Interaction of Propargyl Cation with Tetrahydrofuran: Thermodynamics, Kinetics, and Biological Relevance

Pogban Toure,* Steven Myer, and Gagik G. Melikyan*

Department of Chemistry, California State University—Northridge, Northridge, CA 91330

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Ab initio calculations have been carried out for the reaction of propargyl cation and tetrahydrofuran, a model for the novel stereoselective reductive dimerization of cobalt-complexed propargyl cations, mimicking, on a molecular level, DNA damage inflicted by electrophilic carcinogenic agents. The optimized geometries derived from semiempirical calculations (AM1) have been employed in ab initio calculations using Hartree−Fock (3-21G* and 6-31G* basis sets) and density functional theory (DFT) methods. The highly exothermic character of the major mechanistic pathways, a hydride-ion transfer toward the carbocationic center and a direct coordination of the latter with an oxygen atom in tetrahydrofuran, has been revealed (−49.74 to −72.85 kcal/mol). A two-electron, three-membered "late" transition state was found for the hydride-ion transfer pathway with an activation energy of +24.69 kcal/mol. A direct one-electron oxidation of tetrahydrofuran by propargyl cation is the mechanistic pathway most sensitive toward the calculation technique used: ab initio method employing 3-21G* and 6-31G* basis sets suggests exothermicity for the process in question, whereas DFT calculation using the numerical polarization basis sets indicates moderate endothermicity (+7.74 kcal/mol). The mechanistically distinct pathways thus identified—"*ionic*", "*binding*", and "*radical*"—imply that structural alteration of DNA caused by electrophilic carcinogenic agents may occur by (a) a delivery of hydride-ion originating from 1′ and 4′ positions of the sugar moiety toward the electrophilic center, (b) binding of the electron-deficient species to an oxygen atom in a ribose ring, and (c) a single-electron transfer toward the electrophile with a ribose ring acting as a reducing moiety.

Introduction

The complexation of organic radicals with transition metals alters their electronic, steric, and conformational parameters thus providing an attractive opportunity to control the behavior of these reactive species, otherwise unruly. Although dimerization of ferrocene dates back to 1959,[1] the chemistry of organometallic radicals has received little attention;[2] its current state can be characterized as a transition from infancy to adolescence. Some progress was achieved because of two-dimensional exploration of the field[3] suggesting, as variables, unsaturated organic ligands and metal cores, both mono- and dinuclear. Even at this early stage, the synthetic potential uncovered is truly remarkable: it provides novel methods for inter- and intramolecular radical C−C bond formation readily occurring in a diverse polyfunctional environment. Fundamental knowledge is nevertheless lacking, in particular, with respect to the mode of interaction of a ligand-positioned unpaired electron with the metal cluster, an effect of π-coordination upon thermodynamics, as well as configurational and conformational specifics involved. Our interest in this area was triggered by the prospect of controlling chemoselectivity in manganese(III)-mediated reactions by complexation of conjugated 1,3-enynes with a cobalt cluster.[4] Further systematic efforts directed toward development of the chemistry of transition-metal altered reactive intermediates[5] resulted in a novel method for generation of $Co_2(CO)_6$-complexed propargyl radicals[5e] that involves an interaction of the π-bonded propargyl alcohols and cations with a variety of O- and S-containing organic molecules (Scheme 1). In particular, secondary propargyl alcohol **1** demonstrated remarkable diastereo- and chemoselectivities in the dimerization reaction affording, via cation **2**, dl-isomer **3** as a major product (de 68−94%; **4** 0−14%). The use of homogeneous, easy-to-handle and functionally compatible organic molecules as radical mediators allowed us to develop a viable synthetic method for radical C−C bond formation further enhanced by the presence of a π-bonded metal core.[6] Its versatility was proven by the stereoselective construction of the eight- and nine-membered 1,5-cycloalkadiynes,[5e] otherwise hardly accessible. It is worthy of mention that the significance of this finding extends beyond the scope of organometallic chemistry itself. First, it provides the newest example of a single-electron transfer (SET) between electronically diverse molecular assemblies, a process central to chemistry and biology.[7] Second, it mimics an interaction between electrophilic carcinogenic agents and a ribose ring in DNA (Scheme 2). A number of electrophilic agents, such as chloromethyl methyl ether, ethylene oxide, chloronaphasine, melphalan, chloroambucil, semustine, busulfan, and others, are proven to be carcinogenic to humans.[8] Mechanistically, the cation(oid)−DNA interactions are far from being well understood; among few credible examples are DNA methylation by aliphatic nitrosomethylamines[9a] and epoxide ring-openings in primary metabolites of aflatoxin B1 and benzo[*a*]pyrene.[9b,c] Although DNA bases are widely implicated as primary targets for electrophiles, a ribose ring itself can also undergo structural and electronic changes, leading eventually to a strand cleavage.[9d,e] Conceptually, a carbocationic center could coordinate with an O atom in a ribose ring, abstract a hydride ion from its 1′ or 4′ positions, or act as a recipient of a single electron converting to the respective radical species

* To whom correspondence should be addressed. E-mail: hcchm025@csun.edu.

