ORGANIC LETTERS

2000
Vol. 2, No. 18
2725−2728

Dienophilic Behavior of the Vinylic (C=C) and the Carbonyl (C=O) Bonds of Ketenes in Reactions with 1,3-Diazabuta-1,3-dienes

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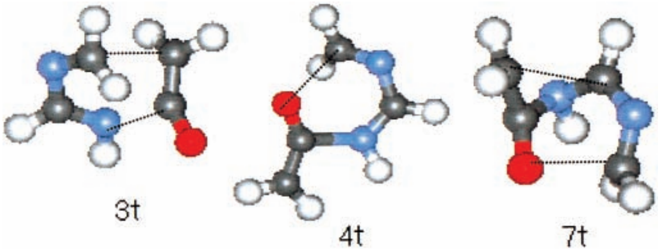
Received March 8, 2000 *(Revised Manuscript Received July 13, 2000)*

ABSTRACT



Ab initio and density functional studies (DFT) on cycloaddition reactions of 1,3-diazabuta-1,3-dienes with ketenes are reported. The vinylic (C=C) and the carbonyl (C=O) units of the ketenes are found to participate in concerted asynchronous [4 + 2] cycloaddition reactions. The transition states (3t, 4t, and 7t) for these paths have been located on the PE surface at the correlated levels of ab initio calculations. A reasonable mechanism for the formation of [4 + 2] and [2 + 2] adducts is presented.

Ketenes have received significant attention owing to their ability to selectively act as facile 2π components across the C=C bond rather than the C=O bond in commonly encountered [2 + 2] cycloaddition reactions with alkenes[1] and imines.[2] Ketenes are generally referred to as poor dienophiles whereas isoelectronic allenes and heterocumulenes are well-known to participate in Diels−Alder reactions with conjugated dienes.[3] This is based on their well-documented preference to produce a four-membered cyclobutanone ring rather than a cyclohexanone ring in reactions with cyclic and acyclic 1,3-dienes.[4] Similarly, the reactions of ketenes with 1-azadienes preferentially give [2 + 2] cycloadducts; the formation of [4 + 2] adducts (across C=C bond of ketenes) has been shown to be an exception.[5]

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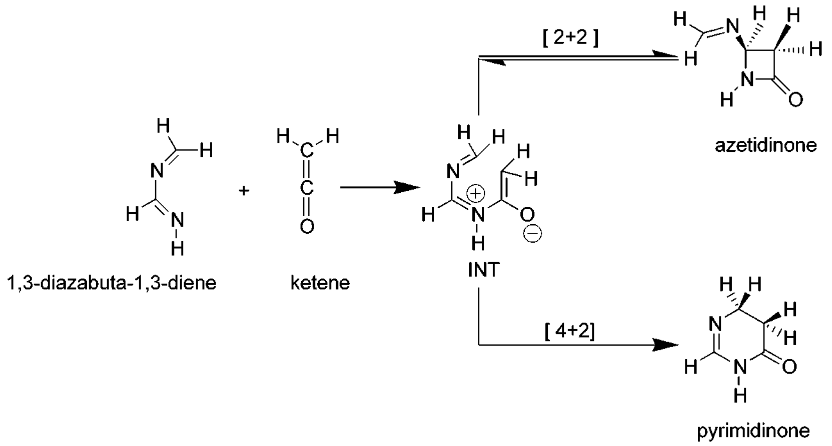
Scheme 1



There are a few examples of exceptional Diels−Alder type reactions of conjugated dienes with C═O bond of ketenes.[4a−c,6]

The reactions of 1,3-diazabuta-1,3-dienes with ketenes give [4 + 2] as well as [2 + 2] cycloadducts[7,8] (Scheme 1), and conversion of [2 + 2] products to the [4 + 2] products has also been observed.[7d] The formation of [4 + 2] cycloadducts is in contrast to the known poor dienophilic character of the C═C bond of ketenes. Wurthwein et al.[7c] have reported that the formation of [2 + 2] cycloadducts in these reactions proceeding through a zwitterionic intermediate is a kinetically controlled process and the observed cycloaddition mode is governed by steric factors. Rossi et al.[7d] have reported that the cyclization of a zwitterionic intermediate to form a four-memebered ring is a reversible process and the size of substituents on N1 of the diazadiene plays an important role in controlling the observed selectivity. However, the stereocontrolled formation of pyrimidinones in a number of reactions of 1,3-diazabuta-1,3-dienes with monosubstituted ketenes is less likely to proceed through a zwitterionic intermediate and possibly involves a highly stereoselective Diels−Alder type cycloaddition. The arguments presented above and our continued interest in the chemistry of azadienes prompted us to perform ab initio MO and density functional studies on the reaction between 1,3-diazabuta-1,3-diene **1** with ketene **2**. We report herein a new feature of ketenes exhibiting dienophilic character across C═C and C═O bonds in a concerted asynchronous reaction with 1,3-diazabuta-1,3-dienes.

