line (obtained by a least-squares computer program) which is $k_f + k_r$ and the equilibrium constant, k_f/k_r.[18] The rate constants obtained by the two methods agreed within ±5%.

Analogous procedures were used for the isomerization of the other olefins (Table V). The gas chromatographic analyses for 2,4,4-trimethyl-1-pentene were performed on 21 ft of 20% DC 200 on Chromosorb P 60–80 mesh. The 1-butene analyses were performed on a 10-ft sqalene on acid-treated Chromosorb 40–60 mesh. The allylbenzene isomerizations were analyzed on 21 ft of Carbowax 20 M.

Registry No. **1**, 763-29-1; **2**, 300-57-2; **3**, 107-39-1; K, 7440-09-7; KOH, 1310-58-3; KO-*tert*-Bu, 865-47-4; NaH, 7646-69-7; $NaBH_4$, 16940-66-2; LiBu, 109-72-8; $NaCH_2SOCH_3$, 32249-19-7; $MgPh_2$, 555-54-4; $NaNH_2$, 7782-92-5; $LiNMe_2$, 26480-00-2;; LiO-*tert*-Bu, 1907-33-1; NaO-*tert*-Bu, 865-48-5; RbO-*tert*-Bu, 3934-10-9; CsO-*tert*-Bu, 3934-09-6; KOMe, 865-33-8; KO-*i*-Pr, 6831-82-9; LiN-*i*-Pr_2, 26396-97-4; Li piperidino, 24316-38-9; Li cyclohexylamine, 26372-63-4; Li aniline, 32249-32-4.

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[18] A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," 2nd ed, Wiley, New York, N. Y., 1961, p 186.

A Novel Intramolecular Free-Radical Cyclization in the Vapor-Phase Arylation of Methyl Benzoate

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Nitrobenzene reacts with methyl benzoate at 500–600° to give phthalide, methyl biphenylcarboxylate, dimethyl biphenyldicarboxylate, and benzene as major products. Methyl *p*-nitrobenzoate with methyl benzoate at 600° gives the same products. Experiments with labeled reagents show that the products arise by hydrogen abstraction, cyclization, and decomposition of the carbomethoxy group of methyl benzoate. Arylation in the liquid phase gives no phthalide; the free-radical cyclization occurs only in the gas phase. Meta substitution predominates in the gas phase, whereas ortho substitution is favored in the liquid phase; apparently thermodynamic factors operating in the intermediate σ complex control the isomer distribution in the gas phase.

Earlier work from this laboratory on high-temperature arylations dealt with the arylation of benzene, aromatic fluorine derivatives, toluene, pyridine, and thiophene.[1] Those reactions involved the thermal decomposition of nitrobenzene above 500° to a phenyl radical and NO_2 in the presence of an excess of the aromatic substrate, and yielded biphenyl and substituted biphenyls as the major products. We have extended the scope of these arylations to include the reactions of methyl benzoate with nitrobenzene and methyl *p*-nitrobenzoate, compared the liquid- and vapor-phase arylations of methyl benzoate, and discovered a novel intramolecular free-radical cyclization.

Experimental Section

Reactions were run in a Vycor tube filled with Vycor chips in an electric furnace under pure dry nitrogen with contact times of 10–18 sec. Solutions of reactants were fed by a syringe whose needle fitted through a rubber septum in a glass adaptor connected to the Vycor tube. The syringe was pumped by an infusion pump (Harvard Apparatus Co., Dover, Mass., compact infusion pump, Model 974) at a rate to give the required contact time. During the reaction a sample of the noncondensable gases was taken for mass spectrometric analysis. The vapors from the reaction were condensed at −60°, the condensate was distilled to recover unreacted material, and the distillates and residues were analyzed by gas chromatography and mass spectrometry.

