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[2 + 2] Photocycloaddition of 2(5*H*)-Furanone to Unsaturated Compounds. Insights from First Principles Calculations and Transient-Absorption Measurements

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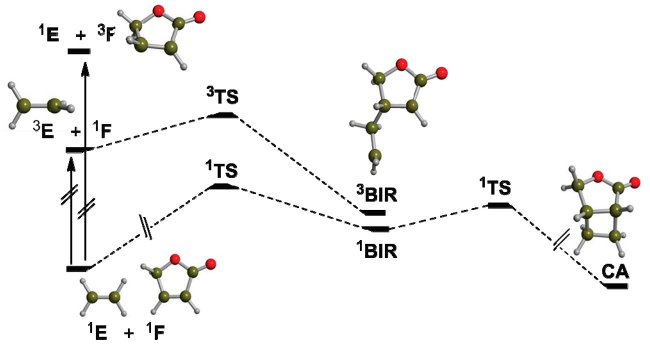
Received February 25, 2010



The [2 + 2] photocycloaddition reaction of 2(5*H*)-furanone to ethylene and acetylene has been investigated by means of DFT and CASSCF methods. In both cases, the reaction involves the formation of a triplet 1,4-biradical intermediate that evolves to the cyclobutane product after spin inversion. For acetylene, the lowest energy path in the triplet surface occurs through the $^3(\pi-\pi^*)$ state of the 2(5*H*)-furanone. However, in the reaction with ethylene the lowest energy path in the triplet surface involves the $^3(\pi-\pi^*)$ state of the alkene. Although reaction through the triplet state of olefins is usually disregarded due to the short lifetime of these species, we have experimentally measured that sensitization of ethylene triplet state can occur at typical synthetic conditions and, thus, lead to photochemical addition to the lactone.

Introduction

The [2 + 2] photocycloaddition of cyclic α,β-unsaturated carbonyl compounds to carbon−carbon multiple bonds is a well-established methodology for the assembly of cyclobutanes,[1−3] which has been widely applied to prepare key intermediates in the total syntheses of natural products.[4−7] In particular, our group has extensively studied the photochemical reactions of homochiral 5-substituted 2(5*H*)-furanones with ethylene, acetylene, and 1,1-diethoxyethylene, and subsequently exploited these processes in the syntheses of cyclobutane pheromones[8−11] and cyclobutane nucleoside analogues (Scheme 1).[12,13] A major factor determining the synthetic application of such photocycloaddition reactions concerns

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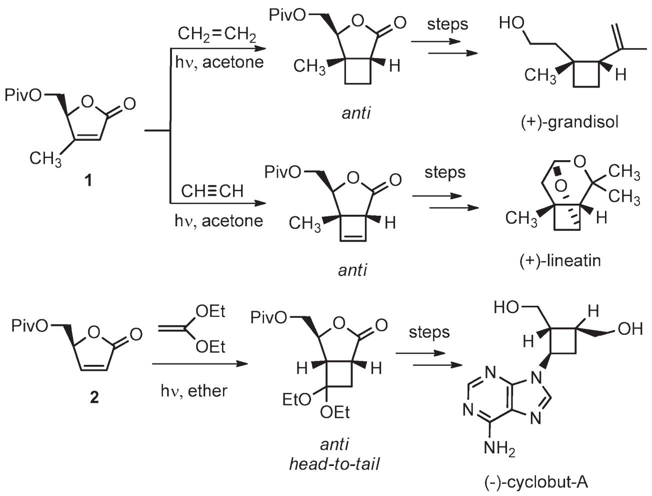
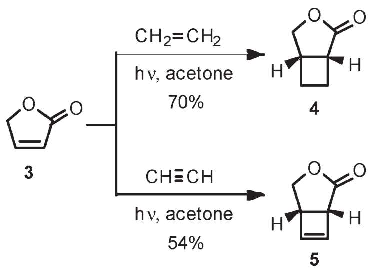
DOI: 10.1021/jo100341a

SCHEME 1



SCHEME 2



the control of their regio- and stereochemistry, an issue that is intimately related to the reaction mechanism. For instance, the photoaddition of ethylene and acetylene to chiral lactone **1** shows facial diastereoselectivity leading to major formation of the anti cycloadducts. On the other hand, photoreaction of the nonsymmetrical olefin 1,1-diethoxyethylene to chiral lactone **2** mainly affords the anti head-to-tail isomer. Conversely, the stereochemistry of the initial alkene seems to be a less relevant factor in this type of reaction, since it is usually lost in the final products obtained from the photocycloaddition process.[11]

The photochemical cycloaddition reaction of alkenes with α,β-unsaturated carbonyl compounds has been studied from both mechanistic and synthetic standpoints for over 30 years. Although a wealth of work has been performed on cyclic enones during this period,[14-16] the number of studies devoted to α,β-unsaturated-γ-lactones have been much more scarce. In the case of enones, the mechanism thoroughly accepted for their [2 + 2] photocycloaddition reactions involves the addition of the ground-state olefin to the triplet excited state $^3(\pi-\pi^*)$ of the enone, thus generating a triplet 1,4-biradical intermediate that eventually evolves to the coupling adduct after spin inversion.[14,15,17-19] Theoretical studies on the [2 + 2] photocycloaddition of acrolein[20,21] and cyclohexenone[22] to ethylene, using ab initio CASSCF calculations and density functional methods, have indeed confirmed that the lowest energy path in the excited triplet state proceeds via the $^3(\pi-\pi^*)$ state of the enone.

To the best of our knowledge, however, theoretical studies of [2 + 2] photocycloaddition involving α,β-unsaturated-γ-lactones have not yet been addressed. These compounds present a larger singlet−triplet energy gap compared to the analogous cyclic enones,[23-26] which may lead to a different reaction mechanism and, therefore, regio- and stereochemistry. In order to rationalize the photoreactivity of α,β-unsaturated-γ-lactones with alkenes and alkynes, herein we present a theoretical investigation of two benchmark reactions: the photochemical [2 + 2] cycloaddition of 2(5*H*)-furanone, **3**, to ethylene and acetylene, which have been described in the literature to deliver the corresponding cyclobutane and cyclobutene adducts **4** and **5**, respectively (Scheme 2).[27] In addition, experimental transient-absorption measurements have been performed on the ethylene-2(5*H*)-furanone system aiming to investigate the photosensitization process of these species in typical synthetic conditions for [2 + 2] photocycloadditions.