Ab initio MO[9a] and density functional calculations[9b] (DFT) have been performed on 1,3-diazabuta-1,3-diene **1** and its reaction with ketene **2** at HF/6-31G*, MP2/6-31G*, and B3LYP/6-311++G**//B3LYP/6-31G* levels, using the Gaussian94W program[10] to understand the mechanism. In this discussion, geometric parameters obtained at the B3LYP/6-31G* level and energies obtained at the B3LYP/6-311++G**//B3LYP/6-31G* level are used, unless otherwise specifically mentioned. Diazadiene **1** can exist in two isomeric forms, **1*E*** and **1*Z***, with respect to the arrangement of substituents on N1 and C2, with an energy difference of only 1.03 kcal/mol and an isomerization barrier of 29.57 kcal/mol. The preferential geometries observed for **1*E*** and **1*Z*** are *s*-cisoid and *s*-trans, respectively. However, in the reaction with ketene, **2**, the resultant zwitterionic intermediates for both **1*E*** and **1*Z*** possess only the *s*-cissoid arrangement, and therefore only such structures are included in the discussion.

The potential energy (PE) surface for the reaction between **1** and **2** is shown in Figure 1, and the structures of the important transition states observed on the PE surface are shown in Figure 2. The PE surface shows that dihydropyrimidinone **3** with a relative energy of −53.8 kcal/mol is highly stable (Table 1). At the HF/6-31G* level, a zwitterionic intermediate can be located on the path leading to the formation of **3**, with a very small stability (∼0.1 kcal/mol at the MP2/6-31G*//HF/6-31G* level). However, on inclusion of electron correlation in the geometical optimization at the MP2 and B3LYP levels, the intermediate cannot be located and all our efforts lead only to transition state **3t**. The transition state **3t** with N1···C5 and C4···C6 bond lengths

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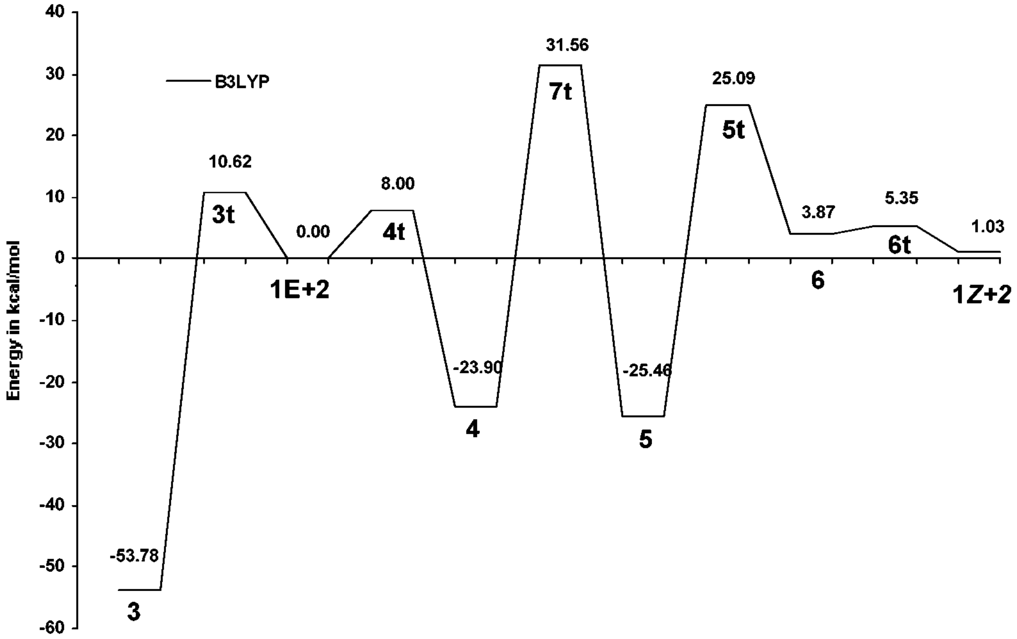


