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DFT Study of the Nucleophilic Addition of Water to Ketenes

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The geometries of the different stationary points of reactants, products, and transition states of the nucleophilic addition of water to cyanoketene and methylcarboxyketene have been identified by optimizing every degree of freedom by density functional theory at the B3LYP/6-31++G** level of theory. The computational results for methylcarboxyketene in both the gas and solvated phase agree with the explanation based on experimental data, according to which the nucleophilic addition of water or alcohols to ketenes obtained from malonates (in our case represented by methylcarboxyketene) occurs by a concerted pseudopericyclic mechanism. The results of the calculations also agree with the experimental data for addition to cyanoketene. This reaction occurs through a zwitterionic intermediate, but in contrast to the previous reaction the solvent is essential for the process to occur.

Introduction

Among the wide variety of reactions employed in organic chemistry to build up an organic synthesis procedure, the acylation of water or alcohol with carboxylic acids or their derivatives is one of the most commonly used. The mechanism of this reaction is strongly dependent on the type of carboxylic derivative, the nature of the alcohol, and the experimental conditions. Thus, the acylation reaction is very sensitive to steric factors; high yields are obtained with unhindered alcohols, but the yield drops drastically when sterically hindered alcohols are involved in the reaction. As a result, much effort has gone into finding a suitable solution to the problem of acylation of tertiary alcohols in organic synthesis.

Recently, Shelkov et al.[1] proposed an efficient mechanism for the acylation of alcohols (including tertiary alcohols) via ketene intermediates. Owing to steric hindrance in the transition state, most conventional mechanisms for the acylation of sterically hindered substrates lead to a tetrahedral intermediate; this issue is particularly important when tertiary alcohols are considered. Shelkov et al. found that the acylation of tertiary alcohols with carboxylic acids having a strong electron-withdrawing substituent in the α position gives high yields. They proposed ketenes as highly reactive intermediates in these reactions as they have quite an exposed carbon atom which causes them to have a very low sensitivity towards steric factors. In their study, the authors suggested two possible mechanisms for the reaction of these ketenes with alcohols: a stepwise addition reaction with the formation of a zwitterionic intermediate and a concerted bimolecular (pseudopericyclic) mechanism that usually proceeds through a six-membered transition state. The two pathways will yield different reaction rates and Shelkov et al. suggested that each of them will occur depending on the ketene substituents.

Recently, Tidwell revised the importance of the ketene chemistry of the last century in an essay[2] and a microreview.[3] Several authors have studied the addition of different molecules to different ketenes. Thus, Sánchez-Andrada et al.[4] described the addition of HF, H_2O, H_2S, NH_3, and HCN to different heterocumulenes, including a ketene. Nguyen and co-workers[5,6] studied the hydration of a ketene and ketene imine pointing out the importance of including several water molecules in the calculations. The energy barriers to the different mechanisms of hydration of ketenes were also determined by Duan and Page[7] in their study of the decomposition of acetic acid and by Skancke[8] in his study of the hydration of ketenes. Birney and coworkers performed ab initio studies[9,10] on the addition of water, formaldehyde, and ammonia to formylketene which supported the existence of a pseudopericyclic mechanism for these addition reactions. However, no comparison has been made between the pseudopericyclic mechanism and other mechanisms for the nucleophilic addition of water or alcohols to ketenes. In order to make this comparison and to illuminate the issue proposed by Shelkov et al. we have performed a quantum chemical study considering the dif-

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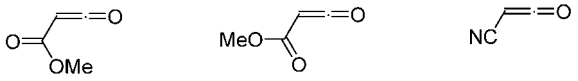
ferent possible mechanisms for the nucleophilic addition to ketenes. In this study we have employed water instead of an alcohol to save computation time (preliminary calculations show no significant differences). The ketenes used in this study are shown in Scheme 1: methylcarboxyketene (**1**) (MeK) and cyanoketene (**2**) (CyK). The former was used as a suitable model to represent ketenes obtained from malonates.



1a **1b** **2**

Scheme 1.

Results and Discussion

Figure 1 shows the minima obtained for the two studied ketenes. Two different conformations are given for MeK; although we found four different minima for this compound, in Figure 1 we represent the two most stable minima as only these are involved in the studied reactions. The energy difference between the two conformations is 0.54 kcal/mol with **1a** being the most stable.

