Cyclobutanediyls: A New Class of Localized Biradicals. Synthesis and EPR Spectroscopy

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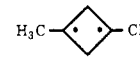
Abstract: Nine triplet cyclobutanediyls (**1**) have been synthesized and observed by matrix isolation EPR spectroscopy. The zero-field splitting (zfs) parameters provide detailed information on the spin densities in these structures. The observed zfs values can be quantitatively modeled by using a straightforward semiempirical scheme, as long as one explicitly incorporates the spin polarization effects known to be important in radicals such as allyl and benzyl. In addition, interpretable hyperfine coupling (hfc) has been observed in many cyclobutanediyls. Spectral simulation produces the hfc constants, which provide further information on spin distribution and indicate that the four-membered ring in **1** is planar. Several new procedures have been developed for the synthesis of the azoalkane precursors, **3**, which are described in detail.

A wide variety of biradicals and related structures have been directly observed by matrix isolation EPR spectroscopy in the more than 20 years since the initial observation of triplet trimethylenemethane (TMM).[2] The overwhelming majority of such studies have involved non-Kekulé molecules[3] (delocalized biradicals). These are fully conjugated π systems, for which one cannot write a classical Kekulé structure with all the electrons paired into bonds. Examples include TMM, *m*-quinodimethane and derivatives, and the 1,8-naphthoquinodimethanes.[4] The non-Kekulé nature and, to a considerable extent, the spin preferences of such structures are set by the topologies of the π systems.[5]

In contrast, direct spectroscopic studies of *localized* hydrocarbon biradicals are rare.[6] Localized biradicals contain two well-defined radical substructures which are not in conjugation with one another in a classical π sense. Note that the radical units themselves can be classically delocalized, such as allyl or benzyl. Localized biradicals are fundamentally different from non-Kekulé or delocalized biradicals in that there are no simple topological rules for predicting ground spin state, etc. Rather, a subtle and sometimes complicated interplay among factors such as ring strain, steric effects, and second-order electronic effects (e.g., through-bond coupling) determines the electronic structure.[7]

In 1984, we reported the EPR spectrum of the localized hydrocarbon triplet biradical 1,3-dimethyl-1,3-cyclobutanediyl (**1**-Me).[8] Almost 10 years earlier, Closs had reported the EPR detection of triplet 1,3-cyclopentanediyl (**2**).[9] Closs' classic study

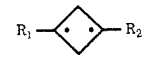


1-Me

2

was the first and, until our work, the only effort of its kind. At the time, the observation of **2** appeared to signal a turning point in the study of this important class of reactive intermediates.[4] For the first time, one would be able to directly probe the spectroscopy and reactivity of localized biradicals, and the many questions concerning the effects of substituents on singlet-triplet preferences and reactivity could be addressed directly. However, the cyclopentanediyl framework proved to be quite sensitive. Minor perturbations led to weak EPR signals or no signals at all.[9] Thus, a systematic study of the role of substituents on localized biradical spectroscopy and reactivity was not possible.

We now report that the cyclobutanediyl framework is much more robust. A variety of structures **1** have been prepared, all of which give intense, interpretable EPR spectra. We describe here the synthetic approaches to such molecules and the EPR spectra of the first key members of the series. Trends in the EPR zero-field splitting (zfs) parameter *D* have provided insights into the spin densities in these structures. In addition, interpretable hyperfine couplings (hfc) to several sets of hydrogens, but especially to those of the ring CH_2 groups, have provided further information on the molecular and electronic structures of these biradicals.



1-Me	R_1=R_2=CH_3
1-CD_3	R_1=R_2=CD_3
1-Et	R_1=R_2=CH_2CH_3
1-Pr	R_1=R_2=*n*-C_3H_7
1-MP	R_1=CH_3 R_2=Ph
1-EV	R_1=CH_2CH_3 R_2=$CHCH_2$
1-Ph	R_1=R_2=Ph
1-Vin	R_1=R_2=$CHCH_2$
1-Vin-*d*6	R_1=R_2=$CDCD_2$

(1) (a) NSF Predoctoral Fellow, 1982-1985. (b) JPL-CSMT Fellow, 1987. (c) Camille and Henry Dreyfus Teacher-Scholar, 1984-1989.

(2) Dowd, P. *J. Am. Chem. Soc.* **1966**, *88*, 2587-2589.

(3) Dewar, M. J. S. *The Molecular Orbital Theory of Organic Chemistry*; McGraw-Hill: New York, 1969; pp 232-233.

(4) Borden, W. T., Ed. *Diradicals*; Wiley: New York, 1982.

(5) For recent discussions of such rules, see: (a) Ovchinnikov, A. A. *Theor. Chim. Acta* **1978**, *47*, 297-304. (b) Klein, D. J.; Nelin, C. J.; Alexander, S.; Matsen, F. A. *J. Chem. Phys.* **1982**, *77*, 3101-3108. (c) Borden, W. T.; Davidson, E. R. *J. Am. Chem. Soc.* **1977**, *99*, 4587-4594. See, however: Dowd, P.; Chang, W.; Paik, Y. H. *J. Am. Chem. Soc.* **1986**, *108*, 7416-7417; **1987**, *109*, 5284-5285; Du, P.; Borden, W. T. *J. Am. Chem. Soc.* **1987**, *109*, 930-931.

(6) Although they are generally not hydrocarbons, localized biradicals derived from Norrish type I and Norrish type II photoreactions are clearly relevant. An overview of early work involving primarily CIDNP (type I) and laser flash photolysis (type II) studies, as well as the dehydrobenzenes, is provided in: Dervan, P. B.; Dougherty, D. A. In *Diradicals*; Borden, W. T., Ed.; Wiley: New York, 1982; pp 107-149. A list of more recent works follows, which is not intended to be exhaustive. Type II biradicals: Scaiano, J. C. *Acc. Chem. Res.* **1982**, *15*, 252-258. Caldwell, R. A.; Majima, T.; Pac, C. *J. Am. Chem. Soc.* **1982**, *104*, 629-630. Scaiano, J. C.; Wagner, P. J. *J. Am. Chem. Soc.* **1984**, *106*, 4626-4627. Johnston, L. J.; Scaiano, J. C.; Sheppard, J. W.; Bays, J. P. *Chem. Phys. Lett.* **1986**, *124*, 493-498. Akiyama, K.; Ikegami, Y.; Tero-Kubota, S. *J. Am. Chem. Soc.* **1987**, *109*, 2538-2539. Type I biradicals and the hydrocarbon biradicals derived by CO loss: Caldwell, R. A.; Sakuragi, H.; Majima, T. *J. Am. Chem. Soc.* **1984**, *106*, 2471-2473. Weir, D.; Scaiano, J. C. *Chem. Phys. Lett.* **1985**, *118*, 526-529. Zimmt, M. B.; Doubleday, C., Jr.; Gould, I. R.; Turro, N. J. *J. Am. Chem. Soc.* **1985**, *107*, 6724-6726. Zimmt, M. B.; Doubleday, C., Jr.; Turro, N. J. *J. Am. Chem. Soc.* **1985**, *107*, 6726-6727; **1986**, *108*, 3618-3620. Johnston, L. J.; Scaiano, J. C. *J. Am. Chem. Soc.* **1986**, *108*, 2349-2353. Closs, G. L.; Forbes, M. D. E. *J. Am. Chem. Soc.* **1987**, *109*, 6185-6187. See also: Mizuno, K.; Ichinose, N.; Otsuji, Y.; Caldwell, R. A. *J. Am. Chem. Soc.* **1985**, *107*, 5797-5798. Sugawara, T.; Bethell, D.; Iwamura, H. *Tetrahedron Lett.* **1984**, *25*, 2375-2378. Localized, triplet biradicals can be trapped by dioxygen. See, for example: Wilson, R. M.; Geiser, F. *J. Am. Chem. Soc.* **1978**, *100*, 2225-2226.

(7) See, for example: (a) Doubleday, C., Jr.; McIver, J. W., Jr.; Page, M. *J. Am. Chem. Soc.* **1982**, *104*, 6533-6542. (b) Goldberg, A. H.; Dougherty, D. A. *J. Am. Chem. Soc.* **1983**, *105*, 284-290. (c) Salem, L.; Rowland, C. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 92-111.

(8) Jain, R.; Snyder, G. J.; Dougherty, D. A. *J. Am. Chem. Soc.* **1984**, *106*, 7294-7295.

(9) Buchwalter, S. L.; Closs, G. L. *J. Am. Chem. Soc.* **1975**, *97*, 3857-3858. Buchwalter, S. L.; Closs, G. L. *J. Am. Chem. Soc.* **1979**, *101*, 4688-4694.

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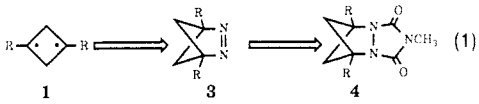
Synthesis

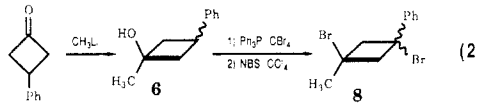
The immediate precursors to biradicals **1** are the substituted 2,3-diazabicyclo[2.1.1]hex-2-enes (**3**), which, in turn, are prepared from the appropriate urazoles **4** (eq 1). Earlier work in our



(1)

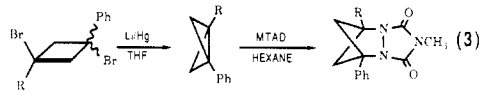
laboratories[10] showed that addition of *N*-methyltriazolinedione (MTAD) across the strained bond of a bicyclobutane is a convenient method for the synthesis of such urazoles.[11] One key to the synthesis of the diazenes, then, is to obtain the appropriately functionalized bicyclobutanes for the MTAD addition.

A fairly general route to substituted bicyclobutanes is based on the reductive coupling of the readily available 1,3-dihalocyclobutanes. For example, the synthesis of the methyl phenyl urazole **5** began with the readily available 3-phenylcyclobutanone[12] (eq 2). Treatment with methyllithium, conversion of the alcohol



(2)

to the bromide **7**, and benzylic bromination gave the dibromides **8** as a mixture of diastereomers. Closure of the dibromides to 1-methyl-3-phenylbicyclobutane (**9**) was accomplished by treatment with lithium amalgam. Thermal addition of MTAD in refluxing *n*-hexane then afforded **5** in good yield (eq 3). As with



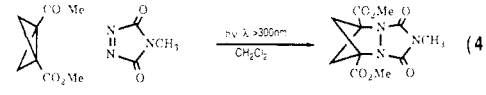
(3)

8 R=CH_3 **9** R=CH_3 **5** R=CH_3

11 R=Ph **12** R=Ph **10** R=Ph

our earlier reported thermal reactions,[10a,b] the addition of MTAD proceeds more cleanly in nonpolar solvents. The synthesis of the diphenyl urazole **10** is strictly analogous to that of **5** beginning with 1,3-dibromo-1,3-diphenylcyclobutane (**11**)[13] as a 1:1 mixture of diastereomers.

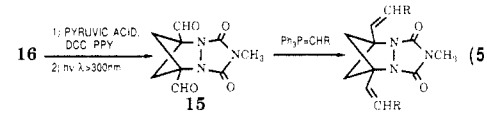
The thermal addition of MTAD to bicyclobutanes is sensitive to substituents at the bridgehead positions. For instance, 1,3-dimethylbicyclobutane reacts rapidly with MTAD at room temperature (as monitored by the disappearance of the red color of MTAD), but 1,3-dicarbomethoxybicyclobutane (**13**) fails to react even at high temperatures. We now report that the *photochemical*[10c,11] addition of MTAD to **13** produces urazole **14** in good yield (eq 4). Given the ready availability of **13** in large quantity,[14] and the potential conversion of the ester functionality of **14** into a variety of substituents, we saw this as a general route to substituted diazenes and biradicals.



(4)

13 **14**

Dialdehyde **15** was selected as the key target in an approach to the synthesis of several hydrocarbon-substituted urazoles via Wittig reactions. However, its synthesis proved to be surprisingly difficult. We first attempted the direct reduction of **14** to **15** using both diisobutylaluminum hydride and sodium bis(2-methoxyethoxy)aluminum hydride, but neither method was successful. Therefore, we adopted a two-step procedure in which the ester functionalities are first reduced to hydroxymethyl groups, producing diol **16**. This can be achieved easily by using either lithium borohydride in THF[15] or sodium borohydride in methanol.[16] Oxidation of the diol was quite difficult, and many procedures, including chromium-based reagents,[17] Swern,[18] lead tetraacetate,[19] and *N*-phenyltriazolinedione[20] oxidations, failed. Though some of these methods left the starting material unchanged, others appeared to fail only in isolation of the product. Believing that hydration of the dialdehyde might be the problem, we sought a completely water-free method. The pyruvate photolysis procedure employed by Binkley[21] appeared attractive, since the aldehyde product is obtained in solution without any workup. Pyrex-filtered photolysis of the dipyruvate ester **17** in dilute benzene solution does give the dialdehyde **15**, which indeed hydrates readily. Therefore, the product was used without isolation in Wittig reactions to give diene urazoles **18**, **19**, and **20** (eq 5).

