adamantane were obtained from the calibration curve. The relative rate constants, $k_{\text{syn-X}}/k_H$ and $k_{\text{anti-X}}/k_H$, were determined on the basis of the relative amounts of products found and were corrected statistically. These results are shown in Table II.

**Supplementary Material Available:** Table IV showing the carbon-13 chemical shifts of syn- and anti-4-substituted 1-acetyladamantanes (1 page). Ordering information is given on any current masthead page.

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# Relative Rates of the Reaction of (Ethoxycarbonyl)carbene with Several Aromatic and Heteroaromatic Compounds. Selectivity and Mechanism

Martin Pomerantz* and Peter Rooney

*Department of Chemistry, The University of Texas at Arlington, Arlington, Texas 76019-0065*

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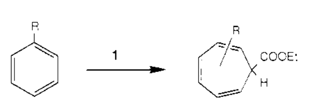
The relative rates of reaction of (ethoxycarbonyl)carbene (1), formed by the thermal decomposition of ethyl diazoacetate (2), with toluene, anisole, phenanthrene, pyridine, quinoline, acridine, furan, benzofuran, dibenzofuran, thiophene, benzothiophene, dibenzothiophene, pyrrole, indole, carbazole, fluorene, 1,2-dimethoxybenzene, 1,4-dimethoxybenzene, 1,2,4-trimethoxybenzene, 1-methoxynaphthalene, 2-methoxynaphthalene, 2,6-dimethoxynaphthalene, and 2,7-dimethoxynaphthalene versus naphthalene at 150 °C were measured. The relative rate data for the four series toluene, naphthalene, and phenanthrene, the furans, the thiophenes, and the pyrroles are consistent with direct addition of 1 to the aromatic ring systems. Significantly, the more nucleophilic ring systems show a selectivity of up to a factor of about 100 relative to the simple benzene derivative toluene. The pyridine, quinoline, acridine series appears to react with 1 by an ylide mechanism, and in these cases, the selectivities are even larger, up to about 150 relative to toluene. Thus, unlike the reaction of 1 with a series of substituted benzenes, where the selectivity is fairly modest, the heteroaromatic systems studied here show selectivities that are quite large. Methoxy substitution on benzene and naphthalene gives rise to only limited increases in selectivity with one or two groups on the ring system; however, 1,2,4-trimethoxybenzene shows a significantly increased selectivity. Experiments using isooctane as the solvent showed a small selectivity decrease, which is consistent with either a complex of 1 with hexafluorobenzene acting as the reactive intermediate or, perhaps more likely, a possible solvent effect involving a polar transition state. Kinetic measurements were consistent with carbene formation being the rate-determining step in these reactions.

## Introduction

The reaction of carbenes, especially (ethoxycarbonyl)carbene (1), formed by the thermal, photochemical, or catalytic decomposition of ethyl diazoacetate (2; eq 1) with a large variety of organic compounds is quite well-known.[1] The thermal decomposition of 2 in the presence of a series of monosubstituted benzenes to form 7-carbethoxycyclohepta-1,3,5-trienes (3; eq 2) was shown to proceed selectively with a Hammett $\rho$ value of $-0.38$ relative to benzene, which demonstrates somewhat preferential addition of the electrophilic carbene to the more electron rich aromatic molecules.[2] The relative rates of this series of aromatic molecules were measured competitively relative to benzene as the standard. The Rh(II)-catalyzed decomposition of 2 in the presence of several substituted benzenes also showed preference for addition to the more electron rich molecules.[3] Table I shows the comparison of the relative reactivity of 1, produced thermally or catalytically, toward several substituted benzenes, all relative to benzene as the standard.[2,3]

$$\underset{2}{N_2CHCOOEt} \xrightarrow[\Delta]{} N_2 + \underset{1}{:CHCOOEt} \qquad (1)$$



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(2)

**Table I. Relative Reactivities of Substituted Aromatic Compounds with 1**

| substrate | Rh(II)[a] | thermal[b] |
|---|---|---|
| (trifluoromethyl)benzene | | 0.55 |
| chlorobenzene | 0.1 | 0.84 |
| fluorobenzene | 0.46 | 0.80 |
| benzene | 1.0 | 1.0 |
| toluene | 1.10 | 1.06 |
| anisole | 1.16 | 1.15 |
| *o*-xylene | 1.6 | |
| *m*-xylene | 1.20 | |
| *p*-xylene | 1.0 | |

[a] Rhodium(II) trifluoroacetate catalyzed, ref 3. [b] Temperature 129.6 °C, ref 2.