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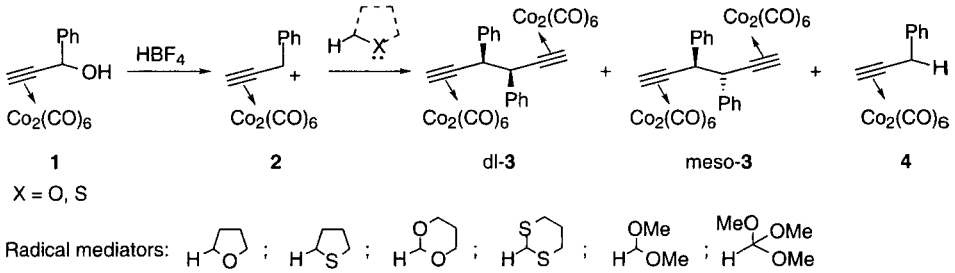
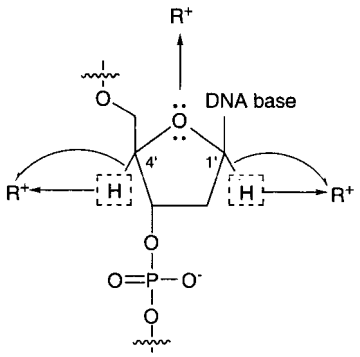
SCHEME 1



SCHEME 2



(Scheme 2). Of immediate relevance is the assessment of the energetics for plausible reaction pathways and tentative intermediates which will allow us to identify the most viable mechanistic alternatives and also to better shape an ongoing, extensive mechanistic probe. We report herein an ab initio study on the mechanism of an interaction of a propargyl cation with tetrahydrofuran (THF), a model for the novel radical C−C bond forming reaction which also has important biological implications.

Computational Methods

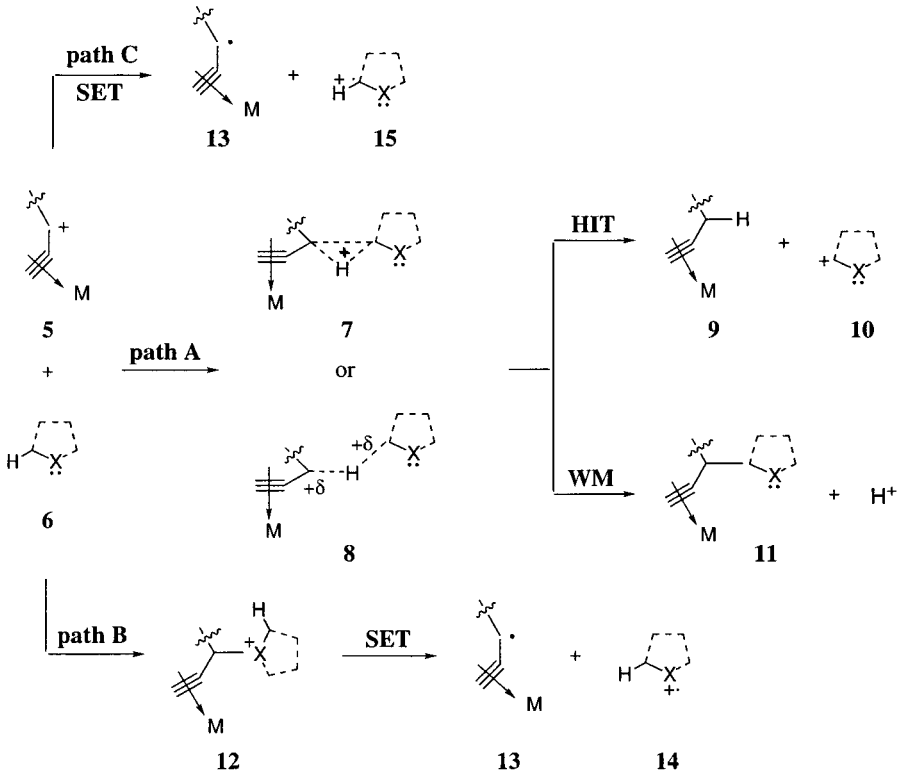
Theoretical calculations were performed using PC Spartan Plus and PC Spartan Pro programs from Wavefunction, Inc.[10] Semiempirical calculations were carried out at the AM1 level[11] with the optimized geometries being further employed in ab initio calculations by the Hartree−Fock (HF) method using 3-21G* and 6-31G* basis sets[12] and by the density functional theory method using the perturbative Becke−Perdew model with numerical polarization basis sets (DFT/pBP/DN*).[13] The geometries and energies of the transition states were determined using the linear synchronous transit (LST) method. Frequency calculations were carried out at the AM1 level and by the HF method using 3-21G* basis sets to allow for determination of true minima and confirmation of the structural characteristics of the transition states.[10]

