ORGANIC
LETTERS

2009
Vol. 11, No. 7
1495−1498

Ultrafast Asynchronous Concerted Excited-State Intramolecular Proton Transfer and Photodecarboxylation of *o*-Acetylphenylacetic Acid Explored by Combined CASPT2 and CASSCF Studies

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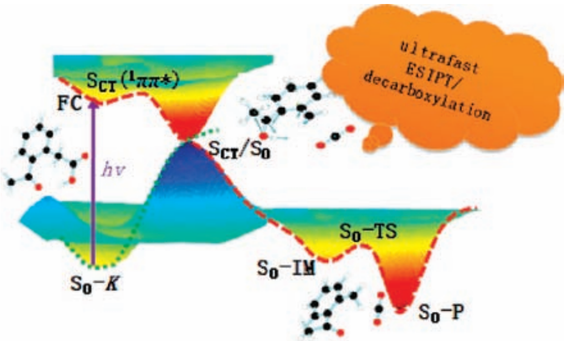
Received January 17, 2009

ABSTRACT



Photodecarboxylation was found to be an ultrafast process for *o*-acetylphenylacetic acid, which is triggered by excited-state intramolecular proton transfer. The reaction starts from the charge-transfer $\pi\pi^*$ singlet state and passes through the conical intersection to the ground state. Subsequent electron transfer and proton transfer in the ground state lead to formation of the final products. This represents a completely new mechanism of photoinduced decarboxylation for various arylcarboxylic acids.

The UV photoinduced decarboxylation of arylcarboxylic acids has received wide attention[1−5] since these acids are nonsteroidal anti-inflammatory agents and have a variety of biochemical and pharmacological applications.[6,7] Photoinduced decarboxylation was found to be an efficient and general reaction for different types of arylcarboxylic acids.[1−5,8] However, the decarboxylation mechanism is very complex, and several issues are still unresolved up to now. The first and most pressing issue involves the nature of the primary chemical step. The polar protic solvent was proposed to be the donor of proton or hydrogen to aid formation of

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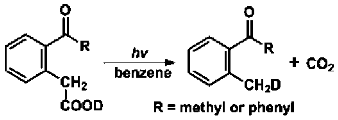
10.1021/ol9001043 CCC: $40.75

products.[1] However, an efficient decarboxylation of *o*-acetylphenyl- and *o*-benzoylphenyl-acetic acids was observed in nonpolar solvent,[8] and the isotopic labeling experiments revealed that the O-deuterated acids yield deuterated *o*-acyltoluene products, as shown in Scheme 1, suggesting an intramolecular proton transfer as the initial step. Another unresolved issue is the possibility of a singlet-mediated mechanism of decarboxylation. The acid form of benzoylphenylacetic acid should behave as a conventional benzophenone, with high intersystem crossing yields and triplet radical-like behavior. However, fluorescence, laser flash photolysis, and quenching studies[1,4] have favored a singlet pathway of decarboxylation for benzoyl-phenylacetic acids in different solvents. More importantly, it is not clear whether the charge-transfer $^1\pi\pi^*$ state is involved in the singlet-mediated mechanism. In addition, the role of potential energy surface intersection in the photodecarboxylation mechanism was not explored for acylphenyl-acetic acids and the related compounds.

