Tetrahedron Vol. 41, No. 8, pp. 1525 to 1530, 1985
Printed in Great Britain

0040–4020/85 $3.00 + .00
Pergamon Press Ltd.

FLASH PHOTOLYSIS STUDIES OF CARBENES AND THEIR IMPACT ON THE SKELL–WOODWORTH RULES[1]

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(*Received in USA* 20 *December* 1983)

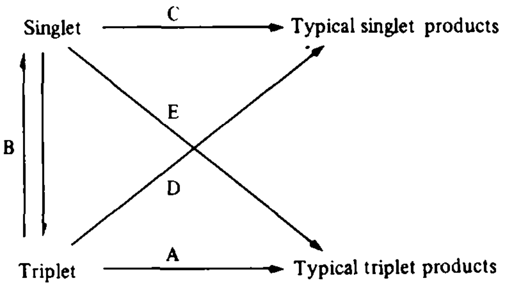
Abstract—The technique of flash photolysis has recently been applied to the study of carbene reaction kinetics and mechanisms. We review the impact of these studies on the Skell–Woodworth rules.

In 1959 Skell and Woodworth formulated a series of rules[2] which described the reactions of carbenes and which became a cornerstone of almost all subsequent studies in the field. In essence, the rules state that it is the spin state of a carbene which limits the kinds of reactions that it will undergo.

When singlet carbenes react with singlet substrates there is obviously no requirement for spin inversion before the final singlet product is formed. Hence, these carbenes should insert into single bonds and add stereospecifically to olefins, but they should not react with triplet molecules such as oxygen.

By contrast when triplet carbenes react with singlet substrates, spin inversion must occur before a product can be formed in its singlet state. Thus, attack at single bonds occurs by atom abstraction and leads to a triplet radical-pair. Olefin addition takes place with loss of stereochemistry (presumably reflecting a biradical mechanism) and reaction with oxygen is facile and concerted since there is a 1/9th probability that the combination of two triplet molecules will lead to a singlet product.

Over the last 7 years flash photolysis techniques have made it possible to monitor the optical absorption spectra and reaction kinetics of carbenes in solution. This in turn has allowed a more rigorous test of the Skell–Woodworth rules as described in Scheme 1.



Scheme 1.

Clearly the rules will be invalid if reactions D and E are commonplace. These possibilities are the subject of this article.

Designing experiments to test the Skell–Woodworth rules

Critical tests of the Skell–Woodworth rules should examine their applicability for different values of ΔH_{TS}, the energy gap between triplet and singlet states. When the singlet state is low lying, its high reactivity usually makes any triplet component insignificant. To the best of our knowledge, there are no examples of triplet-like reactions for carbenes with low lying singlet states.

When the triplet state is the ground state of the carbene, singlet reactivity can be observed under two distinct sets of conditions.

(a) Non-equilibrium conditions, where the singlet is produced at a concentration much higher than would be expected in equilibrium with the triplet.

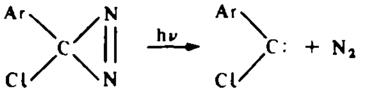
(b) Equilibrium conditions, where the singlet concentration will be determined by the free energy difference between the two carbene states. It has been frequently assumed that this term is dominated by the enthalpic term (ΔH_{TS}). Several situations can be encountered depending on the magnitude of ΔH_{TS}. If ΔH_{TS} is very large (e.g. >10 kcal/mol), the singlet population will be insignificant and only the triplet needs to be considered under equilibrium conditions. This is probably the case for dimesitylcarbene.[3] On the other hand, if ΔH_{TS} is small (i.e. comparable with a few kT), then thermal population of the upper singlet may be expected. This is probably the case for fluorenylidene[4,5] and 1-naphthylcarbene,[6] where singlet-like behaviour seems compatible with a thermally populated singlet state.