It appears that carbene 1 is somewhat selective and that the carbene species produced in the catalyzed reaction is a little more selective than that produced in the thermal reaction.

For the thermal decomposition of 2 in the presence of 2,6-dimethylnaphthalene in competition with naphthalene, it was found that the partial rate factor for the addition of 1 was 1.4 for the 1,2-bond and 4.2 for the 3,4-bond relative to the 1,2-bond of naphthalene (eq 3).[4] Thus, once again, one can conclude that carbene 1 is somewhat selective, and in this case there is also a positional selectivity.

A search of the literature reveals no study of the selectivity of carbene 1 toward fused aromatics, heteroaromatics, and benzo-fused aromatics. In this paper we

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[1] For reviews, see: (a) Kirmse, W. *Carbene Chemistry*, 2nd ed.; Academic: New York, 1971. (b) Marchand, A. P.; MacBrockway, N. *Chem. Rev.* **1974**, *74*, 431. (c) Dave, V.; Warnhoff, E. W. *Org. React.* (*N.Y.*) **1970**, *18*, 217.

[2] Baldwin, J. E.; Smith, R. A. *J. Am. Chem. Soc.* **1967**, *89*, 1886.

[3] Anciaux, A. J.; Demonceau, A.; Noels, A. F.; Hubert, A. J.; Warin, R.; Teyssie, P. *J. Org. Chem.* **1981**, *46*, 873.

[4] Huisgen, R.; Juppe, G. *Tetrahedron* **1961**, *15*, 7.

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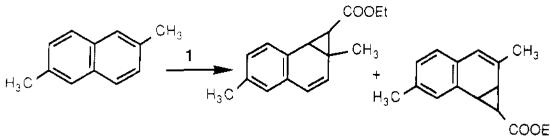

(3)

report the relative reactivity of 1, produced by the thermal decomposition of 2, with toluene, anisole, phenanthrene, pyridine, quinoline, acridine, furan, benzofuran, dibenzofuran, thiophene, benzothiophene, dibenzothiophene, pyrrole, indole, carbazole, fluorene, and several methoxy-substituted aromatics all versus naphthalene. This work not only provides much needed data on the selectivity of thermally produced carbene 1 but also provides required information which we will use in our studies of the reaction of carbene 1 with coal.[5] Since each of these compounds has been identified in various coal extracts,[6] the knowledge of which type of molecules react fastest should prove useful in determining the mechanism(s) of the formation of increased volatiles and solvent extractables from coals treated with 2.

## Results and Discussion

Generation of carbene 1 from ethyl diazoacetate (2) in the presence of two aromatic substrates x and y in an inert solvent creates a competitive system from which the relative rates may be obtained by standard treatment of first-order rate equations.[7] If $x_1$ and $y_1$, the concentrations of x and y at time $t_1$, are known, the relative rate of the reaction of x and y may be written as shown in eq 4, where $x_0$ and $y_0$ are the initial concentrations of x and y respectively.

$$k_{\mathrm{rel}} = k_x/k_y = \log (x_1/x_0)/\log (y_1/y_0) \qquad (4)$$

In principle, these data may be determined by measuring the extent of disappearance of x and y at time $t$ or by measuring the appearance of products at time $t$ due to the reaction of x and y with 1. For reactions in which several isomeric products may be formed, the former is preferred and was adopted here. Product analysis was by capillary gas chromatography. The solvent chosen for these competitive experiments was hexafluorobenzene. Although there is evidence in the literature for small amounts of reaction of hexafluorobenzene with carbene 1 under catalytic[3] and photolytic[8] conditions, there is nothing concerning its thermal reaction. In the present study, if reaction of 1 with the solvent did occur, it did not seem to present a problem. Solutions that were 0.05 M in each of the two competing aromatics and 0.063 M in the carbene precursor could be prepared, reacted, and analyzed conveniently. Attempts to use Freon E-4 (Du Pont), as did Baldwin and Smith[2] in their study of substituted benzenes, were unsuccessful due to the low solubility of the aromatics in this solvent.

