

Pyrrole Anion Addition To Carbon Disulfide: An Ab Initio Study

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ABSTRACT: The reaction pathways of pyrrole-1- and pyrrole-2-carbodithioate anions formation were studied using the MP2/6-31+G* approach. No activation barrier was found on the potential energy surface for the former. By contrast, there is a significant activation barrier on the C2-adduct formation pathway. This can cause a kinetic formation of the thermodynamically less favorable N-adduct from unsubstituted pyrrole and CS₂, while a relative instability of 2(5)-methylpyrrole-1-carbodithioates results in C2- and C3-adducts. © 2004 Wiley Periodicals, Inc. *Int J Quantum Chem* 100: 360–366, 2004

Key words: ab initio calculations; carbon disulfide; pyrrole-1(2)-carbodithioates; pyrrole anion; reaction mechanism

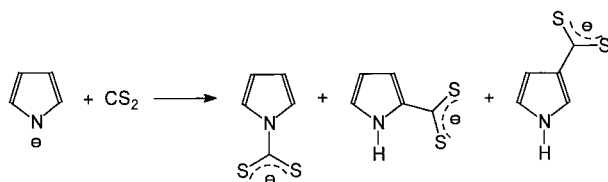
Introduction

Reactions of pyrrole anions with electrophiles are widely used in syntheses of pyrrole derivatives. In particular, pyrroles react with carbon disulfide in superbases media, such as potassium hydroxide solution in dimethyl sulfoxide (KOH/DMSO), forming pyrrolecarbodithioates [1–10], the compounds of a poorly studied class that

look attractive for both biologic and synthetic purposes (Scheme 1). Pyrrole anions in this reaction act as polydent nucleophiles. The unsubstituted pyrrole yields the N-adduct only [1, 3], whereas 2-alkylpyrroles regioselectively form 2-alkylpyrrole-5-carbodithioates [4–8], and the presence of alkyl groups in both 2 and 5 positions controls the reaction toward 3(4) adduct formation [9–11].

Our previous studies of the 1-, 2-, and 3-adducts of CS₂ with mono- and dimethylsubstituted pyrrole anions [11–13] have shown that the thermodynamic stability of the N-form decreases sharply under 2(5) substitution because of the steric hindrances. These results elucidate the substituent effect on the preferable formation of 1-, 2-, or 3-adducts. Neverthe-

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SCHEME 1.

less, the MP2/6-31+G* calculations predict the pyrrole-2-carbodithioate anion to be the most stable isomer, whereas the reaction of CS₂ with unsubstituted pyrrole in the superbase KOH-DMSO system yields pyrrole-1-carbodithioate only. The goal of this work was the study of pyrrole-1- and -2-carbodithioates formation pathways to rationalize the preferable formation of the thermodynamically less stable isomer.

Computational Methods

The potential energy surface (PES) sections were obtained using the restricted Hartree-Fock (RHF) method [14], as well as the Møller and Plesset [15, 16] second-order perturbation theory (MP2) with correlation effects included. The RHF/6-31+G* and MP2/6-31+G* optimization of stationary points was carried out using the GAMESS [17] program. The number of negative Hessian eigenvalues was checked for all the stationary points found. The connection of the transition states with corresponding minima was proved with following the intrinsic reaction coordinate (IRC) using Gonzalez and Schlegel technique [18]. The density functional theory (DFT) calculations with a hybrid Becke's three-parameter exchange functional and the gradient-corrected functional of Lee, Yang, and Parr (B3LYP) functional [19, 20] and the same 6-31+G* basis set were performed using the Gaussian-94 program [21]. Löwdin charges were used to examine charge distribution instead of Mulliken charges, which are less reliable in the extended basis sets.