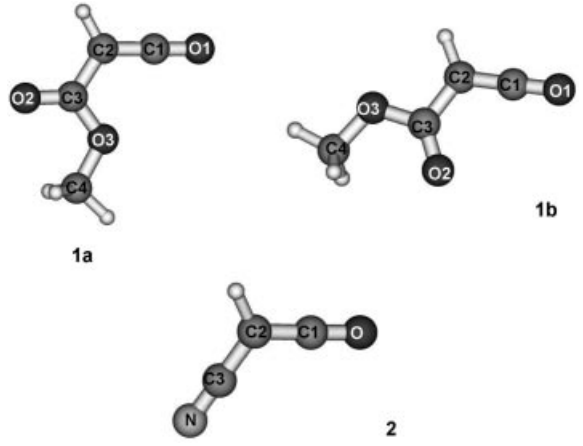
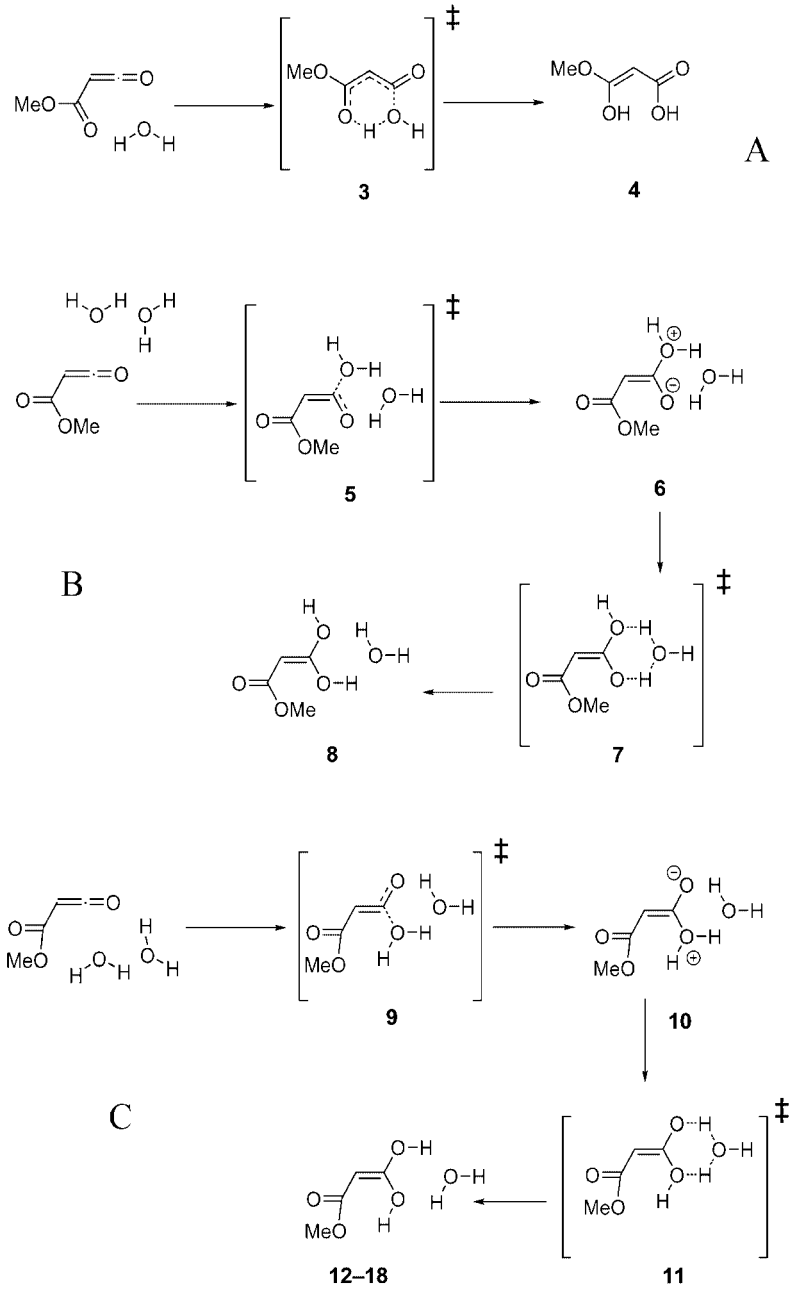


Figure 1. Geometry of the methylcarboxyketene and cyanoketene minima at the B3LYP/6-31++G** level of theory.

The commonly accepted mechanisms for the nucleophilic addition of water or alcohols to ketenes is a stepwise[5,16,17] addition via the formation of a zwitterionic intermediate (pathways B, C and E, F in Scheme 2 and Scheme 3, respectively) and a concerted mechanism[5,18] with a six-membered transition state involving ketene atoms C1 and C2 (looking for a similar mechanism the closest we found was pathway G). However, the presence of strong electron-withdrawing groups, as we have in the ketenes we have studied, stabilizes the zwitterionic compound[19] and favors the stepwise pathway. On the other hand, the nucleophilic addition of alcohols (or water) to acylketenes (like MeK) has a very high reactivity.[20] These reactions occur by a concerted bimolecular mechanism involving a six-membered ring that includes the ketene atoms C1, C2, C3, and O2 (pathway A; the analogous mechanism for CyK is pathway D). Based on these evidences together with the high reactivity of the ketenes obtained from malonates and the existence of steric factors, Shelkov et al.[1] postulated that ketenes derived from malonates (or carboxylic acids) follow a pseudopericyclic mechanism whereas other ketenes with withdrawing-electron groups (like CyK) react through a stepwise pathway involving a zwitterion. In order to study the possible mechanisms for the nucleophilic addition of water to ketenes, several searches were conducted to identify the different transition states of the reactions studied; the starting geometries were chosen using chemical knowledge. In Figure 2, Figure 3, and Figure 4 we present the transition states and intermediates found for the reactions studied.

