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Concurrent Cyclopropanation by Carbenes and Carbanions? A Density Functional Theory Study on the Reaction Pathways

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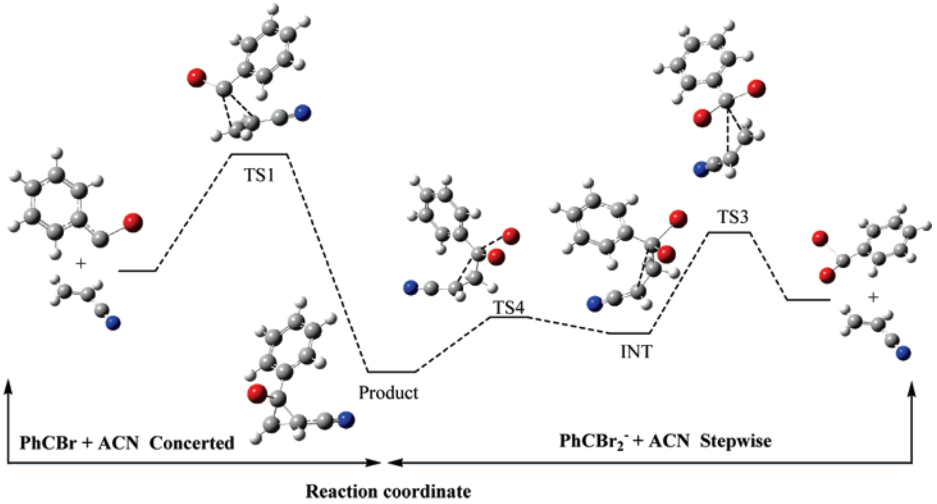

The mechanisms for the addition reactions of phenylhalocarbenes and phenyldihalomethide carbanions with acrylonitrile (ACN) and trimethylethylene (TME) have been investigated using an ab initio BH and HLYP/6-31G (d, p) level of theory. Solvent effects on these reactions have been explored by calculations that included a polarizable continuum model (PCM) for the solvent (THF). These model calculations show that for the addition of phenylhalocarbenes, a TME species may readily undergo addition reactions with carbenes while ACN has a high-energy barrier to overcome. It was also found that phenyldihalomethide carbanions do not readily add to the electron-rich TME. The cyclopropane yields only appear to occur via addition of PhCBr to TME. However, the cyclopropanation proceeds not only via slow addition of phenylhalocarbenes to ACN but also forms through the stepwise reaction of phenyldihalomethide carbanions with ACN. Our calculation results are in good agreement with experimental observations (Moss, R.A.; Tian, J.-Z. *J. Am. Chem. Soc.* **2005**, 127, 8960) that indicate that the cyclopropanation of phenylhalocarbenes and phenyldihalomethide carbanions with ACN are concurrent in THF.

1. Introduction

Cyclopropanes are of interest as synthetic intermediates and as biologically relevant moieties of constrained geometry, and their preparation is typically achieved by cyclopropanation reactions that involve the formal addition of a carbene to an alkene.[1] The initial interaction between the empty p-like orbital of the carbene and the filled π-orbital of the alkene plays an important part in cyclopropanation reactions, and this has been the subject of numerous theoretical studies and has also been practically applied to organic synthesis.[2−15] While the cyclopropanation reactions involving carbenes have received much

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attention, there has been much less interest shown in cyclopropanation reactions involving carbanions. Hine used kinetic and trapping experiments to demonstrate that the trichloromethide carbanion is one of the intermediates formed during the generation of dichlorocarbene by the basic hydrolysis of chloroform in the 1950s.[16] Hine and co-workers also demonstrated that CCl_2 could be trapped by other halide ions to yield trichloromethide carbanions.[17] Trihalomethides are well-established intermediates in other dihalocarbene generative methods, including the reaction of NaI with $PhHgCCl_2Br$[18] and the phase-transfer catalytic generation of CCl_2,[18] CBr_2.[19] In the latter cases, evidence had been observed for rapid dihalocarbene/halide/trichloromethide equilibrations.[20,21] Recently, Moss and Tian[22] observed that (1) the deliberate addition of halide ions resulted in concurrent cyclopropanation of phenylhalocarbenes and phenyldihalomethide carbanions, and this allows a smooth modulation of the selectivity between electron-rich and electron-poor alkenes; (2) the addition of phenylhalocarbenes and phenyldihalomethide carbanions with acrylonitrile (ACN) or trimethylethylene (TME) gave the PhCBr addition product (both as syn/anti isomer mixtures); (3) addition of TBABr gave a smooth increase in the relative reactivity of ACN versus TME; (4) for the reaction of phenyldihalomethide carbanions with ACN, a stepwise addition, rather than a concerted reaction, has been postulated to account for these unprecedented TBABr induced enhancements of PhCBr selectivity toward electron-poor alkenes. To examine the mechanisms of these reactions, we have undertaken a detailed investigation of the addition reactions of phenylhalocarbenes and phenyldihalomethide carbanions with trimethylethylene (TME) and acrylonitrile (ACN) by using density functional theory (DFT) calculations. The purpose of the present DFT study was to locate the transition states for the reactions and to carry out a vibrational analysis at these stationary points. Thus, we hope to clarify the factors that control the activation barriers for these addition reactions. We also want to further investigate the effects of solvent on the thermodynamic and kinetic properties of these reactions. It is well-known that solvent effects play an important role in determining rates of reaction, equilibrium constants, and other quantities of chemical and biochemical processes. Our present study provides some theoretical information about solvent effects on these kinds of reactions.