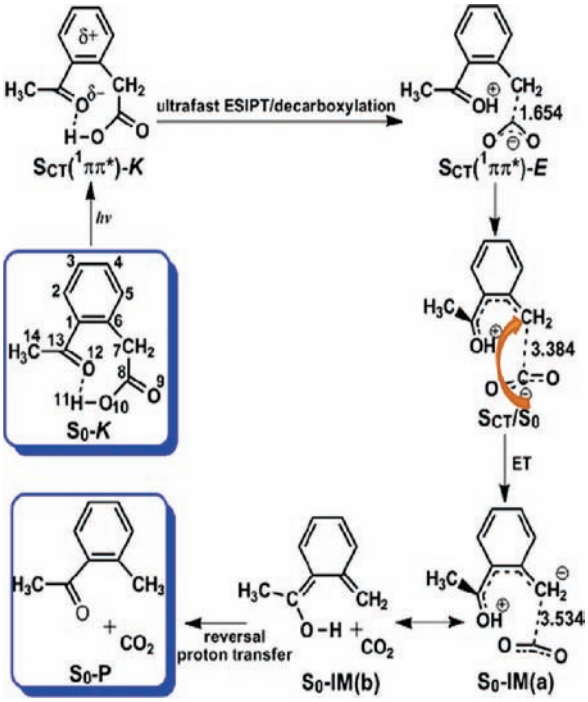
Scheme 1



In this letter, we report the first theoretical study on photoinduced decarboxylation of *o*-acetylphenyl-acetic acid by using combined CASSCF and CASPT2 methods. It was found that excited-state intramolecular proton transfer (ESIPT) is the primary chemical step, which triggers an ultrafast decarboxylation via the conical intersection of the charge-transfer π,π^* singlet and the ground states. Electron transfer and the reversal proton transfer in the ground state play an important role in formation of the final products. The detailed processes are plotted in Scheme 2. Both ESIPT and decarboxylation are ultrafast processes and proceed in an asynchronous concerted way, which represents a new mechanism of photodecarboxylation for various arylcarboxylic acids.

The complete active space self-consistent field (CASSCF) method was used to optimize structures of stationary points for *o*-acetylphenylacetic acid in low-lying states. The intersection structure of S_{CT}/S_0 was determined with the state-averaged CASSCF method. To consider dynamical correlation, the single-point energy is calculated with the second-order perturbation method (CASPT2) on the basis of CASSCF optimized structures. The 6-31G* basis set was used for the CASSCF and CASPT2 calculations. All calculations were performed by using Molcas[9] and Gaussian03[10] program packages.

Scheme 2



We divided the molecule along C1−C13 bond and C7−C8 bond, leading to fragments of 1, 2 and fragments of 3, 4, respectively (see Figure 1). The charge translocation from fragment 1 to 2 (Δq_{2-1}) is defined as the difference between the sum Mulliken atomic charges of fragment 2 (q_{s2}) and

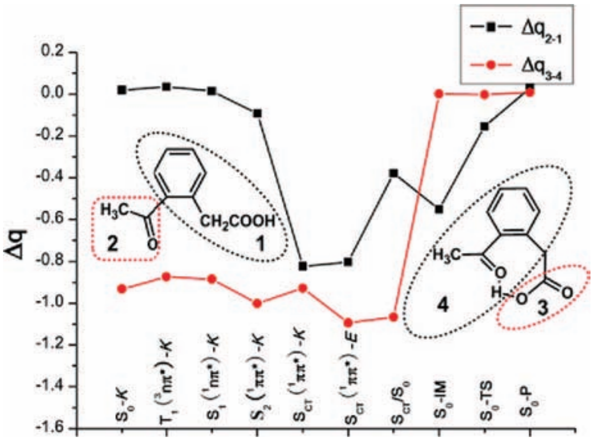


Figure 1. Charge translocation (Δq) values along stationary and intersection points from the phenylacetic acid moiety (1) to the CH_3CO fragment (2) (black line) and from CO_2 (3) to acetyltoluene (4) (red line).

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fragment 1(q_{s1}). The Δq_{4-3} is calculated in the same way. More computational details and results are given in the Supporting Information (SI).