The geometries of the different transition states in the gas phase found for the possible mechanisms for the addition of water to MeK are represented in Figure 2. No significant geometric differences were found in the solvated phase. The transition-state geometries obtained indicate that there are two possible mechanisms for this reaction with MeK: A concerted mechanism (A), indicated by the transition state **3**, and a zwitterionic pathway (B and C), indicated by **7** and **11**. The first mechanism involves one water molecule and the second only occurs when at least two water molecules are included. The presence of this second water molecule is essential to obtain transition states **7** and **11**; this may be due to the zwitterionic character of these transition states as an extra polar molecule is needed to stabilize them. No zwitterionic minimum was found following this mechanism in the gas phase, nor in a solvated medium. This behavior is not common for this pathway which usually occurs via a zwitterionic intermediate (**6** and **10**); this suggests that this mechanism is not very favored. Therefore mechanisms B and C are not really two-step processes; in fact they are only very asynchronous pathways in which zwitterionic formation and water addition take place almost consecutively. The same behavior was found by Nguyen and Raspoet[5] in their study of the hydration of ketenes. They also found that it was necessary to introduce several explicit water molecules to describe the addition mechanism.

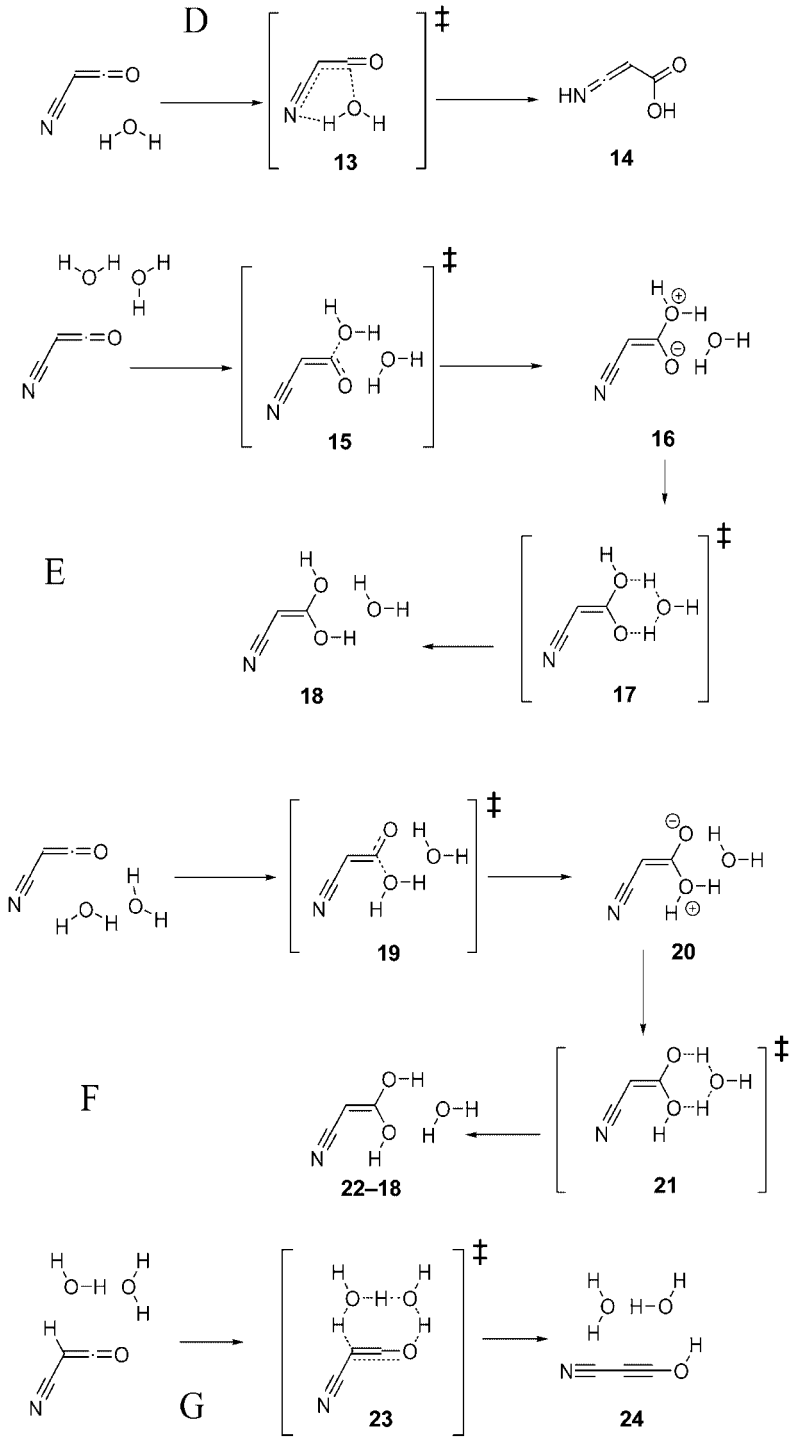
In order to analyze the aromatic characteristics of transition state **3**, ACID (anisotropy of current-induced density) calculations where performed. The ACID method, recently developed by Herges and Geuenich,[21] uses the magnetic properties for a quantitative study of the delocalization in molecules. Also it has been used to distinguish a coarctate from a pseudocoarctate reaction[22,23] and a pericyclic from a pseudopericyclic reaction.[24–28] According to Figure 5, transition state **3** shows two clear disconnections and no diatropic ring current is observed; this situation corresponds to a pseudopericyclic mechanism.[29] Geometries show that transition state **3** has an intermolecular character in which both molecules (water and MeK) basically keep their individuality, however, transition states **7** and **11** already have some intramolecular character since the molecules involved share one or more atoms. It can be deduced from Figure 2 that a concerted mechanism involving a hydrogen atom bonded to C2 did not occur. Neither did water