Figure 1. Energy profile diagram for the cycloaddition reaction of 1,3-diazabuta-1,3-diene (**1**) and ketene (**2**).

of 1.76 and 2.58 Å, respectively, reflects a greater degree of concerted asynchronous [4 + 2] cycloaddition process for the formation of a six-membered ring. The shorter N1−C5 distance in **3t** indicates that the reaction is triggered by a nucleophilic attack of the nitrogen N1 of 1,3-diaza-1,3-butadiene **1** to the central carbon of the ketene. The formation of **3** (path 1, Scheme 2) occurs via a facile process involving an energy barrier of 13.57, 8.05, and 10.62 kcal/mol at the MP2/6-31G*, B3LYP/6-31G*, and B3LYP/6-311++G**//B3LYP/6-31G* levels, respectively. Further, the formation of dihydropyrimidinone is irreversible because of the observed high-energy barrier (~65 kcal/mol) for this process.

The oxadiazine **4**, a [4 + 2] cycloadduct between **1*E*** and the C═O bond of ketene (path 2, Scheme 2), has a smaller stabilization energy (−23.9 kcal/mol), and the energy barrier for its formation via transition structure **4t** is only about 8.0 kcal/mol. The geometrical features of **4t** (with bond lengths N1−C5 = 1.74 and C4−O7 = 2.48 Å, Figure 2) indicate that this reaction also proceeds through a concerted asynchronous cycloaddition process without the involvement of any zwitterionic intermediate. Thus, both C═C and C═O bonds of ketene competitively undergo [4 + 2] cycloaddition reaction with 1,3-diazabuta-1,3-diene: when the C═C bond participates as a 2π component, a more stable product is obtained with a relatively higher energy barrier (10.8 kcal/mol) (path 1), and with the involement of the C═O bond as

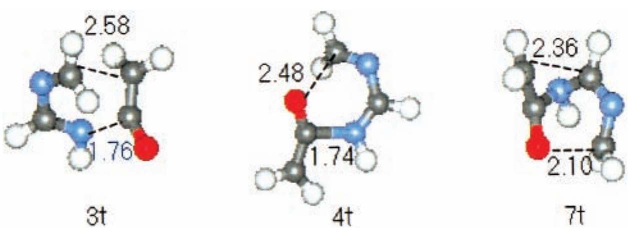


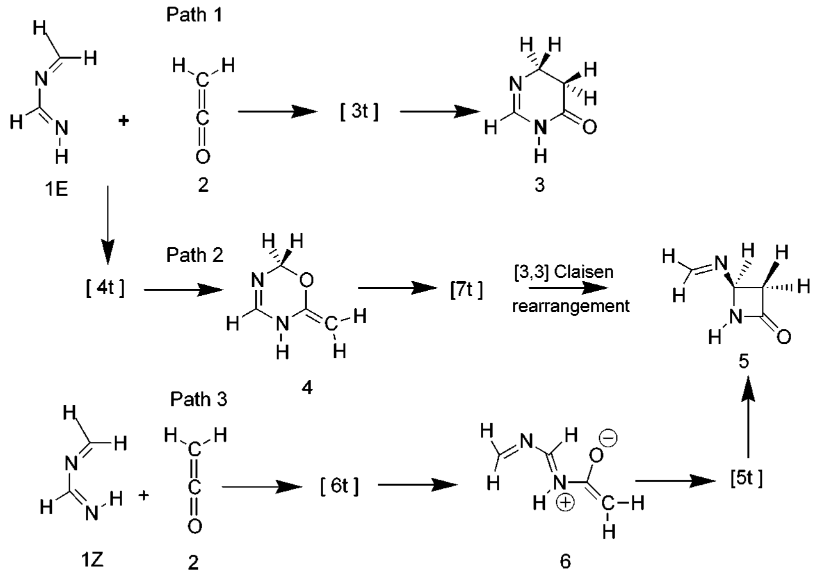
Figure 2. The MP2/6-31G*-optimized structures of the transition states (distances in Å) in the cyloaddition reaction between 1,3-diazabuta-1,3-diene (**1**) and **2**: left, transition state **3t** for the formation of pyrimidinone (**3**); center, transition state **4t** for the formation of oxadiazine (**4**); right, the Claisen rearrangement transition state **7t**.