Results and Discussion

The carbon disulfide molecule, being attacked by the N-position of the pyrrole anion, forms the pyrrole-1-carbodithioate anion (**1**). The RHF/6-31+G* calculations predict this process to be exothermic by 41.72 kcal/mol, the MP2/6-31+G* and B3LYP/

6-31+G* calculated values are 32.23 kcal/mol and 33.11 kcal/mol, respectively. The RHF and MP2 calculated equilibrium N-C(S₂) distances, 1.416 Å and 1.425 Å, are in close agreement, whereas the DFT approach predicts a larger distance, 1.451 Å.

Figure 1 shows the reaction profiles of the 1-adduct formation. The system considered keeps the C_{2v} symmetry along the entire path from reactants (isolated CS₂ and pyrrole anion) to product **1**. All the approaches used indicate the minimum **2** corresponding to the ion-molecular complex in the N-C(S₂) distance region of 3.0–3.5 Å. The stabilization energy of **2** was found to be 2.35 kcal/mol and 1.58 kcal/mol in the RHF and DFT calculations, respectively, whereas the MP2 method predicts a much higher value of 7.84 kcal/mol. Both pyrrole anion and CS₂ molecule in **2** keep their atomic charges (see Figure 1) as well as bond lengths and bond angles, except the ∠SCS bond angle distorted by ≈2.5° when calculated in RHF and MP2 and by 0.8° in the DFT optimized structure.

The RHF approach predicts the 4.94 kcal/mol activation barrier for this complex rearrangement toward **1** and the overall 2.59 kcal/mol activation barrier on the reaction pathway. We are inclined to relate this barrier to the significant charge redistribution required when a carbon disulfide molecule forms the 1-adduct with a pyrrole anion (see Fig. 1). Indeed, in the neutral CS₂ molecule sulfur atoms have a positive charge and the carbon atoms are charged negatively, which prevents the CS₂ and pyrrole anion drawing together. In the final **1** sulfur atoms got negative charges. By contrast, no activation barrier occurs for the CO₂ molecule interaction with a pyrrole anion to form pyrrole-1-carboxylate, despite higher vibration frequency of O-C-O bending when compared with that of S-C-S (667.06 cm⁻¹ and 389.34 cm⁻¹ obtained in our MP2/6-31+G* calculations with a scale factor [22] of 0.89; 673.02 cm⁻¹ and 398.62 cm⁻¹ found experimentally [23] for CS₂ and CO₂, respectively).

The MP2 calculations also indicate similar transition state **3** on this reaction profile. However, the energy of **3** is by 6.79 kcal/mol less than that of reactants. Both the RHF and MP2 approaches reveal minima that correspond to initial ion-molecular complexes; the inner barrier of ≈5 kcal/mol found in the RHF calculations reduces to 1.15 kcal/mol when correlation effects are included on the MP2 level of theory. Finally, the DFT approach (B3LYP/6-31+G*) indicates a plate in the range of N-C distances. Again, the transition state energy is less than that of reactants, and the inner activation bar-