A somewhat different situation may arise for intermediate values of ΔH_{TS} (e.g. $5\ kT \leqslant \Delta H_{TS} \leqslant 10\ kT$). Here we expect triplet dominated chemistry; this may be the case of reaction of diphenylcarbene with olefins and hydrogen donors.[7] A new type of singlet-like behaviour may be possible in this case. Mixing of the T and S levels on route to products (i.e. an avoided surface crossing) could effectively lead to a reaction that from a kinetic point of view is indistinguishable from a "true" triplet insertion.[8] Such a crossing would presumably lead to low pre-exponential factors. Systems of this nature may represent the most critical test of the Skell–Woodworth rules.

The following sections discuss the different situations encountered in laser flash photolysis experiments.

Carbenes with singlet ground states

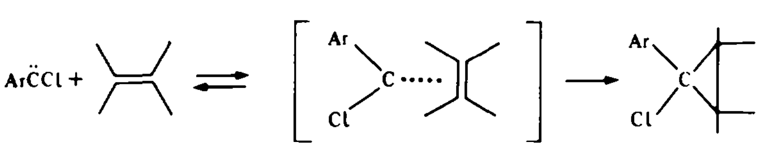
Arylchlorocarbenes are the only carbenes with singlet ground states which have, thus far, been investigated using flash photolysis techniques. The carbenes are formed by photolysis of their parent diazirenes (Eq. 1).[9] As is expected for singlet carbenes,



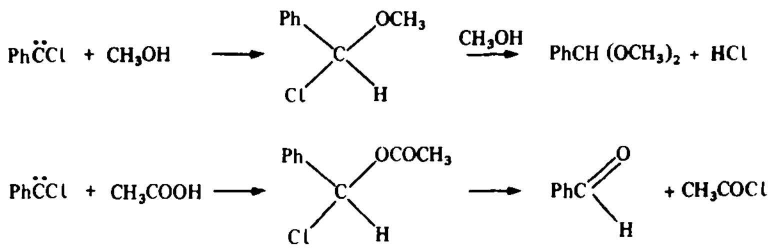
$$\mathrm{ArClC{<}N_2} \xrightarrow{h\nu} \mathrm{ArClC{:}} + \mathrm{N_2} \quad (1)$$

they do not show EPR signals when trapped in inert matrices and in solution do not react with oxygen. Their optical absorption spectra are quenched by olefins and the products of these reactions are cyclopropanes which are formed stereospecifically.[9,10]

The kinetics for olefin addition are rather unusual in that the reactions proceed with small and in some instances negative activation energies. These results were initially explained by invoking reversible formation of a carbene–olefin complex as a precursor to the final product (Eq. 2), although a subsequent explanation has dwelt on the possibility that entropy change is the dominant factor in the free energy of activation.[11]


(2)

Arylchlorocarbenes insert into the O—H bonds of alcohols and of carboxylic acids, e.g. Eqs 3 and 4. The reaction with acetic acid in isooctane is almost diffusion controlled ($k = 3.1 \times 10^9$ M^{-1} s^{-1})[12] and shows normal bimolecular kinetics. However, the reaction with methanol is not first order in methanol concentration. Careful analysis of the reaction kinetics has shown that the carbenes are far more reactive towards methanol oligomers than to monomer. For example, for *p*-anisylchlorocarbene the reaction kinetics are, to a good approximation, first order in oligomer concentration with k(oligomers) $= 4.3 \times 10^9$ M^{-1} s^{-1} (per MeOH unit) and k(monomer) $= 2 \times 10^7$ M^{-1} s^{-1} in isooctane.[13]


(3)
(4)

With t-butyl alcohol, the converse behaviour was observed with the monomer being the more reactive species presumably because the O—H bonds in the oligomers are sterically protected by the bulky t-butyl groups, i.e. k(monomer) $= 2.5 \times 10^6$ M^{-1} s^{-1}.[13] Interestingly, neopentyl alcohol is sufficiently unhindered to show methanol-like behaviour (high oligomer reactivity) (Fig. 1). The interaction of phenylchlorocarbene with 2,3-butanediol in isooctane shows clean first order behaviour within our error limits, with $k_q = 5.4 \times 10^7$ M^{-1} s^{-1}. Presumably, intramolecular H-bonding in dilute solution (<0.05 M) dominates its kinetic behaviour.

