$\omega_2 = \Omega_M$ is readily observed, regardless of the rate of exchange of A and X, thereby establishing the connectivity of the AMX system.

A more quantitative treatment of the exchange effects described above can be realized by considering the evolution of the density matrix $\rho(t)$ in the presence of an intramolecular exchange process[10]

$$\frac{d\rho(t)}{dt} = i[\rho,H] + k(P\rho P - \rho) \qquad (1)$$

where H is the time-independent Hamiltonian for the spin system, k is the exchange rate, and P is an exchange operator which is defined such that if $\Psi(t)$ is the wave function of the system before an exchange, then $P\Psi(t)$ describes the system after an exchange event. Thus, the evolution of a density matrix element ρ_{ij} is unaffected by exchange whenever $\phi_i = P\phi_i$ and $\phi_j = P\phi_j$, where the ϕ_i are the basis states on which ρ and P are defined.

To demonstrate these exchange effects experimentally, proton NMR spectra were recorded for the protein basic pancreatic trypsin inhibitor (BPTI). Wagner and co-workers[11] have established that for a temperature range centered around 30 °C the aromatic ring of phenylalanine-45 is flipping at an intermediate rate, causing significant broadening of the 2,6-H and 3,5-H resonances. Figure 1a is a slice from a DQF-COSY[9,12] spectrum (32 °C) taken parallel to the ω_1 axis at the ω_2 frequency of the Phe45 4-H resonance, showing only the autocorrelation peak for the 4-H. Since no coherence transfer from the 3,5-protons is observed, their resonance frequencies remain undetermined. In fact, if the diagonal peak had been lost due to overlap with other resonances, there would have been no indication of the presence of the spin system at all. Figure 1b is an ω_1 slice through a double quantum spectrum at the Phe45 4-H ω_2 frequency and reveals both a relatively sharp resonance and a very broad, weak peak. The sharp resonance is the remote peak arising from 2Q coherence between the 3-H and 5-H which is transferred to 1Q transitions of the 4-H. Such a peak allows the chemical shift of the 4-H and the sum of the shifts of the 3-H and 5-H resonances to be determined. The broad peak is a direct connectivity resulting from 2Q coherence between the 4-H and 3,5-H; it is observable in this spectrum due to the in-phase character of the multiplet components.[13] Figure 1c shows a slice from a 2Q spectrum recorded at 22 °C; separate resonances are observed (negative peaks) for the direct connectivity of the 4-H to the 3-H and 5-H, due to the decreased exchange rate. Figure 1d is the result obtained at 45 °C, where the 4-H to 3,5-H direct connectivities have coalesced and are starting to become exchange-narrowed. Note that at all three temperatures the remote connectivity has remained relatively sharp. It should also be noted that while the direct peaks in Figure 1 (parts c and d) are quite strong, their partners appear only very weakly at the ω_2 shifts of the 3,5-H resonances (data not shown), due to antiphase multiplet structure in the ω_2 dimension.

The advantages of multiple quantum spectroscopy for studying exchanging systems are not restricted to 2Q experiments. For example, a strong signal which arises from a 3Q coherence actively involving the Phe45 3-, 4-, and 5-H can be observed in a 3Q spectrum of BPTI; this transition is independent of the exchange of the 3,5-H and can be transferred to easily detected single quantum transitions of the 4-H. It should also be pointed out that multiple quantum spectroscopy can be useful for identifying exchanging systems when the traditional strategy of changing the temperature to move the exchange rate to the slow or fast limit, where exchange-broadening is minimized, is not feasible due to thermal degradation of the sample. Another form of 2D spectroscopy which can also be very useful for identifying coupling partners in exchanging systems is the TOCSY experiment;[14] the advantage of this technique is that the multiplet components have in-phase character in both dimensions, thus avoiding the loss of intensity suffered by antiphase peaks due to self-cancellation in the presence of exchange broadening. However, the presence of peaks arising from an exchanging system but not broadened by the exchange is unique to multiple quantum spectroscopy.

