J. Am. Chem. Soc. 1993, 115, 82-86

The Photochemistry of Mixed Anhydrides: A Search for Selectivity in Photochemically Initiated Bond Cleavage Reactions

John H. Penn* and Walter H. Owens

Contribution from the Department of Chemistry, West Virginia University, Morgantown, West Virginia 26506. Received June 15, 1992

Abstract: A number of mixed anhydrides (RC(O)OC(O)R′) have been synthesized for the purpose of exploring the regioselectivity of their photochemical reactions. The photochemical reaction products, quantum yields, and reaction rates have been determined. For those compounds containing no α-hydrogens, high regioselectivity is obtained upon irradiation and can be understood on the basis of the relative C–O bond dissociation energies. The reaction can be quenched by intramolecular electron transfer. For those compounds containing α-hydrogen atoms, the Norrish type II reaction is faster than the corresponding C–O cleavage reactions, resulting in poor regioselectivity.

Introduction

Research in our group has focused on the selective cleavage of chemical bonds.[1] Recent investigations have been targeted toward conversion of the carboxylic acid functional group into other functionality which may be elaborated in synthetic schemes[2] or fossil fuel conversion processes.[3]

The conversion of carboxylic acids to aldehydes has received a great deal of attention by synthetic organic chemists. In all cases,[4] derivatives of the acid (i.e., acid chlorides, amides, esters) are converted to the aldehyde by selective reduction. None of these methods are generally applicable to a variety of functional groups and yields of the desired aldehyde tend to be ≤80%. Since there are difficulties with the reduction of the carboxylic acid derivatives, the standard synthetic procedure for the conversion of carboxylic acids to aldehydes involves the direct reduction of the acid followed by mild oxidation of the resulting alcohol. Recently Fukuyama[2] and co-workers have used the conversion of carboxylic acids to ethyl thiol esters followed by treatment with triethylsilane and a catalytic amount of palladium to yield aldehydes. This reaction appears to be reasonably general and is sufficiently mild to be unreactive toward other potentially reducible functional groups such as amides, sulfides, and olefins. However, the yields of the desired aldehyde are dependent upon the nature of other functional groups in the thiol ester.

To circumvent these problems and to develop a potential one-pot method for the conversion of the carboxylic acid group to a variety of other functional groups, we have investigated the reactions of mixed anhydrides. If the mixed anhydride could be cleaved with high regioselectivity via photochemical (or other) activation methods to the desired acyl radical, then the radical could be "tamed" by a variety of methods to functionalize as desired.[5] Our strategy requires the solving of several problems. (1) The reaction of carboxylic acids to form the mixed anhydrides must proceed in high yields for a variety of attached functionalities. This was easily accomplished through the use of acyl pyridiniums.[6] (2) The regiochemistry of the reaction must be controllable. Previous studies on the photochemical reactions of symmetrical anhydrides, cyclic anhydrides, and a variety of other carboxylic acid derivatives have shown that Norrish type I reactions and C–O cleavage reactions are the predominant excited state reaction pathways of these species, with the stability of the resultant radicals apparently controlling the reaction.[7,8] Calculations of the bond dissociation energies of the two carbonyl C–O bonds (Note bonds B and C in Figure 1) for various substitution patterns, using Benson's rules,[9] showed that 5–6 kcal/mol differences could be obtained between these two bonds. With such a high difference in energy, extremely high regioselectivity should be easily accessible. (3) Most importantly, activation of the cleavage must be accomplished in a way that utilizes the anticipated regioselectivity. We report here on our efforts to initiate the cleavage via photochemical means and the resultant attempts to control the cleavage pathways in a way which might lead to a useful synthetic method.

The compounds selected for this study are shown in Figure 1. These compounds were specifically chosen to vary the number of phenyl groups to systematically change the predicted bond dissociation energy of bonds B, C, and D. These changes may be reflected directly in the reaction rates and quantum efficiencies of the reactions. Compounds **1** have been classified as a group because they contain no α-hydrogens. Compounds **2** have been grouped together because they repesent a benzoic anhydride but contain α-hydrogens which might participate in Norrish type II reactions. Compound **3** was specifically synthesized to verify whether the high regioselectivity pattern observed in **1** might be observed in molecules containing α-hydrogens.

Results

Synthesis of Starting Materials. The syntheses of these mixed anhydrides have been previously described.[6] In brief, the appropriate acyl pyridinium complex is treated with the appropriate carboxylic acid to form the mixed anhydride as shown in eq 1 (see ref 6 for complete details of the synthetic procedures). All reactions producing mixed anhydrides proceeded in ≥93% yield, thereby fulfilling goal 1 of our required strategy for facile transformation of carboxylic acids to other functional groups.

(1)

---

[1] (a) Penn, J. H.; Lin, Z. *J. Am. Chem. Soc.* **1991**, *113*, 1001. (b) Penn, J. H.; Deng, D.-L.; Aleshire, S. K. *J. Org. Chem.* **1988**, *53*, 3572.

[2] Fukuyama, T.; Lin, S.-C.; Li, L. *J. Am. Chem. Soc.* **1990**, *112*, 7050.