The low-lying four singlet states of *o*-acetylphenyl-acetic acid, S_0-*K*, $S_1(^1n\pi^*)$-*K* (localized in the C13−O12 carbonyl group), $S_2(^1\pi\pi^*)$-*K* (localized in the aromatic ring), and $S_{CT}(^1\pi\pi^*)$-*K* (charge transfer from the aromatic ring to the C13−O12 carbonyl group), were optimized at the CASSCF(12e,9o) level. With respect to the S_0-*K* zero level, the relative energies of $S_1(^1n\pi^*)$-*K*, $S_2(^1\pi\pi^*)$-*K*, and $S_{CT}(^1\pi\pi^*)$-*K* were predicted to be, respectively, 81.2, 94.9, and 123.0 kcal/mol by the CASPT2(12e,9o) calculations. The band origins of the $S_1(^1n\pi^*)\leftarrow S_0$ and $S_2(^1\pi\pi^*)\leftarrow S_0$ transitions for acetophenone[11] were observed to be 77.9 and 101.2 kcal/mol, respectively. The $S_{CT}(^1\pi\pi^*)$-$K\leftarrow S_0$-*K* transition has an oscillator strength of 0.31 that is much larger than those for $S_2(^1\pi\pi^*)$-$K\leftarrow S_0$-*K* and $S_1(^1n\pi^*)$-$K\leftarrow S_0$-*K* absorptions (see SI), which shows that the UV irradiation mainly results in the molecule populated in the $S_{CT}(^1\pi\pi^*)$-*K* state.

The charge-transfer character of the $S_{CT}(^1\pi\pi^*)$ state was confirmed by the calculated charge translocations. As depicted in Figure 1 (black line), the $S_{CT}(^1\pi\pi^*)$-$K\leftarrow S_0$-*K* excitation results in ∼0.5 atomic charge translocated from the aromatic ring, leading to a negative charge center at the C13═O12 carbonyl group. Accordingly, the dipolar moment is significantly increased from 7.2 Debye in S_0-*K* to 9.4 Debye in $S_{CT}(^1\pi\pi^*)$-*K*. With respect to the other excitation patterns, the $S_{CT}(^1\pi\pi^*)$-$K\leftarrow S_0$-*K* transition reveals the largest dipolar moment change ($\Delta\mu$) and charge translocation (Δq). Much more negative charges were distributed in the O12 center in $S_{CT}(^1\pi\pi^*)$-*K*, as compared with those in the ground and other excited states. This is an important driving force for ultrafast proton tranfer in the $S_{CT}(^1\pi\pi^*)$ state. It is evident that $S_{CT}(^1\pi\pi^*)$ is a favorable precursor state for proton transfer due to the negative charge center at the carbonyl group as a proton acceptor. Besides charge distribution, the further evidence for $S_{CT}(^1\pi\pi^*)$ as a favorable precursor state for proton transfer comes from the optimized structures. The O12···H11 H-bond distance is predicted to be 1.93 Å in the S_0-*K* state, but the H-bond becomes stronger in $S_{CT}(^1\pi\pi^*)$-*K* with the O12···H11 distance of 1.655 Å, paving a short way for the movement of protons to facilitate the occurrence of proton transfer in the $S_{CT}(^1\pi\pi^*)$ state. Considering two factors mentioned above, excited-state intramolecular proton transfer (ESIPT) for *o*-acetylphenylacetic acid would take place with high efficiency.

The proton transfer process on the $S_{CT}(^1\pi\pi^*)$ state was determined by the CASSCF(12e,9o) stepwise optimizations with the O10−H11 distance fixed at different values and other bond parameters relaxed fully. The CASPT2(12e,9o) calculated relative energies were shown in Figure 2. It is found that the potential energy profile, which connects $S_{CT}(^1\pi\pi^*)$-*K* and its tautomer of $S_{CT}(^1\pi\pi^*)$-*E*, is very flat with a tiny barrier or barrierless on the pathway. This clearly shows that ESIPT is an ultrafast process for *o*-acetylphenyl-acetic acid. The large number of femtosecond real-time probing together with spectroscopic studies has demonstrated that ESIPT can take place within 100 fs.[12] An efficient decarboxylation of *o*-acetylphenyl- and *o*-benzoylphenyl-acetic acids was observed in nonpolar solvent, and the O-deuterated acids yield deuterated *o*-acyltoluene products,[8] which supports occurrence of the intramolecular proton transfer as the initial step of the decarboxylation process. It should be pointed out that the present CASPT2 calculations may overestimate the relative energy of the $S_{CT}(^1\pi\pi^*)$ state, as compared with the excitation wavelength used in the experiment,[8] since the solvent effect is not included in the present work.

