Intervention of Carbonyl and Oxonium Ylides in Reactions of [(Alkoxycarbonyl)phenyl]carbenes in the Gas Phase Forming 3-Alkylphthalides and 2-Alkoxy-1(2*H*)-benzocyclobutenone. ^{13}C and ^{18}O Labeling Studies

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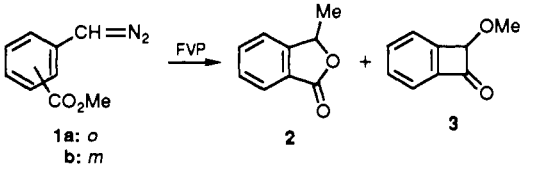
Abstract: The generation of isomeric [(methoxycarbonyl)phenyl]carbenes (**6a-c**) by flash vacuum pyrolysis (FVP, 350-450 °C, 10^{-5} Torr) of the corresponding diazomethanes (**1a-c**) produced 3-methylphthalide (**2**) and 2-methoxy-1(2*H*)-benzocyclobutenone (**3**), presumably as a result of carbene-carbene rearrangement followed by the interaction of the methoxycarbonyl group with the carbene center in the ortho isomer (**6a**). Labeling studies were carried out in order to determine the mechanism of the reaction. Thus, FVP of [*o*-[*carboxy*-^{13}C](methoxycarbonyl)phenyl]diazomethane produced 3-methyl[*carbonyl*-^{13}C]phthalide and 2-methoxy-1(2*H*)-[carbonyl-^{13}C]benzocyclobutenone, thereby indicating that **3** was formed via Stevens-type migration of the acyl group in an oxonium ylide intermediate (**9**). FVP of [*p*-[*carbonyl*-^{18}O](methoxycarbonyl)phenyl]diazomethane, on the other hand, produced 3-methyl[*ether*-^{18}O]phthalide, along with a small amount of 3-methyl[*carbonyl*-^{18}O]phthalide and 3-methoxy-1(2*H*)-[*carbonyl*-^{18}O]benzocyclobutenone, indicating that **2** was produced mainly via 1,5-methyl migration in a carbonyl ylide intermediate (**7**). Generation of other [(alkoxycarbonyl)phenyl]diazomethanes (**16**, where alkoxy = EtO and Pr^{i}O) under similar conditions also produced 3-alkylphthalides (**17**) and 2-alkoxybenzocyclobutenones (**18**), but phthalide **19**, which was not detected in the FVP of **1**, was also formed in this case, presumably as a result of α,β-elimination of alkenes in the oxonium ylide. These results showing the intervention of the oxonium ylide of the ester group are in marked contrast to the observation that, at much lower temperatures in the liquid and solid phases, only the carbonyl ylide has been involved.

Much attention has been paid to the interconversion of substituted phenylcarbenes in which a divalent carbon is transmitted to the position that is accessible for intramolecular reactions.[2] Thus, the isomeric polymethylenes interconvert by a carbene-to-carbene rearrangement mechanism, and they react with the methyl substituent via a hydrogen shift, which ultimately yields benzocyclobutene and styrene.[3] Although the rearrangement can serve as a way of delivering a divalent carbon from one site to another through a benzene ring, its potential has not yet been fully exploited. For example, most substituents employed for such studies have been alkyl groups, and therefore the carbene is trapped mostly by intramolecular C-H bonds. Carbene can interact more effectively with other functional groups, especially those bearing such hetero atoms as oxygen and nitrogen, which can form ylidic intermediates as a result of this interaction.[4] At the same time, it is expected that the modes of reaction of the carbene with those functional groups in the gas phase at high temperatures must be quite different from those in fluid solution at ambient temperatures; therefore, unexpected products may result via ylidic intermediates. The mechanism of interconversion, on the other hand, still continues to plague organic chemists. Thus, the behavior of the species in the gas phase is usually extremely complicated, and even innocent-looking products, which may be formed in high yields, might have been produced by a long series of rearrangements.

In the light of these facts, we generated a phenylcarbene bearing an alkoxycarbonyl group in the gas phase at high temperature in order to determine whether such a functional group could be involved in the rearrangement and in order to discover how the divalent center might interact with a functional group having at least two reactive centers, i.e., both carbonyl and alkoxy oxygens. We found that the alkoxycarbonyl group survived intact during the course of the phenylcarbene rearrangement, resulting in the formation of new types of products that have never before been obtained by reaction in fluid solution at room temperature or in the solid state at low temperature. We also discovered by the labeling studies using ^{13}C and ^{18}O that not only were carbonyl ylides, which are known[5] to be involved in the reaction at much lower temperatures, involved but that so too were oxonium ylides, which have never been observed in the low-temperature reactions, involved in the gas-phase reaction.

Results and Discussion

Thermolysis Products. [(*o*-Methoxycarbonyl)phenyl]diazomethane (**1a**),[5a] produced by heating the sodium salt of the corresponding tosylhydrazone at ca. 80 °C, was pyrolyzed directly by passage through a 350-450 °C quartz tube at 10^{-5} Torr. The volatile products were trapped in a receiver cooled with liquid nitrogen and separated by using silica gel chromatography to afford 3-methylphthalide (**2**)[6] and 2-methoxy-1(2*H*)-benzocyclobutenone (**3**) (eq 1). The structure of the new ketone (**3**)[7]



1a: *o* **b**: *m* **c**: *p** **2** **3** (1)

was determined by the IR, ^1H NMR, ^{13}C NMR, and mass spectra.

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(2) For reviews, see: (a) Gaspar, P. P.; Hsu, J.-P.; Chari, S.; Jones, M., Jr. *Tetrahedron*, **1985**, *41*, 1479. (b) Brown, R. F. C. *Pyrolytic Methods in Organic Chemistry*; Academic Press: New York, 1980; Chapter 5, pp 115-163. (c) Wentrup, C. In *Reactive Intermediates*; Abramovitch, R. A., Ed.; Plenum: New York, 1980; Vol. I, pp 263-320. (d) Wentrup, C. In *Methoden der Organischen Chemie* (Houben-Weyl); Thieme: Stuttgart, 1989; Vol. E19b, pp 824-1021. (e) Jones, W. M. *Acc. Chem. Res.* **1977**, *10*, 353. (f) Jones, W. M. *Rearrangement in Ground and Excited States*; de Mayo, P., Ed.; Academic Press: New York, 1980; Vol. I, pp 95-160.

(3) Vander Stouw, G. G.; Kraska, A. R.; Shechter, H. *J. Am. Chem. Soc.* **1972**, *94*, 1655.

(4) For reviews, see: (a) Moss, R. A., Jones, M., Jr., Eds. *Carbenes*; Wiley: New York, 1973, 1975; Vols. 1 and 2. (b) Kirmse, W. *Carbene Chemistry*; Academic Press: New York, 1971. (c) Wentrup, C. *Reactive Molecules*; Wiley: New York, 1984; Chapter 4. (d) Regitz, M., Ed. *Methoden der Organischen Chemie* (Houben-Weyl); Thieme: Stuttgart, 1989; Vol. E19b.

(5) (a) Hamaguchi, H.; Ibata, T. *Chem. Lett.* **1976**, 287. (b) Ibata, T. *Ibid.* **1976**, 233. (c) Ibata, T.; Moloyama, T.; Hamaguchi, M. *Bull. Chem. Soc. Jpn.* **1976**, *49*, 2298. (d) Hamaguchi, H.; Ibata, T. *Chem. Lett.* **1975**, *169*, 499. (e) Ibata, T.; Hamaguchi, M.; Kiyohara, H. *Ibid.* **1975**, 21.

(6) Jones, P. R.; Jarboe, C. J. *Tetrahedron Lett.* **1969**, 1849.

(7) 2-Hydroxybenzocyclobutenone and its trimethylsilyl derivative have been reported: Carpino, L. A.; Tsao, J.-H. *J. Org. Chem.* **1979**, *44*, 2387.