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Radical Cation Cyclization of 1,5-Hexadiene to Cyclohexene via the Cyclohexane-2,5-diyl Radical Cation Intermediate

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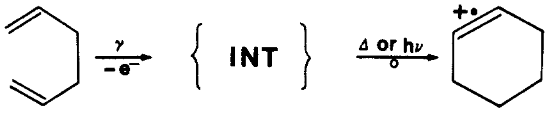
The classical example of a neutral carbon-centered radical cyclization reaction is the regioselective 1,5-ring closure (exo-cyclization) of the 5-hexenyl radical to the cyclopentylcarbinyl radical.[1] Here we report the title reaction, a comparable addition process whereby an α,ω-diene radical cation reacts by endo-cyclization and hydrogen shift(s) to produce a cycloolefin radical cation.

By using the Freon method for the radiolytic generation of radical cations at low temperatures,[2] we have observed the title reaction by ESR spectroscopy in $CFCl_3$, CF_3CCl_3, $CF_2ClCFCl_2$, and $CFCl_2CFCl_2$. In $CFCl_3$, only the cyclohexene radical cation is present immediately after γ irradiation at 77 K of dilute solid solutions (ca. 1 mol %) of 1,5-hexadiene (99.9% from Wiley Organics and 99% from Aldrich). However, when γ-irradiated 1,5-hexadiene solutions in the other three matrices are examined between 77 and 100 K, an intermediate is also observed, and representative results for CF_3CCl_3 solutions will now be described.



As shown in Figure 1, the ESR spectrum of this intermediate species consists of seven equally spaced lines with nearly binomial intensity ratios. Evidence that this signal carrier is the precursor of the cyclohexene radical cation comes from both photobleaching and thermal annealing studies. First, a comparison of the spectral

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(1) (a) Surzur, J.-M. In *Reactive Intermediates*; Abramovitch, R. A., Ed.; Plenum Press: New York, 1981; Vol. 2. (b) Beckwith, A. L. J. *Tetrahedron* **1981**, *37*, 3073. (c) Beckwith, A. L. J.; Ingold, K. U. In *Rearrangements in Ground and Excited States*; de Mayo, P., Ed.; Academic Press: New York, 1980; Vol. 1.

(2) Shida, T.; Haselbach E.; Bally, T. *Acc. Chem. Res.* **1984**, *17*, 180.

0002-7863/88/1510-1974$01.50/0

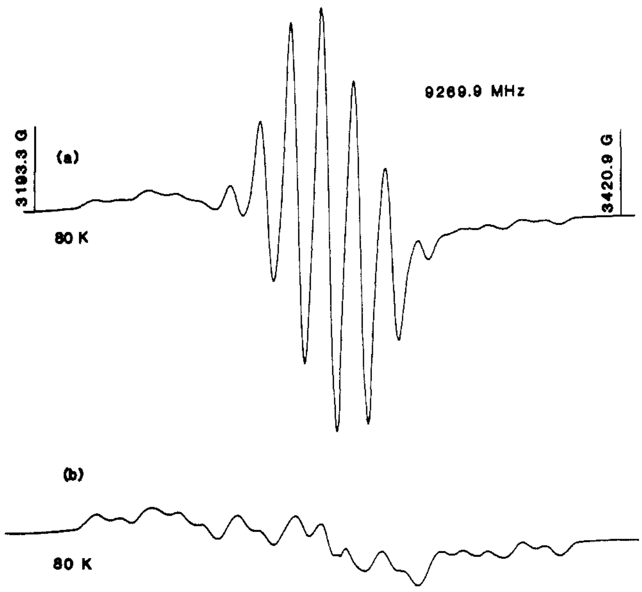
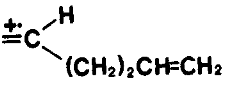