In each case the carbene precursor, 2, was decomposed at 150 °C in the presence of the competing aromatics in a sealed tube for approximately 12 h. Control experiments using a 10-fold excess of 2 in hexafluorobenzene showed no detectable diazo absorption by FTIR when the solution was heated in a sealed tube at 150 °C for 30 min. Each experiment was done in triplicate, and each of the three reaction tubes was analyzed by GC with a minimum of three injections. For each of the nine (or more) injections, a separate $k_{\mathrm{rel}}$ was determined by using eq 4. The average of each of these values was then used in reporting $k_{\mathrm{rel}}$ (Table II).

**Table II. Relative Rate Ratios for the Reaction of 1 versus Naphthalene at 150 °C**

| substrate | $k_{\mathrm{rel}}$ |
|---|---|
| toluene | 0.24 |
| anisole | 0.25[a] |
| naphthalene | 1.0 |
| phenanthrene | 1.8 |
| pyridine | 21[b] |
| quinoline | 27 |
| acridine | 37 |
| thiophene | 1.5 |
| benzothiophene | 1.0 |
| dibenzothiophene | 0 |
| furan | 14 |
| benzofuran | 2.9 |
| dibenzofuran | 0.79 |
| pyrrole | 23 |
| indole | 12 |
| carbazole | 7.5 |
| fluorene | 0.17 |
| 1,2-dimethoxybenzene | 0.48 |
| 1,4-dimethoxybenzene | 0.63 |
| 1,2,4-trimethoxybenzene | 2.4 |
| 1-methoxynaphthalene | 1.5 |
| 2-methoxynaphthalene | 1.3 |
| 2,6-dimethoxynaphthalene | 1.5 |
| 2,7-dimethoxynaphthalene | 1.5 |

[a] Calculated by using $k_{\mathrm{anisole}}/k_{\mathrm{toluene}} = 1.03$ (see text). [b] Corrected for ca. 8% decomposition; see Experimental Section.

The mean standard deviation for all sets of data was calculated to be ±1.5% of the set means. The best sets of data points were ±0.5%. The worst sets were ±4.8%. This is consistent with Baldwin and Smith's reported values of ±1.5%, ±0.5%, and ±6.6% respectively. The mean standard deviation of the reported $k_{\mathrm{rel}}$ values in our experiments was ±27% due to the log function operating on the small molarity values. No values for the mean standard deviation of the relative rate data are reported by Baldwin and Smith for comparison.

A control experiment of anisole versus toluene showed $k_{\mathrm{rel}} = 1.03$, which is consistent with $k_{\mathrm{rel}} = 1.08$ reported by Baldwin and Smith. Attempts at control experiments utilizing benzene were unsuccessful due to the inability to separate it from the solvent hexafluorobenzene by GC.

For the aromatic series toluene, naphthalene, and phenanthrene, it is seen that the order of reactivity increases modestly with increasing ring fusion. This is consistent with the fact that the delocalization energy of the 1,2-bond in each is decreased with additional fused aromatic rings[9] and with the fact that there is less aromatic stabilization energy per electron as more fused rings are added.[10] For example, benzene, naphthalene, and phenanthrene have SCF-MO calculated 1,2-bislocalization energies of 3.46, 2.68, and 2.15 $\beta$, respectively.[9] This means that the 1,2-bond in phenanthrene is weaker and, therefore,

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[5] Pomerantz, M.; Rooney, P. *Energy Fuels* **1987**, *1*, 401.

[6] For example, see: (a) Lumpkin, H. E.; Aczel, T. In *Organic Chemistry of Coal*; Larsen, J. W., Ed.; American Chemical Society: Washington, DC, 1978; Chapter 16. Schweighardt, F. K.; White, C. M.; Friedman, S.; Schultz, J. L. In *Ibid.* Chapter 18. (b) Farcasiu, M. In *Coal Structure*; Gorbaty, M. L., Ouchi, K., Eds.; American Chemical Society: Washington, DC, 1981; Chapter 10. Winans, R. E.; Hayatsu, R.; McBeth, R. L.; Scott, R. G.; Moore, L. P.; Studier, M. H. In *Ibid.* Chapter, 11. (c) Boudou, J. P.; Boulegue, J.; Malechaux, L.; Nip, M.; deLeeuw, J. W.; Boon, J. J. *Fuel* **1987**, *66*, 1558.