2. Computational Methods

Geometries, energies, and first- and second-energy derivatives of all stationary points were fully optimized by hybrid density functional theory (DFT) using the GAUSSIAN 03 program suite.[23] Exchange and correlation were treated by the BHandHLYP method, which is based on Becke's half-and-half method[24] and the gradient-corrected correlation functional of Lee et al.[25] This hybrid DFT method gives more accurate barrier heights than other hybrid DFT methods, such as B3LYP and B3P86.[26] The 6-31G[27] basis set with polarization (d) and (p) were used in all calculations (five-component d functions were used with 5d keyword). Vibrational frequency calculations at the BHandHLYP/6-31G (d, p) level of theory were used to characterize all of the stationary points as either minima (the number of imaginary frequencies (NIMAG = 0) or transition states (NIMAG = 1)). The relative energies are, thus, corrected for vibrational zero-point energies (ZPE, not scaled), and the transition states both to the reactants and the products direction in the reaction paths were examined by using the intrinsic reaction coordinate (IRC).[28] Cyclopropanation reactions are usually done

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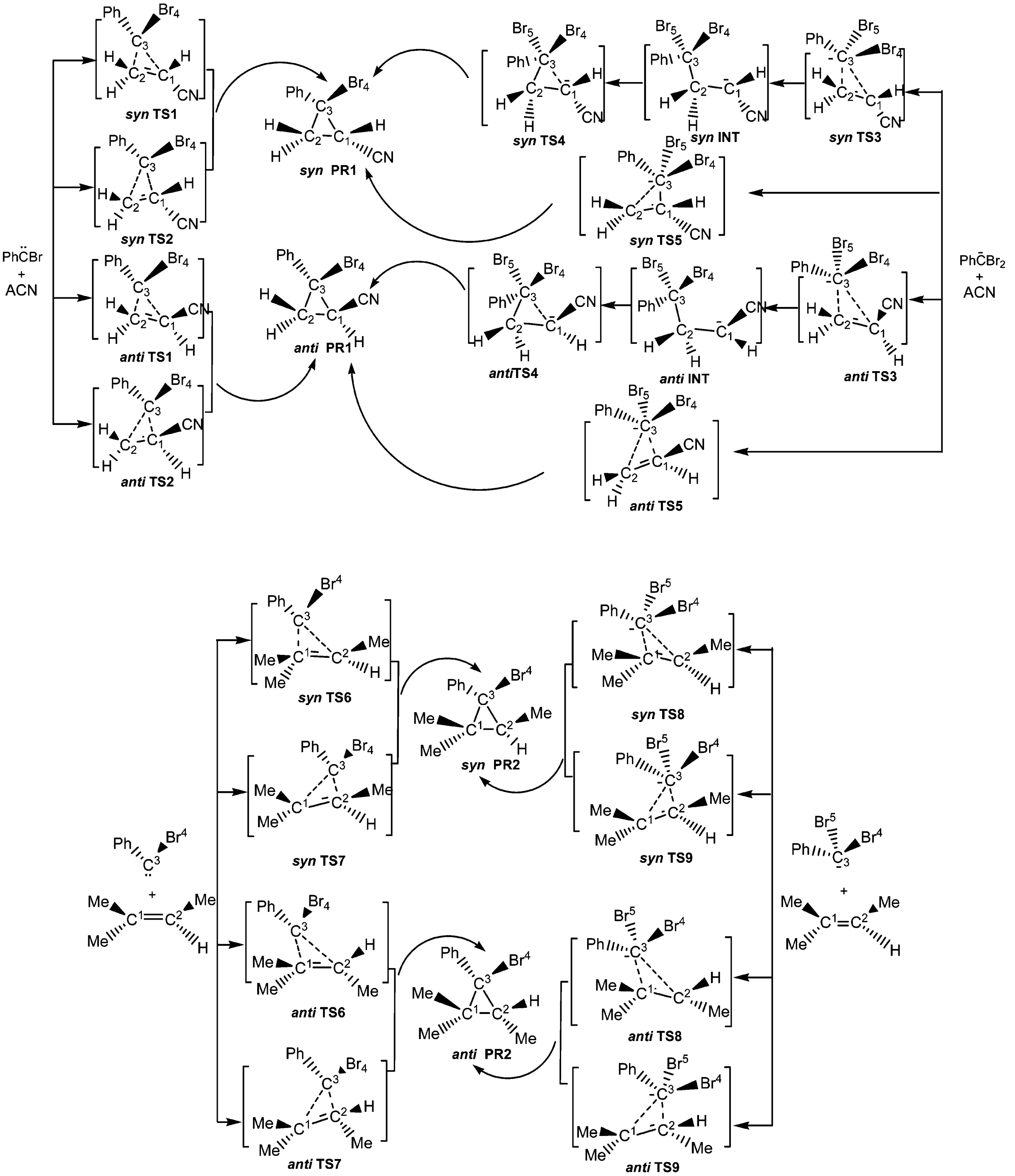