In a typical experiment, a solution of 6.2 g (0.05 mol) of nitrobenzene and 68 g (0.5 mol) of methyl benzoate was passed through a Vycor tube filled with Vycor chips at 600° under a nitrogen flow of 20 cc/min; contact time was 18 sec. The vapors were condensed in a flask at −60°; the condensate was distilled to give 2.9 g of low-boiling products (40–55° at 200 mm), 40.0 g of methyl benzoate, and 9.3 g of residue whose analysis is shown in Table I.

TABLE I

REACTION OF NITROBENZENE AND METHYL *p*-NITROBENZOATE WITH METHYL BENZOATE

Conditions			
Temp, °C	600	600	600
Nitrobenzene, mol	0.05		
Methyl *p*-nitrobenzoate, mol		0.05	0.05
Methyl benzoate, mol	0.50	0.25	0.50
Contact time, sec	18	13	11
Per cent conversion of nitro aromatic	94	72	72
Products[a]	Yield, mol %[b,c]		
Methyl biphenylcarboxylates	25	15	27
Dimethyl biphenyldicarboxylates	4	12	19
Phthalide	17	17	28
Biphenyl	9	3	6

[a] Other products included carbon monoxide, carbon dioxide, formaldehyde, methanol, methane, and methyl terphenylcarboxylates, as well as benzene and methyl benzoate. [b] Calculated on the basis of 0.05 mol of nitrobenzene and methyl *p*-nitrobenzoate giving a theoretical yield of 0.05 mol of each product. [c] Determined by gas chromatography.

Preparation of Aniline-d_5.—A mixture of 10 g of nitrobenzene-d_5, 150 ml of ethanol, 35 ml of 65% hydrazine, and 0.5–0.8 g of wet Raney nickel was refluxed for 1 hr. The filtered reaction mixture was distilled to obtain 5.4 g of deuterated aniline, bp 42° (0.2 mm); isotopic composition 0.1% d_3, 3.7% d_4, 95.2% d_5, 1.0% d_6.

Reaction of Diazotized Aniline-d_5 with Methyl Benzoate.—A solution of 3 g of aniline-d_5, 41 g of methyl benzoate, and 5 g of amyl nitrite was stirred for 5 hr at 120°. The reaction mixture was distilled at 200 mm to give 2.2 g of low-boiling products, 30 g of methyl benzoate, and 11 g of residue. Mass spectrometric analysis showed that the lower boiling products consisted of 96% benzene-d_6 and 4% benzene-d_4; the residue was methyl biphenylcarboxylates-d_5 with small amounts of methyl terphenylcarboxylates-d_9 and -d_{10}.

Analyses.—Mass spectra were measured on a modified Consolidated Model 21-103 instrument with the inlet system at 140°. Isotopic compositions were derived from low-ionizing voltage measurements in which possible isotope effects on sensitivity were ignored. Gas chromatographic separations were run on a column of 10% OV17 on Chromosorb W.

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[1] (a) E. K. Fields and S. Meyerson, *Intra-Science Chem. Rept.*, **3**, 219 (1969); (b) *J. Amer. Chem. Soc.*, **88**, 21 (1966); (c) *J. Org. Chem.*, **35**, 62, 67 (1970); (d) A. I. Feinstein, E. K. Fields, and S. Meyerson, *ibid.*, **35**, 303 (1970).

Results and Discussion

The products from the reaction of nitrobenzene and methyl *p*-nitrobenzoate with methyl benzoate are listed in Table I. The major higher boiling products were methyl biphenylcarboxylates, dimethyl biphenyldicarboxylates, and phthalide. Methyl benzoate alone under the same conditions was recovered in 95% yield. The thermal stability of methyl benzoate suggested that the products formed by a radical-induced decomposition of the carbomethoxy group. To learn more about the mechanism, nitrobenzene-d_5 was allowed to react with methyl benzoate. The isotopic distribution of the products is listed in Table II. The high percentages of undeuterated benzene, methyl biphenylcarboxylates, and methyl terphenylcarboxylates indicate that the major reaction is the radical-induced loss of the carbomethoxy group of methyl benzoate. The aromatic rings of these undeuterated components and the dimethyl biphenyldicarboxylates, and phthalide were derived solely from methyl benzoate. The yield of unlabeled benzene was 87%, based on 1 mol of nitrobenzene-d_5 giving 1 mol of benzene. This high yield suggests the participation of NO_2 as well as the phenyl-d_5 radical in the decarbomethoxylation of methyl benzoate (Scheme I).