Results and Discussion

Energetics and Mechanism. Given in Scheme 3 is a generic representation of the major mechanistic pathways for the interaction of cobalt-complexed propargyl cation **5** with heteroatom-containing radical mediator **6** (X = O, S). As an electron-deficient moiety, a p orbital in cation **5** could coordinate with an α-C−H bond in **6** (p−σ coordination) forming a three-membered, cyclic (**7**) or bent (**8**), transition state (path A). The coordination is analogous to that first postulated for boron−hydrogen bond hydrolysis;[14] it was invoked to interpret the mechanism of the transition metal-induced C−H bond activation,[15] as well as the structural features of boranes[16] and stable organic cations.[17] The intermediate species **7** (or **8**) could follow two mechanistically distinct paths: (a) a hydride-ion transfer (HIT)[18] toward the cationic center affording hydrocarbon **9** and heteroatom-stabilized cationic species **10** and (b) Wagner−Meerwein (WM) type[19] rearrangement forming a new carbon−carbon bond in the propargylation product **11**. Path B represents a *donor−acceptor interaction* between cation **5**, acting as a Lewis acid and a lone pair delivered by the heteroatom. An oxonium salt **12** could then undergo intramolecular homolytic cleavage, giving rise to radical **13** and an oxidized form of the radical mediator **14** with a positive charge localized on the heteroatom. The former could also be generated by a direct one-electron oxidation of an α-C−H bond in radical mediator **6**, a chemically conceivable pathway also affording cation-radical **15** (path C). Because the coupling of radical **13** produces respective dimeric products, paths B and C represent the mechanistic alternatives leading to the formation of 1,5-alkadiynes (type **3** in Scheme 1); to the contrary, path A will be responsible for the share of HIT and WM products.

Ab initio calculations were undertaken with the main goal of assessing, from an energetic standpoint, the relative probabilities of the alternative mechanistic pathways. Both thermodynamics and kinetics were computed using, as a representative model, a simplified version of the parent process, i.e., an *uncomplexed* propargyl cation reacting with THF. The relative energies were obtained by Hartree−Fock calculations using 3-21G* (Figure 1) and 6-31G* (Figure 2) basis sets, as well as by the DFT method (Figure 2) using the perturbative Becke−Perdew model. The sum of the energies of reactants is set to be equal to zero, as is the electronic energy of the hydrogen ion. As evidenced by computational data, a quenching of propargyl cation **A** with THF(**B**)-originated hydride ion is a highly exothermic process (−49.74 kcal/mol), affording hydrocarbon **C** and resonance-stabilized cyclic cation **D**. To the contrary, the formation of Wagner−Meerwein product **E** could hardly be anticipated given the endothermic nature of the process (+147.73 kcal/mol). The transition state for the HIT process (**F**), with an activation energy of +24.69 kcal/mol, has configurational characteristics typical for a "late" transition state: its central unit comprises a highly stretched α-C−H bond of THF, and by its triangular geometry, it closely resembles that in species **7** (Scheme 3). Conversion of **F** to stable products is thermodynamically favored for the HIT process and could hardly occur via the WM pathway. These data are in accord with the experiment: careful GC−MS screening of the crude mixtures did not reveal the presence of any propargylated products (type **E**), whereas the formation of the HIT product (type **C**) is generally observed. The concentration of the latter varies in the range of 0−14%[5e] with the THF-mediated reaction being one of the most selective (HIT < 1%). Probing path B showed that coordination of a lone pair of oxygen (**B**) with