[3] Stock, L. M. *Prepr. Pap., Am. Chem. Soc., Div. Fuel Chem.* **1987**, *32*, 463.

[4] (a) Cha, J. S.; Kim, J. E.; Yoon, M. S.; Kim, Y. S. *Tetrahedron Lett.* **1987**, *28*, 6231. (b) Corriu, R. J. P.; Lanneau, G. F.; Perrot, M. *Tetrahedron Lett.* **1987**, *28*, 3941. (c) Brown, H. C.; Cha, J. S.; Nazer, B.; Yoon, N. M. *J. Am. Chem. Soc.* **1984**, *106*, 8001.

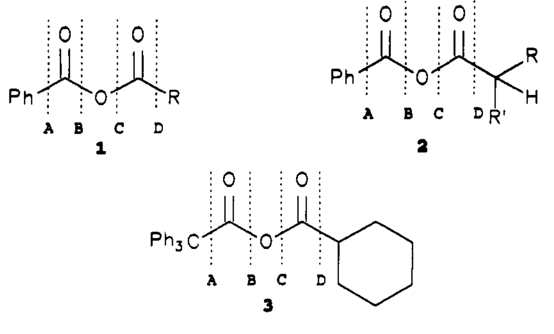
[5] (a) Barton, D. H. R.; Blundell, P.; Jaszberenvi, J. C. *J. Am. Chem. Soc.* **1991**, *113*, 6937. (b) Barton, D. H. R.; Blundell, P.; Jaszberenvi, J. C. *Tetrahedron Lett.* **1989**, *30*, 2341. (c) Barton, D. H. R.; Crich, D.; Kretzschmar, G. *Tetrahedron Lett.* **1984**, *25*, 1055. (d) Ueno, Y. *Pharmazie* **1984**, *39*, 123.

[6] Penn, J. H.; Owens, W. H. *J. Org. Chem.*, submitted for publication.

[7] (a) Scheffer, J. R.; Wostradowsski, R. A. *J. Org. Chem.* **1972**, *37*, 4317. (b) Scheffer, J. R.; Wostradowski, R. A. *Chem. Commun.* **1971**, 144.

[8] (a) Coyle, J. D. *Chem. Rev.* **1978**, *78*, 97 and references cited therein. (b) Roof, A. A. M.; van Woerden, H. F.; Cerfontain, H. *Tetrahedron* **1976**, *32*, 2967. (c) Chamberlain, G. A.; Whittle, E. *J. Chem. Soc., Faraday Trans.* **1975**, *1*, 1978. (d) Hiroka, H. *J. Am. Chem. Soc.* **1973**, *95*, 1664.

[9] Benson, S. W. *Thermochemical Kinetics*, 2nd ed.; John Wiley and Sons: New York, 1976.



1a: R = $C(CH_3)_3$
1b: R = CPh_3

2a: R = R' = H
2b: R = H; R' = Ph
2c: R = R' = Ph

Figure 1. Structures of the compounds selected for study together with possible bonds to cleave.

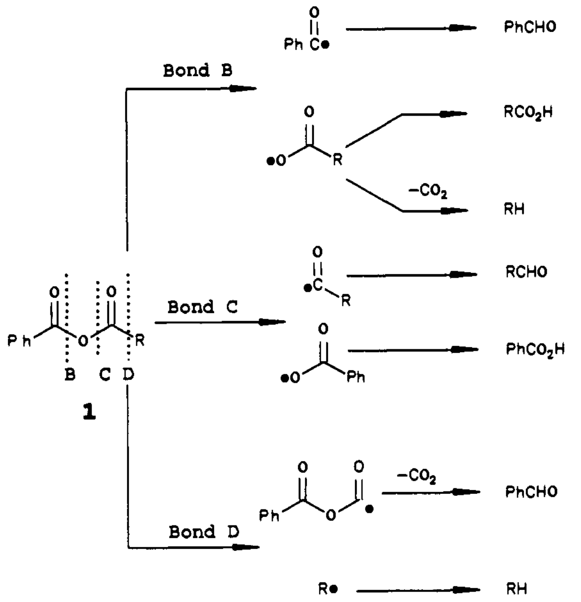


Figure 2. Photochemical bond cleavage reactions of anhydrides 1.

Exploratory Photolysis of Mixed Anhydrides with No α-Hydrogens. Benzoic pivalic anhydride (**1a**) and triphenylacetic benzoic anhydride (**1b**) were irradiated in acetonitrile solution (20 mM) using a Rayonet reactor with 300-nm lamps. The solutions were degassed by bubbling argon through the solution for 60 min prior to irradiation after which the solutions were sealed with latex septa. Since radical intermediates were expected from these reactions, 9,10-dihydroanthracene (DHA, 2 mM) was added as a hydrogen source to trap the radical species. The H-atom donor was kept at a low concentration to ensure that all the light was absorbed by the mixed anhydrides. The products from photolysis of triphenylmethyl **1b** were isolated. In all cases, GCMS, IR, and NMR spectra were identical with those from authentic samples. For solid compounds, mixed melting points firmly established the identities of the products. The products of *tert*-butyl **1a** were identified by comparison of their GCMS spectra and matching of retention times on 2 different GC columns (carbowax and phenylmethylsilicone columns).