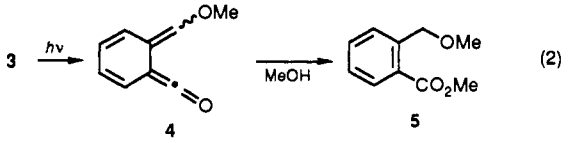
0002-7863/91/1513-8771$02.50/0

Table 1. Yields of Products of [(Methoxycarbonyl)phenyl]diazomethane (**1**) Pyrolysis[a]

substrate	temp[b] (°C)	yield (%)[c] 2	3	2/3
1a	350	45	21	2.1
	400	38	10	3.8
	450	41	8	5.1
1b	350	4	5	0.8
	400	7	4	1.8
	450	19	12	1.6
1c	350	5	7	0.7
	400	11	6	1.8
	450	19	13	1.5

[a] Pyrolysis was carried out by passage through a 350–450 °C quartz tube at 10^{-5} Torr. [b] FVP temperature. [c] Determined by GC. The average of triplicate runs; reproducibility was <5%.

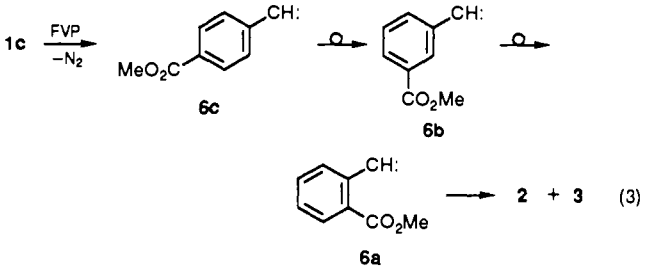
In addition, the benzocyclobutenone framework was confirmed by the finding that the irradiation of **3** in methanol produced methyl (*o*-methoxymethyl)benzoate (**5**), which was obviously formed by photocleavage of **3** to form ketene **4**, followed by nucleophilic attack of the solvent (eq 2).[8] The ratio of **2** to **3**



(2)

tends to increase at higher reaction temperatures. This is apparently attributable to the thermal lability of **3**. Control experiments showed that **3** was thermally less stable than **2**, but that **2** and **3** did not interconvert under the reaction conditions.

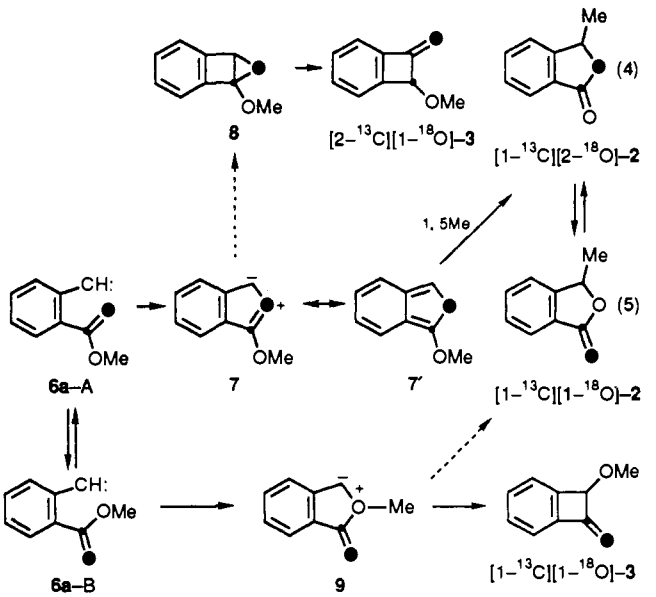
Similar pyrolysis of the meta (**1b**) and para (**1c**) isomers of the diazomethane also afforded the products **2** and **3**, although the ratio changed significantly (vide infra) (Table I). The results are explained in terms of a carbene–carbene rearrangement where [*p*-(methoxycarbonyl)phenyl]carbene (**6c**) rearranges to the meta (**6b**) and ortho isomers (**6a**), which react with the proximate methoxycarbonyl group to yield **2** and **3**, respectively; this suggests that the methoxycarbonyl group remains intact during the course of the phenylcarbene rearrangement (eq 3). Since neither of these



(3)

products was detected in the reactions of **6a** carried out in fluid solutions at much lower temperature,[5] the present reaction serves as another example of the utility of the FVP method as a synthetic tool.

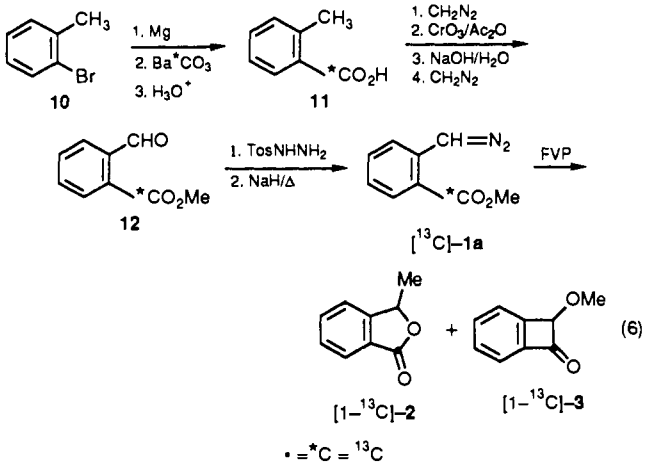
The mechanism of the formation of **2** and **3** from **6a** is then an interesting question. Obviously, these products were formed as a result of the intramolecular interaction of a divalent center with the methoxycarbonyl group at the ortho position. There are two possible intermediates generated as a result of this interaction, the carbonyl (**7**) and oxonium (**9**) ylides. Conceptionally, it is possible to draw a reasonable pathway to **2** and **3** starting from either of the ylides. Thus, formal 1,5-methyl migration in isobenzofuran **7'**[9] (a resonance structure of **7**), which is a thermally allowed sigmatropic shift, will produce **2**, while cyclization to **8** followed by oxygen–hydrogen migration should give **3**. On the other hand, in the ylide **9**, the Stevens-type rearrangement of the Me group will result in the formation of **2**, and acyl migration should afford **3** by ring contraction. Since control experiments showed that **2** and **3** were not interconvertible under the FVP conditions, both products should be formed directly by either, or both, of the ylide intermediates. It is apparent that the labeling experiments will reveal much about which intermediate is actually involved in the reaction. Thus, as marked in eqs 4 and 5, **6** bearing ^{13}C at the methoxycarbonyl carbon will produce **3** bearing ^{13}C at the ether carbon via **8**, whereas **3** bearing ^{13}C at the carbonyl carbon will be formed through **9**. On the other hand, the ^{13}C



labeling experiments will result in **2** bearing the labeled carbon at the carbonyl carbon, irrespective of the ylide intermediates, and hence there can be no discrimination between the intermediates. Thus, we also generated **6** bearing ^{18}O at the carbonyl oxygen, which is expected to yield **2** bearing ^{18}O at the ether oxygen via **7** and ^{18}O at the carbonyl oxygen through **9**.

^{13}C Labeling Experiments

The precursor diazomethane [^{13}C]-**1a** bearing ^{13}C at the methoxycarbonyl carbon was prepared as summarized in eq 6.



(6)

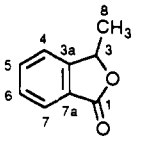
The labeled carbon was conveniently introduced by reacting the Grignard reagent from **10** with $^{13}CO_2$ (98.4%), thus resulting in **11**, which was then converted to the desired diazomethane according to the known procedure (see the Experimental Section). The ^{13}C NMR spectrum of [^{13}C]-**1a** confirmed that the labeled carbon was neither scrambled nor lost during these operations.

FVP of [^{13}C]-**1a** produced [^{13}C]-**2** and [^{13}C]-**3**. ^{1}H and ^{13}C NMR analysis, coupled with MS analysis of the products, clearly

(8) Similar photochemical cleavage of benzocyclobutenone in methanol forming methyl toluate has been observed: Cava, M. P.; Spangler, R. J. *J. Am. Chem. Soc.* **1967**, *89*, 4550.

(9) Stable isobenzofuran was actually isolated in the reaction of (*o*-benzoylphenyl)phenylcarbene: Kumler, P. L.; Bucharat, O. *J. Am. Chem. Soc.* **1968**, *90*, 5640.

