The Chemistry of Trimethylenemethanes, a New Class of Biradical Reactive Intermediates

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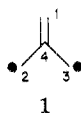
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Biradicals are even-electron molecules that have one bond less than the number permitted by the standard rules of valence. They are frequently invoked as fleeting intermediates in thermal and photochemical reactions. Efforts, largely by inferential methods, to detect them and to describe their properties occupy a central position in current mechanistic research.

The work to be reported here originated in the hope that the chemistry of a special kind of biradical, trimethylenemethane (TMM),[1,2] might be elucidated directly and that such studies might thereby sharpen our ability to predict or understand the behavior of those more elusive biradicals which are not yet amenable to direct examination.

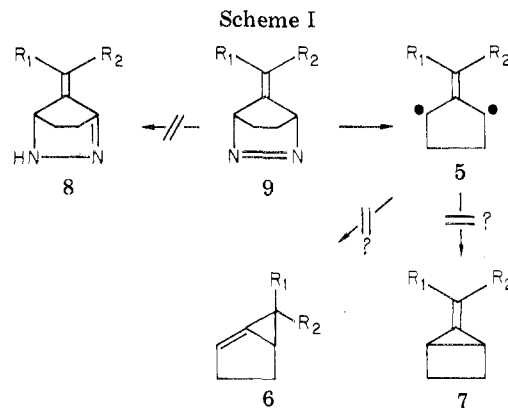Trimethylenemethane (1) and its derivatives ex-

emplify a group of π biradicals for which no Kekulé structure can be written. The HMO approximation and Hund's rule lead to the predicted π-energy levels and occupation pattern shown in Figure 1, which represents a triplet ground state.[3,4] This prediction has been confirmed for the case of the parent compound 1 by electron spin resonance (ESR) spectroscopy in the skillful work of Dowd and his associates.[1c,5]

Despite this success of simple HMO theory, a vigorous and sometimes contentious interplay between experiment and theory has marked the recent development of TMM research. The relative energetic ranking of the nominally nonbonding pair of MOs (NBMOs) and of the molecular spin states (singlet vs. triplet), which control much of the chemical behavior of TMMs, is largely determined by electron repulsion effects. So-called "one-electron" theories, such as the Hückel molecular orbital (HMO) approximation, because of their well-known inability to account properly for electron repulsion, thus cannot come to grips with the essence of the problem. They offer little hope as even qualitative guides to reliable predictions on the reactions of biradicals. Therefore, the development and testing of more sophisticated theory for TMM systems can have general significance for the biradical field as a whole.

More elaborate calculations, including Pariser–Parr–Pople,[6] modified Hückel,[7] INDO,[8] MINDO,[9,10] SCF–CI,[11,12] STO-3G,[13] ab initio,[14] and GVB,[15] agree

Scheme I

a, R_1, R_2 = Me
b, R_1 = H; R_2 = Ph
c, R_1, R_2 = Ph
d, R_1 = H; R_2 = Cl

e, R_1, R_2 = OMe
f, R_1, R_2 = SMe
g, R_1, R_2 = H
h, R_1, R_2 = SO$_2$Me

almost unanimously[12] that the ground state of TMM should be a triplet and the lowest lying excited state a singlet. This ordering of electronic states suggests parallels with the chemistry of carbenes[16–19] and nitrenes,[20,21] many of which also have triplet ground states.

(1) For early experimental work on TMM, see (a) A. C. Day and M. Whiting, *Proc. Chem. Soc., London*, 368 (1964); *J. Chem. Soc. C*, 464 (1966); (b) R. J. Crawford and D. M. Cameron, *J. Am. Chem. Soc.*, 88, 2589 (1966); (c) P. Dowd, *ibid.*, 88, 2587 (1966).

(2) For reviews of the TMM field up to 1972, see (a) P. Dowd, *Acc. Chem. Res.*, 5, 242 (1972); (b) F. Weiss, *Q. Rev., Chem. Soc.*, 24, 278 (1970).

(3) (a) W. A. Moffitt, as cited by C. A. Coulson, *J. Chem. Phys.*, 17, 243 (1949); (b) W. Moffitt, *Trans. Faraday Soc.*, 45, 373 (1949); (c) H. C. Longuet-Higgins, *J. Chem. Phys.*, 18, 265 (1950).

(4) Some biradicals lack the HOMO degeneracy; see (a) R. Gleiter and R. Hoffmann, *Angew. Chem.*, 81, 225 (1969); (b) W. C. Herndon and M. L. Ellzey, Jr., *Tetrahedron Lett.*, 1399 (1974).

(5) R. J. Baseman, D. W. Pratt, M. Chow, and P. Dowd, *J. Am. Chem. Soc.*, 98, 5726 (1976).

(6) W. T. Borden, *Tetrahedron Lett.*, 259 (1967).

(7) W. T. Borden and L. Salem, *J. Am. Chem. Soc.*, 95, 932 (1973).

(8) B. K. Carpenter, R. D. Little, and J. A. Berson, *J. Am. Chem. Soc.*, 98, 5723 (1976).

(9) M. J. S. Dewar and J. S. Wasson, *J. Am. Chem. Soc.*, 93, 3081 (1971).

(10) W. W. Schoeller, *Tetrahedron, Lett.*, 2043 (1973).

(11) D. P. Chong and J. W. Linnett, *Mol. Phys.*, 8, 541 (1964).

(12) See, however, J. Baudet, *J. Chim. Phys. Phys.-Chim. Biol.*, 68, 191 (1971).

(13) (a) W. Hehre, L. Salem, and M. R. Willcott, III, *J. Am. Chem. Soc.*, 96, 4328 (1974); (b) W. T. Borden, *ibid.*, 97, 2906 (1975); 98, 2695 (1976); (c) E. R. Davidson and W. T. Borden, *ibid.*, 99, 2053 (1977); (d) W. T. Borden and E. R. Davidson, *ibid.*, 99, 4587 (1977).

(14) (a) D. R. Yarkony and H. F. Schaefer, *J. Am. Chem. Soc.*, 96, 3754 (1974); (b) E. R. Davidson and W. T. Borden, *J. Chem. Phys.*, 64, 663 (1976).

(15) J. H. Davis and W. A. Goddard, III, *J. Am. Chem. Soc.*, 98, 303 (1976); 99, 4242 (1977).

(16) W. Kirmse, "Carbene Chemistry", 2nd ed., Academic Press, New York, N.Y., 1971.

(17) D. Bethell in "Reactive Organic Intermediates", S. P. McManus, Ed., Academic Press, New York, N.Y., 1973.

(18) G. L. Closs in "Topics in Stereochemistry", E. L. Eliel and N. L. Allinger, Ed., Wiley-Interscience, New York, N.Y., 1968.