SCHEME 3



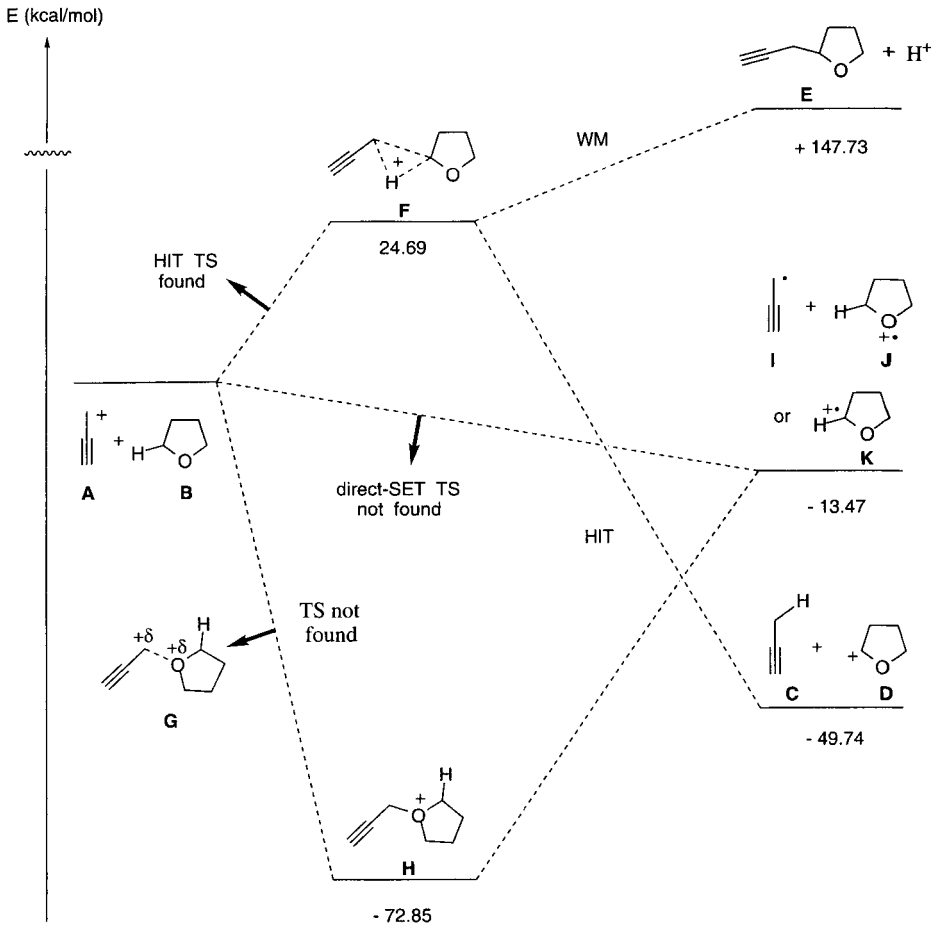


Figure 1. Calculated relative total electronic energies (kcal/mol) for reactants, products, and the transition state by ab initio method using 3-21G* basis sets.

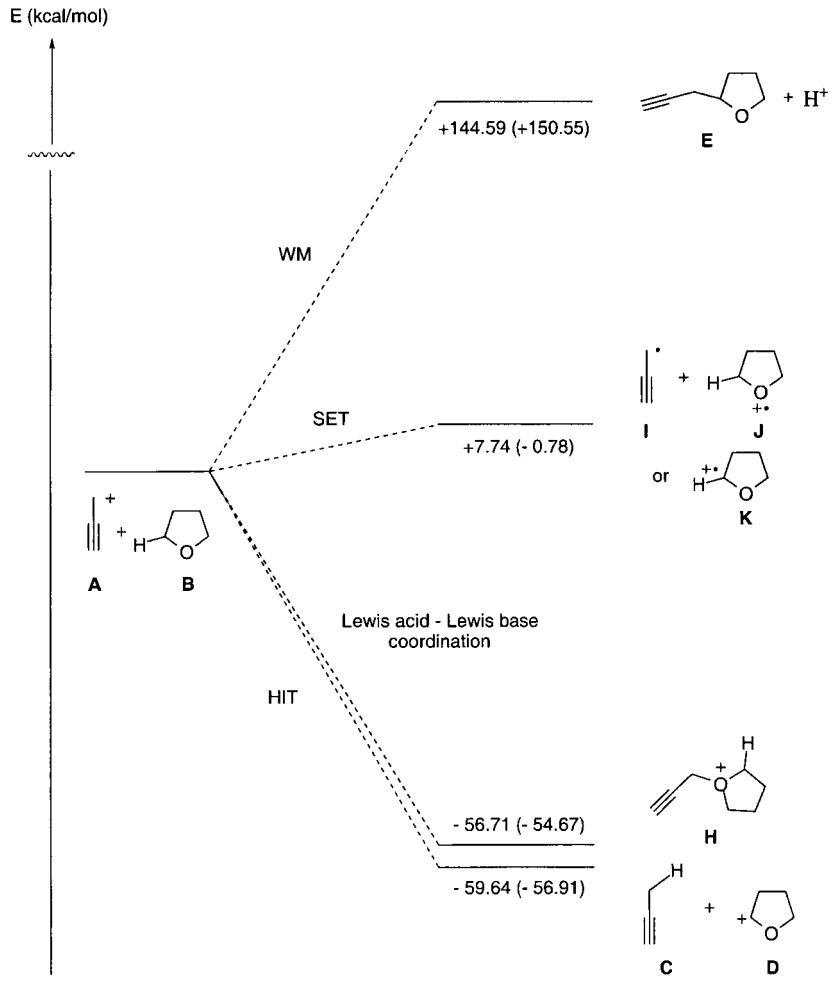
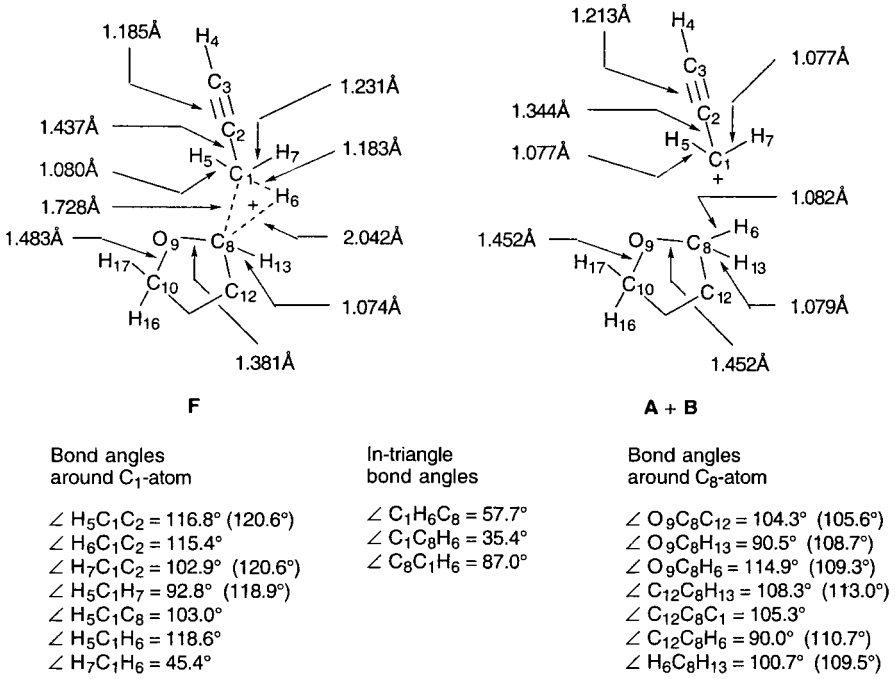