Scheme 2.

add to the C=C bond; this is not surprising because several authors[7,8] have pointed out the high activation energy of this possible mechanism.

The enthalpy profile in the gas and solvated phases for the pathways with MeK is represented in Figure 6. Gibbs energies are also given, but all discussion will be expressed in terms of enthalpies as they lead to the same conclusions. These enthalpies show that the mechanism with the lowest barrier belongs to the pseudopericyclic pathway (A); the enthalpy difference in the gas phase with regard to the zwitterionic mechanism is 4.67 kcal/mol. This difference is high enough to consider the pseudopericyclic process as the only pathway. The height of the energy barrier of the pseudopericyclic mechanism is similar to the result obtained by Birney et al. for the same pathway with (*Z*)-formylketene.[9] As can be seen in Figure 6, transition state **11** is more stable than **7**, which is mainly due to the hydrogen bond in **11** connecting O3 and a hydrogen atom of one of the water molecules. In the solvated phase the differences between the activation enthalpies decrease, but still the enthalpy difference is big enough to consider the pseudopericyclic as the only pathway followed by the reaction. This decrease in the enthalpy difference may be due to the ionic character of **7** and **11**, which are stabilized by the medium. Transition state **7** is more stabilized than **11** because the latter is already stabilized in the gas phase by the above-mentioned hydrogen bond and therefore the effect of the medium is not as important as in transition state **7**. Overall, the computa-



Scheme 3.

tional results in both the gas and solvated phases corroborate the experimental hypothesis given by Shelkov et al., according to which the nucleophilic addition of water or alcohols to ketenes obtained from malonates occurs by a pseudopericyclic mechanism.

Figure 3 shows the transition states obtained in the gas phase for the possible mechanisms for the addition of water to CyK. Transition state **13** appears when the reaction follows a concerted pseudopericyclic mechanism (D); transition states **17** and **21** correspond to a zwitterionic pathway (E and F) and transition state **23** to a concerted mechanism with an eight-membered transition state involving a hydrogen atom bonded to C2 (G). This last mechanism has some similarities with the concerted mechanism[18] involving a six-membered transition state that includes the C1 and C2 atoms. It can be seen that the molecules involved in all the transition states share at least one atom, thereby losing some of the characteristics of the individual molecules. This

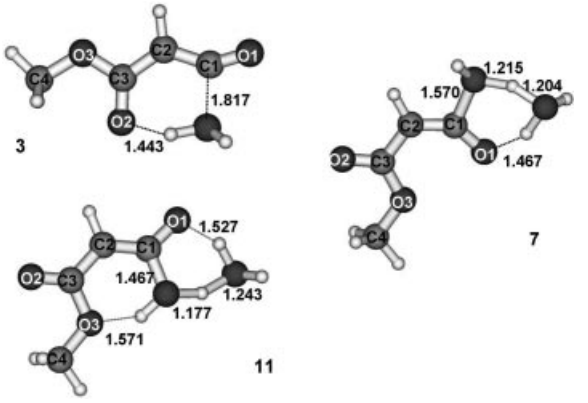


Figure 2. B3LYP/6-31++G** geometries [Å] of the transition states obtained in the gas phase through the possible mechanisms for the addition of water to methylcarboxyketene.