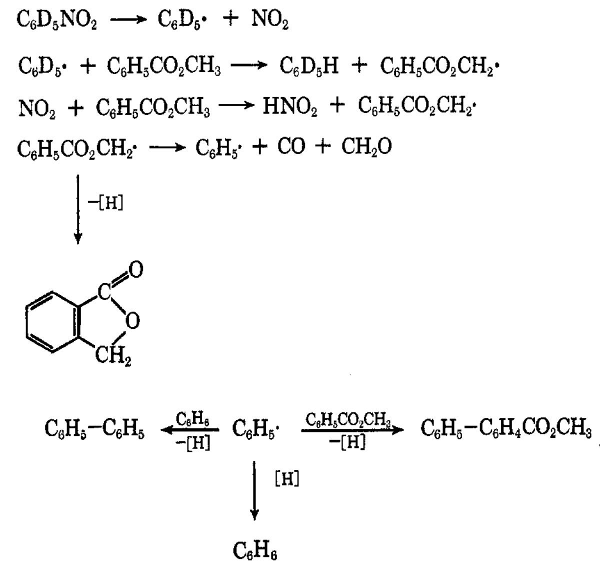
Table II

Reaction of Nitrobenzene-d_5 with Methyl Benzoate[a] (Isotopic Distribution of Products)[b]

D atoms	Benzene	Biphenyl	Methyl biphenyl-carboxylate	Methyl terphenyl-carboxylate
0	62	51	55[c]	43
1	2		2	14
2				
3	1		1	
4	7	12	10	14
5	28	32	32	29
6		2		
7				
8				
9		2		
10		1		

[a] At 600°, contact time 17.9 sec; mole ratio nitrobenzene-d_5: methyl benzoate = 1:10; isotopic composition of nitrobenzene-d_5: 3.3% d_4, 96.7% d_5. [b] Estimated from the low ionizing voltage (7.5 V, uncorrected) mass spectrum. [c] Dimethyl biphenyldicarboxylate, 100; phthalide, 100.

Scheme I



$$C_6D_5NO_2 \longrightarrow C_6D_5\cdot + NO_2$$

$$C_6D_5\cdot + C_6H_5CO_2CH_3 \longrightarrow C_6D_5H + C_6H_5CO_2CH_2\cdot$$

$$NO_2 + C_6H_5CO_2CH_3 \longrightarrow HNO_2 + C_6H_5CO_2CH_2\cdot$$

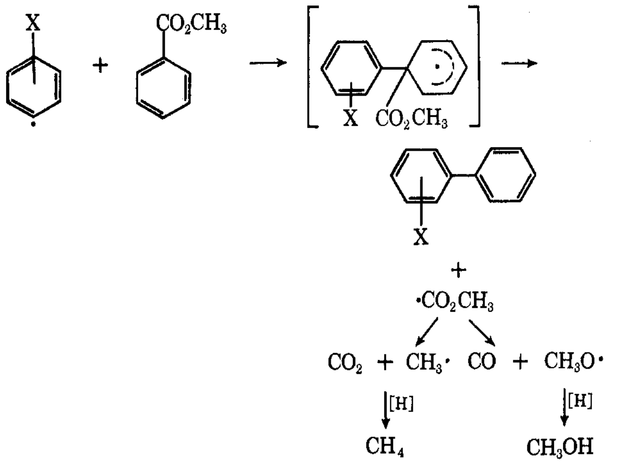
$$C_6H_5CO_2CH_2\cdot \longrightarrow C_6H_5\cdot + CO + CH_2O$$

$$C_6H_5{-}C_6H_5 \xleftarrow[-[H]]{C_6H_6} C_6H_5\cdot \xrightarrow[-[H]]{C_6H_5CO_2CH_3} C_6H_5{-}C_6H_4CO_2CH_3$$