Thus, the laser flash photolysis approach has revealed fascinating and complex mechanisms for these apparently elementary reactions of the singlet carbene. However, despite these complexities the Skell–Woodworth rules survive intact and we know of no case where a singlet carbene has been shown to react forming "triplet-like" products (Scheme 1—reaction D).

Carbenes with triplet ground states

Carbenes with triplet ground states are normally generated by photolysis of their parent diazo compounds (Eq. 5). This process is thought to lead to

$$\mathrm{Ar_2CN_2} \xrightarrow{h\nu} \mathrm{Ar_2C{:}} + \mathrm{N_2} \quad (5)$$

the singlet excited state of the diazo compound which predominantly yields the singlet carbene as the primary product. Intersystem crossing then takes place to give the triplet (Eq. 6).

$$\mathrm{Ar_2C}{\uparrow\downarrow} \rightarrow \mathrm{Ar_2C}{\uparrow\uparrow} \quad (6)$$

The rate constant for singlet to triplet intersystem crossing has been measured for diphenylcarbene ($k = 9.1 \times 10^9$ s^{-1})[14] and fluorenylidene ($k = 3.6 \times 10^9$ s^{-1})[15] in acetonitrile as solvent but there have been no direct measurements of the rate constant for the reverse step.

Testing reaction A

There have been many demonstrations of reactions of type A (Scheme 1). For example, direct photolysis of diphenyldiazomethane ultimately gave the absorption spectrum of diphenylcarbene which was quenched efficiently by isoprene with low regiospecificity to give

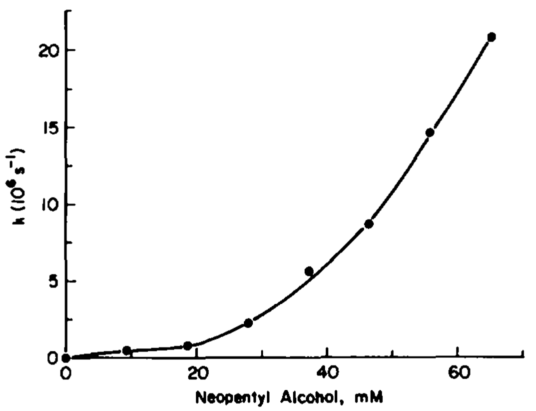
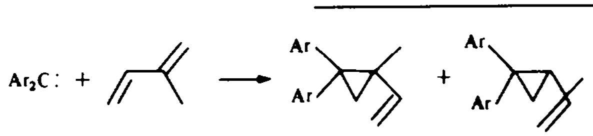


Fig. 1. Rate constants for the reaction of phenylchlorocarbene with neopentyl alcohol in isooctane solvent as a function of alcohol concentration.

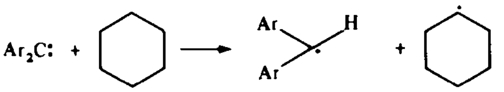


I **II**

(7)

cyclopropanes I and II (Eq. 7); $k_7 = 3.5 \times 10^5\ M^{-1}\,s^{-1}$. These were formed in the ratio 62:38.[14] The same product distribution was obtained when the carbene was formed by triplet sensitization of its parent diazo compound demonstrating that isoprene either did not intercept the singlet carbene or that triplet–singlet equilibration was fast in the time scale of the reaction.