[7] Russell, G. A. In *Technique of Organic Chemistry*, 2nd ed.; Friess, S. L., Lewis, E. S., Weissberger, A., Eds.; Interscience: New York, 1961; Chapter VIII.

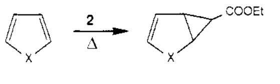
[8] Gale, D. M. *J. Org. Chem.* **1968**, *33*, 2536.

[9] (a) Dewar, M. J. S.; Dougherty, R. C. *The PMO Theory of Organic Chemistry*; Plenum: New York, 1975; pp 150–151. (b) Dewar, M. J. S. *J. Am. Chem. Soc.* **1952**, *74*, 3357.

[10] (a) Carey, F. A.; Sundberg, R. J. *Advanced Organic Chemistry—Part A: Structure and Mechanisms*, 2nd ed.; Plenum: New York, 1984; pp 475–477. (b) Dewar, M. J. S.; deLlano, C. *J. Am. Chem. Soc.* **1969**, *91*, 789.

should be more reactive than the 1,2-bond in benzene. Attempts to experimentally determine $k_{rel}$ of anthracene versus naphthalene failed due to the extremely low solubility of anthracene in hexafluorobenzene. However, it is reasonable to expect that anthracene would be qualitatively similar to phenanthrene since Dewar calculates anthracene to have a 1,2-bislocalization energy of 2.16 $\beta$ (similar to that of phenanthrene above).[9]

The thermal decomposition of **2** in the presence of thiophene,[11,12] benzothiophene,[13-15] furan,[16] and benzofuran[11,15] to give the cyclopropanated products (eq 5, 6; X = S, O) is well established. In addition, benzothiophene has been reported to also react by cyclopropanation of the benzene ring (eq 7).[17]



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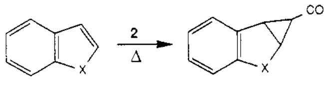

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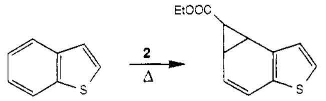
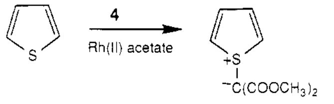


(7)

For the thermal reaction of **2** with benzofuran, the mechanism suggested involves the direct addition of carbene **1** to the enol-ether-type double bond.[1] Our relative rate data (Table II) is consistent with this mechanism. Comparison of furan, benzofuran, and dibenzofuran indicates that reactivity is related to the number of reactive enol-ether-type double bonds. Also, since fluorene is very slightly less reactive than toluene, and anisole is slightly more reactive than toluene (Table II), one would have expected dibenzofuran to be somewhat less reactive than it actually is. The origin of this enhanced reactivity is not apparent.

Although the mechanism of the reaction of **2** with thiophene has not been definitely established, the observations that cyclopropanes form (eq 5 and 6)[11-16] and that a cyclopropane far removed from the sulfur forms in one case (eq 7)[17] suggest that the mechanism is a direct carbene addition to a double bond. No ylides have been observed in reactions of **2** with thiophene molecules.[18] When dimethyl diazomalonate [**4**; $N_2C(COOCH_3)_2$] reacts with thiophene in the presence of rhodium(II) acetate, however, an ylide is isolated (eq 8).[18] The ylide negative charge here



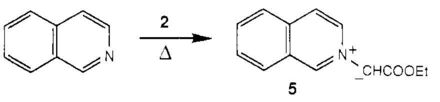
(8)

is stabilized by two ester groups. When the ylide is less stabilized than that shown in eq 8, it cannot be observed. Also, when electron-donating substituents are put on the thiophene ring, the ylides are formed in high yields, but when electron-withdrawing substituents are used, there is no reaction with **4**.[18] Further, as mentioned above, when only one ester is present to stabilize the ylide (use of **2** rather than **4**), no ylide is observed. Thus, a mechanism of direct cyclopropanation of thiophenes by carbene **1** seems most reasonable. If this is indeed the case, then as expected, the relative rates of thiophene, benzothiophene, and dibenzothiophene are seen to parallel those of the furan series.