(19) P. P. Gaspar and G. S. Hammond in "Carbenes", Vol. II, M. Jones, Jr., and R. A. Moss, Ed., Wiley, New York, N.Y., 1974.
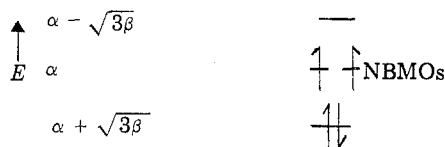
Figure 1. Simple HMO energy levels in units of the Coulomb integral (α) and the resonance integral (β).

Scheme II

Although such parallels do exist, there are unique aspects of TMM chemistry which derive from the presence of three reactive sites rather than one. It is just this difference which suggests that the synthetic potential of TMMs as bidentate reagents capable of 1,3-cycloadditions might be realized. Moreover, the intermolecular chemistry of TMMs can test the ability of theory to predict reactivity and selectivity. In order to achieve these goals, it was first necessary to divert the behavior of the unsubstituted parent TMM system into a new channel by a simple structural device.

Rationale for the Study of the 2-Methylenecyclopenta-1,3-diyls 5. Early attempts to observe intermolecular reactions of the unsubstituted TMM molecule, **1**, were only sporadically successful, primarily
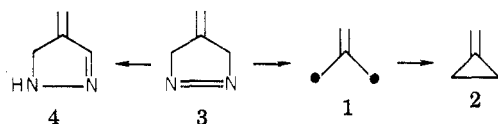
because of the competing intramolecular cyclization to methylenecyclopropane (**2**).[1,2] Another difficulty that plagues the study of the parent system is the ready and irreversible tautomerization of the biradical precursor, 4-methylene-1-pyrazoline (**3**), to the hydrazone **4**. Our decision to incorporate the TMM system into a relatively small ring, **5**, was guided by the hope that incipient strain in the developing bicyclic product, **6** or **7**, would retard cyclization to a methylenecyclopropane and by the conviction that the Bredt rule would preclude tautomerization of the precursor **9** to a hydrazone, **8** (Scheme I). These effects should make the generation and intermolecular capture of the TMM, **5**, easier than those of the parent, **1**, and, in fact, the cycloadditions of the 2-methylenecyclopenta-1,3-diyls now comprise a broadly applicable, high-yield synthetic process.
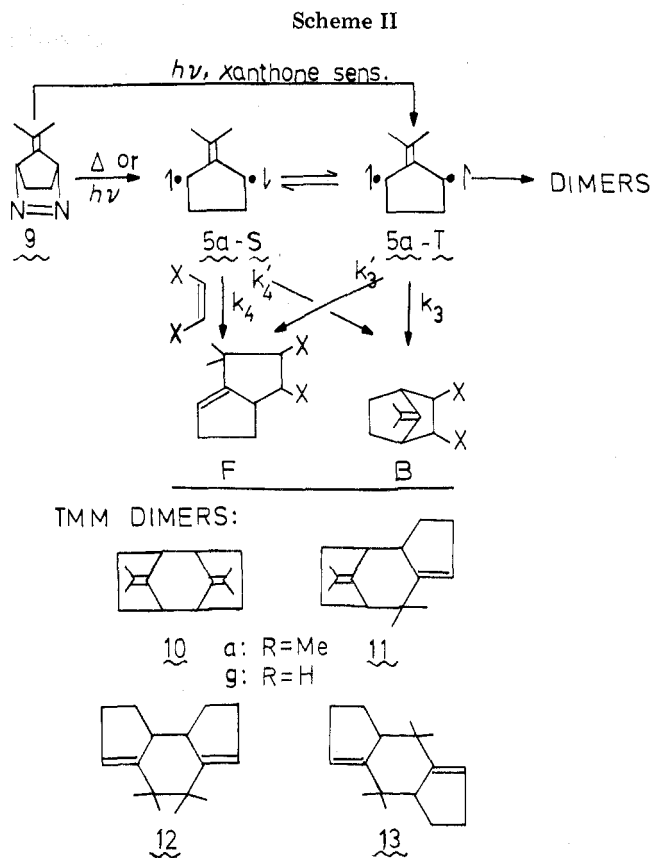
Spin-State Hierarchy and Singlet–Triplet Energy Separation in the Diyls 5. Physical Evidence. The chemical reactivity of a biradical will depend critically upon the total spin of the ground state ($S = 0$ for singlet, $S = 1$ for triplet) and upon the energy difference between the states. For example, if the biradical-forming reaction is spin conservative, a triplet ground state will be generated from a singlet precursor only via a singlet biradical intermediate. This makes it possible in principle to observe products from either or both of the biradical spin states. On the other hand, if the more stable triplet can be populated directly from a precursor, the formation of singlet products is feasible only if the singlet–triplet energy gap is narrow.

Each of the TMM precursors **9a–g** gives a well-defined, long-lived triplet ESR signal when irradiated at 77 K in a polycrystalline benzene matrix.[22–25] That

each of these spectra originates in a ground-state triplet TMM (**5**) is established by the similarity of the zero-field splitting parameter,[26] D (0.018–0.028 cm^{-1}), to that of the parent compound **1**[1c,5] and by the linear dependence of the ESR signal intensity on reciprocal temperature (Curie law[27]).

This demonstrates the spin-state ranking but does not give very precise information on the singlet–triplet energy separation because of the insensitivity of the Curie law plot, which in most cases will appear essentially linear if the value of $E_S - E_T$ is more positive than $\sim$0.2 kcal/mol (triplet ground state) or more negative than about 2 kcal/mol (singlet ground state). Even by working over a large temperature range (14–268 K),[23] we can make only the slightly more restrictive claim for **5a** that the singlet must lie at least 600 cal/mol above the triplet.

Cycloaddition Chemistry of the Singlet and Triplet States of TMM Biradicals

Applications to Synthesis and to a Determination of the Singlet–Triplet Spacing. Triplet–Triplet Dimerization. Scheme II summarizes a large body of information on the chemistry of the dimethyl-substituted diyl **5a**. We describe first the evidence supporting each part of the scheme and then show how the size of the S–T gap can be estimated.

The diazene **9a** is a volatile crystalline solid which decomposes slowly above 40 °C. In solution in the

(20) W. Lwowski, Ed., "Nitrenes", Interscience, New York, N.Y., 1970.

(21) R. A. Abramovitch in "Reactive Organic Intermediates", S. P. McManus, Ed., Academic Press, New York, N.Y., 1973.

(22) J. A. Berson, R. J. Bushby, J. M. McBride, and M. Tremelling, *J. Am. Chem. Soc.*, **93**, 1544 (1971).