FIGURE 1. Reaction routes of phenylhalocarbenes and phenyldihalomethide carbanions with acrylonitrile (ACN) and trimethylethylene (TME).

in polar organic solvents for many carbene reactions. For the title reaction, THF is almost exclusively used as the solvent. To consider the effect of the THF solvent on the title reaction, the polarized continuum model (PCM) was applied,[29] and single-point energy calculations were done at the BHandHLYP/PCM/6-311++G (d, p)//BHandHLYP/6-31G (d, p) level of theory using the geometries along the minimum energy pathway. The dielectric constant was assumed to be 7.58 for the bulk THF.

3. Results and Discussions

The optimized stationary structures (minima, saddle points) on the potential surfaces of the reactions are depicted schematically in Figure 1 with selected key geometry parameters (bond length and bond angles) listed in Table 1. The detailed structural parameters and energies for the structures determined here are collected in the Supporting Information. The relative-energy and the free-energy changes relative to the starting materials ($PhCBr$ $+ACN$, $PhCBr$ $+TME$, $PhCBr_2^-$ $+$ ACN, and $PhCBr_2^-$ $+$ TME) whether in the gas or solvent for these addition reactions

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TABLE 1. Calculated Optimized Geometry Parameters of the Reaction of Phenylhalocarbenes and Phenyldihalomethide Carbanions with Acrylonitrile (ACN) and Trimethylethylene (TME)[a]

	$r(C^1C^2)$	$r(C^1C^3)$	$r(C^2C^3)$	$r(C^3Br^5)$	$\alpha(C^2C^3Br^4)$
PhCBr					
$PhCBr_2^-$				2.018	
ACN	1.326				
TME	1.330				
syn-TS1	1.351	2.741	2.218		106.42
syn-TS2	1.354	2.089	2.528		95.47
syn-TS3	1.346	3.340	2.502	1.999	103.49
syn-TS4	1.482	2.282	1.490	2.457	97.63
syn-TS5	1.434	1.708	2.705	2.032	105.67
syn-INT	1.473	2.566	1.563	2.031	109.17
syn-PR1	1.512	1.510	1.484		115.41
anti-TS1	1.352	2.746	2.217		107.22
anti-TS2	1.353	2.115	2.540		94.72
anti-TS3	1.342	3.465	2.582	2.002	103.95
anti-TS4	1.480	2.314	1.498	2.375	100.29
anti-TS5	1.426	1.740	2.730	2.021	96.06
anti-INT	1.471	1.564	2.562	2.038	109.96

	$r(C^1C^2)$	$r(C^1C^3)$	$r(C^2C^3)$	$r(C^3Br^5)$	$\alpha(C^1C^3Br^4)$
syn-TS6	1.357	2.246	2.519		108.33
syn-TS7	1.357	2.672	2.251		96.65
syn-TS8	1.382	1.965	2.623	2.570	109.31
syn-TS9	1.383	2.681	1.952	2.491	92.00
syn-PR2	1.511	1.513	1.501		117.67
anti-TS6	1.357	2.245	2.519		108.14
anti-TS7	1.356	2.685	2.243		97.49
anti-TS8	1.380	1.977	2.609	2.588	109.24
anti-TS9	1.383	2.669	1.948	2.529	96.29
anti-PR2	1.511	1.512	1.502		118.03

[a] At the BHandHLYP/6-31G (d, p) level of theory, all distances are in angstroms and all angles are given in degrees. The structures of the reaction refer to those shown in Figure 1.