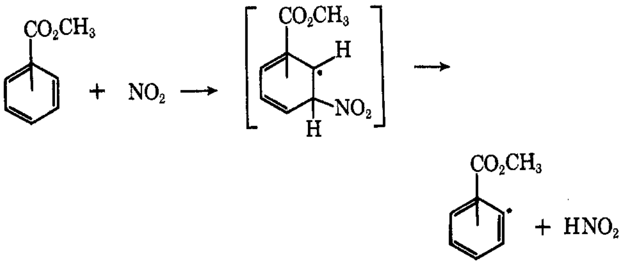
$$C_6H_5\cdot \xrightarrow{[H]} C_6H_6$$

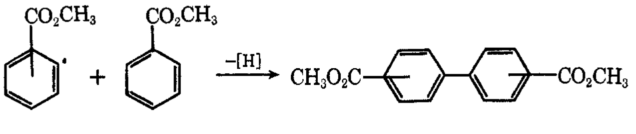
The phenyl-d_5 radical and NO_2 derived from nitrobenzene-d_5 abstract hydrogen from the methyl group of methyl benzoate to give a methyl benzoate radical with the radical site located α to the carboxy group. This intermediate can then decompose to phenyl radical, carbon monoxide, and formaldehyde, as well as undergo an intramolecular cyclization to give phthalide. The formation of phthalide by an intramolecular cyclization of this type has not been described until now.

The phenyl radical derived from methyl benzoate gives benzene by hydrogen abstraction; phenylation of methyl benzoate and benzene yields methyl biphenylcarboxylates and biphenyl, respectively. The formation of carbon dioxide, methanol, and methane in these reactions suggests that methyl biphenylcarboxylates and biphenyl could also result from a reaction involving the displacement and subsequent decomposition of a carbomethoxy group (X = H or CO_2CH_3).

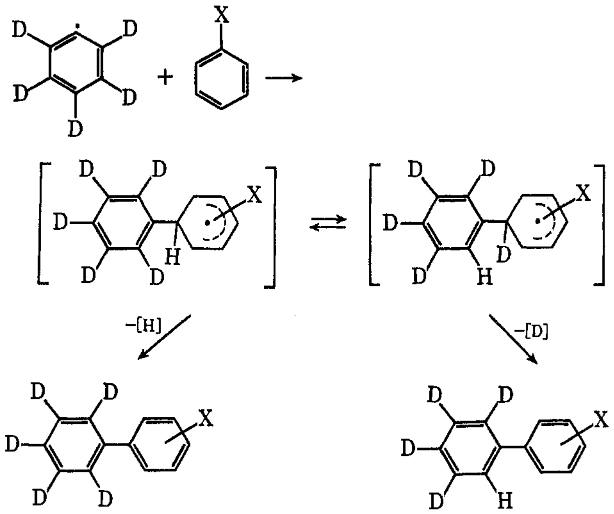


Dimethyl biphenyldicarboxylates form by arylation of methyl benzoate by the methyl benzoate radical. Abstraction of hydrogen from methyl benzoate to give methyl benzoate radicals is probably by addition of NO_2 to methyl benzoate followed by loss of HNO_2.





Arylation of benzene and methyl benzoate by the phenyl-d_5 radical gives biphenyl and the methyl biphenylcarboxylate-d_4 and -d_5. The d_4 species could arise from protium–deuterium exchange in the intermediate cyclohexadienyl radical (X = H or CO_2CH_3). This phenomenon has been observed in the pyrolysis of benzene-*d*.[1b]



Methyl terphenylcarboxylate had a deuterium distribution similar to that of methyl biphenylcarboxylate, and was evidently derived by arylation of the latter.