Table II. ^{13}C NMR Data of **2** Produced by FVP of **1a** or [^{13}C]-**1a**

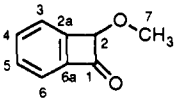


2

	resonance (δ)[a]								
substrate	C-1	C-3	C-3a	C-4	C-5	C-6	C-7	C-7a	C-8
1a	170.4 (10.3)	77.8 (90.4)	151.2 (15.2)	134.1 (100)	121.6 (92.5)	129.1 (99.1)	125.5 (97.5)	125.7 (26.2)	20.4 (92.5)
[^{13}C]-**1a**	170.2 (100)	77.6 (8.1)	*b*	133.9 (10.1)	121.6 (6.1)	129.1 (6.2)	125.6 (8.1)	*b*	20.4 (10.8)

[a] Parts per million downfield from Me_4Si in $CDCl_3$. Values in parentheses are relative intensities. [b] No visible resonances within the limit of detection.

Table III. ^{13}C NMR Data of **3** Produced by FVP of **1a** or [^{13}C]-**1a**



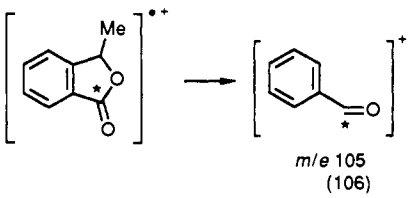
3

	resonance (δ)[a]								
substrate	C-1	C-2	C-2a	C-3	C-4	C-5	C-6	C-6a	C-7
1a	190.2 (10.2)	93.2 (50.8)	156.0 (22.2)	124.3 (97.0)	135.5 (100)	121.5 (86.4)	131.4 (85.5)	147.7 (19.6)	57.0 (91.0)
[^{13}C]-**1a**	190.1 (100)	94.0 (4.4)	*b*	124.5 (5.2)	135.4 (7.6)	121.4 (8.9)	131.4 (6.0)	*b*	56.9 (5.2)

[a,b] See footnotes a and b in Table II.

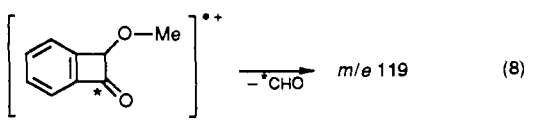
indicated that the ^{13}C carbon was located almost exclusively at the carbonyl carbon, not only in **2** but also in **3**. Thus, [^{13}C]-**2** showed essentially the same coupling patterns as the unlabeled **2** in its ^1H NMR spectrum, indicating that ^{13}C was not located at the C-3 carbon, while the methine proton of [^{13}C]-**3** appeared as a doublet with a small coupling constant (~2 Hz) due to ^{13}C–C–H coupling. This suggests that the ^{13}C was located at the C-1 carbon. The ^{13}C NMR data of [^{13}C]-**2** and [^{13}C]-**3**, summarized in Tables II and III, in addition to the data produced from the unlabeled **1a** provided clear-cut evidence supporting the above assignments. The percentage labels measured by integration for the ^{13}C-labeled products showed 100% of the labels to be at the carbonyl carbon of **2** and 93.6% at the carbonyl carbon of **3**. No double-labeled products were observed, and no label was lost. Intermolecular carbon transfers are thus unlikely.

The mass spectrum of unlabeled **2** showed a 100% peak at *m/e* 105, corresponding to the fragment shown below (eq 7). Additional peaks at *m/e* 104 (3.3%) and 106 (7.8%) correspond to the M − 1 and M + 1 peaks for the fragment PhCO, respectively.



(7)

The mass spectrum of [^{13}C]-**2** showed peaks at *m/e* 105 (12.4%), 106 (100%), and 107 (6.9%). From those values, we calculated 94.4% of the labels to be contained at the carbonyl carbon, assuming that the fragmentation occurs without an isotopic effect. On the other hand, the mass spectrum of unlabeled **3** showed peaks at *m/e* 119 and 121, which were also present in the mass spectrum of labeled **3**. Presumably, the peak at *m/e* 119 must correspond to the fragment formed as a result of the loss of the carbonyl group via the McLafferty-type rearrangement. Then, from the ratio

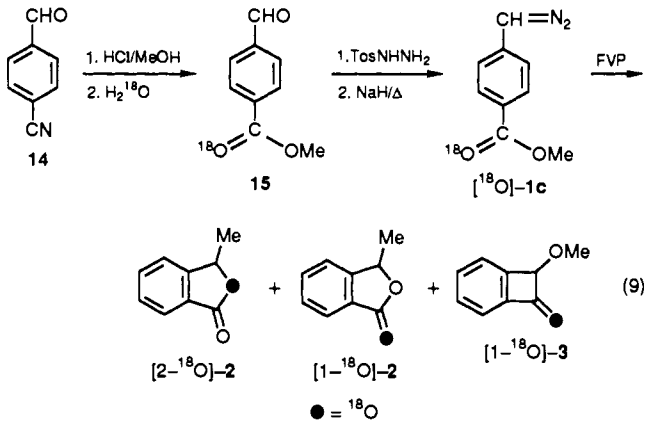


(8)

of 119/121 found in the labeled and unlabeled **3**, the content of the labels at the carbonyl carbon was calculated to be 97.8%. The observation presented unambiguous evidence showing that **3** was formed solely from the oxonium ylide **9**, presumably by the Stevens rearrangement of the acyl group.

^{18}O Labeling Experiments

The diazomethane containing ^{18}O at the methoxycarbonyl oxygen was prepared according to the procedures summarized in eq 9 (see the Experimental Section). Since attempts to prepare the ortho isomer of **15** using a similar reaction were unsuccessful, presumably due to the interaction between the substituents at the ortho positions, the para and meta diazomethanes were prepared, although there is a possibility that ^{18}O may be scrambled during the carbene–carbene rearrangement. However, this possibility



(9)

was eliminated (vide infra). The labeled oxygen was conveniently introduced into the carbonyl oxygen position by reacting the imino ether from **14** with $H_2{}^{18}O$ (99.2%), thereby forming **15**, which was diazotized by the usual method (eq 9). The content of ^{18}O in **15** was estimated to be 83.0% on the basis of MS analysis. The fact that no scrambling of ^{18}O between the carbonyl and ether oxygens took place during the diazotization procedure was suggested by the fact that the IR spectrum of [^{18}O]-**1c** showed an absorption at 1685 cm^{-1} due to C=^{18}O stretching, in addition to a weak absorption resulting from unlabeled C=O exhibited at 1719 cm^{-1}. Also **15**, regenerated by the $^1O_2$ oxidation of [^{18}O]-**1c**, exhibited essentially the same mass spectrum as that of the starting

Table IV. MS Data of 3 Produced by FVP of [^{18}O]-1c

temp[a] (°C)	ion (m/e)	ion intens[b] unlabeled	ion intens[b] labeled (cor intens)[c]	product ratio 3/[^{18}O]-3	product ratio [1-^{18}O]-3/[2-^{18}O]-3
350	150	0.3	6.9	19.0/81.0	
	148	7.3	1.6		
	135	1.0	100	17.9/82.0	
	133	100	22.0		
	121	1.4	1.7 (1.4)		99.7/0.3
	119	33.3	38.4 (31.1)		
450	150		4.3	63.2/36.8	
	148		6.9		
	135		63.8	61.4/38.6	
	133	100			
	121		1.8 (0.5)		100/0
	119		54.0 (22.5)		

[a] FVP temperature. [b] Measured on a Shimadzu GCMS (QP-1000). [c] Corrected intensities based on ion intensities of unlabeled samples.

Table V. MS Data of 2 Produced by FVP of [^{18}O]-1c

temp[a] (°C)	ion (m/e)	ion intens[b] unlabeled	ion intens[b] labeled (cor intens)[c]	product ratio 2/[^{18}O]-2	product ratio [2-^{18}O]-2/[1-^{18}O]-2
350	150	0.3	18.4	19.0/81.0	
	148	16.9	4.4		
	135	0.5	65.6	18.5/81.5	
	133	53.2	15.1		
	107	0.6	18.7 (18.5)		80.3/19.7
	105	100	100 (70.4)		
450	150		16.4	21.6/78.4	
	148		4.6		
	135		67.3	19.6/80.4	
	133		16.6		
	107		19.1 (18.9)		79.7/20.3
	105		100 (72.8)		

[a-c] See footnotes in Table IV.

materials (14). Although [^{18}O]-1b was prepared according to almost the exact same procedure, only the results employing [^{18}O]-1c will be described here, since essentially the same results were obtained.