As expected, the products resulting from photolysis of **1** can be easily rationalized by the analysis in Figure 2. Bond B cleavage leads to a radical pair from which benzaldehyde and RH or RCO_2H can be formed by hydrogen atom abstraction. Bond D cleavage proceeds similarly in that RH and PhCHO can be formed following decarboxylation and hydrogen atom abstraction. We note that bond B and bond D cleavage pathways result in similar products. The alternative cleavage pathway (i.e., bond C) results in $PhCO_2H$ and RCHO following hydrogen atom abstraction.

Table I. Photochemical Results for **1**

compd[a]	irrad time (h)	conv (%)	product yield[d] (mol %) PhCHO	RCO_2H	RH	$PhCO_2H$	RCHO
1a	10	18	97.2	7.2		20.1	
1b	26	9.4	96.3	2.0	101.0	1.9	0.8
1b[b]	26	10.3	98.6	1.7	99.1	1.4	0.3
1b[c]	26	9.8	99.2	2.1	100.6	1.5	0.5

[a] Reactions with added DHA as a hydrogen source. [b] Photolysis at 254 nm. [c] Triplet sensitized reaction with benzophenone. [d] Product yields are estimated to be ±5%.

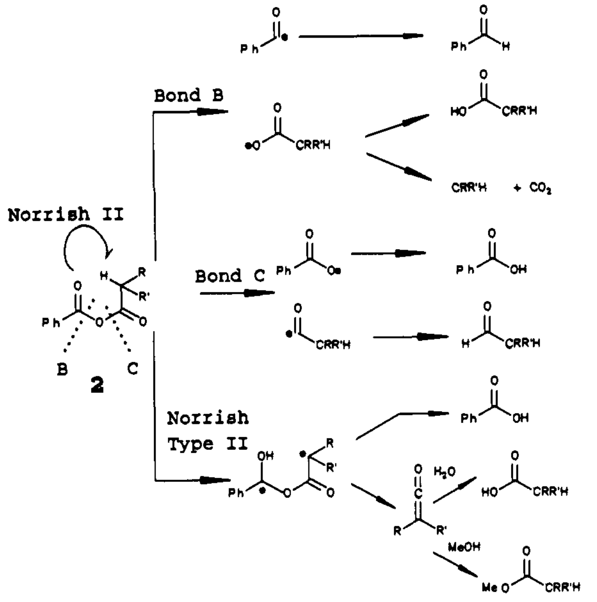


Figure 3. Photochemical reaction pathways for anhydrides **2**.

The quantitative results of these reactions are summarized in Table I and are shown diagrammatically in Figure 2. We estimate our error to be ±5% for all compounds. The amount of conversion was intentionally kept to a minimum value to avoid total consumption of the H-atom donor. These results were obtained from GC analysis using hexadecane as a internal standard. The mass balance for photoreactions of **1a** is not good. However, since $(CH_3)_3CCO_2^•$ is known to decarboxylate rapidly to $(CH_3)_3C^•$ ($k = 1.6 \times 10^9$ s^{-1}),[10] the resulting $(CH_3)_3CH$ or $(CH_3)_2C{=}CH_2$ formed by hydrogen abstraction would be sufficiently volatile as to make their analysis difficult. We have searched exhaustively for $(CH_3)_3CCHO$ in the reactions of **1a** but have been unable to detect any. Most informative is the addition of a small amount of a standard sample following the photoreactions in order to simulate the production of this material in solution. On the basis of these experiments, we conclude that the amount of $(CH_3)_3CCHO$ is ≤0.5%.

Exploratory Photolysis of Mixed Anhydrides Containing α-Hydrogens. Given the high regioselectivity of the reactions of **1b**, we were encouraged to attempt to generalize the regioselectivity of these mixed anhydrides. For this purpose, the influence of the triphenylmethyl group was evaluated by systematically deleting phenyl groups in the series **2c**, **2b**, and **2a**. Compound **3** was specifically synthesized in order to evaluate the possible competition of Norrish type II processes which would detract from the high regioselectivity observed in **1b**. The irradiations of **2** were performed in a manner analogous to the irradiation of **1**. The samples were irradiated in a degassed acetonitrile solution in a Rayonet reactor at 300 nm. The products from photolysis of DHA solutions of diphenyl **2c**, monophenyl **2b**, and cyclohexyl **3** were isolated. GCMS, IR, and NMR spectra of the isolated products

---

(10) Braun, W.; Rajbenbach, L.; Eirich, F. R. *J. Phys. Chem.* **1962**, *66*, 1591.