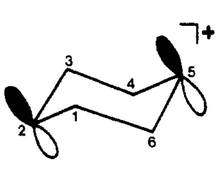
Figure 1. ESR spectra of a γ-irradiated CF_3CCl_3 solution of 1,5-hexadiene at 80 K recorded under the same instrumental conditions (a) before and (b) after photobleaching with visible light (see text for assignments). An identical photobleaching effect was also produced by red light (λ > 620 nm).

line intensities outside the seven-line pattern in Figure 1 reveals that visible-light photobleaching of the intermediate is accompanied by a marked increase in the poorly resolved background spectrum due to the cyclohexene radical cation. This latter spectrum is better resolved at higher temperatures, and Figure 2 shows that the thermal decay of the intermediate at 90 K is likewise accompanied by a distinct growth in the signals from the cyclohexene radical cation (spectra (a) and (b)), the ESR parameters obtained from spectrum (c) at 140 K[3] agreeing with those reported previously for this cation.[4]

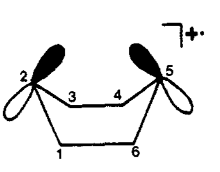
Considering that the spectrum of the intermediate is well resolved at low temperatures and that its binomial seven-line pattern implies nearly identical couplings to six hydrogens (A(6H) = 11.9 G; g = 2.0029), an assignment to the localized olefin cation **1** seems unlikely. To the contrary, these ESR characteristics indicate an intermediate with much higher symmetry and relatively little overall anisotropy, suggesting predominant coupling to a group of equivalent β-hydrogens.



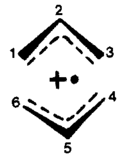
1



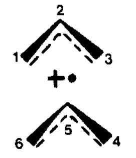
2a



2b



3a



3b

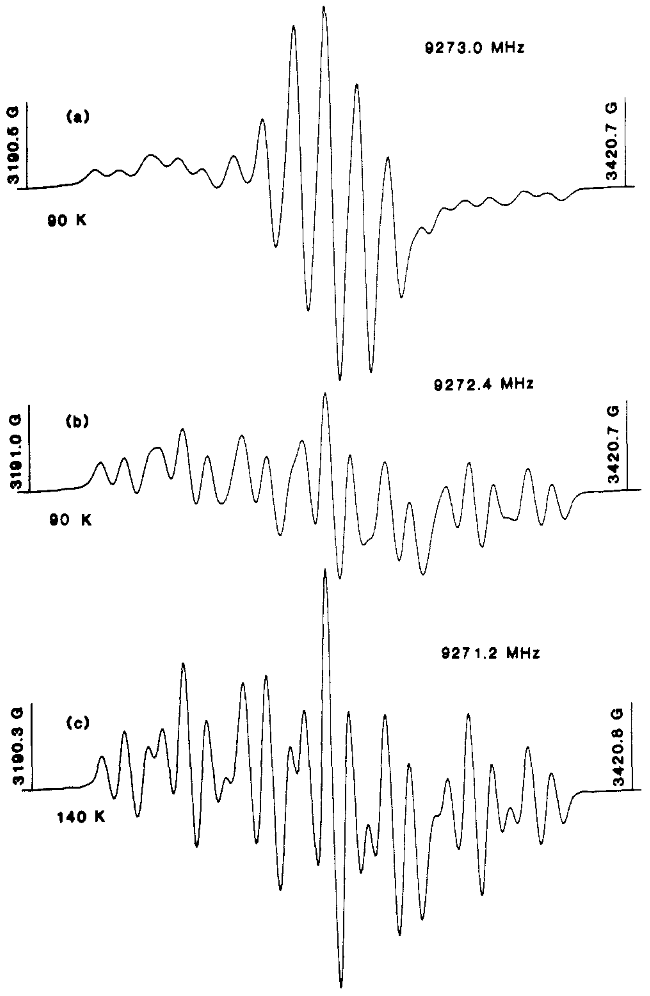


Figure 2. ESR spectra of a γ-irradiated CF_3CCl_3 solution of 1,5-hexadiene recorded under the same instrumental conditions (a) before and (b) after thermal annealing at 90 K; spectrum (c) was recorded subsequently at 140 K (see text for assignments).