(23) M. S. Platz, J. M. McBride, R. D. Little, J. J. Harrison, A. Shaw, S. E. Potter, and J. A. Berson, *J. Am. Chem. Soc.*, **98**, 5725 (1976).

(24) L. Shen, Ph.D. Thesis, Yale University, planned for 1978.

(25) R. Siemionko, Ph.D. Thesis, Yale University, planned for 1978.

(26) For an exposition of the ESR spectroscopy of triplet molecules, see E. Wasserman and R. S. Hutton, *Acc. Chem. Res.*, **10**, 27 (1977).

(27) The Curie law behavior of the **5** series was previously summarized[28] as IT = constant. This implies a zero intercept of the intensity vs. $1/T$ plot, but, in fact, finite intercepts usually are observed (Curie–Weiss law).

absence of any trapping agent, the thermal or photochemical decomposition leads exclusively to a set of dimers of the TMM **5a** which have the structures **10a–13a** (Scheme II).[25] The same dimers are obtained from thermolysis of **9a** in the gas phase. Each dimer can exist in two diastereomeric forms, so that eight are possible in principle. Our original analyses[22] detected four of these, but later work has indicated the presence of at least two more. Similar products, **10g–13g**, are obtained[25] from the diazene **9g**.

The dimers formed in the solution-phase thermolysis seem to be products largely, if not exclusively, of a triplet + triplet (T + T) reaction. Their formation is accompanied by strong chemically induced nuclear polarization (CIDNP) of the product protons, observed as emissions in the NMR spectrum.[22] Extension[28] of the radical-pair theory of CIDNP to the case of biradical dimerization leads to the prediction that CIDNP will occur only if at least one of the reacting partners is a triplet. Thus, if the CIDNP-generating process is representative of the bulk of the dimer-forming process, only the reactions singlet + triplet (S + T) or T + T, but not S + S, need be considered.

More direct support for T + T as the mechanism of the bulk of the dimerization can be obtained by measurements of the absolute rates in viscous media by ESR spectroscopy.[29] The dimerization is a second-order reaction, whose rate constant, k_2, is about 0.13 times the bimolecular encounter rate constant, k_d. Second-order kinetics could be compatible with either of two mechanisms: (1) direct T + T dimerization or (2) a rapid equilibrium T $\rightleftharpoons$ S, with equilibrium constant K, followed by the reaction S + T. In the latter case, the observed second-order rate constant, k_2, would be related to the true S + T mechanistic rate constant, k_m, by the equation $k_2 = k_m K$. However, it can be shown[29,30a] that k_m would have to be larger than the diffusion-controlled limit, k_d, to fit the data to mechanism 2.[30d]

Capture of the Diyl by Olefins. When the thermal decomposition of diazene **9a** is carried out in the presence of a high concentration of certain olefinic trapping agents, dimer formation is suppressed, and near-quantitative yields of olefin + diyl cycloadducts are obtained.[31] That this reaction represents capture of a reactive intermediate and not a bimolecular reaction of the olefin with **9a** is indicated by the observation[32] that the thermal decomposition of **9a** is a first-order reaction, being unaffected by the concentration of olefin.

Conjugated olefins are the best trapping agents, and high yields of cycloadducts are observed with conjugated dienes, styrene, and α,β-unsaturated esters or nitriles.[32,33] The highly regiospecific formation of
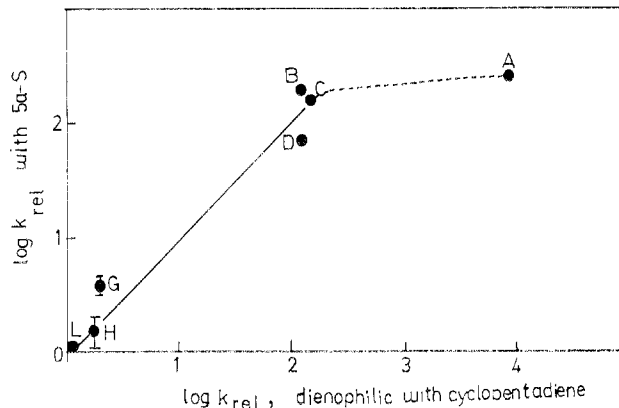

Figure 2. Relationship of dienophilic reactivity of olefins reacting with cyclopentadiene against their diylophilic reactivity in reaction with the singlet TMM biradical **5a-S**. The letters identify the olefins maleic anhydride (A), *trans*-fumaronitrile (B), *cis*-fumaronitrile (C), dimethyl fumarate (D), acrylonitrile (G), methyl acrylate (H), and dimethyl maleate (L).

bicyclo[3.3.0]oct-1-ene (F) products (see below) at high concentrations of the trapping agent constitutes an especially facile synthesis of a ring system that is not readily accessible[34] by other means.

It is possible to rank a series of olefins in terms of their gross diylophilic reactivities by competition experiments based upon product yields, but the results become more meaningful after the reactivities are dissected into their singlet and triplet components. The key observation in this analysis is the "dilution effect", in which the composition of cycloaddition products changes as the initial concentration of trapping olefin changes.[33] According to Scheme II, the cascade mechanism, diazene → S $\rightleftharpoons$ T, that is initiated by thermal decomposition of **9a** offers the opportunity to intercept S before spin equilibrium is achieved, provided the trapping olefin is at sufficiently high concentration. Dilution of the olefin should diminish the amount of product of singlet provenance. Once the limiting "pure singlet" and "pure triplet" product compositions are known, mixtures of singlet and triplet products can be analyzed as linear combinations of the limiting values. The dissection[33] is greatly facilitated by the observations that oxygen selectively scavenges the triplet and that the singlet products are formed not only with high stereospecificity for cis addition but also with high regiospecificity for the fused (F) structure (of which more later).

The diylophilic reactivities[33] of a series of olefins toward the singlet diyl roughly parallel the Diels–Alder dienophilic reactivities[35] of these olefins toward cyclopentadiene (Figure 2). The mechanistic similarity implied by this relationship is supported by the well-known cis-addition stereospecificity of the Diels–Alder reaction.

In Figure 2, it is clear that the correlation breaks down at high reactivity, maleic anhydride (A) being a less reactive singlet diylophile than would be predicted from its dienophilicity. This may be understood as a

(28) G. L. Closs, *J. Am. Chem. Soc.*, **93**, 1546 (1971).

(29) M. S. Platz and J. A. Berson, *J. Am. Chem. Soc.*, **98**, 6743 (1976).