In the pyrrole, indole, carbazole series, once again, the order is the same also suggesting a similar mechanism. One of the most significant observations is that the selectivity of (ethoxycarbonyl)carbene (**1**) is about 100-fold relative to toluene, a simple benzene derivative. Pyrroles and indoles are known to undergo $\alpha$-substitution[19] and $\beta$-substitution[13,20,21] to produce (ethoxycarbonyl)methyl derivatives (C–H insertion type products) while in a few cases cyclopropanes are formed.[22] Indeed, a number of pyrrole–carbene reactions are postulated to go through cyclopropanes which rearrange or ring-expand[1] while others are suggested to go through direct electrophilic substitution.[21] In no case, however, has an ylide been shown to be an intermediate.

The order from one heteroatom series to the other (pyrroles, furans, and thiophenes) is exactly the sequence observed in various reactions where electron donation is important from the heteroatom. Thus, for example, electrophilic aromatic substitution rates are in the order $PhNR_2 > PhOR > PhSR$.[23] This points out the electrophilic nature of the carbene and underscores the fact that (ethoxycarbonyl)carbene (**1**) can be quite selective with the right system. While our data clearly shows that the more nucleophilic the ring system, the greater the selectivity, there is no compelling reason at this time to choose either the direct, one-step, polar cyclopropanation mechanism or the two-step electrophilic substitution mechanism[21] over the other.

There is one series that appears anomalous, however, and that is pyridine, quinoline, and acridine. Since the nitrogen in these systems renders them less reactive in reactions such as electrophilic aromatic substitution, it would be expected that these compounds react more slowly than their carbocyclic counterparts with carbene **1**. However, they react from 20 to about 100 times faster! This strongly suggests an alternative mechanism for reaction. Although the reaction of **2** with pyridine and quinoline in the presence of $CuSO_4$ gives the 3-ethoxycarbonyl derivatives,[24] the thermolysis of **2** with isoquinoline provided the stable ylide **5**[25] shown in eq 9. This



**5**
(9)

suggests that the alternative mechanism likely involves

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(11) Steinkoph, W.; Augestad-Jensen, H. *Justus Liebigs Ann. Chem.* **1922**, *428*, 154.

(12) Gillespie, R. J.; Porter, A. E. A. *J. Chem. Soc., Perkin Trans. 1* **1979**, 2624.

(13) Badgen, G. M.; Christie, B. J.; Rodda, H. J.; Pryke, J. M. *J. Chem. Soc.* **1958**, 1179.

(14) Wenkert, E.; Alonso, M. E.; Gottlieb, H. E.; Sanchez, E. L.; Pellicciari, R.; Cogolli, P. *J. Org. Chem.* **1977**, *42*, 3945.

(15) Badger, G. M.; Rodda, H. J.; Sasse, J. M. *J. Chem. Soc.* **1958**, 4777.

(16) (a) Schenck, G. O.; Steinmetz, R. *Justus Liebigs Ann. Chem.* **1963**, *668*, 19. (b) Nefedov, O. M.; Shostakovsky, V. M. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 646. (c) Wenkert, E.; Bakuzis, M. L. F.; Buckwalter, B. L.; Woodgate, P. D. *Synth. Commun.* **1981**, *11*, 533.

(17) (a) Sullivan, D.; Pettit, R. *Tetrahedron Lett.* **1963**, 401. (b) Turnbo, R. G.; Sullivan, D. L.; Pettit, R. *J. Am. Chem. Soc.* **1964**, *86*, 5630.

(18) Gillespie, R. J.; Murray-Rust, J.; Murray-Rust, P.; Porter, A. E. A. *J. Chem. Soc.* **1978**, 83.

(19) Nenitzescu, C. D.; Solomonica, E. *Ber. Dtsch. Chem. Ges. B* **1931**, *64*, 1924.

(20) Maryanoff, B. E. *J. Heterocycl. Chem.* **1977**, *14*, 177.

(21) Maryanoff, B. E. *J. Org. Chem.* **1979**, *44*, 4410.