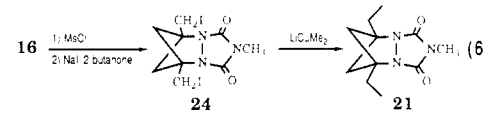


(5)

18 R=H
19 R=CH_3
20 R=Ph

Deuteriated divinyl urazole **18**-d_6 was prepared by following the above procedure using sodium borodeuteride in the reduction step and deuteriated phosphonium salt in the Wittig reaction. Proton NMR analysis revealed that the vinylic methylene groups were 68% deuteriated.

The syntheses of the diethyl (**21**) and dipropyl (**22**) urazoles also utilized the diol **16** (eq 6). The bismesylate (**23**) of diol **16**

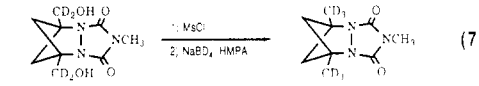


(6)

24 **21**

was treated with sodium iodide in refluxing 2-butanone to give diiodide **24**. Lithium dimethylcopper[22] then converts **24** to diethyl urazole **21**. Another route to **21** involves catalytic hydrogenation of divinyl urazole **18**. The dipropyl urazole (**22**) was similarly prepared by hydrogenation of **19**.

Synthesis of hexadeuteriated dimethyl urazole **25**-d_6 (eq 7) involves mesylation of **16**-d_4 followed by treatment with sodium borodeuteride in HMPA[23] to afford **25**-d_6.



(7)

16-d_4 **25**-d_6

The unsymmetrical ethyl vinyl urazole **26** was prepared by two methods. Catalytic hydrogenation of **18** using 1 equiv of hydrogen resulted in a 1:2:1 mixture of **18**, **26**, and **21**, respectively, which could be separated by preparative TLC and HPLC. Due to the difficulty of the separation, an alternative synthesis was developed which utilizes an epoxide protecting group (eq 8). The mono-

(10) (a) Chang, M. H.; Dougherty, D. A. *J. Org. Chem.* **1981**, *46*, 4092–4093. (b) Chang, M. H.; Jain, R.; Dougherty, D. A. *J. Am. Chem. Soc.* **1984**, *106*, 4211–4217. (c) Snyder, G. J.; Dougherty, D. A. *J. Am. Chem. Soc.* **1985**, *107*, 1774–1775.

(11) See also: Amey, R. L.; Smart, B. E. *J. Org. Chem.* **1981**, *46*, 4090–4092.

(12) Falmagne, J.-B.; Escudero, J.; Taleb-Sahraoui, S.; Ghosez, L. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 870–880. We have found that 3-phenylcyclobutanone can be easily prepared in multigram quantities by reductive dechlorination of 2,2-dichloro-3-phenylcyclobutanone (Krepski, L. R.; Hassner, A. *J. Org. Chem.* **1978**, *43*, 2879–2882) with zinc in refluxing acetic acid (Bak, D. A.; Brady, W. T. *J. Org. Chem.* **1979**, *44*, 107–110. Stewart, E. G., unpublished results).

(13) Farnum, D. G.; Mostashari, A.; Hagedorn, A. A., III. *J. Org. Chem.* **1971**, *36*, 698–702.

(14) Coffey, C. E. U.S. Patent 3657317, 1972.

(15) Nystrom, R. F.; Chaikin, S. W.; Brown, W. G. *J. Am. Chem. Soc.* **1949**, *71*, 3245–3246.

(16) Brown, M. S.; Rapoport, H. *J. Org. Chem.* **1963**, *28*, 3261–3263.

(17) (a) Herscovici, J.; Egron, M.-J.; Antonakis, K. *J. Chem. Soc., Perkin Trans. 1* **1982**, 1967–1973. (b) Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, 2647–2650. (c) Sharpless, K. B.; Akashi, K. *J. Am. Chem. Soc.* **1975**, *97*, 5927–5928.

(18) Mancuso, A. J.; Huang, S.-L.; Swern, D. *J. Org. Chem.* **1978**, *43*, 2480–2482.

(19) Partch, R. E. *J. Org. Chem.* **1965**, *30*, 2498–2502.

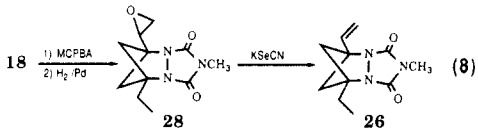
(20) Cookson, R. C.; Stevens, I. D. R.; Watts, C. T. *J. Chem. Soc., Chem. Commun.* **1966**, 744.

(21) Binkley, R. W. *J. Org. Chem.* **1976**, *41*, 3030–3031.

(22) Ireland, R. E.; Daub, J. P. *J. Org. Chem.* **1981**, *46*, 479–485.

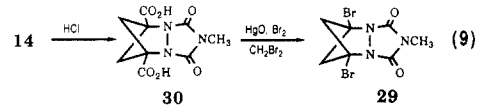
(23) Boland, W.; Ney, P.; Jaenicke, L. *Synthesis* **1980**, 1015–1017.

epoxide (**27**) of **18** was catalytically hydrogenated to yield saturated epoxide **28**, which was deoxygenated by treatment with potassium selenocyanate[24] to give **26**.



(8)

Conversion of the diester urazole **14** to dibromo urazole **29** (eq 9) was accomplished in two steps: hydrolysis, followed by decarboxylative bromination. Since the urazole moiety is labile

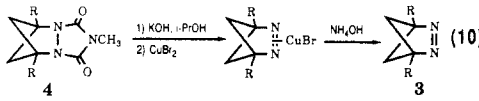


(9)

toward nucleophiles, acid-catalyzed hydrolysis was required to convert **14** to dicarboxylic acid **30**. Subjecting **30** to the conditions of the modified Hunsdiecker reaction[25] afforded dibromo urazole **29** in good yield.

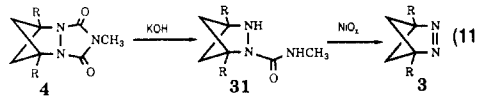
These studies, and others we have described,[10c] illustrate the insensitivity of the urazole moiety to a wide variety of synthetic procedures. Thus, we anticipate that an even wider array of substituted diazabicyclohexenes will be accessible, and we are pursuing such structures.

Two methods were employed for the conversion of the urazoles to diazenes. The standard route involving a base hydrolysis (typically refluxing KOH/2-propanol) followed by oxidation via the copper complexes[26] was used for most of the stable diazenes (eq 10). Minor variations of this procedure also worked for the



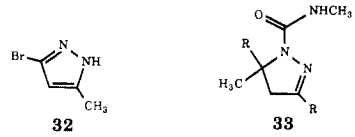
(10)

thermally unstable (vide infra) diazenes **3**-Vin and **3**-EV. However, an alternative procedure developed in our laboratories[10c] was found to be more satisfactory for these diazenes and for others on which the standard method failed. This procedure involves partial hydrolysis of the urazoles and isolation of the product semicarbazides (**31**) (eq 11). Oxidation of the semicarbazides with nickel peroxide[27] then affords the desired diazenes.



(11)

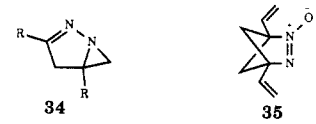
An obstacle to the success of the nickel peroxide method was the propensity of several of the semicarbazides to rearrange. These rearrangements were not studied extensively, but they appear to involve cleavage of a ring C–C bond to give five-membered-ring heterocycles. For instance, hydrolysis of the dibromo urazole **29** with potassium hydroxide in refluxing 2-propanol gave pyrazole **32** as a single product. Semicarbazides lacking a good leaving group (e.g., R = phenyl or vinyl) decomposed to give heterocycles such as **33**. These side reactions were minimized by using precautions such as room temperature hydrolyses, exclusion of oxygen, and immediate oxidation of the semicarbazides. Rearrangement



was especially fast in the hydrolysis of **20**, precluding the isolation of the distyryl diazene.

Diazene Reactivity. As for the parent (**3**-H),[10a] diazabicyclohexenes with hydrocarbon substituents thermally decompose to produce the analogous bicyclobutane as the sole product. The stability of the diazenes is highly dependent upon the radical-delocalizing ability of the bridgehead substituents.[28] The parent and alkyl-substituted diazenes are stable up to 100 °C, while the ethyl vinyl diazene **3**-EV decomposes with a half-life of ca. 6 h at room temperature. The divinyl and diphenyl diazenes (**3**-Vin and **3**-Ph) both decompose at temperatures above −30 °C.

The photochemistry of the various diazenes differs dramatically. The simplest cases are **3**-Vin, **3**-EV, and **3**-Ph, all of which give only the corresponding bicyclobutanes upon either direct or sensitized photolysis, independent of temperature. The photochemistry of the parent diazene (**3**-H) has previously been reported,[29] and the dimethyl diazene **3**-Me shows completely analogous behavior. For these diazenes, direct photolysis gives mainly the corresponding bicyclobutane, but triplet-sensitized photolysis affords predominantly nitrogen-retained products, 1,2-diazabicyclo[3.1.0]hex-2-enes (**34**). Product ratios are also strongly temperature dependent, reflecting increasing yields of triplet product **34** at lower temperatures.[29]



We also prepared the divinyl azoxy compound, **35**, in order to investigate its viability as a precursor to **1**-Vin. An azoxy precursor has been used successfully in the synthesis of a reactive isoindene.[30] We followed the general synthetic procedure of Olsen and Snyder:[31] potassium hydroxide hydrolysis of urazole **18** in the presence of hydrogen peroxide. As expected from the behavior of the other azoxy compounds, **35** is significantly more stable than the diazene **3**-Vin, being indefinitely stable at room temperature. Thus, ease of synthesis and handling make **35** attractive as a possible alternate precursor. Its photochemistry, however, proved to be far too inefficient to allow accumulation of **1**-Vin under cryogenic conditions.

EPR Spectroscopy

General Considerations. The EPR spectroscopy of organic triplets is highly informative but somewhat different from the more common EPR of doublets (free radicals). For that reason we will provide a brief overview of the basic principles.[32-34] The expert can move to the next section.

There are two important differences between doublet and triplet EPR, as they are conventionally applied. The first concerns the energy level pattern. At zero field, the two spin states ($m_s = \pm^1/_2$) of a doublet are degenerate. Application of an external magnetic field splits these levels, and an allowed ($\Delta m_s = 1$) transition between them can be observed. The spectrum consists of one line, which may be extensively split by hyperfine coupling. In contrast, the three spin states of a triplet ($m_s = 0, \pm 1$), are nondegenerate, even in the absence of an external magnetic field. This zero-field splitting (zfs) results from a dipolar coupling between the unpaired spins. In effect, the unpaired spins create an internal magnetic field which splits the magnetic sublevels. Application of an external magnetic field greatly magnifies this splitting and produces the usual resonance conditions. Most importantly, the dipolar

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Table I. Zero-Field Splitting Parameters for Cyclobutanediyls

	obsd[a]		calcd[a,b]	
biradical	$\|D/hc\|$	$\|E/hc\|$	$\|D/hc\|$	$\|E/hc\|$
1-Me	0.112	0.005	0.112	0.005
1-CD_3	0.112	0.005	0.112	0.005
1-Et	0.112	0.005	0.112	0.005
1-Pr	0.112	0.005	0.112	0.005
1-MP	0.082	0.003	0.081	0.003
1-EV	0.074	0.003	0.074	0.003
1-Ph	0.060	0.002	0.061	0.002
1-Vin	0.050	0.001	0.050	0.001
1-Vin-d_6	0.050	0.001	0.050	0.001

[a] In cm^{-1}. [b] Calculated D and E values are derived from the fits of Figures 2 and 3, respectively.

coupling, and hence the zfs, depends strongly on the average distance, r, between the unpaired spins.. In particular, the interaction varies as $1/r^3$. The relative energies of the three triplet levels at zero field are typically described by two zfs parameters, D and E. It is D which varies as $1/r^3$, while E is a probe of the symmetry of the biradical.

