THE PHOTOCHEMISTRY OF AMIDES

AND PHTHALIMIDES

by

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Thesis submitted to the Faculty of the Graduate School of the University of Maryland in partial fulfillment of the requirements of the degree of Doctor of Philosophy 1977 VOI. 1 (up 2- CHEM)

APPROVAL SHEET

The Photochemistry of Amides and Title of Thesis: Phthalimides

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ABSTRACT

Title of Dissertation: The Photochemistry of Amides and Phthalimides Michael William Bowen, Doctor of Philosophy, 1977 Dissertation directed by: Dr. Paul H. Mazzocchi Associate Professor of Organic Chemistry

N-Alkyl amides undergo photodecomposition much slower than their ketone, ester, and aldehyde analogs. The Norrish Type II process in amides is also less important than in these other classes of compounds due to electronic and geometric effects. Type II products account for less than 10% of the decomposed amides in all cases and usually less than 5%.

A 2% solution of amide in dioxane, when irradiated through quartz with light >200 nm, did not decompose in the Type II fashion to yield N-alkyl acetamides, alkenes, and unsubstituted amides. The preferred reaction mode was the Norrish Type I process where the 0=C + N bond or the 0=C + Cbond was cleaved to yield either an acyl radical and amine radical or an acyl radical and alkyl radical. These photochemically unstable radicals, once produced, rapidly underwent secondary reactions to yield smaller molecules. These molecules were detected, underwent further reactions (polymerization; photoreduction), or interacted with the solvent.

The dimers of dioxane and cyclohexane, created via hydrogen abstraction, were the main products of amide photodecomposition in these solvents. Small aldehydes and alkenes, produced as intermediates, underwent inefficient photoreductions with solvent to afford alkyl dioxanes and cyclohexanes and the two diastereomers of (2-p-dioxyl) ethanol as other major products. The alcohols were also produced by photoreduction of acetaldehyde and hexanal as well as by direct photodecomposition of dioxane.

Tertiary amides reacted faster than secondary amides. The Type I reaction was accelerated by electronic (inductive) factors. The Type II reaction was also more efficient due to geometric and electronic factors. The Type I amine product, dihexylamine, was observed as an intermediate in the photodecomposition of N,N-dihexylhexanoamide.

Unsymmetrical anilide imides photodecomposed in dioxane to yield a wide variety of products. The Photo-Fries decomposition mode was most favored where acyl groups migrated to positions ortho and para to the amine substituent. For example, N-acetyl-butyranilide decomposed to yield o- and pacetoaniline, o- and p-butyraniline, o- and p-acetobutyranilide, and o- and p-butyracetanilide. Very little Type II decomposition was observed, that is, N-acetyl-butyranilide yielding N,N-diacetylaniline or o- and p-acetoacetanilide.

N-Alkylphthalimides were the sole group of amides or imides reported in the literature to undergo efficient γ hydrogen abstraction. These compounds underwent initial γ -hydrogen abstraction to yield a l,4-biradical followed by ring closure to form an azacyclobutanol intermediate. The intermediate then underwent retrotransannular ring opening to yield various 3,4-benzo-6,7-dihydro(lH)azepine-2,5-diones. Dihydrophthalimide alkenes were minor products in acetonitrile which arose after the initial γ -hydrogen abstraction via subsequent δ -hydrogen transfer.

Quantum yield determination as well as mechanistic investigation was conducted. The quantum yields varied from 0.023 to 0.003. Photolysis of an optically active phthalimide with an asymmetric γ -position to yield starting material of the same activity proved that the initial hydrogen abstraction was irreversible. A Type I cleavage to yield phthalic anhydride on treatment with silica gel and heat was important when the γ -position was tertiary.

A quenching study of these N-alkylphthalimides with piperylene showed acceleration of starting material disappearance but decrease in product formation. An additional reaction process was interfering with the azepinedione formation. Liquid chromatography showed formation of several highly alkylated products which could not be isolated in pure form.

N-Methylphthalimide, which could not ring expand, was irradiated with various alkenes to produce analogous Nmethyl-azepinediones. The mechanism involved a 2+2 cycloaddition of the double bond to the C-N bond to yield a dipolar azacyclobutane intermediate. The intermediate with a retrotransannular ring opening yielded the observed 3,4benzo-6,7-dihydro-l-methylazepine-2,5-diones. These reactions prove that the C-N bond in phthalimide is of a substantial double bond character.

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Acknowledgments

The author wishes to express appreciation to the people most instrumental in completing this thesis.

A great debt of gratitude is due Professor Paul Mazzocchi for his patience and guidance during my course of study. The author thanks other faculty members Bruce Jarvis, Steven Olin, and Stuart Staley for their advice and insight. The author also thanks fellow graduate students C.W. Jameson, T. Halchak, R. Lustig, H. Tamburin, and P. Nicholas for meaningful discussions of problems encountered. Three undergraduates, Edward Bodurgil, Joseph Crimi, and Ronald Wolff must be acknowledged for their assistance.

The author would like to also thank the following at Rhodia, Inc. for their cooperation and encouragement: E.G. Rand (Fragrance Manager), V. Marsello, Harold Larsen (Senior Perfumer), Gilbert Miller, and A. Daughtry.

The author wishes to show appreciation to his parents whose assistance and inspiration were invaluable during the investigation and writing. Finally, but not least, the author must acknowledge his wife, Linda, whose patience and understanding were instrumental in the completion of this thesis.

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AL, INTRODUCTION

PART I

Photochemistry of Amides

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§1. INTRODUCTION

Considerable interest has been shown in the design and synthesis of photo- and biodegradable polymers. Nylon, which contains amide linkages, was selected for investigation because of its similarity to compounds occurring in living systems. It was believed that this similarity might be used to our advantage for preparation of a biodegradable polymer.

Guillet¹ demonstrated that polymers of olefins with side chain carbonyl groups quite efficiently underwent a photochemical cleavage which severed the "backbone" of the polymer and thereby reduced the molecular weight. These lower molecular weight products could be isolated and tested for degradability. The photochemistry of these products could also be studied.

The photochemical decomposition of amides was documented but not extensively studied. Cleavage similar to that reported for the polyolefin reaction was proposed by Norrish² for the decomposition of amides, and it was assumed that the basic monomer units of a polymer would degrade by the same mechanism as the polymer itself. Different N-alkylamides would be used as models, and their study could be applied to the design of more complex amides and hence to polymers. In order for a monomer to be useful in a polymer design, that monomer must readily photodegrade.

Previous work in our research group indicated that prior work on amide photochemistry might be in error. N-alkylamides did not decompose as readily as expected, based on earlier

1 a

information. Recent work in the literature, by other investigators, has substantiated these observations.

The photochemistry of various N-alkylamides was investigated under the conditions reported by the previous researchers. Various inconsistencies concerning amide reactivity and the mechanism of these reactions were reconciled in this study.

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§2. HISTORICAL

Previous work on the photochemistry of amides was mostly based on the experiments of Booth and Norrish.² Norrish believed the primary decomposition processes were similar to the Type I and Type II processes in ketones and aldehydes shown below:

$$\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{2}\operatorname{CR}^{\prime} \xrightarrow{\operatorname{hv}} \operatorname{RCH}_{2}\operatorname{CH}_{2}^{2}\operatorname{CH}_{2}^{\prime}^{0} \xrightarrow{\operatorname{hv}} \cdot \operatorname{R}^{\prime}$$

Type I

$$\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{2}\operatorname{CR}' \xrightarrow{\operatorname{hv}} \operatorname{RCH}_{2}\operatorname{CH}_{2}^{2}\operatorname{CH}_{2}^{\bullet} + \operatorname{CR}'$$

Type II
$$\operatorname{RCH}_2\operatorname{CH}_2\operatorname{CH}_2^{\circ}\operatorname{CR'} \xrightarrow{\operatorname{hv}} \operatorname{RCH} = \operatorname{CH}_2 + \operatorname{CH}_3^{\circ}\operatorname{CR'}$$

Their work was done with unsubstituted amides, acetamide, proprionamide, butyramide, valeramide, and hexanoamide. These reactions were conducted in dioxane or in hydrocarbon solvents. Dioxane was used as a solvent because it was superior to hexane for dissolving amides and because it was a better hydrogen source for any radicals produced. The irradiations were conducted under vacuum with a 400 Watt mercury lamp at room temperature.

The photodecomposition of hexanoamide, valeramide, butyramide, and acetamide, followed by removal of the gas fraction at liquid nitrogen temperature, yielded hydrogen and carbon monoxide. The relative amounts of these products could be altered by filtering out low wavelength light. When the wavelength of irradiation was increased, the amount of hydrogen produced decreased relative to the yield of carbon monoxide.

A sample of butyramide, which was irradiated in dioxane, decomposed to give ethylene, ostensibly the alkene product from a Type II decomposition. Similarly, valeramide yielded propene, and hexanoamide yielded 1-butene. In contrast, proprionamide yielded ethylene as the unsaturation product. Ethylene was an unlikely product because what was understood to be the conventional Type II decomposition of proprionamide should generate a methyl radical, which would subsequently produce methane. (Methane was not observed.)

In order to explain these reactions Booth and Norrish proposed the following mechanistic scheme:

$$CH_3CH_2CH_2CH_2 \xrightarrow{0} hv CH_3CH_2CH_2NH_2 + CO Type I$$

Primary processes

$$CH_3CH_2CH_2^{O}CH_2 \xrightarrow{hv} CH_2 = CH_2 + CH_3^{O}CH_2$$
 Type II

Secondary processes

$$\begin{array}{c} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{NH}_{2} \xrightarrow{hv} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{NH}^{\bullet} + \operatorname{H}^{\bullet} \\ \operatorname{CH}_{3}\operatorname{CNH}_{2} \xrightarrow{hv} \operatorname{CH}_{3}\operatorname{NH}_{2} + \operatorname{CO} & \operatorname{Type} \mathrm{I} \end{array}$$

 $\begin{array}{c} h \, \nu \\ \text{CH}_{3} \text{NH}_{2} \longrightarrow \text{CH}_{3} \text{NH} + \text{H} \, \cdot \end{array}$

 $H \cdot + \text{solvent} \longrightarrow H_2 + \text{solvent} \cdot$

Booth and Norrish's work also included a study of alkyl amines. These amines on irradiation yielded unsaturated hydrocarbons, hydrogen, and simpler amines plus polymer. Type I and Type II processes were also proposed for the amines. (Naturally the secondary processes for amides would be those discovered for amines.) It must be pointed out that propylamine (the product of carbon monoxide extrusion) was not positively identified as a product in the photodecomposition of butyramide. Chemical tests indicated only that primary amines were formed.

Booth and Norrish differentiated Type I reactions for aldehydes from those for ketones and stated that amides follow the aldehyde process. Type I reactions of the ketone type yield acyl radicals, which either abstract hydrogen to give aldehydes or combine to yield α , β -diketones as shown below:

$$\begin{array}{c} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}}_{2}\overset{h}{\overset{}_{\operatorname{CH}}} \xrightarrow{h}{\overset{}_{\operatorname{CH}}} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} + \cdot \operatorname{NH}_{2} \quad (\operatorname{Type I-ketone type}) \\ \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} + \circ \underbrace{0} & \underbrace{0} & \xrightarrow{0} & \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} + \circ \underbrace{0} & \underbrace{0} & \operatorname{(abstraction)} \\ \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} + \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} \cdot \to \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} + \circ \underbrace{0} & \underbrace{0} & \operatorname{(abstraction)} \\ \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} \cdot + \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} \cdot \to \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} \cdot \operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} \cdot \\ & \underbrace{0} & \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{0}{\overset{}_{\operatorname{CH}}} \cdot \end{array} \right)$$

When neither aldehydes nor diketones were detected, this Type I process was discounted as a decomposition mode where no Type II process was possible. If the Type I ketone process were significant, then the following scheme would be operative:

$$CH_3 \xrightarrow{O} CNH_2 \longrightarrow CH_3 + CNH_2$$
 (Type I ketone)

Several conclusions, which have affected subsequent work and understanding of amide photochemistry, were made by Booth and Norrish. The light absorbing moiety was shown to be 0C-NH rather than the carbonyl or amine function independently. The decomposition mechanism was similar to aldehydes and ketones. Scission next to the carbonyl in the ketone Type I reaction was discounted due to the absence of aldehydes and α,β -diketones, which were not detected in chemical tests. They concluded that the important pathway was the Type II process which yielded alkenes and acetamide. Secondary processes and aldehyde Type I processes accounted for carbon monoxide and hydrogen production as well as the presence of the primary amines.

Spall and Steacie³ investigated the photodecomposition of acetamide at elevated temperatures. Their results partially agreed with those of Booth and Norrish but differed on some major points. The major components of acetamide decomposition were acetonitrile, water, carbon monoxide, methane, ethane, and ammonia. The mechanistic processes which lead

to these products are shown below:

$$NH_{2} \cdot + R \cdot \longrightarrow RNH_{2}$$
$$(CH_{3} \stackrel{0}{C} \cdot \longrightarrow CH_{3} + CO)$$

 $(CH_3^{O}C \cdot \xrightarrow{O} CO + CH_3)$

The first two reactions in the scheme were designated as the primary processes. It was determined that the formation of acetonitrile and water, however, occurred without irradiation under similar conditions. The other primary reaction was the Type I of Booth and Norrish. The hydrogens on nitrogen were replaced with deuterium in order to determine which hydrogens were abstracted by the methyl radicals. The methane produced was analyzed by mass spectroscopy, and the ratio of 17:16 mass was found to be very low implying that the α -hydrogens rather than nitrogen hydrogens were being abstracted.