Table II. Photochemical Results for Compounds Containing α-Hydrogens

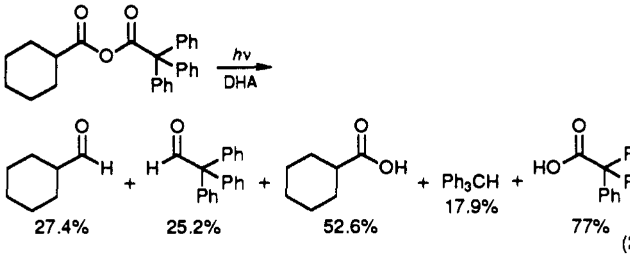
		irrad time (h)	conv (%)	product yields (mol %)						
				PhCHO	CHRR′CHO	$PhCO_2H$	$CHRR'CO_2H$	$PhCO_2Me$	$CHRR'CO_2Me$	CH_2RR'
2a	DHA	5.5	31	43.0	6.0	73.5	77.4			
	MeOH	5.5	43	36.4	4.2	67.8	62.9	11.3	23.5	
2b	DHA	12	24	16.4	13.0	83.6	77.4			9.2
	MeOH	12	25	15.2	14.4	86.2	6.4	2.8	69.8	6.5
	BZP[a]	12	25	17.1	13.6	82.9	78.2			9.5
2c	DHA	21	11	47.6	12.6	59.0	75.7			5.6
	MeOH	21	13	42.3	13.1	61.2	38.9	0.9	50.4	5.1
	BZP[a]	21	12	46.8	13.4	60.3	76.1			6.1

[a] Triplet sensitized reactions with benzophenone.

were identical with those obtained from authentic material. For all solid samples, mixed melting points served to confirm the identity of the products. For methanolic solutions, the methyl esters were identified only by their GCMS spectra. For acetic benzoic anhydride (**2a**), all products were identified exclusively by GC and GCMS techniques on a minimum of two independent GC columns (carbowax and phenylmethylsilicone).

Analogously to the photoreactions of **1**, the photoproducts of **2** can be rationalized as shown in Figure 3. Cleavage of bond B or bond D yields a radical pair from which PhCHO and either $CRR'CO_2H$ or CRR′H are obtained. Cleavage of bond C yields $PhCO_2H$ and CRR′HCHO. The Norrish type II reaction yields an intermediate biradical which can easily cleave to yield $PhCO_2H$ and a ketene. The ketene can be trapped either by H_2O or by MeOH to yield the carboxylic acid or the methyl ester, depending on reaction conditions.

The quantitative analyses of the reactions are presented in Table II for benzoic anhydrides **2** and in eq 2 for cyclohexyl anhydride **3**. These results were obtained from GC analyses using hexadecane as an internal standard. Control experiments showed that MeOH did not react with these anhydrides to any appreciable extent during the time scale of the experiments.



(2)

Sensitized Photolysis. Irradiations of degassed solutions containing 0.1 M benzophenone and 0.01 M mixed anhydrides **2b**, **2c**, and **1b** were performed. With these concentrations, benzophenone absorbs $\geq$96% of the incident light. The overall conversion amounts were unchanged by irradiation of the benzophenone rather than **2** or **3**. The product yields are given in Tables I and II. Since the product yields reproduce the "fingerprint" of reactivity for these compounds and since the conversion amounts were unchanged within experimental error, we conclude that the triplet excited state is responsible for the observed reactivity.

Quantitative Photochemical Measurements. Quantitative photophysical data were obtained for all of the mixed anhydrides. For all compounds, the quantum yield of disappearance of the starting material (ϕ_d) was measured by valerophenone actinometry.[11] The conversion of the anhydrides to products was measured by GC analysis as described above. In these experiments, the optical density of the actinometer at 300 nm was carefully adjusted to be identical with that of the anhydrides to ensure that the same amount of light was absorbed by sample and actinometer. The excited state lifetimes (τ's) were determined using Stern–Volmer quenching techniques with biphenyl as an excited state quencher assuming that quenching occurred at the diffusion-controlled limit (2×10^{10} m^{-1} s^{-1}).[12]

Discussion

Regiochemistry of Bond Cleavages. The regiochemistry of bond cleavage is most easily understood from those compounds containing no α-hydrogen atoms, i.e., compounds **1a** and **1b** (Table I). These compounds do not have Norrish type II processes readily available to them, making an analysis of their reaction pathways easier. The relative magnitude of the aldehyde yields allows an analysis of the regioselectivity of the photochemical reaction. This rationale follows from the relatively slow decarbonylation rates from aryl and alkyl acyl radicals relative to diffusion-controlled processes in which the added hydrogen donor (i.e., DHA) reacts with the acyl radicals. For example, the rate of decarbonylation[13] of $(CH_3)_3CC(\bullet)O$ is 1 s^{-1} while the rate of decarboxylation[14] of $(CH_3)_3CCO_2^\bullet$ to give $(CH_3)_3C^\bullet$ is ca. 10^9 s^{-1}. While the exact magnitude of the decarbonylation and decarboxylation reactions is substituent dependent, we believe that these numbers justify our assumption that the aldehyde yields reflect the direction of the bond cleavage.

As seen in Table I, the selectivity of cleavage of triphenylmethyl **1b** is quite high with an approximate selectivity of 96.3:0.8. The regioselectivity of this cleavage is in the desired direction, with bond B being preferred. Interestingly, triphenylmethane is formed as the major product partner to benzaldehyde. This presumably derives from the fast decarboxylation of the $Ph_3CCO_2^\bullet$. This is in accord with known decarboxylation rates of alkyl acyloxy radicals which typically are in the range of 10^9 s^{-1}.[14] Given the absence of $(CH_3)_3CCHO$ in the photoreactions of **1a**, it is tempting to conclude that the regioselectivity is also high for **1a*** to give exclusively bond B cleavage. However, given the problems with material balance in this reaction, we can envision several alternative explanations of the data which do not require regioselectivity of bond cleavage for **1a***.