Methods

Computational Details. Molecular geometries and harmonic vibrational frequencies of all the considered structures have been obtained using methods based on the density functional theory (DFT), which has been proved to be a cost-effective methodology to describe the structure and thermochemistry of a wide range of systems.[28-30] However, when computing reaction barriers of radical processes, it can lead to results that significantly vary depending on the amount of exact exchange introduced in the functional.[31-34] Thus, it is important to calibrate the functional used to describe the energetics of the reactions of interest. Because of that, we have tested two different DFT approaches for the photochemical reaction of ethylene with the 2(5*H*)-furanone **3**: (i) the nonlocal hybrid three-parameter functional B3LYP[35-37] (20% of Hartree−Fock (HF) exchange) and (ii) the meta hybrid functional MPWB1K[38] (44% HF exchange), along with the 6-31++G(d,p) basis set. In order to confirm the nature (minimum or transition state) of the stationary points

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harmonic vibrational frequency calculations were carried out in all cases using the same levels of calculation. When visual inspection of the imaginary frequency vectors did not permit to identify the minima connected by a given transition state clearly, we carried out intrinsic reaction coordinate calculations (IRC) in order to confirm the minima connected by the transition state.

In addition, some selected reaction barriers and the lowest energy point of the triplet−singlet (T/S) intersection space have been investigated at the CASSCF level[39] using the same basis set. Harmonic vibrational frequencies were also computed at the CASSCF in order to confirm the nature of the stationary points. For the CASSCF calculations on the reaction between ethylene and **3**, the active space used comprised six electrons in six orbitals, which included the π and π^* orbitals of ethylene and the π and π^* orbitals of the C=C and C=O moieties of **3**. For the CASSCF calculations on **3**, the active space included the π and π^* orbitals of the C=C and C=O moieties and the oxygen n orbital, i.e., six electrons in five orbitals. In these cases, single-point calculations using the B3LYP and MPWB1K density functional methods or the CASPT2 methods were performed at the CASSCF-optimized geometries.

Singlet−triplet excitation energies of several species of interest were calculated using the highly correlated CCSD(T)[40,41] at the DFT-optimized geometries using the same 6-31++G(d,p) basis set. In CASPT2 and CCSD(T) calculations all valence electrons were correlated.

Open-shell DFT calculations have been performed using a spin unrestricted formalism. For open-shell singlet states, unrestricted calculations have been carried out by breaking the symmetry between the α and β spin densities. As expected, for singlet biradical intermediates the resulting $\langle S^2 \rangle$ values lie between 0.9 and 1.0; namely, they are biradicals with an almost equal mixing of singlet and triplet spin states. The transition structures associated to product formation and reversion to reactants present smaller $\langle S^2 \rangle$ values (~0.6), and thus, they are less spin contaminated. Spin-projected energies can be obtained by using the spin correction procedure of Yamaguchi et al.[42] However, this spin-projection procedure has been shown to overcorrect for triplet contamination and thus, the corrected values are not necessarily a better approximation to the true singlet energy. Indeed, it has been determined that spin contaminated and spin projected energies provide an upper and lower bounds to the true singlet energy. Overall, and considering that geometry optimizations are based on uncorrected energies, the energies reported in this work have not been corrected for spin contamination. All calculations have been performed using the 6-31++G(d,p) basis set with Gaussian 03 package.[43] Net atomic charges and spin densities have been calculated using the natural population analysis of Weinhold et al.[44,45]

Experimental Details. Transient-absorption measurements have been carried out in a laser flash-photolysis system (LK60) equipped with a Xe lamp, an arc pulser, a monochromator and a photomultiplier tube (PMT, R928)[46] to experimentally investigate the photosensitization process for the ethylene-2(5*H*)-furanone system at typical synthetic conditions (i.e., using acetone as triplet sensitizer). In these experiments, the fourth harmonic (λ_{exc} = 266 nm) of a pulsed Nd:YAG laser (pulse width ca. 9 ns, power = 1 mJ/pulse) was used for laser excitation of N_2-purged acetone-ethylene and acetone-2(5*H*)-furanone mixtures in acetonitrile solution. The signal from the PMT was collected in a 500 MHz oscilloscope (Agilent Infiniium) and transferred to an Accorn PCRisk station. In this way, the decay kinetics of photogenerated transient species could be measured and subsequently analyzed by means of nonlinear least-squares exponential fittings. In the case of the measurements on the acetone−ethylene mixtures, the lifetime of the acetone triplet state was retrieved from a monoexponential fit of the decay registered at the maximum of its transient-absorption spectrum (302 nm). Conversely, biexponential functions were fitted to the transient-absorption decays measured for acetone−furanone mixtures at 302 nm, since both acetone and furanone triplet states absorb at the detection wavelength, thus giving rise to two different decay components: one component with a constant lifetime value but an increasing intensity with furanone concentration (i.e., the decay of furanone triplet state), and a second component with a decreasing lifetime with furanone concentration (i.e., the decay of acetone triplet state).

Results and Discussion

First, we will describe the theoretical study of the photochemical [2 + 2] cycloaddition of 2(5*H*)-furanone, **3**, to ethylene and acetylene (see Scheme 2). Then, experimental evidence will be presented that support that the reaction pathway evolving through the triplet state of ethylene might contribute to the overall photocycloaddition process between this alkene and lactone **3**. Finally, the implications of the theoretical and experimental results obtained will be discussed in terms of the reaction mechanism for the photochemical [2 + 2] cycloadditions between α,β-unsaturated-γ-lactones and multiple carbon−carbon bonds.

Reaction of Ethylene and 2(5*H*)-Furanone. The attack of ethylene to the 2(5*H*)-furanone, **3**, can take place either at the α- or β-carbon atoms of the lactone. As found for acrolein,[21] results show that the β attack is favored by 0.8−1.4 kcal mol^{-1} (depending on the considered isomer) at the B3LYP level and by 0.5−1.3 kcal mol^{-1} at the MPWB1K level. In addition, since in this particular case both processes lead to the same final product, we will only discuss the results obtained for the reaction pathway evolving through the attack of ethylene to the β carbon atom of the lactone, as depicted in Scheme 3. Hereafter, the species will be labeled adding a superscript 1 or 3 to refer to their singlet or triplet spin state and a subscript e or a to refer to the involvement of ethylene or acetylene in the reaction.