Steacie did not overlook the fact that ammonia, carbon monoxide, and methane could have been produced by initial C-N bond cleavage to form an acetyl and an amine radical as shown below:

$$CH_{3} \stackrel{0}{\overset{}_{\text{CNH}}}_{2} \xrightarrow{h\nu} CH_{3} \stackrel{0}{\overset{}_{\text{C}}}_{2} + \cdot NH_{2}$$

$$CH_{3} \stackrel{0}{\overset{}_{\text{C}}}_{2} \xrightarrow{} CO + \cdot CH_{3}$$



Although it was not conclusively shown that C-N bond cleavage did not occur, it was assumed that C-C bond cleavage would occur for the following reasons.

If C-N bond cleavage occurred, the ratio of $(2 \times \text{ethane} + \text{methane})/\text{CO}$ should be one or less because the acetyl radical would decompose efficiently thermally as shown above.⁴ C-C bond cleavage would yield CH_3 and $\frac{0}{\text{CNH}_2}$. If the second radical did not always decompose spontaneously, the numerator of the expression (methane + 2×ethane) would be larger than the denominator (CO).^{*} This condition was observed.

Secondly, when bond energies are considered, a C-C bond scission is favored over C-N. The bond dissociation energies are 75 Kcal/mole and 94 Kcal/mole respectively, a difference of 19 Kcal/mole. (Although C-C bond cleavage is favored, other factors such as radical stability in the transition state lower the C-N bond energy and favor this cleavage.)

Thirdly, change to shorter wavelength irradiation favored production of carbon monoxide over methane and ethane. If the assumption is made that excess energy is divided between the two incipient radicals according to mass, the .CNH₂

Methane + 2×ethane = methyl radicals produced because two methyl radicals are used for each molecule of ethane. radical would possess 28 Kcal/mole at 2537Å and 37 Kcal/ mole at 2300Å. The calculated bond dissociation energy of the radical to yield CO and $\cdot NH_2$ is on the order of 35 Kcal/ mole or approximately the excess energy available. The probability of spontaneous decomposition for $\cdot CNH_2$ would be increased. Shorter wavelength irradiation should further induce decomposition and a lower (methane = 2× ethane)/CO ratio. All these conditions were observed. The same conditions would be true for CH_3G as an intermediate.

No Type II reactions were possible for acetamide, but Spall and Steacie did reaffirm the Type I reaction of the ketone type. It was significant, however, that no methylamine, the product of Booth and Norrish's Type I aldehyde process, was detected.

Further evidence for the Type I (ketone) reaction in amides was reported by Rideal and Mitchell⁵. Irradiation at 2350-2500Å of a uniform monolayer of stearanilide in aqueous acid support yielded stearic acid and aniline. These products arose from the reaction of the incipient acyl and imine free radicals with water. N-benzylstearamide and $N-\beta$ -phenylethylstearamide according to Carpenter⁶ photodegrade similarly to yield stearic acid and benzylamine and β -phenylethylamine respectively. These amides, however, also contained other chromophores.

The next step in the elucidation of the photodegradive mechanism of amides, and the first significant investigation

of simple N-alkyl amides was the work of Sharkey and Mochel.⁷ The study was one of photooxidation rather than a strict decomposition.

N-Pentylhexanoamide was Sharkey's amide of choice because its low melting point allowed study in the liquid state. When the lower wavelengths (<3000Å) were filtered out, the oxidation occurred very slowly as evidenced by the low consumption of oxygen. Irradiation at 50°C for 285 hours yielded aldehydes, acids, and hexanoamide. The acids were identified by comparison of chromatographic elution rates with those of known samples. Aldehydes were identified by the isolation by column chromatography of their individual 2,4-dinitrophenylhydrazone derivatives. The only positively identified gaseous products were CO and CO₂.

 $CH_{3}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{3}CH_{3} \xrightarrow{h_{V}} CH_{3}(CH_{2})_{4}CH_{2}CH_{2}CH_{4}CH_{2}$

+
$$CH_3CH_2CH$$
 + CH_3C-OH + $CH_3(CH_2)_3CH$
minor minor major
 C D E
+ $CH_3CH_2CH_2CH$ + CH_3CH_2CH + CH_3CH_2CH
minor minor minor
 E G H



In order to determine the mechanism three C¹⁴ labelled amides were used. The relative radioactivities of the products were measured, and the results are shown below:

$$CH_{3}(CH_{2})_{3}CH_{2}CH_{2}CH_{1}(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}} A (85\%) + B (inactive) +$$

$$CH_{3}(CH_{2})_{3}CH_{2}CH_{2}(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}} A (85\%) + B (inactive) +$$

$$CH_{3}(CH_{2})_{3}CH_{2}CH_{2}(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}} A (85\%) + B (inactive) +$$

$$E (inactive) + F (inactive) +$$

$$CH_{3}(CH_{2})_{3}CH_{2}CH_{2}(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}} A (85\%) + B (inactive) +$$

$$E (inactive) + F (inactive) +$$

$$E (inactive) + F (inactive) +$$

$$E (inactive) + F (inactive) +$$

 $CH_{3}(CH_{2})_{3}C^{14}H_{2}^{O}CH_{2}(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}} \bigwedge (98\%) + \bigoplus (7\%) + \bigoplus (6\%) + \bigoplus (6\%) + \bigoplus (1)$ $CH_{3}(CH_{2})_{3}C^{14}H_{2}^{O}CH_{2}(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}} \bigwedge (98\%) + \bigoplus (7\%) + \bigoplus (6\%) + \bigoplus (1)$ $CH_{3}(CH_{2})_{3}C^{14}H_{2}^{O}CH_{2}(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}} \bigwedge (98\%) + \bigoplus (7\%) + \bigoplus (6\%) + \bigoplus (6\%) + \bigoplus (1)$ $Q_{2} = \sum (1) \sum (1)$

Sharkey's evidence from the previous experiments indicated that the hydrogens on the carbon adjacent to nitrogen were active in photooxidation. In order to further test this conclusion a series of amides was studied where the stability of the radicals formed or the number of abstractible hydrogens was varied. The efficiencies of the reactions were measured by the quantities of oxygen consumed and the acid titers of the individual reaction mixtures. Tert-amyl hexanoamide consumed no oxygen, as expected, since there were no hydrogens on the carbon adjacent to nitrogen. Multiple substitution on the carbon α to the carbonyl (N-pentyl-2,2-dimethylhexanoamide) did not affect the amount of oxygen consumed over a set of irradiation times. In contrast to the earlier findings of Spall and Steacie these results show that the hydrogens on the carbon α to the carbonyl are not easily abstracted. When the number of hydrogens on carbon adjacent to nitrogen was increased (N-methyl-N-ethylhexanoamide), the amount of oxygen consumed was increased.

In view of the observed evidence Sharkey proposed the following mechanism:

$$\begin{array}{c} \begin{array}{c} 0\\ RCNHCH_2 R' & \longrightarrow \\ RC & + \\ \end{array} \end{array} \begin{array}{c} 0\\ RC & + \\ RC & + \\ \end{array} \end{array} \begin{array}{c} 0\\ RC & + \\ \end{array} \begin{array}{c} 0\\ RC & + \\ \end{array} \end{array} \begin{array}{c} 0\\ RC & + \\ \end{array} \begin{array}{c} 0\\ \end{array} \begin{array}{c} 0\\ RC & + \\ \end{array} \begin{array}{c} 0\\ \end{array} \end{array} \begin{array}{c} 0\\ \end{array} \begin{array}{c} 0\\ RC & + \\ \end{array} \begin{array}{c} 0\\ RC & + \\ \end{array} \begin{array}{c} 0\\ \end{array} \begin{array}{c} 0\\ \end{array} \begin{array}{c} 0\\ \end{array} \begin{array}{c} 0\\ RC & + \\ \end{array} \begin{array}{c} 0\\ \end{array} \end{array} \begin{array}{c} 0\\ \end{array} \begin{array}{c} 0\\ \end{array} \end{array} \begin{array}{c} 0\\ \end{array} \end{array} \begin{array}{c} 0\\ \end{array} \begin{array}{c} 0\\ \end{array} \end{array}$$
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No direct evidence for Type I (ketone) reaction was found since neither hexanal nor pentylamine was isolated. Both, however, may have been formed but further oxidized to hexanoic acid, valeraldehyde, or valeric acid. The initial log N-pentylhexanoamide yielded 260 mg (<4%) hexanoamide,which was equivalent to the sum of valeric acid and valeraldehyde produced.

Lock and Sagar⁸ showed that various N-alkylamides autooxidized thermally, catalytically, or photochemically to yield products not previously reported by Sharkey and Mochel⁷. The major products reported were N-acylamides (In addition N-formylamides were formed in thermal reactions). For example, the major product of N-propylproprionamide was N-proprionoylproprionamide. The reaction scheme should be revised to show:

 $\begin{array}{c} 0 \\ 11 \\ 11 \\ RCNHCH_2 R' \\ \end{array} \begin{array}{c} 0 \\ h \nu \\ RCNHCR' \\ 0 \\ 11 \\ RCNHCR' \\ 11 \\ RCNH_2 \\ \end{array} \begin{array}{c} 0 \\ RCNHCR' \\ 11 \\ RCNHC$

Moore⁹ investigated the photodecomposition of polyamides and found that, following irradiation, nylon showed a loss of tensile strength and color. Products were analyzed following hydrolysis of the polymer. For example, when Nylon 66 was photodegraded and hydrolyzed, besides the expected adipic acid and hexane diamine, carbon monoxide, carbon dioxide, pentylamine, pentanoic acid and acetic acid were produced. The reaction was essentially a photooxidation at long wavelengths, but at shorter wavelengths other reactions not requiring oxygen took precedence. On the basis of the isolated products, the following mechanistic scheme was proposed:

 $\sim \operatorname{COCH}_{2}\operatorname{CH}$

The oxidative process, however, was described differently:
$$\sim \operatorname{CO(CH}_{2})_{4} \operatorname{CONH-CH}_{2} \xrightarrow[hv]{hv} \sim \operatorname{CO(CH}_{2})_{4} \operatorname{CONHCH}_{1} + XH$$
$$\sim \operatorname{NH(CH}_{2})_{5} \qquad \sim \operatorname{NH(CH}_{2})_{5}$$

$$\sim \operatorname{CO(CH}_{2})_{4} \operatorname{CONHCH} \xrightarrow{\circ}_{2} \sim \operatorname{CO(CH}_{2})_{4} \operatorname{CONHCH} \xrightarrow{\circ}_{2} \sim \operatorname{NH-(CH}_{2})_{5} \sim \operatorname{NH-(CH}_{2})_{5}$$

$$\xrightarrow{\text{Path 2}} \sim \text{co(cH}_2)_4 \text{ conhcho} + \\ \sim \text{NHCH}_2 \text{CH}_2 \text{CH}_2 \text{CH}_2 \overset{\circ}{\text{CH}}_2$$

$$\sim \text{CO(CH}_2)_4 \xrightarrow{\text{CONHCH-OH}} \xrightarrow{\text{CO(CH}_2)_4 \text{CONH}_2} + \xrightarrow{\text{NH(CH}_2)_4 \text{CH}_2 \text{CHO}} \xrightarrow{\text{CO(CH}_2)_4 \text{CONH}_2} + \xrightarrow{\text{NH(CH}_2)_4 \text{CH}_2 \text{CHO}}$$

 $\sim \mathrm{NHCH}_2 \mathrm{CH}_2 \mathrm{CH}_2 \mathrm{CH}_2 \mathrm{CH}_2 \mathrm{CH}_2 \cdot \xrightarrow{\mathrm{XH}} \mathrm{X} \cdot + \sim \mathrm{NH(CH}_2)_4 \mathrm{CH}_3$

In order to better elucidate the mechanism of polyamide photodecomposition, Moore also investigated the decomposition of simple N-alkylamides. Most irradiations were conducted on neat solutions at elevated temperature (40°C) in oxygen flow systems. For example, when N-hexylhexanoamide, Nbutyloctanoamide and N-heptylhexanoamide were irradiated neat in the presence of oxygen, the following products were isolated:

$$CH_{3}(CH_{2})_{4} \stackrel{0}{\overset{}_{\text{CNH}}} (CH_{2})_{5}CH_{3} \stackrel{hv}{\longrightarrow} CH_{2} = CH(CH_{2})_{2}CH_{3} + CH_{3}(CH_{2})_{3}CH_{3} + CH_{3}(CH_{2})_{4}COOH + CH_{3}(CH_{2})_{4}COOH + (major) + (major) + (major) + CH_{3}(CH_{2})_{3}COOH + CH_{3}(CH_{2})_{2}COOH + CH_{3}CH_{2}COOH + CH_{3}(CH_{2})_{4}COOH + CO_{2} + CH_{3}(CH_{2})_{4}CONH_{2} + CH_{3}(CH_{2})_{4}CONH_{2$$

$$CH_{3}(CH_{2})_{6}^{0}CNH(CH_{2})_{3}CH_{3} \xrightarrow{h_{V}}{0_{2}} H_{2}^{0} + CO_{2} + CO + CH_{3}(CH_{2})_{5}CH_{3} (major) + CH_{3}(CH_{2})_{4}CH_{3} + CH_{3}(CH_{2})_{3}CH_{3} + CH_{2}^{-}CH_{2}(CH_{2})_{4}CH_{3} + CH_{2}^{-}CH_{2}(CH_{2})_{3}CH_{3} + CH_{2}^{-}CH_{2}(CH$$

On the basis of these products the following mechanistic scheme was proposed for the photooxidation, analogous to that of Spall and Steacie:

 $\begin{array}{cccc} \operatorname{RCONHCH}_{2}\operatorname{R}' &+ & X & \longrightarrow & X\operatorname{H} &+ & \operatorname{RCONHCHR}' \\ \operatorname{RCONHCHR}' &+ & \operatorname{O}_{2} & \longrightarrow & \operatorname{RCONHCHR}' \\ & & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & & \\ & & & & & & \\ & & & & & & \\ & & & & & & \\ & & & & & & \\ & & & & & & \\ & & & & & & \\ & & & & & & \\ & & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & & \\ & & & & \\ & & & & \\ & & & &$



Again, as with Sharkey and Sagar, the primary reactive site was the methylene group α to nitrogen. The mechanistic routes to isolated products could be easily drawn for both the simple amides and polyamides.