A legitimate mechanistic question in the analysis of this regiochemistry concerns the order of cleavage of bonds B and D during the formation of Ph_3CH from compound **1b**. This question arises because of the known propensity for ketones[15] and anhydrides[8] to undergo Norrish type I processes which result in α-cleavage reactions. For compounds **1**, **2**, and **3**, this pathway would result in cleavage of bonds A or D depending on the compound. With our current data, we are unable to answer this question. As shown in Figure 2, cleavage of bond D in **1b** results in formation of $Ph_3C^\bullet$ and a radical which can lose CO_2 rapidly to yield $PhC^\bullet O$. Even if this radical were to abstract hydrogen faster than decarboxylation, the resulting PhC(O)OCHO would be expected to yield $PhCO_2H$ under our analytical conditions by reaction with H_2O. Therefore, this reaction pathway would go undetected. Thus, for the purposes of the photoreactivity of these anhydrides, bond D cleavage is indistinguishable from bond B cleavage. In a similar fashion, bond A cleavage is indistinguishable from bond

---

(11) Pitts, J. N., Jr.; Hess, L. D.; Baum, E. J.; Schuck, E. A.; Wan, J. K. S.; Leermakers, P. A.; Vesely, G. *Photochem. Photobiol.* **1965**, *4*, 305.

(12) Wagner, P. J.; Kochevar, I. *J. Am. Chem. Soc.* **1969**, *91*, 2232.

(13) Kerr, J. A.; Calvert, J. G. *J. Phys. Chem.* **1965**, *69*, 1022.

(14) Braun, W.; Rajbenbach, L.; Eirich, F. R. *J. Phys. Chem.* **1962**, *66*, 1591.

(15) (a) Turro, N. J.; McDaniel, D. M. *J. Am. Chem. Soc.* **1970**, *92*, 5727. (b) Agosta, W. C.; Smith, A. B.; Kende, A. S.; Eilerman, R. G.; Renham, J. *Tetrahedron Lett.* **1969**, 4517. (c) Paquette, L. A.; Eizember, R. F. *J. Am. Chem. Soc.* **1967**, *89*, 6205. (d) Crandell, J. K.; Arrington, J. P.; Hen, J. *J. Am. Chem. Soc.* **1967**, *89*, 6208.

Table III. Photophysical Measurements of Mixed Anhydrides

	ϕ_d	$k_q\tau$	τ (ns)	reaction pathway	$\chi_i{}^a$ (%)	$k_i{}^b$ (s^{-1})
1a	0.36	6500	340	bond B	97.2	1.0×10^6
				bond C		
1b	0.03	140	7.6	bond B	98.6	3.7×10^6
				bond C	0.8	6.7×10^4
2a	0.64					
2b	0.09	3400	180	bond B	16.4	8.2×10^4
				bond C	13.0	6.4×10^4
				Norrish II	70.6	3.5×10^5
2c	0.07	2300	120	bond B	47.6	2.8×10^5
				bond C	12.6	7.4×10^4
				Norrish II	39.8	2.3×10^5
3	0.16	3800	200	bond B	27.4	2.2×10^5
				bond C	25.2	2.0×10^5
				Norrish II	47.4	3.8×10^5

[a] χ_i represents the fraction of the total reactivity that originates from reaction pathway i. [b] k_i represents the reaction rate for reaction pathway i.

C cleavage. Our discussions of bond B and bond C cleavage are intended to include bonds D and A, respectively.

The regioselectivity of the photochemical reactions for compounds containing α-hydrogens (i.e., **2** and **3**) can be elucidated using the relative amounts of aldehyde formed from cleavage of bond B or bond C (Table II). This technique also relies on the assumption that decarbonylation of the acyl radical is slow relative to the hydrogen atom abstraction reaction to yield aldehydes as discussed above. A further consideration for **2** and **3** is the Norrish type II reaction. The α-hydrogens allow for an additional reaction pathway to be followed from **2*** and **3***. An estimate of the relative fractions of each reaction pathway is obtained by consideration of the relative amount of aldehydes and by the analysis of the reactions as in Figure 3. Monophenyl **2b** is representative and will be used to explain how the magnitude of each of the relative fractions of each pathway is obtained. PhCHO and $PhCH_2CHO$ are products which can only be obtained by cleavage of bonds B and C, respectively. This signifies that 16.4% of PhCHO and of products resulting from $PhCH_2CO_2{}^\bullet$ would be formed through cleavage of bond B. Since 9.2% toluene is observed (i.e., the loss of CO_2), only 7.2% of the $PhCH_2CO_2H$ arises via the bond B cleavage pathway. Similarly, 13.0% of $PhCH_2CHO$ and products resulting from $PhCO_2{}^\bullet$ are formed via cleavage of bond C. Since no benzene is observed as a product, the 13.0% of $PhCO_2H$ must originate from this reaction. The remainder of the product mixture (i.e., 70.6%) is assumed to originate from a Norrish type II process. In accord with this expectation, the total amount of $PhCH_2CO_2H$ is expected to be 77.8% (70.6% from Norrish type II processes and 7.2% from the bond B cleavage pathway) while the observed amount is 77.4%.