Scheme 3 shows that the attack of ethylene (**E**) to 2(5*H*)-furanone (**F**) in the excited triplet state leads to a triplet 1,4-biradical intermediate ($^3\mathbf{BIR_e}$), which can evolve to the singlet

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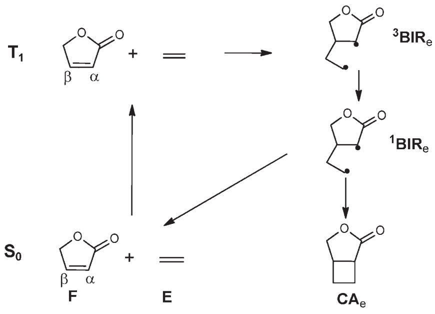
SCHEME 3



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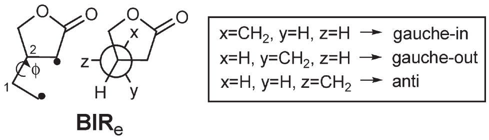

1,4-biradical ^{1}**BIR$_\mathbf{e}$** through an intersystem crossing. The ^{1}**BIR$_\mathbf{e}$** biradical can fragment into ethylene and lactone both in the ground state returning to the initial reactants or deliver the final cycloadduct product of the reaction (**CA$_\mathbf{e}$**), processes that take place through the ^{1}**TS$_\mathbf{e(R)}$** and ^{1}**TS$_\mathbf{e(P)}$** transition states, respectively.

The biradical intermediate **BIR$_\mathbf{e}$** can present several conformers upon rotation around the newly formed bond. In particular, we have localized three conformational isomers for the α and β attachment, the so-called gauche-in, gauche-out, and anti isomers, as depicted in Scheme 4 for the attack to the β carbon atom. The energy barriers for the formation of these three conformers are very similar: 4.7, 5.4, and 5.1 kcal mol^{-1} (MPWB1K) and 6.5, 6.5, and 6.3 kcal mol^{-1} (B3LYP) for the gauche-in, gauche-out, and anti isomers arising from the attack to the β carbon atom of the lactone. Conversely, we have calculated that only the gauche-in and gauche-out conformers lead to the formation of the final photocycloaddition product. Accordingly, we will only focus on the reaction pathways involving these two conformational isomers in the following discussion, which were found to be very similar and with only small energy differences of their stationary points (see below).

Figure 1 shows the optimized structures of the relevant stationary points involved in the [2 + 2] photocycloaddition of **3** to ethylene evolving through either the gauche-in or gauche-out conformers of the biradical triplet state of the system, while Figure 2 depicts the schematic energy profiles of the reaction, both at the B3LYP and MPWB1K levels of theory. It is worth mentioning that the geometries optimized with these two functionals are very similar. In fact, the main difference found concerns the bond distances, which are systematically larger at the B3LYP level by about 0.01−0.04 Å.

The attack of ethylene to 2(5*H*)-furanone in the triplet surface leads to ^{3}**BIR$_\mathbf{e}$** through the ^{3}**TS$_\mathbf{e}$** transition state. It can be observed in Figure 1 that the ethylene moiety displays a nonplanar configuration in the ^{3}**TS$_\mathbf{e}$** structure (i.e., the torsional angle ϕ around the C−C bond is ~90°), whereas the furanone ring remains planar. This indicates that the minimum energy reaction path through the triplet state of the system corresponds to the attack of ethylene in its triplet state to the ground state of furanone. This is confirmed by natural population analysis, which shows that the spin density is mainly located at the ethylene moiety of this stationary point. Indeed, the energy of this transition state is clearly below the energy of the ground state of ethylene plus the triplet excited state of furanone, thus confirming that the lowest energy path evolves via the triplet state of ethylene. This is not surprising considering that the singlet−triplet excitation energy in furanone is larger than that of ethylene (see Figure 2).

It should be taken into account that the triplet state of ethylene can also decay to its ground singlet state through an intersystem crossing, a process competing with the attack to the 2(5*H*)-furanone. To address this issue, we have determined, at the CASSCF level, the lowest energy point of the (T_1/S_0) intersection space at which intersystem crossing is expected to be more favorable. Subsequent energy calculations at the B3LYP//CASSCF and MPWB1K//CASSCF levels show that this point lies 0.2 kcal mol^{-1}, at both levels of calculation, above the twisted $^3(\pi-\pi^*)$ minimum of ethylene. Thus, the lifetime of triplet ethylene is expected to be short, as experimentally found.[47]

As commented previously, in order to obtain the final cycloaddition product, the intermediate ^{3}**BIR$_\mathbf{e}$** must evolve to the singlet 1,4-biradical ^{1}**BIR$_\mathbf{e}$** through an intersystem crossing. For 1,4-biradical species, triplet and singlet surfaces are known to be very close in energy so that the intersystem crossing can take place in a wide range of geometries.[21,22] Figure 1 shows the geometry of ^{1}**BIR$_\mathbf{e}$** (for the gauche-in and gauche-out conformers), which is compared to that for ^{3}**BIR$_\mathbf{e}$**. Noticeably, these two intermediates present very close geometrical parameters both at the B3LYP and MPWB1K levels. Moreover, their energies are also very similar (see Figure 2), thereby confirming that these two stationary points sit near the intersystem crossing region between the ground-state singlet and triplet energy surfaces of the system.

Once formed via intersystem crossing, the singlet 1,4-biradical ^{1}**BIR$_\mathbf{e}$** intermediate can evolve back to the initial reactants through the ^{1}**TS$_\mathbf{e(R)}$** transition state or yield the product of the reaction, **CA$_\mathbf{e}$**, through the ^{1}**TS$_\mathbf{e(P)}$** transition state (see Figure 2). According to the MPWB1K energies computed for ^{1}**TS$_\mathbf{e(R)}$** and ^{1}**TS$_\mathbf{e(P)}$** transition states, the reaction channel leading to the cycloaddition product is favored over reversion to reactants. However, a different result is found at the B3LYP level, the transition state reverting back to reactants being of equal (gauche-in) or even lower (gauche-out) energy than that leading to products. To shed light on this issue, the two reaction pathways (back-reaction and formation of the cycloaddition product) involving the intermediate ^{1}**BIR$_\mathbf{e}$** were further investigated at the multireference CASPT2//CASSCF level. Since the larger difference between MPWB1K and B3LYP results was found for the process involving the gauche-out isomer, the multireference calculations were only performed for this reaction pathway. With this methodology, a barrier of 2.6 kcal mol^{-1} was found for the dissociation process of ^{1}**BIR$_\mathbf{e}$** to give back the initial reactants, while an energy barrier of 0.3 kcal mol^{-1} was computed for the generation of the product **CA$_\mathbf{e}$**. Therefore, this confirms the results obtained at the MPWB1K level, i.e., ^{1}**BIR$_\mathbf{e}$** mainly evolves to the formation of the cycloaddition product.