The absorption spectrum of triplet diphenylcarbene was quenched relatively sluggishly by cyclohexane to yield the diphenylmethyl radical (Eq. 8),[7] whereas the analogous reaction with fluorenylidene[5] was far more brisk, with an overall rate constant $8.3 \times 10^7\ M^{-1}\,s^{-1}$. However, product studies on the fluorenylidene system in submillimolar solutions show very little dicyclohexyl and 9,9′-*bis*-fluorenylidene but produce a very high yield of III (Eq. 9). This result led to the conclusion that the abstraction process being observed by flash photolysis represented a minor reaction pathway and that the major reaction involved triplet to singlet intersystem crossing followed by insertion of the singlet into the C—H bond of the cycloalkane. Of course, this conclusion assumes the validity of the Skell–Woodworth rules and implies that the triplet–singlet energy gap is small enough for there to be significant population of the latter at ambient temperatures. However, the experimental observations would be equally consistent with a competition between A and D reactions.



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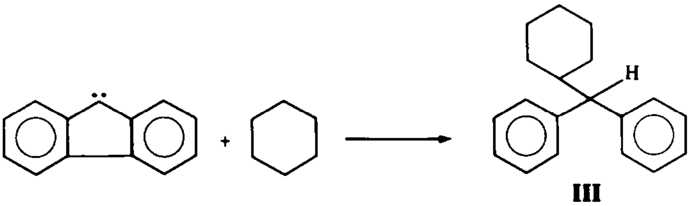


III

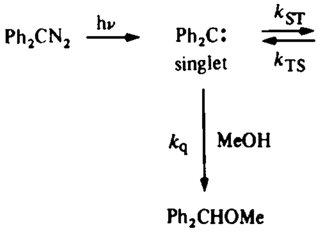
(9)

Tests of mechanisms 'B plus C' versus D

The reactions of most diarylcarbenes with methanol, nitriles and ketones present similar difficulties to those described above. For example, the optical absorption spectrum of triplet diphenylcarbene is quenched by methanol,[8] a substrate in its singlet state, and yields the normal "insertion" product. This property was first recognized by Bethell *et al.*[16] who deduced that this reaction was taking place from product studies. These authors carefully pointed out that the experimental evidence did not allow a differentiation between a B plus C mechanism versus that of D (Scheme 1). However, it was subsequently assumed that the Skell–Woodworth rules applied in this situation and therefore that the B plus C mechanism was operative.

Schemes based on this hypothesis were developed to measure the energy gap between the triplet and singlet states of the carbene (Scheme 2). The rate constant for the reaction of the singlet carbene with methanol in CH_3CN was calculated by using the known rate of singlet-to-triplet intersystem crossing[14] combined with a Stern–Volmer approach and was found to be $5 \times 10^{10}\ M^{-1}\,s^{-1}$. Now measurements of the rate constant for triplet quenching by methanol yield the equilibrium constant relating the singlet and triplet states, since Eq. 10 must necessarily apply if the reaction occurs exclusively by the B plus C route.