The second difference between doublet and triplet EPR is that, typically, the former is obtained in fluid media, while the latter is obtained in frozen glasses or solids. Thus, doublet spectra are nicely isotropic, but triplet spectra are highly anisotropic. Since there are three levels, one would expect two allowed ($\Delta m_s = 1$) transitions in a triplet. However, in a sample of randomly oriented, but nonreorienting triplets, each orientation produces its own pair of resonances. This leads to an essentially limitless number of lines in the absorption spectrum. Fortunately, though, one in effect selectively observes only those molecules which have one of their three principal magnetic axes nearly aligned with the external magnetic field (the canonical orientations). There are thus $3 \times 2 = 6$ transitions observed. In addition, a technically "forbidden" $\Delta m_s = 2$ transition is frequently seen at half-field.[35] As discussed below, this transition is intrinsically less anisotropic than the $\Delta m_s = 1$ transitions, and so only a single, broad line is observed. It is a simple matter to extract the zfs parameters D and E from such spectra,[32] and thereby obtain an estimate of the average separation of the spins. Thus, triplet EPR provides an extremely informative probe of biradical structure.

Zero-Field Splittings. Photolysis of frozen solutions of the diazenes **3** in 2-methyltetrahydrofuran (MTHF) and a variety of other solvents at 4 K produces EPR spectra for the corresponding triplet cyclobutanediyls (**1**). Figure 1 shows some of these spectra, and Table I lists the observed zfs parameters. The anticipated six lines are clearly visible in the spectrum of **1**-Me, along with the $\Delta m_s = 2$ transition. For the other structures, the value of E is relatively small. This leads to an apparent four-line spectrum.[32] As expected, the biradicals with fully saturated substituents show identical zfs, with $|D/hc| = 0.112$ cm^{-1}. This D value has been compared[8] with $|D/hc| = 0.084$ cm^{-1}, which has been reported for **2**.[9] The larger D value in the dialkylcyclobutanediyls is a consequence of the $1/r^3$ dependence of D, since the four-membered ring brings the radical centers closer together than the five-membered ring.

When R_1 and R_2 are delocalizing substituents, the value of D decreases. On average, the unpaired spins are further apart in the delocalized cyclobutanediyls, and the $1/r^3$ dependence leads to a decrease in D. Qualitatively, the trend along the series is as expected. It may at first seem surprising that **1**-Ph shows a significantly larger D value than **1**-Vin. Recall, however, that the Hückel coefficient at the CH_2 in the nonbonding molecular orbital (NBMO) of benzyl ($2/\sqrt{7}$) is *larger* than that in allyl ($1/\sqrt{2}$). Thus, the spin density at the ring carbons is higher in the diphenyl structure. Given the $1/r^3$ distance dependence, this effect dominates the D value.

The D values in Table I can be correlated to theoretical values obtained by using a semiempirical method for zfs calculations

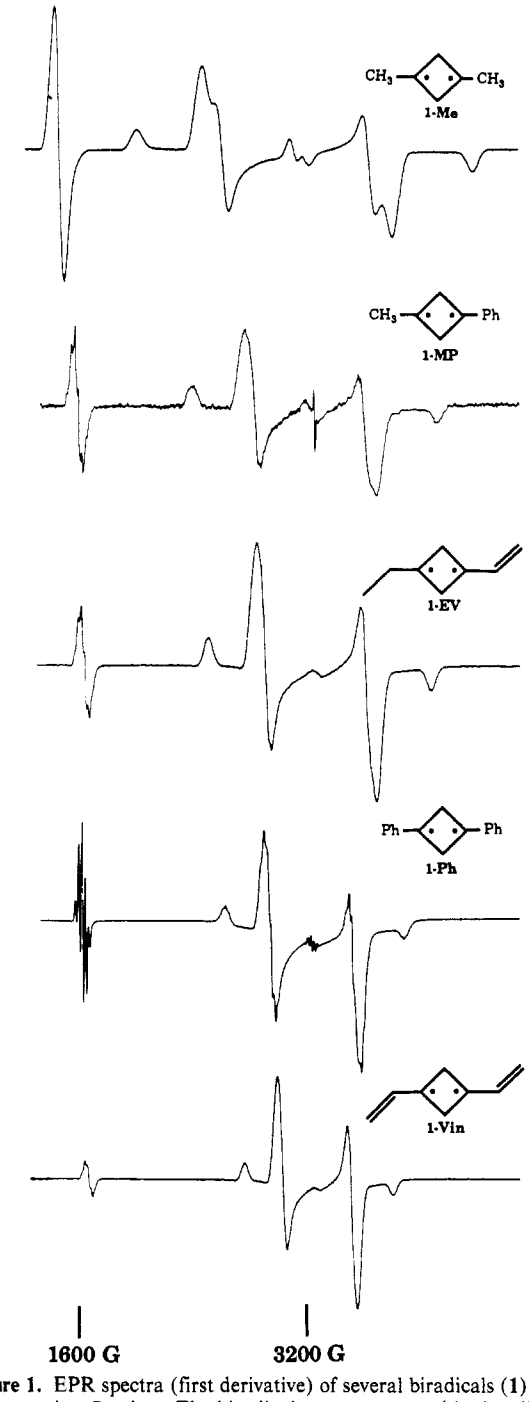

Figure 1. EPR spectra (first derivative) of several biradicals (**1**) in order of decreasing D value. The biradicals were generated by irradiation of the appropriate diazene precursors (**3**) in an MTHF matrix at 4 K. Lines in the region of 3200 G arise from free radicals and from double quantum transitions.[34]

described previously.[36] The distances between the radical centers in the ring were taken from ab initio optimized geometries of the parent cyclobutanediyl (**1**-H, 2.10 Å)[7b,37] and of **2** (2.37 Å).[38] The use of Hückel spin densities in the calculations allowed semiquantitative reproduction of the D values. However, it is well-known that in delocalized monoradicals such as allyl and benzyl, spin polarization effects produce spin densities that deviate significantly from those predicted by Hückel theory.[39] We have

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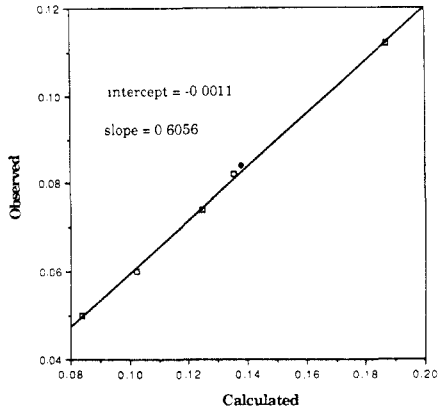

Figure 2. Observed vs calculated $|D/hc|$ values (cm^{-1}) for **1** (open boxes). The value for **2** (filled diamond) was not included in the least-squares analysis.

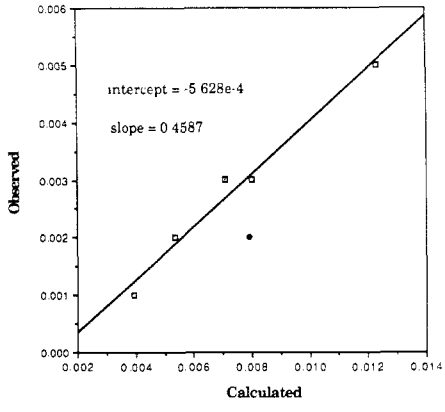

Figure 3. Observed vs calculated $|E/hc|$ values (cm^{-1}) for **1** (open boxes). The value for **2** (filled diamond) was not included in the least-squares analysis.

approximated such spin polarization effects in our calculations by using "experimental" spin densities determined for allyl and benzyl radicals from hyperfine measurements.[40] We assumed complete localization for alkyl-substituted radicals. With this approach, very good agreement between theory and experiment was obtained. A plot of experimental vs calculated D values (Figure 2) shows an excellent correlation, giving a least-squares line with a near-zero intercept. The calculated value for cyclopentanediyl (**2**) was not included in the least-squares fit, but as shown in Figure 2, it falls very close to the line. The calculated D values, which have been scaled by using the fit from Figure 2, are shown in Table I for comparison with the experimental values.

A similar correlation has been obtained for the experimental and calculated E values (Figure 3, Table I). The accurate calculation of E values is more difficult, since E represents much smaller energy separations than D. Still, the correlation of calculated and observed E values across the cyclobutanediyl series is quite acceptable, although the value for **2** is significantly off the line.

Hyperfine Coupling. Six of the cyclobutanediyls display splittings due to hfc in their half-field ($\Delta m_s = 2$) transitions (Figure 4). It was at first surprising to see these splittings, some of them quite well resolved, because of the anisotropies involved in powder spectra. Indeed, the observation of interpretable hyperfine in triplet EPR is relatively rare,[10c,41] except for single-crystal samples.[42] We have found, however, that these splittings can be readily interpreted, providing values for the hfc constants (a_H) of several protons in these structures. Of course, these coupling constants provide important structural information through standard relationships[32,43] such as the McConnell equation (eq 12) for α protons (those directly attached to radical centers) and

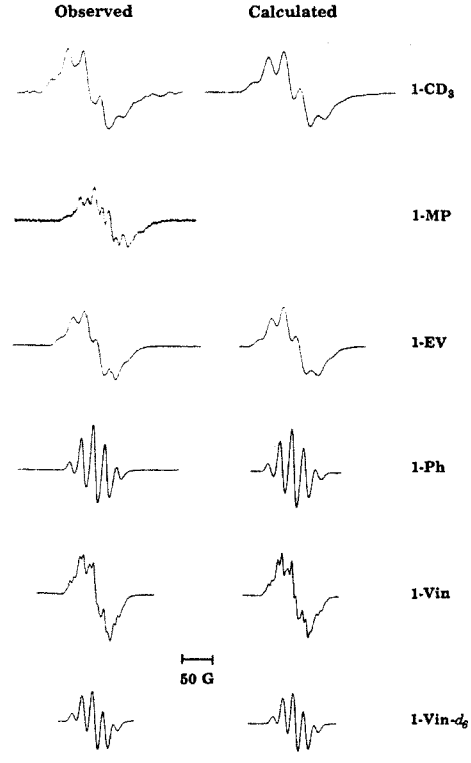

Figure 4. Hyperfine structure in the $\Delta m_s = 2$ region of several biradicals **1**.

$$a^{\alpha}_{H} = Q\rho \quad (12)$$

$$a^{\beta}_{H} = A + \rho C \cos^2 \theta \quad (13)$$

a related expression (eq 13) for β protons (those on carbons adjacent to radical centers). In these equations, ρ is the spin density at a radical center; Q, A, and C are empirical constants with typical values of 20–30, 0–5, and 40–45 G, respectively; and θ is the angle between the axis of the radical p orbital on the α carbon and the β C–H bond.

A first source of anisotropy to be considered is that which is intrinsic to the hfc tensor, and α and β couplings are different in this regard. It is generally recognized that the hfc tensor for β couplings is relatively isotropic,[43,44] and so splittings due to β couplings can be directly related to isotropic a^{β}_{H} values. In contrast, the α hfc tensor is generally quite anisotropic.[44] However, Sternlicht[45] has shown that for *planar* organic radicals in randomly oriented, nonreorienting (powder) samples, the splittings observed from α hfc are approximately equal to the isotropic hfc constants (a^{α}_{H}) and the lines are fairly symmetrical. Thus, anisotropies introduced by the hfc tensors should be relatively small in our spectra.

Our goal, of course, is to relate the splittings we observe in our triplet spectra to spin densities, as is done for radical spectra. There is, however, an important difference between biradicals and simple radicals. A typical magnetic nucleus in a localized biradical will effectively interact with only one of the two spins of the triplet. This is always true for α protons and will be true for β protons

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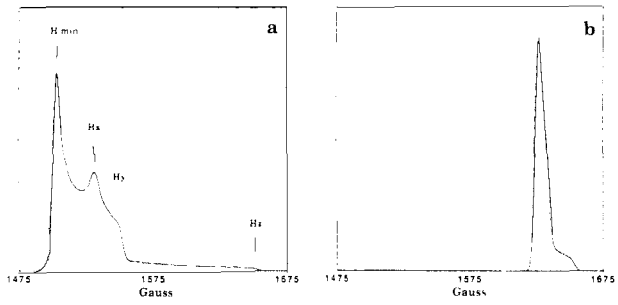

Figure 5. Simulated absorbance spectra in the $\Delta m_s = 2$ region of **1**-Me (a) and **1**-Vin (b) in the absence of hyperfine coupling.