Figure 2. Calculated relative total electronic energies (kcal/mol) for reactants and products by the DFT method using numerical polarization basis sets [figures in parentheses indicate respective values obtained by ab initio method using 6-31G* basis sets].

cationic center (**A**) is favored thermodynamically (−72.85 kcal/mol), although respective transition state (**G**) could not be structurally characterized. The subsequent homolysis of the C−O bond in oxonium complex **H**, generating propargyl radical **I** and cation-radical **J**, seems unlikely because of its highly endothermic nature (+59.38 kcal/mol). In fact, oxonium complex **H** is lying at the bottom of the energetic well and could hardly serve as a viable source of propargyl radical **I**. This conclusion is supported by the fact that an interaction of Co-complexed cations with O, S, P, and N nucleophiles gives rise to respective solvolysis products or onium species, whereas formation of radical-derived products has not been observed.[20] The third alternative, a direct SET from an α-C−H bond toward the carbocationic center, appeared to be an exothermic process (−13.47 kcal/mol) affording radical **I** and cation-radical **K**.[21]

Higher level ab initio calculations by the Hartree−Fock method using 6-31G* basis sets[12] and by the DFT method[13] allowed further refinement of quantitative data (Figure 2). The WM pathway still remains highly unfavorable (+144.59 kcal/mol), whereas both HIT and "binding" modes retained a higher degree of exothermicity (−59.64 and −56.71 kcal/mol, respectively). The SET reaction suffered the most significant transformation: the DFT method revealed some endothermicity for the electron-transfer process (+7.74 kcal/mol), whereas the HF method using 6-31G* basis sets suggested a negligible change in energy level (−0.78 kcal/mol). Despite its alleged endothermic nature, the SET remains a viable mechanistic pathway along with its "ionic"and "binding" counterparts, HIT and Lewis acid−Lewis base coordination, respectively. In fact, it is the only process which explains the formation of propargyl radicals, an experimentally observed outcome of the organometallic reaction. The oxonium complex **H** could not account for generation of propargyl radicals because homolytic cleavage of the C−O bond, although chemically conceivable, would require a significant investment of energy (DFT: +64.45 kcal/mol). To the contrary, the radical reaction, although a moderately endothermic process, can still occur driven by the fast diffusion-controlled follow-up chemistry. The radical generation might also be *kinetically* preferable because of the tentatively lower energetic profile of a single electron travelling (tunneling?) from THF toward the cationic center.

Transition State for the HIT Process. The transition state **F** (Figure 3) which could only be located by RHF/3-12G* has structural characteristics distinct from those of "free" propargyl cation and THF. Attendant with a coordination of a p orbital with an α-C−H bond are substantial alterations in bond lengths and bond angles within and in close proximity to the three-membered ring. The noteworthy structural features of **F** include (1) a highly stretched C_8-H_6 bond (2.042 Å vs 1.082 Å) and nearly completed C_1-H_6 bond (1.183 Å vs 1.080 Å), both indicative of the "late" transition state, (2) a short distance between C_1 and C_8 atoms (1.728 Å) which is substantially less than the sum of van der Waals radii (3.30−3.40 Å),[22] (3) significant stretching of the C_1-H_7 bond (1.231 Å vs 1.077 Å) making H_7 atom even more distant than an incoming atom H_6 (1.183 Å), and (4) shortening of the C_8-O_9 bond (1.381 Å vs



Bond angles around C_1-atom	In-triangle bond angles	Bond angles around C_8-atom
∠ $H_5C_1C_2$ = 116.8° (120.6°)	∠ $C_1H_6C_8$ = 57.7°	∠ $O_9C_8C_{12}$ = 104.3° (105.6°)
∠ $H_6C_1C_2$ = 115.4°	∠ $C_1C_8H_6$ = 35.4°	∠ $O_9C_8H_{13}$ = 90.5° (108.7°)
∠ $H_7C_1C_2$ = 102.9° (120.6°)	∠ $C_8C_1H_6$ = 87.0°	∠ $O_9C_8H_6$ = 114.9° (109.3°)
∠ $H_5C_1H_7$ = 92.8° (118.9°)		∠ $C_{12}C_8H_{13}$ = 108.3° (113.0°)
∠ $H_5C_1C_8$ = 103.0°		∠ $C_{12}C_8C_1$ = 105.3°
∠ $H_5C_1H_6$ = 118.6°		∠ $C_{12}C_8H_6$ = 90.0° (110.7°)
∠ $H_7C_1H_6$ = 45.4°		∠ $H_6C_8H_{13}$ = 100.7° (109.5°)

Figure 3. Two-electron three-centered transition state for HIT process [figures in parentheses indicate respective values of bond angles in propargyl cation (**A**) and THF (**B**)].