$$k_{obs} = k_q/K_{eq} \qquad (10)$$

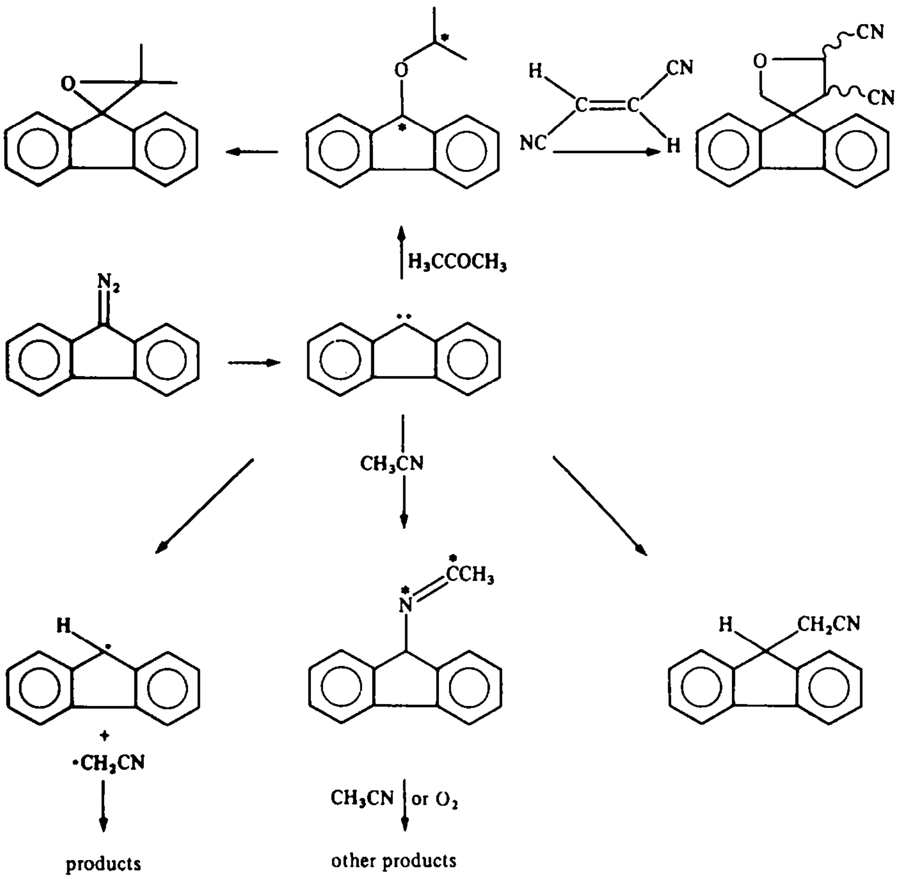


Scheme 2.

The values obtained were $k_{obs} = 2.6 \times 10^7\ M^{-1}\,s^{-1}$ and hence $K = 1.4 \times 10^3$.[8] On the assumption that the only entropy difference between the spin states of the carbene is due solely to the electronic degeneracy of the triplet, the enthalpy gap between the states was calculated to be 4.3 kcal mol^{-1}.

It was possible to check this conclusion by the simple expedient of measuring the activation energy for methanol quenching of the triplet carbene. Following Eq. 10, this should have been equal to the enthalpy difference between the states plus the activation energy for the reaction of the singlet with methanol. Since the latter is an essentially diffusion controlled process, its activation energy must be *ca* 2 kcal mol^{-1}. Thus the overall activation energy should have been *ca* 6–8 kcal mol^{-1}. In fact, the measured values were much lower being 3.6, 2.5, 1.7 and 1.2 kcal mol^{-1} in isooctane, chlorobenzene, acetonitrile and benzene respectively as the solvents, and in all cases the expected ether was formed in >90% yield.[8]

The obvious implication of these results is that the B plus C combination is not operative. Mechanism D offers a more likely explanation; now the activation



(11)

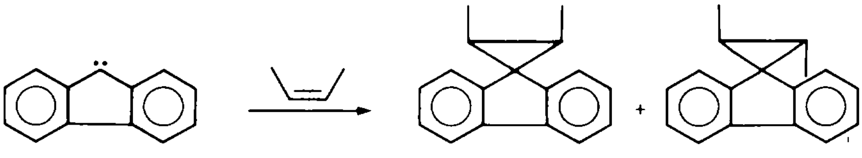
energies simply pertain to the type D process. In essence, when the triplet carbene and a molecule of methanol move along the reaction coordinate, mixing between the triplet and singlet manifolds becomes possible so that the product is formed in its singlet state. Of course, state mixing induced by the substrate molecule will presumably be most effective if the true energy gap between the states of the carbene is small. The rather large solvent effects of the reaction lend some credibility to this view.