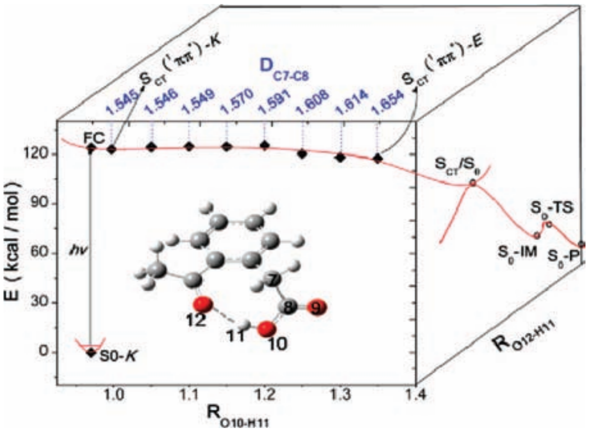

Figure 2. Potential energy profiles of ESIPT, decarboxylation, and subsequent process in the ground state.

As shown in Figure 2, the C7−C8 distance (D_{C7-C8}) is remarkably elongated with the evolvement of proton transfer in the $S_{CT}(^1\pi\pi^*)$ state, leading to partial breaking of the C7−C8 bond with the distance of 1.65 Å in $S_{CT}(^1\pi\pi^*)$-*E*. In addition, the O10−C8−O9 angle is gradually increased from 123.7° in $S_{CT}(^1\pi\pi^*)$-*K* to 133.5° in $S_{CT}(^1\pi\pi^*)$-*E*. These changes in structure reveal that the decarboxylation is triggered by the excited-state intramolecular proton transfer. Actually, the ESIPT and decarboxylation processes occur

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in an asynchronous concerted way. Experimentally, it has been found that an ultrafast ESIPT process can couple with other different processes.[13]

The conical intersection of the $S_{CT}(^1\pi\pi^*)$ and S_0 surfaces, referred to as S_{CT}/S_0 hereafter, was determined with the state-averaged CASSCF(12e,9o) optimization. The S_{CT}/S_0 conical intersection was found to be 31.4 kcal/mol lower than $S_{CT}(^1\pi\pi^*)$-*E* in energy by the CASPT2(12e,9o) calculations. The C7−C8 bond is broken at the S_{CT}/S_0 structure with the C7−C8 distance of 3.384 Å, and the O10−C8−O9 moiety of the S_{CT}/S_0 structure appears to have structural characteristics of CO_2. However, there is about −0.5 atomic charge distributed in the O10−C8−O9 moiety. As shown in Figure 1 (red line), there is a sharp turning point of charge translocation at the S_{CT}/S_0 structure. Once the system passes through the S_{CT}/S_0 conical intersection, electron transfer occurs from the CO_2 group to the acetyltoluene moiety. The initially formed S_0-IM(a) intermediate is of zwitterionic character and is easily converted into an enol form of S_0-IM(b) (see Scheme 2). A similar enol intermediate was detected in the photodecarboxylation of *p*-benzolphenyl-acetic acid.[3d] Generally, internal conversion at a conical intersection takes place in a time scale of subpicoseconds.[14] As pointed out before, there is a tiny barrier on the ESIPT pathway, and ESIPT is an ultrafast process. Thus, the UV photoinduced decarboxylation is also an ultrafast process for *o*-acetylphenyl-acetic acid and the related compounds. This is consistent with the experimental observations[1−5,8] that photoinduced decarboxylation is a very efficient reaction for arylcarboxylic acids.

