253 (5), 237 (11), 221 (18), 206 (18), 205 (38), 204 (22), 203 (34).

5,12-Dimethyl-5,12-dihydro-3,7,10,14-tetra-*tert*-butyl-1,8-didehydro[14]annulene (30b). The annulene **12** (201 mg, 0.5 mmol) in 20 mL of dry THF was reduced with lithium at −78 °C in a sealed glass ampule. When the dianion formation was complete the color of the solution turned to dark red. The ampule was opened under an argon atmosphere, the solution was allowed to warm to −40 °C, and an excess of freshly distilled dimethyl sulfate was added. The solvent was removed under reduced pressure and the residue chromatographed over Alox (neutral, act. II–III, 60 cm, ϕ = 3 cm). Hexane eluted a red fraction which gave 40 mg of the starting materials and a colorless fraction. After removal of the solvent and recrystallization from methanol one obtained 216 mg (50%) of **30b**: mp 243–244 °C (colorless needles); ^1H NMR (60 MHz, $CDCl_3$) δ 5.72 (d, 4 H), 4.67 (m, 2 H), 1.24 (s, 36 H), 1.17 (d, 6 H); ^{13}C NMR (20 MHz, $CDCl_3$) δ 136.6 (C-4, -6, -11, -13), 133.3 (C-3, -7, -10, -14), 94.1 (C-1, -2, -8, -9), 39.4 (C-5, -12), 35.9 (C-3a, -7a, -10a, -14a), 29.9 (CH_3, *tert*-butyl), 23.0 (C-3a, -12a); MS (70 eV), *m/e* (rel intensity) 432 ($M^{\bullet+}$, 8), 417 ($M^{\bullet+} - CH_3$, 4), 402 ($M^{\bullet+} - 2CH_3$, 9), 57 (*tert*-butyl, 100); exact mass calcd for $C_{32}H_{48}$ 432.3756, found 432.3750.

5,12-Dicarbomethoxy-5,12-dihydro-3,7,10,14-tetra-*tert*-butyl-1,8-didehydro[14]annulene (30c) and 5,12-Bis(bromopropyl)-5,12-dihydro-3,7,10,14-tetra-*tert*-butyl-1,8-didehydro[14]annulene (30d). The annulene **12** (201 mg, 0.5 mmol) was reduced and the resulting dianion quenched as described above. The quenching reagents were (a) methyl chloroformate and (b) 3-dibromopropane. (a) Chromatography over Alox (neutral, act. I–II) with hexane/ether (4:1) and recrystallization from methanol gave 145 mg (45%) of the diester **30c**. (b) Chromatography over Alox (neutral, act. III) and recrystallization from methanol gave 120 mg (37%) of the diadduct **30d**. The amount of recovered (reoxidized) starting material was 53 mg. **30c**: mp 227 °C (colorless needles); ^1H NMR (60 MHz, $CDCl_3$) δ 5.66 (s, 6 H), 3.72 (s, 6 H), 1.20 (s, 36 H); MS (70 eV), *m/e* (rel intensity) 520 ($M^{\bullet+}$, 13), 463 ($M^{\bullet+}$ − *tert*-butyl, 20), 57 (*tert*-butyl, 100); exact mass calcd for $C_{34}H_{48}O_4$ 520.3575, found 520.3567. **30d**: mp 144–146 °C (colorless needles); ^1H NMR (60 MHz, $CDCl_3$) δ 5.45 (d, 4 H), 4.90–4.37 (m, 2 H), 3.47 (t, 4 H), 2.27–1.44 (m, 8 H), 1.20 (s, 36 H); UV (CH_2Cl_2) 275 (12 709), 250 (27 980) nm; MS (70 eV), *m/e* (rel intensity) 648, 646, 644 ($M^{\bullet+}$, 22), 587, 589, 591 ($M^{\bullet+}$ − *tert*-butyl, 29), 531, 533, 535 ($M^{\bullet+}$ − 2*tert*-butyl, 50), 475, 477, 479 ($M^{\bullet+}$ − 3*tert*-butyl, 50); exact mass calcd for $C_{36}H_{54}Br_2$ 646.2572, found 646.2564.

Acknowledgment. We thank the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie for financial support.

Investigation of the 2,7-Dihalofluorenylidenes: Search for Heavy Atom Effects in the Reactions of Triplet Carbenes

Stanton F. Rak, Stephen C. Lapin, Daniel E. Falvey, and Gary B. Schuster*

Contribution from the Department of Chemistry, Roger Adams Laboratory, University of Illinois, Urbana, Illinois 61801-3731.

Received March 4, 1987

Abstract: The properties of the 2,7-dihalofluorenylidenes (Cl, Br, I) were examined by laser and EPR spectroscopy and by conventional chemical analyses. Their reactions with alcohols and olefins were studied. No evidence was found for the operation of a heavy atom effect in their reaction with methyl alcohol. Analysis of the kinetic and product results indicates an energy gap between the triplet (ground state) and the singlet for the three dihalofluorenylidenes of 4.2 ± 0.5 kcal/mol, ca. twice the value of fluorenylidene itself.

The keystone of carbene chemistry is spin–specific reactivity. In this model, reactions are identified as originating from the singlet or triplet spin states of a carbene. For example, the well-known Skell–Woodworth hypothesis is used to classify stereospecific cyclopropanation as a reaction of the singlet state while the nonstereospecific outcome is assigned to reaction of the triplet state.[1] Similarly, in reactions with alcohols, singlet carbenes generally are thought to add across the oxygen–hydrogen bond to form ethers[2] (eq 1) and the triplets are believed to abstract hydrogen atoms to create radical pairs (eq 2).[3] This notion of spin-specificity has been challenged by the suggestion that triplet diphenylcarbene (DPC) can add to alcohols to form ethers in a concerted reaction.[4,5] This hypothesis may be tested by searching for an intramolecular heavy atom effect in a series of substituted fluorenylidenes. The results of this investigation are reported herein.