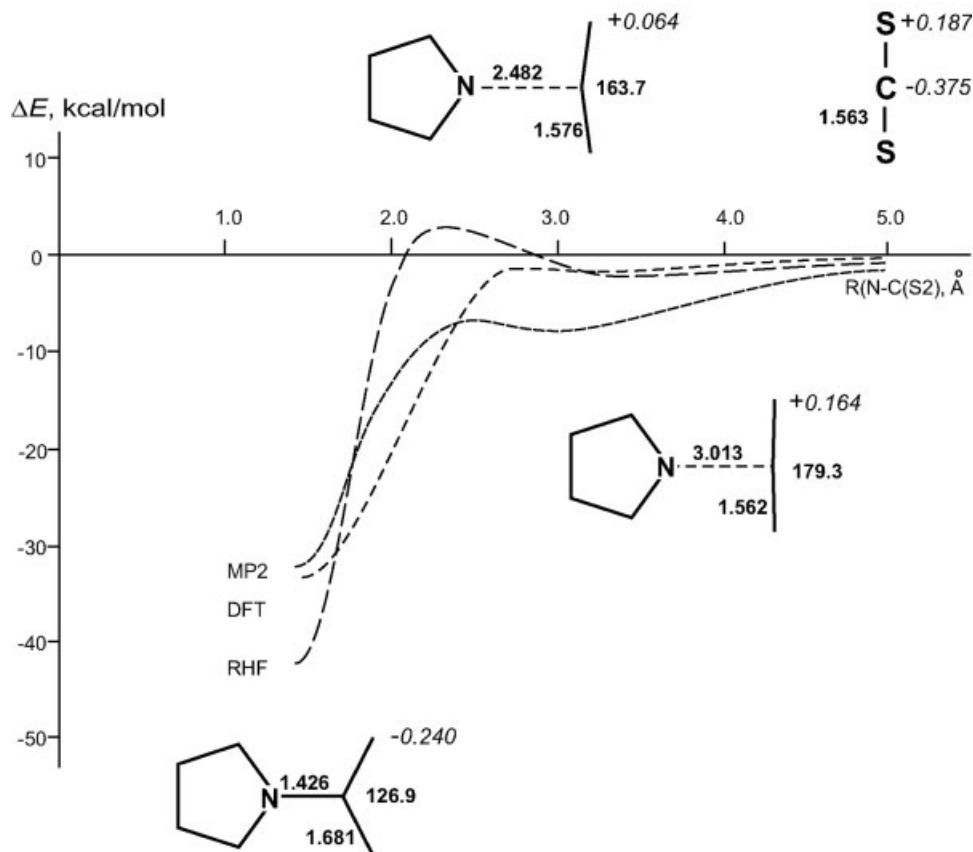


FIGURE 1. The RHF/6-31+G*, MP2/6-31+G* and B3LYP/6-31+G* reaction profiles of pyrrole-1-carbodithioate formation. The MP2/6-31+G* distances (Å), bond angles (°), and Löwdin charges (a.u.).

rier in the B3LYP/6-31+G* calculation is as small as 0.31 kcal/mol. These results suggest that the pyrrole-1-carbodithioate formation occurs with no activation barrier. The opposite takes place in the pyrrole-2-carbodithioate formation reaction.

The attack to the CS_2 molecule with the pyrrole anion C2 position results in π -complex **4** formation (see Fig. 2). One should note a specific orientation of the CS_2 molecule in this complex caused by the charge distribution mentioned above. The MP2/6-31+G* calculations display a marked stability of the π -complex relative to isolated CS_2 and pyrrole anion: the total energy decreases by 14.08 kcal/mol when this structure is formed.

The classic σ -complex **6** is by 1.22 kcal/mol less stable than **4** in the MP2/6-31+G* calculation, but it is still favorable as compared with reactants by 12.86 kcal/mol. The large part of the excess negative charge in **6** is concentrated on sulfur atoms, the most charged S being the most distant from nitro-

gen center (see Fig. 2). Reorganization of the π -complex **4** into σ -complex **6** passes through the transition state TS1 (**5**; see Fig. 2), and the activation barrier for the π -complex conversion into the σ -complex was found to be 8.48 kcal/mol. However, this barrier is by 5.60 kcal/mol less than the π -complex dissociation energy.

The farther transformation of **6** should provide a hydrogen atom transfer toward the N-position of the ring. Several ways could be suggested for this process, including mechanisms with a gegenion participation. However, the specific cation solvation is characteristic of KOH/DMSO media [24, 25]; hence, here we consider the intramolecular isomerization only.

Variation of the C2-H distance and optimization of the rest structural parameters reveals the hydrogen atom tends to move towards the nearest and the most negative sulfur atom rather than nitrogen one. Hence, further transformation of the σ -com-