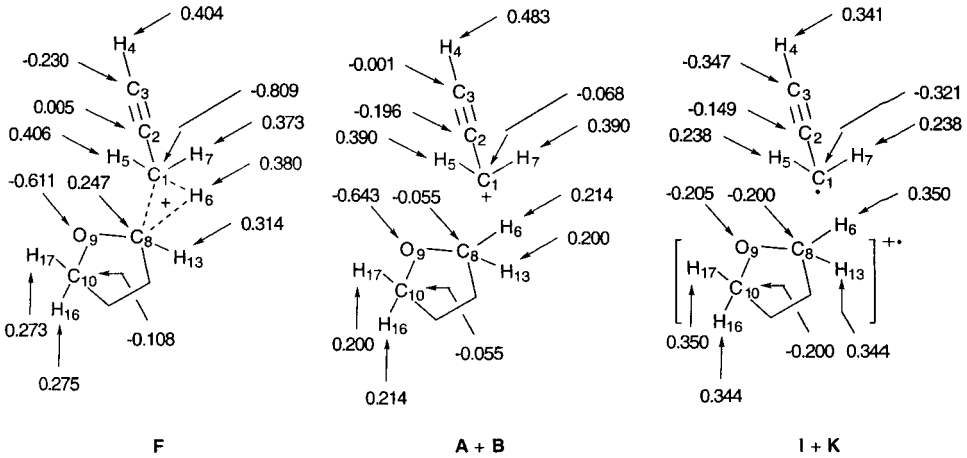


Figure 4. Transition state for HIT process: Mulliken charge distribution.

1.452 Å) apparently caused by a donation of the lone-pair toward an increasingly electrophilic C_8 atom. The configurations of pentacoordinated C_1 and C_8 atoms represent distorted trigonal bipyramids; because of *p*−*σ coordination*,[15] atom C_1 increases its coordination number by two, a reminescence of "oxidative addition" reaction to the transition metal.[23] Atoms H_5, H_6, and C_2 create a nearly planar trigonal arrangement around the C_1 atom (∠ $H_5C_1C_2$ = 116.8°, ∠ $H_6C_1C_2$ = 115.4°, ∠ $H_5C_1H_6$ = 118.6°) with the C_1−C_8 bond being almost perpendicular to the plane (∠ $H_6C_1C_8$ = 87.0°).

Charge Distribution. Charge distribution is another essential parameter affected by *p-σ coordination* (Figure 4). Overall, the propargyl unit turns more negative, whereas a THF moiety, acting as an electron source, acquires an additional positive charge. In particular, the C_1 atom increases its negative charge (−0.809 vs −0.068) affecting, by alteration, the C_3 atom of the triple bond (−0.230 vs −0.001). The effect of coordination upon hydrogen atoms H_5 and H_7 remains moderate (Δ0.016−0.017); most importantly, a newly acquired inequivalency of H_5 and H_7 can be seen from Mulliken charge distributions (0.373 vs 0.406), as well as bond lengths (Figure 4). In the THF molecule, a transfer of an electron toward the cationic center primarily affects a donating unit, C_8−H_6 bond (H_6 0.380 vs 0.214; C_8 +0.247 vs −0.055). A secondary effect of electron redistribution could be seen in the more electropositive nature of the O_9 atom (−0.611 vs −0.643) and H_{13} atom (0.314 vs 0.200). For comparison, given in Figure 4 is also a charge distribution in propargyl radical **I** and THF-derived cation-radical **K**, the entities formed by a single-electron-transfer mechanism (path C, Scheme 3). It is noteworthy that although the C_1 atom, receiving an extra electron, becomes more electronegative (−0.321 vs −0.068), the buildup of negative charge is considerably less than that in the transition state **F** (−0.809 vs −0.321). A loss of electron by THF triggers a significant electronic redistribution along *σ* bonds with α-H atoms and O_9 atom acquiring more electropositive nature; the latter has even lesser negative charge than that in the transition state **F** (−0.205 vs −0.611).

Conclusions

On the basis of computational data, we conclude that an interaction of the propargyl cation with THF may occur by three

competing mechanisms: a hydride-ion transfer, giving rise to a respective hydrocarbon ("*ionic pathway*"), Lewis acid−Lewis base coordination of a p orbital in the propargyl cation and a lone pair of an oxygen atom in THF ("*binding pathway*"), and a single-electron-transfer toward the propargyl cation responsible for the formation of the key radical intermediate ("*radical pathway*"). Thermodynamics vary widely with the former two being most favored (−59.64 and −56.71 kcal/mol, respectively); the Wagner-Meerwein pathway lies on the opposite end of the scale (+144.59 kcal/mol), whereas the SET reaction exhibits relatively light exo- and endothermicity. The latter is regarded as the only viable mechanistic pathway leading to the target radical species. Because the parent process mimics an interaction of electrophilic carcinogenic agents (propargyl cation) with a ribose ring in DNA (THF), the newly acquired data suggest that a structural alteration of DNA strand could occur by (a) a delivery, toward the electrophilic center, of hydride ion originating from 1′ and 4′ positions of the sugar moiety, (b) binding of the electron-deficient species to an oxygen atom in a ribose ring, and (c) a single-electron-transfer toward the electrophile with a ribose ring acting as a reducing moiety.