Table II. Hyperfine Simulation Parameters

biradical	a^{β}_{H}[a,b]	other[a,b]
1-CD_3	32	3 (2D), 1.5 (4D)
1-EV	23	vinyl: 2 (1H), 7 (2H)
		ethyl: 5 (1 H), 21 (1 H)
1-Ph	22.5	3 (4 H; ortho); 3 (2 H; para); 0.5 (4 H; meta)
1-Vin	19	2 (2 H), 7 (4 H)
1-Vin-d_6	19	1.5 (4 D)

[a] In gauss. [b] Coupling constants rounded to the nearest 0.5 G.

in the R groups of **1**. When electron-exchange terms are much greater than the hyperfine interaction, nuclei of this type are expected to produce couplings which are half those seen in analogous free radicals.[46-48] For example, in allyl radical, the magnitudes of the α couplings are ca. 14 G for the terminal (CH_2) hydrogens and ca. 4 G for the central hydrogen. On the basis of the above arguments, one would expect the analogous hydrogens in **1**-Vin to produce 7- and 2-G splittings, respectively, and this is what is observed (see below). The exception to this rule is the set of β hydrogens that are on the four-membered ring of **1**. These can couple directly to both radical centers, and so the splittings that arise from them should be of the same magnitude as analogous splittings in simple radicals. As described below our simulations fully support this analysis.

There is another source of anisotropy in these triplet spectra, namely, the intrinsic orientational anisotropy of the $\Delta m_s = 2$ transition.[35] Just as there are, in effect, two observable $\Delta m_s = 1$ transitions for each of the three canonical orientations of a triplet, so there is *one* $\Delta m_s = 2$ transition for each canonical orientation. In addition, a fourth $\Delta m_s = 2$ transition, termed H_{min}, occurs at lower field than the other three (H_x, H_y, and H_z). The positions of these transitions can be calculated easily from the zfs parameters.[35] In addition, the intensities of these transitions decrease through the series H_{min}, H_x, H_y, H_z (Figure 5). Thus, the largest contributions to the line shape come from resonances at H_{min}, H_x, and H_y. From Figure 5, it is clear that for biradicals with relatively small D values (e.g., **1**-Vin and **1**-Ph) the separation between H_{min} and H_x is on the order of the spectral line width (5–6 G). Thus, the spectra are very nearly isotropic, and simple splitting patterns can be observed. In contrast, biradicals with large D values (e.g., **1**-CD_3) have a large separation between H_{min} and H_x (30 G), and as a result the line shape for the $\Delta m_s = 2$ transition should be broad and unsymmetrical, even in the absence of any hfc. If there is hfc, it is superimposed onto the patterns of Figure 5.

Quantitative interpretation of the hyperfine splitting patterns of Figure 4 required spectral simulation. Our program, based on the algorithm of Kottis and Lefebvre,[35] assumes isotropic hfc and equal transition probabilities for all orientations. The simulations explicitly include the orientational anisotropy of the $\Delta m_s = 2$ transition. The resulting calculated spectra are shown for the five cyclobutanediyls which exhibit interpretable hyperfine in Figure 4. The agreement between experiment and theory is quite satisfactory, given the approximations involved. In Table II we list the coupling constants used in the simulations.

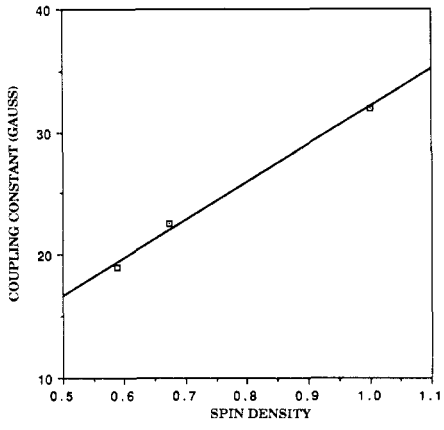

Figure 6. Correlation of a^{β}_{H} for **1** with spin densities according to eq 13, using the coupling constants of Table II. **1**-EV is not included (see text).

Two of the biradicals, **1**-Ph and **1**-Vin-d_6, display well-defined five-line patterns in their half-field transitions, which may be attributed to the dominant hyperfine interaction with the four β hydrogens of the cyclobutanediyl ring. But despite the apparent simplicity of the patterns, simulations show that the β-hyperfine interaction alone does not account for the observed spectrum. *Accurate simulations* required the inclusion of the smaller couplings to other nuclei. In addition, the simulation of **1**-Vin-d_6 is a statistically weighted average over the d_2 through d_6 compounds present in the sample due to incomplete deuteriation in the synthesis. Due to the dominant β-hyperfine interaction, **1**-Ph and **1**-Vin-d_6 also exhibit hyperfine splitting patterns in the $\Delta m_s = 1$ transitions that are identical with those in the $\Delta m_s = 2$ region, though they are less well resolved. With the data from **1**-Vin-d_6 in hand, the simulation for **1**-Vin was straightforward. For both **1**-Ph and **1**-Vin the α couplings observed in the substituents are as expected—they are half the values seen for analogous protons in the benzyl and allyl radicals. In **1**-CD_3, a simple five-line pattern as for **1**-Ph is not observed because of the anisotropy of the $\Delta m_s = 2$ transition. The simulation, though, treats this spectrum well, although the line broadening required to achieve a good fit was much greater for **1**-CD_3 than for other spectra.

An important feature of these spectra is the fact that the ring CH_2 protons of a given biradical all have identical coupling constants. Given the dependence of a^{β}_{H} on θ this requires that *the cyclobutanediyl ring is planar* in all these structures. This is the first structural information of this kind for a localized biradical and is in accord with our theoretical predictions.[37] The observation of equivalent couplings would also be consistent with a pair of rapidly interconverting nonplanar forms, but this would seem to be unlikely at 3.8 K. Also, the intrinsic broadness of triplet EPR lines introduces some uncertainty, in that small differences in hfc constants would be absorbed into the line widths. Our simulations, though, indicate that differences as small as 1.0 G, implying differences in θ of ca. 2°, could be detected in the spectra of **1**-Ph. The uncertainty is greater in a more complex spectrum, such as that from **1**-CD_3. Thus, it is perhaps best to say that cyclobutanediyls are planar, or nearly so. Note that in the biradical precursors (azoalkanes **3**) the cyclobutane moiety is very highly puckered (flap angle ca. 58°). Clearly, a considerable structural reorganization occurs within the matrix site after N_2 loss from **3**. Apparently, the restraining forces of the matrix material are not overwhelming, an observation that is quite relevant to efforts to characterize the matrix decay kinetics of such biradicals.[49]

As indicated in eq 13, the values of a^{β}_{H} for the ring protons provide another gauge of spin density at the cyclobutanediyl radical carbons. It is apparent from Table II that a^{β}_{H} does decrease with increasing delocalization, just as the zfs D value does. We have only three accurately determined values for a^{β}_{H}, but if we plot them according to eq 13, the result of Figure 6 is obtained. The intercept is 1.2 G, a quite reasonable value for A. The slope is

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30.9 G. If we set C = 42.5 G, the value of θ is 31°, which is in good agreement with our theoretically determined[37] value of 27°. Of course, three data points are hardly enough to provide an accurate determination of θ. However, the results summarized in Figure 6 again show that the spectral data we have obtained for the cyclobutanediyls agree both in absolute magnitude and in trends along the series with expectations based upon analogies to conventional radical chemistry. For example, the 32-G value of a^{β}_{H} seen for **1**-CD_3 is in good agreement with an expected value of 34 G derived from measurements on the cyclobutyl radical.[50]

These results indicate that hfc in triplet spectra could be a more widely applicable tool than had previously been anticipated. For example, splittings are clearly observable in the $\Delta m_s = 2$ transition for Closs' biradical **2**.[9] Based on our results, reasonable estimates of a_H values would be 32 G for the C2 β protons, 16 G (i.e., 32 ÷ 2) for the C4 and C5 β protons, and 12 G (half of 24 G, a common value for a^{α}_{H}) for C1 and C3 α protons. Using these values, the essential features of the spectrum are well reproduced.

The level of complexity in the hyperfine patterns of triplet spectra that can be interpreted is limited. For example, only a broad featureless $\Delta m_s = 2$ line is observed for **1**-Me, and the pattern for **1**-MP (Figure 4) has not yielded to simulation. This could be a consequence of multiple conformations for the methyl groups. Remembering the angle dependence of eq 13, this could greatly complicate the spectra. Even if the methyls are rapidly rotating at 4 K (perhaps via tunneling), the number of lines they would produce, superimposed on the quintet from the ring β protons, would create a poorly resolved spectrum. We have been able to simulate the spectrum for **1**-EV, but the simulations required five large couplings, instead of the usual four due to the ring protons. This could indicate that one of the CH_2 protons of the ethyl group has $\theta \approx 0°$, which, after application of the factor of one-half, would produce a coupling similar to the ring protons. This uncertainty, coupled with the fact that it is not completely clear what value of ρ should be used for the ring protons, is the reason that the value of a^{β}_{H} for **1**-EV was not included in the fit of Figure 6. If it is included, the line obtained does not change significantly.

Discussion

We have found that a wide range of triplet cyclobutanediyls (**1**) can be prepared and directly observed by EPR spectroscopy. Most importantly, delocalizing substituents such as phenyl and vinyl are tolerated. In fact, they increase biradical stability.[49] It would thus appear that the triplet cyclobutanediyl framework is more tolerant to substituent perturbations than that of cyclopentanediyl (**2**), although the substitutional studies on **2** were limited. We propose two factors that could contribute to this difference. First, theory predicted some time ago[7b] (in fact, long before the observation of **1**-Me) that the intrinsic preference for a triplet ground state is roughly twice as large for **1**-H as for **2** (1.7 vs 0.9 kcal/mol). Although we have no direct data on the ground spin state, the fact that we can observe all the cyclobutanediyls at temperatures as low as 3.8 K does strongly support this prediction. A second factor is the diminished conformational flexibility of the four-membered ring vs the five-membered ring. Taken together, these two arguments suggest that perhaps in the cyclopentanediyl, relatively small substituent changes alter the conformation of the ring enough to produce a singlet ground state. Singlet–triplet gaps are well-known to be sensitive to the relative orientations of the orbitals involved,[7] and the existence of a triplet ground state appears to be a necessary criterion for success in these experiments.

The EPR spectra of the cyclobutanediyls provide valuable structural information. The D value is a sensitive probe of spin distribution, and we have shown that the trends in the data can be quantitatively modeled by using a relatively simple scheme for zfs calculations. It is, however, necessary to use wave functions that include the spin polarization effects known to strongly influence the spin distributions in delocalized radicals and biradicals. In the present case, this could be done by using "experimental" spin densities determined for allyl and benzyl.

Similarly, hfc to the ring CH_2 protons was observed to be quantitatively correlated to the spin densities at the ring radical centers. Importantly, the hfc shows that all the cyclobutanediyls observed thus far are effectively planar.

The present work establishes a foundation for the systematic study of the effects of substituents on the spectroscopy and reactivity of localized 1,3-biradicals. We are intensively investigating the matrix isolation reactivities of the hydrocarbon biradicals described herein and will report the results shortly.[49] In addition, we are adapting the synthetic protocols developed to a wide array of new structures that will include polar and heavy-atom substituents. These should provide further insights into the fundamental nature of simple biradicals.

Experimental Section

General. ^1H NMR spectra were recorded on a Varian EM-390 spectrometer. Fourier transform NMR spectra (^1H and ^{13}C) were recorded on a Varian XL-200, JEOL FX-90Q, or JEOL GX-400 spectrometer. An INEPTNON[51] pulse sequence was employed to determine true carbon–hydrogen coupling constants. Ultraviolet spectra were recorded on a Hewlett-Packard 8451A diode array spectrophotometer. Infrared spectra were recorded on a Shimadzu IR-435 or a Mattson Instruments Sirius 100 FT-IR spectrometer fitted with a Starlab minicomputer. Mass spectra were obtained by the Caltech Analytical Facility and the U.C. Riverside Analytical Facility. Analytical gas chromatography was performed on a Hewlett-Packard 5840A chromatograph equipped with a flame-ionization detector. Preparative gas chromatography was performed on a Varian Aerograph Model 920 chromatograph with a thermal conductivity detector. High-pressure liquid chromatography was performed with a Perkin-Elmer Series 2 liquid chromatograph. Melting points are uncorrected.

Tetrahydrofuran was distilled from benzophenone ketyl prior to use. All other solvents were reagent grade and used as purchased unless otherwise indicated. Column chromatography was performed by the method of Still[52] employing 230–400 mesh silica gel.