Table I. X-Band EPR Spectra of Carbenes in MTHF Glass at 8 K

carbene	transitions, G	$\|D\|$, cm^{-1}	$\|E\|$, cm^{-1}	g_{perp}	g_{par}
CFL	1038 z_1 2156 double quantum 4544 x_2 5685 y_2 7810 z_2	0.4158	0.0287	2.002	2.003
BFL	1014 z_1 2170 double quantum 4550 x_2 5668 y_2 7790 z_2	0.4134	0.0281	2.000	2.002
IFL	963 z_1 4543 x_2 5639 y_2 7747 z_2	0.4088	0.0277	2.000	2.003
DPC	997 z_1 4717 x_2 5491 y_2 7748 z_2	0.4101	0.0196	2.033	2.002

Results

1. EPR Spectroscopy. The most certain way to identify a triplet carbene is to observe its characteristic EPR spectrum. We ir-

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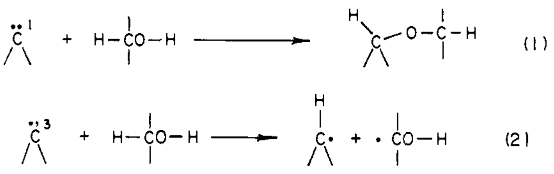
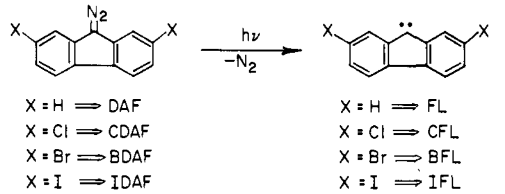
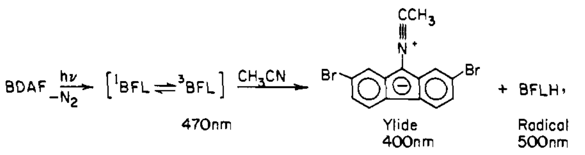


radiated the 2,7-dihalo-9-diazofluorenes (XDAF) in glassy 2-methyltetrahydrofuran at 8 K. In each case we observed an EPR spectrum characteristic of a ground-state triplet carbene, eq 3. These spectra were analyzed with the spin Hamiltonian to give the zero-field parameters and *g* shifts (Table I).[6,7]

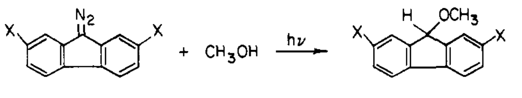


2. Transient Absorption Spectroscopy. Laser flash photolysis of DAF in acetonitrile has been intensively studied by several groups and is now well defined.[8] Photolysis of the dihalodiazofluorenes under similar conditions gives results that are directly analogous to those of DAF. Figure 1 shows the transient absorption spectra recorded 10, 20, and 100 ns after irradiation (337 nm, 10 ns, 7 mJ) of DBAF in acetonitrile solution. The band at ca. 470 nm is present immediately on the time scale of this experiment. This feature is assigned to ^{3}BFL. As the carbene is consumed, absorption bands at ca. 400 nm and 500 nm grow into the spectrum. These features are assigned to the nitrile ylide formed by addition to the carbene to acetonitrile and to the 2,7-dibromo-9-fluorenyl radical (BFLH) formed by hydrogen atom abstraction respectively (eq 4).



The apparent half-life of ^{3}BFL in acetonitrile solution is ca. 10 ns. This is quite similar to the half-life of ^{3}FL ($t_{1/2}$ = 17 ns) but is too short for us to measure precisely with the nitrogen laser apparatus.[9] The spectral and kinetic properties of the CFL and IFL are essentially indistinguishable from those of BFL.

3. Direct Irradiation of XDAF in Methyl Alcohol. Photolysis of many diazo compounds in neat alcohols gives ethers in good yields.[10] The dihalodiazofluorenes are no exception. Irradiation (350 nm) of methyl alcohol solutions of XDAF gives the expected ethers (eq 5) in ca. 90% yield. The minor side products obtained are a consequence of secondary photolysis of the ethers.[11] Thus the reaction of the dihalocarbenes with methyl alcohol appears to mimic that of FL. However, closer examination reveals important differences,



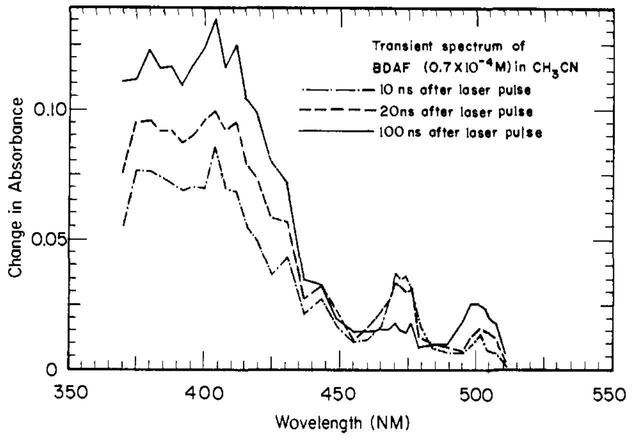


Figure 1. Transient absorption spectra recorded after irradiation of BDAF in deoxygenated acetonitrile. The band centered at ca. 400 nm is assigned to the ylide, that at ca. 470 nm to the triplet carbene, and that at ca. 500 nm to the dibromofluorenyl radical.

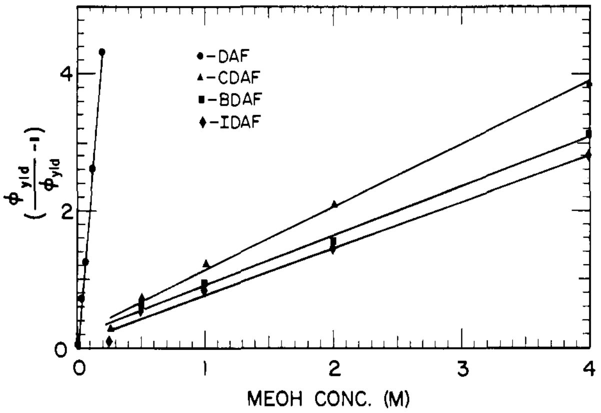


Figure 2. Stern–Volmer analysis of the competition of XDAF for reaction with acetonitrile to form the ylide (monitored at 400 nm, 500 ns after the laser flash) and reaction with methyl alcohol to form the ether.