Confirmation of this analysis is provided by the quenching experiments with MeOH. The aldehyde yields are within experimental error of those obtained in CH_3CN alone. Since $PhCH_2CO_2CH_3$ can only be formed by the Norrish type II process, the anticipated yield of $PhCH_2CO_2CH_3$ is 70.4% (observed 69.8%), while the anticipated yield of 7.2% $PhCH_2CO_2H$ is consistent with the observed amount of 6.4%. The small quantity of $PhCO_2CH_3$ which is observed likely derives from the solvolysis of **2** as determined by a control experiment with no irradiation.

By this procedure, the relative ratios of each reaction pathway can be calculated for **2b** to be 16.4, 13.0, and 70.6% for reactions to cleave bond B, bond C, and the Norrish type II process. Data for **2c** and **3** can be calculated in a similar fashion. These relative fractions can be used to calculate rate constants for each individual reaction pathway as shown in Table III. The reaction rates for a given pathway (k_i) were calculated using eq 3, where χ_i is the

$$k_i = \chi_i \frac{\phi_d}{\tau} \tag{3}$$

fraction of a given reaction pathway with respect to the overall reactivity, τ is the lifetime of the excited anhydride, and ϕ_d is the quantum yield of disappearance for the anhydride.

A critical question concerning the validity of this analysis concerns the 7.2% of $PhCH_2CO_2H$ formed via the bond B cleavage reaction of **2b** and the ca. 40% of Ph_2CHCO_2H formed from **2c**. Pincock and co-workers[16] demonstrated that the rates of decarboxylation of aryl alkyl radicals in MeOH are ca. 5×10^9 s^{-1}. When this rate is compared to the rate of H-atom abstraction anticipated from the hydrogen donor DHA (estimated to be 2×10^7 s^{-1} from $[DHA]_0 = 0.002$ M and the rate of diffusion of 1×10^{10} M^{-1} s^{-1}), the formation of $PhCH_2CO_2H$ via the bond B cleavage pathway is hard to accept.

Two rationales may explain the observed data. In the first rationale, Pincock et al.[16] have shown that irradiation of aromatic and alkyl esters yields radical pairs which undergo subsequent electron transfer to yield aryl alkyl cations and carboxylate anions. Using this mechanism, anhydrides **2** would be expected to yield an acylium cation and a carboxylate anion. Although the acylium cations may be expected to do a hydride abstraction from DHA to generate the aldehydes observed, there is no hydride source available with added MeOH. Methyl esters would be expected. Since only small amounts of methyl esters, consistent with the amounts formed by hydrolysis during the time scale of the experiment, are observed, this mechanism cannot explain the observed data.

In the second rationale, the reactive carboxylate radical may interact with solvent molecules faster than decarboxylation. Although radical reactions with CH_3CN are not generally considered in photochemical reactions, two factors make such a pathway an attractive explanation. The reactivity of CH_3CN can be estimated by consideration of the bond dissociation energy (BDE) of the C–H bonds. The BDE of CH_3CN (93–95 kcal/mol) is diminished from CH_3CH_3 (98 kcal/mol) due to considerable resonance stabilization of the radical by the cyano group.[17] The reactivity of the carboxylate radical is exemplified by the reaction of resonance stabilized $PhCO_2{}^\bullet$ with solvent molecules of benzene to form a cyclohexadienyl radical which occurs with a high rate (ca. 10^8 s^{-1}).[18] Thus, if the reactions of the nonresonance stabilized carboxylate radicals encountered in this study with CH_3CN are faster than the rates of decarboxylation, the resulting ${}^\bullet CH_2CN$ would act as a radical carrier to eventually react with DHA on a time scale consistent with diffusional processes. The role of CH_3CN to act as a H-atom shuttle has been previously postulated.[19]

The rate constants as derived in Table III are somewhat remarkable. For compounds **1b**, **2b**, and **2c**, the rate of cleavage of bond C is identical within experimental error. If the rate of cleavage of bond C was controlled solely by the bond dissociation energy (BDE), then the constancy of the rate constant would not be surprising. However, such circumstances in which a photochemical reaction is controlled by a single factor are rare. Thus, we hesitate to firmly conclude that the BDE is the sole controlling factor in the cleavage of this bond.

The cleavage of bond B does show a modest change in reaction rates as one considers the effects of changing the number of phenyl substituents in the series **2b**, **2c**, and **1b**. To analyze the origins of this reaction rate behavior, it is important to recognize that bond B and D cleavage pathways are indistinguishable while bond A and C cleavage pathways are likewise indistinguishable. Consider the cleavage of bond D which represents a Norrish type I reaction pathway. Correlations of the radical energies with

---

(16) (a) Hilborn, J. W.; Pincock, J. A. *J. Am. Chem. Soc.* **1991**, *113*, 2683. (b) DeCosta, D. P.; Pincock, J. A. *J. Am. Chem. Soc.* **1989**, *111*, 8948.