1-Methyl-3-phenylcyclobutanol (6). A solution of 3-phenylcyclobutanone[12] (200 mg, 1.37 mmol) in 3 mL of dry ether was added dropwise to an ice-cold ether solution of methyllithium (1.3 mL, 2.0 mmol) over 20 min. After stirring at room temperature for 20 min, the reaction was quenched by addition of water (ca. 10 mL). The ether solution was dried over $MgSO_4$, concentrated, and purified by flash chromatography (7:3 petroleum ether–ethyl acetate) to give 195 mg (88%) of a diastereomeric mixture (83:17 syn:anti) of the alcohols as a colorless oil. Syn isomer: ^1H NMR ($CDCl_3$) δ 1.50 (s, 3 H), 2.00 (bs, 1 H), 2.22 (m, 2 H), 2.51 (m, 2 H), 3.06 (quintet, 1 H, J = 8.8 Hz), 7.27 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 27.33, 30.24, 45.52, 68.96, 125.70, 126.31, 128.01, 128.05. Anti isomer: ^1H NMR ($CDCl_3$) δ 1.36 (s, 3 H), 1.69 (bs, 1 H), 2.25 (m, 2 H), 2.50 (m, 2 H), 3.75 (quintet, 1 H, J = 8.5 Hz), 7.24 (m, 5 H).

1-Bromo-1-methyl-3-phenylcyclobutane (7). To a solution of **6** (112 mg, 0.691 mmol) in 6.5 mL of dry acetonitrile under argon were added triphenylphosphine (615 mg, 2.35 mmol) and carbon tetrabromide (780 mg, 2.35 mmol). After stirring at room temperature for 16 h, the mixture was filtered and concentrated to give a yellow oil. Careful flash chromatography (petroleum ether–benzene, 0–5%, gradient) gave 80 mg (45%) of **7** as a mixture of diastereomers (65:35 anti:syn). Anti isomer: ^1H NMR ($CDCl_3$) δ 1.90 (s, 3 H), 2.45 (m, 2 H), 3.0 (m, 2 H), 4.05 (quintet, 1 H, J = 8.5 Hz), 7.3 (m, 5 H). Syn isomer: ^1H NMR ($CDCl_3$) 2.10 (s, 3 H), 2.90 (m, 2 H), 3.0 (m, 2 H), 3.45 (quintet, 1 H, J = 8.5 Hz), 7.3 (m, 5 H).

1,3-Dibromo-1-methyl-3-phenylcyclobutane (8). A solution containing **7** (72 mg, 0.32 mmol), *N*-bromosuccinimide (57 mg, 0.32 mmol), and dibenzoyl peroxide (3 mg) in 3 mL of carbon tetrachloride was allowed to reflux under argon until the NBS had been consumed (1.5 h). The cooled solution was filtered and concentrated to afford 97 mg of a 1:1 diastereomeric mixture of **8** as a viscous oil. Syn isomer: ^1H NMR ($CDCl_3$) δ 1.60 (s, 3 H), 3.5 (m, 2 H), 3.8 (m, 2 H), 7.4 (m, 5 H). Anti isomer: ^1H NMR ($CDCl_3$) δ 2.30 (s, 3 H), 3.5 (m, 2 H), 3.8 (m, 2 H), 7.4 (m, 5 H).

(49) Sponsler, M. B.; Jain, R.; Coms, F. D.; Dougherty, D. A., manuscript in preparation.

(50) This value was obtained by taking the observed a^{β}_{H} for cyclobutyl (37 G; Fessenden, R. W.; Schuler, R. H. *J. Chem. Phys.* **1963**, *39*, 2147–2195) and scaling by 0.919, the correction for substitution by CH_3. See ref 32, p 121.

(51) Morris, G. A.; Freeman, R. *J. Am. Chem. Soc.* **1979**, *101*, 760–762. Benn, R.; Günther, H. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 350–380.

(52) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923–2925.

1-Methyl-3-phenylbicyclo[1.1.0]butane (9). To a solution of dibromide **8** (95 mg, 0.31 mmol) in 2 mL of tetrahydrofuran was added 1.5 g of freshly pulverized 2% lithium amalgam.[53] The heterogeneous mixture was allowed to stir at room temperature under argon for 12 h. After the dark gray slurry had been filtered through Celite, tetrahydrofuran (3 mL), CH_2Cl_2 (10 mL), and 5% sodium bicarbonate were added to the filtrate and thoroughly mixed. The organic solution was dried over Na_2SO_4 and concentrated to afford 40 mg of a volatile oil, which was used immediately in the next step. ^1H NMR ($CDCl_3$) δ 1.20 (s, 2 H), 1.35 (s, 3 H), 2.05 (s, 2 H), 7.25 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 11.60 (q, J = 127 Hz), 16.02 (s), 20.08 (s), 34.60 (t, J = 161 Hz), 124.41 (d, J = 161 Hz), 125.27 (d, J = 158 Hz), 128.11 (d, J = 159 Hz), 138.33 (s).

1,4-Dimethyl-7-phenyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (5). To a solution of bicyclobutane **9** (45 mg, 0.31 mmol) in 30 mL of refluxing *n*-hexane under a stream of argon was added a solution of MTAD (47 mg, 0.42 mmol) in 5.5 mL of ether until the red color of MTAD persisted (ca. 3.5 mL). After the hexane was removed, the crude solid was triturated with CH_2Cl_2. The dichloromethane solution was then concentrated and purified by flash chromatography (4:1 benzene–ethyl acetate) to afford **5** (30 mg, 37% from **7**) as a white crystalline solid: mp 143.5–145.5 °C; ^1H NMR (C_6D_6) δ 1.42 (m, 2 H), 1.57 (s, 3 H), 1.76 (m, 2 H), 2.51 (s, 3 H), 7.15 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 16.10 (q, J = 128 Hz), 25.79 (q, J = 141 Hz), 47.87 (t, J = 145 Hz), 69.81 (s), 74.20 (s), 126.78 (d, J = 158 Hz), 128.12 (d, J = 159 Hz), 128.62 (d, J = 162 Hz), 133.18 (s), 159.20 (s), 159.74 (s); mass spectrum (EI), *m/e* 257, 242, 199, 185, 143 (100), 129, 103, 91, 77; exact mass calcd for $C_{14}H_{15}N_3O_2$ 257.1164, found 257.1167.

Hydrolysis of 5. A suspension of urazole **5** (9.5 mg, 0.037 mmol) and freshly crushed KOH (19 mg, 0.3 mmol, 87%) in 2 mL of degassed 2-propanol was allowed to reflux for 10 min under argon. The cooled solution was then acidified by dropwise addition of degassed 3 N HCl until decarboxylation ceased (ca. 250 μL). The solution was then neutralized with degassed 1 N NH_3. Degassed water (1 mL) was added to dissolve the salts, and then the solution was extracted with degassed CH_2Cl_2 (2 × 2.5 mL). The organic solution was dried with Na_2SO_4, filtered, and concentrated to leave 8.5 mg of a light yellow oil. High-field ^1H NMR analysis revealed that >90% of the product consisted of a 1:1 mixture of semicarbazides **31**-MPa and **31**-MPb and <10% consisted of a rearranged semicarbazide **33**-MP. All attempts to purify this mixture failed. **31**-MPa: ^1H NMR ($CDCl_3$) δ 1.90 (s, 3 H), 1.98 (bs, 4 H), 2.82 (d, 3 H, J = 5 Hz), 4.30 (bs, 1 H), 6.75 (bs, 1 H), 7.28 (m, 5 H). **31**-MPb: ^1H NMR ($CDCl_3$) δ 1.44 (s, 3 H), 1.98 (bs, 4 H), 2.70 (d, 3 H, J = 5 Hz), 4.30 (bs, 1 H), 6.50 (bs, 1 H), 7.28 (m, 5 H). **33**-MP: ^1H NMR ($CDCl_3$) δ 1.62 (s, 6 H), 2.88 (d, 3 H, J = 5 Hz), 3.08 (s, 2 H), 6.04 (bs, 1 H), 7.28 (m, 3 H), 7.64 (m, 2 H).

1-Methyl-4-phenyl-2,3-diazabicyclo[2.1.1]hex-2-ene (3-MP). To a cooled solution (−50 °C) of semicarbazides **31**-MPa and **31**-MPb (ca. 8 mg, 0.035 mmol) in 3.5 mL of distilled CH_2Cl_2 under argon was added nickel peroxide[27] (130 mg, 0.60 mmol of active oxidant). After 1 h of stirring, the cold slurry was transferred via a Teflon cannula onto a cold filtration frit and vacuum filtered into a cold receiving flask. The solvent was removed at −50 °C under high vacuum to leave a slightly yellow, crystalline solid: ^1H NMR ($CDCl_3$) δ 1.89 (s, 3 H), 2.12 (m, 2 H), 2.59 (m, 2 H), 7.45 (m, 5 H); UV ($CDCl_3$) λ_{max} 344 nm.

1,3-Diphenylbicyclo[1.1.0]butane (12). To a solution of dibromide **11**[13] (203 mg, 0.55 mmol) in 4 mL of tetrahydrofuran was added 1.0 g of freshly pulverized 2% lithium amalgam.[53] The heterogeneous mixture was allowed to stir for 2 h under an argon atmosphere. After the dark gray slurry was filtered through Celite, tetrahydrofuran (5 mL), CH_2Cl_2 (10 mL), and 5% sodium bicarbonate (30 mL) were added to the filtrate and thoroughly mixed. The organic solution was dried over Na_2SO_4 and concentrated to afford 104 mg of waxy yellow crystals, which were immediately used in the next step. ^1H NMR ($CDCl_3$) δ 1.60 (s, 2 H), 2.80 (s, 2 H), 7.22 (m, 10 H); ^{13}C NMR ($CDCl_3$) δ 28.72 (s), 32.59 (tdd, $^1J_{CH}$ = 160 Hz, $^3J_{CH}$ = 13.9, 4.4 Hz), 124.93 (d, $^1J_{CH}$ = 161 Hz), 124.96 (d, $^1J_{CH}$ = 160 Hz), 127.86 (d, $^1J_{CH}$ = 159 Hz), 135.53 (s).

1,7-Diphenyl-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (10). To a refluxing solution of 1,3-diphenylbicyclobutane (**12**) (225 mg, 1.1 mmol) in *n*-hexane was added a solution of MTAD (140 mg, 1.2 mmol) in 40 mL of diethyl ether over 45 min while under a stream of argon. The solvent was then removed under reduced pressure, and the crude material was purified by flash chromatography (4:1 benzene–ethyl acetate) to give 103 mg (28% from **11**) of **10** as a white crystalline solid: mp 207.5–208.5 °C; ^1H NMR ($CDCl_3$) δ 2.52 (m, 4 H), 2.86 (s, 3 H), 7.33 (m, 10 H); ^{13}C NMR ($CDCl_3$) δ 25.76 (q, J_{CH} = 140 Hz), 47.38 (t, J_{CH} = 143 Hz), 73.72 (s), 126.84 (d, J_{CH} = 157 Hz), 128.18 (d, J_{CH} = 166 Hz), 128.73 (d, J_{CH} = 160 Hz), 132.99 (s), 159.15 (s); mass spectrum (EI), *m/e* 319, 234, 206, 205 (100), 169, 117; exact mass calcd for $C_{19}H_{17}N_3O_2$ 319.1321, found 319.1318.

Semicarbazide 31-Ph. To a 5-mL flask containing **10** (15 mg, 47 mmol) were added 23 mg of KOH and 1.5 mL of degassed 2-propanol. The contents of the flask were brought to reflux under an argon atmosphere for 10 min. The cooled solution was then carefully acidified by dropwise addition of degassed 3 N HCl until CO_2 evolution ceased (250 μL). The solution was then neutralized by dropwise addition of degassed 1 N NH_3. Degassed water was added to dissolve the salts and then the solution was extracted with two 1.5-mL portions of degassed CH_2Cl_2 (distilled from CaH_2). The extracts were dried by filtration through $MgSO_4$. The solvent was removed by passing a stream of argon over the solution and then subjecting the residue to high vacuum to leave a yellow oil. High-field ^1H NMR analysis shows that the product consists of 90% semicarbazide **31**-Ph and 10% of rearranged semicarbazide **33**-Ph. All attempts to purify **31**-Ph failed. **31**-Ph: ^1H NMR ($CDCl_3$) δ 2.40 (m, 4 H), 2.75 (d, 3 H, J = 5 Hz), 6.63 (bs, 1 H), 7.4 (m, 10 H). **33**-Ph: ^1H NMR ($CDCl_3$) δ 2.05 (s, 3 H), 2.86 (d, 3 H, J = 5 Hz), 3.42 (m, 2 H), 6.17 (bs, 1 H), 7.4 (m, 8 H), 7.70 (m, 2 H).