Table 1. Absolute (au) and Relative Energies (kcal/mol) of the Reactant, Transition Structures, and Product for the Cycloaddition Reaction of **1** and **2** at Various Levels of Theory

				relative energies(+ZPE)[c]		
structure	NIF[a]	MP2/6-31G*	ZPE[b]	**A**	**B**	**C**
1*E* + 2	0	−339.631331	58.03	0.00	0.00	0.00
3t	1	−339.613771	60.58	13.57	8.05	10.62
3	0	−339.736819	64.84	−59.38	−60.70	−53.78
4t	1	−339.617797	60.57	11.03	5.70	8.00
4	0	−339.681374	63.97	−25.46	−30.88	−23.90
7t	1	−339.592116	61.70	28.28	25.77	31.56
5	0	−339.690215	63.15	−31.83	−31.75	−25.46
5t	1	−339.597353	60.35	23.64	21.14	25.09
6	0	−339.622671	60.61	8.01	1.45	3.87
6t	1	−339.622591	60.17	7.62	3.14	5.35
1*Z* + 2	0	−339.630074	57.90	0.66	0.52	1.03

[a] Number of imaginary frequencies obtained at MP2/6-31G* level. [b] Zero point energy correction obtained from MP2/6-31G* vibrational frequencies and scaled by a factor of 0.9676. [c] Relative energies computed after ZPE correction at MP2/6-31G*(**A**), B3LYP/6-31G*(**B**), and B3LYP/6-311++G**//B3LYP/6-31G* (**C**).

Scheme 2. Proposed Mechanism for the Cycloaddition Reaction of 1,3-Diazabuta-1,3-diene with Ketene



a 2π component, a less stable product is obtained with a relatively smaller energy barrier (8.0 kcal/mol) (path 2). The steric interactions for path 2 are less significant as compared to those in path 1 due to the lack of any substituent on oxygen. Oxadiazine **4** has an envelope-like structure with the cyclic CH_2 group slightly above the plane of rest of the molecule. A larger stabilization of dihydropyrimidinone **3** relative to that of **4** is presumably due to the presence of an amide moiety in **3**.

Azetidinone **5** can be obtained via zwitterionic intermediate **6** (path 3, Scheme 2) formed by the reaction of **1*Z*** with ketene **2**. The cyclization of intermediate **6** through transition state **5t** involves an energy barrier of 25.09 kcal/mol. The ring closure of intermediate **6** to form [4 + 2] adduct is less likely because of the large distance between the C4 and C6 carbon atoms. All our attempts to locate a transition state for the [2 + 2] cycloaddition path between **1*E*** and **2** to give azetidinonone **5** were in vain, and complete optimizations to locate a transtion state for such a process led either to **3t** or **4t**. Hence, it may be concluded that **1*E*** does not form a [2 + 2] cycloadduct with ketene.

Recently Machiguchi et al. reported that the ketene carbonyl group acts as an excellent dienophile and explained the formation of 1,2-cycloadducts via [3,3] sigmatropic rearrangement of the initially formed 1,4-cycloadducts. Transition state **7t** for a similar [3,3] Claisen rearrangement has also been located on the PE path by connecting oxadiazine **4** and azetidinone **5** at the correlated levels. The energy barrier for conversion of **4** to **5** is 55.46 kcal/mol, and for the reverse process it is 57.02 kcal/mol. However, the presence of bulkier substituents might reduce the energy barriers due to steric interactions. The transformation of azetidinone to pyrimidinone as observed by Rossi et al. may occur either (1) by reversal of oxadiazine to **1*E*** or (2) by reversal of azetidinone to **1*Z*** and isomerization to **1*E***. Further work on the Claisen rearrangement route for conversion of oxadiazine to azetidinone and azetidinone to pyrimidinone is in progress.

Supporting Information Available: Geometries of all the structures discussed in the text and 3D transition structures of **3t**, **4t**, and **7t**. This material is available free of charge via the Internet at http://pubs.acs.org.

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