The reaction of methyl *p*-nitrobenzoate with methyl benzoate gave the same products as the nitrobenzene reaction (Table I). Although higher yields of dimethyl biphenyldicarboxylates were obtained from the former reaction, significant amounts of methyl biphenylcarboxylates were formed. Increasing the mole ratio of methyl *p*-nitrobenzoate to methyl benzoate from 1:5 to 1:10 did not have an appreciable effect on the yield of the dimethyl biphenyldicarboxylates.[2] The reactions which lead to the formation of phthalide and methyl biphenylcarboxylates (Scheme I) compete with the direct arylation of methyl benzoate and result in low yields of dimethyl biphenyldicarboxylates.

Comparison of Liquid- and Vapor-Phase Arylation of Methyl Benzoate.—Homolytic arylation of methyl benozate hitherto has been studied exclusively in the liquid phase.[3,4] Low reactivity toward phenyl radical of the C–H bond of the methyl group of methyl benzoate has been observed at 60°.[5] In other studies phenyl radicals were produced by thermal decomposition of benzoyl peroxide[3] and aprotic diazotization of aniline;[4] the only products reported were methyl biphenylcarboxylates. To determine whether decarbomethoxylation occurs in the liquid phase, we examined the reaction of the phenyl-d_5 radical made by the aprotic diazotization of aniline-d_5, with methyl benzoate at 120°. The major products were methyl biphenylcarboxylate-d_5 and benzene-d_5, along with small amounts of biphenyl-d_{10} and methyl terphenylcarboxylate-d_9 and -d_{10}. Phthalide and biphenyl-d_5 were not formed; evidently abstraction of methyl hydrogens α to the carboxyl group with subsequent loss of the carbomethoxy group does not occur in the liquid phase. The preferred arylation of methyl benzoate in the liquid phase suggests a high $\Delta H^{\ddagger}$ for the hydrogen abstraction reaction.

Another difference between the liquid- and vapor-phase arylations of methyl benzoate was the isomer distribution of the methyl biphenylcarboxylates, shown in Table III.

TABLE III

PHENYLATION OF METHYL BENZOATE

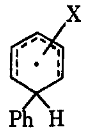
Source of phenyl radical	Isomer distribution of $PhPhCO_2CH_3$, % Ortho	Meta	Para
Benzoyl peroxide at 80° [a]	58	17	25
Aprotic diazotization of aniline at 120°	45	24	31
Nitrobenzene at 600°	9	52	39

[a] Reference 3.

Ortho substitution predominates in the liquid phase, whereas meta substitution is favored in the vapor phase. Meta substitution was also favored in the vapor-phase phenylation of chlorobenzene in which azobenzene was employed as the source of phenyl radicals.[6] The following mechanism has been generally accepted[7,8] for the liquid-phase homolytic arylation of arenes.

$$\text{radical source} \longrightarrow \text{Ph}\cdot \qquad (1)$$

$$\text{Ph}\cdot + \text{PhX} \longrightarrow \qquad (2)$$



(*o*, *m*, *p*) σ complex

$$\sigma\,\text{complex} + \text{R}\cdot \longrightarrow \text{PhPhX} + \text{RH} \qquad (3)$$

Isomer distributions are determined by step 2. However, if we assume that this step is reversible and neglect small differences in the relative rates of step 3, then the high meta percentage observed in the vapor phase can be rationalized on the basis of thermodynamic factors such as steric hindrance.[6] This rationalization is supported by the high meta percentages observed in the thermodynamic equilibria of $PhPhCl$[9] and $PhPhCH_3$,[10] which at 160 and 60°, respectively, are ortho, 3, 2.7%; meta, 64, 64.3%; para, 33, 33%. Thermal isomerization does not occur at 600° as evidenced by the recovery of unchanged dimethyl 4,4′-biphenyldicarboxylate from a separate experiment in which this isomer was submitted to the reaction conditions given in Table I alone.