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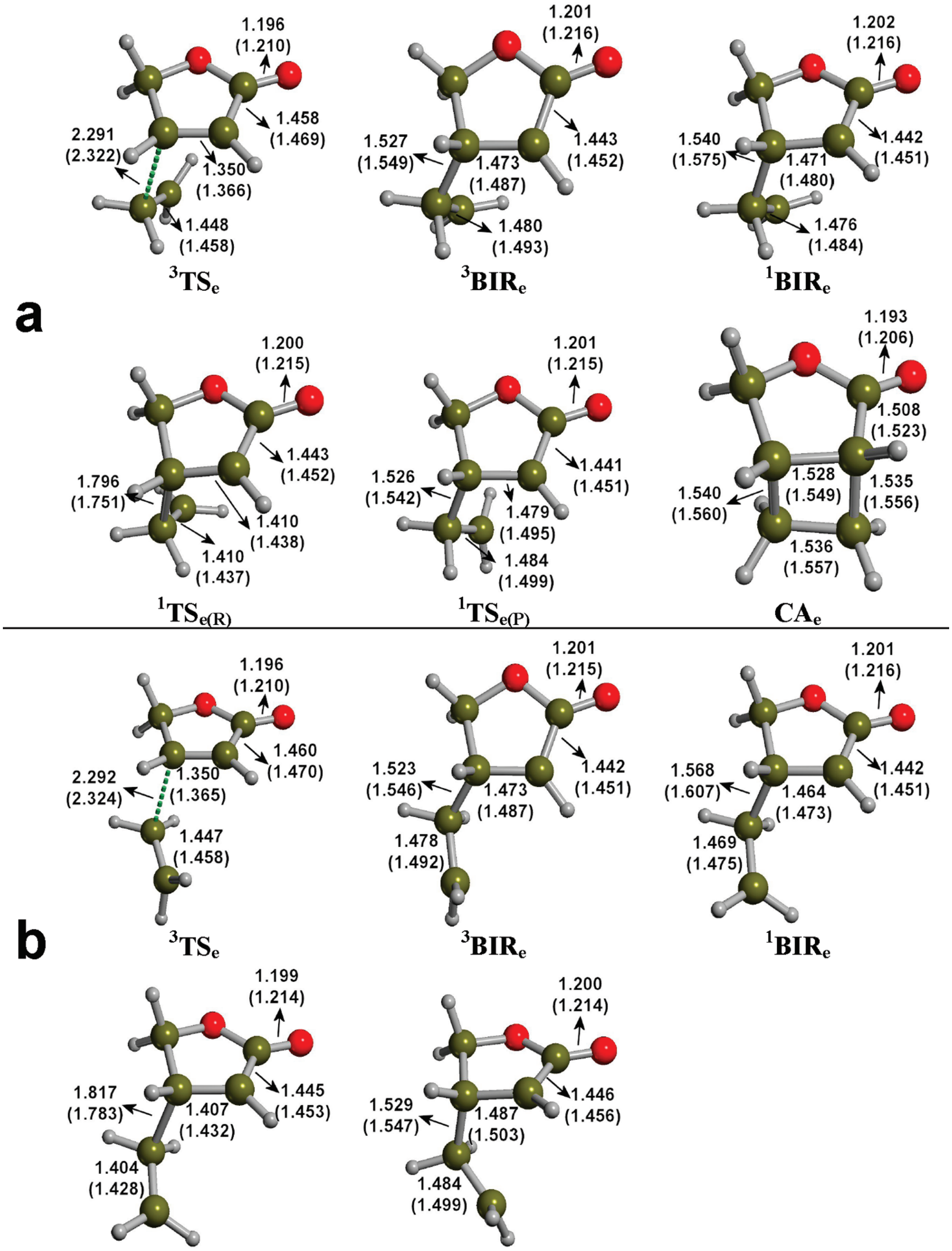

FIGURE 1. MPWB1K and B3LYP (values in parentheses) optimized geometries of the different stationary points involved in the reaction between ethylene and 2(5*H*)-furanone for the gauche-in (a) and gauche-out (b) isomers. Distances are given in angstroms.

Reaction of Acetylene and 2(5*H*)-Furanone. As previously observed for the reaction with ethylene, acetylene can attack either the α or *β* carbon atoms of the lactone. Once again, we have theoretically investigated both reaction pathways, for which similar results have been obtained. Since those two pathways lead to the same final photocycloaddition product, here we only show the results corresponding to the attack to the *β* carbon atom of the lactone, which we found to be favored by 5.5 kcal mol^{-1}.

The 1,4-biradical intermediate formed (^{3}**BIR**$_a$) can present *cis* and *trans* configurations (see Scheme 5). Moreover, this species can give rise to several different conformers upon rotation around the newly formed bond. As in the case of ethylene, we have considered three different conformational isomers for the attack to the *β* carbon atom, as depicted in Scheme 5.

In the C3a and C5a isomers, the radical carbon atom of the acetylene moiety is eclipsed with the C3 and C5 atoms, respectively; in the out isomer, it points toward the upper face of the ring. Preliminary calculations at the MPWB1K/6-31G(d) level proved that formation of the C3a conformer of the ^{3}**BIR**$_{a\text{-}cis}$ intermediate shows the lowest energy barrier. Moreover, as discussed below, the C3a isomer of the ^{1}**BIR**$_{a\text{-}trans}$ intermediate is the only suitable for the formation of the desired cyclization product. Thus, for the sake of simplicity we have only selected the C3a isomers for further discussion.