Table II. Estimates of Observed Rate Constants from Stern–Volmer Analysis[a]

carbene	K_{SV}, M^{-1} MeOH	k^{obsd}, M^{-1} s^{-1} α-methylstyrene[c]
FL[b]	22	1.1×10^9
CFL	0.93	3.6×10^9
BFL	0.70	3.9×10^9
IFL	0.73	3.3×10^9

[a] The observed rate constants may contain contributions from both the singlet and triplet carbene. [b] Reference 8a. [c] The values for XFL were calculated with the half-life of XFL set at 10 ns. As noted in the text, this is near the resolution limit of the laser and therefore may be more than typically unreliable. The relative values are trustworthy.

An estimate of the reactivity of the dihalocarbenes with methyl alcohol can be obtained with time-resolved Stern–Volmer techniques.[8a] In this experiment the reaction with the alcohol is assumed to compete with ylide formation and the decrease in ylide yield is related to the alcohol concentration through eq 6. Thus, a plot of the ratio of ϕ^0_{yld} (the ylide in the absence of methyl alcohol) to ϕ_{yld} against alcohol concentration is anticipated to be

$$\frac{\phi^0_{yld}}{\phi_{yld}} = 1 + K_{SV}[\mathrm{MeOH}] = k^{obsd}_{\mathrm{MeOH}}\tau_{\mathrm{XFL}}[\mathrm{MeOH}] \qquad (6)$$

linear (slope = K_{SV}) and to have k^{obsd}_{MeOH} as a component. The processes that compose k^{obsd}_{MeOH} may contain contributions from the reaction of both the singlet and triplet carbene. The results of these experiments are plotted on Figure 2 for the dihalocarbenes and for fluorenylidene itself. It is apparent that the three dihalocarbenes are approximately equally reactive with methyl alcohol but that they are all less reactive than fluorenylidene. This finding is confirmed by product studies which show that a much higher alcohol concentration is required to trap the halogenated

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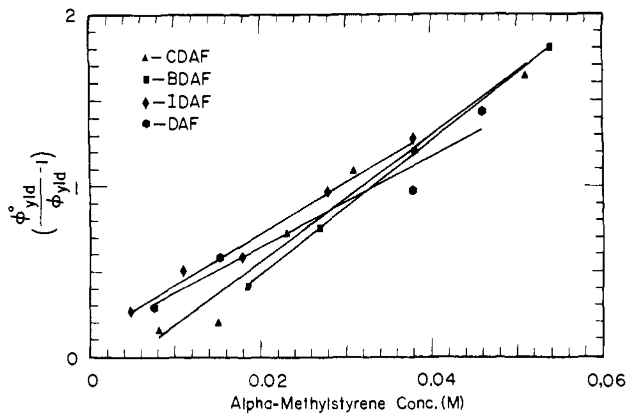
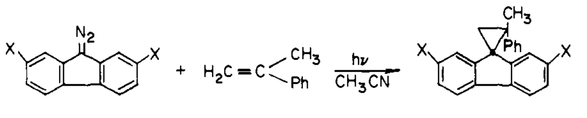


Figure 3. Stern–Volmer analysis of the competition of XDAF for reaction with acetonitrile to form the ylide (monitored at 400 nm, 500 ns after the laser flash) and reaction with α-methylstyrene to form a cyclopropane.

carbenes as the ether than is required for FL. The rate data are summarized in Table II.

4. Direct Irradiation of XDAF in the Presence of α-Methylstyrene. Addition of a carbene to an olefin to form a cyclopropane is the classical way to diagnose the multiplicity of the reacting carbene. Irradiation of the dihalodiazofluorenes in acetonitrile containing 2.0 M α-methylstyrene gives the expected cyclopropane in ca. 80% yield (eq 7). The stereochemistry of this reaction was probed by employing (E)-β-deuterio-α-methylstyrene.



(7)

The three dihalocarbenes give similar results. In the presence of 2.0 M (E)-β-deuterio-α-methylstyrene, the cyclopropane is formed with ca. 78% retention of configuration.[12] Under these conditions FL reacts with 50% retention of configuration. Significantly, the stereochemical outcome of this reaction (probed only for CFL) depends on the concentration of the styrene. Retention rises to 83% in neat olefin, and when the olefin concentration is decreased to 0.1 M, it drops to 71%.

The reactivity of the dihalofluorenylidenes toward α-methylstyrene can be examined by application of the same Stern–Volmer procedure that was described for methyl alcohol. The results of these experiments are plotted on Figure 3. The reactivity of the dihalofluorenylidenes is much more like that of FL in the cyclopropanation reaction than it is for the reaction with methyl alcohol. The rate data are summarized in Table II.

5. Triplet-Sensitized Reactions of XDAF. Triplet sensitization provides a direct route to triplet carbenes. Irradiation ($\lambda > 398$ nm) of acetonitrile solutions containing 2,3-dibenzofluorenone (sensitizer), the diazo compound, and 5.0 M methyl alcohol leads to rapid reaction. Control experiments established that the sensitizer triplet is quenched at a diffusion-limited rate by the diazo compound and that the reaction is quenched by low concentrations of anthracene (triplet quencher). These observations confirm the operation of a conventional triplet energy transfer mechanism.

The outcome of the triplet-sensitized reaction depends on the identity of the diazo compound. For DAF, the yield of ether is essentially quantitative.[8a] But for the XDAF, the ether yield is much lower (X = Cl, 26%; X = Br 29%; X = I 28%). Triplet-sensitized irradiations of XDAF in the presence of α-methylstyrene (0.1 M) uniformly give the expected cyclopropanes in nearly quantitative yield. Analysis of the stereochemistry of this reaction with the deuteriated styrene shows that it occurs with total randomization of configuration. Control experiments reveal that this is not due to prior isomerization of the styrene or to isomerization of the cyclopropane after its formation. This finding demonstrates that cyclopropanation originates exclusively with reaction of ^{3}XFL under these conditions. In contrast, FL reacts with 16% retention of configuration by triplet sensitization.