The isomer distributions of the products from the reaction of methyl *p*-nitrobenzoate with methyl benzoate are listed in Table IV. The dimethyl biphenyldicarboxylate isomers show a high meta percentage and are consistent with the data from the other vapor-phase

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[2] Decreasing the mole ratios of nitrobenzene:benzene and nitrobenzene:pyridine resulted in increased yields of biphenyl and phenylpyridines, respectively.[1c]

[3] D. H. Hey, F. C. Saunders, and G. H. Williams, *J. Chem. Soc.*, 3409 (1964).

[4] L. Friedman and J. F. Chlebowski, *J. Org. Chem.*, **33**, 1633 (1968).

[5] G. A. Russell and R. Bridger, *J. Amer. Chem. Soc.*, **85**, 3754 (1963).

[6] R. Louw and J. W. Rothuizen, *Tetrahedron Lett.*, 3807 (1967).

[7] D. R. Augood and G. H. Williams, *Chem. Rev.*, **47**, 123 (1957).

[8] G. H. Williams, "Homolytic Aromatic Substitution," Pergamon Press, London, 1960, Chapter 4.

[9] H. Weingarten, *J. Org. Chem.*, **27**, 2024 (1962).

[10] R. M. Koca, private communication.

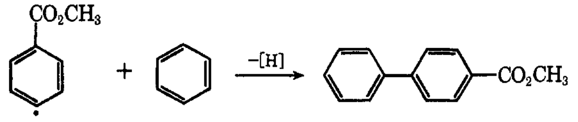
Table IV

Isomer Distributions from Reaction of Methyl *p*-Nitrobenzoate with Methyl Benzoate[a] at 600°

Methyl biphenylcarboxylate isomer	1:5[b]	1:10
2	6	7
3	36	40
4	58	53
Dimethyl biphenyldicarboxylate isomer		
2,4′	9	12
3,4′	56	64
4,4′	35	24

[a] Conditions given in Table I. [b] Mole ratio methyl *p*-nitrobenzoate:methyl benzoate.

arylations. Isomer distributions of the methyl biphenylcarboxylates are difficult to interpret, as they may arise either from the reaction of a phenyl radical with methyl benzoate or from the interaction of a methyl benzoate radical ($CH_3O_2CPh\cdot$) with benzene. The high para percentage suggests the latter.



Differences in isomer distribution of arylation products, as well as differences in the nature of the products formed, provide a sharp contrast between free-radical attack on methyl benzoate in the gas phase *vs.* the liquid phase. Formation of phthalide from methyl benzoate by reaction with radicals in the gas phase represents a new type of intramolecular alkylation. This reaction is being studied further to extend its synthetic utility.

Registry No.—Methyl benzoate, 93-58-3; nitrobenzene, 98-95-3; methyl *p*-nitrobenzoate, 619-50-1.

Acknowledgment.—We acknowledge with thanks the assistance of D. K. Albert and S. Meyerson of the American Oil Company for gas chromatographic and mass spectrometric analyses.

A Novel Route to Bicyclo[2.2.2]octenetetracarboxylic Acid Dianhydrides

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Acetoxy-1,3-dienes, generated *in situ* from mesityl oxide, 2-cyclopentylidenecyclopentanone, 2-cyclohexenylcyclohexanone, and pulegone, undergo the Diels–Alder reaction with 2 equiv of maleic anhydride to yield bicyclo[2.2.2]oct-7-ene-2,3,5,6-tetracarboxylic acid dianhydride derivatives. Hydrolysis of dianhydrides **7** and **8** derived from 2-cyclopentylidenecyclopentanone and pulegone yields tetracarboxylic acids, whereas hydrolysis of dianhydrides **4** and **6** derived from mesityl oxide and 2-cyclohexenylcyclohexanone affords triacid lactone derivatives. Ozonolysis of tetramethyl ester **13** derived from **7** results in exclusive allylic oxidation yielding the unsaturated keto tetramethyl ester **15**, and lead tetraacetate oxidation of the corresponding tetraacid **12** occurs with participation of the carbon–carbon double bond affording a mixture of dilactones **16** and **17**.