(30) (a) The argument[29] depends on the accuracy of the Stokes–Einstein estimate of k_d. Professor J. Saltiel has called our attention to observations (ref 30b,c) which suggest that, in alcohol solvents, k_d may be twice as large as the theoretical value. This would tend to weaken the argument, since then k_m could be as small as $1.5k_d$. (b) W. R. Ware and J. S. Novros, *J. Phys. Chem.*, **70**, 3247 (1966); (c) J. Saltiel, D. W. L. Chang, E. D. Megarity, A. D. Rousseau, P. T. Shannon, B. Thomas, and A. K. Uriarte, *Pure Appl. Chem.*, **41**, 559 (1975). (d) J. J. Gajewski, A. Yeshurun, and E. J. Bair, *J. Am. Chem. Soc.*, **94**, 2138 (1972), report evidence of a different kind that the triplet of parent TMM is involved in a gas phase reaction leading to the TMM dimer 1,4-bismethylenecyclohexane.

(31) J. A. Berson, D. M. McDaniel, and L. R. Corwin, *J. Am. Chem. Soc.*, **94**, 5508 (1972).

(32) J. A. Berson, D. M. McDaniel, and L. R. Corwin, *J. Am. Chem. Soc.*, **94**, 5509 (1972).

(33) (a) J. A. Berson, C. D. Duncan, and L. R. Corwin, *J. Am. Chem. Soc.*, **96**, 6175 (1974); (b) J. A. Berson, L. R. Corwin, and J. H. Davis, *J. Am. Chem. Soc.*, **96**, 6177 (1974).

(34) Cf. W. A. Agosta and S. Wolff, *J. Org. Chem.*, **40**, 1699 (1975).

(35) J. Sauer, H. Wiest, and A. Mielert, *Chem. Ber.*, **97**, 3183 (1964).

kind of reactivity saturation effect, if it is assumed that the absolute rates at the upper end of the singlet diylophile scale approach the encounter-controlled limit. In fact, one can construct a reasonable argument, which is too long to reproduce here, to suggest that the absolute rate of the reaction of singlet diyl **5a-S** with maleic anhydride must be within an order of magnitude of the encounter frequency.

Absolute Rates of the Triplet plus Olefin Reactions. By a variation of the low-temperature, high-viscosity, ESR spectroscopic techniques used to study the triplet–triplet dimerization, we have measured absolute rates of reaction of the triplet diyl **5a-T** with several trapping olefins at 143.5 K.[29] As a check on the internal consistency of the relative triplet reactivities so derived, we have extrapolated the ratio of absolute rates for dimethyl fumarate vs. acrylonitrile to 333 K and obtained[29] a ratio that is within experimental error of the ratio measured[33] at the latter temperature in direct competition experiments in fluid medium.

The measured absolute rates are first order in triplet and first order in olefin, with second-order rate constants ranging from 0.12 for styrene to 3.2 for dimethyl fumarate (in units of 1 M^{-1} s^{-1}) in the propanolic medium. The latter value corresponds to about 2×10^{-4} times the diffusion-controlled rate constant under these conditions. In the case of acrylonitrile, the temperature variation of the rate constant gives Arrhenius parameters $E_a = 6.3$ kcal/mol, log $A = 8.9$ (A in seconds). These are very similar to those observed for free radical–olefin additions.[36]

Circumvention of the Cascade Mechanism. Direct Generation and Capture of the Triplet. Xanthone is an efficient sensitizer of the photodeazetation of the diazene **9a**, presumably by way of a
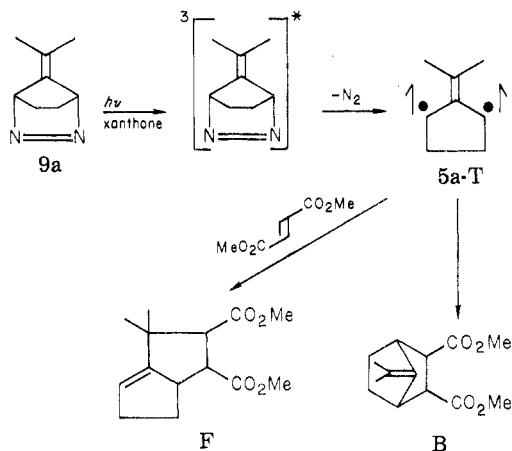
triplet state of the reactant.[37] The first capturable biradical formed under these conditions (CH_3CN solution, 0–20 °C) is the triplet state of **5a**, which can be readily recognized by the low fused/bridged (F/B) ratio of cycloadducts that is characteristic of the reactions of the "pure" triplet with methyl acrylate, acrylonitrile, and dimethyl fumarate. By setting up an alternative requirement ($S = 1 \rightarrow S = 1$) for spin conservation, this entry populates the triplet biradical (**5a-T**) state directly. The requirement for spin conservation in the singlet manifold ($S = 0 \rightarrow S = 0$) can be perceived in

the thermal and direct photochemical paths not only from the generation of a different first intermediate (**5a-S**) as already described but also from the activation entropy of the thermal deazetation of **9a**. This parameter is about normal ($\Delta S \simeq +8$ eu)[37] for a fragmentation and contrasts with the value $\Delta S \simeq -1$ eu for 3-methylenepyrazoline (**3**), where a thermal spin-forbidden process, directly generating triplet TMM (**1**), has been postulated.[38]

Capture of the Singlet from a Spin-Equilibrated Mixture. Size of the Singlet–Triplet Energy Spacing. The information acquired about Scheme II now can be used to deduce the size of the S–T energy gap. The experiment[39] involves the preparation of a mixture of **5a-S** and **5a-T** *at thermal spin equilibrium* by irradiation of a solution of diazene **9a** and a trapping olefin in a rigid glassy or polycrystalline benzene matrix at 77 K. It is experimentally demonstrated[39] that the diyl and the olefin are kept separate from each other and cannot react until the matrix is molten. These conditions differ from those of the direct irradiation of **9a**–olefin mixtures in fluid medium, where the first-formed biradical species can be intercepted before spin equilibration. From Scheme II, it is easy to show that the ratio, X_S/X_T, of products from **5a-S** and **5a-T** in the molten matrix experiments will be given by $X_S/X_t = K(k_4 + k'_4)/(k_3 + k'_3)$, where K is the equilibrium constant $[5a-S]_{eq}/[5a-T]_{eq}$. Since **5a** has a triplet ground state, products of capture of the singlet will be formed in detectable amounts only if the ratio $(k_4 + k'_4)/(k_3 + k'_3)$ of the singlet and triplet capture rates is large. When the trapping olefin is acetonitrile or methyl acrylate, this requirement is not satisfied, and products are formed in the typical triplet distribution,[37] but with dimethyl maleate and dimethyl fumarate, substantial amounts of singlet products are found.[39]

The maximum value of the capture rate ratio is determined by combining the measured rate, $k_3 + k'_3$, from the ESR kinetics described above with the restriction that $k_4 + k'_4$ cannot exceed the diffusion-controlled limit. This and the observed product ratio, X_S/X_T, permit the calculations of $K \geq 6.7 \times 10^{-4}$–$2.9 \times 10^{-2}$ and the singlet–triplet energy spacing, $\Delta E \leq 1.4$–3.5 kcal/mol.

