010 Å as a result of the O−H···O interaction. Similarly, the S−H bond length increases by 0.009 Å as a result of the S−H···S interaction. The C−S bond length decreases by 0.023 Å, and the OCS and CSH bond angles increase marginally by 0.8° and 0.1°, respectively. Otherwise, in the thione form the C=S bond length increases by 0.012 Å.



**(1a)**



**(2a)**



**(1-2a)**

**Figure 6.** Selected optimized geometries of the alternative dimer structures calculated at the MP2 level with the 6-311++G** basis set. With zero-point corrections, the complexation energies amount to −24, −31 and −29 kJ/mol for **1a**, **2a**, and **1**−**2a**, respectively.

The O−H bond length increases by 0.011 Å, whereas the C−O bond length decreases by 0.019 Å and the SCO and the COH angles increase by 1.7° and 3.6°, respectively.

Overall, the geometrical parameters alter more significantly in the following order: thiol dimer < thiol−thione dimer < thione dimer. This provides a further indication that the O−H···S interactions are stronger than the S−H···O interactions, whereas the S−H···S and O−H···O interactions are situated in between.

*(C2) Alternative Dimers.* Figure 6 displays three alternative dimers **1a**, **2a**, and **1**−**2a** of MTFA. The difference in stability between these dimers is more pronounced than in the cyclic dimers discussed above. The thiol dimer **1a** becomes 34 kJ/mol more stable than the thione dimer **2a** and 15 kJ/mol more stable than the thiol−thione dimer **1**−**2a** [values at MP2/6-311G++(d,p) + ZPE]. This can be easily explained by the fact that the complexation energy of the thione dimer **2a** amounts now only to 7 kJ/mol more than in the thiol **1a**. This is about half of the difference in the cyclic dimer **1c** and **2c**. The difference in complexation energies between both thiol−thione and thiol dimers is less altered as compared with the cylic dimer and amount now to 5 kJ/mol.

The greater stabilization of the cyclic dimers **1c** and **2c** is consistent with the low-temperature infrared results reported earlier by De Scicastro and Sandorfy,[27] who showed that only the cyclic structures remain at the lower temperatures, even though the possibility of having alternative structures is more likely at intermediate temperatures.

## Concluding Remarks

A theoretical study has been performed on the influence of the solvent on the thiol−thione tautomeric equilibrium of MTFA. Both forms convert into each other by a 1,3-hydrogen shift. Particular attention was focused on specific solvent effects. These were assessed by constructing supermolecules formed by a solute molecule and a model solvent molecule, namely dimethyl ether.

The most interesting chemical result is that in a polar and aprotic solvent, specific interactions between solute and solvent molecules resulting in strong molecular complexes play an important, if not crucial, role in the control of the thermodynamic equilibrium. Concerning complexes of MTFA with dimethyl ether, the hydrogen-bonded interactions in O−H···O complexes of thione acid are consistently stronger than S−H···O complexes of thiol acid and tip thus the balance in favor of the thione form. Such a shifting of the equilibrium is in agreement with the experimental observations in THF by Kato et al.[21] These results also point out the need for considering specific interactions in the understanding of similar phenomena. It would also be interesting to study theoretically the substituent effect by investigating thiocarboxylic acid as well, bearing groups such as methyl (thioacetic acid) or phenyl, because the spectroscopic measurements[21] were carried out with large R groups such as R = 4-$CH_3OC_6H_4$.

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