(17) Karelson, M.; Katritzky, A. R.; Zerner, M. C. *J. Org. Chem.* **1991**, *56*, 134–7 and reference therein.

(18) (a) Korth, H. G.; Chateauneuf, J.; Lusztyk, J.; Ingold, K. U. *J. Org. Chem.* **1991**, *56*, 2405–10. (b) Chateauneuf, J.; Lusztyk, J.; Ingold, K. U. *J. Am. Chem. Soc.* **1988**, *110*, 2886–93.

(19) Eberson, L. *Acta Chem. Scand., Ser. B* **1980**, *B34*, 481–92.

(20) (a) Gleiter, R. *Acc. Chem. Res.* **1990**, *23*, 369. (b) Kovač, B.; Allan, M.; Heilbronner, E. *Helv. Chim. Acta* **1981**, *64*, 430. (c) Heilbronner, E.; Maier, J. P. *Helv. Chim. Acta* **1974**, *57*, 151. (d) Hoffman, R. *Acc. Chem. Res.* **1971**, *4*, 1.

photochemical Norrish type I reaction rates have been observed previously.[8] If one considers only the effects of changing phenyl substitution (i.e., **2b**, **2c**, **1b**) then a modest correlation of bond D cleavage (equivalent to bond B cleavage) to radical stabilization energies is observed. However, the *tert*-butyl substituted **1a** shows a faster bond cleavage rate than does monophenyl substituted **2b**. This does not correlate to the BDE of $(CH_3)_3CH$ and $PhCH_3$ (92 and 85 kcal/mol, respectively). This implies that other factors (e.g., steric effects, stereoelectronic effects) are involved in determining the bond cleavage reaction rates of the C–O bonds (equivalently bond D).

Efficiency of Bond Cleavage Reactions. The data presented in Table II also show an interesting relationship in reaction efficiency. This is most dramatic in the contrast between the ϕ_d for **1a** and **1b**. The origin of this effect is expressed in the excited state lifetimes of the series **2b**, **2c**, and **1b** (180, 120, 7.6 ns, respectively) in which the formally nonconjugated phenyl groups are added systematically to the mixed anhydride. The data are easily rationalized by using the Rehm-Weller equation for excited state electron transfer reactions (eq 4) where ΔG_{et} is the ΔG for electron transfer, $E_{1/2}(D/D^+)$ is the oxidation potential of the electron donor, $E_{1/2}(A/A^-)$ is the reduction potential of the acceptor, and E_{00} is the excited state energy of the molecule. The

$$\Delta G_{et} = E_{1/2}(D/D^+) - E_{1/2}(A/A^-) - E_{00} \qquad (4)$$

electron transfer can be either intramolecular or intermolecular. In this series of compounds, the electron donor is the phenylmethyl portion of the molecule for which the $E_{1/2}(D/D^+)$ is predicted to be relatively constant or to decrease somewhat if interactions of the phenyl groups are considered.[1,20] The $E_{1/2}(A/A^-)$, as measured by cyclic voltammetry and predicted by theoretical calculations,[6] increases by ca. 0.6 V as the number of phenyl groups are increased in this series of compounds. This effect is due to the change in the relative orientation of the carbonyl groups as dictated by increasing steric demands of the phenyl groups.[6] E_{00} is also predicted to increase as the carbonyl groups are reoriented relative to each other since the calculated n_s–π^* E_{00} increases as the twist angle increases. The sum total of the effects of $E_{1/2}$(A/A$^-$) and E_{00} are additive, since these effects operate to make for a lower energy electron transfer from the aryl groups to the excited state anhydride system. Confirming our analysis that electron transfer is responsible for the decreased ϕ of **1b** is $(CH_3)_3C$ **1a**. The lowest energy conformation and all electronic properties of the carbonyl groups are similar to that for **1b**.[6] However, the absence of phenyl groups leaves only alkyl groups which are known to be very difficult to oxidize. The result is no electron transfer and a long-lived excited state (τ = 340 ns).

An alternative rationale for the diminished τ's for **2c** and **1b** is from an anomaly in the Stern–Volmer quenching experiments. Since steric effects are known to result in decreased quenching efficiencies,[21] the increased steric interactions afforded by triphenyl **1b** might be expected to result in anomalous behavior (i.e., low lifetime). However, the long lifetime observed for sterically congested **1a** rules out a diminished quenching efficiency argument.

The long lifetime for **1a** has the net result that slower reactions can compete efficiently with excited state deactivation processes. Thus, the bond cleavage reaction rate for **1a** is somewhat slower than that for **1b**, even though efficiency of cleavage of **1a** is much higher. This finding suggests that truly regioselective chemistry may be obtained with high efficiency if the electron transfer quenching can be eliminated in these compounds. Studies attempting to verify this phenomenon are currently underway in our laboratories.

Summary

An understanding of the bond cleavage pathways of mixed anhydrides has been obtained. The photochemical reactions of mixed anhydrides containing no α-hydrogens can be highly regioselective (e.g., **1b**). Although the reactions can be highly regioselective, intramolecular or intermolecular electron transfer quenching can operate to dramatically decrease the efficiency of the reaction. Mixed anhydrides containing α-hydrogens undergo Norrish type II processes in competition with bond cleavage of the C–O bonds.