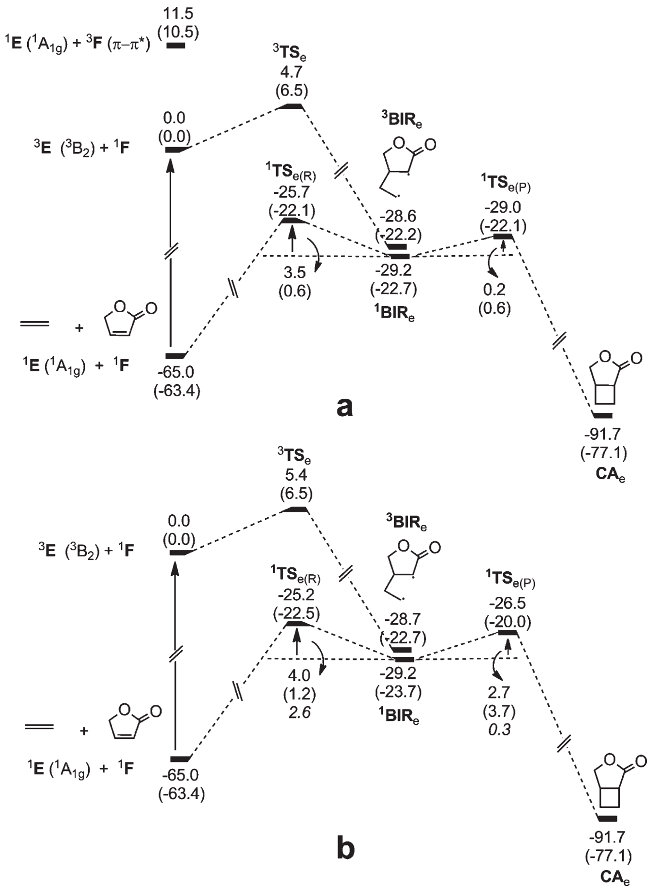

FIGURE 2. Schematic potential energy profile for the reaction of ethylene and 2(5*H*)-furanone at the MPWB1K and B3LYP (values in parentheses) levels of calculation for the gauche-in (a) and gauche-out (b) isomers. For $^{1}\mathbf{TS_{e(R)}}$ and $^{1}\mathbf{TS_{e(P)}}$ of the gauche-out isomer, relative energies at the CASPT2//CASSCF (values in italics) are also included. Energies are in kcal mol^{-1}.

SCHEME 5

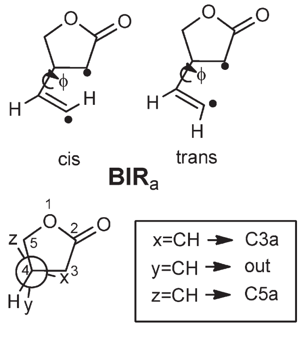

Figure 3 shows the optimized structures of the relevant stationary points involved in the [2 + 2] photocycloaddition of 2(5*H*)-furanone to acetylene, while Figure 4 depicts the schematic energy profile of the reaction. In this case calculations have only been performed at the MPWB1K level, since previous results for the reaction of 2(5*H*)-furanone with ethylene have shown that this functional better compares to CASPT2/CASSCF than B3LYP.

Analysis of the geometries and spin densities of the transition state associated to the attack of acetylene to 2(5*H*)-furanone ($^{3}\mathbf{TS_{a}}$) indicates that the lowest energy path in the triplet state of this system involves the ground state of acetylene and the triplet state of the 2(5*H*)-furanone, as it is generally accepted for the [2 + 2] photocycloaddition of cyclic α,β-unsaturated carbonyl compounds to carbon–carbon multiple bonds.[14,15,17–19]

The reaction profile shown in Figure 4 is similar to that previously found for the cycloaddition process with ethylene. Thus, its first step consists on the attack of acetylene to excited furanone to yield the $^{3}\mathbf{BIR_{a(cis)}}$ intermediate through the $^{3}\mathbf{TS_{a}}$ transition state and a small energy barrier of 0.3 kcal mol^{-1}. This process has to compete with the decay of the triplet state of 2(5*H*)-furanone to its ground singlet state through intersystem crossing. The energy difference between the lowest energy point of the T_1/S_0 intersection space and the minimum of 2(5*H*)-furanone triplet state is 5.5 kcal mol^{-1} at the MPWB1K//CASSCF level. Therefore, the formation of the intermediate is expected to be favored over the deactivation of furanone triplet. Subsequently, the $^{3}\mathbf{BIR_{a\text{-}cis}}$ intermediate can evolve to the singlet 1,4-biradical $^{1}\mathbf{BIR_{a\text{-}cis}}$ through intersystem crossing. As shown in Figures 3 and 4, the $^{3}\mathbf{BIR_{a\text{-}cis}}$ and $^{1}\mathbf{BIR_{a\text{-}cis}}$ stationary points are almost degenerate and their geometries are very similar, which indicates that they are located close to the intersystem crossing region between the singlet and triplet energy surfaces. A closer look to the geometry of the $^{1}\mathbf{BIR_{a\text{-}cis}}$ intermediate clearly indicates that it does not present the suitable conformation to obtain the final cyclic product $^{1}\mathbf{CA_{a}}$. Instead, it must first evolve to the $^{1}\mathbf{BIR_{a\text{-}trans}}$ intermediate prior to cyclization, a *cis*–*trans* interconversion process that was found to take place through the $^{1}\mathbf{TS_{(cis-trans)}}$ transition state with an energy of 4.3 kcal mol^{-1}. As observed for $^{3}\mathbf{BIR_{a\text{-}cis}}$ and $^{1}\mathbf{BIR_{a\text{-}cis}}$, this transition state as well as the $^{1}\mathbf{BIR_{a\text{-}trans}}$ intermediate with *trans* configuration sit near the intersystem crossing region, since they are almost degenerate with respect to their counterparts in the triplet potential energy surface.

Alternatively to the *cis-trans* isomerization, $^{1}\mathbf{BIR_{a\text{-}cis}}$ can also dissociate to yield the initial reactants through the $\mathbf{TS_{a\text{-}cis(R)}}$ transition state, which has an energy of 3.7 kcal mol^{-1}. This dissociation energy barrier is slightly smaller than that for the *cis-trans* interconversion, which suggests that both reaction channels will take place with similar rates. Finally, the $^{1}\mathbf{BIR_{a\text{-}trans}}$ intermediate formed by *cis-trans* isomerization can evolve to the cycloaddition product $^{1}\mathbf{CA_{a}}$ through the $^{1}\mathbf{TS_{a\text{-}trans(P)}}$ transition state with a small barrier of 0.5 kcal mol^{-1}.

Triplet Sensitization of 2(5*H*)-Furanone vs Triplet Sensitization of the Carbon–carbon Unsaturated Compound. It is widely accepted that [2 + 2] photocycloaddition of cyclic α,β-unsaturated carbonyl compounds to carbon–carbon multiple bonds proceed via triplet sensitization of the carbonyl moiety.[15] The quantum-mechanical calculations performed in this work demonstrate that it is indeed expected for the reaction of 2(5*H*)-furanone with acetylene. However, our theoretical results reveal that the minimum energy path for the photoinduced cycloaddition between ethylene and 2(5*H*)-furanone involves the triplet state of the alkene instead of that of the lactone. To investigate experimentally this situation, we have performed transient-absorption measurements on the ethylene-2(5*H*)-furanone system using a nanosecond laser flash photolysis system.