1,4-Diphenyl-2,3-diazabicyclo[2.1.1]hex-2-ene (3-Ph). A 10-mL two-necked oven-dried pear flask was fitted with an addition ampule charged with 130 mg of nickel peroxide.[27] The atmosphere was replaced with argon, and **31**-Ph (16 mg, 0.054 mmol) in 3.5 mL of dry CH_2Cl_2 (distilled from CaH_2) was added via syringe. After the solution was cooled to −50 °C, the contents of the ampule were added over 2 min. After 2 h of stirring, the slurry was transferred via a Teflon cannula to a precooled (−78 °C) filtration frit and vacuum filtered into a cold receiving flask. The CH_2Cl_2 was removed under high vacuum at −50 °C to leave a white crystalline solid: ^1H NMR (CD_2Cl_2, −70 °C) δ 2.55 (m, 2 H), 3.00 (m, 2 H), 7.4 (m, 10 H); UV (MTHF) λ_{max} 345 nm.

1,7-Dicarbomethoxy-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (14). A CH_2Cl_2 solution of 1,3-dicarbomethoxybicyclobutane[14] (3.29 g, 19.4 mmol) and MTAD (2.74 g, 24.3 mmol) was photolyzed with a Hanovia 450-W medium-pressure mercury arc lamp and a Pyrex filter. Filtration and recrystallization from ethyl acetate afforded 3.28 g (11.6 mmol, 60%) of **14** as a white solid: mp 176.5–177.5 °C; ^1H NMR ($CDCl_3$) δ 2.26 (m, 2 H), 2.69 (m, 2 H), 3.03 (s, 3 H), 3.85 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 26.0 (NCH_3), 45.0 (CH_2), 53.2 (OCH_3), 68.9 (bridgehead), 159.7 (NCO), 164.4 (OCO); IR ($CHCl_3$) 3037, 2956, 1793, 1750 (sh), 1719, 1442, 1397, 1322, 1237, 1163, 1066 cm^{-1}; UV (CH_2Cl_2) λ_{max} 246 nm (ϵ 270); mass spectrum (EI), *m/e* 283, 251, 224, 194, 168, 167 (100), 166, 152, 139, 135; anal. C, H, N.

1,7-Bis(hydroxymethyl)-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (16). Sodium borohydride (2.85 g, 75.3 mmol) was added carefully to a stirred suspension of **14** (2.13 g, 7.53 mmol) in 50 mL of methanol. The resulting solution was refluxed under nitrogen for 2 h. After the solution cooled to room temperature, 3 N HCl (ca. 20 mL) was added to neutralize the solution. The methanol was removed by rotary evaporation, and the resulting aqueous solution was freeze-dried. Extraction with ethanol and flash chromatography (9:1 CH_2Cl_2–ethanol; R_f 0.35) gave 1.31 g 5.77 mmol, 77%) of **16** as a colorless oil: ^1H NMR ($CDCl_3$) δ 1.92 (m, 4 H), 2.98 (s, 3 H), 3.72 (t, 2 H), 4.03 (d, 4 H); ^{13}C NMR ($CDCl_3$) δ 26.1 (NCH_3), 42.8 (CH_2), 60.2 (CH_2O), 73.6 (bridgehead), 160.8 (CO); IR ($CDCl_3$) 3440, 2930, 1760, 1692, 1550, 1265 cm^{-1}; mass spectrum (EI), *m/e* 227, 196, 139, 113, 112 (100), 109, 95, 83, 59; exact mass calcd 227.0906, found 227.0907.

1,7-Bis((pyruvyloxy)methyl)-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]-nonane-3,5-dione (17). To a solution of diol **16** (1.54 g, 6.8 mmol) in 10 mL of CH_2Cl_2 were added pyruvic acid (1.74 g, 19.8 mmol) and 4-pyrrolidinopyridine (PPY, 200 mg, 1.3 mmol). 1,3-Dicyclohexylcarbodiimide[54] (DCC), 4.08 g, 19.8 mmol) was then added carefully to this solution. The reaction was stopped after 20 min. Filtration, removal of solvent, and flash chromatography over carefully dried (overnight in oven) silica (1:1 ethyl acetate–methylene chloride; R_f 0.36) gave 2.44 g (6.6 mmol, 98%) of **17** in the form of a yellow oil: ^1H NMR ($CDCl_3$) δ 1.85 (m, 2 H), 2.3 (m, 2 H), 2.4 (s, 4 H), 2.98 (s, 3 H), 4.85 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 26.5 (NCH_3), 33.3 (CH_3), 42.7 (CH_2), 61.2 (OCH_2), 70.3 (bridgehead), 159.6 and 159.8 (CO_2 and CON), 190.7 (CO).

1,7-Diethenyl-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (18). A solution of dipyruvate **17** (100 mg, 0.27 mmol) in 250 mL of benzene (freshly distilled from calcium hydride under nitrogen) was photolyzed for 3 h with a Hanovia 450-W medium-pressure mercury arc lamp and a Pyrex filter.[21] The solution was poured into a 500-mL flask, and the solvent was removed until only about 40 mL remained. This dialdehyde solution was degassed and used immediately in the next step.

To a degassed suspension of methyltriphenylphosphonium bromide (486 mg, 1.36 mmol) in 40 mL of benzene (freshly distilled from calcium

(53) Alexander, J.; Krishna Rao, G. S. *J. Chem. Educ.* **1970**, *47*, 277.

(54) Hassner, A.; Alexanian, V. *Tetrahedron* **1978**, 4475–4478.

hydride under nitrogen) was added a 1.47 M solution of *n*-butyllithium (0.83 mL, 1.23 mmol), and the yellow reaction mixture was allowed to stir for 1 h. The previously prepared dialdehyde solution was then added to the stirred ylide solution via cannula. The reaction mixture turned an orange-rust color. After 20 min, 25 mL of 5% aqueous HCl was added and the color disappeared. The layers were separated and the aqueous layer was extracted with diethyl ether (2 × 50 mL). The combined organic layer was washed with 20 mL each of 5% HCl, a saturated solution of sodium bicarbonate, and water. This solution was then dried over $MgSO_4$, filtered, rotovapped, and flash chromatographed to obtain 31.2 mg (0.14 mmol, 52%) of the diene as a colorless oil: ^1H NMR ($CDCl_3$) δ 2.05 (m, 2 H), 2.19 (m, 2 H), 3.02 (s, 3 H), 5.40 (m, 4 H), 6.45 (dd, 2 H); ^{13}C NMR ($CDCl_3$) δ 25.6 (NCH_3), 46.4 (CH_2), 72.6 (bridgehead), 119.8 (CH_2), 130.4 (CH), 159.9 (CO); IR ($CDCl_3$) 2940, 1776, 1710, 1446, 1392, 1008 cm^{-1}; mass spectrum (EI), *m/e* 219, 218, 178, 161, 134, 133, 105 (100), 91; exact mass calcd 219.1008, found 219.1007.

1,7-Bis(hydroxydideuteriomethyl)-4-methyl-2,4,6-triazatricyclo-[5.1.1.0^{2,6}]nonane-3,5-dione (16-d_4). Sodium borodeuteride was used in the procedure for the synthesis of **16** to obtain **16**-d_4: ^1H NMR ($CDCl_3$) δ 1.92 (m, 4 H), 2.98 (s, 3 H), 3.55 (br s, 2 H), 4.03 (br s, 0.19 H: 91% D).

1,7-Bis(trideuterioethenyl)-4-methyl-2,4,6-triazacyclo[5.1.1.0^{2,6}]nonane-3,5-dione (18-d_6). The procedure for **17** was followed using **16**-d_4 in order to prepare **17**-d_4. The procedure for **18** was then followed, substituting **17**-d_4 and (trideuteriomethyl)triphenylphosphonium iodide. *tert*-Butyllithium was used in place of *n*-butyllithium, and the ylide solution was stirred for 6.5 h. ^1H NMR ($CDCl_3$) δ 2.05 (m, 2 H), 2.19 (m, 2 H), 3.02 (s, 3 H), 5.40 (m, 1.28 H: 68% D), 6.45 (br s, 0.18 H: 91% D).

1,4-Diethenyl-2,3-diazabicyclo[2.1.1]hex-2-ene (3-Vin). Method A. A mixture of potassium hydroxide (258 mg, 86%, 3.96 mmol) in 0.5 mL of 2-propanol was thoroughly degassed by nitrogen bubbling and then heated to reflux. A degassed solution of urazole **18** (107 mg, 0.49 mmol) in 2 mL of 2-propanol was added, and the resulting mixture was refluxed under nitrogen for 2 h. The solvent was then removed in a stream of nitrogen. The resulting paste was cooled in ice, acidified with degassed 3 N HCl, and warmed to 40 °C for 10 min. The mixture was cooled in ice and neutralized with 1 mL of degassed 1 N NH_3. A degassed solution of cupric bromide (273 mg, 1.22 mmol) in 0.5 mL of water was added with stirring, followed by 1 mL of degassed 1 N NH_3 (added slowly, making sure the solution did not become alkaline). The reddish-brown precipitate was filtered, washed with water, ethanol, and ether, and then air-dried. A second crop of precipitate was collected after adding more aqueous NH_3 to the filtrate. A total yield of 110 mg of copper complex was obtained and stored in the freezer until needed.

The copper complex (35 mg) was placed in a 2-mL Mixxor extractor (Rainin) with 1 mL of dichloromethane and cooled to −50 °C in a dry ice/acetonitrile bath. Cold, concentrated ammonium hydroxide (1 mL) was added and the layers were mixed, producing a yellow organic layer and a dark blue aqueous phase. The aqueous phase was removed and the organic layer extracted seven more times, or until the aqueous extracts became colorless. A bath-jacketed fritted funnel was loaded with layers (~8 mm) of $MgSO_4$, grade V alumina, and a pad of glass wool and then flushed with nitrogen. The funnel and receiving flask were cooled to −78 °C (dry ice/acetone), the adsorbents were wetted with CH_2Cl_2, and the product solution was transferred onto the adsorbents via a Teflon cannula. Vacuum was applied to the receiving flask while excess nitrogen was supplied above the filter, and the adsorbents were washed with 5 mL of cold CH_2Cl_2. The solvent was removed from the filtrate at −50 °C on a vacuum line, leaving **3**-Vin (~8 mg, 38%, measured by NMR integration vs *tert*-butyl methyl ether as an internal standard) as a pale yellow oil.

Method B. A degassed solution of urazole **18** (31 mg, 0.14 mmol) in 2.5 mL of 2-propanol was added to potassium hydroxide (84 mg, 87%, 1.30 mmol) under nitrogen at room temperature. The mixture was heated to 45 °C with stirring for 40 min. After cooling, the solvent was evaporated in a stream of nitrogen. The resulting paste was cooled in ice, acidified with degassed 3 N HCl, heated to 40 °C for 10 min, cooled again in ice, and made slightly basic (pH 8) with degassed 1 N NH_3. The aqueous solution was extracted with eight 0.5-mL portions of degassed CH_2Cl_2, passing all extracts through $MgSO_4$ under nitrogen. The solvent was removed in a stream of nitrogen, giving yellow crystals of **31**-Vin. ^1H NMR ($CDCl_3$) δ 1.83 (m, 2 H), 1.98 (m, 2 H), 2.79 (d, 3 H), 5.22 (m, 4 H), 6.04 (dd, 1 H), 6.59 (br s, 1 H), 6.65 (dd, 1 H). The crystals were redissolved in 2 mL of degassed CH_2Cl_2 and cooled to −50 °C. Nickel peroxide[27] (351 mg, 1.40 mmol of active oxidant) was added from a solid addition ampule, and the mixture was stirred at −50 °C for 1.5 h. The mixture was then filtered through Celite at −78 °C, and the solvent was removed on a vacuum line at −50 °C. Yield ~15 mg (~80%); ^1H NMR ($CDCl_3$, −60 °C) δ 2.09 (m, 2 H), 2.53 (m, 2 H), 5.4 (m, 4 H), 6.59 (dd, 2 H); ^{13}C NMR ($CDCl_3$) δ 63.7 ($^1J_{CH}$ = 147.8 Hz), 88.1, 119.6 ($^1J_{CH}$ = 157.0 Hz), 132.0 ($^1J_{CH}$ = 157.0 Hz); UV ($CDCl_3$) λ_{max} 345 nm.

