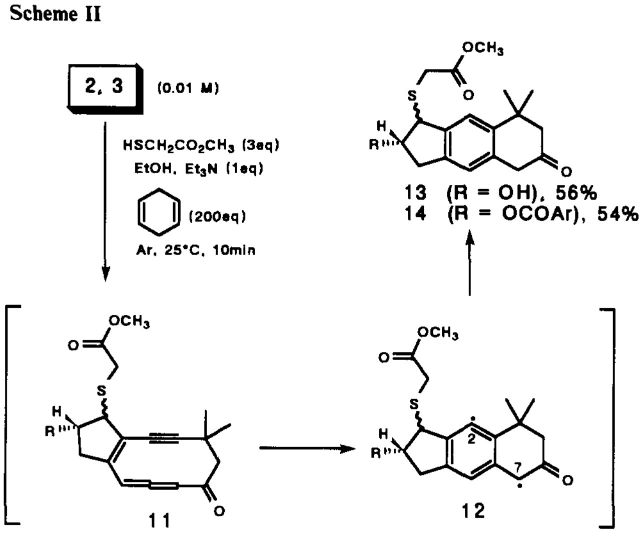
J. Am. Chem. Soc. 1991, 113, 9853-9855

Scheme II



are currently under investigation in our laboratory.

Acknowledgment. We thank Dr. Hideo Komatsu, Toyohiko Miki, and Toshihiro Hinokitani, POLA Pharmaceutical R & D Laboratory, for testing the biological activities. Financial support by the Ministry of Education, Science and Culture, Japan, and the Mitsubishi, the CIBA-GEIGY, the Shorai, and the TERUMO Science Foundations are acknowledged.

Supplementary Material Available: Spectral and HRMS data for all new compounds, photograph of the electrophoretic gel for form I DNA cutting, and histogram of DNA cleavage pattern by **2** (8 pages). Ordering information is given on any current masthead page.

Matrix ESR Evidence for the Formation of the Bicyclo[3.2.0]hepta-2,6-diene Radical Cation Both from Ionized Quadricyclane and as an Intermediate in the Radical Cation Photoisomerization of Norbornadiene to Cycloheptatriene

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In previous matrix-isolation studies,[1-3] the only reported product of quadricyclane (**1**) ionization was the same species generated from norbornadiene (**2**) and characterized as $2^{\bullet+}$. Similarly, the gas-phase ions formed from **1** and **2** were found to be mutually indistinguishable by mass spectrometry.[4] On the other hand, evidence for a distinct radical cation $1^{\bullet+}$ that rapidly isomerizes to $2^{\bullet+}$ has been obtained from CIDNP[5a-d] and pulse radiolysis[5e] studies in solution. Here we report that under matrix-isolation conditions of especially high dilution, ionization of **1** leads to the bicyclo[3.2.0]hepta-2,6-diene radical cation ($3^{\bullet+}$), which is also shown to represent an important new intermediate on this much-studied $C_7H_8^{\bullet+}$ potential energy surface.[1-5]

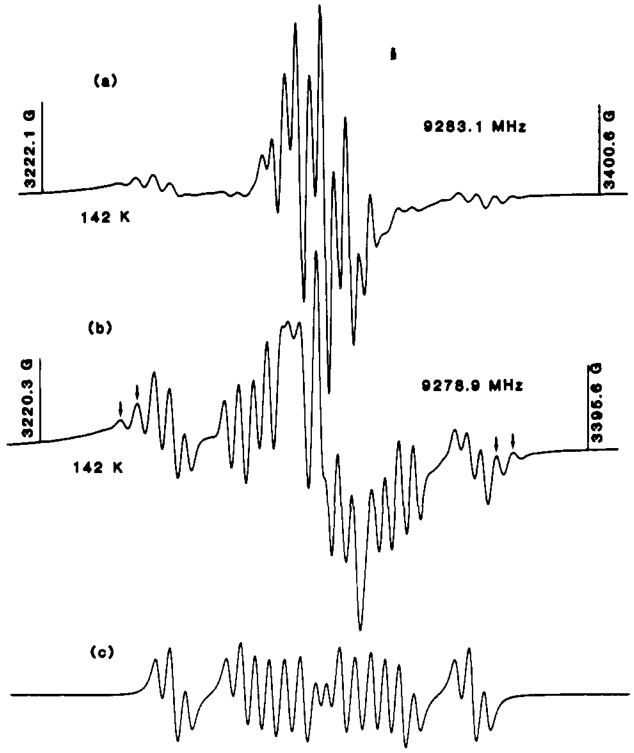
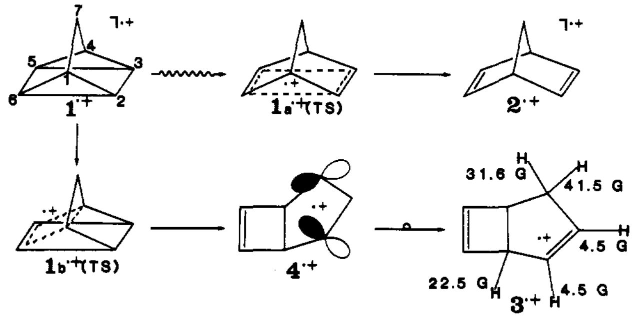