FVP of [^{18}O]-1c again produced 2 and 3, which were analyzed by IR and MS by using the conventional technique. The position, as well as the content, of the labels was conveniently determined by monitoring the relevant fragment peaks, which have been confirmed in the ^{13}C-labeled samples (vide supra). Thus, the *m/e* 105 peak is used as a key fragment containing the carbonyl oxygen in 2 (eq 7), while the *m/e* 119 peak is regarded as a decarbonylated fragment of 3 (eq 8). However, the results summarized in Tables IV and V, provided somewhat less clear-cut data compared to that obtained in the ^{13}C labeling experiments. This is partly due to the expected reactivity of the carbonyl oxygen with water present in the system. First, the cyclobutenone (3) was found to lose significant amounts of the labeled oxygen, depending on the pyrolysis temperature (Table IV). Thus, the ^{18}O content in 3 determined by using the parent (150/148) and base peaks ($M^+ - CH_3$, 135/133) decreased from 82% at 350 °C to 38% at 450 °C. This is presumably due to the addition of water (H_2O) to the carbonyl group of [^{18}O]-3, followed by the elimination of $H_2{}^{18}O$ from the resulting hydrate. Control experiments showed that the ^{18}O content of [^{18}O]-3 decreased either upon passing through the pyrolysis tube or by refluxing in benzene containing a small amount of H_2O. Comparison of the IR spectrum of 3 and [1-^{18}O]-3, however, indicated that ^{18}O is located in the carbonyl group. Thus, the IR spectrum of [1-^{18}O]-3 shows a strong absorption at 1735 cm^{-1} due to C=^{18}O stretching, in addition to a rather weak absorption due to unlabeled C=O appearing at 1765 cm^{-1}, but no additional absorption due to an ^{18}O isotopic shift is apparent in the C—O stretching regions. A more quantitative result was obtained by MS analysis of the fragment (*m/e* 119) formed as a result of the loss of CO (eq 8). Thus, analysis of the fragment (*m/e* 121/119) using the mass spectrum of [^{18}O]-3 showed that the labeled oxygen was almost exclusively located at the carbonyl oxygen. Not only is this observation in accord with the result of the ^{13}C labeling experiment but it also eliminates the possibility that the labeled oxygen is scrambled between the carbonyl and ether oxygens during the rearrangement. This suggests that the ylide 9 was not formed by 1,3-Me migration of the ylide 7, since this rearrangement will produce 3 bearing ^{18}O at the ether oxygen.

Judging from the parent (150/148) and base peaks (135/133) (Table V), the ^{18}O content in [^{18}O]-2 was not decreased during the pyrolysis. Control experiments reveal that the amount of ^{18}O in [^{18}O]-2 was not decreased appreciably even upon the treatment in refluxing benzene/H_2O. However, analysis of the fragments and intensities of the MS of [^{18}O]-2 showed that, although [2-^{18}O]-2 was formed predominantly, [1-^{18}O]-2 was also produced and increased at the higher pyrolysis temperature (Table V). Thus, the ratios of [2-^{18}O]-2/[1-^{18}O]-2 observed at 350 and 450 °C were 80.3/19.7 and 79.7/20.3, respectively. These results may indicate that 2 was mainly formed via the ylide 7 but that the oxonium ylide 9 also produced 2 by methyl migration in competition with acyl migration. Control experiments, however, reveal the fact that [1-^{18}O]-2 and [2-^{18}O]-2 interconverts under FVP conditions, especially at higher temperature. For example, the passing of the 79.7/20.3 mixture of [2-^{18}O]-2/[1-^{18}O]-2 through the FVP tube at 450 °C resulted in the 66.6/33.4 mixture of [2-^{18}O]-2/[1-^{18}O]-2, without any appreciable loss of the total amount of 2. Thus, it may be possible to assume that [2-^{18}O]-2 was formed initially from the ylide 7 but was converted to [1-^{18}O]-2 by secondary thermal isomerization in the hot tube. In accordance with the expectation that the thermal isomerization process should be reduced at a lower temperature, examination of the effect of temperature on the thermal isomerization using [2-^{18}O]-2/[1-^{18}O]-2 mixtures revealed that the interconversion was essentially quenched when the reaction was conducted at <300 °C. FVP of [^{18}O]-1c at 300 °C again afforded, however, a mixture of [2-^{18}O]-2 and [1-^{18}O]-2 in a ratio of 79.0/21.0. When FVP was carried out at 250 °C, no prominent formation of 2 and 3 was observed, and a large amount of the diazomethane was recovered unchanged. The results may support the former explanation that 2 was formed mainly via 7 and partly from 9. However, one cannot rigorously eliminate the latter scenario if one takes into account chemical activation,[10] that the heat of reaction is channeled into secondary intramolecular reactions. Thus, if [2-^{18}O]-2 is formed from 7 by an exothermic reaction, the heat of the reaction in the gas phase may not dissipate efficiently through collisions. Therefore [2-^{18}O]-2 can undergo C–O bond cleavage upon formation, isomerizing to [1-^{18}O]-2.

Effect of Precursors

The results summarized in Table I clearly indicate that the ratio of the two products varies significantly with the reaction temperature and the precursor. Thus, the thermolysis of [*o*-(methoxycarbonyl)phenyl]diazomethane (1a) produced a higher fraction of 2 over 3 than did the meta and para isomers. Such an anomalous product ratio from an ortho isomer has been noted[11] in the thermolysis of the isomeric tolyldiazomethanes: the ortho isomer gives nearly three times as much benzocyclobutene as styrene, while from the meta and para isomers the ratio is approximately 0.8. Admitting that benzocyclobutene is derived from *o*-tolylmethylene while styrene is derived from α-methylphenylmethylene, several mechanisms in which *p*- and *m*-tolylmethylenes rearrange to α-methylphenylmethylene without recourse to the ortho isomer have been proposed[2a] to accommodate the experimental observation. However, the present results cannot be explained by any of these mechanisms, since both 2 and 3 are apparently derived from the ortho isomer in this case. Accepting that 3 is predominantly formed from the oxonium ylide 9 while most of 2 is derived from the carbonyl ylide 7, and that interconversion between 7 and

(10) For example, see: Bock, H.; Dammel, R. *J. Am. Chem. Soc.* **1988**, *110*, 5261 and references cited therein.

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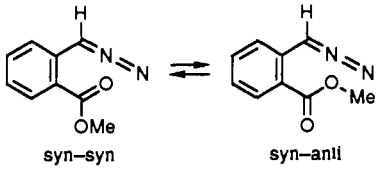
9 is not attained in both directions, the product ratio may reflect the relative population of the carbene conformers **6a**-A and -B (eq 4 and 5), since in **6a**-A the carbene center will be trapped by the carbonyl oxygen, while the ether oxygen in **6a**-B would attack the carbene center. One then would expect that the relative population in **6a** formed from **1a** is different from that in **6a** generated from **1b** and **1c**, since the relative population in **6a** directly formed from **1a** must reflect that of **1a**; while in **6a** produced from **1b** and **1c** after the repeated rearrangement, the equilibrium between the two conformers must be attained.

Therefore, the predominant formation of **2** over **3** in FVP of **1a** then means that in this case conformer A is dominant in **6a**. This is understood when one analyzes the stability of the conformer in **1a**. There are four coplanar conformers for **1a** (i.e., syn–syn, syn–anti, anti–syn, and anti–anti), where syn and anti are termed according to the relative relationship between the diazo and carbonyl groups. For the diazo syn isomers, one would expect that the diazo–carbonyl interaction is sterically less hindered than the diazo–methoxy interaction, and hence that the syn–syn isomer is favored over the syn–anti one (eq 10). A similar argument



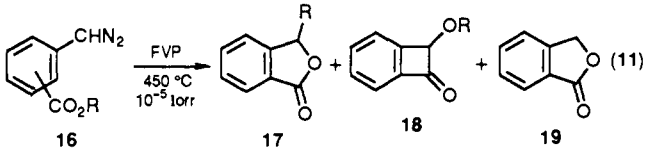
(10)

can be applied to the diazo anti isomers. This is in agreement with the observation that **2** is favored over **3** in the FVP of **1a**.