The logical candidate therefore is the radical cation of cyclohexane-2,5-diyl[5] in its chair (**2a**) or boat (**2b**) forms, and theoretical calculations[6] indicate that it can readily be formed by an exothermic C_1–C_6 ring closure from the 1,5-hexadiene radical cation. This intermediate is a delocalized species with one electron shared between the 2p orbitals at C_2 and C_5 rather than a distonic radical cation consisting of noninteracting alkyl radical and carbenium ion centers as represented by a single valence-bond structure. The actual structure may also reflect a contribution from the corresponding representations for the diallyl radical cation shown in **3a** and **3b**, the effect being to elongate the C_1–C_6 and C_3–C_4 bonds in the cyclic structures and to bend the $C_1C_2C_3$ and $C_4C_5C_6$ planes inwardly toward the $C_1C_3C_4C_6$ plane.[7] Accordingly, the equivalent C_5–C_4 and C_5–C_6 radical conformations at C_5 (and similarly at C_2) will be modified from those of a normal cyclohexyl radical, as depicted below by the clockwise rotation around the C_5–C_4 bond. Assuming that a spin density of 0.5 resides at C_2 and C_5, similar hyperfine couplings of ca. 12 G are then expected for the four axial β-hydrogens (θ = 135°) and two α-hydrogens through the use of the appropriate Heller–McConnell $\cos^2\theta$ and McConnell relations,[8] the proportionality constants for unit spin

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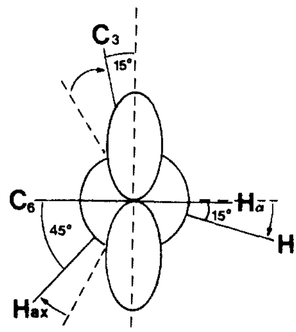
(3) Simulation of the cyclohexene radical cation spectrum gave the following ESR parameters: $A(2H_\alpha)$ = 8.0 G; $A(2H_{\beta 1})$ = 54.8 G; $A(2H_{\beta 2})$ = 22.6 G; $A(2H_\gamma)$ = 0.7 G; g = 2.0033.

(4) Shida, T.; Egawa, Y.; Kubodera, H.; Kato, T. *J. Chem. Phys.* **1980**, *73*, 5963.

(5) To avoid confusion, we retain the carbon numbering of its 1,5-hexadiene cation precursor in describing this intermediate, although it would be designated as the cyclohexane-1,4-diyl radical cation according to the usual rules of nomenclature.

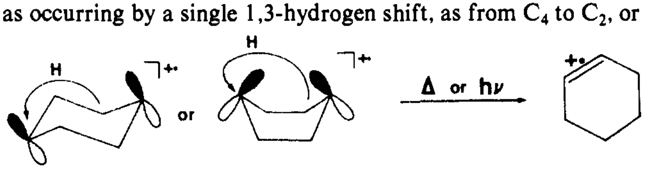
(6) Bauld, N. L.; Bellville, D. J.; Pabon, R.; Chelsky, R.; Green, G. *J. Am. Chem. Soc.* **1983**, *105*, 2378.

(7) These geometrical changes serve to increase "through-bond" and "through-space" delocalization between the radical centers at C_2 and C_5 in **2a** and **2b**, respectively.



density being taken as 48 and 24 G for the β and α hydrogens, respectively. This model agrees well with the experimental result of a 11.9 G coupling to six equivalent hydrogens. Moreover, this structure is expected to have a strong charge-resonance electronic absorption band,[9] which is consistent with the intense blue color and ease of photobleaching by red light ($\lambda > 620$ nm).