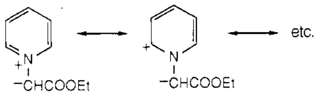
(22) Fowler, F. W. *J. Chem. Soc., Chem. Commun.* **1969**, 1359.

(23) Norman, R. O. C.; Taylor, R. *Electrophilic Substitution in Benzenoid Compounds*; Elsevier: Amsterdam, 1965; Chapters 2 and 5. Ingold, C. K. *Structure and Mechanism in Organic Chemistry*, 2nd ed.; Cornell University: Ithaca, New York, 1969; Chapter 6.

(24) Marolt, V.; Stanovnik, B.; Tisler, M.; Vercek, B. *Vestn. Slov. Kem. Drus.* **1978**, *25*, 265; *Chem. Abstr.* **1978**, *89*, 179821*f*.

(25) Zugravescu, I.; Rucinschi, E.; Surpateanu, G. *Tetrahedron Lett.* **1970**, 941.

ylides. If one assumes that steric problems are not important, then a comparison of ylides **6**, **7**, and **8** (eq 10, 11, and 12) reveals that the stability is **8** > **7** > **6** since more resonance forms involving delocalization of the positive charge onto the aromatic ring carbons can be drawn for **8** than for **7** and more for **7** than for **6**. Thus, acridine can react faster than quinoline and pyridine.



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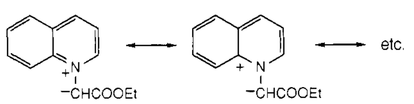
**6**



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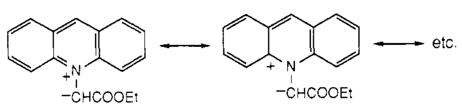
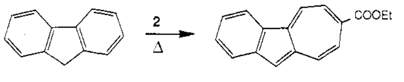
**7**



(12)

**8**

It should also be mentioned again that fluorene is slightly less reactive than toluene, indicating that the somewhat electron withdrawing effect of a substituent benzene ring is felt on the other ring. The products of the reaction of **2** with fluorenes are benzazulenes as shown in eq 13.[26]



(13)

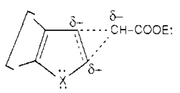
Finally, several methoxy-substituted benzenes and naphthalenes were analyzed to determine how the simple electron-donating substituents would affect $k_{\mathrm{rel}}$ versus naphthalene (Table II). The addition of a second methoxy group in anisole resulted in an approximately 2-fold increase in rate for 1,2-dimethoxybenzene and a slightly greater than 2-fold rate increase for 1,4-dimethoxybenzene. Interestingly, the addition of a third methoxy group in 1,2,4-trimethoxybenzene results in a 10-fold increase in rate relative to anisole. Clearly, the electron-donating effect of three methoxy groups is much greater than any steric hindrance present in the 1,2,4-trimethoxybenzene. For the case where methoxy group(s) are substituted in naphthalene, we see that a simple methoxy group enhances the rate by a factor of 1.3–1.5 while putting one methoxy group in each ring does not increase the rate very much over that with a single methoxy. Thus, carbene **1** is significantly selective only when there are several oxygens attached to a single ring.

Very recently Gaspar et al. suggested that the carbene fluorenylidene forms a complex with hexafluorobenzene when the latter is used as a solvent, and so the fluorenylidene reacts as a carbenoid rather than a free carbene.[27] To probe whether (ethoxycarbonyl)carbene (**1**) forms a complex with $C_6F_6$ and thus enhances its selectivity, we examined the reaction of **1** with several acceptors over a fairly large range of relative reactivities in isooctane as the solvent. Isooctane was chosen since it is not likely to form any type of complex and has only C–H bonds available for reaction with the carbene and the slightly more reactive secondary and tertiary hydrogens are sterically hindered. We found it necessary to use somewhat greater concentrations of ethyl diazoacetate (**2**; 0.375 M) and the acceptor and naphthalene (0.094 M in each) in order to readily quantify the relative reactivity in the presence of solvent which is also reacting. The results shown in Table III indicate that the carbene **1** is a little less selective in isooctane than in $C_6F_6$ although it is still remarkably selective. This relatively small decrease in selectivity is consistent with a complex between $C_6F_6$ and **1** being the reactive intermediate (this complex not being able to form with isooctane), or more likely, it is a simple solvent effect. Not only are the concentrations of the reactants somewhat higher in the isooctane, but if there is polar character in the transition state, such as shown in **9**, and there is a spectrum of polarity depending on the heteroatom X, then the reaction would be expected to go faster in $C_6F_6$ and there should be a compression in the overall range in selectivities.