On the other hand, a mechanism[11,12] including the intervention of the diazo compound to explain the product ratios in FVP in the isomeric tolyldiazomethane must be considered. For instance, it has been proposed[12] that *o*-tolyldiazomethane can "leak away" to benzocyclobutene without passing through *o*-tolylmethylene as a result of facile hydrogen atom transfer in the diazomethane. It is very tempting, then, to draw a similar mechanism regarding the present reaction where the thermally excited diazomethane (**1a**) can directly produce **2** without generating free carbene. The attack of a diazo carbon atom on the neighboring methyl group to expel the carboxylate group followed by the subsequent attacks on the resulting diazo carbon leading to **2** is a possible route.

Effect of Alkoxy Group

FVP of other [(alkoxycarbonyl)phenyl]diazomethanes also provided further evidence supporting the mechanism advanced above. Thus, FVP of *o*- or [*p*-(ethoxycarbonyl)phenyl]diazomethanes (**16a**) afforded 3-ethylphthalide (**17a**) and 2-ethoxybenzocyclobutenone (**18a**) along with the third product, **19**, which was not formed in the FVP of **1**. FVP of isopropoxy derivatives (**16b**) also produced those three types of products (**17b**, **18b**, and **19**) (eq 11).



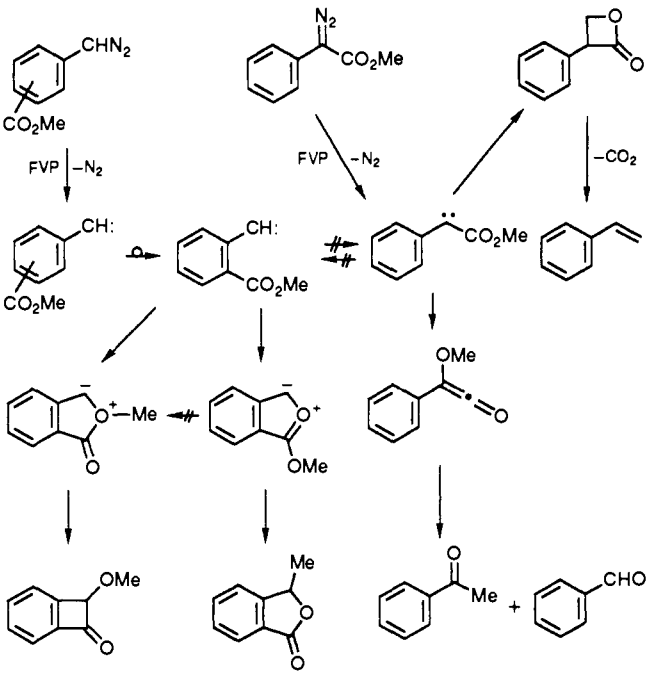
(11)

16 **17** **18** **19**

		yield (%)			
		17	**18**	**19**	**17/(18 + 19)**
16a: R = Et	(*o*)	44	8	12	2.2
	(*p*)	19	12	14	0.7
16b: R = Pr^i	(*o*)	25	3	12	1.7
	(*p*)	10	3	10	0.8

What is a mechanism for the formation of **19**? Control experiments showed that neither **17** nor **18** produced **19** under the FVP conditions, which suggests that **19** is formed as a primary product. Therefore, the most probable pathway may be an α,β-

Scheme I



elimination forming the alkene in the oxonium ylide intermediates.[13] It is generally accepted that most ylides bearing β-hydrogens undergo, α,β-elimination, forming alkenes in competition with the Stevens rearrangement.[13] For example, methoxycarbonylcarbene reacts with benzyl alkyl ether to produce a C–O displacement product along with all the possible C–H insertion products, but the displacement product gains at the expense of the C–H insertion products when the ethyl group is introduced. CIDNP studies demonstrate[20b] that the latter is formed by the Hoffman-type elimination of ethylene in the oxonium ylide.

^{18}O labeling experiments using [^{18}O]-**16a** failed to provide conclusive evidence to prove that the carbonyl ylides are not precursors for the formation of **19**, probably due to rapid thermal scrambling of the labeled oxygen in **19** under the FVP conditions. Nevertheless, highly unimolecular reaction conditions coupled with evidence[20] supporting the intramolecular nature of the elimination suggest that **19** must be formed almost exclusively from oxonium ylide.

Concluding Remarks

The results presented above clearly indicate that alkoxycarbonyl groups remain intact in the course of the phenylcarbene rearrangement and are trapped by the carbene center at the ortho position to give not only carbonyl ylides but also oxonium ylides. Secondly, the carbonyl ylide produces 3-alkylphthalide, whereas the oxonium ylide undergoes the Stevens-type acyl migration, which forms 2-alkoxybenzocyclobutenone. The nature of each mechanism for the formation of 3-alkylphthalide is not clear at

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present. Although a formal 1,5-methyl shift seems reasonable in terms of the symmetry rule, steric matters such as orbital control between the migrating methyl group and the destination carbon during the migration intrude. Consequently, the intermolecular process[21a] is an attractive alternative. "Cross" experiments were carried out in order to examine this possibility. Thus, [^{18}O]-**1c** and **16a** were copyrolyzed in the hot tube, and the pyrolysates were analyzed by GC–MS. This indicated that "crossed" phthalides (i.e., 3-ethylphthalide carrying the labeled oxygen) were detected to a very small but significant extent. The results suggest that some of the phthalides are formed via an intermolecular pathway. However, in the light of the highly unimolecular conditions (10^{-5} Torr), it is not easy to draw a simple mechanism for the intermolecular process in the hot tube.

Interestingly enough, the formation of the oxonium ylide in competition with the carbonyl ylide reveals the fact that, when generated at much lower temperature, the phenylcarbene **6** is trapped almost exclusively by the carbonyl oxygen of the alkoxycarbonyl group at the ortho position, producing the carbonyl ylide.[5] For example, generation of **6a** in MeOH either photolytically or catalytically produced cyclic orthobenzoate quantitatively,[5a] thereby indicating the intervention of the carbonyl ylide. More importantly, direct observation of the carbonyl ylide has been made[14] using matrix isolation techniques. Thus, photolysis of **1a** matrix isolated in argon at 10 K and monitored by IR spectroscopy indicates that both the diazo and carbonyl groups disappear simultaneously, resulting in the formation of a new species showing absorptions at 1653, 1590, 1501, 1431, and 1096 cm^{-1}. The photoproduct is assigned as the carbonyl ylide **7** on the basis of spectral analysis as well as its secondary photochemical ring closure. This forms 1-methoxybenzocyclobutadiene oxide. The observation that no other species exhibiting a new carbonyl stretching absorption appears during the irradiation suggests that the oxonium ylide **9** is not formed under these experimental conditions.

Oxonium ylides can be generated either by deprotonation of the oxonium ion[15] or by the interaction of carbenes with the unshared electron pairs of oxygen,[16] and they are attracting increasing interest as intermediates leading to useful products as well as for their mechanistic importance. However, the oxonium ylides thus far reported have been rather simple ones. Thus, oxygen compounds utilized for the trapping of carbenes that result in oxonium ylides include dioxanes,[17] epoxides,[18] allylic ethers,[19] aliphatic ethers,[20] allylic acetals,[21b] and oxetanes,[22] where the most basic center is always the ether oxygen. In other words, no oxonium ylides bearing electron-withdrawing α-substituents have been reported. In this light, special attention should be paid to the unprecedented oxonium ylide formed in the reaction of **6a** by the interaction of the carbene with the alkoxy oxygen of the ester group. One may expect that the carbene is initially trapped by the carbonyl oxygen to yield the carbonyl ylide **7**, which then undergoes 1,3-Me migration to generate the oxonium ylide **9** under these conditions. This possibility is eliminated by the finding that [^{18}O]-**6** produced [1-^{18}O]-**3** almost exclusively from **9**; this indicates that **9** is formed directly by the attack of alkoxy oxygen on the carbenic center at the ortho position. Apparently, the formation of this unusual ylide in the present reaction, which is considered to be thermodynamically less stable than the carbonyl ylide, must reflect the high energy gained by heat as well as by the highly unimolecular nature created under high vacuum. The results also suggest that the FVP conditions may serve as a very attractive method to generate other highly functionalized oxonium ylides that otherwise are impossible to form.

Despite the ring strain in **3**, the predominant formation of benzocyclobutenone, probably by acyl migration over the phthalide via methyl migration in the ylide **9**, is initially rather surprising. However, this is in accord with the observation[20d] that, in oxonium ylides generated from arylcarbenes carrying an alkoxyalkyl group in the ortho position, alkyl shifts occur to a very minor extent if no benzyl groups are available. In terms of the radical pair mechanism of the Stevens rearrangement,[13] these observations suggest a more facile homolysis of oxonium ylides as compared with ammonium ylides.