Figure 1. ESR spectra of γ-irradiated solid solutions containing (a) ca. 0.1 mol % and (b) ca. 0.03 mol % of quadricyclane in CF_3CCl_3 (dose, 0.3 Mrad). The main patterns in spectra a and b are assigned to $2^{\bullet+}$ and $3^{\bullet+}$, respectively; the extra components marked by arrows are from $5^{\bullet+}$. Spectrum c was simulated using the coupling constants for $3^{\bullet+}$ given in the text.

Scheme I



As shown in Figure 1a, the ESR spectrum generated by the radiolytic oxidation[6] of a ca. 0.1 mol % solid solution of **1** in CF_3CCl_3 is dominated by a quintet-of-triplets ($a(4H) = 8.0$ G; $a(2H) = 3.1$ G) pattern in the center which is clearly recognizable as that of $2^{\bullet+}$.[3,7] The additional signals seen in the wings, however, are considerably stronger than any corresponding signal obtained from the oxidation of **2**, suggesting that a second species is formed from **1** but not from **2**. On lowering the concentration of **1** more than 3-fold, a dramatic change in the spectrum of the oxidized products was observed (Figure 1b). Here the outer signals are

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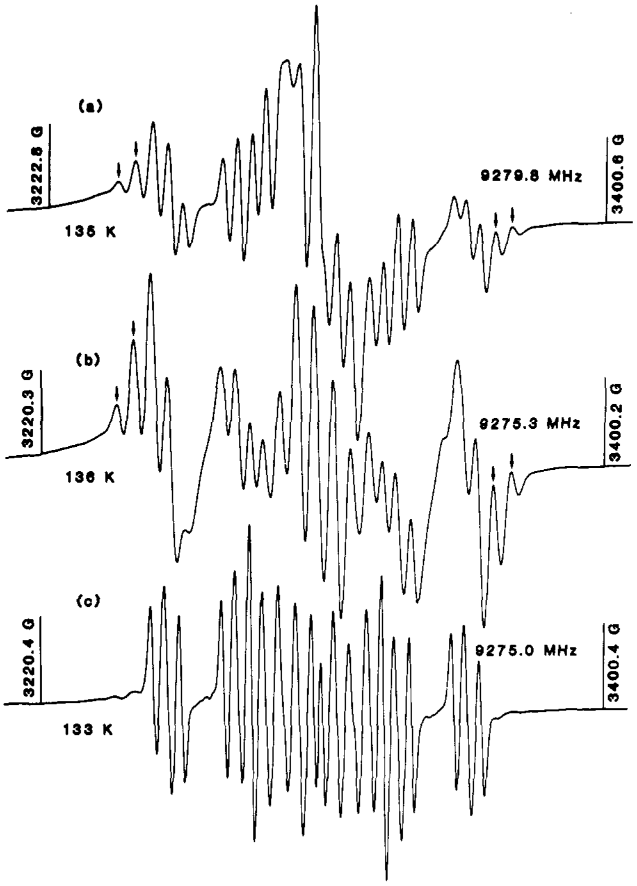
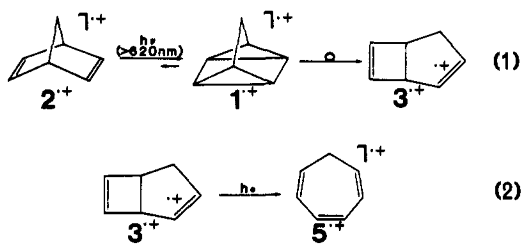