1,7-Bis(((methylsulfonyl)oxy)methyl)-4-methyl-2,4,6-triazatricyclo-[5.1.1.0^{2,6}]nonane-3,5-dione (23). A mixture of diol **16** (370 mg, 1.63 mmol) and triethylamine (0.68 mL, 495 mg, 4.89 mmol) in 25 mL of CH_2Cl_2 was cooled in an ice-water bath. Under an atmosphere of nitrogen, mesyl chloride (0.28 mL, 411 mg, 3.58 mmol) was then added dropwise over a period of 5 min. After stirring for 0.5 h, the heterogeneous reaction mixture was washed with 10 mL each of cold water, cold 10% HCl, cold saturated sodium bicarbonate solution, and cold saturated sodium chloride solution. The CH_2Cl_2 layer was separated and dried over $MgSO_4$, filtered, and rotovapped to give 602 mg (1.57 mmol, 94%) of **23** as a white solid: ^1H NMR ($CDCl_3$) δ 1.93 (m, 2 H), 2.39 (m, 2 H), 3.03 (s, 3 H), 3.08 (s, 6 H), 4.80 (s, 4 H).

1,7-Bis(iodomethyl)-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (24). A mixture of **23** (601 mg, 1.57 mmol) and sodium iodide (1.18 g, 7.85 mmol) in 50 mL of 2-butanone was brought to reflux under a nitrogen atmosphere. After 1 h the solvent was removed from the heterogeneous mixture, and the yellow solid was extracted with 50 mL of ether. The solution was then washed with 25 mL of water and 25 mL of a 10% solution of sodium thiosulfate, dried over $MgSO_4$, filtered, and concentrated to obtain 609 mg (1.36 mmol, 85%) of **24** as a white solid: ^1H NMR ($CDCl_3$) δ 1.88 (m, 2 H), 2.46 (m, 2 H), 3.03 (s, 3 H), 3.82 (s, 4 H); UV ($CDCl_3$) λ_{max} 265 nm.

1,7-Diethyl-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (21). To a 500-mL flask charged with copper(I) bromide–dimethyl sulfide complex (9.11 g, 44.3 mmol) and 90 mL of diethyl ether, and maintained at 0 °C under a nitrogen atmosphere, 56 mL of a 1.6 M solution of methyllithium in diethyl ether (88.0 mmol) was added slowly. A yellow precipitate first appeared and then disappeared. Diiodide **24** (990 mg, 2.21 mmol) in 50 mL of ether and 10 mL of CH_2Cl_2 (for solubility) was then added dropwise over a period of 15 min. The reaction was stopped after another 15 min when all the starting material and the monoiodide were gone (TLC). After quenching with 75 mL of a saturated solution of ammonium chloride and warming to room temperature, the organic layer was separated, washed with water, and dried over $MgSO_4$. Filtration, removal of solvent, and flash chromatography (1:1 ether–petroleum ether; R_f = 0.35) gave 117 mg (0.5 mmol, 26%) of **21** as a colorless oil: ^1H NMR ($CDCl_3$) δ 1.00 (t, 6 H), 1.62 (m, 2 H), 1.75 (m, 2 H), 2.09 (q, 4 H), 2.96 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 9.3 (CH_3), 22.2 (CH_2), 25.5 (NCH_3), 43.6 (CH_2), 74.5 (bridgehead), 159.8 (CO); mass spectrum (EI), *m/e* 223, 195, 194 (100), 151, 137, 109, 95; exact mass calcd 223.1321, found 223.1319.

Hydrogenation of 18. The oil **18** was dissolved in 10 mL of ethyl acetate, and a pinch of palladium on carbon catalyst was added. Hydrogenation on a Parr shaker (45 psi, 1 h), filtration through Celite, and removal of solvent gave clean urazole **21** as a colorless oil.

1,4-Diethyl-2,3-diazabicyclo[2.1.1]hex-2-ene (3-Et). To a hot solution (40–45 °C) of potassium hydroxide (50 mg, 86%, 0.75 mmol) in 1 mL of 2-propanol (previously flushed with nitrogen for 15 min) was added **21** (25 mg, 0.1 mmol) and the mixture was refluxed under nitrogen for 2 h and subsequently cooled in an ice-water bath. The reaction mixture was acidified with 3 N HCl, warmed to about 40 °C for 10 min, cooled to room temperature, and neutralized with 1 N NH_3. A solution of cupric bromide (56 mg, 0.25 mmol) in 1 mL of water was added dropwise with gentle stirring. The pH was adjusted to about 6 with 1 N NH_3, and the reaction flask was kept at room temperature for 1 h. Reddish-brown crystals of the copper complex separated and were filtered, washed (with water and diethyl ether), and air-dried. To a suspension of the complex in 30 mL of diethyl ether was added 25 mL of 1 N NH_3 at 0 °C with vigorous stirring. The ethereal layer was separated and the aqueous layer was extracted with ether. The combined organic phase was dried over $MgSO_4$. After filtration, the ether was distilled off through a 10-cm Vigreaux column. Care was taken not to heat the solution over 40 °C. When about 1.5 mL of the solution remained, the distillation was stopped, and pure **3**-Et was isolated by preparative gas chromatography. A 10 ft × $^1/_4$ in. column of 10% UCW-982 on Chromosorb WAW-DMCS mesh size 80/100 was used. At a column temperature of 85 °C and a helium flow of 120 mL min^{-1}, the retention time for **3**-Et was 14 min and the product was isolated as a colorless oil: ^1H NMR (acetone-d_6) δ 1.07 (t, 6 H), 1.77 (m, 2 H), 1.98 (m, 2 H), 2.13 (q, 4 H); ^{13}C NMR ($CDCl_3$) δ 10.7 (CH_3), 23.0 (CH_2), 60.5 (CH_2), 88.9 (bridgehead); UV (ether) λ_{max} 344 nm.

1,7-Dipropyl-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (22). The procedure for **18** was used, except that ethyltriphenylphosphonium bromide was used and after drying, the crude diene was dissolved in ethyl acetate and subjected to hydrogenation over palladium on carbon on a Parr shaker (45 psi, 1 h). Filtration through Celite and

removal of solvent gave a 56% yield of urazole **22** as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 0.95 (t, 6 H), 1.49 (m, 4 H), 1.67 (m, 2 H), 1.86 (m, 2 H), 2.05 (m, 4 H), 2.98 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 14.4 (CH_3), 18.8 (CH_2), 25.7 (NCH_3), 31.3 (CH_2), 44.9 (bridging CH_2), 73.8 (bridgehead), 159.3 (CO).

1,4-Dipropyl-2,3-diazabicyclo[2.1.1]hex-2-ene (3-Pr). The procedure for **3**-Et was used, except that **3**-Pr was purified by low-temperature recrystallization from ether, although the crystals melted when warmed to room temperature: ^{1}H NMR (C_6D_6) δ 0.90 (t, 6 H), 1.11 (m, 2 H), 1.41 (m, 4 H), 1.84 (m, 4 H), 1.93 (m, 4 H); ^{13}C NMR (C_6D_6) δ 15.1 (CH_3), 20.3 (CH_2), 32.7 (CH_2), 61.5 (CH_2), 87.9 (bridgehead); UV (ether) λ_{max} 346 nm.

1,7-Bis(((methylsulfonyl)oxy)dideuteriomethyl)-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (23-d_4). The tetradeuterio diol **16**-d_4 was used in the procedure for the synthesis of **23** to obtain **23**-d_4.

1,7-Bis(trideuteriomethyl)-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (25-d_6). To a solution of **23**-d_4 (106 mg, 0.27 mmol) in 6 mL of hexamethylphosphoric triamide was added sodium borodeuteride[23] (67 mg, 1.62 mmol), and the mixture was stirred at room temperature for 32 h. After quenching with 10 mL of a saturated solution of sodium chloride, the reaction mixture was extracted with diethyl ether (3 × 15 mL). The organic layer was dried over $MgSO_4$, filtered, concentrated, and flash chromatographed to obtain 51 mg (0.25 mmol, 91%) of **25**-d_6 as a colorless oil. The ^{1}H NMR spectrum showed that deuterium incorporation was about 95%.

1,4-Bis(trideuteriomethyl)-2,3-diazabicyclo[2.1.1]hex-2-ene (3-CD_3). The urazole **25**-d_6 was used in the previously described procedure[10b] to obtain **3**-CD_3.

7-Ethenyl-4-methyl-1-oxiranyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (27). Divinyl urazole **18** (65 mg, 0.30 mmol) was dissolved in 4 mL of chloroform with *m*-chloroperbenzoic acid (62 mg, 0.36 mmol) and heated to reflux under nitrogen for 2 h. After washing with saturated sodium bicarbonate, the resulting mixture of **18** and **27** was separated by using flash chromatography with pentane–ethyl acetate (5:4) as solvent. The recovered **18** was resubmitted to the epoxidation conditions and separated, resulting in a combined yield of 22 mg of **27** (0.094 mmol, 52% based on 26 mg of recovered **18**) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 1.9 (m, 4 H), 2.63 (m, 1 H), 2.97 (m, 1 H), 3.03 (s, 3 H), 3.68 (m, 1 H), 5.37 (m, 2 H), 6.42 (dd, 1 H); ^{13}C NMR ($CDCl_3$) δ 25.7, 42.0, 44.8, 45.5, 47.5, 71.6, 72.9, 120.1, 130.0, 159.1, 160.2.

7-Ethyl-4-methyl-1-oxiranyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (28). To a stirred solution of **27** (22 mg, 0.094 mmol) in 4 mL of ethyl acetate was added a small amount of activated palladium on carbon, giving a gray suspension. The flask was evacuated and filled with hydrogen at atmospheric pressure for 1 h. The mixture was again degassed and then filtered through Celite. Rotary evaporation gave **28** (21 mg, 0.089 mmol, 95%) as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 1.04 (t, 3 H), 1.9 (m, 6 H), 2.61 (m, 1 H), 2.92 (m, 1 H), 3.02 (s, 3 H), 3.65 (m, 1 H); ^{13}C NMR ($CDCl_3$) δ 9.2, 22.1, 25.6, 40.7, 43.3, 45.5, 47.7, 72.0, 74.5, 159.8.

1-Ethenyl-4-methyl-7-ethyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (26). Potassium selenocyanate[24] (15 mg, 0.10 mmol) was added to a stirred solution of **28** (21 mg, 0.089 mg) in 3.5 mL of methanol–water (10:1). The solution was refluxed under nitrogen for 12 h, then filtered through glass wool, diluted with 10 mL of water, and extracted with ether. The ether solution was dried over $MgSO_4$ and purified by flash chromatography using pentane–ethyl acetate (7:4). **26** (13 mg, 66%) was obtained as a colorless oil: ^{1}H NMR ($CDCl_3$) δ 1.07 (t, 3 H), 1.87 (m, 2 H), 2.02 (m, 2 H), 2.17 (q, 2 H), 3.01 (s, 3 H), 5.39 (m, 2 H) 6.44 (dd, 1 H); ^{13}C NMR ($CDCl_3$) δ 9.6, 22.5, 25.8, 45.2, 73.2, 74.2, 119.4, 130.6, 159.5, 159.6; mass spectrum (EI), *m/e* 221, 220, 194, 193, 192 (100), 137, 135, 107, 106, 93, 79; exact mass calcd 221.1164, found 221.1168.

Partial Hydrogenation of 18. To a stirred solution of **18** (80 mg, 0.37 mmol) in 1.5 mL of ethyl acetate was added 5 mg of activated palladium on carbon. The solution was degassed (using a Firestone valve) and left under vacuum. Hydrogen gas (8.2 mL, 0.37 mmol) was added via syringe, and the flask was brought to atmospheric pressure by adding nitrogen. After 10 min, the solution was degassed and filtered through Celite. ^{1}H NMR indicated a 1:2:1 mixture of **18**, **26**, and **21**. The mixture was partially purified by preparative TLC, eluting three times with pentane–ether (2:1) and collecting the middle two-thirds of the band. The resulting mixture was further purified by HPLC using a Whatman Partisil 10 ODS-3 column and cyclohexane–2-propanol (99:1) at 10 mL/min. Yield 10 mg of **26** (45%, assuming 1:2:1 product mixture).