Having characterized the intermediate, its photoinduced or thermal conversion to the cyclohexene radical cation is interpreted as occurring by a single 1,3-hydrogen shift, as from C_4 to C_2, or



2a

2b

conceivably by two consecutive 1,2-hydrogen shifts.[10,11] From a study of the thermal reaction between 77 and 90 K in CF_3CCl_3, the activation energy is estimated to be 4.5 kcal mol^{-1}. Thus, the cyclohexane-2,5-diyl radical cation resides in a shallow potential energy minimum on the reaction path connecting the 1,5-hexadiene and cyclohexene cations, and since it is calculated to be 34 kcal mol^{-1} more stable than the 1,5-hexadiene radical cation,[6] a degenerate radical cation Cope rearrangement is strongly disfavored. Therefore, isomerization to the cyclohexene radical cation may be the only available reaction path in this case.

Finally, we note the striking contrast between the title reaction and the absence of cyclohexene formation in the degenerate Cope rearrangement of neutral 1,5-hexadiene,[12] although the cyclohexane-2,5-diyl radical cation intermediate in the former is isostructural with the transition state[13] or diradicaloid intermediate[14] in the latter, and cyclohexene formation is calculated to be exothermic for both radical cation (36 kcal mol^{-1}) and neutral (21 kcal mol^{-1}) processes. Consequently, if a diradical *intermediate* is formed in the neutral Cope rearrangement, it presumably cannot exist in a very deep potential well since this feature might be expected to allow hydrogen transfer, and therefore cyclohexene formation, to compete with the electrocyclic cleavage reaction.

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Supplementary Material Available: Comparisons of the ESR spectra obtained from γ-irradiated solid solutions of 1,5-hexadiene and cyclohexene: (a) in $CFCl_3$ at 135 K (together with a simulated spectrum of the cyclohexene radical cation) and (b) in $CF_2ClCFCl_2$ at 100 K (2 pages). Ordering information is given on any current masthead page.

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[8] See, e.g.: Gordy, W. *Theory and Applications of Electron Spin Resonance*; Wiley: New York, 1980; Chapter VI, p 198.

[9] The charge resonance band for the "three-electron bond" in the isostructural dithiane radical cation has been described: (a) Shida, T.; Momose, T. *J. Mol. Struct.* **1985**, *126*, 159. (b) Asmus, K.-D. *Acc. Chem. Res.* **1979**, *12*, 436.

[10] The possibility that the hydrogen shift occurs before 1,6-ring closure has also been carefully considered. In this case, the "snakelike" distonic species $CH_2\overset{...}{-}{}^{+}CH\overset{...}{-}CH{-}(CH_2)_2{-}CH_2^{\bullet}$ comprised of an allylic cation and an alkyl radical would probably be the intermediate.[11] This species could also give a seven-line hyperfine pattern with an ca. 12-G spacing if the $RCH_2CH_2^{\bullet}$ radical center were to adopt an eclipsed rather than the usual bisected conformation,[8] such that $A(2H_\beta) = 12$ G and $A(2H_\alpha) = 24$ G. However, the line intensity ratios in Figure 1 are inconsistent with this assignment, especially considering that lines 1, 2, 6, and 7 of such a 1:2:3:4:3:2:1 pattern should be selectively broadened at low temperatures by the usual residual α-hydrogen hyperfine anisotropy. Ab initio MO calculations (Bellville, D. J.; Bauld, N. L. *Tetrahedron* **1986**, *42*, 6167) originally suggested that this type of distonic intermediate constitutes a minimum along the path of the "role-reversed" Diels–Alder cycloaddition of *s-cis*-1,3-butadiene radical cation to ethylene, although the barrier to its endocyclization was calculated to be only 2.7 kcal mol^{-1}. With a better basis set, however, this minimum disappears, indicating a concerted reaction (Bauld, N. L.; Bellville, D. J.; Harirchian, B.; Lorenz, K. T.; Pabon, R. A., Jr.; Reynolds, D. W.; Wirth, D. D.; Chiou, H.-S.; Marsh, B. K. *Acc. Chem. Res.* **1987**, *20*, 371, footnote 19).