Clearly, the small singlet–triplet separation in **5a** implied by this result is not in accord with the values near 20 kcal/mol predicted for the parent TMM, **1**, by the sophisticated quantum mechanical calculations described above. This is not necessarily a contradiction, since comparably detailed calculations on **5a** are not yet available. There are, in fact, suggestions from both calculation and experiment (see below) that incorporation of the TMM system in the five-membered ring may split the NBMO levels substantially. Perhaps the S–T gap in the 2-methylenecyclopenta-1,3-diyl series (**5**) is smaller than in the parent, **1**. It is also possible[39] that the highly strained methylenecyclopropane **15** (see the next section) has an energy intermediate between those of the triplet and singlet diyls and is the true reactive "singlet".

Dowd and Chow[40] have recently reported the Arrhenius activation energy of 7 kcal/mol for the ring

(36) J. M. Tedder and J. C. Walton, *Acc. Chem. Res.*, 9, 183 (1976), and references cited therein.

(37) J. A. Berson, C. D. Duncan, G. C. O'Connell, and M. S. Platz, *J. Am. Chem. Soc.*, 98, 2358 (1976).

(38) R. J. Crawford and D. M. Cameron, *J. Am. Chem. Soc.*, 88, 2589 (1966).

(39) M. S. Platz and J. A. Berson, *J. Am. Chem. Soc.*, 99, 5178 (1977).

(40) P. Dowd and M. Chow, *J. Am. Chem. Soc.*, 99, 6438 (1977).

closure of the parent TMM, **1**, to methylenecyclopropane (**2**). One interpretation of this number is as a *maximum* value for the singlet–triplet gap. This assumes that the pathway for the thermal closure requires triplet → singlet conversion and then cyclization of the singlet. If an activation energy is needed for the second step, the actual S–T gap is <7 kcal/mol. However, an alternative interpretation would recognize that the spin-conservative closures of the triplet and singlet diyls involve energy surfaces that cross, since the total spins of the ground and excited states exchange values during the reaction. To the extent that there is a finite probability of mixing at the crossing, where spin is not a good quantum number, the actual reaction path may lead from triplet diyl to singlet methylenecyclopropane over an energy maximum that lies well below the singlet diyl. In this case, 7 kcal/mol would be a *minimum* value for the S–T gap in **1**.

Nature of the Singlet Diyl. Bicyclic Hydrocarbons. In Scheme II, the first interceptable intermediate is formulated as the singlet diyl **5a-S**. The evidence cited so far might also be interpreted, perhaps less economically, as supporting alternative schemes in which the role of the capturable singlet in the cascade mechanism is played by a diazenyl biradical, **14a**, or one


14a: R=H
   b: R=D

15a: R=H
   b: R=D

16a: R=H
   b: R=D
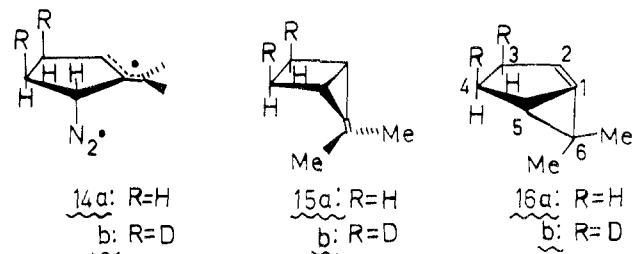
of the bicyclic hydrocarbons, **15a** or **16a**. Compound **16a**, for example, might react with high regiospecificity across the weak C_5–C_6 bond and, hence, might provide a plausible explanation for one of the most striking characteristics of the singlet intermediate, the formation of fused (F) rather than bridged (B) cycloadducts. We offer[41] evidence against these alternatives based upon stereospecific isotope labeling experiments, low-temperature flash photolysis kinetics, and quantitative photophysical studies. The arguments cannot be repeated here in detail, but they consist essentially of two demonstrations: first, that the capturable intermediate in the direct photolysis of diazene **9a** has actual or time-averaged symmetry relative to the plane of the five-membered ring, a structural feature that could not be fulfilled (except fortuitously) by **14b–16b**, and, second, that any intermediate that exists between the photoexcited state of **9a** and the triplet diyl **5a-T** must have a rate constant for conversion to the latter that is greater than 14 s^{-1} at 4.2 K. The upper limit for the strength of any bond that must be broken to form **5a-T** is therefore 270 cal/mol, a value that is less than RT at room temperature and would preclude capture of the alleged intermediate.

Although we believe that these experiments rule out the bicyclic hydrocarbons **15** and **16** as the first capturable intermediates in the cascade from **9a** (Scheme II), alternative interpretations might be constructed. Therefore, an experimental distinction, based on dif-

(41) M. S. Platz, D. R. Kelsey, J. A. Berson, N. J. Turro, and M. Mirbach, *J. Am. Chem. Soc.*, **99**, 2009 (1977).

Scheme III
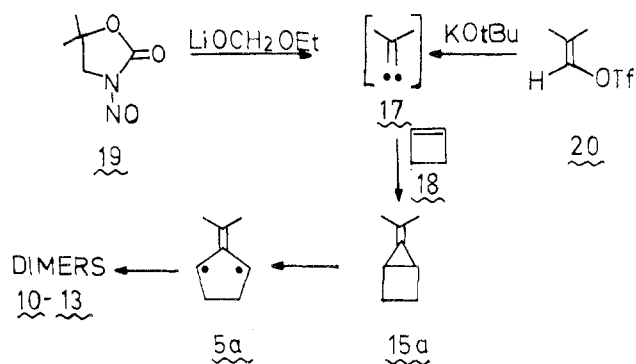
ferences in chemical reactivity, between a true singlet biradical and these highly strained substances existing on the borderline of covalency is a subtle but important goal, which has stimulated us to explore other synthetic routes.

5-Isopropylidenebicyclo[2.1.0]pentane (**15a**) apparently is formed when dimethylvinylidene (**17**) is generated in the presence of cyclobutene (**18**),[22,42,43] since among the many products of this reaction are the dimers **10–13** of the TMM **5a** (see Scheme II for structures). The simplest interpretation is that the bicyclic hydrocarbon **15a** is formed by carbene addition and suffers cleavage of the bridge bond to form the diyl **5a** (Scheme III). It is not yet clear whether the bond rupture takes place at the temperature of the reaction mixture (ca. −20 °C) or only later at the higher temperatures prevailing during isolation of the products.