1-Ethenyl-4-ethyl-2,3-diazabicyclo[2.1.1]hex-2-ene (3-EV). Both methods described for **3**-Vin were used for the preparation of **3**-EV, though method B was found preferable. ^{1}H NMR ($CDCl_3$) δ 1.09 (t, 3 H), 1.89 (m, 2 H), 2.2 (m, 4 H), 5.35 (m, 2 H), 6.57 (dd, 1 H); ^{13}C NMR ($CDCl_3$) δ 10.4, 22.5, 62.1, 88.2, 89.0, 119.2, 133.0; UV ($CDCl_3$) λ_{max} 345 nm.

3,5-Dioxo-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-1,7-dicarboxylic Acid (30). A suspension of diester **14** (213 mg, 0.75 mmol) in 5 mL of 0.5 N HCl was refluxed for 2 h under an argon atmosphere. The resulting solution was freeze-dried to give 185 mg (96%) of **30** as a white solid: ^{1}H NMR (acetone-d_6) δ 2.30 (m, 2 H), 2.86 (m, 2 H), 3.03 (s, 3 H); ^{13}C NMR (D_2O) δ 27.58 (CH_3), 46.34 (CH_2), 71.48 (bridgehead), 162.27 (CO), 168.73 (CO_2H).

1,7-Dibromo-4-methyl-2,4,6-triazatricyclo[5.1.1.0^{2,6}]nonane-3,5-dione (29). To a refluxing suspension of diacid **30** (173 mg, 0.678 mmol) and red mercuric oxide (352 mg, 1.63 mmol) in 5.5 mL of dibromomethane (distilled from P_2O_5) was added a solution of bromine (540 mg, 3.4 mmol) in 2 mL of dibromomethane over 2 h under an argon atmosphere. The solution was allowed to reflux for an additional hour. The cooled solution was then filtered to remove the precipitated $HgBr_2$. The filtrate was washed with 1 N HCl (2 × 10 mL) and water (2 × 10 mL) to remove the dissolved $HgBr_2$. The resulting solution was dried over $MgSO_4$, filtered, and concentrated to give a yellow solid which upon flash chromatography (7:3 petroleum ether–ethyl acetate) gave 126 mg (58%) of dibromide **29** as a white crystalline solid: ^{1}H NMR ($CDCl_3$) δ 2.63 (m, 2 H), 2.78 (m, 2 H), 3.09 (s, 3 H); ^{13}C NMR ($CDCl_3$) 26.44 (q, J_{CH} = 142 Hz), 55.80 (t, J_{CH} = 152 Hz), 62.19 (s), 157.66 (s); mass spectrum (EI), *m/e* 327 (M + 4), 325 (M + 2), 323 (M), 187 (100%, M − 136); exact mass calcd for $C_7H_7Br_2N_3O_2$ 322.8905, found 322.8899.

Hydrolysis of Dibromo Urazole 29. To a 10-mL flask containing **29** (26 mg, 0.080 mmol) and freshly crushed potassium hydroxide (38 mg, 0.6 mmol) was added 3 mL of degassed 2-propanol. The atmosphere was replaced with argon, and the mixture was allowed to stir for 1.5 h. The solution was then carefully acidified by dropwise addition of degassed 3 N HCl until decarboxylation ceased. The solution was brought to neutrality by addition of 1 N NH_3. Enough degassed water was added to dissolve the salts, and the solution was extracted with CH_2Cl_2 (2 × 2 mL). The extracts were passed through a column of $MgSO_4$ during filtration into a 10-mL flask. The solution was concentrated by passing a stream of argon over it, and then the last traces of solvent were removed under high vacuum to leave 24 mg (100%) of **31**-Br as a white crystalline solid: ^{1}H NMR ($CDCl_3$) δ 2.58 (m, 4 H), 2.82 (d, 3 H, J = 5 Hz), 4.75 (br s, 1 H), 6.57 (br s, 1 H).

Employing the above procedure in refluxing 2-propanol for 10 min gives pyrazole **32** as the only product as a white crystalline solid: ^{1}H NMR ($CDCl_3$) δ 2.36 (s, 3 H), 6.05 (s, 1 H), 11.75 (bs 1 H); ^{13}C NMR ($CDCl_3$) δ 11.50 (q, J_{CH} = 128 Hz), 106.94 (d, J_{CH} = 181 Hz), 126.25 (s), 141.47 (s); mass spectrum (EI), *m/e* 162 (M + 2), 160 (100%, M), 81 (M − 79).

1,4-Dibromo-2,3-diazabicyclo[2.2.1]hex-2-ene (3-Br).[55] To a 10-mL two-necked flask fitted with an addition ampule charged with nickel peroxide (300 mg) under an argon atmosphere was added **31**-Br (24 mg, 0.080 mmol) in 4.5 mL of dry CH_2Cl_2. The nickel peroxide[27] was then added to the stirring semicarbazide solution over 1 min. The slurry was allowed to stir at room temperature for 20 min, then transferred to a filtration frit via cannula, and vacuum filtered into a 10-mL flask. The solvent was removed under high vacuum at −50 °C to leave a slightly yellow, volatile oil: ^{1}H NMR ($CDCl_3$) δ 2.66 (m, 2 H), 3.04 (m, 2 H); UV ($CDCl_3$) λ_{max} 334 nm.

1,4-Diethenyl-2,3-diazabicyclo[2.1.1]hex-2-ene *N*-Oxide (35). A stirred solution of urazole **18** (16 mg, 0.073 mmol) in 0.2 mL of ethylene glycol and 0.5 mL of 30% hydrogen perioxide was heated to 50 °C. A solution of potassium hydroxide (295 mg, 87%, 4.6 mmol) in 0.35 mL of water was added over 5 min. An additional 0.1 mL of hydrogen peroxide was added every 30 min. After 3 h, the solution was extracted with dichloromethane. The extracts were dried over $MgSO_4$ and purified by flash chromatography using pentane–ethyl acetate (3:1). A colorless oil (6.6 mg, 60%) was obtained: ^{1}H NMR ($CDCl_3$) δ 2.75 (m, 2 H), 2.96 (m, 2 H), 5.45 (m, 4 H), 6.26 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 61.5, 80.1 (low *S/N*), 90.2 (low *S/N*), 119.4, 122.2, 128.1, 132.1; mass spectrum (DCI/NH_3), *m/e* 151, 134, 121 (100), 120, 105, 93, 91, 78, 67, 65.

Photolysis Experiments. The photochemistry of the parent diazene (**3**-H) has been previously reported[29] and the dimethyldiazene (**3**-Me) shows completely analogous behavior.[56] Photolyses of the other diazenes (**3**-Vin, **3**-EV, and **3**-Ph) were carried out on degassed samples in sealed 5-mm quartz NMR tubes using an Oriel 1000-W mercury–xenon arc lamp. Various optical filter combinations (Schott) were employed to obtain the desired wavelength range. Sensitized photolyses were per-

(55) Preliminary investigations of the reactivity of **3**-Br reveal that its thermal chemistry and photochemistry are significantly different from that of the hydrocarbon series described here. We are currently studying these transformations and will report our findings at a later date.

(56) Jain, R. Ph.D. Dissertation, California Institute of Technology, 1987.

formed by using either benzophenone or thioxanthone. All experiments gave the corresponding bicyclobutane as the sole product as monitored by high-field ^{1}H NMR.

1,3-Diethenylbicyclo[1.1.0]butane (36): ^{1}H NMR ($CDCl_3$) δ 1.32 (s, 2 H), 2.16 (s, 2 H), 5.03 (m, 4 H), 5.82 (dd, 2 H).

1-Ethyl-3-ethenylbicyclo[1.1.0]butane (37): ^{1}H NMR ($CDCl_3$) δ 0.85 (m, 5 H), 1.65 (m, 4 H), 4.96 (m, 2 H), 4.66 (dd, 1 H).

EPR Experiments. A Varian E-line Century Series X-band spectrometer equipped with an Oxford Instruments ESR-900 liquid-helium continuous-flow cryostat was used to obtain EPR spectra at low temperature. The temperature at the sample was calibrated with a carbon–glass resistance sensor (Lakeshore Cryotronics) placed inside a sample tube. During each experiment the temperature was monitored continuously by a gold–chromel thermocouple fixed 1 cm below the sample in the quartz dewar. The temperature was varied by using either the helium flow rate or the automatic DTC2 temperature controller.

An Oriel 1000-W mercury–xenon arc lamp was focused into the microwave cavity for photolysis. Various optical filters (Schott, Corning, Oriel) or a grating monochromator (Oriel Model 77250) were used to obtain narrow bands of light in the desired wavelength range.

Samples were prepared from solutions of 1–3 mg of diazene in 300 μL of solvent (MTHF was freshly vacuum-transferred from benzophenone ketyl). The solution was placed in 4- or 4.5-mm-o.d. quartz EPR tubes equipped with high-vacuum stopcocks. The samples were then degassed (three freeze–pump–thaw cycles), frozen in liquid nitrogen, and cooled to 4 K in the EPR cavity.

Simulation of Triplet EPR Spectra. The theoretical treatment of triplet EPR spectroscopy has been developed by Kottis and Lefebvre.[35] Using their analysis, we have developed computer programs to simulate powder EPR spectra. We have also incorporated isotropic hyperfine coupling into these simulations. Instead of introducing a new term into the Hamiltonian, we have taken the much simpler route of splitting each resonance line into the appropriate number of lines with intensities following Pascal's triangle. Multiple coupling constants can be introduced by repeating this process, and then intensities for each field strength are added. A consistent line-width factor of 5 G was used for all spectra, except for the $\Delta m_s = 2$ lines of **1**-EV and **1**-CD_3, which required line widths of 15 and 26 G, respectively. Due to the limited number of data points (250), the accuracy of the coupling constants used in the simulations was limited by the width of the individual $\Delta m_s = 2$ transition. Typical G/point ratios varied from 0.72 to 1.6. We must emphasize here that this approach is by no means a rigorous treatment of hfc.

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Note Added in Proof. More recent theoretical work (J. Pranata and D. A. Dougherty, manuscript in preparation) indicates that the preferred geometries for the parent cyclobutanediyl and **1**-Me contain a planar carbon framework, but the radical centers are pyramidalized (C_{2h} symmetry). In addition, the theory suggests that pyramidal inversion in **1**-H via quantum-mechanical tunneling could be rapid even at 4 K. This could provide an explanation for the substantial broadening of the $\Delta m_s = 2$ lines of **1**-CD_3. Conformational mobility of alkyl side chains could also contribute to this effect.

Registry No. **1**-Me, 92937-60-5; **1**-CO_3, 112422-80-7; **1**-Et, 112422-81-8; **1**-Pr, 112422-82-9; **1**-MP, 112422-83-0; **1**-EV, 112422-84-1; **1**-Ph, 112422-85-2; **1**-Vin, 112422-86-3; **1**-Vin-d_6, 112422-87-4; **3**-Me, 90742-83-9; **3**-CD_3, 112422-75-0; **3**-Et, 112422-71-6; **3**-Pr, 112422-72-7; **3**-MP, 112422-66-9; **3**-EV, 112422-76-1; **3**-Ph, 112422-67-0; **3**-Vin, 112422-69-2; **3**-Vin-d_6, 112422-79-4; **3**-Br, 112422-78-3; **5**, 112422-40-9; *syn*-**6**, 112422-37-4; *anti*-**6**, 112422-41-0; *syn*-**7**, 112422-42-1; *anti*-**7**, 112422-38-5; *syn*-**8**, 112422-39-6; *anti*-**8**, 112422-43-2; **9**, 112422-44-3; **10**, 112422-45-4; *syn*-**11**, 27396-24-3; *anti*-**11**, 27396-25-4; **12**, 112422-46-5; **13**, 23745-74-6; **14**, 112422-47-6; **16**, 112422-49-8; **16**-d_4, 112422-68-1; **17**, 112422-50-1; **18**, 112422-51-2; **18**-d_6, 112438-18-3; **21**, 112422-52-3; **22**, 112422-53-4; **23**, 112422-54-5; **23**-d_4, 112422-73-8; **24**, 112422-55-6; **25**-d_6, 112422-74-9; **26**, 112438-09-2; **27**, 112422-57-8; **28**, 112422-58-9; **29**, 112422-59-0; **30**, 112422-60-3; **31**-MP (1-phenyl-4-methyl isomer), 112422-61-4; **31**-MP (1-methyl-4-phenyl isomer), 112422-62-5; **31**-Ph, 112422-48-7; **31**-Vin, 112422-70-5; **31**-Br, 112422-77-2; **32**, 57097-81-1; **33**-MP, 112438-17-2; **33**-Ph, 112422-56-7; **35**, 112422-63-6; **36**, 112422-64-7; **37**, 112422-65-8; 3-phenylcyclobutanone, 52784-31-3.