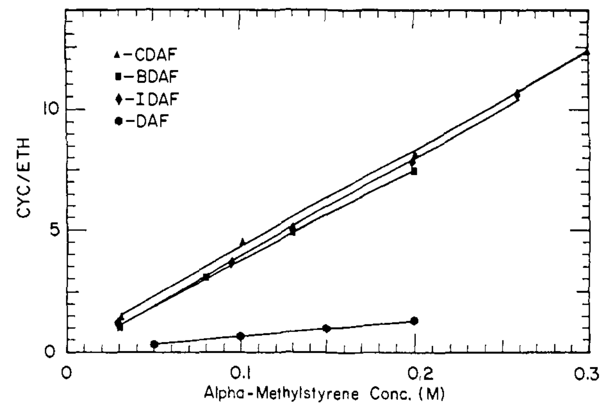
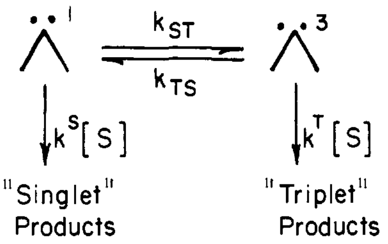


Figure 4. Triplet-sensitized competition between reaction with α-methylstyrene to form the cyclopropane and reaction with methyl alcohol to form the ether. The methyl alcohol concentration is held constant at 5.0 M for CDAF, BDAF, and IDAF and at 1.0 M for DAF.

Scheme I



The triplet-sensitized reactions of XDAF with methyl alcohol and styrene can be put on a more quantitative footing by examination of the product yields as the concentrations of the trapping agents are varied in a competition experiment. The results are shown graphically on Figure 4 where the ratio of the yields of cyclopropane to ether are plotted as the styrene concentration is increased and the alcohol concentration is held constant (5.0 M for XDAF, 1.0 M for DAF). An analogous plot is obtained when the alcohol concentration is varied at fixed styrene concentration. The slopes of the lines in Figure 4 represent, in a phenomenological sense, a comparison of the ability of ^{3}XFL to form ether from alcohol in competition with its trapping by styrene. Triplet fluorenylidene is ca. 30 times more likely to form ether than are the dihalofluorenylidenes which behave essentially independently of the identity of the halogen. A more precise interpretation of the magnitude of the slopes of these plots first requires postulation of a reaction mechanism. This is reserved for the Discussion section.

Discussion

The prime objective of this work was to explore the effect of halogen substitution on the properties of fluorenylidenes. One specific question we wished to probe concerns the way in which a carbene in its triplet ground state combines with an alcohol to form an ether. Before proceeding to the analysis of the present results, it is pertinent to review briefly two of the mechanisms that have been proposed for this transformation.

The realization that a triplet carbene can form products characteristic of the singlet led Bethell[13] to suggest that equilibration between carbene spin states can compete with irreversible reaction of the triplet. This concept is embodied in Scheme I. According to this hypothesis, the triplet carbene serves as a reservoir for the more reactive ($k^s > k^t$) singlet state. An equilibrium constant ($K_{eq} = k_{st}/k_{ts}$) is defined that depends on the free energy difference ($\Delta G_{st} = -RT \ln K_{eq}$) between the

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[12] Retention is defined as [retained − inverted]/[retained + inverted].

[13] Bethell, D.; Hayes, J.; Newall, A. R. *J. Chem. Soc., Perkin Trans. 2* **1974**, 1307 and references cited therein.

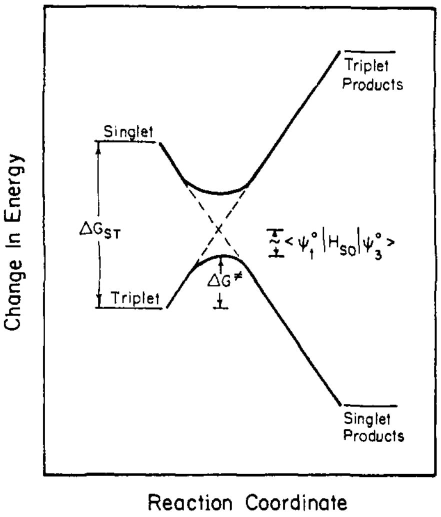

Figure 5. Reaction coordinate diagram for the hypothetical direct reaction of a triplet carbene with an alcohol to form a singlet product.

carbene spin states. This mechanism has been adapted to provide values for ΔG_{st} from estimates of k_{st} and k_{ts}.[10,14] It has the additional advantage that it accommodates the widely held principle that a triplet intermediate cannot form a singlet product in a single step.

More recently, Griller, Nazran and Scaiano[4] have advanced an alternative mechanism supported primarily by analysis of the temperature dependence of the reaction of diphenylcarbene with methyl alcohol.[15] The proposal, illustrated in Figure 5, features a concerted reaction of the triplet carbene with alcohol to form directly the singlet products. The transition state for this reaction is created by the avoided crossing of the zero-order singlet and triplet reaction potential energy surfaces, For such a process, the rate of reaction will be controlled by the extent of mixing between the pure triplet and the pure singlet wave functions. The investigation of the dihalofluorenylidenes reveals several significant facts that help to discriminate between these two mechanistic hypotheses.

It is apparent that there are two distinct and identifiable states responsible for the reactions of the dihalofluorenylidenes. One of these dominates when the carbene is formed by triplet sensitization. It adds to olefins with total randomization of stereochemistry and reacts with alcohols to form ethers with only modest efficiency. This state is identified without controversy as the triplet ground state that is detected by EPR spectroscopy. The second state is formed in the direct irradiation. It adds to olefins with retention of configuration and combines very efficiently with alcohols to form ethers, This species is identified as the singlet state. It is somewhat higher in energy than the triplet ground state.

Methyl alcohol reacts to form ethers with ^{3}XFL far more slowly than it does with ^{3}FL. This is revealed in the product studies, the laser kinetics, and the triplet sensitization experiments. Regardless of the mechanism chosen to represent the reaction of triplet carbenes with alcohols, the rate retardation by halogen substitution can be traced to a common origin: an increase in the magnitude of ΔG_{st}. This is obviously the case for the rapid equilibrium model where the concentration of the singlet carbene in solution is related exponentially to the value of ΔG_{st}. For the concerted reaction hypothesis, the magnitude of ΔG_{st} can be directly related to $\Delta G^{\ddagger}$, the activation energy for reaction, by perturbation theory, Fundamentally, as ΔG_{st} increases, so does $\Delta G^{\ddagger}$.