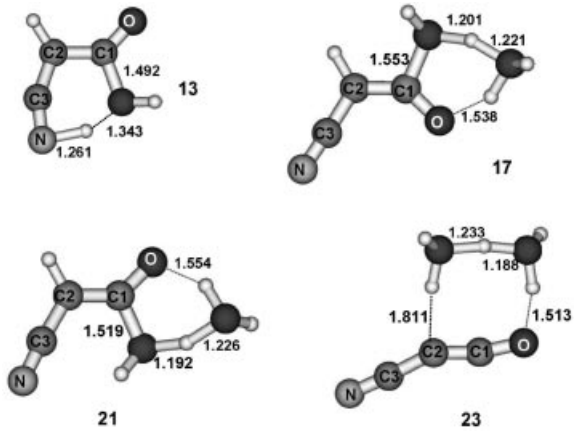


Figure 3. B3LYP/6-31++G** geometries [Å] of the transition states obtained in the gas phase through the possible mechanisms for the addition of water to cyanoketene.

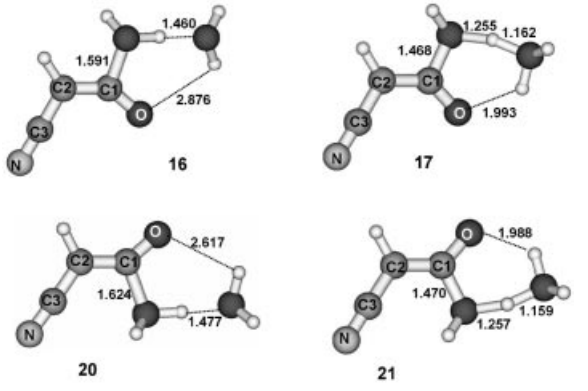


Figure 4. B3LYP/6-31++G** geometries [Å] of the transition states and zwitterionic intermediates obtained in a solvated medium by the zwitterionic mechanism for the addition of water to cyanoketene.

fact is especially relevant for **13** because in the transition state for this mechanism with MeK (pathway A), the molecules involved keep their individual characteristics. The enthalpy profile obtained for the different pathways is given in Figure 7 together with the Gibbs energies. It can be seen

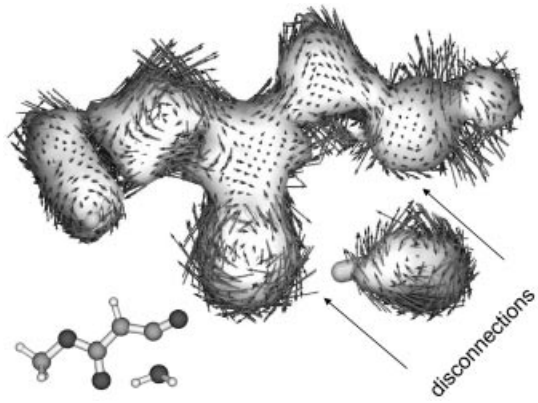


Figure 5. ACID plot for transition state **3**. The current density vectors (green arrows with red tips) are plotted on the isosurface of value 0.030 and the magnetic field points from the paper to the reader. The topology of the delocalized electrons exhibits two clear disconnections.

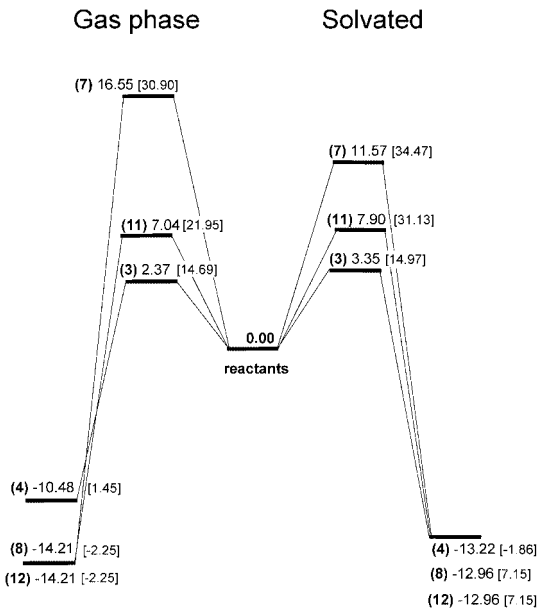


Figure 6. Enthalpy (kcal/mol) profile at 298.15 K for reactions of methylcarboxyketene (MeK). Gibbs free energies are given in brackets. We considered the most stable complexes as reactants. Since products **8** and **12** are torsional conformers, we chose the most stable ones for this figure.

that the mechanisms D and G have much higher barriers than the mechanisms E and F represented by **17** and **21**. Therefore it can be considered that no reaction will occur through transition states **13** and **23**. With regard to **17** and **21**, the activation enthalpy of the latter is 4.87 kcal/mol smaller, as can be seen in Figure 7. Therefore in the gas phase the reaction will follow pathway F, proceeding via **21**. This is anomalous behavior as commonly, in the zwitterionic transition state, the geometry is determined by steric factors[30] that favor *trans* attack (mechanism E). We did not find a clear explanation for this issue; it could be due to some attractive interaction between the CN moiety and