Under typical synthetic experimental conditions, reactant triplet-state formation in a [2 + 2] photocycloaddition

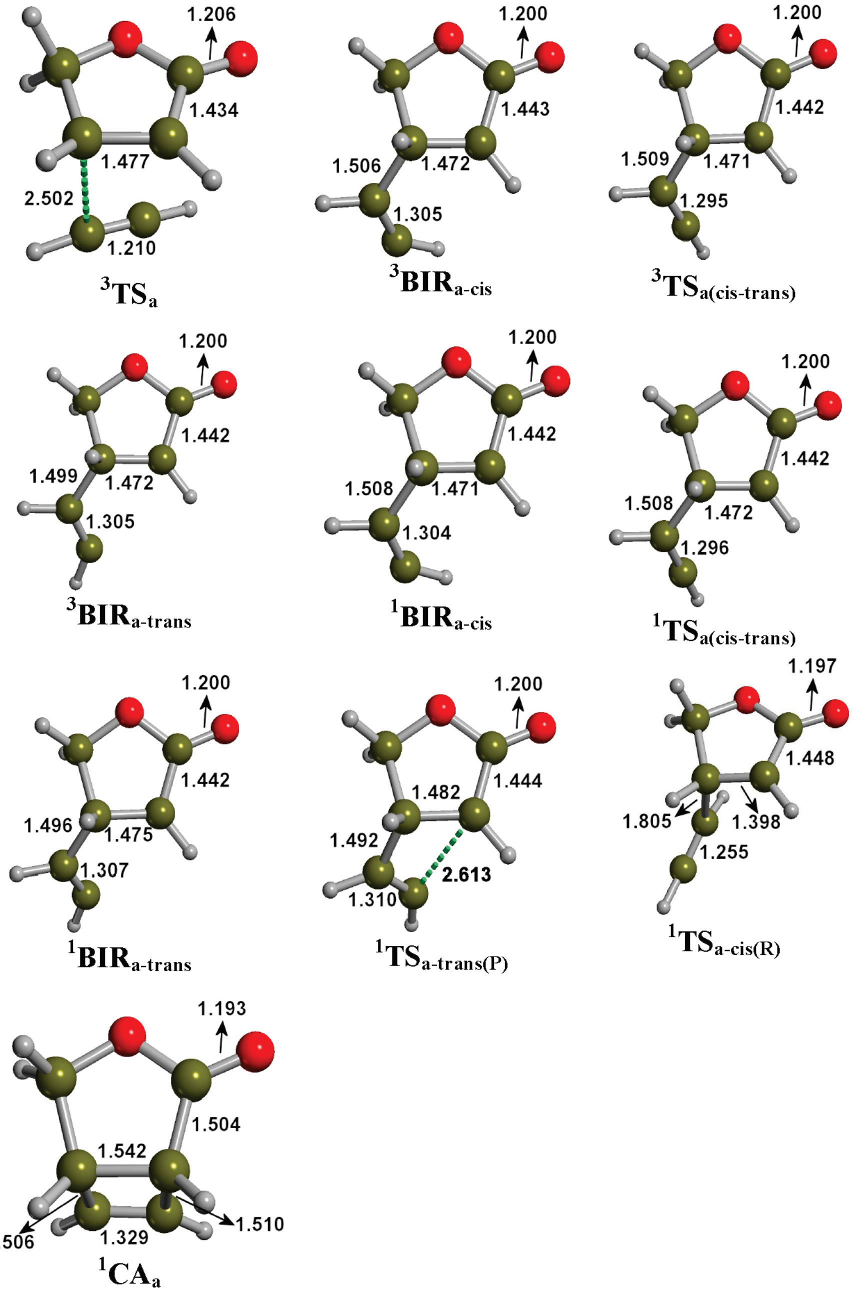

FIGURE 3. MPWB1K-optimized geometries of the different stationary points involved in the reaction between acetylene and 2(5*H*)-furanone. Distances are given in angstroms.

between a lactone and an olefin is often not attained by direct excitation of these species but it involves the use of a triplet sensitizer. In fact, this is specially indicated if the reaction has to proceed via triplet excitation of ethylene due to the high energy of the singlet–singlet absorption transition of the alkene.[48] Instead, ethylene triplet state must be generated via energy transfer from other photoinduced triplet states in the reaction mixture. In our studies, we have employed acetone as such triplet sensitizer, thus mimicking standard synthetic conditions in which acetone is used as solvent for the photocycloaddition process.

To assess the triplet energy transfer efficiencies of acetone to ethylene, we have monitored the time-resolved transient absorption of acetone triplet state in acetone-ethylene mixtures. Upon excitation of an N_2-purged solution of acetone in acetonitrile (c = 0.1 M) with a laser pulse at 266 nm, acetone triplet state is generated, whose transient absorption is found to peak at ~302 nm and decay with a characteristic exponential lifetime of 47 μs, in good agreement with previous reported data.[49] When the acetone solution is saturated with ethylene, a much faster decay of acetone triplet state absorption is measured with a characteristic exponential lifetime of

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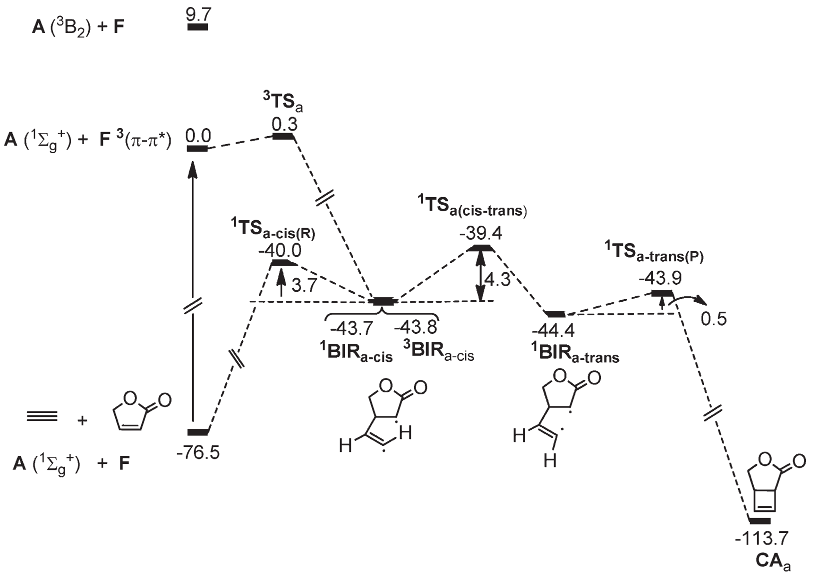

FIGURE 4. Schematic potential energy profile for the reaction of acetylene and 2(5*H*)-furanone at the MPWB1K level of calculation. Energies are in kcal mol^{-1}.