Figure 2. ESR spectra of γ-irradiated (dose, 0.3 Mrad) solid solutions containing (a) ca. 0.03 mol % of quadricyclane in CF_3CCl_3, (b) ca. 0.1 mol % of bicyclo[3.2.0]hepta-2,6-diene[17] in CF_3CCl_3, and (c) ca. 0.1 mol % of bicyclo[3.2.0]hepta-2,6-diene in $CFCl_2CFCl_2$. The patterns are all assigned to **3**$^{\bullet+}$, spectrum c showing the best resolution. The extra components marked by arrows in spectra a and b are from **5**$^{\bullet+}$.

greatly enhanced relative to those in spectrum a, and moreover, the pattern from **2**$^{\bullet+}$ is now largely obscured by the inner components of the predominating species. The analysis of this wider spectrum presented some initial difficulties, but once it was recognized that the four outermost components originated from some admixture of cycloheptatriene radical cation (**5**$^{\bullet+}$),[8] the remaining lines were fit to the simulated spectrum (c) with the following hyperfine parameters (G): 41.5 (1 H), 31.6 (1 H), 22.5 (1 H), 4.5 (2 H).

A vital clue to the identification of this new signal carrier came from a recent study of the bicyclo[3.2.1]oct-2-ene radical cation,[9] which showed that the coupling to olefinic hydrogens in a bicyclic radical cation can be unusually small and less than 6 G. This information led to the consideration of **3**$^{\bullet+}$ as a candidate, and the results presented in Figure 2 establish the assignment unequivocally;[8a] furthermore, the localization of the positive hole at the olefin group in the five-membered ring, as required by the distribution (2 H_α and 3 H_β) of the hyperfine couplings, is corroborated by AM1-UHF calculations.[10] The H_β hyperfine parameters for **3**$^{\bullet+}$ of 41.5, 31.6, and 22.5 G are assigned to C4-H_{exo}, C4-H_{endo}, and C1-H by comparison with the calculated values.[11]

Scheme II



The results can be described phenomenologically (Scheme I) in terms of two transition states, **1a**$^{\bullet+}$ and **1b**$^{\bullet+}$, for the reaction of a vibrationally excited **1**$^{\bullet+}$ produced by vertical ionization, the concentration dependence resulting from vibrational energy transfer from excited **1**$^{\bullet+}$ to neutral **1**, possibly within clusters of **1** dispersed in the matrix. Thus, the low-energy path through **1a**$^{\bullet+}$ to **2**$^{\bullet+}$ is followed when excess vibrational energy in **1**$^{\bullet+}$ is rapidly quenched at high concentrations of **1**, a compound having closely similar vibrational frequency characteristics, whereas the higher energy path via **1b**$^{\bullet+}$ becomes available only under high-dilution conditions, when vibrationally excited **1**$^{\bullet+}$ relaxes more slowly through weaker matrix interactions.

Fittingly, the transition states **1a**$^{\bullet+}$ and **1b**$^{\bullet+}$ correspond to the two alternate ways for the simultaneous opening of a pair of identical C–C bonds (2–6,3–5 or 1–6,4–5) in the cyclopropane rings of **1**$^{\bullet+}$. These transition states may well be correlated with the ground and excited *electronic* states of **1**$^{\bullet+}$, since the $^2B_1$ ground state has long C2–C6, C3–C5 bonds and short C1–C6, C4–C5 bonds[12] while this bonding situation is exactly reversed in the $^2A_2$ (first Koopmans) excited state.[1,13] Accordingly, **1b**$^{\bullet+}$ is naturally associated with the excited-state path[13] leading to the putative bicyclo[3.2.0]hept-6-ene-2,4-diyl radical cation (**4**$^{\bullet+}$), which may isomerize through a 1,2-hydrogen shift to form **3**$^{\bullet+}$. Congeneric 1,3-diyl radical cations generated by oxidation of bicyclo[2.1.0]pentane and its *syn*- and *anti*-5-methyl derivatives react similarly.[14,15]