**Table III. Relative Rate Ratios for the Reaction of 1 versus Naphthalene at 150 °C in Two Solvents**

| compound | $k_{\mathrm{rel}}$ | |
|---|---|---|
| | $C_6F_6$[a] | isooctane[a] |
| phenanthrene | 1.8 | 1.4 |
| furan | 14 | 6.8 |
| pyrrole | 23 | 15 |

[a] Solvent.



**9**

Finally, in order to demonstrate that the rate-determining step in these reactions was formation of the carbene **1**, and not the reaction of the aromatic substrate with either **1** or **2**, we measured the kinetics for three of the systems and a control of **2** without an aromatic acceptor. The rate constants, at 150 °C, for acridine, carbazole, benzofuran, and the control were 0.08, 0.07, 0.08, and 0.09 $\mathrm{min}^{-1}$ respectively. Thus, since all were the same within experimental error, the rate-determining step must be carbene formation in all cases.

## Conclusion

The relative rates of the thermal reaction of ethyl diazoacetate (**2**) to produce (ethoxycarbonyl)carbene (**1**) with toluene, anisole, phenanthrene, pyridine, quinoline, acridine, furan, benzofuran, dibenzofuran, thiophene, benzothiophene, dibenzothiophene, pyrrole, indole, carbazole, fluorene, and several methoxy-substituted aromatics versus naphthalene at 150 °C were measured. The data for the four series toluene, naphthalene, and phenanthrene, the furans, the thiophenes, and the pyrroles are consistent with direct addition of the carbene to the ring with the nucleophilic ring systems showing very significant selectivities of up to about 100 relative to toluene, a simple benzene derivative. The pyridine, quinoline, acridine series appears to react with **1** by an ylide mechanism, and the selectivities here are larger, up to about 150 relative to toluene. Thus, in contrast to the series of substituted benzenes where carbene **1** is only somewhat selective, it appears to be very much more selective with fused aromatic, heteroaromatic, and fused heteroaromatic systems. Methoxy substitution on benzene and naphthalene shows only limited increased selectivity toward **1**. However, when three methoxy groups are on a benzene ring, the selectivity increases significantly. Using isooctane as the solvent, rather than hexafluorobenzene, with three acceptors of differing reactivities relative to naphthalene showed that the selectivities decreased somewhat although they were

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(26) Treibs, W. *Justus Liebigs Ann. Chem.* **1957**, *603*, 145.

(27) Gaspar, P. P.; Mack, D. P.; Lin, C.-T.; Stanley, G. G.; Jones, M., Jr. *J. Org. Chem.* **1988**, *53*, 675.

still substantial. This can be interpreted as either a carbene–$C_6F_6$ complex acting as the reactive intermediate or, perhaps more likely, as a solvent effect, on a polar transition state. Kinetic measurements were consistent with carbene formation being the rate-determining step in these reactions.

## Experimental Section

**Apparatus and Materials.** Hexafluorobenzene (PCR Inc., >99.5%) was used without further purification. Ethyl diazoacetate was prepared from ethyl glycinate hydrochloride and distilled; bp 24–26 °C (1.5 Torr) [lit.[28] bp 29–31 °C (5 Torr)]. Benzofuran (Aldrich, 99.5%) was checked for purity by GC and used without further purification. All of the other reagents were commercially available. Liquids were each distilled and stored over 4-Å molecular sieves. All solids were recrystallized at least once and melting points confirmed. All reagents were checked for purity by GC and were >99.5% pure.

Reaction tubes were made from 10 mm o.d. heavy-walled Pyrex cut to 10-cm lengths; the glass was cleaned with chromic acid, washed with aqueous sodium hydroxide, rinsed with deionized water, dried at 120–130 °C, and stored in a desiccator over Drierite.

Thermal kinetic runs were carried out in an oil bath maintained at 150 ± 0.3 °C by a Cenco 250-W heater and Brownwill Scientific regulator controlled by a Precision Scientific electronic relay.