TABLE 2. Relative Energies and Free Energies (kcal/mol) for the Reactions of Phenylhalocarbenes and Phenyldihalomethide Carbanions with ACN and TME[a]

species	ΔE_{gas}^{rel}	ΔG_{gas}^{rel} (298 K)	ΔE_{sol}^{rel}	ΔG_{sol}^{rel} (298 K)
PhCBr + ACN	0.0	0.0	0.0	0.0
syn-TS1	2.04	13.56	6.50	16.14
syn-TS2	7.43	19.72	13.13	22.86
syn-PR1	−69.03	−56.11	−65.17	−54.22
anti-TS1	2.97	14.70	6.46	16.43
anti-TS2	9.35	21.42	13.11	22.93
anti-PR1	−68.23	−55.45	−64.95	−54.11
$PhCBr_2^-$ + ACN	0.0	0.0	0.0	0.0
syn-TS3	−10.01	0.97	0.96	12.01
syn-INT	−23.04	−10.54	−19.58	−8.59
syn-TS4	−23.65	−10.66	−19.66	−7.78
syn-TS5	6.54	19.77	13.74	25.68
anti-TS3	−10.11	0.78	0.97	12.31
anti-INT	−22.67	−10.04	−20.31	−9.14
anti-TS4	−22.79	−10.06	−20.71	−8.05
anti-TS5	7.58	20.76	14.75	26.43
syn-PR1 + Br^-	−63.03	−51.43	−67.56	−53.44
anti-PR1+ Br^-	−64.81	−53.16	−67.37	−53.6
PhCBr + TME	0.0	0.0	0.0	0.0
syn-TS6	3.45	16.51	7.25	17.33
syn-TS7	2.39	15.37	5.74	15.36
anti-TS6	3.52	16.79	7.12	17.25
anti-TS7	2.33	15.32	5.94	15.73
syn-PR2	−66.70	−52.71	−62.63	−51.33
anti-PR2	−65.70	−51.55	−61.97	−50.62
$PhCBr_2^-$+ TME	0.0	0.0	0.0	0.0
syn-TS8	23.88	36.75	26.31	36.74
syn-TS9	22.65	35.46	25.01	36.12
syn-PR2 + Br^-	−55.77	−42.58	−63.15	−48.51
anti-TS8	24.63	37.22	25.70	35.67
anti-TS9	23.35	35.79	25.16	34.59
anti-PR2 + Br^-	−55.12	−41.79	−62.79	−48.01

[a] These values were calculated at the BHandHLYP/6-31G (d, p) level of theory and include the zero-point energy correction employing a single-point PCM calculation to model the effect of the solvent (THF) at the BHandHLYP/PCM/6-311++G (d, p)//BHandHLYP/6-31G (d, p) level of theory.

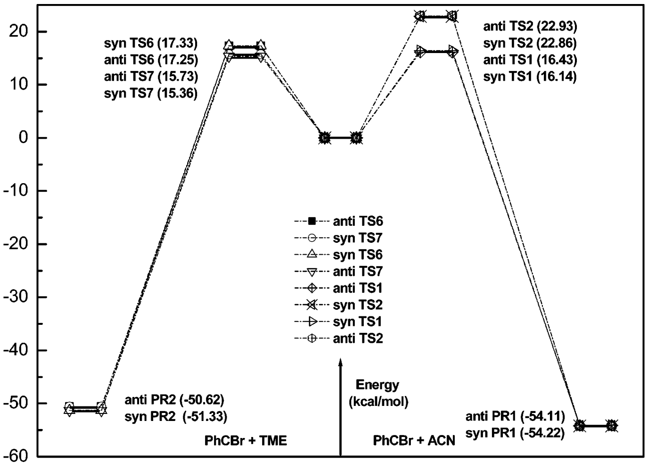

FIGURE 2. Free-energy profiles for the addition reaction of phenylhalocarbene with ACN and TME.

are presented in Table 2. Unless otherwise noted, the relative energies and the free energies discussed later refer to the value in THF solvent. Free-energy profiles for the reactions of phenylhalocarbene with ACN and TME are shown in Figure 2. Finally, the exothermicity for the reaction of PhCBr + (TBA)Br = (TBA)$PhCBr_2$ was calculated to be 57.13 kcal/mol considering the solvation effect (THF), using NH_4Br as a model molecule for the TBABr. Furthermore, the formed $PhCBr_2^-$ is quenched by alkenes immediately, and this makes the equilibrium shift toward $PhCBr_2^-$. This indicates that the formation of $PhCBr_2^-$ is a very favorable process. In addition, for PhCBr, the excitation energies from the singlet ground state to the first triplet excited state are 4.1 kcal/mol (in THF). Thus, only the singlet potential surface was considered throughout this work.