It should be carefully noted that the above interpretation of the reaction kinetics is evidence in favour of a type D mechanism. Any interpretation which clings to the Skell–Woodworth rules and seeks to explain the data in terms of a major solvent effect on the triplet–singlet energy gap, is confronted with serious difficulties with the self-consistency of the activation energies and A factors which have been discussed in considerable detail elsewhere.[8] Independent picosecond experiments also suggest that excited triplet diphenylcarbene reacts readily with methanol in apparent violation of the rules of spin-conservation.[17]

The same dilemma applies to the reactions of diarylcarbenes with nitriles and ketones, molecules which again quench the optical absorption spectra of the triplet carbenes (see Eq. 11 for examples of the chemistry involved).[5,6,18]

In these cases, kinetic investigations have not dealt with the temperature dependencies of the reactions and therefore allow no discrimination between the D *vs* type B plus C mechanisms. However, there are two pieces of evidence which suggest that when the energy gap between the spin states of the carbenes are sufficiently small, substrates and solvents may have profound effects on the relationships between the states.

First, careful labelling studies on the reactions of diphenylcarbenes with amines show that while reaction of the initially formed singlet state with the amine is rapid, reaction of the triplet, through a B plus C mechanism, does not take place even though this mechanism has been invoked to explain the closely related reaction of the triplet with methanol.[19]



(12)

IV **V**

Secondly, the reaction of fluorenylidene with *cis*-2-butene in acetonitrile as solvent Eq. 12 yields IV and V in the ratio 2 : 1 at all concentrations of olefin. Whereas when the hexafluorobenzene is used as solvent the ratio changes to 0.3[20] implying that rate constants for the intersystem crossing processes are strongly dependent on subtle changes in the reaction conditions making it difficult to apply the Skell–Woodworth rules with confidence in situations where the gap is small.

One solution to this dilemma is to search for carbenes in which the triplet–singlet gap is large and to test for their compliance with the rules. Some years ago, Zimmerman and Paskovich[21] suggested that dimesitylcarbene was such a case. Recent EPR[22] and laser flash photolysis studies[3] bear out their conclusions.

EPR studies of dimesitylcarbene, both in glasses and in single crystals[22] of its diazo compound suggest that it has a structure in which the aryl groups are orthogonal and which is far closer to linear than that of diphenylcarbene for which the central C—C—C angle is 148°.[23] This structural difference is presumably due to the steric influence of the *ortho* methyl groups. However, it has important electronic consequences.

Theory indicates that opening the central C—C—C angle in diphenylcarbene requires little energy (*ca* 3 kcal mole^{-1}).[24] Thus the triplet state of dimesitylcarbene will not be substantially destabilized with respect to that of diphenylcarbene. However, the same structural change dramatically destabilizes the singlet state which has both electrons in the same orbital. Thus the triplet-single gap in dimesitylcarbene ought to be substantially greater than that in diphenylcarbene.

It should be noted that the singlet state in which the electrons are in separate orthogonal orbitals with antiparallel spins will become increasingly stabilized as the carbene tends towards linearity.[24] However, even if such a state becomes the singlet ground state, it will probably resemble the triplet in its reactivity since it is electronically quite different from the singlet state which has both electrons in the same orbital and uses them in concert as a lone pair.

The chemistries of the triplet and "lone pair" singlet state of dimesitylcarbene conform exactly to the predictions of the Skell–Woodworth rules. Thus the triplet carbene dimerizes to form the sterically congested olefin in preference to reacting with the parent (singlet) diazo compound to form an azine. Hydrogen abstraction takes place in competition with dimerization even when good hydrogen donors such as cyclopentane are used as solvent. The same behaviour is observed for olefin addition which takes place with loss of stereochemistry. In this reaction the carbene is generated by photolysis of its parent diazo compound and as expected the ratio of dimer to cyclopropanes increases with increasing light intensity as expected for a bimolecular reaction in competition with a pseudo-first order reaction (Eqs 13–15).