Capillary GC was done on a Varian Model 3700 gas chromatograph using a 0.32 mm × 30 m DB5+ column with injector temperature at 270 °C and FID detector at 300 °C. Temperature programming varied slightly for different sets of samples to maximize the separation required for each analysis and also minimize the time required. Data collection was done by using a Dynamic Solutions/Millipore Maxima 820 chromatography work station utilizing an NEC APC IV color personal computer.[29] HPLC was done on a Waters/Millipore system consisting of two Model 501 pumps, U6K injector, and 481 variable wavelength UV/vis detector set at 380 nm, with a 30 cm × 3.9 mm μBondapak C18 reverse-phase column. The solvent system was methanol/water, 80:20 (v/v), with a flow rate of 1.3 mL/min. FTIR spectroscopy was carried out on a Biorad-Digilab FTS-40 instrument.

**Thermal Kinetic Runs.** Solutions for the control experiments of toluene versus anisole and toluene versus naphthalene runs were prepared by weighing the substrates into a 10-mL volumetric flask and diluting to the 10-mL mark with hexafluorobenzene to produce a solution that was 0.050 M in each component. Ethyl diazoacetate was added to a 5-mL volumetric flask with a calibrated syringe and diluted to the 5-mL mark with the above hexafluorobenzene mixture to give a solution 0.125 M in ethyl diazoacetate and 0.0490 M in each aromatic component. Due to the very low solubility of carbazole in hexafluorobenzene, the relative rate data was obtained by preparing 10 mL of 0.025 M carbazole and 0.025 M naphthalene in hexafluorobenzene. Ethyl diazoacetate was added to a 5-mL volumetric flask and diluted with the hexafluorobenzene solution to give a solution 0.063 M in ethyl diazoacetate and 0.0247 M each in carbazole and naphthalene. All other solutions were prepared similarly to the latter method except that ethyl diazoacetate was added to the 5-mL volumetric flask and diluted to the 5-mL mark with the hexafluorobenzene mixture to give a solution 0.063 M in ethyl diazoacetate and 0.0494 M in each aromatic component. Reaction tubes were filled with about 0.38 mL of the hexafluorobenzene solution and sealed. The tubes were placed in the oil bath at 150 °C for approximately 12 h and allowed to react.

The linearity of the FID detector response was confirmed for the appropriate components and concentration range.

Control experiments showed that no decomposition occurred when each of the aromatic substrates was heated for 19 h in sealed tubes at 150 ± 5 °C. The only exception to this was pyridine, which showed slight discoloration after heating. GC analysis of the reaction tube showed 8% decomposition. Therefore, the relative rate value reported (Table II) is the value corrected for 8% decomposition of pyridine.

The experiments using isooctane as solvent were done by weighing the substrates into a 10-mL volumetric flask and diluting to the 10-mL mark with isooctane to produce a solution that was 0.100 M in each component. Ethyl diazoacetate (**2**) was added to a 5-mL volumetric flask with a calibrated syringe and diluted to the 5-mL mark with the above isooctane solution to give a solution 0.375 M in ethyl diazoacetate and 0.094 M in each aromatic component.

The runs to obtain the rate constants were done by preparing solutions that were 0.025 M in carbazole, 0.050 M in acridine and benzofuran, and 0.100 M in ethyl diazoacetate (**2**), with $C_6F_6$ as the solvent. A control experiment using only 0.100 M ethyl diazoacetate (**2**) in $C_6F_6$ was also done. The reaction tubes were each filled with about 0.38 mL of the $C_6F_6$ solution, sealed, and put in an oil bath at 150.0 ± 0.3 °C. Tubes were removed after 5, 10, 15, and 20 min, quenched in dry ice/acetone, and analyzed by HPLC for disappearance of ethyl diazoacetate (**2**). Analysis assuming first-order kinetics gave good straight lines and rate constants for acridine, carbazole, benzofuran, and the control of 0.08, 0.07, 0.08, and 0.09 $\text{min}^{-1}$ respectively.

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[28] Searle, N. E. *Organic Syntheses*; Wiley: New York, 1963; Collect. Vol. IV, p 424.

[29] Andrew, M. *Chromatography* **1987**, 21.