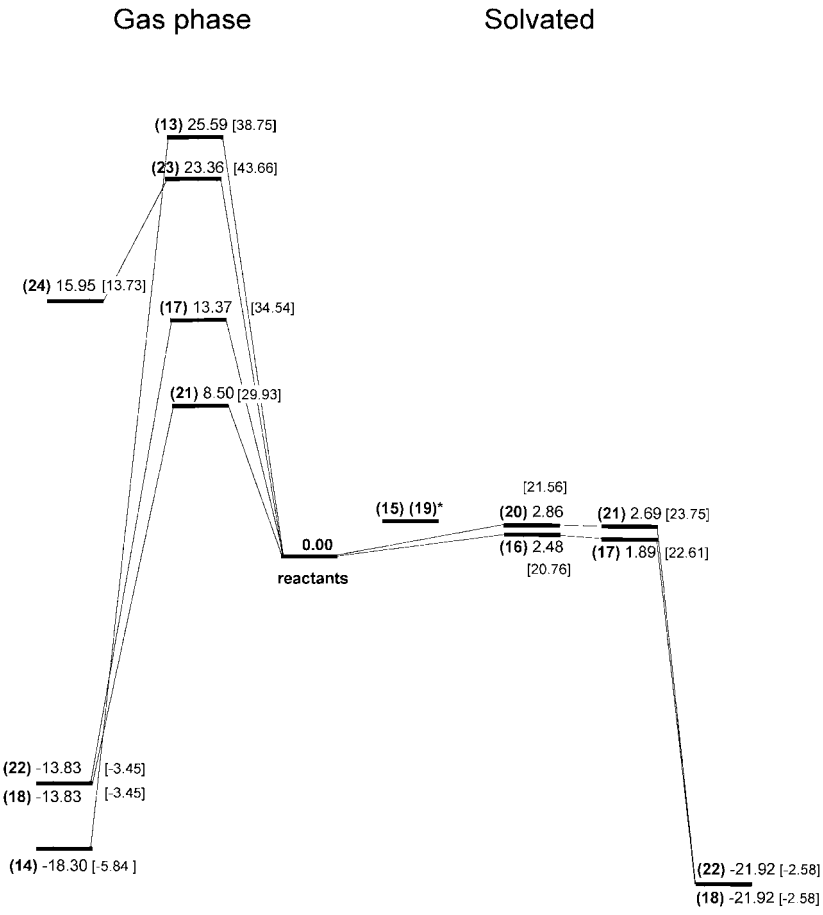


Figure 7. Enthalpy (kcal/mol) profile at 298.15 K for reactions of cyanoketene (CyK). Gibbs free energies are given in brackets. We considered the most stable complexes as reactants. Since products **18** and **22** are torsional conformers, we chose the most stable ones for this figure. In the solvated phase and according to the electronic energies, transition states **17** and **21** have higher energies than minima **16** and **20**, respectively; however, the relative stabilities change when thermodynamic corrections are included to calculate the enthalpies. The asterisk indicates that transition states **15** and **19** were not found; the barrier heights for these transition states were estimated, see text.

a hydrogen atom belonging to a water molecule. Yet it does not seem very important to answer the question about the mechanism of this reaction as even the lowest barrier (transition state **21**) obtained for this mechanism is substantial and does not explain the experimental reaction rates in solution. On the other hand, neither did we find any zwitterionic intermediate in the gas phase, as usually happens in this kind of reaction. The same behavior was found by Nguyen and Raspoet[5] for the hydration of ketenes.

Experiments have been performed in solution and therefore calculations including the effect of solvent were performed in systems with CyK. Calculations were only carried out to study mechanisms E and F since D and G can be neglected owing to their very high activation enthalpies. Calculations performed in the solvated phase show that under these conditions the zwitterionic mechanism is different to that in the gas phase and it becomes a two-step pathway, which is more common in this kind of reaction. The same was found by Nguyen and Raspoet[5] for addition to ketenes in the solvated phase. In this stepwise mechanism the reactants undergo a reaction to yield a stable zwitterionic intermediate (it appears as a minimum) and from this zwitterion a new reaction gives the final product. These reactions proceed through two different transition states. The zwitterionic intermediates **16** and **20** and the transition states **17** and **21** between the intermediates and products for both the *trans* and *cis* attacks are represented in Figure 4. We were unable to find the transition states **15** and **19** between the reactants and the zwitterionic intermediates as the distances defining these transition states are so long that it is almost an intermolecular complex and there are several stationary points corresponding to intermolecular complexes close to them; all attempts to find **15** and **19** converged to these stationary points. Figure 4 shows that in both cases the zwitterionic intermediate needs a second water molecule to stabilize it. The enthalpy profile of the reaction from the intermediate to the products is given in Figure 7. The enthalpy differences are significantly smaller than those in the gas phase. These very small values give very high reaction rates, as has been shown experimentally.[1,17] Transition state **17** has a lower enthalpy than minimum **16** and transition state **21** is lower than minimum **20** due to thermodynamic corrections to the energy. According to the electronic energies, minima **16** and **20** are 1.33 and 1.76 kcal/

Table 1. Energy and enthalpy (in parentheses) differences (kcal/mol) between different transition states and the minima of cyanoketene (CyK) and methylcarboxyketene (MeK).