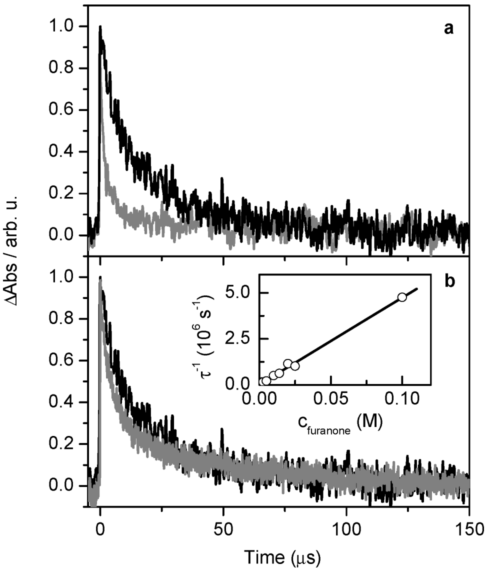

FIGURE 5. (a) Transient-absorption decays of N_2-purged 0.1 M solution of acetone in acetonitrile (black) and ethylene-saturated 0.1 M solution of acetone in acetonitrile (gray) after laser pulse excitation at 266 nm and detection at 302 nm. (b) Transient-absorption decays of N_2-purged 0.1 M solution of acetone in acetonitrile (black) and N_2-purged 0.1 M solution of acetone in acetonitrile that is 0.01 M in 2(5*H*)-furanone (gray) after laser pulse excitation at 266 nm and detection at 302 nm. The inset in (b) plots the inverse of the acetone triplet lifetime (τ^{-1}) recovered from exponential fit of the decays against the concentration of 2(5*H*)-furanone in the mixture, as well as the corresponding linear fit.

2.1 μs, as shown in Figure 5a. This clearly demonstrates that ethylene quenches acetone triplet state, a process for which a rate constant equal to k_q(ethylene) = 2×10^7 s^{-1}[50] has been determined by applying the Stern–Volmer equation.[51] Such deactivation process to yield the ground-state ketone can be ascribed to either triplet energy transfer to the alkene or revertible chemical addition.[52] In our case, we have observed the formation of a byproduct, polyethylene, upon irradiation of the investigated acetone–ethylene mixture. Since photo-induced polymerization of ethylene is promoted by triplet state formation of the alkene[53] this suggests the occurrence of triplet state ethylene sensitization by acetone at typical synthetic conditions. Moreover, it also indicates that the lifetime of such ethylene triplet state should be long enough as to undertake intermolecular reactions, as for instance, with 2(5*H*)-furanone to yield a photocycloadduct.

However, at typical synthetic conditions, triplet sensitization of 2(5*H*)-furanone by acetone can not be overlooked, since the adiabatic singlet–triplet energy of this lactone is similar to that of ethylene (see Figure 2). Accordingly, we have also evaluated the effect of 2(5*H*)-furanone on acetone triplet state lifetime by recording the transient absorption decay of a N_2-purged solution of acetone in acetonitrile upon addition of several amounts of the lactone. Two main features are observed in these experiments, as depicted in Figure 5b. On the one hand, the presence of 2(5*H*)-furanone in the mixture makes the transient absorption decay at 302 nm be no longer monoexponential, but biexponential, since both the triplet states of acetone and the lactone absorb at this wavelength.[54] More importantly, analysis of the acetone triplet state lifetime determined from the biexponential decays allows us concluding that it decreases with increasing

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(50) To derive k_q(ethylene) the ethylene concentration in the saturated solution must be known as well. To our knowledge, the solubility (s) of ethylene in acetonitrile has not been reported so far, and we have estimated this value by integration of the ^{1}H NMR signals of a saturated solution of ethylene in acetonitrile (s = 0.029 M).

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(53) Miyuki, H.; Hidemasa, O.; Tsukasa, K.; Tsutomu, K. *J. Polym. Sci., Part A: Polym. Chem.* **1970**, *8*, 3295.

(54) Although the transient absorption of 2(5*H*)-furanone triplet state in acetone is found to peak at ~360 nm, this species gives rise to a residual absorption signal at 302 nm, whose intensity is much lower than that of ethylene triplet state but rises with increasing concentration of 2(5*H*)-furanone until a significant contribution to the overall decay trace is displayed at this wavelength. It is important to note that 2(5*H*)-furanone triplet state may be generated both by direct absorption of the lactone at 266 nm and sensitization via ethylene triplet state.

TABLE 1. Singlet–triplet Adiabatic Excitation Energies, in kcal mol^{-1}

	B3LYP	MPWB1K	CCSD(T)[a]	CASPT2[b]	expt
acetylene	83.9	86.2	84.0		82.6[c]
ethylene	63.4	65.0	66.3	63.6	58 ± 3[d]
2(5*H*)-furanone	73.9	76.5	76.3	70.7	75–80[e]
5,6-dihydro-2*H*-pyran-2-one	65.3	67.4	69.2		
2-cyclopentenone	69.9	72.0	72.9		73[f]
2-cyclohexenone	63.7	65.7	67.9		

[a] Single-point energy at the MPWB1K-optimized geometries. [b] Single-point energy at the CASSCF-optimized geometries. [c] Reference 56. [d] Reference 57. [e] Estimated values based on triplet senzitization and quenching experiments: refs 24–26. [f] Reference 23.

concentration of 2(5*H*)-furanone, thus suggesting the occurrence of triplet energy transfer to produce 2(5*H*)-furanone triplet state. From the Stern–Volmer plot shown in the inset of Figure 5b, the triplet state deactivation rate constant for the acetone-ethylene couple is measured to be k_q(2(5*H*)-furanone) = $4.7 \times 10^{7}\ \mathrm{s}^{-1}$. Interestingly, comparison of this value with k_q(ethylene) indicates that sensitization of ethylene and 2(5*H*)-furanone triplet states by acetone proceeds with similar rates. In fact, sensitization of ethylene triplet state over generation of 2(5*H*)-furanone triplet state is expected to be favored at typical synthetic conditions, where very high amounts of sensitizer (e.g., acetone as solvent) and larger concentrations of ethylene than 2(5*H*)-furanone (e.g., saturated solution of ethylene and 0.005 M of lactone) are employed. Together with the theoretical results demonstrating that the minimum energy path proceeds via the triplet state of the alkene, this indicates that such reaction pathway might significantly contribute to the overall photocycloaddition process. Nevertheless, the actual contribution of each of the possible pathways to this reaction will also depend on additional dynamical aspects, such as the energy transfer rate from 2(5*H*)-furanone triplet state to ethylene triplet state (since both can be sensitized by acetone and the latter is lower in energy) and the lifetimes of those triplet species. Such lifetimes will be very sensitive to the occurrence of competing triplet-state relaxation processes. For instance, 1,2-disubstituted alkenes can undergo (*E*)-(*Z*) photoisomerization in photocycloaddition reactions to enones,[55] which may diminish the efficiency of the photoreaction process evolving through the triplet state of the olefin as well as partially justify the loss of the configuration of the starting olefin in the final cycloadduct.