3.1. Cyclopropanation by Carbenes. Inspection of Figure 1 shows that the attack of carbon atom of the phenylhalocarbene on C^1 or C^2 of the alkenes leads to the two different pathways, which all involve a concerted [2 + 1] addition through only one transition state (*syn*-TS1, *syn*-TS2, *anti*-TS1, *anti*-TS2, *syn*-TS6, *syn*-TS7, *anti*-TS6, and *anti*-TS7) to yield a syn/anti isomeric mixture product. Vibrational analysis shows that all of these TS structures are a first-order saddle point with only one imaginary frequency of 274i, 398i, 275i, 382i, 258i, 230i, 230i, and 229i cm^{-1} for *syn*-TS1, *syn*-TS2, *anti*-TS1, *anti*-TS2, *syn*-TS6, *syn*-TS7, *anti*-TS6, and *anti*-TS7, respectively. Moreover, the IRC calculations confirmed that these TSs connect the corresponding reactants and products. As shown in Figure 1, the transition states of all the reaction pathways investigated have a common structure in which the carbene is slightly off-center. Examination of Figure 1 reveals that in all of the TS structures, the carbon atom of the carbene is initially attacked at only one of the carbon atoms in the alkenes. For instance, the distances of C^1-C^3 and C^2-C^3 for *syn*-TS1, *syn*-TS2, *anti*-TS1, *anti*-TS2, *syn*-TS6, *syn*-TS7, *anti*-TS6, and *anti*-TS7 are 2.741, 2.218; 2.089, 2.528; 2.746, 2.217; 2.115, 2.540; 2.246, 2.519; 2.672, 2.251; 2.245, 2.519; and 2.685, 2.243 Å, respectively. This means that the mechanism of the singlet carbene addition to the alkene is an asynchronous one. A similar asynchronous approach has been previously found for the addition of a singlet carbene to ethylene.[2−6] As the reaction goes from the reactant to the transition state, the distances between the C^1 and C^2 atoms change from 1.326 to 1.351, 1.354, 1.352, and 1.353 Å for *syn*-TS1, *syn*-TS2, *anti*-TS1, and *anti*-TS2, respectively. For *syn*-TS6, *syn*-TS7, *anti*-TS6, and *anti*-TS7, the distance of C^1-C^2 bond was also stretched from 1.330 to 1.357, 1.357, 1.357, and 1.356 Å, respectively. These changes can be mainly attributed to the interaction of the phenylhalocarbene with the π orbital of alkene associated with a slight elongation of the C^1-C^2 bonds. The angles of $C^2-C^3-Br^4$ and $C^1-C^3-Br^4$ are 106.42°, 107.22°, 95.47°, 94.72°, 108.33°, 108.33°, 96.65°, and 97.49° for *syn*-TS1, *anti*-TS1, *syn*-TS2, *anti*-TS2 *syn*-TS6, *anti*-TS6, *syn*-TS7, and *anti*-TS7, respectively. This indicates the onset of the sp^2-sp^3 rehybridization required for cyclopropane formation. Furthermore, the $C^2-C^3-Br^4$ and $C^1-C^3-Br^4$ angles in *syn*-TS2, *anti*-TS2, *syn*-TS6, and *anti*-TS6 are smaller than those in *syn*-TS1, *anti*-TS1, *syn*-TS6, and *anti*-TS6. This can mainly be attributed to the steric hindrance between the phenyl and CN moieties that make the $C^2-C^3-Br^4$ and $C^1-C^3-Br^4$ angles distorted in the *syn*-TS2, *anti*-TS2, *syn*-TS7, and *anti*-TS7 structures. As the reaction goes from the transition state to the product, the C^1-C^2 double bond completes its change from a double bond to a single bond and the C^1-C^3 and C^2-C^3 bonds become completely formed. From these changes in the bond distances and the bond angles, we can find that all of the transition states have similar structures that are close to those of the reactants whether for the ACN or TME cyclopropanation reactions. As will be discussed below, the cycloaddition reaction is exothermic. According to the Hammond postulate,[30] the reaction should have an early transition state close to the reactants and our results are consistent with this.