Moore also irradiated N-butyloctanoamide under nitrogen, in vacuum, and in cyclohexane solvent. N-heptylhexanoamide was irradiated neat in vacuum. The products isolated are shown below:

$$\xrightarrow{h\nu}_{N_2 \text{ flow}} \xrightarrow{CH_3(CH_2)_5CH_3 + CH_2 = CH(CH_2)_3CH_3} + CH_2(CH_2)_6COOH$$

 $\begin{array}{c} \text{CH}_{3}(\text{CH}_{2})_{6}\text{CONH}(\text{CH}_{2})_{3}\text{CH}_{3} \xrightarrow{\text{hv}} \text{CH}_{3}(\text{CH}_{2})_{5}\text{CH}_{3} + \text{CH}_{2} = \text{CH}(\text{CH}_{2})_{4}\text{CH}_{3} + \\ \text{CH}_{2} = \text{CH}(\text{CH}_{2})_{3}\text{CH}_{3} \text{ (major)} + \\ \text{CH}_{2} = \text{CH}(\text{CH}_{2})_{2}\text{CH}_{3} + \text{CH}_{2} = \text{CH}(\text{CH}_{2}\text{CH}_{3} + \\ + \text{CH}_{3}(\text{CH}_{2})_{6}\text{COOH} \end{array}$

hν

no alkenes

Cyclohexane

 $CH_{3}(CH_{2})_{4}CONH(CH_{2})_{6}CH_{3} \xrightarrow{hv} CH_{3}(CH_{2})_{3}CH_{3} + CH_{2}=CH(CH_{2})_{2}CH_{3}$ $+ CH_{3}(CH_{2})_{4}COOH \quad (with and without hydrolysis) + CH_{3}COOH \quad (hydrol-$

ysis) + heptylamine

Using the work of Cottrell¹⁰, Moore assumed that the bond was the weakest bond in the amide molecule. Of C - Nthe two amine bonds the N-CH $_2$ bond was assumed to be the weaker because the CO-N would be strengthened by resonance energy from the amide linkage. These bond energies were measured for homolytic splitting to free radicals where intramolecular scission would alter the relative bond energies. Mazzocchi and Thomas¹¹ found that application of ground state bond energies to excited state reactions is often incorrect. For example, in the photolysis of N-alkylpyrrolidinones, despite higher bond energy in the ground state, the important amide cleavage is CO-N rather than CH_2 -CO or N-CH₂. On the basis of the relative ground state bond energies and the products obtained, Moore proposed the following mechanistic scheme for non-oxidative photodecomposition of amides, which has many steps in common with those in the scheme of Booth and Norrish:

(1) $\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}$ - $\operatorname{CONHCH}_{2}\operatorname{CH}_{2}\operatorname{R}' \xrightarrow{h_{\mathcal{V}}} \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\overset{\circ}{\operatorname{CO}} + \operatorname{NHCH}_{2}\operatorname{CH}_{2}\operatorname{R}'$ (2) $\operatorname{RCH}_{2}\operatorname{CH}_{2}\overset{\circ}{\operatorname{CH}}_{2}\overset{\circ}{\operatorname{CO}} \xrightarrow{h_{\mathcal{V}}} \operatorname{RCH}_{2}\operatorname{CH}_{2}\overset{\circ}{\operatorname{CH}}_{2} + \operatorname{CO}$

(3)
$$\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2} + \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2} \longrightarrow \operatorname{RCH}_{2}\operatorname{CH}_{2} + \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}$$

(4) $\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2} + \operatorname{XH} \longrightarrow \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{3} + \operatorname{X}$
(5) $\operatorname{R}'\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{NH} \cdot + \operatorname{XH} \longrightarrow \operatorname{R'}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{NH}_{2} + \operatorname{X}$
or
(6) $\operatorname{R}'\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2} \longrightarrow \operatorname{Polymer}$ (?)
(7) $\operatorname{RCH}_{2}\operatorname{R'}$
(8) $\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CONH}_{2}\operatorname{CH}_{2}\operatorname{R'} \xrightarrow{\operatorname{hv}} \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CONH}_{2} + \operatorname{X}$
(10) $\operatorname{R'}\operatorname{CH}_{2}\operatorname{CH}_{2} + \operatorname{R'}\operatorname{CH}_{2}\operatorname{CH}_{2} \xrightarrow{\operatorname{CH}}_{2}\operatorname{CH}_{3} + \operatorname{R'}\operatorname{CH}_{2}\operatorname{CH}_{2} + \operatorname{X}$
(11) $\operatorname{R'}\operatorname{CH}_{2}\operatorname{CH}_{2} + \operatorname{XH} \longrightarrow \operatorname{R'}\operatorname{CH}_{2}\operatorname{CH}_{3} + \operatorname{X}$
(12) $\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CONH}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{R'} \xrightarrow{\operatorname{Type II}}_{\operatorname{hv}} \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CONH}_{2} + \operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{R'}$
(13) $\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{R'} \xrightarrow{\operatorname{Type II}}_{\operatorname{hv}} \operatorname{RCH} = \operatorname{CH}_{2} + \operatorname{CH}_{3}\operatorname{CONH}\operatorname{CH}_{2} \operatorname{CH}_{2} \operatorname{CH}_{2}\operatorname{CH}_{2} \operatorname{CH}_{2} \operatorname{CH}_{2} \operatorname{CONH}_{2} \operatorname{CH}_{2} \operatorname{CH}_{2}\operatorname{CH}_{2} \operatorname{CH}_{2} \operatorname{$

Equations (1)-(11) pertain to the products arising from an initial Type I reaction. Equations (1), (2), and (4) explain the formation of heptane from N-butyloctanoamide decomposition and of pentane from N-heptylhexanoamide decomposition. Isolation of 1-pentene from N-heptylhexanoamide and 1-heptene from N-butyloctanoamide decomposition would be explained by Equation (3). Equations (9)-(11) illustrate an alternate Type I process, which accounts for the formation of butene from N-butyloctanoamide decomposition via cleavage of the "weaker" N-CH, bond.

An alternate means for the production of the major alkene product, pentene, from N-hexylhexanoamide and N-heptylhexanoamide according to Moore would be:

 $\operatorname{RCH}_2\operatorname{CH}_2\operatorname{CH}_2\operatorname{CONHR}'' \xrightarrow{h\nu} \operatorname{RCH}_2\operatorname{CH}=\operatorname{CH}_2 + \operatorname{OCHNR}''.$

This process could not be proven by hydrolysis because formic acid and acetic acid were indistinguishable with the analytical method used.

The carbon monoxide extrusion process of Booth and Norrish is shown in equation (7). It is significant that Moore claimed to find heptylamine, the product of initial standard Type I reaction followed by hydrogen abstraction by the amine radical (equations (1) and (5)), condensed in a cold trap when N-heptylhexanoamide was irradiated under vacuum. When N-butyloctanoamide and N-heptylhexanoamide were irradiated under vacuum, N-butylheptylamine and N-pentylheptylamine respectively should have been isolated either in the cold traps or from reaction mixture if the carbon monoxide extrusion process were important.

Equations (11) and (12), which Moore viewed as important in the amide photodegradation, illustrated the Type II process of aldehydes and ketones also proposed by Norrish. Although hexanoamide was present in the N-heptylhexanoamide reaction mixture, and octanoamide was present in the N-butyloctanoamide reaction mixture under photooxidative conditions, the N-alkyl amides were absent when the irradiation was conducted under nitrogen or in a vacuum. The second product from this Type II cleavage would be 1-heptane (from N-heptylhexanoamide), 1-butene (from N-butyloctanoamide), or 1-hexene (from N-hexylhexanoamide), but none of these products were detected in the respective reaction mixtures.

The second Type II reaction (Equation (13)) would yield an acetamide as well as an alkene. Acetamide when hydrolyzed would yield acetic acid, which was generally detected in the photooxidation reaction mixture following hydrolysis. Parent ions should be detectable for N-hexylacetamide, N-butylacetamide, and N-heptylacetamide in the amide photoreaction mixtures of N-hexylhexanoamide, N-butyloctanoamide and N-heptylhexanoamide respectively, but only N-heptylacetamide was detected. N-heptylacetamide, however, was only detected in minor amounts in photooxidative processes, and no evidence other than a peak in mass spec at m⁺/e 129 and 116 was presented. The alternate alkene product 1-hexene, however, was observed for decomposition of N-butyloctanoamide in the absence of oxygen.

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Although Moore stated that Type I, Type II, and carbon monoxide extrusion processes were important in amide and polyamide decomposition, the experimental evidence indicated that only the Type I process, with some variations, would serve to explain the observed photo-products. Admittedly the analysis procedures used would have failed to detect some minor products. Also, reaction modes for neat samples would differ markedly from 2% solutions, but the photolysis with cyclohexane showed no isolated products, only the absence of alkenes. Type II and extrusion products were either present in minor amounts or absent.

Nicholls and Leermakers¹² further substantiated the lack of importance of Type II reactions and carbon monoxide extrusion in the amide photodecomposition. When the relative photodecomposition rates of various carbonyl compounds were compared, Leermakers observed that aliphatic acids and amides reacted considerably slower than aldehydes, ketones, and esters. Prolonged irradiation at 2537Å of unsubstituted amides in dioxane and acetonitrile showed no reaction.

When solutions of N,N-dimethylamides in dioxane and cyclohexane were irradiated at 2537Å, the reaction rate was greatly accelerated. The relative rates of reaction and quantum yields were virtually equal for N,N-dimethylbutyramide, N,N-dimethylproprionamide, and N,N-dimethylacetamide. Glpc analysis of the N,N-dimethylbutyramide reaction mixture showed none of the Type II product, N,Ndimethylacetamide.

In case the Type II product was produced but further decomposed before detection, a cophotolysis was conducted with N,N-dimethylacetamide and N,N-dimethylbutyramide and with N,N-dimethylacetamide and N,N-dimethylproprionamide. In neither case did the acetamide disappear faster than the other amide. The nearly equal reaction rates were further evidence that the Type II reactions were not occurring. Although Type II reaction was found to occur in aliphatic acids, Type I reactions were found by Leermakers to be the most significant for aliphatic amides. Relative decomposition rates and therefore Type I processes were accelerated by adding alkyl groups to nitrogen. He proposed the following simple mechanism to explain the decomposition:

(1)
$$\operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}^{2}\operatorname{CH}_{2}^{2} \xrightarrow{\operatorname{CH}_{3}} \xrightarrow{\operatorname{hv}} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}^{2}\operatorname{CH}_{2}^{2} \xrightarrow{\operatorname{CH}_{3}} \xrightarrow{\operatorname{hv}} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}^{2} \xrightarrow{\operatorname{CH}_{3}} \xrightarrow{$$

The initial reaction was the Type I C-N bond cleavage followed by fragmentation of the acyl radical to yield carbon monoxide. Propyldimethylamine, which could have been formed by carbon monoxide extrusion, was detected in small quantities in the N-N-dimethylbutyramide reaction and postulated to arise via recombination of the propyl radical with the dimethylamine radical. Regardless, Type II reactions were not observed in simple or N,N-dimethylamides by Leermakers.¹²

§3. RESULTS AND DISCUSSION

When 2% solutions of N-hexylhexanoamide were irradiated in dioxane or methanol, the results differed from those predicted by Booth and Norrish.² Irradiations were unproductive when short wavelength light was filtered out. Solutions containing amide and hydrocarbon internal standard showed no appreciable starting material disappearance with 2500Å wavelength irradiation (i.e., Corex filtered or selective monochromator irradiation at 2537Å) after more than 100 hours. Similar solutions showed considerable starting material disappearance when irradiated through vycor (>2100Å) or quartz (>1950Å).