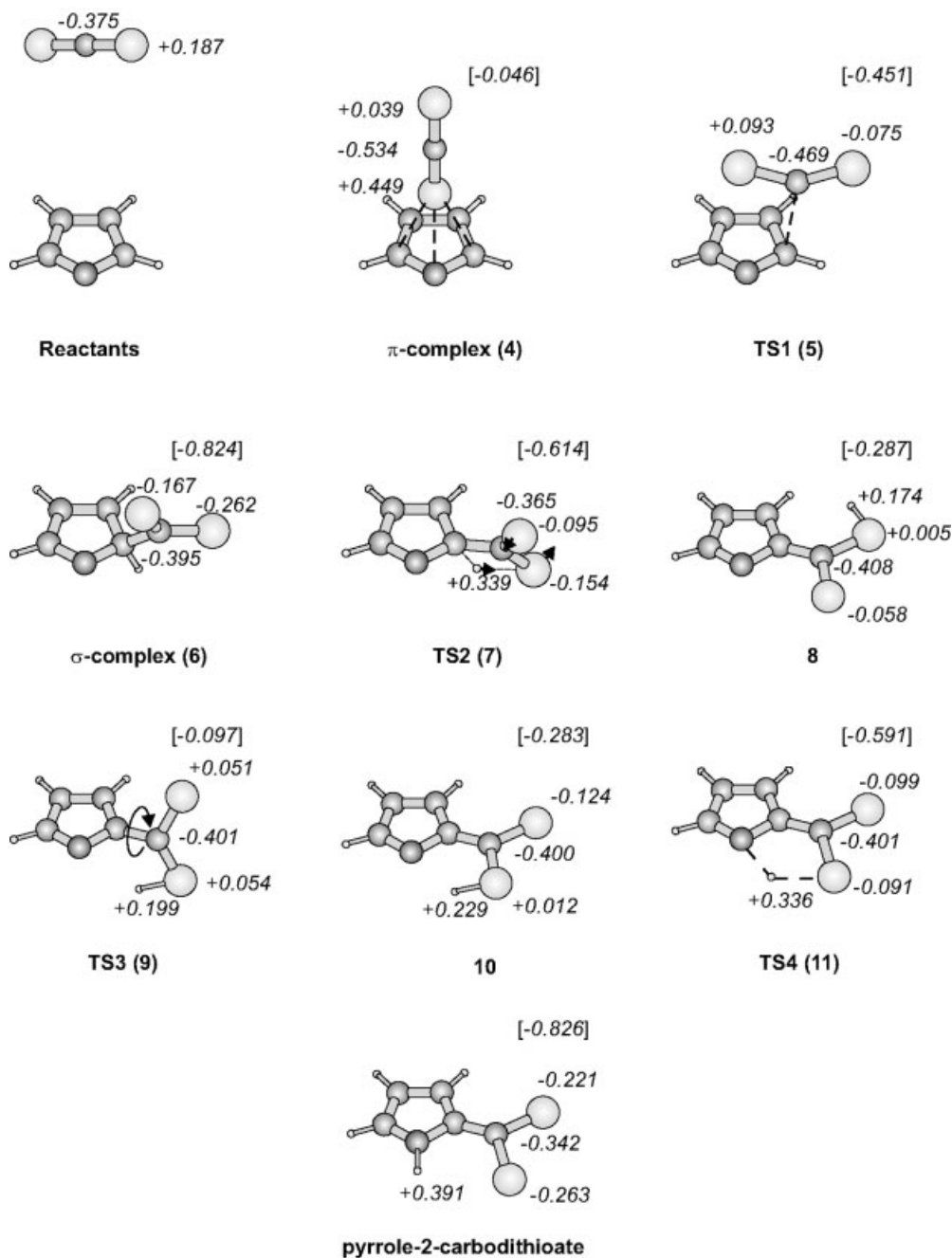


FIGURE 2. Characteristic structures of the pyrrole-2-dithioate formation profile. Löwdin atomic charges (a.u.) and total CS₂ charge (in brackets).

plex is associated with the C-H bond cleavage and the S-H bond formation and results in the structure 8 (see Fig. 2) that is by 4.83 kcal/mol more stable than the σ -complex 6. The transition state TS2 (7) connects these two minima, and the MP2 calculated activation barrier for this transformation is 29.67 kcal/mol. Moreover, the energy of the transition

state 7 exceeds the energy level of reactants by 16.87 kcal/mol.