It is an important matter to understand why 2,7-dihalogenation increases the magnitude of ΔG_{st}. These substituents are located at pseudo-meta positions where they are electron withdrawing inductively. Electron withdrawal from the already electron defficient singlet carbene raises its energy relative to that of the less susceptible, radical-like triplet. This behavior is precicted from the simplest application of molecular orbital theory.[17,18] It is significant that the electron-withdrawing abilities of Cl, Br, and I in meta positions are virtually identical. This is demonstrated by the unwavering values of their σ_m substituent constants (0.37, 0.37, and 0,34, respectively).[19] Thus, the properties of XFL are predicted to be essentially independent of the identity of X if electron withdrawal is the only factor causing their difference from FL, The three halogenated fluorenylidenes we studied are consistent with this prediction, There are no qualitative or quantitative differences in their spectroscopic or chemical properties.

Incorporation of heavy atoms in molecules is often observed to increase the rates of reactions that require a change in total spin multiplicity, This is due to an increase in the spin–orbit coupling interaction that mixes the pure singlet and triplet wave functions.[20-22] The ENDOR spectrum of FL reveals observable odd-electron density at the 2- and 7-positions, the points of heavy atom attachment.[23] If operating, the heavy atom effect will have a predictably different impact on the two mechanisms postulated to accommodate the reaction of triplet carbenes with alcohols to form singlet carbene-derived products. For the equilibrium model, there would be no heavy atom effect on the rate of reaction, The value of the equilibrium constant (K_{eq}) is set by ΔG_{st}, a thermodynamic quantity, and combination of a singlet carbene with the singlet alcohol to form the singlet ether product does not involve a change of spin, On the other hand, if the concerted reaction mechanism is operating, then the transition state of the rate-limiting step is formed by the avoided crossing of different spin states. The energy correction to the perturbed state (transition state) is the matrix element for the perturbation Hamiltonian over the unperturbed wave functions (to first order) (eq 8 and Figure 5). Thus the barrier in the slow, rate-limiting step is determined entirely by the magnitude of spin-orbit coupling.

$$E_{TS}' = \langle \psi_s^0 | \mathbf{H}_{so} | \psi_t^0 \rangle \tag{8}$$

We searched for independent evidence of increased spin–orbit coupling in the triplet dihalofluorenylidenes by careful analysis of their EPR spectra. In particular, the *g* shifts of these carbenes should vary in proportion to the magnitude of this interaction.[24] It is not possible to obtain the three independent shifts from the spectra of the randomly oriented carbenes. However, we calculated g_{par} and g_{perp} (to the molecular plane). These are listed in Table I. Within the experimental error, there are no discernible differences among the dihalofluorenylidenes. This is not too surprising, since heavy atom effects are typically observed only when spin–orbit coupling in their absence is weak. The short lifetime of singlet fluorenylidene (280 ps) indicates strong mixing in the absence of heavy atom perturbation. However, this finding does not necessarily apply directly to the transition state in the concerted reaction model. In this case, the heavy atom perturbation operates precisely at the point where the rate of the slow step would be

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(15) In the time since this mechanism was introduced, the rate of intersystem crossing of singlet diphenylcarbene and the discovery of a significant solvent effect[16] on ΔG_{st} have eliminated some of the discrepancy between the equilibrium model and the measurements of the temperature dependence.

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accelerated by increased spin–orbit coupling. The absence of a heavy atom acceleration is most consistent with the equilibrium model for the reaction of these triplet carbenes to form ethers, However, this finding cannot be used to rule out the direct reaction mechanism with certainty. It is possible that the heavy atom perturbation at the transition state is too small to detect experimentally.

Finally, it is possible with the results of the triplet sensitization experiments and assumption of the equilibrium model to estimate K_{eq} for the three halogen-substituted carbenes. These values can be expressed as shown in eq 9, where C and E are the yields of cyclopropane and ether, and k^{t}_{sty} and k^{s}_{MeOH} are respectively the

$$C/E = \frac{K_{eq}k^{t}_{Sty}[\mathrm{Sty}]}{k^{s}_{MeOH}[\mathrm{MeOH}]} \tag{9}$$

rate constants for reaction of the triplet carbene with α-methylstyrene and that for the singlet carbene reacting with methyl alcohol. We approximate k^{t}_{sty} with k^{obsd}_{sty} (recall the outcome of the triplet-sensitized reactions of the deuteriated styrene) and assign $k^{s}_{MeOH} = k_{diff} = 2 \times 10^{10}$ M^{-1} s^{-1}. With these assumptions the slopes in Figure 4 give K_{eq} equal to 1100 ± 100 for each of the three dihalofluorenylidenes. This corresponds to $\Delta G_{st} = 4.2 \pm 0.5$ kcal/mol which is ca. twice the value obtained for FL by using precisely the same assumptions.[8a] Even if the reported ΔG_{st} obtained is distorted by some participation of the hypothetical concerted mechanism, the relative values are accurate. The effect of halogen substitution on ΔG_{st} follows the trend previously observed where electron-withdrawing groups increase the singlet–triplet splitting.

Experimental Section

General Procedures, Proton magnetic resonance (^{1}H NMR) spectra were recorded on Varian Associates XL-200 (200 MHz) or Nicolet NT 360 (360 MHz) spectrometers operating in the FT mode with tetramethylsilane as an internal standard (unless otherwise noted). Mass spectra (MS) were obtained with a Varian MAT CH-5 and 731 mass spectrometers. Steady-state ultraviolet–visible (UV–vis) absorption spectra were recorded with a Perkin-Elmer Model 552 spectrophotometer. Spinning-disk chromatographic separations were performed on a Harrison Research Model 7924 T Chromatotron. Elemental analyses were performed by the Analysis Laboratory, University of Illinois. Electron paramagnetic resonance (EPR) spectra were recorded at the University of Illinois ESR Research Center on a Bruker/IBM ER-200D-SRC X-band spectrometer equipped with an Air Products LTR liquid helium cryostat.