[11] Additional evidence against an acyclic distonic intermediate produced by a hydrogen shift[10] comes from our very recent studies on 1,1,6,6-tetradeuterio-1,5-hexadiene (Guo, Q.-X.; Williams, F., unpublished results). The ESR spectrum of the intermediate in this case is a sharp 12-G quintet which clearly rules out $CD_2\overset{...}{-}{}^{+}CH\overset{...}{-}CH{-}(CH_2)_2{-}CD_2^{\bullet}$ but is nicely consistent with the structure of the cyclized diyl radical cation proposed in the present paper.

[12] (a) Gajewski, J. J. *Hydrocarbon Thermal Isomerizations*; Academic Press: New York, 1981; pp 166–176. (b) Rhoads, S. J. In *Molecular Rearrangements*; de Mayo, P., Ed.; Wiley-Interscience: New York, 1963; Vol. 1, p 655. (c) Doering, W. v. E.; Roth, W. R. *Tetrahedron* **1962**, *18*, 67. Doering, W. v. E.; Roth, W. R. *Angew. Chem.* **1963**, *75*, 27; *Angew. Chem., Intl. Ed. Engl.* **1963**, *2*, 115.

[13] Osamura, Y.; Kato, S.; Morokuma, K.; Feller, D.; Davidson, E. R.; Borden, W. T. *J. Am. Chem. Soc.* **1984**, *106*, 3362.

[14] (a) Doering, W. v. E.; Toscano, V. G.; Beasley, G. H. *Tetrahedron* **1971**, *27*, 5299. (b) Dewar, M. J. S. *J. Am. Chem. Soc.* **1984**, *106*, 209 and references contained therein. (c) Dewar, M. J. S.; Jie, C. *J. Am. Chem. Soc.* **1987**, *109*, 5893. (d) Dewar, M. J. S.; Jie, C. *J. Chem. Soc., Chem. Commun.* **1987**, 1451.

Direct Conversion of Aldehydes to Seleno- and Thioaldehydes

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The chemistry of molecules having unstable carbon–heteroatom multiple bonds is of great importance and interest. Until quite recently, the chemistry of selenoaldehydes has remained almost undeveloped because of their high reactivity and difficulty of preparation.[1] The isolation of several selenoaldehydes stabilized by electron-donating groups[2] or by coordination to the transition metals such as chromium and tungsten[3a] has been reported. Though monomeric selenoaldehydes have not been isolated as free species without resort to such stabilizations as yet, they have been known to react with 1,3-dienes to give the corresponding Diels–Alder adducts[3b-5] or isomerize to benzoselenane.[6] The utmost important problem in selenoaldehyde chemistry is still to find a practical preparative method. The most efficient method for

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[1] Reviews: *Organic Compounds of Sulphur, Selenium, and Tellurium*; Specialist Periodical Reports; The Chemical Society: London, 1970–1981; Vol. 1–6. Paulmier, C. *Selenium Reagents and Intermediates in Organic Synthesis*; Baldwin, J. E., Ed.; Pergamon Press: 1986; pp 58–83.

[2] Reid, D. H.; Webster, R. G.; McKenzie, S. *J. Chem. Soc., Perkin Trans. 1* **1979**, 2334–2339.

[3] (a) Fischer, H.; Zeuner, S.; Riede, J. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 726–727. (b) Fischer, H.; Gerbing, U.; Riede, J.; Benn, R. *Ibid.* **1986**, *25*, 78–79.

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[6] Okazaki, R.; Ishii, A.; Inamoto, N. *J. Chem. Soc., Chem. Commun.* **1986**, 71–72.

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