Finally, interconversion between [*o*-(methoxycarbonyl)phenyl]carbene and α-(methoxycarbonyl)phenylcarbene was examined. FVP of methyl α-diazophenylacetate resulted in the formation of complex mixtures of at least seven products, comprised of styrene, benzaldehyde, acetophenone, methyl phenylacetate, biphenyl, diphenylmethane, and bibenzyl, none of which were detected in the pyrolysate of **1c**. Neither of the two products (**2** and **3**) formed from [*o*-(methoxycarbonyl)phenyl]carbene were detected. The exact mechanism for the formation of these complex mixtures is not known at present. However, by analogy with the mechanism proposed[23] for the reactions of bis(methoxycarbonyl)carbene in the gas phase to form methyl acrylate, methyl acetylacetate, methyl acetate, and methyl vinyl ether, styrene can be explained in terms of α-CH insertion forming an α-lactone, followed by decarboxylation, while acetophenone may be formed via the Wolff rearrangement followed by decarboxylation. The results indicate that interconversion between [*o*-(methoxycarbonyl)phenyl]carbene and α-(methoxycarbonyl)phenylcarbene is not attained in both directions. The rearrangement of the α to the ortho isomer of the carbene is largely prevented due to the facile migration reaction leading to stable products often accessible for the α isomer. For instance, α-tolylmethylene gives styrene as a result of 1,2-H migration before it rearranges to *o*-tolylmethylene. The rearrangement from the ortho to α isomer, on the other hand, is observed in some cases. For instance, phenylcarbenes having alkyl, alkylsilyl, alkylgermyl, and alkylstannyl substituents are able to get past the ortho position.[24] In this light, alkoxycarbonyl groups are considered to be very efficient intramolecular traps in the phenylcarbene rearrangement system.

Experimental Section

General Methods. IR spectra were measured on a JASCO IR-G recording spectrophotometer, and the mass spectra were recorded on a Shimadzu QP-1000 mass spectrometer (70 eV). The content of isotopes in the products was conveniently determined by GCMS techniques. In order to avoid possible error due to partial separation of the isotopic mixtures by GC, the mass fragmentography technique was employed. Thus, the total ion mass of each compound (m/e) was integrated in each GC peak and used as the numerical value for the analytical calculations. When an isotopic composition was obtained based on a fragment ion, it was assumed that the fragmentation occurred without an isotope effect. ^{1}H and ^{13}C NMR spectra were determined with JEOL JNM-MH-100 and Hitachi R-90H NMR spectrometers, respectively, in $CDCl_3$ with Me_4Si as an internal standard. The GC analyses were performed on a Yanagimoto instrument, Model G-80. The GC column A was prepared from 5% SE-30 on Diasolid L (5.0 mm × 2.0 m); column B consisted of 5% PEG-20M on Diasolid L (5.0 mm × 2.0 m). Thin-layer chromatography was done on a Merck Kieselgel 60 PF_{254}. Column chromatography was carried out on silica gel (ICN for dry column chromatography).

Materials. Barium carbonate (98.4% ^{13}C) and $H_2{}^{18}O$ (99.2% ^{18}O) purchased from Isotec Inc. were used without further purification. Anhydrous tetrahydrofuran (THF) and ether were distilled over sodium and benzophenone under argon.

o-(Methoxycarbonyl)benzaldehyde was prepared by the method of Barry et al.,[25] and *m*-(methoxycarbonyl)benzaldehyde was prepared following the procedure of Williams.[26] *o*-(Ethoxycarbonyl)- and *o*-(isoproxycarbonyl)benzaldehyde were prepared from phthalimide by Oppe's method,[27] and *p*-(ethoxycarbonyl)- and *p*-(isopropoxycarbonyl)-benzaldehyde were obtained from the corresponding acids by modification of the method of Barry et al.[25] 3-Methylphthalide (**2**) was prepared from *o*-acetylbenzoic acid by the procedure of Jones et al.[6] All other

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chemicals were used as received or distilled before use as specified.

[*o*-(Methoxycarbonyl)phenyl]diazomethane (1a). By following the procedure of Creary,[28] a solution of *o*-(methoxycarbonyl)benzaldehyde (0.61 g, 3.7 mmol) and tosylhydrazine (0.69 g, 3.7 mmol) in anhydrous THF (5 mL) was stirred at room temperature. The progress of the reaction was monitored by TLC, which indicated that the starting materials were consumed within 5 min. To the reaction mixture was added a suspension of NaH (0.15 g, 3.7 mmol) in anhydrous THF (5 mL) under N_2, and the mixture was stirred for 30 min at room temperature to produce the white tosylhydrazone salt, which was collected by suction filtration under N_2 and washed with petroleum ether. Drying the solid in vacuo at room temperature gave the sodium salt of *o*-(methoxycarbonyl)benzaldehyde tosylhydrazone (1.1 g, 84%) as a white solid. This salt (0.5 g) was placed in a sublimation apparatus equipped with an ice-cooled cold finger and heated at 140 °C ($2-5 \times 10^{-5}$ Torr) for 30 min to give the diazomethane (**1a**, 0.23 g, 91%) as orange crystals deposited on the cold finger: mp 32.5–34.5 °C; ^{1}H NMR (CCl_4) δ 3.82 (s, 3 H), 6.78 (s, 1 H), 7.01–6.94 (m, 2 H), 7.37 (dd, J = 7.9, 8.1 Hz, 1 H). 7.95 (d, J = 6.9 Hz, 1 H); IR (KBr) 2060, 1719 cm^{-1}.

The following diazomethanes used in this study were prepared by a similar procedure to that described above.

[*m*-(Methoxycarbonyl)phenyl]diazomethane (1b): 48.9%; mp 29.5–30.5 °C; ^{1}H NMR (CCl_4) δ 3.84 (s, 3 H), 4.95 (s, 1 H), 6.98 (d, J = 7.4 Hz, 1 H), 7.25 (t, J = 7.4 Hz, 1 H), 7.48 (bs, 1 H), 7.58 (d, J = 7.4 Hz, 1 H); IR (KBr) 2070, 1725 cm^{-1}.

[*p*-(Methoxycarbonyl)phenyl]diazomethane (1c): 52%; mp 43–49 °C; ^{1}H NMR (CCl_4) δ 3.83 (s, 3 H), 4.93 (s, 1 H), 6.86 (d, J = 8.0 Hz, 2 H), 7.83 (d, J = 8.0 Hz, 2 H); IR (KBr) 2060, 1719 cm^{-1}.

[*o*-(Ethoxycarbonyl)phenyl]diazomethane (*o*-16a): 50.8%, red oil; ^{1}H NMR (CCl_4) δ 1.36 (t, J = 7.2 Hz, 3 H), 4.26 (q, J = 7.2 Hz, 2 H), 6.75 (s, 1 H), 6.92 (d, J = 7.5 Hz, 1 H), 7.25–7.41 (m, 2 H), 7.91 (d, J = 7.5 Hz, 1 H); IR (neat, NaCl) 2060, 1709 cm^{-1}.

[*p*-(Ethoxycarbonyl)phenyl]diazomethane (*p*-16a): 77.5%; mp 51.0–53.0 °C; ^{1}H NMR (CCl_4) δ 1.36 (t, J = 7.8 Hz, 3 H), 4.29 (q, J = 7.8 Hz, 2 H), 4.98 (s, 2 H), 6.89 (d, J = 8.0 Hz, 2 H), 7.90 (d, J = 8.0 Hz, 2 H); IR (KBr) 2065, 1695 cm^{-1}.

[*o*-(Isopropoxycarbonyl)phenyl]diazomethane (*o*-16b): 61.7%, red oil; ^{1}H NMR (CCl_4) δ 1.32 (d, J = 6.3 Hz, 6 H), 5.14 (sept, J = 6.3 Hz, 1 H), 6.77 (s, 1 H), 6.90–6.98 (m, 2 H), 7.33 (dd, J = 7.5, 8.2 Hz, 1 H), 7.95 (d, J = 7.5 Hz, 1 H); IR (neat, NaCl) 2060, 1705 cm^{-1}.