Frontier molecular orbital (FMO) analysis has been successful in accounting for a range of addition reactions. Thus, the highest occupied molecular orbital−lowest unoccupied molecular orbital (HOMO−LUMO) energies of PhCBr, TME, and ACN are calculated at the HF/6-31G level of theory on the basis of the BH and HLYP/6-31G (d, p) structures.[31] According to this theory, the electrophilic selectivity addition is dominated by relatively small LUMO (carbene)−HOMO (alkene) differential orbital energies, whereas the nucleophilic selectivity addition features small LUMO (alkene)−HOMO (carbene) differential energies.[7−8] A small differential orbital energy leads to large transition state stabilization energies and, thus, to a lower activation energy. Our calculation results show that the differential energies of the LUMO (carbene)−HOMO (ACN) and the LUMO (ACN)−HOMO (carbene) are 0.42108 eV and 0.43781 eV, respectively. The small difference between the LUMO (carbene)−HOMO (ACN) and the LUMO (ACN)−HOMO (carbene) clearly indicates that the normally electrophilic phenylhalocarbene is exposed as latent ambiphile in the reactions with ACN. However, the differential energies of the LUMO (carbene)−HOMO (TME) and the LUMO (TME)−HOMO (carbene) are 0.35212 eV and 0.53861 eV, respectively. The large difference between the LUMO (carbene)−HOMO (TME) and the LUMO (TME)−HOMO (carbene) indicates an electrophilic selectivity addition between phenylhalocarbene and TME. The above calculated results are consistent with the experimental observations by Moss and co-workers.[13−14a,22] Table 2 lists the calculated free energies of activation and reaction of the reactions studied. The free energies of activation for the *syn*-TS1, *syn*-TS2, *anti*-TS1, and *anti*-TS2 are 16.14, 22.86, 16.43, and 22.93 kcal/mol, respectively, and the free energies of the reaction are −54.22 and −54.11 kcal/mol for syn and anti, respectively. The *syn*-TS1 and *anti*-TS1 have lower free energies of activation than *syn*-TS2 and *anti*-TS2 for ACN. According to the frontier molecular orbital (FMO) analysis, the attack on C^2 has nucleophilic selectivity but the attack on C^1 has electrophilic selectivity for the ACN. Examination of Table 2 shows that the free energies of activation for the *syn*-TS6, *syn*-TS7, *anti*-TS6, and *anti*-TS7 are 17.33, 15.36, 17.25, and 15.73 kcal/mol, respectively, and the free energies of reaction are −51.33 and −50.62 kcal/mol for the syn and anti reactions, respectively. These values indicate that the attack of the carbene on the alkene has electrophilic selectivity whether for C^1 or C^2 of TME. Our calculations indicate that an electronegative or π-donating substitution has a large effect on the addition barriers. In other words, the TME species readily undergoes addition reactions with carbenes while ACN has a higher energy to overcome the barrier to cycloaddition. From the above calculated results, we can see that attack at C^2 for ACN and TME is the major pathway for these addition reactions and that these addition reactions will yield a syn/anti isomeric product mixture.

It is intriguing to compare the addition reactions for the TME and ACN systems. The methyl substituent has suitable C−H σ-bonding orbital which will interact with the π bond which raises the energy of the HOMO and LUMO and thus renders the olefin to be more reactive as a Lewis base. Of course, the electrons of the HOMO are also delocalized onto the methyl substituent. The probability of attack by an electrophile will be governed by the magnitude of the coefficient at a particular atomic position. Polarization of the HOMO away from the point of attachment of the methyl substituent directs an electrophile attack to that carbon. However, the CN substituent, which has a π^* orbital which will interact with the π bond, lowers the energy of the HOMO and LUMO and thus renders the olefin to be less reactive as a Lewis base and more reactive as a Lewis acid. The electrons of the HOMO are also delocalized onto the CN moiety. Polarization of the LUMO away from the point of attachment of the CN substituent directs a nucleophilic attack to that carbon.[32]

3.2. Cyclopropanation by a Carbanion. Cyclopropanation by a carbanion is different from that of a carbene. The addition process simply involves a reversal of the steps in response to an equilibrium constant that favors the addition product over the alkene. The rate-determining step is the addition of the nucleophile (k_1) to give the carbanion intermediate. This step is then followed by a relatively fast loss of halide coupled with ring closure (k_2). The rate constants of the alkene additions are very sensitive to the nature of the attached substituents and their ability to stabilize the carbanion intermediate.[1a,22] Table 2 lists the activation free energies and the reaction free energies for the addition reactions of phenyldihalomethide carbanions with ACN and TME in the gas phase and in THF solvents. The free-energy profiles for the reactions are shown in Figure 3.

Inspection of Figure 1 shows that the attack between the carbon atoms of the phenyldihalomethide carbanion on C^2 of ACN will lead to a stepwise pathway to yield the addition product. First, a “Michael” addition of the phenyldihalomethide

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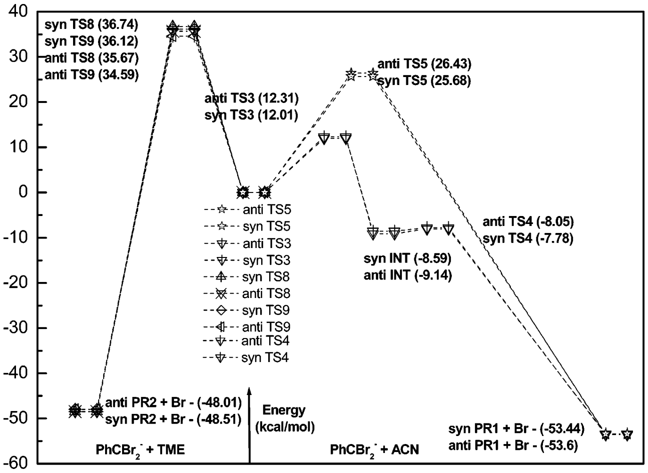