According to Norrish the predicted Type I, Type II, and carbon monoxide extrusion products of a 2% N-hexylhexanoamide in dioxane irradiation would be as follows:

$$CH_{3}(CH_{2})_{4}^{0}CNH(CH_{2})_{5}CH_{3} \xrightarrow{h_{v}} CH_{3}CH_{2$$

$$\xrightarrow{\text{hv}} \text{CH}_2 = \text{CHCH}_2 \text{CH}_3 + \\ \xrightarrow{\text{Type II}} \text{CH}_3 \text{CNH(CH}_2)_5 \text{CH}_3$$

$$\xrightarrow{\text{hv}} \text{CH}_2 = \text{CH}(\text{CH}_2)_3 \text{CH}_3 + CH_2 \text{CH}_2 \text{CH}_2 \text{CNH}_2$$

$$\xrightarrow{hv} CO + CH_3(CH_2)_5NH(CH_2)_4CH_3$$
CO extrusion

Glpc analysis of the reaction mixture samples taken at various intervals showed none of the above mentioned products. In addition, the reaction rates for disappearance of starting material were much lower than for other types of carbonyl compounds.

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Carbonyl Photoreactivities

It was observed that amides were nearly unreactive when compared with other carbonyl compounds such as aldehydes, ketones, and esters. Starting material disappearance is one measure of the reactivity of a compound. A second method to measure the reactivity is the quantum yield Φ which is defined as follows:

 Φ = moles product/einsteins

In the equation moles of product produced is self-explanatory, and einsteins is defined as the moles of photons absorbed by the sample. Since several different photochemical mechanisms can be operating simultaneously, the total quantum yield is the sum of the quantum yields of the individual reactions or processes occurring.

The photochemistry of carbonyl compounds is described by two types of reactions, the Norrish Type I and the Norrish Type II. Many carbonyl compounds react by both processes to yield products. The relative amounts of Type I vs. Type II for a given compound are usually expressed in terms of quantum yields, may vary according to irradiation wavelength, and are determined by a combination of electronic and geometric factors.

The Norrish Type I process involves initial scission of the carbonyl carbon- α atom bond (C, H, N, O etc.) to yield an acyl radical and another radical whose type depends

on the starting material. The acyl radical can then undergo secondary decarbonylation to yield carbon monoxide and a primary alkyl radical or can abstract hydrogen from another starting material molecule or the solvent to yield an aldehyde.

$$R-CH_{2}-\overset{0}{C}-X-R' \xrightarrow{h\nu}_{Type I} R-CH_{2}-\overset{0}{C} + \cdot X-R'$$

$$\xrightarrow{or}_{\frac{h\nu}{Type I}} R-CH_{2} + \overset{0}{\cdot}C-X-R'$$

$$R-CH_{2}-\overset{0}{C} + CO + R-\dot{C}H_{2}$$

$$R' - X - \overset{0}{C} \cdot \longrightarrow CO + R' - X \cdot$$

$$R - CH_2 - \overset{0}{C} \cdot + ZH \longrightarrow Z \cdot + R - CH_2 - \overset{0}{C} - H$$

$$R' - X - \overset{0}{C} \cdot + ZH \longrightarrow Z \cdot + R' - X - \overset{0}{C} - H$$

0

X = C, O, N

Norrish Type II reactions usually proceed through a six-membered transition state where hydrogen is abstracted from the carbon γ to the carbonyl to yield a 1,4-diradical. The diradical can cleave to yield an olefin and carbonyl compound as shown below. An alternate process, shown by

Wagner¹³ and Yang¹⁴, is closure of the diradical to yield a cyclobutanol. Another secondary process is δ -hydrogen trans-fer to yield an alkene alcohol of the type R-CHOH-X-CH₂-CH=CH-R'



Figure 1. Type II Reaction Mechanisms for Carbonyl Compounds

In the case of ketones Calvert and Pitts¹⁵ observed that all known aliphatic ketones with γ -hydrogens reacted to some extent by the Type II reaction. For methyl n-butyl ketone the ratio of Type II to Type I quantum yields was ~7 at 3100Å and ~4 at 2537Å.¹⁶ Photolysis of labelled 2-pentanone showed a ratio of ~0.5 at 3130Å and 1 at 2537-2650Å.¹⁷ For ketones with longer side chains, such as methyl hexyl ketone or methyl heptyl ketone,¹⁸ Type II processes are nearly exclusive while Type I is proposed merely from analogy with other ketones. Type II processes were investigated by Scala and coworkers¹⁹ for esters and carbonates. Their experiments indicated that the oxygen α to the carbonyl favors Type II transition state formation more than a methylene group. The transition state involves OH bond formation as well as Y-H bond scission, hence, the C-H bond dissociation energy would be a large determining factor in Type II reactions for esters, as well as for other carbonyl compounds. Earlier work by Ausloos²⁰ and Wijnen²¹ showed the importance of Type II processes in the photodissociation of propyl acetate where $\Phi_{Type II/Type I} = 3.7 (<2400Å)$, isopropyl acetate where $\Phi_{Type II/Type I} = 8 (<2400Å)$, and propyl proprionate where the ratio was 0.5. Gano^{22,23} also observed the high efficiency of Type II processes in esters.

Type II reactions contribute heavily in the photodecompositions of aldehydes, although there is only one possible cleavage. Calvert²⁴ determined ${}^{\Phi}$ Type II ^{to} be 0.17 for 2-methylbutanal, and the reaction mode amounted to 20% of the overall reaction. Trottman-Dickenson²⁵ showed that Type II elimination was a major process in valeraldehyde. Norrish²⁶ determined ${}^{\Phi}$ Type II/Type I = 0.7 for isovaleraldehyde.

Aliphatic carboxylic acids also undergo Type II reactions. Nicholls and Leermakers¹² investigated the formation of acetic acid from butyric and valeric acid at 2537\AA . The quantum yields for acetic acid formation were 0.05 and 0.08 respectively, which, when compared with quantum yields

for starting material disappearance, shows 33% and 50% of the reactions respectively went by the Type II process. Photolysis in cyclohexane of 4-phenylbutyric acid and 5phenylvaleric acid showed little starting material disappearance and no acetic acid formation. What reaction had occurred was primarily due to the phenyl ring.

Even anhydrides have been observed to undergo a variation of the Type II process to yield an acid and ketene. Acetic anhydride decomposition is ~50% Type II according to Ausloos.²⁷ He further stated that proprionic anhydride yields methyl ketene and proprionic acid for about 50% of the detected product.

Consequently, it can be seen that Type II reactions are significant for nearly every type of carbonyl compound photodecomposition. The amount of Type II varies within a class of compounds and between classes of compounds.

Electronic Effects in Amide Type II Reactions

A cursory comparison of Type II quantum yields for an amide like N-hexylhexanoamide and a ketone like 2-hexanone reveals a great difference in their photoreactivity. The factors which allow Type II reactions in ketones are evidently absent or altered in amides.

For example, the quantum yield for the Type II processes for 2-hexanone has been accurately determined by Noyes^{16,28,29} at ~0.45. N-hexylhexanoamide has four γ -hydrogens available for abstraction or twice as many as 2-hexanone. Type II quantum yields for this amide and other secondary aliphatic amides studied, based on the long irradiation period with a quartz-filtered Hanovia lamp, are estimated to be at least an order of magnitude less than 0.01.

The Type II reactivity of carbonyl compounds must depend to no small degree on the bond strength or bond dissociation energy of the γ -hydrogens. The easier the γ hydrogen bond is to break the higher the reaction rate for hydrogen abstraction would be. Wagner¹³ and Yang³⁰ showed that for a series of butyrophenones where the γ -hydrogen was varied from primary to tertiary, the overall reaction rate increased but not the quantum yield for Type II reaction as shown in Table I.

Table I

13	c v Cube	+ i tuer	nts o	n Triplet	State	Reactivity
Effects c	r y-sub	Stituer		- <u> </u>	d Dut	monhonones
and Type II	Quantum	Yield	for	Substitute	<u>Buty</u>	rophenones
G	-					

Compound	γ-Hydrogen	10 ⁻⁸ k _r (sec ⁻¹)	Type II
PhCOCH2CH2CH3	1	0.08	0.36
PhCOCH ₂ CH ₂ CH ₂ CH ₃	2	1.3	0.33
PhCOCH ₂ CH ₂ CH ₂ (CH ₃) ₂ ³¹	3	4.8	0.25
PhCOCH ₂ CH ₂ (CH ₃) ₂	1	0.20	0.36
PhCOCH ₂ CH ₂ CH(CH ₃)OCH ₃ ³	1 2	7.0	0.21
PhCOCH ₂ CH ₂ CH ₂ C(CH ₃) ₃	2	2.0	0.24
PhCOCH2CH2CH2Ph	benzylic	4.2	0.50
PhCOCH ₂ CH ₂ CH ₂ CH=CH ₂	allylic	5.0	0.26
PhCOCH ₂ CH ₂ CH ₂ OH	1	3.9	0.31
PhCOCH2CH2CH2OCH3	1	6.2	0.23
PhCOCH ₂ CH ₂ CH ₂ N(CH ₃) ₂	1	4.0	0.03
PhCOCH2CH2CH2CL	l	0.3	0.09
PhCOCH ₂ CH ₂ CH ₂ CO ₂ CH ₃	1	0.1	0.50
PhCOCH ₂ CH ₂ CH ₂ CN	1	0.05	0.30
£			

Several observations can be made from the table. Namely the quantum yield for Type II reactions (Φ Type II) does not parallel the ketone reactivity. This fact is illustrated where the reactivity increased by a factor of 6 from primary to tertiary for γ -hydrogens, as expected from the bond strengths, but the Type II quantum yield decreased from 0.35 to 0.25. Another interpretation of these results, from the standpoint of induction, is that an increase in the number of methyl groups either increases the stability of the incipient 1,4-diradical or increases the electron density (nucleophilicity) of the hydrogen. This interpretation is substantiated by the increased reactivity of 4-methoxybutyrophenone and 4-N,N-dimethylaminobutyrophenone over

in the γ -position greatly decrease the reactivity of the butyrophenones. In Table II withdrawing groups in the δ -position of valerophenone are compared with their Hammett σ_{τ} values, reactivities, and Type II quantum yields.

		3	1		 Τ.	T
110	7	D		\bigcirc	۱.	
1	a	D	1.	0	1.	-

Ind	luctive ¹³	Effects	on	Triplet	State	Reactivity	
of	δ-Substit	tuted Va	ler	ophenones	(Pho	сосн_сн_сн_сн	R)

Substituent (R)	I	$\frac{10^{-8}}{r} (\text{sec}^{-1})$	Φ Type II
Alkyl	-0.05	L.5	0.30
Н	0	1.3	0.33
CH ₂ Cl	0.20	0.6	0.44
CO ₂ C ₆ H ₅	0.28	0.5	0.34
CO ₂ CH ₃	0.30	0.4	0.63
CO ₂ H ¹³	0.4	0.27	0.55
Cl	0.47	0.2	0.58
CN	0.56	0.1	0.46

Once again reactivity and Type II reaction quantum yield have no consistent relationship. There is good correlation between the reaction rate constant and the σ_{I} . As before the stronger withdrawing groups exerted the greater deactivation, even from the ε -position. From a graph of Table II a ρ -value of -2 was determined.

Yang³² and Wagner³³ found that substituents on the benzene ring also influenced reactivity and quantum yield. Yang observed that for photoreduction of acetophenone donating groups on the ring reduce reactivity while withdrawing groups such as trifluoromethyl increase reaction rate. Wagner observed that varying substituent ring position changed the reactivities of valerophenones. In addition, he found a p-methoxy substituent strongly electron donating, had a rate constant $10^{-8}k_r(\sec^{-1}) = 0.66$ compared with 20 for p-methyl (weakly donating) and 140 for unsubstituted valerophenone.

The -2 ρ value for substituents in the δ position, deactivation by donating groups on the aromatic ring for phenones, activation by donating groups in the γ -position, and deactivation by withdrawing groups in the γ and δ positions substantiate the assertion of Wagner^{31,34} that the carbonyl oxygen in Type II reactions is electrophilic, and that ketones are more reactive when the γ -hydrogen is more nucleophilic. He was able to show a similarity between the intermediate in ketone Type II reaction and the tertbutyl alkoxy radical. Comparison of the reactivity of (CH₃)₃C-0• with an analogous series of γ -hydrogens and the reactivity of the various γ and δ substituted phenones showed marked similarity.

Earlier studies by Walling³⁵ originated the concept of oxygen's electrophilicity in Type II reactions. The electronic excitation of interest is $n \rightarrow \Pi^*$ where an electron is promoted from one of oxygen's lone pairs to the lowest empty orbital, the antibonding carbonyl Π orbital. A resonance form of the ketone excited state shown below illustrates a positive charge on oxygen³⁶, which would make the oxygen electrophilic.