$$(Mes)_2CN_2 \xrightarrow{h\nu} (Mes)_2C: + N_2 \qquad (13)$$

$$(Mes)_2C: + (Mes)_2C: \rightarrow (Mes)_2C{=}C(Mes)_2 \qquad (14)$$

All of the above reactions of triplet dimesitylcarbene proceed far more slowly than those of diphenylcarbene and since this effect cannot be due to thermodynamic stabilization, we must conclude that dimesitylcarbene is relatively persistent.[3]

Triplet dimesitylcarbene reacts readily with oxygen since this is a spin allowed triplet–triplet reaction which leads to a singlet product (Eq. 16). However, unlike other diarylcarbenes it does not react with alcohols, ketones or nitriles implying a consistency with the

$$(Mes)_2C: + O_2 \rightarrow (Mes)_2COO \qquad (16)$$

$$(Mes) \equiv 2,4,6\text{-trimethylphenyl}$$

Skell–Woodworth rules which has not previously been observed. That is, the triplet state cannot access the singlet manifold by either B plus C or D mechanisms.

Stern–Volmer type experiments show that the singlet state of dimesitylcarbene is quenched readily by alcohols and nitriles (Eq. 17).

$$\begin{aligned}&(Mes)_2C: + MeOH \rightarrow (Mes)_2CHOMe\\&(Mes)_2C: + CH_3CN \rightarrow (Mes)_2\bar{C}{-}\overset{+}{N}{\equiv}CCH_3\end{aligned} \qquad (17)$$

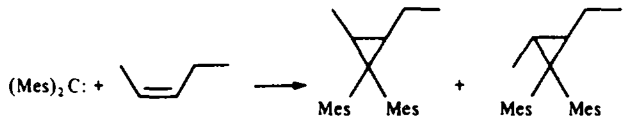
The rate constant for the reactions with methanol and acetonitrile has been measured relative to that for singlet to triplet intersystem crossing which must be $> 10^8$ s^{-1} since it occurs within the laser pulse width (8 ns). As a result they can only be reported as lower limits, *viz* $k = 2 \times 10^7$ M^{-1} s^{-1} and 8×10^6 M^{-1} s^{-1}. Thus it would seem that when the triplet–singlet energy gap is sufficiently large, at least one diarylcarbene conforms exactly to the Skell–Woodworth predictions.

An obvious extension of this idea is to seek carbenes which have structures intermediate between those of diphenylcarbene and dimesitylcarbene. The two simplest choices would be mesitylphenyl and mesityltolylcarbene.[25] EPR studies on these carbenes in various matrices suggest that their structures are, indeed, intermediate between those of diphenylcarbene and dimesitylcarbene as judged by their *D* and *E* parameters, the trend towards linearity being diphenyl < mesitylphenyl < mesityltoluyl < dimesitylcarbene.

Laser flash photolysis of mesitylphenyldiazomethane and mesityltolyldiazomethane in acetonitrile or isooctane gave absorption spectra with $\lambda_{max} = 320$ nm. These were assigned to the triplet carbenes. At 25° in isooctane, the carbenes had the following lifetimes: mesitylphenylcarbene (20 μs) and mesityltolylcarbene (90 μs) and lie intermediate between dimesitylcarbene (200 μs) and diphenylcarbene (1.7 μs). Unlike dimesitylcarbene, the signals due to both mesitylphenyl and mesityltoluylcarbene are quenched by added methanol. The observed rate constants are more than 2 orders of magnitude slower than those observed for diphenylcarbene.

SUMMARY

Laser flash photolysis studies of carbene reaction kinetics have revealed a variety of unusual and



(15)

fascinating reaction mechanisms. For carbenes, where the energy separation between singlet and triplet states is large, the chemistry of the ground state conforms to the predictions of the Skell–Woodworth rules. However, when the separation between the states is smaller such sharp distinctions do not apply and conformity with the rules is questionable.

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