FIGURE 3. Free-energy profiles for the addition reactions of the phenyldihalomethide carbanion with ACN and TME.

carbanion and ACN leads to a very early asynchronous TS (*syn*-TS3 and *anti*-TS3 with a very small imaginary frequency of 22i and 23i cm^{-1}, respectively, and IRC calculations confirmed that these TS connect the corresponding reactants and intermediates) with the distances of C^1-C^3, C^2-C^3 of 3.340, 2.502 and 3.465, 2.582 Å for *syn*-TS3 and *anti*-TS3, respectively. Compared with ACN, the distance of C^1-C^2 is only elongated by 0.019 and 0.015 Å for *syn*-TS3 and *anti*-TS3, respectively. Furthermore, the distances of C^3-Br^4 and C^4-Br^5 are 1.977, 1.999 and 1.993, 2.002 Å and the $C^2-C^3-Br^4$ angles are 103.49° and 103.95° for *syn*-TS3 and *anti*-TS3, respectively. These very early TSs lead to a carbanion intermediate (*syn*-INT and *anti*-INT) stabilized by the attached CN substituent. From Table 1, we can see that the distances of C^1-C^3, C^2-C^3 are 2.566, 1.563 and 2.562, 1.564 Å and the distances of C^3-Br^4 and C^3-Br^5 are 1.987, 2.031 and 1.971, 2.038 Å for the *syn*-INT and *anti*-INT, respectively. Moreover, the $C^2-C^3-Br^4$ angles are close to a tetrahedral angle (109.17° and 109.96° for the *syn*-INT and *anti*-INT, respectively), suggesting that the C^3 atom has essentially sp^3 hybridization and that the distance of C^1-C^2 (1.473, 1.471 Å for the *syn*-INT and *anti*-INT, respectively) is close to bond lengths expected for a C−C single bond. These changes in the bond angles and bond distances show that the C^4-Br^5 bond will be cleaved and that the carbanion intermediate will yield a syn/anti isomer product mixture in one step through a ring closure TS (*syn*-TS4 and *anti*-TS4 with only one imaginary frequency of 177i and 142i cm^{-1}, respectively, and IRC calculations confirmed that these TSs connect the corresponding reactants and intermediates). Compared with INT, the distances of C^1-C^2 are slightly stretched from 1.473, 1.471 Å to 1.482, 1.480 Å, respectively, and the C^4-Br^5 bonds are nearly broken and now are 2.457 and 2.375 Å for *syn*-TS4 and *anti*-TS4, respectively. Furthermore, the distances of C^2-C^3 are shortened from 2.566, 2.562 to 2.282, 2.314 Å, respectively. As the reaction goes to the product, the C^3-Br^5 bond is completely broken and the C^1-C^3 or C^2-C^3 single bond becomes completely formed.

The attack between the carbon atoms of the phenyldihalomethide carbanion with C^1 of ACN or C^1 and C^2 of TME will not lead to a stable carbanion intermediate and will rather involve a concerted addition through only one transition state (*syn*-TS5, *anti*-TS5, *syn*-TS8, *syn*-TS9, *anti*-TS8, and *anti*-TS9 with only one imaginary frequency of 208i, 133i, 452i, 464i, 461i, and 462i cm^{-1}, respectively, and IRC calculations confirmed that these TSs connect the corresponding reactants and products) to yield syn/anti isomer product mixtures. Inspection of Table 1 reveals that the distances of C^1-C^2 are elongated by 0.107, 0.099, 0.052, 0.053, 0.050, and 0.053 Å with respect to those in ACN and TME. Meanwhile, the C^3-Br^5 bonds of *syn*-TS5, *anti*-TS5, *syn*-TS8, *syn*-TS9, *anti*-TS8, and *anti*-TS9 are elongated from 2.018 to 2.032, 2.021, 2.570, 2.491, 2.588, and 2.529 Å, respectively. The C^1-C^3 and C^2-C^3 bonds of *syn*-TS5, *anti*-TS5, *syn*-TS8, *anti*-TS8, *syn*-TS9, and *anti*-TS9 are 1.708, 1.740, 1.965, 1.977, 1.952, and 1.948 Å, respectively. As the reaction goes from the transition state to the product, the C^3-Br^5 bond is completely broken and the C^1-C^2 double bond completes its change from a double bond to a single bond and the C^1-C^3 or C^2-C^3 single bond becomes completely formed.