Further ESR studies have demonstrated that **3**$^{\bullet+}$ is an intermediate in the photoisomerization of **2**$^{\bullet+}$ to **5**$^{\bullet+}$. The $^2A_1$ photoexcited state of **2**$^{\bullet+}$ possesses some 30 kcal/mol more energy than the equilibrated $^2B_1$ ground state of **1**$^{\bullet+}$ [16] and therefore can produce **1**$^{\bullet+}$ well above the small barriers separating the ground states of **1**$^{\bullet+}$, **2**$^{\bullet+}$, and **3**$^{\bullet+}$. Thus, the formation of **3**$^{\bullet+}$ by the 635-nm photoactivation of **2**$^{\bullet+}$ is attributed to a pathway through excited **1**$^{\bullet+}$; isomerization of **1**$^{\bullet+}$ to **3**$^{\bullet+}$ is irreversible, so the reaction is driven photochemically (Scheme II). Subsequent photobleaching with unfiltered light from a tungsten lamp caused the ESR components characteristic of **3**$^{\bullet+}$ to diminish uniformly in intensity while the triplet-of-quintets (a(2H) = 51.6 G; a(4H) = 5.6 G) pattern from **5**$^{\bullet+}$ grew in strongly; the spectrum was identical to that produced by the direct radiolytic oxidation of **5**.[8b] The sequence of isomerizations and intermediates depicted in Scheme II clearly extends prior understandings of the photochemical interconversions of these ions[2] and may have some ap-

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(8) (a) Cycloheptatriene radical cation (**5**$^{\bullet+}$) is also produced along with **3**$^{\bullet+}$ by the oxidation of **3** in CF_3CCl_3 (Figure 2b). (b) A dynamic ESR study of **5**$^{\bullet+}$ will be reported elsewhere: Dai, S.; Chen, G.-F.; Wang, J. T.; Williams, F., to be published.

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(11) The AM1-UHF calculated ^1H hyperfine parameters (G) for **3**$^{\bullet+}$ are 45.8 (C4-H_{exo}), 37.6 (C4-H_{endo}), 22.0 (C1-H), 9.2 (C3-H), and 8.9 (C2-H); the 1s spin densities after annihilation were multiplied by 1177 G: Clark, T.; Nelsen, S. F. *J. Am. Chem. Soc.* **1988**, *110*, 868.

(12) The C1–C6 and C4–C5 pair of bonds are, of course, equivalent to the C1–C2 and C3–C4 pair in this analysis.

(13) In the two-state model, loss of vibrational energy deprives the electronically excited state of sufficient energy to pass over the higher energy transition state **1b**$^{\bullet+}$, in which case the excited state relaxes to the ground state by molecular distortions from C_{2v} symmetry which mix these two states. Furthermore, it can be inferred from the symmetry properties of the orbitals[1] that the pathways from the $^2B_1$ ground state and the $^2A_2$ excited state of **1**$^{\bullet+}$ to **2**$^{\bullet+}$ and **4**$^{\bullet+}$, respectively, would each involve a surface crossing if the symmetry plane bisecting the C2–C3 and C5–C6 bonds were to be retained. Such crossing points would then correspond to the transition states **1a**$^{\bullet+}$ and **1b**$^{\bullet+}$, and each crossing allows the SOMO to develop in π rather than π^* orbitals of the product.

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(16) The excess energy made available by the 635-nm photoexcitation[1] of **2**$^{\bullet+}$ ($\bar{\nu}$ = 15 748 cm^{-1}) *referenced to* **1**$^{\bullet+}$ is given by $hc\bar{\nu} - \Delta H(\mathbf{2}^{\bullet+} \rightarrow \mathbf{1}^{\bullet+})$ = 45 kcal/mol − 13 kcal/mol[1] = 32 kcal/mol.

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plicability to the evergreen problem concerning mass spectrometric rearrangements of $C_7H_8^{\bullet+}$ isomers.[4]

Acknowledgment. We thank Professor J. E. Bartmess for helpful discussions. We are also indebted to a referee for suggesting that a two-state model would be consistent with the formation of $2^{\bullet+}$ and $3^{\bullet+}$ from $1^{\bullet+}$. The research at the University of Tennessee was supported by the Division of Chemical Sciences, Office of Basic Energy Sciences, U.S. Department of Energy (Grant No. DE-FG05-88ER13852). This work was supported at Syracuse University by the National Science Foundation and aided through technical assistance by Ms. Karla A. Villarica.