A more complete study[46] now is available in the case of the bicyclic hydrocarbon **25**, which, like **16a**, is a derivative of the bicyclo[3.1.0]hex-1-ene system. This work extends the elegant investigations on a similar system begun by the late Professor Köbrich and his collaborators at the University of Hanover.[47,48]

By direct NMR examination of the reaction mixture, we find that decomposition of the carbenoid **21** occurs
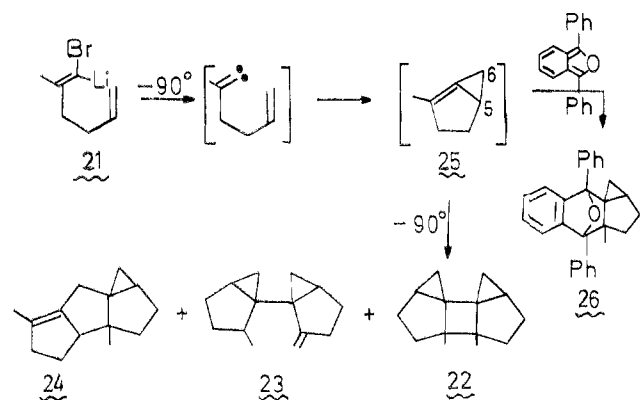
at −90 °C. The spectrum shows no resonances that can

(42) D. Cichra, unpublished work at Yale University.

(43) Generation of **17** by the base-induced decomposition of N-nitroso-5,5-dimethyloxazolidone (**19**) by the method of Newman[44] or by α-elimination from dimethylvinylidene trifluoromethanesulfonate (**20**) by the method of Stang[45] in the presence of **18** both gave dimers of **5a**.

(44) M. S. Newman and A. O. M. Okarodudu, *J. Am. Chem. Soc.*, **90**, 4189 (1968), and subsequent papers by Newman and his co-workers.

(45) P. J. Stang, M. G. Mangum, D. P. Fox, and P. Haak, *J. Am. Chem. Soc.*, **96**, 4562 (1974).

(46) M. Rule and J. A. Berson, *Tetrahedron Lett.*, in press.

(47) G. Köbrich and H. Heinemann, *Chem. Commun.*, 493 (1969).

(48) G. Köbrich, *Angew. Chem., Int. Ed. Engl.*, **12**, 464 (1973).

be attributed to the bicyclic hydrocarbon **25**, but absorptions of three dimeric products, **22**,[49] **23**, and **24**,[49] appear within 1 min. Products **22** and **23**, respectively, result from [2 + 2] cycloaddition and "ene" dimerization of **25**. The release of enormous ring strain must contribute to the extraordinary ease of these reactions. The monomeric hydrocarbon **25** also can be captured with 1,3-diphenylisobenzofuran as a 2:1 mixture of two steroisomeric Diels–Alder adducts, **26**.[46]

There are two conceivable mechanisms for the formation of dimer **24**. In one of these, the formation of **24** might occur by preliminary ring cleavage of **25** to the
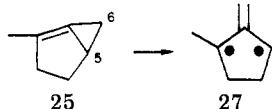
TMM **27** and capture of the latter by **25**. If the cleavage step **25** → **27** is rate determining, we must conclude that the strength of the C-5–C-6 bond of **25** cannot be greater than ~11 kcal/mol.

Alternatively, **24** might result from a [2 + 2] cycloaddition of 2 mol of **25**, involving the weak C-5–C-6 σ bond of one molecule and the π bond of another. The absence of the typical TMM + TMM dimers analogous to **10–13** (Scheme II) tends to favor this as the more satisfactory interpretation. If this is the actual mechanism, the acceleration attributable to ring strain can be appreciated by comparison of the rate, which is fast at –90 °C, to that of the formally analogous σ + π cycloaddition of bicyclo[2.1.0]pentane to maleic anhydride, which occurs over several hours in a sealed tube at +120 °C.[50]
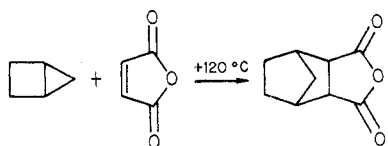

These experiments demonstrate that bicyclo[3.1.0]hex-1-ene derivatives have quite a different chemistry from that of the singlet TMM diyls generated by deazetation of the diazene precursors **9a** or **9g**. Further work is needed to provide a similar test for the isomeric 5-alkylidenebicyclo[2.1.0]pentane system.

Orbital Symmetry Control of the Reactions of the Singlet Diyl 5g. Hierarchy of the NBMOs. The cycloaddition reactions of the triplet diyl **5a**-T with olefins show very low regiospecificity, the ratios of fused (F) to bridged (B) products ranging between 0.8 and 2.7.[33,37] In contrast, the cycloadducts from the singlet form of **5a**,[33,37] and as we have recently found[51] of **5g**, are almost purely fused, with F/B ratios in the range of 31–75. The high regiospecificity of the singlet has been rationalized on the hypothesis that the reactive form has a bisected configuration and that this causes a destabilizing torsion about the developing π bond in the transition state for the formation of bridged cycloadduct.[33] However, our present view of the matter is different, and we now have adopted the working hypothesis that although planar ⇌ bisected interconversion may be facile, the regiospecificity of the

cycloaddition, as well as a number of other phenomena, is best explained as a manifestation of orbital symmetry control, which is exerted by the energetic ranking of the two nominal NBMOs of the planar singlet TMM.

In D_{3h} parent TMM, **1**, one of the degenerate NBMOs is symmetric (S) and the other antisymmetric
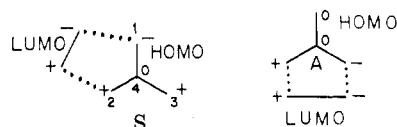
(A) with respect to a vertical symmetry plane. If the degeneracy were lifted by Jahn–Teller distortion or by substitution, and if the orbital separation were enough to permit the reactive form of the diyl to be the closed shell singlet, frontier orbital interactions (HOMO–LUMO)[52] with an olefin would favor concerted cycloaddition at the sites of *opposite* phase in the sterically preferred suprafacial–suprafacial geometry.

The observed preference for fused **5a**– or **5g**–olefin cycloadducts suggests that the HOMO of these diyls is S-NBMO. What causes the energy ordering A-NBMO > S-NBMO? Although it is qualitatively true that the bond angle contraction in 2-methylenecyclopenta-1,3-diyls (e.g., **5g**) tends to stabilize the symmetric

S-NBMO   A-NBMO

5a, R = Me
  e, R = OMe
  g, R = H
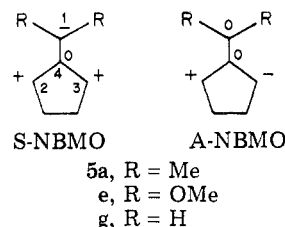
component because of the in-phase transannular π interaction,[6] the more detailed calculations[13c] show this effect to be quite small. In unsubstituted TMM, **1**, a C-2–C-4–C-3 bond angle distorted from the trigonal to 110° causes a splitting of only ~0.2 kcal/mol. More recently, however, extended HMO (EH) calculations[53] on the cyclopentadiyl **5g**, although they agree with the STO-3G-CI results[13c] in predicting that the angular contraction effect will be small, also predict a large (18 kcal/mol) reinforcement resulting in selective destabilization of the antisymmetric component of the NBMO pair by the interaction of the TMM π system with the σ orbitals of the bridging CH_2 groups of the ring. It would be useful to know whether so large a splitting would survive a more sophisticated calculation.