 $R_{2}C = \ddot{0}: \xrightarrow{h\nu} R_{2}\dot{C} - \ddot{0} \iff R_{2}\ddot{C} - \ddot{0}:$

Walling observed that inductive effects for hydrogen abstraction from toluene by tert-butoxy radicals proceeds in the order p-methoxytoluene > toluene > p-chlorotoluene. Benzophenone triplets were observed to abstract in the same order,which was similar to the inductive effects observed by Wagner for other ketones.

N-hexylhexanoamide has secondary hydrogens in the γ -position. The difference between the amide, and ketones like 2-hexanone, must be other than γ -hydrogen bond strength. Nitrogen is more electronegative than carbon. By induction, therefore, the nitrogen would be a σ withdrawer, and the carbonyl oxygen would be more electrophilic and should increase Type II reactivity.

Amides, however, are often shown with their dipolar resonance structure

$$R - \stackrel{0}{C} - \stackrel{\cdots}{N} \stackrel{R'}{\underset{R''}{\longleftarrow}} R - \stackrel{0}{\stackrel{C}{C}} = \stackrel{N}{\underset{R''}{\oplus}} R',$$

The major contributing structure was presumed to be the amide form, and Beak³⁷ substantiated the assumption with a collection of ultraviolet data on select compounds.



Specker and Gawroch's³⁸ work on the above tautomers provided the foundation for Beak's work by showing that the equilibrium lies far in favor of the amide despite the extra stability to be attained with the aromatic ring system in the iminol form.

The iminol form with negative charge on oxygen shows a nucleophilic rather than electrophilic oxygen. The dipolar form, according to Pauling³⁹ contributes to the point where the C-N bond has 40% double bond character. Idoux and Zarrillo⁴⁰ substantiated the I character of the C-N bond by proving that the bond would transmit conjugation in one direction. The low Type II reactivity of amides could be a reflection of the high electron density on oxygen in the excited state.

Physical studies by Nakagura⁴¹ on formamide and acrolein show that the 1717Å band of formamide arises from the charge transfer species rather than from an absorption analogous to the 1560Å band of formaldehyde. His wave functions show that the amount that the charge transfer species contributes varies from 20% in the ground state to 60% in the excited state. The electronic transition involves substantial electron transfer from a donating to an electron accepting group. Nakagura used a polarized ultraviolet absorption study of Peterson and Simpson⁴² to prove that the 1717Å band of formamide corresponds to the 1860Å band of formaldehyde. The direction of the transition moment for myristamide was inclined by 5-9° toward the carbon-nitrogen

axis and away from the oxygen-nitrogen axis, which shows this interpretation of the absorption spectra to be in line with the calculations.

The Mullikin electron population distribution is applied to the Π electrons in the formamide ground state in Table III.

Table III

Charge Density in the Formamide Ground State 43

Atom	et Charge	∏ Electron Density	
H [⊥] *	+0.357	0	
H ² *	+0.368	0	
з* Н	+0.152	0	
С	+0.258	0.695	
Ν	-0.758	1.806	
0	-0.377	1.499	

The nitrogen in the ground state evidently loses 0.2Π electrons to the carbonyl,which is already imbalanced toward oxygen. The nitrogen, although Π electron-poor, is overall electron-rich with a net charge of -0.758, which substantiates the assertion that nitrogen is a Π donor and a σ acceptor. Under these conditions another resonance

"H¹, H² and H³ were assigned in formamide as shown:



form, which must be included on an equal basis with the iminol form, is another dipolar structure.



The theoretical excited states for formamide were calculated using two molecular orbital methods. The first is the virtual orbital theory which shows electronic configurations of electrons promoted from higher occupied orbitals to lower unoccupied (virtual) orbitals. The weakness of this method is that it disregards correlation energy changes due to the alteration of electron pairs in the closed shell ground and open shell excited state, and the disregarding of electronic rearrangement, which certainly occurs with the unexcited electrons. Where these factors cannot be overlooked, Rydberg calculations are performed. Table IV shows that there is fair agreement of the two methods on the orbital population densities of interest.

A comparison of the ground, $n \rightarrow \Pi^*$, and $\Pi \rightarrow \Pi^*$ states shows a large change in the 3a", 10a', and 2a" molecular orbitals. The n orbital (10a') shows oxygen with 78% of the orbital in the ground state, but in the $n \rightarrow \Pi^*$ state the oxygen holds 94% of the orbital. A similar rearrangement occurs for the 2a" molecular orbital in the $\Pi \rightarrow \Pi^*$ transition. These calculations reaffirm the previous experimental assertion of Walling³⁵ and Wagner³⁴ that there is substantial electron density on oxygen in the excited state. The calculations show as well that there is some double bond character between carbon and nitrogen and indicates Π donation. These calculations also substantiate the assertion that the polarized excited state reflects the ground state configuration.

	0.1.+0]	Populatio	on Analys	sis for	Forma	mide ⁴⁴	
	Gre	ound Stat	е	n→ (trip	∏* let)	n→ (trip	∏* let)
Atom	n(10a')	(2a")	(3a")	10a'	<u>3a''</u>	2a''	3a''
		Rydb	erg Calo	culatio	n		
H -	0.009	0.0	0.0	0.003	0.0	0.0	0.0
H a	0.007	0.0	0.0	0.001	0.0	0.0	0.0
2 H _	0.110	0.0	0.0	0.030	0.0	0.0	0.0
3 C(val)	0.033	0.016	0.003	0.004	0.849	0.081	0.666
N(val)	0.058	0.519	0.003	0.019	0.079	0.210	0.124
O(val)	0.781	0.458	0.006	0.945	0.074	0.074	0.199
	Virt	ual Molec	cular Or	bital C	Calcula	tion	
Н	0.008	0.0	0.0	0.003	0.0	0.0	0.0
"1 Н	0.007	0.0	0.0	0.002	0.0	0.0	0.0
2	0.112	0.0	0.0	0.030	0.0	0.0	0.0
C(val)	0.033	0.017	0.724	0.002	0.846	0.099	0.662
N(val)	0.058	0.522	0.067	0.019	0.080	0.188	0.125
0(val)	0.782	0.461	0.209	0.944	0.074	0.713	0.213

T		1			T	Υ <i>Τ</i>	
1	а	D	1	e	1	V	

Donation of I electrons from the carbonyl to the nitrogen is also possible. Irradiation of N-haloamides yields an N-amidyl radical. With reverse I donation the 3I electron system would be analogous to an allyl radical or a dipolar iminol and would make the oxygen reactive as well as the nitrogen. The radicals in the ground state are shown below:



Johnson and Greene⁴⁶ irradiated N-chloro-N-(l,l-dimethylpentyl) acetamide in cyclohexane. If both the oxygen and nitrogen were reactive, there would be two possible Norrish Type II l,5-hydrogen abstractions,which are shown in the following reaction schemes:





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The investigators observed nearly quantitative formation (95%) of N-(1,1-dimethyl-4-chloropentyl) acetamide with the remaining 5% being N-(1,1-dimethylpentyl) acetamide. The chlorinated amide products arising from Pathway A, however, were not observed, although a pair of secondary and six primary hydrogens were available for 1,5-abstraction. When a quencher was added to stop the HCl propagation chain, the yield of Path B product increased to 100%. The following irradiations substantiated these results.





The 1,5-hydrogen abstraction by nitrogen was favored over that by oxygen despite the deactivating chlorine γ to

the nitrogen. There is no I back donation as the oxygen does not abstract hydrogen, which substantiates the observation of Chow and Joseph⁴⁷ that the reactivity of the oxygen is nil.

Amides then show lack of Type II reactivity due to the combination of the nitrogen's σ withdrawal from its electronegativity and I donation by the lone pair. The combination puts high electron density on oxygen making the oxygen nucleophilic rather than electrophilic as required for Type II reactivity. The adjacent oxygen in esters, however, is also electronegative and has two lone pairs available for I donation. Under the conditions above the esters should not undergo Type II reactions. It has already been noted that Scala¹⁹ concluded that esters efficiently undergo Type II reactions.

This discrepancy can be resolved by using the work of Pople, Del Bene, and Ditchfield.⁴⁸ The calculations showed the relative excitation energies for a series of substituents on HCO-X. The excitation energies were found to decrease in the order $X = NH_2 > OH > F > CH_3$. The total excitation energy was partially the sum of two components, σ withdrawal and I donation. Variation of the X substituent effects σ withdrawal in the order $F > OH > NH_2 > CH_3$. The variation effects I donation by X in the order $NH_2 >$ $OH > F > CH_3$.

The change in electronic excitation energy is due to changes in the individual orbital energies. There are four

main effects of which two are a direct result of Π donation. The Π^* orbital energy is increased. The donation increases the negative charge on the carbonyl oxygen (relative to HCHO), which effects a lower effective nuclear charge on oxygen causing the lone pair to be less tightly held. The σ withdrawal, however, stabilizes the carbonyl oxygen lone pair. The withdrawal also lowers the effective nuclear charge on oxygen and carbon which lowers the Π^* orbital energy.

The overall $n \rightarrow \Pi^*$ excitation energy is the sum of these competing effects. The NH of amides has greater Π donation but lesser σ withdrawal than OH. Decreased Π donation tends to decrease the $n \rightarrow \Pi^*$ transition energy, but all effects must be considered before explaining calculated values of n and Π^* orbitals in monosubstituted carbonyl compounds.

The comparative Type II reactivities of esters and amides can be explained under these terms. The σ withdrawal and Π donation apparently operate in opposite directions to give a net result that the $n \rightarrow \Pi$ * transitions for amides and esters are of nearly equal magnitude as shown in Figure 2.



N-amides HCHO (strong I donor) O-esters (strong σ withdrawer)

Figure 2. Comparative II and σ Effects on $n \rightarrow II^*$ Transitions in Esters and Ketones

In esters both the n and Π^* orbitals have lowered energy due to σ withdrawal. In amides the n and Π^* orbitals have raised energy due to the Π donation of nitrogen. The individual orbitals in amides and esters, although apparently raised or lowered to the same degree, do not have the same electronic structure (configuration). The carbonyl oxygen in amides due to Π donation has a high electron density,which as previously mentioned is not condusive to Type II reaction. Thus, although the $n \rightarrow \Pi^*$ transition energy is nearly the same, the nature of the reactivities of the two compounds are different. Geometric Effects in Amide Type II Reactions

A second factor which could effect the Type II reactivity of amides is the geometry of the amide bond. It has already been noted that the C-N bond has substantial double bond character due to II donation, which at least would restrict bond rotation. Wagner¹³ observed that molecules without the ability to attain a proper geometry, that is a six-member transition state, would undergo Type II reaction relatively inefficiently. For example, γ abstraction is preferred to δ abstraction by a factor of 20:1. Padwa⁴⁹ and Padwa and Eastman⁵⁰ observed that the close proximity of the hydrogen to the carbonyl oxygen is essential for Type II reactions. In exo-2-benzoylbicyclo [2.1.1] pentane the γ -hydrogens are in closer proximity to the oxygen in the triplet state than normal and are more reactive than the $\gamma\text{-hydrogens}$ of valerophenone. In phenyl cycloalkyl ketones the γ -hydrogens are held away from the carbonyl oxygen. As a result the triplet of phenylcyclopentyl ketone is 1/8 as reactive as that of valerophenone. Phenylcyclohexyl ketone does not undergo the Type II reaction.

The steric requirements ⁵¹ for Type II reactions make it important that no additional torsional strain be introduced during rotation to the transition state conformation. Any partially eclipsed conformation might be expected to make the Type II reactions less efficient. Simple alkyl substituents on the α , β , γ , and δ positions show only

inductive effects for γ -hydrogen abstraction rather than the expected steric effects. Hence, the α , β and β , γ C-C bonds must have staggered conformations.

At first, it was assumed that the oxygen, hydrogen, and γ -carbon must be coplanar for abstraction. That conformation would result in eclipsed conformations and torsional strain and be susceptible to steric substituent effects. In addition, this transition state conformation would appear to favor δ abstraction over γ abstraction from the standpoint of angle and torsional considerations (all atoms coplanar, at 120° optimum). A six-membered chair conformation, however, allows for the strain-free system and a minimum of steric hindrance for most alkyl substituents as shown below. This conformation accounts for the



ketone



alkoxy radical

similarity, alluded to previously, of the $n \rightarrow \pi^*$ Type II hydrogen abstraction and the hydrogen abstraction in alkoxy radicals. (Hesse⁵² observed the C-H-O angle to be much less than 180° for abstraction in alkoxy radicals.) Hydrogen abstraction from the δ position requires a sevenmembered transition state with its inherent torsional strain. The strain accounts for the lower δ -hydrogen abstraction rate.