Low-Temperature EPR Spectra of Carbenes, Solutions (2×10^{-2}–5×10^{-2} M) of the corresponding diazo compound in 2-methyltetrahydrofuran (washed with aqueous NaOH and distilled from sodium) were placed in 4 mm o.d. quartz EPR tubes. The samples were frozen at 8 K in the cavity of the EPR spectrometer and irradiated (16–19 min) with a Hg penlamp (unfiltered) through a cavity grating which transmitted ca. 50% of the incident light.

The EPR spectrum was then scanned from 400 to 8400 G at X-band (9.428–9.437 GHz). The exact field positions were recorded with a Varian NMR gaussmeter and the cavity frequency was measured with an EPI Model 548A microwave frequency counter. In each case a large free radical signal near 3400 G ($g = 2$) was observed. Similar samples irradiated at 77 K gave extremely weak carbene spectra which disappeared after ca. 1 h at 77 K. Carbene spectra could be obtained at 77 K upon irradiation of inhomogeneous suspensions of the corresponding diazo compounds in Fluorolube oil. However, the interpretation of these spectra was complicated because 2–3 peaks were observed near 1000 G (z_1 transition) for each of the dihalofluorenylidenes.

The D, E, and g values for each carbene were determined by solving a set of four simultaneous equations derived by Wasserman et al.[24] for the z_1, x_2, y_2, and z_2 transitions of randomly oriented triplets. By our approximation $g_{\parallel} = g_x = g_y$.

Nanosecond Laser Flash Photolysis. The laser flash photolysis apparatus has been described previously.[9] Sample concentrations were adjusted so that the diazo compound absorbed a significant portion of the laser light (ca. 7×10^{-4} M). Solutions were placed in a 1.0-cm quartz cuvette equipped with a stirring bar and a Teflon stopcock. Oxygen was removed by purging the solution with dry nitrogen for 3–4 min.

Preparation of 2,7-Dihalo-9-diazofluorenes, The general procedure of Dewhurst and Shah was employed to prepare the dihalofluorenones from 9-fluorenone.[26a,b] The ketones were converted to hydrazones by treatment with 85% hydrazine hydrate in refluxing *n*-butyl alcohol. Oxidation of the hydrazones were modeled after the procedure described by Schönberg et al.[27] IDAF: mp 177 °C dec; ^{1}H NMR (CDCl$_3$) δ 7.63 (m, 4 H), 7.82 (m, 2 H). Anal. Calcd for $C_{13}H_6N_2I_2$: C, 35.28; H, 1.36; N, 6.31; I, 57.16. Found: C, 35.28; H, 1.55; N, 6.28; I, 57.05. MS (10 eV), *m/e* (relative abundance) 416 (100), 162 (47). Molecular ion calcd for $C_{13}H_6N_2I_2$, *m/e* 443.8623; found 443.8626. CDAF: mp 174–175 °C dec; ^{1}H NMR (CDCl$_3$) δ 7.29 (d of d, $J_1 = 8$ Hz, $J_2 = 2$ Hz, 2 H), 7.43 (d, $J = 2$ Hz, 2 H), 7.78 (d, $J = 8$ Hz, 2 H). Anal. Calcd for $C_{13}H_6N_2Cl_2$: C, 59.80; H, 2.32; N, 10.73; Cl, 27.15. Found: C, 60.10; H, 2.28; N, 10.89; Cl, 27.16. MS (10 eV), *m/e* (relative abundance) 232 (100), 197 (78). Molecular ion calcd for $C_{13}H_6N_2Cl_2$, *m/e* 259.9905; found 259.9901. FT–IR: (CHCl$_3$) 2068 cm^{-1}, diazo. BDAF: mp 177–178 °C dec; ^{1}H NMR (CDCl$_3$) δ 7.43 (d of d, $J_1 = 8$ Hz, $J_2 = 2$ Hz, 2 H), 7.62 (d, $J = 2$ Hz, 2 H), 7.74 (d, $J = 8$ Hz, 2 H). Anal. Calcd for $C_{13}H_6N_2Br_2$: C, 44.61; H, 1.73; N, 8.01 Br, 45.66. Found: C, 44.53; H, 1.76; N, 7.96; Br, 45.53. MS (10 eV), *m/e* (relative abundance) 322 (100), 243 (58), 162 (35). Molecular ion calcd for $C_{13}H_6N_2Br_2$, *m/e* 347.8894; found 347.8890.

Photolysis of XDAF (X = Cl, Br, I, H[8a]) in Methyl Alcohol, A nitrogen-purged solution of CDAF (1.37×10^{-3} M) in methyl alcohol (75.0 mL) was irradiated in a Rayonet photochemical reactor (350-nm lamps) until greater than 95% of the absorption of the diazo compound at 348 nm disappeared (47 min). Another sample was prepared similarly and used as a dark control. The solvent was removed from the samples under reduced pressure and the ^{1}H NMR spectra were taken with *p*-dioxane as an internal standard. 2,7-Dichlorofluorenyl methyl ether was the major product (90%). The products were separated with spinning-disk chromatography (silica gel). The dark control showed that there was no ether formation in the absence of light. Dichlorofluorenyl methyl ether: 90% yield; ^{1}H NMR (CDCl$_3$) δ 3.09 (s, 3 H), 5.54 (s, 1 H), 7.37 (d of d, $J_1 = 8$ Hz, $J_2 = 2$ Hz, 2 H), 7.55 (d of 8 Hz superimposed on another peak, 4 H). MS (70 eV), *m/e* (relative abundance) 229 (100), 214 (29), 264 (26). Molecular ion calcd for $C_{14}H_{10}OCl_2$, *m/e* 264.0114; found 264.0111. 2,7-Dichlorofluorene: 5% yield; ^{1}H NMR (CDCl$_3$) δ 3.88 (s, 2 H), 7.35 (d of d, $J_1 = 8$ Hz, $J_2 = 1$ Hz, 2 H), 7.51 (d, $J = 1$ Hz, 2 H), 7.65 (d, $J = 8$ Hz, 2 H). MS (70 eV), *m/e* (relative abundance) 199 (100), 234 (30), 163 (28). Molecular ion calcd for $C_{13}H_8Cl_2$, *m/e* 234.0004; found 234.000. 2,2′,7,7′-Tetrachloro-9-fluorenyl dimer: <4% yield; ^{1}H NMR (CDCl$_3$) δ 4.71 (s, 2 H), 7.3–7.6 (m, 12 H). MS (70 eV), *m/e* (relative abundance) 233 (100), 163 (19), 466 (8). Molecular ion calcd for $C_{26}H_{14}Cl_4$, *m/e* 465.9859; found 465.9854.