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Supporting Information Available: Calculated heats of formation (AM1; kcal/mol) and total electronic energies (Hartrees) determined by the Hartree−Fock method with 3-21G* and 6-31G* basis sets and by the DFT method.

References and Notes

(1) Rinehart, K. L.; Michejda, C. J.; Kittle, P. A. *J. Am. Chem. Soc.* **1959**, *81*, 3162.

(2) (a) *Organometallic Radical Processes*; Trogler, W. C., Ed.; Elsevier: Amsterdam, 1990; Chapters 3, 4, 9, 10. (b) Collman, J. R.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987. (c) Astruc, D. *Electron Transfer and Radical Processes in Transition-Metal Chemistry*; VCH: New York, 1995; Chapters 3, 5, 6.

(3) (Pentadienyl radical) $Fe(CO)_3$: (a) Mahler, J. E.; Gibson, D. H.; Pettit, R. *J. Am. Chem. Soc.* **1963**, *85*, 3959. (b) Sapienza, R. S.; Riley, P. E.; Davis, R. E.; Pettit, R. *J. Organomet. Chem.* **1976**, *121*, C35. (c) Pearson, A. J.; Chen, Y.-S.; Daroux, M. L.; Tanaka, A. A.; Zettler, M. *J. Chem. Soc. Chem. Commun.* **1987**, 155. (propargyl radical) $Cp_2Mo_2(CO)_4$: (d) Le Berre-Cosquer, N.; Kergoat, R.; L'Haridon, P. *Organometallics* **1992**, *11*, 721. (benzyl radical) $Cr(CO)_3$: (e) Top, S.; Jaouen, G. *J. Organomet. Chem.* **1987**, *336*, 143. (f) Merlic, C. A.; Walsh, J. C.; Tantillo, D. J.; Houk, K. N. *J. Am. Chem. Soc.* **1999**, *121*, 3596; ferrocenyl radical: (g) Cais, M.; Eisenstadt, A. *J. Chem. Soc.* **1965**, *30*, 1148. (h) Cais, M.; Askhenazi, P.; Dani, S.; Gottlieb, J. *J. Organomet. Chem.* **1977**, *540*, 127. $CpCo(\eta^5\text{-}C_7H_9)$ radical: (i) Geiger, W. E.; Genneth, Th.; Lane, G. A. *Organometallics* **1986**, *5*, 1352. (propargyl radical) $Co_2(CO)_6$: (j) Padmanabhan, S.; Nicholas, K. M. *J. Organomet. Chem.* **1981**, *212*, 115. (k) Salazar, K. L.; Khan, M. A.; Nicholas, K. M. *J. Am. Chem. Soc.* **1997**, *119*, 9053.

(4) (a) Melikyan, G. G. *Org. React.* **1997**, *49*, 427. (b) Melikyan, G. G. *Aldrichim. Acta* **1998**, 50. (c) Melikyan, G. G.; Vostrowsky, O.; Bauer, W.; Bestmann, H. J. *J. Organomet. Chem.* **1992**, *423*, C24.

(5) (a) Melikyan, G. G.; Mkrtchyan, V. M.; Atanesyan, K. A.; Asaryan, G. Kh.; Badanyan, Sh. O. *Bioorg. Khim.* **1990**, *16*, 1000; C.A.113(25): 230995j. (b) Melikyan, G. G.; Mineif, A.; Vostrowsky, O.; Bestmann, H. J. *Synthesis* **1991**, 633. (c) Melikyan, G. G.; Bright, S.; Monroe, T.; Hardcastle, K. M.; Ciurash, J. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 161. (d) Melikyan, G. G.; Deravakian, A. *J. Organomet. Chem.* **1997**, *544*, 143. (e) Melikyan, G. G.; Deravakian, A.; Myer, S.; Yadegar, S.; Hardcastle, K. I.; Ciurash, J.; Toure, P. *J. Organomet. Chem.* **1999**, *578*, 68. (f) Melikyan, G. G.; Amiryan, F.; Visi, M.; Hardcastle, K. I.; Bales, B. L.; Aslanyan, G.; Badanyan, Sh. H. *Inorg. Chim. Acta* **2000**, *308*, 45.

(6) A detailed mechanistic study, including measurements of kinetic isotope effect, is currently in progress; the results will be reported in forthcoming full account.