Singlet–Triplet Excitation Energies. Overall, the quantum-mechanical calculations performed in this work demonstrate that the minimum energy path for the photoinduced cycloaddition between 2(5*H*)-furanone and acetylene involves the triplet state of the lactone, in agreement with the widely accepted assumption that [2 + 2] photocycloaddition of cyclic α,β-unsaturated carbonyl compounds to carbon–carbon multiple bonds proceed via triplet sensitization of the carbonyl moiety.[15] However, our theoretical results reveal that the minimum energy path for the photoinduced cycloaddition between ethylene and 2(5*H*)-furanone involves the triplet state of the alkene instead of that of the lactone, a reaction pathway whose contribution to the overall process is supported by our additional experimental studies. As a simple way to predict whether the minimum energy path for the [2 + 2] photocycloaddition evolves via the triplet state of the carbonyl compound or of the species with carbon–carbon multiple bonds, we propose analyzing the relative singlet–triplet energy gap of the reactants. With this aim, we have computed the adiabatic singlet–triplet excitation energies of several species of interest that may be involved in this kind of reactions. Excitation energies at different levels of theory are given in Table 1 (optimal geometries of all these species in their singlet (S_0) and triplet (π–π^*) (T_1) states are included in Figure S1 of the Supporting Information).

Clearly, the excitation energies of enones and lactones computed at the B3LYP level are somewhat underestimated compared to the values obtained at both MPWB1K and CCSDT(T)//MPWB1K levels. On the other hand, there is an excellent agreement between the MPWB1K and CCSD(T) values, which are moreover in very good agreement with the available experimental data. For ethylene and acetylene, excitation energies are somewhat overestimated at all levels of calculation.

It can be observed in Table 1 that the value of the excitation energy of the considered cyclic compounds decreases with the size of the ring. This can be understood considering that the T_1 excited state corresponds to a twisted structure. In the case of acyclic systems the C–C–C–C torsion angle around the initial C–C double bond is around 90° as in the case of triplet ethylene. However, in the case of cyclic compounds the value of the torsion angle depends on the rigidity of the ring. Five-membered ring compounds are more rigid (the values of the torsion angle are 25.8° for 2(5*H*)-furanone and 24.4° for 2-cyclopentenone at the MPWB1K level) than six-membered rings (torsion angle is 34.2° both for 5,6-dihydro-2*H*-pyran-2-one and 2-cyclohexenone). That is, increasing the ring-size allows larger geometrical relaxation for the T_1 twisted structure, and consequently, the excitation energy decreases.

On the other hand, if one compares compounds of the same ring size, the excitation energies for lactones are larger than for enones. This is due to the presence of the oxygen atom in the ring of the lactone which lowers the energy of the HOMO orbital as compared to the enone compounds.

Finally, it should be noted that the excitation energy of acetylene is larger than that of the lactones and enones considered. However, the excitation value for ethylene is of the same order as that of the six-membered ring compounds but clearly smaller than for the five-membered ring compounds. This indicates that triplet sensitization of ethylene is less energetically demanding than that of the lactone, thus suggesting that their photocycloaddition reaction could evolve through the triplet state of the alkene instead of that of the enone. We expect this dual mechanism (alkene triplet state + lactone singlet state or alkene singlet state + lactone triplet state) to influence the facial diastereoselectivity of

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(57) Qi, F.; Sorkhabi, O.; Suits, A. G. *J. Chem. Phys.* **2000**, *112*, 10707.

[2 + 2] photocycloadditions involving chiral furanones (see Scheme 1), since the approach of the olefin to the furanone should be controlled by the geometry of the reactants, the singlet and triplet states of the alkene and lactone being significantly different (see Figure S1, Supporting Information). Therefore, the validity of the computational method selected herein to treat [2 + 2] photocycloadditions for the benchmark systems ethylene + 2(5*H*)-furanone and acetylene + 2(5*H*)-furanone has been tested, and work is in progress to theoretically investigate the effect of the reaction mechanism on the photoreactions with homochiral 5-substituted 2(5*H*)-furanones.

Conclusions

The [2 + 2] photocycloaddition reaction of 2(5*H*)-furanone to ethylene and acetylene has been investigated by means of DFT and CASSCF methods. In both cases, the reaction involves the formation of a triplet 1,4-biradical intermediate that, after spin−spin inversion, evolves to the cyclobutane derivative. For acetylene, the lowest energy path in the triplet state involves the ground state of acetylene and the triplet $^3(\pi-\pi^*)$ excited state of the 2(5*H*)-furanone. However, for ethylene, calculations show that the lowest triplet surface involves the reaction of ethylene in its triplet $^3(\pi-\pi^*)$ state with the ground state of furanone. Although [2 + 2] photocycloaddition of cyclic α,β-unsaturated carbonyl compounds to carbon−carbon double bonds through the triplet state of alkenes is usually disregarded because of the short lifetimes of these species, some experimental evidence appears to indicate that they can contribute to the overall process. First, transient-absorption measurements on the ethylene-2(5*H*)-furanone system using a nanosecond laser flash photolysis system have shown that sensitization of ethylene and 2(5*H*)-furanone triplet states at typical synthetic conditions proceeds with similar rates. Second, formation of polyethylene as byproduct is observed. Thus, although the deactivation of the triplet state of ethylene is expected to be fast due to facile intersystem crossing near the twisted minimum on the T_1 $^3(\pi-\pi^*)$ potential energy surface, the lifetime of this species appears to be large enough as to result in photopolymerization. If similar considerations apply in the reaction of ethylene triplet state with furanone, this reaction pathway will significantly contribute to the overall photocycloaddition process. The occurrence of such mechanism could then influence the stereochemistry of the products formed in photochemical reactions involving chiral lactones.

Acknowledgment. Financial support from “Ministerio de Ciencia e Innovación” (MICINN) and “Departament d’Universitats, Recerca i Societat de la Informació” (DURSI), through the CTQ2008-06381/BQU, SGR2005-00244, CTQ2007-60613(BQU) and CTQ2009-07469(BQU) projects, and the use of the Catalonia Supercomputer Centre (CESCA) are gratefully acknowledged.

Supporting Information Available: Atom coordinates for all of the optimized structures and computed absolute potential energies. This material is available free of charge via the Internet at http://pubs.acs.org.