The procedure for photolysis of BDAF in methyl alcohol was identical with that described for CDAF. Dibromofluorenyl methyl ether: 89% yield; ^{1}H NMR (CDCl$_3$) δ 3.09 (s, 3 H), 5.54 (s, 1 H), 7.51 (m, 4 H), 7.73 (m, 2 H). MS (70 eV), *m/e* (relative abundance) 273 (100), 163 (57), 82 (52). Molecular ion calcd for $C_{14}H_{10}OBr_2$, *m/e* 351.9110; found 351.9104. 2,7-Dibromofluorene: 6% yield; ^{1}H NMR (CDCl$_3$) δ 3.88 (s, 2 H), 7.50 (d of d, $J_1 = 8$ Hz, $J_2 = 2$ Hz, 2 H), 7.61 (d, $J = 8$ Hz, 2 H), 7.67 (d, $J = 2$ Hz, 2 H). MS (70 eV), *m/e* (relative abundance) 243 (100), 324 (57), 82 (45). Molecular ion calcd for $C_{13}H_8Br_2$, *m/e* 321.8998 found 321.8995. 2,2′,7,7′-Tetrabromo-9-fluorenyl dimer: <4% yield; ^{1}H NMR (CDCl$_3$) δ 4.70 (s, 2 H), 7.5 (m, 12 H). MS (10 eV), *m/e* (relative abundance) 323 (100), 420 (49), 648 (17). Molecular ion calcd for $C_{26}H_{14}Br_4$, *m/e* 641.7797; found 641.7812.

The photolysis of IDAF in methyl alcohol also paralleled that described for CDAF except that the concentration of the diazo compound was reduced to (2.2×10^{-4} M) due to solubility limitations. The solution was degassed by freeze–pump–thaw cycles at 10^{-4} Torr. Diiodofluorenyl methyl ether: 93% yield; ^{1}H NMR (CDCl$_3$) δ 3.09 (s, 3 H), 5.51 (s, 1 H), 7.38 (d, $J = 8$ Hz, 2 H), 7.72 (d of d, $J_1 = 8$ Hz, $J_2 = 1$ Hz, 2 H), 7.92 (d, $J = 1$ Hz, 2 H). MS (10 eV), *m/e* (relative abundance) 448 (87), 321 (100). Molecular ion calcd for $C_{14}H_{10}OI_2$, *m/e* 447.8823; found 447.8825. 2,7-Diiodofluorene: 4% yield; ^{1}H NMR (CDCl$_3$) δ 3.85 (s, 2 H), 7.50 (d, $J = 8$ Hz, 2 H), 7.71 (d of d, $J_1 = 8$ Hz, $J_2 = 1$ Hz, 2 H), 7.88 (d, $J = 1$ Hz, 2 H); MS (10 eV), *m/e* (relative abundance) 57 (100), 164 (59). Molecular ion calcd for $C_{13}H_8I_2$, *m/e* 417.8713; found 417.8710.

Photolysis of XDAF (X = Cl, Br, I) in α-Methylstyrene, A nitrogen-purged solution of CDAF (3.83×10^{-3} M) and 2.0 M α-methylstyrene in CH$_3$CN (25 mL) was irradiated in a Rayonet photochemical reactor (350-nm lamps) until >95% of the absorption of the diazo compound at 354 nm had disappeared (85 min). 2,7-Dichlorocyclopropane: 79% yield; ^{1}H NMR (CDCl$_3$) δ 1.79 (s, 3 H, methyl), 2.09 (d, $J = 6$ Hz,

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1 H, cyclopropyl), 2,41 (d, $J = 6$ Hz, 1 H cyclopropyl), 5,84 (d, $J = 2$ Hz, 1 H, Ar), 6.53 (br d, 1 H, Ar), 7.1–7.8 (m, 9 H, Ar). MS (70 eV), m/e (relative abundance) 265 (100), 84 (78), 350 (69). Molecular ion calcd for $C_{22}H_{16}Cl_2$, m/e 350.0675; found 350.0670. 2,7-Dibromocyclopropane: 79% yield; ^{1}H NMR ($CDCl_3$) δ 1.78 (s, 3 H), 2.09 (d, $J = 6$ Hz, 1 H), 2.40 (d, $J = 6$ Hz, 1 H), 5.84 (d, $J = 2$ Hz, 1 H), 6.52 (br d, 1 H), 7.2–7.7 (m, 9 H). MS (70 eV), m/e (relative abundance) 265 (100), 440 (66), 280 (31). Molecular ion calcd for $C_{22}H_{16}Br_2$, m/e 437.9628; found 437.9623. 2,7-Diiodocyclopropane: 76% yield; ^{1}H NMR ($CDCl_3$) δ 1.7 (s, 3 H), 2.08 (d, $J = 6$ Hz, 1 H), 2.39 (d, $J = 6$ Hz, 1 H), 6.03 (d, $J = 1$ Hz, 1 H), 6.50 (br d, 1 H), 7.2–7.7 (m, 9 H). MS (10 eV), m/e (relative abundance) 265 (96), 534 (100). Molecular ion calcd for $C_{22}H_{16}I_2$, m/e 533.9340; found 533.9339. 2,2′,7,7′-Tetraiodo dimeric azine: 5% yield; mp >250 °C. Anal. Calcd for $C_{26}H_{12}N_2I_4$: C, 36.31; H, 1.41; N, 3.26. Found: C, 36.36; H, 1.61; N, 3.56. MS (70 eV), m/e (relative abundance) 860 (69), 733 (18), 324 (24). Molecular ion calcd for $C_{26}H_{12}N_2I_4$, m/e 859.7185; found 859.7191.