Environment	MeK	CyK			
	7–**11**	**17**–**21**	**23**–**21**	**16**–**20**	**16**–React
Gas phase	9.30 (9.50)	4.95 (4.87)	17.26 (16.49)	–	–
Solvated[a]	3.56 (3.68)	–0.82 (–0.79)	–	–0.39 (–0.38)	1.85 (2.48)

[a] Different mechanism in CyK with regard to the gas phase (see text).

mol more stable than transition states **17** and **21**, respectively. Note that, unlike the gas phase, transition state **17** has the lowest barrier and that the reaction will mainly proceed through pathway E. This is a result of a reversal in the relative stabilities of **17** and **21**, as can be seen in Table 1, **16** and **17** being more stable than **20** and **21**, respectively. These observations fit in with experimental[1] results: a *trans* attack together with high reaction rates. There remains, however, a question that must be solved before the previous statements can be considered. It involves the transition states **15** and **19** between the reactants and the zwitterionic intermediates. If the activation energies associated with these transition states is very high, the reaction will not follow the zwitterionic mechanism and the previous statements will be erroneous. As has already been mentioned, we were unable to find these transition states. In order to decrease the significance of this problem and to get some idea about the height of the barrier, we performed restricted optimizations on the zwitterionic intermediates **16** and **20**. All coordinates were relaxed except for the distance between C1 and the water oxygen; this distance was changed in steps of 0.1 Å and then fixed. A restricted optimization was performed for each step. This procedure gives transition state **15** with a C1–O distance 0.4 Å larger than that for **16** and an energy 1.24 kcal/mol higher. Between **19** and **20** the distance is 0.3 Å larger and the energy 0.57 kcal/mol higher. Considering these results, it is most likely that the reaction from reactants to the intermediates will have a small barrier and that it will not change the conclusions obtained about the mechanism for the addition of water to CyK. Therefore it can be concluded that, as for MeK, the calculations confirm the experimental results in the reaction of water with CyK and predict a zwitterionic two-step pathway. Furthermore, it has been checked that this mechanism is only possible in a solvated phase.

Conclusions

In this work, DFT calculations have been performed to study the mechanism for the addition of water to cyanoketene and methylcarboxyketene. Several pathways have been analyzed for each compound. In these studies several stationary points were found in order to evaluate the height of the energy barriers.

The calculations performed for MeK showed that the addition reaction proceeds through a concerted pseudopericyclic mechanism. This result agrees with the suggestion by Shelkov et al.[1] based on experimental data. It was also seen that the presence of solvent does not have an important effect on this mechanism and substantial changes do not appear in the solvated medium.

For CyK the results also agree with experimental data as the mechanism predicted by the calculations involves a zwitterionic intermediate. However, and unlike the MeK mechanism, in this case the solvent is essential because the compounds will not react in the gas phase and the pathway changes in the solvated phase. This is due to the stabilization produced by the solvent in the zwitterionic intermediate and transition states as a consequence of their polar character.

Computational Details

Different geometries of the stationary points of the reactants, products and transition states of the studied reactions were located by optimizing every degree of freedom (except one that is maximized for the transition state) by density functional theory (DFT) calculations using the B3LYP functional. Several calculations were conducted at the B3LYP/6-31++G** level of theory. Minima and transition states were characterized from harmonic frequencies and force constants (zero negative force constants at each minimum and one negative force constant for the transition state) calculated at the same level of theory. The pathway for each reaction was obtained by using the intrinsic reaction coordinate (IRC) with mass-weighted coordinates. In order to consider the effect of solvent on the different stationary points involved in the studied reactions, DFT optimizations and frequency calculations, including a polarized continuum model, PCM,[11–13] were also performed (with water as solvent).

The activation enthalpy ($\Delta H^{\neq}$) was also obtained from Equation (1), where ΔH_{ts} and ΔH_{react} are the enthalpies for the transition state and the reactant (in the most stable intermolecular complex with a geometry analogous to the transition state), respectively. The enthalpies were determined at 298.15 K from the expressions derived from quantum statistical thermodynamics for ideal gases.[14] All computations were performed by using the Gaussian 98 software package.[15]

$$\Delta H^{\neq} = \Delta H_{ts} - \Delta H_{react} \quad (1)$$

Supporting Information (see also the footnote on the first page of this article): Geometries and energies of all relevant structures in both gas and solvated phases.