Experimental Section

Melting points were determined with a Laboratory Devices Mel-Temp apparatus and were uncorrected. Gas-liquid chromatography analyses were performed on a Hewlett-Packard Model 5890A GLC equipped with a 10-m 5% phenylmethylsilicone or a Carbowax 20M Megabore column. HPLC analyses were conducted on a Waters Associates Protein Peptides I system capable of gradient elution and UV detection at 254 nm. The HPLC system was equipped with a C_8 250-nm column. Integration of all chromatographic signals was performed by a Hewlett-Packard Model 3390A digital integrator. GCMS data were acquired with a Hewlett-Packard 5970 Series mass spectrometer equipped with a 5890 Series II GC with a 25-m 5% phenylmethylsilicone column. IR spectra were recorded on either a Perkin-Elmer 1600 Series FTIR or a MIDAC FTIR spectrophotometer. ^{1}H and ^{13}C NMR spectra (δ (ppm) and J (hertz)) were acquired on a JEOL GX-270 spectrometer in $CDCl_3$ or acetone-d_6 with TMS as an internal standard. Photochemical reactions were carried out in a Rayonet reactor at 300 nm unless otherwise indicated.

9,10-Dihydroanthracene (available from Aldrich Chemical) was used without further purification. Acetonitrile was freshly distilled from CaH_2, followed by distillation from P_2O_5, and finally distilled from K_2CO_3. Hexane, benzene, and ether were freshly distilled from $LiAlH_4$. Pyridine was distilled over KOH for 4 h prior to use. Benzoic acid, triphenylacetic acid, cyclohexanecarboxylic acid, *p*-bromotoluene, 3,5-dinitrobenzoyl chloride, benzoyl chloride, phenylacetic acid, phenylacetyl chloride, phenylacetic acid, tetraethylammonium perchlorate, and cyclohexanecarboxyl chloride are available from Aldrich Chemical Co. and were used without further purification. Diphenylacetyl chloride (available from Aldrich Chemical Co.) was recrystallized from $CHCl_3$ previous to usage. Acetic benzoic anhydride (**2a**), benzoic phenylacetic anhydride (**2b**), and trimethylacetic benzoic anhydride (**1a**) were prepared by the methods described by Blumberg and MacKellar.[22] Complete details of these syntheses have been previously described.[6]

Photochemical Reactions of Mixed Anhydrides. A typical photochemical experiment involves preparation of solutions 0.02 M in anhydride and 0.002 M in 9,10-dihydroanthracene (DHA) or 0.004 M in methanol in dry acetonitrile. The reaction mixtures are contained in quartz tubes and are degassed for 1 h with argon prior to irradiation and then sealed with a latex septum. The solutions were irradiated at 300 nm in a Rayonet reactor for the indicated length of time. Following irradiation, the reaction mixtures were placed on a 20 × 200 mm SiO_2 column and eluted with 250 mL of hexane/ethyl acetate (5:1) followed by 300 mL of hexane/ethyl acetate (2:3). In all cases, experimental spectra and melting points were compared to those of authentic materials to confirm structural assignments. Quantitative analysis of the photochemical reactions was conducted utilizing HPLC/GC techniques with naphthalene or hexadecane as internal standards. HPLC results were within experimental error to those results obtained by GC in all cases.

Quantum Efficiency Determinations. Degassed solutions of the appropriate anhydride were irradiated simultaneously with a solution of valerophenone as an actinometer (ϕ = 0.33).[11] Concentrations of the anhydride and valerophenone were adjusted to give equivalent optical densities by UV-vis spectroscopy. The solutions were irradiated for 10–21 h at 300 nm in a merry-go-round apparatus to give ≤15% conversion of the anhydrides as determined by HPLC and GC analysis. The conversion yields of valerophenone were measured by GC analysis using hexadecane as an internal standard.

Stern–Volmer Quenching Determinations. Degassed solutions of the appropriate anhydride with biphenyl (quencher) were irradiated simultaneously with a solution of valerophenone in the merry-go-round reactor. Quantitative analyses of the photolysates were obtained by HPLC and GC techniques.

Triplet Sensitization of Mixed Anhydrides. Degassed solutions of the appropriate anhydride (0.01 M) with benzophenone (0.1 M) were irradiated in the Rayonet reactor at 300 nm for the indicated time period. Quantitative analyses of the photolysates were obtained by HPLC and GC techniques.

---

[21] (a) Yang, N. C.; Feit, E. D.; Hui, M. H.; Turro, N. J.; Dalton, J. C. *J. Am. Chem. Soc.* **1970**, *92*, 6974. (b) Yang, N. C.; Feit, E. D. *J. Am. Chem. Soc.* **1968**, *90*, 504. (c) Penn, J. H.; Gan, L.-X.; Eaton, T. A.; Chan, E. Y.; Lin, Z. *J. Org. Chem.* **1988**, *53*, 1519.

[22] Blumberg, J. H.; MacKellar, D. G. (FMC Corp.), U.S. 3,560,529 (cl. 240-346.8; c 08f), 1968, 4 pp.