Triplet-Sensitized Irradiation of XDAF (X = H, Cl, Br, I) in the Presence of Methyl Alcohol. Four nitrogen-purged 5.0 M MeOH/CH_3CN solutions (25.0 mL) containing one of the XDAF (1.5×10^{-3} M for X = H, Cl, Br; 1.0×10^{-3} M for X = I) and 2,3-benzofluorenone (4.5×10^{-3} M) were prepared. The samples were individually irradiated (>398 nm) to completion (50 min) through a Corning 3-74 filter with a 200-W high-pressure mercury arc lamp. Under these conditions, nearly all the light is absorbed by the 2,3-benzofluorenone. The solvent was removed under vacuum. The ^{1}H NMR spectra were recorded with *p*-dioxane as internal standard. Three products were observed in each case. X = H: ether 84%, fluorene 7%, 9-fluorenyl dimer 4%. X = Cl: ether 26%, dichlorofluorene 9%, tetrachloro-9-fluorenyl dimer 22%. X = Br: ether 29%, dibromofluorene 6%, tetrabromo-9-fluorenyl dimer 20%. X = I: ether 28%, diiodofluorene 6%, tetraiodo-9-fluorenyl dimer 14%.

Triplet-Sensitized Irradiation of XDAF with α-Methylstyrene. Four N_2-purged solutions of α-methylstyrene (0.1 M) in CH_3CN (25 mL) and benzofluorenone were prepared and irradiated according to the procedure described above. The expected cyclopropanes are the major products (X = H, 95%; X = Cl, 94%; X = Br, >95%; X = I, 92%).

Irradiation of XDAF with (*E*)-α-Methyl-β-deuteriostyrene.[28a,b] Three N_2-purged solutions of the deuteriated styrene in CH_3CN (A, 0.1 M; B, 2.15 M; C, neat) containing CDAF (1×10^{-2} M) were prepared and irradiated (350 nm) until ca. 80% of the diazo compound was consumed (UV). The solvent was removed and the unreacted α-methylstyrene was collected by bulb-to-bulb distillation. The ^{1}H NMR spectra of the cyclopropanes is the same as for the undeuteriated sample except that the cyclopropyl protons appear as singlets. Integration of these spectra gives the stereochemical results reported above. The NMR spectrum of the recovered α-methylstyrene showed that no significant isomerization had occurred. A control experiment showed that cyclopropane formation required light. Similar experiments were performed for BDAF and for IDAF.

Triplet-Sensitized Photolysis of XDAF with (*E*)-α-Methyl-β-deuteriostyrene. Two N_2-purged solutions of the deuteriated styrene in CH_3CN (A, 0.1 M; B, 1.0 M) containing CDAF (1×10^{-2} M) and benzofluorenone were irradiated through a Corning 3-74 filter (>398 nm). After irradiation the solvent was removed and ^{1}H NMR spectra of the product and unreacted deuteriated methylstyrene were recorded. The unreacted styrene was not isomerized. An additional control experiment showed that the cyclopropanes are not isomerized by the reaction conditions. The stereochemistry of the cyclopropane product was determined from integration of the NMR spectrum. Retention of configuration was 0% for A and <5% for B. Similar experiments were carried out (0.1 M α-methylstyrene) for BDAF, IDAF, and DAF. For these three compounds, cyclopropane was formed with 0%, 0%, and 16% retention, respectively.

Triplet-Sensitized Competition between Methyl Alcohol and α-Methylstyrene. Four samples were prepared containing CDAF (1.5×10^{-3} M), benzofluorenone (4.5×10^{-3} M), methyl alcohol (5.0 M), and α-methylstyrene (0.03–0.3 M) in CH_3CN (25 mL). The samples were purged with N_2 and irradiated (>398 nm) for 50 min when >95% of the diazo compound was consumed (UV). The yields of the previously identified ether and cyclopropane products were determined by NMR spectroscopy and plotted as shown on Figure 4.

BDAF was similarly examined (α-methylstyrene 0.03–0.2 M) as was IDAF (9.0×10^{-4} M). For DAF the concentration of methyl alcohol was lowered to 1.0 M because at the higher concentration an insignificant yield of cyclopropane resulted. The results of these experiments are also shown on Figure 4.

Finally, a related competition experiment with the α-methylstyrene concentration held constant (0.1 M, X = Cl, Br; 1.0 M, X = H) and the methyl alcohol concentration varied (1.0–4.0 M, X = Cl, Br; 0.05–0.4 M, X = H) gives exactly analogous results.

Acknowledgment. Some preliminary experiments were performed by Maria Sweetser. This work was supported by the National Science Foundation. The University of Illinois ESR Research Center is supported by the National Institutes of Health (Grant RR01811),

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The Conformational Equilibrium of Chorismate in Solution: Implications for the Mechanism of the Non-Enzymic and the Enzyme-Catalyzed Rearrangement of Chorismate to Prephenate

Shelley D. Copley and Jeremy R. Knowles*

Contribution from the Department of Chemistry, Harvard University, Cambridge, Massachusetts 02138. *Received November 28, 1986*

Abstract: The temperature variation of the ^{1}H NMR coupling constants of chorismic acid and of the bis(tetra-*n*-butylammonium) salts of chorismate and of 4-*O*-methylchorismate in water and in methanol has been studied. The results show that 10–40% of each of these species is present in the pseudo-diaxial form in aqueous solution at 25 °C. In methanol solution, chorismate exists as the pseudo-diequatorial conformer. The rate of the Claisen rearrangement of chorismate is 100 times slower in methanol than in water, while the rearrangements of chorismic acid and of 4-*O*-methylchorismate are slowed by 11-fold and 7-fold, respectively. These results together suggest that the non-enzymic rearrangement of chorismate involves a dipolar transition state having some of the character of a tight ion pair between the enol pyruvate anion and the cyclohexadienyl cation. The relatively small difference in the free energies of the two conformers of chorismate in aqueous solution further suggests that the enzyme chorismate mutase can directly select the pseudo-diaxial conformer (from which the Claisen rearrangement occurs) from solution.

Chorismate (**1**) occupies a central position in the biosynthesis of the three aromatic amino acids and of a number of other metabolites in microorganisms and plants.[1] In the path to phenylalanine and tyrosine, chorismate undergoes what is formally

0002-7863/87/1509-5008$01.50/0