[*p*-(Isopropoxycarbonyl)phenyl]diazomethane (*p*-16b): 51.8%, red oil; ^{1}H NMR (CCl_4) δ 1.33 (d, J = 6.9 Hz, 6 H), 5.00 (s, 1 H), 5.17 (sept, J = 6.9 Hz, 1 H), 6.83 (d, J = 8.4 Hz, 2 H), 7.86 (d, J = 8.4 Hz, 2 H); IR (neat, NaCl) 2070, 1710 cm^{-1}.

Flash Vacuum Pyrolysis. The apparatus used for the FVP consisted of a quartz tube (30 mm i.d. × 35 cm long) maintained at the desired temperature by resistance wire. The tube was filled with a loose plug of quartz wool 10 cm below the top of the heated zone. At the top of the tube, provision was made for the introduction of solid reactants via a solid addition tube. The lower end of the tube was filled with consecutive U-tubes that were immersed in liquid nitrogen. The pyrolysis tube bent near the bottom such that the pyrolysis zone was angled about 35° from the vertical.

In a typical experiment, ca. 1 mmol of the diazo compound or the precursor sodium tosylhydrazonate was placed in the top tubes, which were gradually heated up to 130 °C at 10^{-5} Torr so that most of the diazo compound sublimed into the hot tube. The volatile products were collected in a trap cooled with liquid nitrogen, and individual components were isolated either by preparative TLC or GC and identified by NMR and MS. For analytical runs, the sample was washed out of the trap with *n*-hexane; the wash was diluted to 5.0 mL and an internal standard was added for GC analysis.

FVP of [(Methoxycarbonyl)phenyl]diazomethanes 1. FVP of **1a** (200–300 mg) was conducted at 350 °C (10^{-5} Torr), and the products were trapped at −196 °C. The pyrolysate was collected by washing the condensate with *n*-hexane. GC–MS analysis of the mixture showed the presence of two volatile components, both showing the molecular ion at m/e 148. A preparative TLC of the residue developed with $CHCl_3/n$-C_6H_{14} (3/7) was used to obtain samples of the two components. The faster moving component (16.7 mg, 16%) was assigned as the benzocyclobutenone (**3**) and the slower moving one (41.8 mg, 40%) as the phthalide (**2**) on the basis of the following spectroscopic data.

3-Methylphthalide (2): ^{1}H NMR (CCl_4) δ 1.60 (d, J = 7.0 Hz, 3 H), 5.50 (q, J = 7.0 Hz. 1 H), 7.36–7.81 (m, 4 H); ^{13}C NMR, see Table II; MS, see Table V; IR (neat, NaCl) 1762 cm^{-1}.

2-Methoxy-1(2*H*)-benzocyclobutenone (3): ^{1}H NMR (CCl_4) δ 3.48 (s, 3 H), 5.43 (s, 1 H), 7.40–7.65 (m, 4 H); MS, see Table IV; ^{13}C NMR, see Table III; IR (neat, NaCl) 1768 cm^{-1}; high-resolution mass spectrum for $C_9H_8O_2$ (M^+) calcd 148.0524, found 148.0525.

FVP of 1b and 1c also produced **2** and **3** as determined by spectroscopic comparison with the products obtained in the FVP of **1a**.

FVP of 16. FVP was carried out as described above and the following products were isolated by preparative TLC.

3-Ethylphthalide (17a): ^{1}H NMR (CCl_4) δ 0.99 (t, J = 7.0 Hz, 3 H), 1.82–2.30 (m, 2 H), 5.35 (dd, J = 6.8, 4.2 Hz, 1 H), 7.30–7.67 (m, 3 H), 7.79 (d, J = 6.8 Hz, 1 H); MS m/e (rel intensity) 152 (M^+, 7.5), 133 (100), 105 (44.7); IR (neat, NaCl) 1760 cm^{-1}; high-resolution mass spectrum for $C_{10}H_{10}O_2$ (M^+) calcd 162.0681, found 162.0683.

2-Ethoxy-1(2*H*)-benzocyclobutenone (18a): ^{1}H NMR (CCl_4) δ 1.25 (t, J = 6.6 Hz, 3 H), 3.50–3.97 (m, 2 H), 5.44 (s, 1 H), 7.41–7.63 (m, 4 H); MS m/e (rel intensity) 133 (100), 105 (42.3); IR (neat, NaCl), 1770 cm^{-1}; high resolution mass spectrum for $C_{10}H_{10}O_2$ (M^+) calcd 162.0681, found 162.0680.

3-Isopropylphthalide (17b): ^{1}H NMR (CCl_4) δ 0.77 (d, J = 6.5 Hz, 3 H), 1.10 (d, J = 6.8 Hz, 3 H), 2.09–2.33 (m, 1 H), 5.25 (d, J = 3.8 Hz, 1 H), 7.33–7.65 (m, 3 H), 7.76 (d, J = 6.8 Hz, 1 H); MS m/e (rel intensity) 176 (M^+, 8.3), 133 (100), 105 (39.4); IR (neat, NaCl) 1762 cm^{-1}; high-resolution mass spectrum for $C_{11}H_{12}O_2$ (M^+) calcd 176.0838, found 176.0837.

3-Isopropoxy-1(2*H*)-benzocyclobutenone (18b): ^{1}H NMR (CCl_4) δ 1.25 (d, J = 5.9 Hz, 6 H), 3.96 (sept, J = 5.9 Hz, 1 H), 5.44 (s, I H), 7.40–7.71 (m, 4 H); MS m/e (rel intensity) 133 (96.8), 105 (100); IR (neat, NaCl) 1771 cm^{-1}; high-resolution mass spectrum for $C_{11}H_{12}O_2$ (M^+) calcd 176.0837, found 176.0835.

Preparation of [*o*-[*carboxy*-^{13}C](methoxycarbonyl)phenyl]diazomethane ([^{13}C]-1a). [*carboxy*-^{13}C]-*o*-Toluic acid (**11**) was prepared from (*o*-methylphenyl)magnesium bromide and 99% ^{13}C barium carbonate according to the procedure reported by Dauben et al.[29] The acid (490 mg, 3.6 mmol) was treated with CH_2N_2 to give methyl [*carboxy*-^{13}C]-*o*-toluate as a yellow oil (530 mg, 97.5%): ^{1}H NMR (CCl_4) δ 2.55 (s, 3 H), 3.81 (d, $J_{^{13}C-H}$ = 3 Hz, 3 H), 6.98–7.33 (m, 3 H), 7.69–7.86 (m, 1 H); MS (rel intensity) 151 (M^+, 50), 120 (100), 91 (81). To a solution of the methyl ester (530 mg, 3.5 mmol) in acetic anhydride (5.1 mL) and acetic acid (6 mL) was slowly added, with stirring, concentrated H_2SO_4 (0.8 mL) and then chromium trioxide (0.95 g, 9.5 mmol) in small portions at such a rate that the temperature did not rise above 5 °C. The stirring was continued for 1 h after the trioxide had been added, and usual workup afforded crude *o*-[*carboxy*-^{13}C](methoxycarbonyl)benzal diacetate (430 mg, 45.9%). The crude diacetate (430 mg) was refluxed in 10% NaOH aqueous solution (3 mL) for 30 min. After cooling, acidification of the reaction mixture followed by extraction with ether and evaporation of the solvent gave crude *o*-[*carboxy*-^{13}C]carboxybenzaldehyde (150 mg, 61.7%). The crude acid (150 mg) was treated with CH_2N_2 to give the corresponding methyl ester (**12**), which was purified by distillation: bp 85–90 °C (0.3 Torr); ^{1}H NMR (CCl_4) δ 3.98 (d, J = 4 Hz, 3 H), 7.51–7.65 (m, 2 H), 7.66–7.97 (m, 2 H), 10.53 (s, 1 H). The ester (**12**) was treated with tosylhydrazine to give the corresponding tosylhydrazone as a yellowish oil: ^{1}H NMR ($CDCl_3$) δ 2.36 (s, 3 H), 3.83 (d, $J_{^{13}C-H}$ = 4.0 Hz, 3 H), 7.11–7.49 (m, 4 H), 7.64–7.92 (m, 4 H), 8.55 (s, 1 H), 8.77 (s, 1 H). The tosylhydrazone was treated with NaH to form the white tosylhydrazone salt, which was heated in the top tube to generate [^{13}C]-**1a** in the hot tube.