The transformation discussed brings to the structure 8. A migrating hydrogen atom 8 is positioned distant from the nitrogen atom. The other structure 10 with this hydrogen atom close to nitrogen center is by 8.16 kcal/mol more stable. Such a marked



SCHEME 2.

energy difference among these conformers is quite natural with regard to the charge distribution in **8** and **10** (see Fig. 2). The repulsion of two negative charged centers N and S cause a relative instability of **8**, while the larger distance between these centers results in less repulsion in **10**. An additional stabilization of **10** may be caused by the interaction of the pyrrole nitrogen atom with the proton of CSSH group. Nevertheless, we could find no pathway for the direct transformation of the σ -complex **6** to this structure.

With regard to a considerable thermodynamic preference of **10**, one could expect the less stable conformer **8** to rearrange readily toward **10** by rotation over the C–C(S₂) ordinary bond. However, this rotation requires the extremely high activation energy of 11.50 kcal/mol. Such a marked rotational barrier evidences the importance of the conjugation effects (Scheme 2) in the stabilization of pyrrolecarbodithioate anions. Indeed, in the transition state TS3 (**9**; see Fig. 2), the negative charge of carbodithioate group decreases by 0.190 a.u. when compared with **8** and by 0.186 a.u. with respect to **10**. The C–C(S₂) bond lengthens from 1.426 Å in **8** to 1.466 Å in **9** and shortens again to 1.428 Å in **10**.

The hydrogen atom transfer from CS₂ group to the N atom through a transition state TS4 (**11**; see Fig. 2) accomplishes the formation of pyrrole-2-carbodithioate anion. This process is exothermic by 11.54 kcal/mol, but the only 5.40 kcal/mol activation barrier accompanies the cleavage of the S–H bond of the –CS₂H group and simultaneous formation of the N–H bond.

The results obtained give rise to the description of the pyrrole-2-carbodithioate formation as a sequential process, where the hydrogen transfer toward the carbodithioate group SC₂ is a limiting stage (see Fig. 3). The overall activation energy calculated in the MP2/6-31+G* approach is 16.87 kcal/mol. Such a significant activation barrier can cause a kinetic preference of the less stable pyrrole-1-carbodithioate formation, inasmuch as the latter exothermic by 32.23 kcal/mol process requires no activation energy.

Introduction of alkyl group to the 2 position results in destabilization of pyrrole-1-carbodithioates due to the steric interactions. The N–C bond in 2-methylpyrrole-1-carbodithioate weakens by 5.78 kcal/mol as compared with that in pyrrole-1-carbodithioate, and the N-adduct becomes unfavorable by 11.28 kcal/mol relative to 2-methylpyrrole-5-carbodithioate. Hence, 2-alkylpyrrole anions react with CS₂, yielding 5-adducts.

The same effect in 2,5-dialkylpyrroles makes 2,5-dialkylpyrrole-1-carbodithioates substantially unfavorable even compared with the 2,5-dialkylpyrrole-3-carbodithioates. Indeed, the energy of 2,5-dimethylpyrrole-1-carbodithioate formation from the corresponding anion and CS₂ falls to 17.50 kcal/mol, whereas the formation energy of 2,5-dimethylpyrrole-3-carbodithioate calculated in the MP2/6-31+G* is 24.43 kcal/mol. So, 2,5-dialkylpyrroles react with carbon disulfide, yielding 2,5-dialkylpyrrole-3-carbodithioates only.

Conclusions

The pyrrole anion addition to carbon disulfide molecule was studied using the MP2/6-31+G* approach. Both N-position attack, the most common for pyrrole anions, and C2 addition, yielding the most stable isomer, were considered.