Cyclic acetoxy 1,3-dienes, generated *in situ* from cyclic 1,2-, 1,3-, and 1,4-diketones, and from α,β-unsaturated ketones, react with maleic anhydride,[2] *p*-benzoquinone,[3] and dimethyl acetylenedicarboxylate[4] to yield oxygenated bicyclo[2.2.2]alkene derivatives. We have now extended this study to acyclic and exocyclic α,β-unsaturated ketones and find that reaction takes place with 2 equiv, rather than 1 of maleic anhydride to afford, instead of the expected acetoxy cyclohexenedicarboxylic anhydride,[5,6] bicyclo[2.2.2]oct-7-enetetracarboxylic acid dianhydride derivatives.

Heating mesityl oxide in isopropenyl acetate containing a catalytic amount of *p*-toluenesulfonic acid with 2.3 equiv of maleic anhydride affords 1,8-dimethylbicyclo[2.2.2]oct-7-ene-2,3,5,6-tetracarboxylic acid dianhydride (**4**). Dianhydride **4** was identified by spectral analysis and by comparison with an authentic sample of **4** prepared by the reaction of 4,6-dimethyl-2-pyrone with maleic anhydride.[7]

The bridgehead methyl group of adduct **4** exhibits a unique nmr resonance signal at δ 1.98 ppm which is at lower field than the vinyl methyl group which resonates at 1.78 ppm. Examination of molecular models indicates that the methyl group is in the deshielding cone of two rigidly held anhydride carbonyls. Hydrolysis of adduct **4** with sodium bicarbonate solution, followed by acidification with hydrochloric acid and esterification with diazomethane, gives trimethyl ester lactone **5**[8] in which the bridgehead methyl group is found at 1.0 ppm, a chemical shift which is normal for methyl attached to a saturated carbon atom. We attribute this change to the free rotation permitted for the carbonyl groups of the carbomethoxy groups and subsequent removal of the deshielding effect displayed by the dianhydride.

A plausible pathway for the formation of dianhydride **4** in the condensation of mesityl oxide with maleic anhydride is shown in Scheme I. 1,2 or 1,4 elimination of acetic acid from the initially formed monoadduct[9] would yield dienes **2** or **3**. Under the conditions of the reaction, dienes **2** and **3** might be inter-

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[1] David Ross Research Fellow, 1968–1969.

[2] C. M. Cimarusti and J. Wolinsky, *J. Amer. Chem. Soc.*, **90**, 113 (1968).

[3] J. Wolinsky and R. B. Login, *J. Org. Chem.*, **35**, 1987 (1970).

[4] J. Wolinsky and R. B. Login, *ibid.*, **35**, 3205 (1970).

[5] H. J. Hagemeyer and D. C. Hull, *Ind. Eng. Chem.*, **41**, 2920 (1949).

[6] W. Flaig, *Justus Liebigs Ann. Chem.*, **568**, 1 (1950).

[7] O. Diels and K. Alder, *ibid.*, **490**, 259 (1931).

[8] Diels and Alder[7] reported the hydrolysis and esterification of **4** by this procedure and assigned the product, mp 155°, as a tetramethyl ester. The product we have isolated shows mp 153–154° and on the basis of its ir, nmr, and mass spectra is clearly trimethyl ester lactone **5**.

[9] P. Blanc, *Helv. Chim. Acta*, **44**, 1 (1961).