FVP of [^{13}C]-1a. FVP was carried out as described above and the following products were isolated by preparative TLC.

3-Methyl[*carbonyl*-^{13}C]phthalide ([1-^{13}C]-2): ^{1}H NMR (CCl_4) δ 1.61 (d, J = 7.0 Hz, 3 H), 5.41 (q, J = 7.0 Hz, 1 H), 7.26–7.89 (m, 4 H); ^{13}C NMR, see Table II; MS (rel intensity) 149 (M^+, 21) 134 (63), 106 (100), 77 (31); IR (neat, NaCl) 1720 cm^{-1} (unlabeled 1762 cm^{-1}).

2-Methoxy-1(2*H*)-[*carbonyl*-^{13}C]benzocyclobutenone ([1-^{13}C]-3): ^{1}H NMR (CCl_4) δ 3.48 (s, 3 H), 5.41 (d, $J_{^{13}C-H}$ = 2.0 Hz, 1 H), 7.35–7.70 (m, 4 H); ^{13}C NMR, see Table III; MS (rel intensity) 149 (M^+, 7), 134 (100), 119 (30), 91 (50), 89 (54); IR (neat NaCl) 1725 cm^{-1} (unlabeled 1768 cm^{-1}).

Preparation of [*p*-[*carbonyl*-^{18}O](Methoxycarbonyl)phenyl]diazomethane ([^{18}O]-1c). Following the method of Bender,[30] a solution of *p*-cyanobenzaldehyde (**14**, 0.5 g, 3.8 mmol) in absolute methanol (0.23 mL, 5.7 mmol) and $CHCl_3$ (0.5 mL) was saturated with dry HCl, which was stirred at 0 °C and allowed to stand overnight. After evaporation of the solvent, the residue was washed with dry ethyl ether and dried in vacuo to give *p*-(methoxyiminomethyl)benzaldehyde hydrochloride as a pale yellow solid (590 mg, 77.8%). The imino ether (0.1 g, 0.5 mmol) was dissolved in $H_2{}^{18}O$ (99.2%, 50 μL, 2.5 mmol) and absolute THF (50 μL) and heated at 70 °C for 3.5 h. Cooling, extraction with ether, drying

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(Na_2SO_4), filtration, and concentration under reduced pressure gave *p*-[*carbonyl*-^{18}O](methoxycarbonyl)benzaldehyde (**15**, 70 mg, 85.4%) as a white solid: mp 59.0–60.5 °C; ^{1}H NMR ($CDCl_3$) δ 3.95 (s, 3 H), 7.89 (d, J = 8.0 Hz, 2 H), 8.15 (d, J = 8.0 Hz, 2 H), 10.00 (bs, 1 H); MS *m/e* (rel intensity) 168 (49.5), 166 (31.3), 164 (4.3), 137 (100), 135 (59.3), 133 (8.1), 107 (37.2), 105 (21.6); IR (neat, NaCl) 1722, 1690, 1655, 1575 cm^{-1}. From the MS data, the product was shown to be a 5.0/12.0/24.6/58.4 mixture of 4-OHCC$_6$H$_4$CO$_2$Me/4-^{18}OHCC$_6$H$_4$CO$_2$Me/4-OHCC$_6$H$_4$C(^{18}O)OMe/4-^{18}OHCC$_6$H$_4$C(^{18}O)OMe, and the % ^{18}O incorporation at the carbonyl oxygen was calculated to be 83.0%.

The labeled benzaldehyde (70 mg, 0.42 mmol) was treated with tosylhydrazine (78 mg, 0.42 mmol) followed by NaH to give the sodium tosylhydrazonate (140 mg, 98.2%), which was heated at 120 °C under reduced pressure (10^{-5} Torr) to give the desired diazomethane [^{18}O]-**1c** (70.2%) as an orange solid: mp 40.5–43.0 °C; ^{1}H NMR (CCl_4) δ 3.83 (s, 3 H), 4.93 (s, 1 H), 6.86 (d, J = 8.0 Hz, 2 H), 7.85 (d, J = 8.0 Hz, 2 H); IR (KBr) 2060, 1685 cm^{-1} (unlabeled 1719 cm^{-1}).

FVP of [*p*-[*carbonyl*-^{18}O]-(Methoxycarbonyl)phenyl]diazomethane. FVP was carried out as described above, and the following products were isolated by preparative TLC.

3-Methyl[*carbonyl*-^{18}O]phthalide ([^{18}O]-2): ^{1}H NMR (CCl_4) δ 1.57 (d, J = 8.0 Hz, 3 H), 5.50 (q, J = 8.0 Hz, 1 H), 7.31–7.93 (m, 4 H); IR (neat, NaCl) 1759, 1738 cm^{-1} (unlabeled 1762 cm^{-1}); MS, see Table V.

3-Methoxy-1(2*H*)-[*carbonyl*-^{18}O]benzocyclobutenone ([^{18}O]-3): ^{1}H NMR (CCl_4) δ 3.45 (s, 3 H), 5.21 (s, 1 H), 7.31–7.76 (m, 4 H); IR (neat, NaCl) 1735 cm^{-1} (unlabeled 1768 cm^{-1}); MS, see Table IV.

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Facile Proton Transfer Reactions of *N,N*-Dimethylaniline Cation Radicals

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Abstract: Ring-substituted *N,N*-dimethylaniline (DMA) cation radicals undergo rapid proton transfer reactions with acetate ion or pyridine in acetonitrile. The difference in pK_a of the parent DMA and DMA$^{\bullet+}$ was estimated to equal 27 using electrode potentials in a thermochemical cycle. Second-order rate constants for the reaction with acetate ion at 298 K ranged from 3.2×10^6 for the *p*-methoxy-substituted cation radical to 3×10^9 M^{-1} s^{-1} for the corresponding *p*-nitro derivative. Rate constants for the reactions of the cation radicals with pyridine were observed to be as much as 10^6 lower than with acetate ion. Activation parameters for the two series of reactions differed markedly. Enthalpies of activation ($\Delta H^{\ddagger}$) on the order of 20 kcal/mol and large positive activation entropies ($\Delta S^{\ddagger}$), 35–53 eu, were characteristic of the acetate ion reactions, while for pyridine, $\Delta H^{\ddagger}$ ranged from 2 to 13 kcal/mol and $\Delta S^{\ddagger}$ values were large and negative, −15 to −29 eu. Large k_H/k_D values for reactions of ArN(CD$_3$)$_2^{\bullet+}$ implicate proton transfer as the rate-determining step in both reaction series. The differences in activation parameters for the two sets of reactions were attributed to differences in the position of the preequilibrium between base and cation radicals. A large equilibrium constant is expected for the reversible ion combination between acetate ion and the cation radicals.

Introduction

Although the thermodynamics of proton transfer reactions of cation radicals has recently received a great deal of attention,[2-4] much less is known about the kinetic acidities of these reactive intermediates.[5-8] Cation radicals of methylbenzenes undergo highly exergonic proton transfer reactions to pyridine bases in acetonitrile at moderate rates.[5] The kinetics of aryl proton transfer from 9-phenylanthracene cation radical, which undergoes facile nucleophilic attack by acetate ion[9] or pyridine,[10] to 2,6-di-*tert*-butylpyridine has recently been reported.[6] Proton transfer from the nitrogen of 9-amino-10-phenylanthracene cation radical is the exclusive reaction with pyridine in acetonitrile at 298 K, with a second-order rate constant of about 10^7 M^{-1} s^{-1}.[7]

Proton transfer from *N,N*-dimethylaniline (DMA) cation radicals is implicated in anodic nucleophilic substitution at the α-position to nitrogen by cyanide ion in acetonitrile[11] or methoxide ion in methanol.[12] In the absence of base, dimerization of *N,N*-dimethylaniline cation radicals in acetonitrile takes place even when the 4-positions are substituted with a halogen.[13] The observation that strongly nucleophilic cyanide ion attacked an α-proton[11] rather than a ring position of DMA$^{\bullet+}$ suggested suitably 4-substituted *N,N*-dimethylaniline cation radicals as substrates for cation radical deprotonation studies. Since the charge on DMA$^{\bullet+}$ is expected to be strongly localized on nitrogen, the

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