An extension of the frontier MO rationale to the case of a conjugated diene, where the LUMO (ψ_3) is in phase at the termini and out of phase at C-1 and C-2, predicts two kinds of cycloadducts, bridged 1,4 (B14) and fused 1,2 (F12). Attempts to confirm this prediction with piperylene, an acyclic 1,3-diene, are unsatisfactory because very little 1,4 product is formed in the singlet addition, although the 1,2 adduct, as predicted, is entirely fused. One can encourage some 1,4 addition by forcing together the ends of the diene system in a ring, as in cyclopentadiene. The major products of the

(49) Or its cycloaddition regioisomer.

(50) P. G. Gassman, K. T. Mansfield, and T. J. Murphy, *J. Am. Chem. Soc.*, **90**, 4746 (1968).

(51) R. Siemionko, A. Shaw, G. O'Connell, R. D. Little, B. K. Carpenter, L. Shen, and J. A. Berson, *Tetrahedron Lett.*, in press.

(52) (a) K. Fukui in "Molecular Orbitals in Chemistry, Physics, and Biology", P.-O. Löwdin and B. Pullman, Ed., Academic Press, New York, N.Y., 1964, pp 513 ff; (b) K. N. Houk, *Acc. Chem. Res.*, **8**, 361 (1975), and references cited therein; (c) R. Sustmann, *Tetrahedron Lett.*, 2717 (1971); (d) I. Fleming, "Frontier Orbitals and Organic Chemical Reactions", Wiley, New York, N.Y., 1976, Chapter 4.

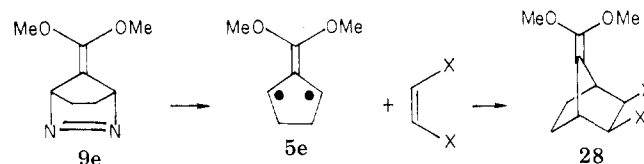(53) W. W. Schoeller, *J. Chem. Soc., Perkin Trans. 2*, in press.
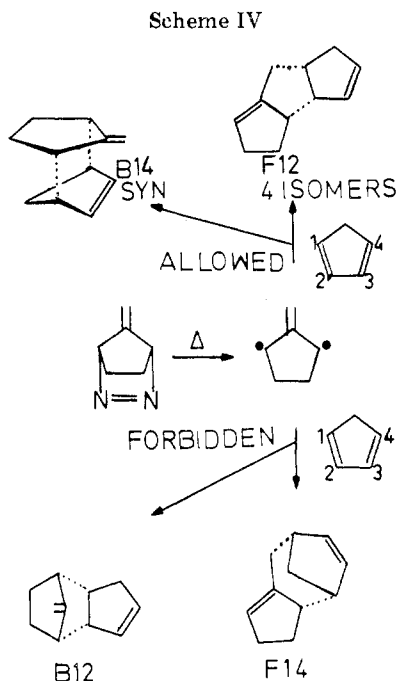
Scheme IV

reaction of this substance with the **5g** singlet generated from the diazene, **9g**, are[51] B14 and F12 (Scheme IV, where the dotted bonds show the sites of reaction). The "allowed" products predominate over the "forbidden" ones by at least 30:1. The hypothesis[33] that the reactive form of the singlet diyl is bisected offers no rationalization for the switch in regiospecificity between 1,2 and 1,4 cycloaddition.

The syn B14 compound shown in Scheme IV predominates over the anti isomer by a ratio of about 20:1. It seems reasonable to ascribe the stereospecificity also to orbital symmetry. The syn isomer is the one predicted by application of the same kind of secondary HOMO–LUMO interactions that rationalize the much-discussed preference for endo addition in the Diels–Alder reaction.[52a,54]

In principle, polar substituents offer another way of lifting the degeneracy of the TMM NBMOs. Qualitative perturbational arguments[8] suggest that, in C_{2v} symmetry, electron-withdrawing substituents on the unique carbon (C-1 of **5g**) should stabilize the symmetric component, S-NBMO, whereas the opposite effect, selective stabilization of the antisymmetric component, A-NBMO, should result from substitution at C-2 and C-3. Conversely, electron-releasing substituents at C-1 should stabilize A-NBMO and, at C-2 or C-3, should stabilize S-NBMO.

The effect of electron-releasing substituents at C-1 therefore opposes the π–σ bond interaction in **5g**, and with strong donor substituents, one might hope to invert the NBMO order and make an antisymmetric orbital the HOMO. This would predict a reversal of regiospecificity, from F12 in the 1,2 cycloadditions of **5g** to B12 in those of **5e**. We recently have confirmed this prediction in the reactions of the diazene **9e** with acrylonitrile, dimethyl fumarate, and dimethyl maleate.[55] In the latter two cases, the cycloadducts result from highly stereospecific cis addition, as would be

(54) Cf. R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry", Academic Press, New York, N.Y., 1970, pp 145 ff.
(55) A. Shaw, R. D. Little, G. O'Connell, L. Shen, and J. A. Berson, unpublished results.

expected of a concerted singlet reaction. All three diylophiles give largely or entirely bridged cycloadducts. The product from dimethyl maleate has predominantly the exo configuration, **28**, as would be predicted by the secondary orbital interactions with singlet **5e**. It remains to be seen whether the now anticipated rereversal to fused adduct will occur in the 1,4 additions of **5e** with dienes.

Space precludes all but a cursory mention of several other phenomena in TMM chemistry which find simple explanations as orbital hierarchy effects. The thermal deazetation of the bridged diazene **9a** is accompanied

9a, R = Me   29
e, R = OMe
h, R = SO₂Me
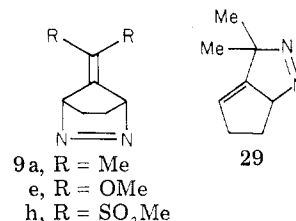
by a rearrangement to the fused isomer **29**.[56] Apparently, **9a** suffers nonconcerted thermal cleavage of only one C–N bond at a time, as would be expected if the HOMO of the corresponding diyl **5a** were symmetric and the two-bond cycloreversion therefore were forbidden. It seems more than incidental that the photodeazetation of **9a** has a quantum yield near unity,[41] and recovered diazene from partial photolysis has not rearranged.[56] These observations suggest that a concerted reaction may be allowed in the diazene excited state, where the orbital symmetry restrictions appropriate to the thermal reaction do not apply.