Substituted amides of the form RCONHR' exist in two rotameric forms shown below:



trans

There is a substantial barrier to rotation, on the order of 15 Kcal, which varies with the nature of the R and R' groups, to prevent the interconversion. The cis form would be analogous to the phenyl cycloalkyl ketones where the hydrogens were too far from the oxygen for Type II reaction. La Planche and Rogers⁵³ showed by low temperature NMR

that the cis form was practically non-existent where R was a methyl or larger group for a spectrum of mono-substituted amides where $R' = CH_3$, CH_2CH_3 , $CH(CH_3)_2$, and $C(CH_3)_3$. The cis form becomes increasingly important in formamides as the R' group becomes bulkier, for example, tert-butyl. Dimerization, which occurs with formanilides in solution, requires the cis form, and as the concentration of amide is increased, the cis form becomes more favored. The cis form is more important in formanilides in general than for any of the N-alkyl amides.⁵⁴

Unsymmetrically disubstituted amides show conformational preferences according to steric considerations. In acetamides the bulkier group prefers to be cis to the oxygen and trans
to the methyl group. In formamides La Planche and Rogers⁵⁵ have found the reverse to be true for methyl N-alkyl formamides. The larger alkyl group prefers to be cis to the formyl H, and the preference is larger as the alkyl group becomes bulkier. Hence, the geometric preference about the hindered C-N bond appears to favor Type II reaction for the amides studied.

It was also observed experimentally that the C-C=0 and OCN-C bonds were not freely rotating as expected, and substituents on the carbons showed geometric preferences. The two angles of interest in describing these preferences are ψ and ϕ shown below.



Haigler, Leiserowitz, and Tuval⁵⁶ measured the torsion angle ϕ for different N-methyl amides and ψ for different N-substituted acetamides by X-ray crystallography. The preference for ϕ is an angle in N-methyl compounds where one C-H bond is anti to the OC-N bond. The preferred angle ψ in acetamides results in one C-H bond being eclipsed with the OC-N bond. (Acetyl glycine appeared to have free rotation and no preference with respect for ψ .) Hammaker and Gugler⁵⁷ proposed the following confor-

mation for N,N-diethylacetamide on the basis of chemical shifts in the NMR:



Although the spectroscopic data appears to be weak, steric considerations make the structure a logical selection. The geometry in this case of an N,N-dialkyl amide appears to be consistent with that necessary for Type II reactions.

Although no work was available to list the geometric preferences on the carbonyl or the nitrogen side of monoalkyl amides, steric considerations would indicate that R groups, such as pentyl, would rotate away from the center of the molecule. The carbon-carbon single bonds remote from the carbonyl, however, would experience only very slight restriction to rotation and on either side of the carbonyl could attain the conformation necessary for Type II reaction. Since that conformation is not necessarily preferred as Wagner¹³ observed it to be for ketones, geometry could reduce the Type II yield in amides but not by the amount observed for esters.

Photolysis of <u>N-hexylhexanoamide</u>

N-hexylhexanoamide <u>1</u> was prepared by addition of a hexanoyl chloride in THF solution to a hexylamine solution in 10% sodium hydroxide and purified by vacuum distillation. A 2% solution of <u>1</u> in spectrograde dioxane was irradiated for 125 hours with a Hanovia 450W mercury arc. Samples were taken and analyzed by glpc. None of the products expected from either Type I or Type II reactions was observed.

There were, however, three main products in the reaction mixture which were isolated by vacuum distillation and purified by preparative glpc. The major product was difficult to characterize by NMR. The NMR showed a pair of alkyl doublets with a substantial absorption in the $3 - 4\delta$ region where protons on the dioxane ring generally absorb. A second column divided the product into two components, each containing the dioxyl signal and an alkyl doublet. The parent ion at m⁺/e 132 and OH band in the IR characterized the first two products as the two diastereomeric α methyl dioxane methanols 2 and 3. The other two products were characterized by spectra and melting points as the two diastereomeric dimers of dioxane, 4 and 5. The dimers 4 and 5 were also observed in other photochemical reactions with dioxane by Pfordte.⁵⁸

The same reaction was run in a stoppered quartz tube. The reaction mixture was solidified in dry ice-acetone,

and gas IR of the vapor phase failed to show any of the expected l-butene. Gas IR did show the presence of CO. Low temperature glpc of the sealed tube reaction mixture failed to show any l-hexene. Pentane and a trace of l-butene were verified by coinjection. The results observed are detailed in the scheme.



 $CO + C_5H_{12} + CH_2 = CHCH_2CH_3$

The formation of 4 and 5 is a clear indication that radical processes are occurring. There are several possible reasons why none of the Type I or Type II products were observed. These products may be photochemically unstable undergoing polymerization, secondary reactions, or or interaction with solvents.

In order to determine the source of 2 and 3 a 3% sample of acetaldehyde in dioxane was irradiated for ten hours with the Hanovia lamp. Acetaldehyde was observed to undergo photoreduction to yield 2 and 3.

$$CH_3CHO \xrightarrow{0}_{hv} 2 + 3 + 4 + 5$$

This reaction is analogous to the one observed by Shima and Tsutsumi⁵⁹ where acetone photochemically added to dioxane to yield α, α -dimethyl dioxane methanol. Other ketones were also observed to undergo photoreduction with dioxane.^{60,61} Acetaldehyde was a possible intermediate in the decomposition of 1 and could be envisioned as arising via decomposition of hexanal, one of the expected Type I products.

An independent photolysis of hexanal in dioxane was also found to yield 2 and 3. After 30 minutes irradiation acetaldehyde was detected as expected via an initial Type II reaction. The reaction must also yield 1-butene, although its presence was not verified. Pentane was formed as a result of initial Type I cleavage followed by hydrogen abstraction from solvent.



Acetaldehyde build up was observed for two reasons. The concentration of hexanal was much greater than acetaldehyde and because they have virtually the same UV absorption hexanal would be favored to react over acetaldehyde. Type II reactions are also more efficient and occur more rapidly than the photoreduction. Thus, the hexanal would react rapidly to yield acetaldehyde, which would photoreduce at a slower rate. Either the Type II reaction or the photoreduction of hexanal, however, would be much faster than the photodecomposition of 1; hence intermediates would not build up in the reaction mixture and would be undetectable.

It is significant to note that Watterson and Shama⁶² in their study of the photochemical decomposition of acid hydrazides generated N-amidyl radicals,which abstracted hydrogen to yield simple amides. They observed only Type I reaction from these amides and were able to observe aldehydes formed in the reaction. Also products of amine radicals were detected.

Since initial Type I cleavage of 1 is proposed, the disappearance of the hexylamine radical must be explained. Amine irradiation in cyclohexane yielded addition products, solvent dimer, and polymer.⁶³ Under our reaction conditions (125 hours irradiation with the Hanovia lamp) no volatile nitrogen containing products were observed when a 2% hexylamine in dioxane solution was irradiated. Presumably they were contained in the polymeric residue.

Photolysis of Dioxane

Dioxane was chosen as a solvent for the amide study for three reasons. The amides have good solubility in dioxane. The solvent has transparency in the UV region of interest. The last and most important reason is that dioxane was the solvent used by Booth and Norrish.² The products 2, 3, 4, and 5 were common not only to the studies on amides but were also present in the work of Mazzocchi and Bodurgil⁶⁴ on N-alkyl substituted imides. There was the possibility that these products arose from the solvent itself.

A 200 ml sample of spectrograde dioxane was purged with nitrogen and irradiated through quartz with the Hanovia lamp for 200 hours. The reaction progress was monitored by glpc. Formation of 2, 3, 4, and 5 was detected by glpc. Product isolation by vacuum distillation and preparative glpc verified the analytical glpc results.



The formation of the dimers 4 and 5 can be explained by initial formation of a dioxyl radical by hydrogen abstraction from dioxane. In a reaction such as amide photodecomposition the radical source is obvious. For dioxane the radical probably arises via C-H bond excitation at 1850Å. Similar radicals have been observed for alcohols irradiated in this UV region.⁶⁵

The incipient dioxyl radical could either abstract hydrogen from another dioxane molecule with no net change or undergo C-O bond cleavage to give the open chain radical shown in Scheme II. Subsequent hydrogen abstraction would yield ethoxyacetaldehyde. Ethoxyacetaldehyde would be expected to undergo efficient Type II reaction to yield two molecules of acetaldehyde. Methoxyacetone was observed by Srinivasan⁶⁶ to undergo efficient Type II reaction (ϕ = 0.32) to yield acetone and formaldehyde. It has been shown by Wagner^{51,34} that oxygen adjacent to hydrogen dramatically increases the amount of abstraction by a factor of up to 80 (either substituent) for γ and δ hydrogens in ketones. The analogous n-octyloxyacetaldehyde in dioxane was observed to yield small steady-state quantities of acetaldehyde as well as $\stackrel{2}{\sim}$ and $\stackrel{3}{\sim}$, which are the proven photoreduction products of acetaldehyde.



In order to test the viability of the ethoxyacetaldehyde intermediate, a solution of dioxane and a catalytic amount of benzoyl peroxide was heated to 125° for 96 hours. Glpc analysis of the reaction mixture showed one minor product which could not be isolated. Attempts to prepare the DNPH derivative of the aldehyde from solution were also unsuccessful.

Quantitative studies on amides in dioxane were rendered difficult by formation of 4 and 5. The presence of acetaldehyde could exert either sensitizing or quenching effects. Determination of how much, if any, 2 and 3 was produced via amide photodecomposition versus solvent photodecomposition would be impossible since no other photoproduct of 1 could be quantified.

Photolysis of N-hexylproprionamide

In order to determine how much 2 and 3 was produced by amide decomposition, an amide was selected which would not yield 2 and 3. N-hexylproprionamide 6 would yield a proprionyl radical after the proposed initial Type I cleavage. Hydrogen abstraction would yield proprionaldehyde, which would not undergo the secondary Type II reaction. Proprionaldehyde might then be expected to undergo photoreduction with dioxane similar to acetaldehyde.

A two percent solution of 6 in 500 ml spectrograde dioxane was irradiated with the Hanovia lamp for 204 hours. The reaction was monitored by glpc, and 2, 3, 4, and 5were identified. Vacuum distillation followed by preparative glpc afforded 2 and another product, which was characterized by its mass m+/e 146, IR OHstretch, and NMR as the expected dioxane alcohol of proprionaldehyde photoreduction.



A five percent solution of proprionaldehyde in spectrograde dioxane was irradiated for 10 hours with the Hanovia

lamp. Vacuum distillation followed by preparative glpc on two columns yielded the two diasteromeric l-dioxane propanols, 7 and 8.



Alcohols 7 and 8 are secondary photoproducts from 6. Clearly 2 and 3 in this case cannot result from amide decomposition. The results suggest that part of the alcohol products arise via solvent decomposition in all of the amide-dioxane photoreactions.

An analogous reaction was observed with isobutyraldehyde in dioxane which, like proprionaldehyde, cannot undergo the Type II reaction. A solution of 10 g isobutyraldehyde in 200 ml dioxane was irradiated for 10 hours with the Hanovia lamp. Traces of 2 and 3, minor amounts of 4 and 5, and two other major products were isolated after vacuum distillation and preparative glpc of the reaction mixture. Spectra were interpreted for the major products by analogy to those of 2 and 3 and 7 and 8. The major products were identified as the diastereomers of α -isopropyl dioxane methanol.



Theoretically, the aldehyde addition to solvent could be used synthetically. Benzaldehyde, p-tolualdehyde, phenylacetaldehyde, and any of the previous aldehydes,which could not easily undergo Type II reaction, could be added to dioxane or a similar solvent without numerous side reactions.

Photolysis of N-hexylhexanoamide-α-d

An alternate means of determining the amount of 2 and 3 arising via decomposition of 1 versus direct decomposition of dioxane is to irradiate an amide labelled in the α position. This amide would produce 2 and 3 labelled on the methyl group. The product could then be isolated and the alkyl versus dioxyl region could be compared by NMR or the m⁺/e 133 and 132 peaks could be compared by mass spec.

The labelled acid was prepared by a method analogous to that of Pfeiffer and Silbert.⁶⁷ The dianion of hexanoic acid was generated with lithium diisopropyl amide and quenched with D_20 . Vacuum distillation of the acid followed by analysis by NMR and mass spec showed the acid to be labelled 48% α -d₁. Some of the α -d₁ label was lost in the generation of the acid chloride with thionyl chloride. The amide was prepared by the general method and observed to be α -d₁ 28% over the unlabelled amide.

$$2 \operatorname{Li}^{+} \operatorname{N}(\operatorname{CHCH}_{3})_{2} + \operatorname{CH}_{3}(\operatorname{CH}_{2})_{3}\operatorname{CH}_{2}^{\circ}\operatorname{C-OH}$$

$$\xrightarrow{\operatorname{HMPA}} \operatorname{CH}_{3}(\operatorname{CH}_{2})_{3}\overline{\operatorname{CHC}}^{\circ}\operatorname{C-O}^{-} \xrightarrow{D_{2}^{\circ}\operatorname{O}}$$

$$\operatorname{CH}_{3}(\operatorname{CH}_{2})_{3}\operatorname{CH-C-OD}^{\circ} + \operatorname{SOCl}_{2} \xrightarrow{}$$

CH₃(CH₂)₃CHC-Cl CH₃(CH₂)₃CHC-Cl

СН₃(СН₂)₃ СНСИН(СН₂)₅ СН₃

A two percent solution of the labelled amide in dioxane was irradiated for 138 hours with the Hanovia lamp. Approximately 50% of the amide was decomposed at this point. The partially labelled alcohol was collected as before and the m⁺/e 133/132 peak comparison was made with a sample of alcohol made from unlabelled amide. The comparison of 0.136 from the labelled amide and 0.092 from the unlabelled amide showed a deuterium enrichment of 4.4%. When the enrichment of the alcohol was compared with the 28% enrichment in the amide, it was concluded that 15% of the alcohol was produced by amide decomposition and the remaining 85% by solvent decomposition.