Intermolecular Radical Reactions of Unsaturated Chromium and Tungsten Carbene Complexes

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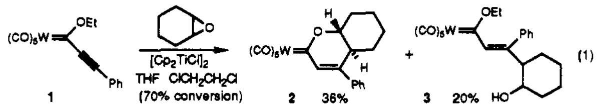
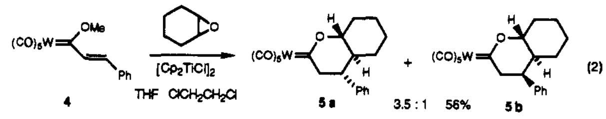
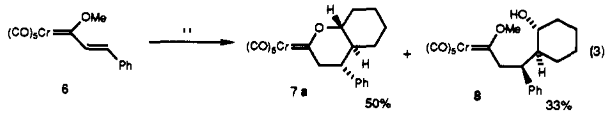
The use of radicals in organic synthesis has seen phenomenal development as chemists have found methods to control their reactivity.[1] While radical reactions can be performed under mild conditions and are tolerant of a variety of functional groups, reaction stereoselectivity and functionalization of product radicals remain as important areas of research.[2] A potentially powerful solution to these concerns is the use of transition metals to template radical reactions in order to control stereoselectivity and functionalization. Although transition-metal complexes have been utilized to generate organic radicals[3,4] and odd-electron-count organometallic complexes have been isolated and characterized,[5] radical reactions on metal-coordinated unsaturated ligands have not been explored in synthetic terms. In fact, for most organometallic species with applications to organic synthesis, only even-electron processes such as nucleophilic and electrophilic addition have been investigated.[6] We have initiated a program to examine coupling reactions, cyclizations, and other radical processes in metal-coordinated polyene and polyenyl systems and report herein the first intermolecular radical coupling reactions of carbene complexes and alkyl radicals.

Radical additions to α,β-unsaturated chromium and tungsten carbene complexes were chosen for study after considering the highly electrophilic nature of Fischer carbene complexes,[7] the relative nucleophilic behavior of alkyl-substituted radicals,[1] analogy to the reactivity of α,β-unsaturated esters, and the synthetic utility of Fischer carbene complexes.[7] Although most synthetically useful radical reactions are performed as chain processes,[8] we utilized stoichiometric generation of alkyl radicals and trapping by unsaturated Fischer carbene complexes. The generation of alkyl radicals by reaction of titanocene monochloride dimer and epoxides developed by Nugent and RajanBabu was most successful.[4] Simultaneous syringe pump addition of cyclohexene oxide (1.5 equiv) and titanocene monochloride dimer (1.5 equiv) to a solution of carbene complex **1** cooled to −20 °C followed by quenching with ethereal HCl (3 equiv) provided adducts **2** and **3** (eq 1).[9] The dihydropyranylidene complex **2** was a single isomer containing a trans-fused ring junction as evidenced by the coupling of the methine proton geminal to oxygen (3.78 ppm, td, $J = 11.9, 4.1$ Hz). Acyclic alcohol **3** was also a single isomer.[10] Although modest in yield, the key importance of these products is that they demonstrate the first coupling of an organic radical with a carbene complex.[11]



Reaction of styrenyl carbene **4** was more successful, providing the adducts **5a** and **5b** (3.5:1 by ^1H NMR) in 56% yield (eq 2). Again, the ring fusions were only trans[12] and the product ratio reflects the equatorial and axial phenyl group isomers, respectively. Chromium carbene complexes are equally effective in the radical coupling reactions as demonstrated by complex **6** (eq 3). Interestingly, product **8** did not cyclize under the reaction conditions, but readily cyclized upon subsequent treatment with catalytic sodium methoxide, providing the isomer of **7a**.





Abstraction of allylic hydrogen atoms by the alkyl radicals is not a concern as the propenyl complexes provided similar results (eqs 4, 5, 7). The modest stereoselectivity observed at the β-position in the reaction of tungsten complex **9** and cyclohexene oxide (eq 4) is diminished when an acyclic epoxide is used (eqs 7, 8). In a direct comparison between carbene complexes and esters in radical coupling reactions, reaction of excess methyl crotonate substrate (10 equiv) at room temperature provided a

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[9] All new compounds were fully characterized by ^1H NMR, ^{13}C NMR, and infrared spectroscopy, and elemental composition was established by combustion analysis and/or high-resolution mass spectroscopy.

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[12] The proton geminal to the alkoxy substituent appeared as a triplet of doublets ($J = 11.1, 4.4$ Hz) at 4.09 ppm in the ^1H NMR spectrum.

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