The reaction profiles obtained indicate no activation barrier on the pathway of the pyrrole anion attack to carbon disulfide by nitrogen center. On the contrary, the C2 addition yielding pyrrole-2-carbodithioate appears a multistage process with marked activation energy. These might cause a predominant kinetic formation of pyrrole-1-carbodithioate from unsubstituted pyrrole, because that reaction occurs with no activation barrier and the energy of product is by only 5.25 kcal/mol higher than that of pyrrole-2-carbodithioate. The N–C bond formed is strong enough to resist rearrangement to the most stable 2-adduct. Introduction of the methyl group in the 2-position weakens the N–C bond and increases the energy gap between the 1- and 2-adducts. These result in selective formation of 2-methylpyrrole-5-carbodithioate from 2-methylpyrrole under the same condition. Finally, the steric hindrance in 2,5-dimethylpyrrole dramatically decreases the N-adduct stability by, and directs the CS₂ addition towards, 2,5-dimethylpyrrole-3-carbodithioate formation.

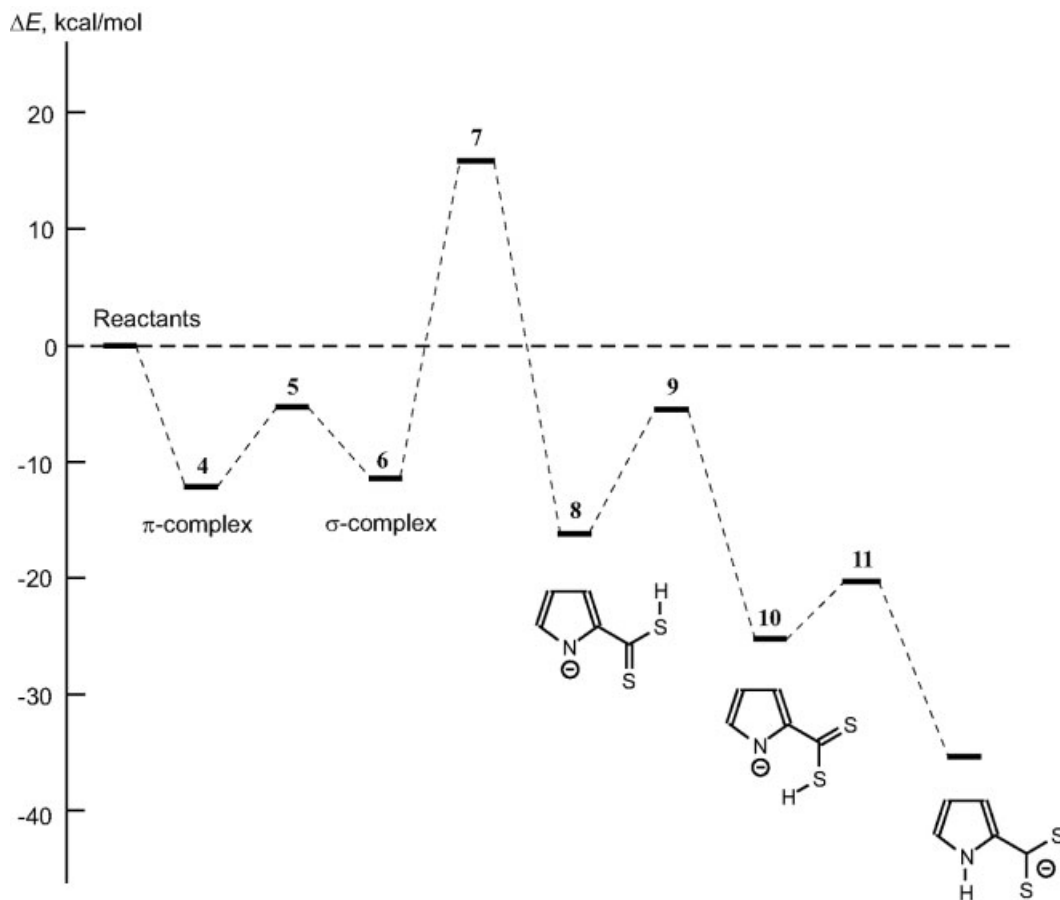


FIGURE 3. Pyrrole-2-carbodithioate formation profile (MP2/6-31+G*).

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