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Photolysis of Amides in Cyclohexane

In order to alleviate the difficulty of solvent participation when dioxane was used, several amides were irradiated in cyclohexane, which, like dioxane, was a solvent of choice in many photochemical reactions. Although the nonpolar character of cyclohexane results in poor solubility of amides, cyclohexane exhibits the desired UV transparency in the wavelength range of the irradiation.

When 210 ml of a 2% solution of 1 in cyclohexane was irradiated for 115 hours, glpc analysis showed the reaction mixture to be complex. One major product and numerous minor products were formed. The products were identified, by comparison with authentic samples following vacuum distillation and preparative glpc, as butylcyclohexane 11, pentylcyclohexane 12, methyl cyclohexyl carbinol 13, and bicyclohexyl 14 (the major product). Pentane was detected in the reaction mixture, but hexylcyclohexane, the product of initial Type II reaction to yield hexanoamide, was not detected.

The product yields were determined in a separate reaction where the irradiation was conducted with internal standards, eicosane and hexadecane. The calculations were made on the basis of response factors for expected products and amounts of reacted starting material. The yields of the three hydrocarbon products varied from sample to sample. The exact details of the product percent yields are given

in the experimental section, and the percent yields of three products are shown in Table V.

Table V

Percent Yields for Photodecomposition of N-hexylhexanoamide in Cyclohexane

Time Hours	n-But	ylcyclc	hexane	n-Pent	ylcyclo	phexane	Bicyclohexyl	L
11		1.4%			4.1%		29.9%	
8		2.0%			5.1%		33.6%	
13		2.6%			5.2%		40.0%	
1 ~								

From the experimental section it was observed that the ratio of standards to each other was constant during the irradiation, which indicated that neither standard was in sufficient concentration to act as a hydrogen source or participate in the reaction. Another reaction was carried out in a stoppered tube, and IR of the head space gas showed carbon monoxide to be present.



By no stretch of the imagination do the product yields account for the amide decomposed. It must be noted, however, that all reactions to yield the above products are not equally efficient. For example, each molecule of 12 and 14 requires a combination of two radicals, or these could account for as much or more than 78% of the decomposed starting material.

Acetaldehyde, when irradiated in cyclohexane, yielded three products, 13, 14, and methyl cyclohexyl ketone. The major product was 14, and the other two products appeared to be produced inefficiently. An irradiation of acetaldehyde in cyclohexane with an internal standard was conducted until nearly total conversion of starting material was attained. Under glpc conditions where the alcohol and ketone had the same retention time the yield for both was calculated to be 7.2%. The inefficiency of this photoreduction suggests that acetaldehyde, the secondary product of initial Type I amide cleavage, is formed in the amide decomposition in reasonable yield. The acetaldehyde yield could be 10% of the total reaction yield, which is much more than initial product anal-

The following mechanism is proposed for the photodecomposition of $\frac{1}{2}$ in cyclohexane on the basis of experimental evidence:

$$\stackrel{h\nu}{\underset{\text{Type I}}{\overset{\text{H}}{\longrightarrow}}} CH_{3}CH_{2}CH_{2}CH_{2}CH + CNHCH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{2}CH_{3} (1)$$

$$\cdot \text{NH(CH}_2)_3 \text{CH}_3 \longrightarrow \text{Polymer}$$
 (11)

$$1 \xrightarrow{h\nu} CH_3(CH_2)_4CONH_2 + CH_2 = CH(CH_2)_3CH_3$$
(12)
Type II (12)

$$\bigcirc + CH_2 = CH(CH_2)_3 CH_3 \longrightarrow \bigcirc & (13)$$

As previously stated on page 20, Mazzocchi and Thomas¹¹ observed in their work on N-alkylpyrrolidinones that the Type I reaction involves cleavage of the C-N bond only and not the C-C bond shown in equation (1). Equations (12) and (13), involving an initial Type II reaction, operate only inefficiently.

To verify the proposed mechanism, 6 was irradiated in cyclohexane. The major product was again 14 with small amounts of ethyl cyclohexyl carbinol and ethyl cyclohexyl ketone. No methylcyclohexane was observed. Proprionaldehyde irradiated in cyclohexane yielded the same three products observed in the photodecomposition of 6, as expected.

Solvent Effects on Amide Photodecomposition

It has been stated that the carbonyl oxygen in the Type II excited state in ketones is electrophilic. It was shown by Wagner^{31,34} that protic solvents such as tert-butanol or methanol enhance Type II reactivity. The polar solvating power apparently stabilizes the incipient partially polar transition state. Cyclohexane, diisopropyl ether, dioxane, acetonitrile, and methanol were selected to represent a solvent polarity spectrum. Irradiation in this set of solvents should indicate whether solvent polarity affects amide photoreactivity in general and can increase amide Type II reactivity in particular.

Solutions of l containing internal standards were irradiated, and Type II product formation and starting material disappearance were monitored by glpc for samples taken at different times. The method for Type II product yield determination is listed in detail in the experimental section. Product yields were calculated using the response factors for hexanoamide and N-hexylacetamide (the primary Type II products) on the basis of starting material decomposition. The predominant product of the Type II products was N-hexylacetamide so the total response factor used in the yield calculation was weighted in favor of the acetamide.

The maximum Type II combined product yields are shown in Table VI.

Table VI

Type II Product Yields from Photodecomposition of 1

Solvent	Time (Hrs.)	Moles 1 Decomposed x 10 ⁻⁵	Moles Type II Product x 10 ⁻⁶	Percent Yield Type II Product
Cyclohexane	10	18.4	8.3	4.5
Diisopropyl ether	10	7.5	3.8	5.0
Dioxane	10	7.7	6.4	8.3
Acetonitrile	10	1.4	6.7	4.8
Methanol	21	17.0	2.7	1.6

The expected increase in Type II products with increasing polarity, especially methanol, did not occur. It can also be observed in Figure 3 and Table XVII that starting material decomposition was not accelerated by increased solvent polarity. Since a maximum of 8% product was formed via Type II reaction, the remaining 90% of the reaction must be Type I. Recent work by Lewis and Heine⁶⁸ on substituted deoxybenzoins indicates that in Type I reactions the early transition state has a moderate degree of ionic character as shown:



This 8% yield was the largest Type II yield observed for any of the monosubstituted alkyl amides. In no other experiment was >4% Type II product observed.



Donating Z substituents accelerate the reaction by stabilizing the positive charge while X withdrawers stabilize the negative charge on the carbonyl carbon. A polar solvent, such as methanol, should accelerate Type I photodecomposition by stabilizing a charged species, but Figure 3 and Table XVI show no significant advantage in Type I reactions. It may be that the initial reaction is not affected by solvent, and the incipient radicals are affected only by the ease (relative number) of hydrogen abstraction.

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Determination of Mechanism by Competitive Reactions

There is the possibility that the Type II products were more photoreactive than the starting material and that the long irradiation times required to decompose 1 would also decompose any reactive Type II products formed. Any reactive Type II product would not be detected unless the initial reaction was efficient. For example, 1-hexene, a Type II reaction product, could react several times faster than 1 under the reaction conditions and would not be detected by glpc.

The first Type II product to be tested by competitive reaction was N-hexylacetamide. Independent photolysis of a 2% solution of the amide in dioxane with an internal standard showed that this amide decomposed at approximately the same rate as 1. The products of decomposition were 2, 3, 4, and 5 as well as carbon monoxide. The similarity of the products and reaction rates indicates that the added possibility for Type II reaction in 1 does not alter the mode or rate of reaction because the UV absorbing amide moiety is the same in both cases.

To test the possibility that N-hexylacetamide is an intermediate in the photodecomposition of $\underline{1}$ a solution of $\underline{1}$, N-hexylacetamide, and an internal standard in dioxane was irradiated, and samples were taken at 0, 4, 8, and 12 hours. The samples were analyzed by glpc. The ratio of the area of the acetamide to that of $\underline{1}$ should be constant

for all samples including the zero hour sample if the rate of decomposition is the same for both amides. The ratio was found to be constant at 0.25.



The rates k_1 and k_3 are equal, hence, any loss of 1, would be accompanied by a similar loss of acetamide. Under these circumstances N-hexylacetamide is not an intermediate of 1.

The alternative Type II process in the photodecomposition of 1 yields 1-hexene and hexanoamide. Theoretically there should be equal amounts of both, but hexanoamide was only sparingly soluble in dioxane. Other long-chainedalkenes such as 1-octene and 1-decene were observed by Elad⁶⁹ to react with dioxane and 1,3-dioxolane in an inefficient addition reaction (5% yield).

Irradiation of a 10% solution of freshly distilled 1-hexene in dioxane for 10 hours yielded a product which was not present in the photodecomposition of 1. Vacuum distillation of the reaction mixture followed by preparative glpc yielded a small quantity of liquid characterized by its spectra and analysis as hexyldioxane 15. The reaction is obviously analogous to that observed by Elad⁶⁹, and the mechanism for its formation is analogous to that previously proposed for formation of butylcyclohexane.



A solution of 1 and 1-hexene and internal standards cyclohexane and hexadecane in dioxane was irradiated with the Hanovia lamp. Samples were taken at 0, 6, 17, 40, 65½, and 98 hours and immediately analyzed by glpc. The results of the glpc analysis are shown in Table XIX.

A plot of the relative rates of disappearance of starting materials and of appearance of products 4, 5, and 15 as ratios with the internal standards is shown in Figure 4. The ratios from Table XX were modified to better show the reaction rates as follows: a. 1 : hexadecane $\times \frac{1}{2}$; b. l-hexene: cyclohexane $\times 1$; c. 4 + 5: hexadecane $\times 10$; and d. 15 : hexadecane $\times 5$.

From Figure IV several observations can be made. The rate of disappearance for 1 is much slower than that for 1-hexene, which might account for the absence of the alkene in previous photodecompositions of 1. Formation of 1-hexene, however, must be accompanied by hexanoamide formation, which could be detected. In addition, 1-butene, the product of a secondary Type II reaction, was detected under similar reaction conditions. Neither hexylcyclohexane nor 15,

Ratio of Compound to Standard



products of 1-hexene and solvent, was detected. The production of 4 and 5 paralleled decomposition of 1, slow but fairly constant. The production of 1,5 and decomposition of 1-hexene were rapid at first until reaching steady state levels.

Several conditions make 1-hexene and hence hexanoamide (initial Type II reaction products) unlikely intermediates in the photodecomposition of 1. Although 1-hexene photodecomposes faster than 1, either 1-hexene or one of its solvent addition products should be observed, since an analogous alkene, 1-butene was observed. Hexanoamide was observed in only trace amounts.

Photolysis of Other N-alkylamides

In order to determine whether the results observed in the photolysis of $\frac{1}{2}$ could be applied to other N-alkylamides, several other amides were photolyzed. For the following amides the results were consistent with those for $\frac{1}{2}$.

$$\begin{array}{c} 0 \\ H \\ RCH_2CNHR' \xrightarrow{h\nu} 2 + 3 + 4 + 5 + CO + RCH_3 + R=CH_2 \\ 16 \\ 0 \end{array}$$

	R	R '
16a	C ₄ H ₉	CH3
16b	^C 2 ^H 5	C ₆ H ₁₃
160	H	с ₆ н ₁₃
16d	C7 ^H 15	C ₆ H ₁₃
16e	с _ц н ₉	C ₆ H _{l3}
16f	ΦCH ₂	C ₆ H ₁₃
160	(CH ₃) ₂ CHCH ₂	C ₆ ^H 13
16b	СцНа	сн ₂ сн(сн ₃) ₂
161	C ₄ H ₉	C ₂ H ₅
161	C ₄ H ₉	С ₄ Н ₉
1.6k	C ₄ H ₉	C ₈ H ₁₇
161	C ₄ H ₉	СН(СН ₃)(СН ₂) ₄ СН
1.6m	Н	СН(СН ₃)(СН ₂) ₄ СН
TOW		

It is apparent that the same mechanism operates for this series of amides that operates for $\frac{1}{2}$, an initial Type I cleavage to afford an acyl radical. The radical then

abstracts hydrogen to yield an aldehyde, which undergoes subsequent Type II reaction to yield acetaldehyde. The acetaldehyde is then photoreduced to yield 2 and 3.