From Table 2 and Figure 3, it can be seen that the free energies of activation for the first step are calculated to be 12.01 and 12.31 kcal/mol for *syn*-TS3 and *anti*-TS3, respectively, and that the free energies of reaction for the carbanion intermediates are −8.59 and −9.14 kcal/mol for the *syn*-INT and *anti*-INT, respectively. As we discussed above, this step also is the rate-determining step. The small free energies of activation indicate that the formation of the *syn*-INT and *anti*-INT is a favorable processes. The relatively lower barriers found for the first step can mainly be attributed to the following two reasons. First, there are only relatively small structural changes taking place as one goes from the reactants to the transition states. Thus, only a little energy is needed to go from the reactants to the transition states. Second, the addition of TBABr leads to the phenyldihalomethide carbanion which increases the nucleophilic selectivity of the phenylhalocarbene. From INT to PR, the free energies of activation are calculated to be only 0.81 and 1.09 kcal/mol for *syn*-TS4 and *anti*-TS4, respectively. The free energies changes are −44.85 and −44.46 kcal/mol for syn and anti, respectively, and the free energies of reaction are −53.44 and −53.6 kcal/mol for syn and anti, respectively. These calculation results indicate that the second ring closure step is a very favorable process. However, we have already demonstrated that the attack on C^1 for ACN has electrophilic selectivity, and thus the increase of TBABr would make the concerted reaction an unfavorable pathway. From Table 2, one can see that the free energies of activation are 25.68 and 26.43 kcal/mol for *syn*-TS5 and *anti*-TS5, respectively. This means that the stepwise addition of the phenyldihalomethide carbanion with ACN will be the major reaction pathway. However, for the addition of the phenyldihalomethide carbanions with TME, the free energies of activation are 36.74, 36.12, 35.67, and 34.59 kcal/mol for *syn*-TS8, *syn*-TS9, *anti*-TS8, and *anti*-TS9, respectively, and the free energies of reaction are −48.51 and −48.01 kcal/mol for syn and anti, respectively. These relatively high barriers indicate that phenyldihalomethide carbanion does not readily add to the electron-rich TME.

It is interesting to compare the addition reaction for the phenylhalocarbene and phenyldihalomethide carbanion. The results of the calculations presented here indicate that the addition of the phenyldihalomethide carbanion seems to select nucleophilically between ACN and TME. The phenyldihalomethide carbanion does not readily add to the electron-rich TME. The cyclopropane yields only appear to occur via addition of PhCBr to TME. However, the addition of the phenylhalocarbene seems to select electrophilically between ACN and TME. The cyclopropane forms not only via the slow addition of the phenylhalocarbenes to ACN but also forms through the stepwise reaction of the phenyldihalomethide carbanions to ACN. In other words, the cyclopropanation by phenylhalocarbenes and phenyldihalomethide carbanions with ACN is concurrent in THF, and this is consistent with experimental observations by Moss and Tian that this cyclopropanation takes place concurrently.[22]

4. Conclusion

In summary, this work has provided the first theoretical study for the title reactions. With the above analysis in mind, the following conclusions can be drawn: (1) for the addition of phenylhalocarbenes, the electronegative or π-donating substitution significantly affects the addition barriers. In other words, the TME species readily undergoes addition reactions with carbenes while ACN has a higher energy to overcome the barrier for cycloaddition. The attack of C^2 of ACN and TME is the major pathway for these addition reactions and yields a syn/anti isomeric mixture of products. (2) The addition of TBABr leads to the formation of phenyldihalomethide carbanions, which increase the nucleophilic selectivity of the cycloaddition. The phenyldihalomethide carbanion prefers to attack at C^2 of ACN through a stepwise pathway; first, the rate-determining step of Michael addition of the phenyldihalomethide carbanion to form a carbanion intermediate occurs through an early asynchronous TS with a small reaction barrier. Then, this carbanion intermediate yields a syn/anti isomeric product mixture in one step with a very small barrier. (3) In good agreement with experimental observations, the phenyldihalomethide carbanions do not readily add to the electron-rich TME, and the cyclopropane yields only take place via addition of PhCBr to TME. However, the cyclopropane forms not only via slow addition of phenylhalocarbenes to ACN but also forms through the stepwise reaction of the phenyldihalomethide carbanions to ACN. In other words, the cyclopropanation by phenylhalocarbenes and phenyldihalomethide carbanions with ACN is concurrent in THF.

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Supporting Information Available: The complete citation for ref 28, the Cartesian coordinates for the calculated stationary structures, and the sum of the electronic and zero-point energies for the transition and ground states obtained from the DFT calculations. This material is available free of charge via the Internet at http://pubs.acs.org.

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