Acknowledgments

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[1] R. Shelkov, M. Nahmany, A. Melman, *J. Org. Chem.* **2002**, *67*, 8975.
[2] T. T. Tidwell, *Angew. Chem. Int. Ed.* **2005**, *44*, 5778.
[3] T. T. Tidwell, *Eur. J. Org. Chem.* **2006**, 563.
[4] P. Sánchez-Andrada, I. Alkorta, J. Elguero, *J. Mol. Struct. (THEOCHEM)* **2001**, *544*, 5.
[5] M. T. Nugyen, G. Raspoet, *Can. J. Chem.* **1999**, *77*, 817.
[6] M. T. Nugyen, G. Raspoet, L. G. Vanquickenborne, *J. Chem. Soc., Perkin Trans. 2* **1999**, 813.
[7] X. Duan, M. Page, *J. Am. Chem. Soc.* **1995**, *117*, 5114.
[8] P. N. Skancke, *J. Phys. Chem.* **1992**, *96*, 8065.
[9] D. M. Birney, P.-E. Wagenseller, *J. Am. Chem. Soc.* **1994**, *116*, 6262.
[10] D. M. Birney, X. Xu, S. Han, X. Huang, *J. Org. Chem.* **1997**, *62*, 7114.
[11] S. Miertus, E. Scrocco, J. Tomasi, *Chem. Phys.* **1981**, *55*, 117.
[12] V. Barone, M. Cossi, J. Tomasi, *J. Comput. Chem.* **1998**, *19*, 404.
[13] E. Cánces, B. Mennuci, J. Tomasi, *J. Chem. Phys.* **1997**, *107*, 3032.
[14] L. A. Curtis, D. J. Fruip, M. Blander, *J. Am. Chem. Soc.* **1978**, *100*, 79.
[15] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. J. A. Zakrzewski, J. Montgomery, R. E. Stratmann, J. C. Burant, S. Pprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, A. G. Baboul, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. G. Johnson, W. Chen, M. W. Wong, J. L. Andres, M. Head-Gordon, E. S. Replogle, J. A. Pople, *Gaussian 98 (Revision A.9)*, Gaussian, Inc., Pittsburgh, PA, **1998**.
[16] H. R. Seikali, T. T. Tidwell, *Tetrahedron* **1986**, *42*, 2587.
[17] B. D. Wagner, B. R. Arnold, G. W. Brown, J. Lusztyk, *J. Am. Chem. Soc.* **1998**, *120*, 1827.
[18] M. T. Nguyen, A. F. Hegarty, *J. Am. Chem. Soc.* **1984**, *106*, 1551.
[19] A. D. Allen, J. Andrados, A. J. Kresge, M. A. McAllister, T. T. Tidwell, *J. Am. Chem. Soc.* **1992**, *114*, 1878.
[20] Y. Chiang, A. J. Kresge, Q. Meng, Y. Morita, Y. Yamamoto, *J. Am. Chem. Soc.* **1999**, *121*, 8345.
[21] R. Herges, D. Geuenich, *J. Phys. Chem. A* **2001**, *105*, 3214.
[22] R. Herges, A. Papafilippopoulos, *Angew. Chem. Int. Ed.* **2001**, *40*, 4671.
[23] D. B. Kimball, T. J. R. Weakley, R. Herges, M. M. Haley, *J. Am. Chem. Soc.* **2002**, *124*, 13463.
[24] M. M. Montero-Campillo, J. Rodríguez-Otero, E. M. Cabaleiro-Lago, *J. Phys. Chem. A* **2004**, *108*, 8373.
[25] A. Peña-Gallego, J. Rodríguez-Otero, E. M. Cabaleiro-Lago, *J. Org. Chem.* **2004**, *69*, 7013.
[26] E. M. Cabaleiro-Lago, J. Rodriguez-Otero, S. M. Varela-Varela, A. Peña-Gallego, J. M. Hermida-Ramon, *J. Org. Chem.* **2005**, *70*, 3921.
[27] E. M. Cabaleiro-Lago, J. Rodriguez-Otero, I. Gonzalez-Lopez, A. Peña-Gallego, J. M. Hermida-Ramon, *J. Phys. Chem. A* **2005**, *109*, 5636.
[28] A. Peña-Gallego, J. Rodriguez-Otero, E. M. Cabaleiro-Lago, *Eur. J. Org. Chem.* **2005**, 3228.
[29] J. A. Ross, R. P. Seiders, D. M. Lemal, *J. Am. Chem. Soc.* **1976**, *98*, 4325.
[30] T. T. Tidwell, *Acc. Chem. Res.* **1990**, *23*, 273.

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