The isomerization pathway of the S_0-IM(b) intermediate to *o*-acetyltoluene was traced, and a transition state was determined on the pathway, referred to as S_0-TS in Figures 1 and 2. The barrier height was predicted to be less than 5.0 kcal/mol at the CASPT2//CASSCF level. After the CO_2 molecule is formed, the system is left with sufficient internal energies to overcome the barrier, achieving a fast process of reversal proton transfer in the ground state and yielding a final product of *o*-acetyltoluene.

An intramolecular proton transfer has been suggested as the initial step in the decarboxylation process of *o*-acetylphenyl- and *o*-benzoylphenyl-acetic acids.[8] The n,π^* excited-state of the ketone chromophore was proposed as the precursor state where γ-hydrogen abstract occurs, generating a biradical. The biradical undergoes isomerization, rearrangement, and proton transfer, forming the final products of CO_2 and *o*-acetyltoluene.[8] We investigated the possibility of H11 (atom or proton) transfer from O10 along the S_0 and T_1 pathways. The barrier height for the H11 transfer was predicted to be 65.8 kcal/mol in the $T_1(^3n\pi^*)$ state and 40.1 kcal/mol in the S_0 state by the CASSCF/6-31G* calculations, which cannot account for efficient decarboxylation observed in experiment.[8] There is little possibility for the initial H11 transfer along the S_0 or T_1 pathway, as compared with ultrafast asynchronous concerted ESIPT and decarboxylation along the $S_{CT}(^1\pi\pi^*)$ state.

Photochemical reactions generally occur from the lowest excited singlet or triplet state regardless of the initial exited state populated by photoexcitation (Kasha's rule).[15] We investigated a series of aromatic carbonyl compounds, showing that Norrish type I and II reactions take place in the lowest triplet state via $S_1/T_1/T_2$ three surface intersection.[16] However, the decarboxylation of *o*-acetylphenyl-acetic acid starts from the highly excited singlet state with charge-transfer character, which represents unusual photochemistry for aromatic ketones. Ultrafast photodecarboxylation in *o*-acetylphenyl-acetic acid provides a case of anti-Kasha's rule in aromatic carbonyl compounds. The present work not only well elucidates the experimental observations[8] but also first provides the evidence of ultrafast events in aromatic carbonyl compounds. This is a new example of ESIPT coupled with the photochemical process[12,13] and may stimulate the research interests of scientists in the field of ultrafast laser spectroscopy. *m*-Acetylphenyl-acetic acid has been shown to undergo efficient photodecarboxylation in aqueous solutions.[17] Probably, water bridge assisted intramolecular proton transfer as the primary mechanism is feasible for the meta-isomer of *o*-acetylphenyl-acetic acid. We will move our attention to this issue and report results in due course.

In summary, we report the first CASPT2//CASSCF study on photodecarboxylation of *o*-acetylphenyl-acetic acid. S_{CT}-$(^1\pi\pi^*)$ was found to be the precursor state where an intramolecular proton transfer occurs, which triggers an ultrafast decarboxylation. The ESIPT and decarboxylation processes proceed in an asynchronous concerted way. The S_{CT}/S_0 conical intersection, electron transfer, and the reversal proton transfer in the ground state play an important role in formation of the final products. It can be expected that ultrafast asynchronous concerted ESIPT and decarboxylation could be a common phenomenon for different types of *o*-acylphenyl-acetic acids and the related compounds. The present work not only well elucidates the experimental observations but also first provides the evidence of ultrafast events in aromatic carbonyl compounds, which may stimulate the research interests of scientists in the field of ultrafast laser spectroscopy.

Acknowledgment. This work was supported by grants from the NSFC (Grant No. 20720102038) and from the Major State Basic Research Development Programs (Grant No. 2004CB719903).

Supporting Information Available: Computational details, Tables, Cartesian Coordinates, and absolute energies. This material is available free of charge via the Internet at http://pubs.acs.org.

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