(7) (a) Cannon, R. D. *Electron-Transfer Reactions*; Butterworth: London, 1980. (b) *Electron Transfer in Inorganic, Organic and Biological Systems*, Bolton, J. R., Mataga, N., McLendon, G., Eds.; Advances in Chemistry; Series 228; American Chemical Society: Washington, DC, 1991; For SET-induced organic and organometallic transformations, see: (c) Kochi, J. K. *Angew. Chem., Int. Ed.* **1988**, *27*, 1227. (d) Ashby, E. C. *Acc. Chem. Res.* **1988**, *21*, 414. (e) Dalko, P. I. *Tetrahedron* **1995**, *51*, 7579.

(8) International Agency for Research on Cancer (IARC, http://www.iarc.fr); Group I: Carcinogenic to humans (http://193.51.164.11/monoeval/crthgr01.html).

(9) (a) von Hofe, E.; Schmerold, I.; Lijinsky, W.; Jeltsch, W.; Kleihues, P. *Carcinogenesis* **1987**, *8*, 1337. (b) Bailey, E. A.; Iyer, R. S.; Stone, M. P.; Harris, T. M.; Essigmann, J. M. *Proc. Natl. Acad. Sci. U.S.A.* **1996**, *93*, 1535. (c) Schwartz, J. L.; Rice, J. S.; Luxon, B. A.; Sayer, J. M.; Xie, G.; Yeh, H. J.; Liu, X.; Jerina, D. M.; Gorenstein, D. G. *Biochemistry* **1997**, *36*, 11069. (d) Giese, B.; Beyrich-Graf, X.; Burger, J. *Angew. Chem.* **1993**, *32*, 1742. (e) Beyrich-Graf, X.; Muller, S. N.; Giese, B. *Tetr. Lett.* **1998**, *39*, 1553.

(10) (a) *PC Spartan Plus*, Tutorial and Users Guide; Wavefunction, Inc.: Irvine, CA, 1997. (b) Hehre, W. J.; Yu, J.; Klunzinger, P. E.; Lou, L. *A Brief Guide to Molecular Mechanics and Quantum Chemical Calculations*; Wavefunction, Inc.: Irvine, CA, 1998.

(11) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Steward, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902.

(12) Pietro, W. J.; Francl, M. M.; Hehre, W. J.; DeFrees, D. J.; Pople, J. A.; Brinkley, J. S. *J. Am. Chem. Soc.* **1982**, *104*, 5039.

(13) (a) Becke, A. D. *Phys. Rev. A* **1988**, *38*, 3089. (b) Perdew, J. P. *Phys. Rev. B* **1986**, *33*, 8822.

(14) Hawthorne, M. F.; Lewis, E. S. *J. Am. Chem. Soc.* **1958**, *80*, 4296.

(15) (a) Hall, C.; Perutz, R. N. *Chem. Rev.* **1996**, *96*, 3125. (b) Crabtree, R. H. *Chem. Rev.* **1995**, *95*, 987. (c) Arndtsen, B. A.; Bergman, R. G.; Mobley, T. A.; Peterson, T. H. *Acc. Chem. Res.* **1995**, *28*, 154.

(16) (a) Brown, H. C.; Klender, G. *J. Inorg. Chem.* **1962**, *1*, 204. (b) Cotton, F. A.; Wilkinson, G. *Advanced Inorganic Chemistry*, 3rd ed.; Wiley: New York, 1988; Chapter 6.

(17) (a) Laube, T. *Acc. Chem. Res.* **1995**, *28*, 399. (b) Sorensen, T. S. In *Stable Carbocation Chemistry*; Prakash, G. K. S., Schleyer, P. v. R., Eds.; Wiley: New York, 1997; Chapter 3.

(18) (a) Nenitzescu, C. D. In *Carbonium Ions*; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley: New York, 1968; Vol. 4, Chapter 13. (b) Meerwein, H.; Hederich, V.; Morschel, H.; Wunderlich, K. *Ann. Chem.* **1960**, *635*, 1.

(19) Kaupp, G. *Top. Curr. Chem.* **1988**, *146*, 57.

(20) (a) Saha, M.; Nicholas, K. M. *J. Am. Chem. Soc.* **1984**, *49*, 417. (b) Gruselle, M.; Philomin, V.; Chaminant, F.; Jaouen, G. *J. Organomet. Chem.* **1990**, *399*, 317. (c) Roth, K. D.; Muller, U. *Tetrahedron Lett.* **1993**, 2919. (d) Gelling, A.; Mohmand, F.; Jeffery, J. C.; Went, M. J. *J. Chem. Soc., Dalton. Trans.* **1993**, 1857. (e) Kuhn, O.; Rau, D.; Mayr, H. *J. Am. Chem. Soc.* **1998**, *120*, 900. (f) Gruselle, M.; Malezieux, B.; Vaissermann, J. *Organometallics* **1998**, *17*, 2337.

(21) The program does not have a capability of recognizing the site of a one-electron oxidation of THF, i.e., species J and K are thermodynamically degenerate.

(22) Huheey, J. E.; Keiter, E. A.; Keiter, R. L. *Inorganic Chemistry*, 4th ed.; Harper Collins: New York, 1993; Chapter 6.

(23) Collman, J. R.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987; Chapter 5.