Since the HOMO of the singlet dimethoxydiyl, **5e**, is now believed to be antisymmetric, the orbital symmetry relationships are reversed from those in the dimethyl system, and *thermal* deazetation of the corresponding dimethoxydiazene **9e** becomes allowed. This inversion of symmetry manifests itself in the great difference in thermal stability between the dimethyl- (**9a**) and dimethoxydiazenes (**9e**). Roughly extrapolated to a common temperature at –10 °C, the relative deazetation rates of the dimethoxy and dimethyl compounds are about 100 000:1.[37,55]

Electron-withdrawing substituents at C-1 should restore (and reinforce) the symmetric HOMO preference. We therefore would expect the dimethanesulfonyldiazene **9h** to be quite stable thermally, and recent experience seems to confirm this prediction.[24]

It should be emphasized that although the present interpretation of the regiospecificity of singlet cycloaddition postulates a planar species as the *reactive* form, it is noncommittal on the relative stabilities of the planar and bisected diyls and on the rate of their interconversion.

Prospects. We plan to develop the photochemistry and spectroscopy of TMM triplets begun with the observations[57] of matrix isolated diyls **5a** and **5c**, which

(56) D. Cichra, M. S. Platz, and J. A. Berson, *J. Am. Chem. Soc.*, **99**, 8507 (1977).

have delineated the ultraviolet–visible absorption and emission spectra of these species. One might hope also to obtain direct ultraviolet spectroscopic measurements of the various rate constants of the cascade mechanism (Scheme II) by flash photolysis techniques. Direct tests for the intervention of a bisected singlet intermediate and for internal heavy atom effects on the intersystem crossing rate, as well as the preparation of "high spin" compounds containing four or more unpaired electrons, are projects under active study. It seems likely that

many of the techniques used here could be applied to the investigation of other biradical species.

(57) Cf. N. J. Turro, M. Mirbach, N. Harrit, J. A. Berson, and M. S. Platz, *J. Am. Chem. Soc.*, in press.

# Some Aspects of Organosulfur-Mediated Synthetic Methods

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Organosulfur chemistry continues to play a major role in chemical research. While past trends emphasized sulfur compounds for their intrinsic interest, recent efforts are increasingly focusing on the incorporation of sulfur as a temporary control element in an organic molecule. Such sulfur substituents can direct formation of C–C bonds and adjust the oxidation level of carbon. The tremendous flexibility offered by sulfur as a result of its ability to stabilize a reactive carbon species such as a cation, radical, anion, carbene, etc. provides an almost unique opportunity in devising new reactions and reagents. Especially valuable is the juxtaposition of a sulfur substituent α to a carbonyl group. Recently developed reactions and reagents incorporating such a structural feature and their application in synthesis will be considered in this Account.

The utility of sulfur as a chemical control element stems in part from the ease with which it can be introduced into organic molecules (see eq 1).[1-5] Not only


(1)

2   **3**
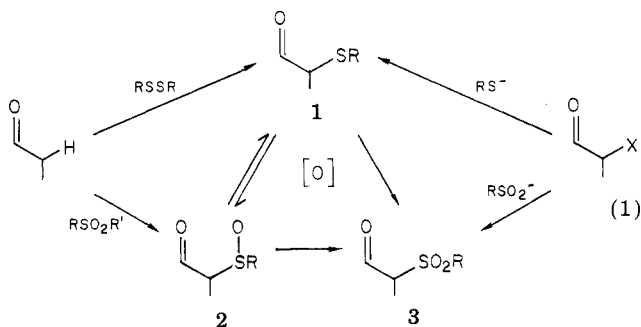
can the sulfur substituents be introduced directly into carbonyl compounds by replacement of C–H or C–X (X

= halogen) bonds but also new reagents (vide infra) offer the opportunity to incorporate this structural unit into a starting material for carbon–carbon bond formation. In addition to being able to synthesize the sulfoxides and sulfones directly, they are also available by controlled oxidation of the sulfides. Generally, for any given substrate, the sulfide **1**, sulfoxide **2**, or sulfone **3** is readily available, and each has its own application.

Dehydrogenation via Sulfoxide Pyrolysis

The selective sulfenylation or sulfinylation of carbonyl compounds followed by thermolytic extrusion of a sulfenic acid constitutes an exceptionally mild and
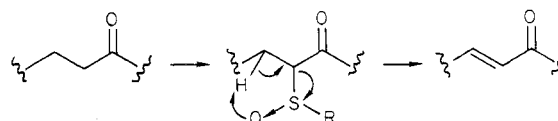
general route for converting a saturated compound to its α,β-unsaturated derivative.[2] The temperatures vary as a function of R. For R = aryl (e.g., **4**), a temperature of 25–80 °C is normal, whereas for R = alkyl (e.g. **5**), a temperature of 110–130 °C is common. The mildness of the conditions is demonstrated by the success with **4** and the exceedingly broad variety of functional groups compatible with the reaction. The formation of only the queen's substance of bees (**6**) from **5** illustrates the pure *E* configuration obtained with disubstituted olefins.

(1) For a review, see B. M. Trost, *Chem. Rev.*, **78**, in press.
(2) B. M. Trost, T. N. Salzmann, and K. Hiroi, *J. Am. Chem. Soc.*, **98**, 4887 (1976); B. M. Trost and T. N. Salzmann, *ibid.*, **95**, 6840 (1973).
(3) D. Seebach and M. Teschner, *Chem. Ber.*, **109**, 1601 (1976); *Tetrahedron Lett.*, 5113 (1973).
(4) (a) R. M. Coates and H. D. Pigott, *Synthesis*, 319 (1975); (b) H. J. Monteiro and J. P. De Souza, *Tetrahedron Lett.*, 921 (1975); (c) B. M. Trost and L. H. Latimer, *J. Org. Chem.*, **43**, 1031 (1978).
(5) R. Otto and A. Rossing, *Chem. Ber.*, **23**, 756 (1890); F. Asinger, M. Thiel, and I. Kalzendorf, *Justus Liebigs Ann. Chem.*, **610**, 25 (1957); F. Asinger, W. Schafer, and H. Triem, *Monatsch. Chem.*, **97**, 1510 (1966); W. E. Truce and R. Knospe, *J. Am. Chem. Soc.*, **77**, 5063 (1955).
(6) B. M. Trost and B. E. Williams, unpublished observations; B. E. Williams, Ph.D. Thesis, University of Wisconsin, 1977.