To verify the mechanism a 2% solution of N-hexyl-2-methylvaleramide in dioxane was irradiated. The usual products 2, 3, 4, and 5 were identified, but in addition small quantities of 7 and 8 were observed. The only explanation for 7 and 8 is initial Type I cleavage to yield the acyl radical. Subsequent hydrogen abstraction followed by the predicted Type II reaction of the aldehyde would afford proprionaldehyde, which inefficiently photoreduces in dioxane to yield $\frac{7}{2}$ and $\frac{8}{2}$. The Type II reaction is analogous to that observed in 2-methylbutanal by Gruver and Calvert.²⁴ It was observed by Bamford and Norrish²⁶ that isovaleraldehyde also underwent Type II reaction efficiently. No $\,\,{}^{6}_{\sim}\,$ (hexylproprionamide) or 2methylvaleramide was observed in the reaction. The following mechanistic scheme illustrates the photodecomposition of N-hexyl-2-methylvaleramide:

(2)
$$\operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{0}^{\operatorname{CH}_{2}} + \bigcirc \longrightarrow \bigcirc \stackrel{\circ}{\longrightarrow} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{\operatorname{CH}_{3}} \bigcirc \stackrel{\circ}{\longrightarrow} \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{1} \bigcirc \bigcirc \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{1} \bigcirc \bigcirc \operatorname{CH}_{3}\operatorname{CH}_{2}\operatorname{CH}_{$$

(3)
$$CH_3CH_2CH_2CH_2CH \xrightarrow{CH_3} \xrightarrow{h_v} CH_3CH=CH_2 + CH_3CH_2CHO$$

 $Type II$

(4)
$$CH_3CH_2CHO \xrightarrow{hv} 7 + 8$$

(5)
$$CH_3CH_2CH_2CH_2CHCNH(CH_2)_5CH_3 \xrightarrow{hv}_{Type II} CH_2=CH(CH_2)_3CH_3 +$$

$$\xrightarrow{h_{\mathcal{V}}} CH_2 = CHCH_3 + CH_2 CNH(CH_2)_5 CH_3$$

Several anomalies, however, were observed. Styrene was not observed, and propylbenzene was observed in smaller quantities in the photolysis of 16f than pentane in the photolysis of 1. The probable reason is that the phenyl group alters the photoreactivity of the secondary products. Despite random sampling during reactions, no amine was detected for the series of amides. A rough estimate of the photodecomposition rates of these amides showed that they decomposed at nearly the same rate, which is quite different from ketones where the rate of Y-hydrogen abstraction differs significantly for primary, secondary, and tertiary sites.

Relation of Y-Position to Amide Photoreactivity

As previously noted the γ -position in ketones is a determining factor in their photoreactivity. Tertiary hydrogens are more reactive than secondary hydrogens by a factor of ~3.5 in butyrophenones¹³ despite a 2:1 ratio of γ -hydrogens. The reactivity per hydrogen would favor tertiary hydrogens by a factor of ~7:1 over secondary. Two reasons for the increased reactivity could be decreased bond strength for the tertiary γ -hydrogen or the electron donating effect of the extra methyl group, which increases the nucleophilicity of the tertiary hydrogen.³¹

Two amides were selected with tertiary Y-positions and masses similar to 1. Three solutions of freshly distilled N-hexyl-4-methylvaleramide, isobutylhexanoamide, and 1 in sodium-dried t-butanol with an internal standard were irradiated simultaneously in sealed tubes following freezepump-thaw degassing. The system selected allows comparison of tertiary versus secondary hydrogen abstraction even in the same molecule. Under careful scrutiny it can be observed whether the nature of the hydrogen to be abstracted affects the amount of Type II reaction in amides. Tertiary hydrogens on both the carbonyl and amine sides were compared with secondary hydrogens.

The solutions were irradiated for 2 hours with the Hanovia lamp, which yielded just over 10% starting material conversion. The solvent, tert-butanol, according to Wagner,³⁴

should promote Type II reaction. Glpc analysis of the irradiated samples showed no Type II product for any of the three amides. When compared to the ratios of amide to standard in the zero-hour samples, the same ratio in the irradiated samples showed that the three amides had decomposed at approximately the same rate. The ratio T_i/T_0 was the same at 0.89 for all three amides.

The Y-position thus had no effect on the photodecomposition of amides despite decreases in bond energy, increases in stability of the incipient radical, and an increase in the nucleophilicity of the hydrogen to be abstracted. Indirectly, this evidence shows again that Type II reactions do not operate efficiently for N-alkylamides, and the important process is Type I in the amide photodecomposition.

Photolysis of Unsubstituted Amides

In order to exactly duplicate the work of Booth and Norrish² a series of unsubstituted amides was synthesized from the acid chlorides, purified, and irradiated in dioxane solutions. Norrish observed no aldehyde formation and hence assumed Type I reactions were not important.

The generation of carbon monoxide and unidentified primary amines was evidence for a carbon monoxide extrusion process. Irradiation of the unsubstituted amides showed the presence of carbon monoxide in the infrared spectrum of the head space gas. No amines were detected due to photoinstability for the long irradiation period. Generation of carbon monoxide could be explained as a secondary product following initial Type I cleavage.

 $\begin{array}{c} h\nu \\ \text{RCONH}_2 \xrightarrow{} \text{RCO} + \cdot \text{NH}_2 \\ \hline \text{Type I} \end{array}$

RCO • −−−−→ R• + CO

The primary alkyl amines observed by Booth and Norrish would arise via radical recombination or combination of the amine with the decomposing solvent.

Although radical recombination appears to be statistically unlikely, the recombination can occur with surprising efficiency due to a phenomenon called the cage effect. Primary investigation of the cage effect was conducted by Frank and Rabinowitch.⁷⁰ When the excited state dissociates

to radicals, the radicals must escape a cage of solvent molecules to avoid recombination or solvent interaction. Thus, there would be a high probability of recombination with radicals having a low diffusion rate or in viscous solvents where the radicals cannot escape. For example, the cage effect would be very important when tert-butanol is the solvent. Previously it has been stated that all the main products of N-alkylamide decomposition result from solvent interaction. Indeed many Type I reactions and photoreductions such as with benzophenone⁷¹ require solvent interaction.

Three compounds investigated by Booth and Norrish,² butyramide, valeramide, and hexanoamide, ostensibly could undergo Type II reactions to yield an alkene and acetamide. Electron donating alkyl groups on nitrogen should increase the I donation and thereby decrease the electrophilicity of the oxygen. Electrophilic oxygen is necessary for Type II reactions according to Wagner.^{31,34} Unsubstituted amides where there are no donating groups on nitrogen then should undergo Type II reaction more readily than N-alkylamides, which have an alkyl donating group. Presence of these expected alkenes was their evidence for the importance of Type II reactions despite the absence of acetamide. Although alkenes were not observed directly, minor quantities of addition products analogous to that observed by photoreduction of 1-hexene in dioxane were detected.
Hexanoamide in dioxane was observed to yield 2, 3, 4, and 5. Under the predictions of Booth and Norrish 1butene and acetamide should be major products of Type II reactions. As previously shown, in the case of the irradiation of 1 versus N-hexylacetamide in dioxane only the amide moiety absorbs light. Consequently, there should be a detectable acetamide build up if initial Type II reaction is important. The hexanoamide would absorb most of the light since it would be the major constituent of the reaction mixture. No 1-butene or acetamide was detected.

The Type II products predicted by Booth and Norrish for the photodecomposition of butyramide would be acetamide and ethylene. No acetamide was detected, and the infrared spectrum of the head space gas showed carbon monoxide but no ethylene. A secondary addition product of ethylene and dioxane was isolated from the reaction mixture and purified by glpc. The product was characterized as ethyl dioxane by the ethyl pattern in the NMR and m^+/e 120. The major products of the reaction, 2, 3, 4, and 5, were arising via Type I reaction.

One possible reason why neither ethylene nor l-butene was detected is that both are volatile and may have escaped from the reaction vessel. A Type II photodecomposition of octanoamide would yield l-hexene and acetamide. This alkene is less volatile and would remain in solution. Only traces of acetamide and no l-hexene were detected in the reaction mixture. The major products of the reaction were

again 2, 3, 4, and 5. A small quantity of hexyldioxane, 15, was also detected. Thus, mostly Type I with only a possibility of a trace of Type II reaction, was observed for octanoamide.

Type II photodecomposition of 4-phenylbutyramide would yield an intermediate benzyl radical, which would be relatively stable compared with the previous secondary radicals. This added radical stability did not increase the amount of Type II reaction. Neither of the Type II products, acetamide and styrene, was observed. The major products were 2 + 3 + 4 + 5, which arose as a result of the Type I reactions previously mentioned. Although only a small quantity of propylbenzene, the product of the decarbonylation of the 4-phenylbutyryl radical, was observed. Type I reaction is still the primary process. An alternative reaction of the 4-phenylbutyryl radical would have been closure to yield α -tetralone, which was not detected. It is obvious that Type II reactions are not important even when the incipient radical is benzylic.

In order to make a valid comparison with N-alkylamides proprionamide was irradiated in dioxane. As with the alkylamide \pounds there were the same six major products, 2, 3, 4, 5, 7, and 8. Therefore, the mechanism proposed for the photodecomposition of N-alkylamides apparently applies for unsubstituted amides also.

The following scheme illustrates the series of amides studied and the products observed:



19 20 (minor)

	17	18	19	20
	1./ P	R'	R'	R **
1 7 -	R R H	18a CH ₃	19a CH ₃	20a $^{C}2^{H}_{5}$
⊥‰a	n = C H = -	18b CH3	19b CH ₃	$2 \stackrel{\text{Oc}}{\sim} \text{n-C}_{6}^{\text{H}} \text{13}$
	11 05 11	18c CH3	19c CH ₃	
174	$n - C_7^H 15$	18d CH3	$19d$ CH $_3$	
170	$\phi CH_2 CH_2 CH_2$	1≳e* CH ₂ CH ₃	l9e* CH ₂ CH ₃	
	3 2	and CH ₃	and CH ₃	

An alternate explanation for the presence of alkenes in Booth and Norrish's investigation² and the secondary products previously mentioned are shown in the following mechanistic scheme:

$$\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}\operatorname{CNH}_{2} \xrightarrow{h_{\mathcal{V}}} \operatorname{RCH}=\operatorname{CH}_{2} + \operatorname{CH}_{3}\operatorname{CNH}_{2}$$

^{*}It is obvious that $R'=C_{25}$ in 18e and 19e arises via amide photodecomposition while $R'=CH_3$ in 18e and 19e arises from solvent decomposition.

$$\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{0}\operatorname{CH}_{2} \xrightarrow{h\nu}_{\operatorname{Type I}} \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{0}\operatorname{CH}_{2} \xrightarrow{0} + \cdot \operatorname{NH}_{2}$$

$$\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{0}\operatorname{CH}_{2} \xrightarrow{0} + \cdot \operatorname{XH} \longrightarrow \operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{0}\operatorname{CH}_{2} + \cdot \operatorname{X}$$

$$\operatorname{RCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{0}\operatorname{CH}_{2} \xrightarrow{h\nu}_{\operatorname{Type II}} \operatorname{CH}_{3}\operatorname{CHO} + \operatorname{RCH}_{2}\operatorname{CH}_{2}$$

$$\operatorname{CH}_{3}\operatorname{CHO} \xrightarrow{h\nu}_{\operatorname{CH}} 2 + 3$$

$$\operatorname{RCH}_2\operatorname{CH}_2^{\circ} \xrightarrow{h_{\mathcal{V}}} \overset{\circ}{\bigcirc} \operatorname{CH}_2\operatorname{CH}_2^{\circ} \overset{\circ}{\bigcirc}$$

Thus, Type I reactions are the most important for unsubstituted amides. Type II reactions, contrary to Booth and Norrish, are relatively unimportant, and their carbon monoxide extrusion can be explained by initial Type I of the C-N bond, followed by fragmentation of the hexyl radical, and recombination of the amine and alkyl fragments in the solvent cage.

Photolysis of N,N-dialkylamides

N,N-dialkylamides photodecomposed much faster than the monosubstituted amides. For example, a 2% solution of N,Ndihexylhexanoamide was completely decomposed after 68 hours. Nicholls and Leermakers¹² also observed increased reaction rates for N,N-disubstituted amides over monosubstituted and unsubstituted amides. Previous observations showed that Type I reactions were the most important for the unsubstituted and monosubstituted amides. Lewis and Heine's⁶⁸ illustration of the transition state for Type I reactions, shown on page 73, is consistent with the rate data. The extra donating group on nitrogen has the effect of stabilizing the partial positive charge in the transition state.



Nicholls and Leermakers¹² had identified the products of the photodecomposition of several N,N-dialkylamides. In a preliminary investigation the products were tentatively identified on the basis of glpc analysis on two columns, and mechanisms for their photodecomposition were tentatively proposed. A symmetrically disubstituted amide, N,N-dihexylhexanoamide, 21, and an unsymmetrically disubstituted amide, N-methyl-N-butylhexanoamide, 22, were irradiated

in order to clarify the decomposition procedure. A solution of 4 g 21 in 210 ml freshly distilled dioxane was irradiated 68 hours with the Hanovia lamp. Samples were taken at 0, 13, 20, 21, and 68 hours and immediately analyzed by glpc.

Low temperature glpc showed the presence of pentane and 1-butene, which were previously proposed to arise via secondary Type II reaction of hexanal after the initial Type I cleavage of the amide. In addition, a substantial quantity of 1-hexene was detected. This product could only arise via initial Type II reaction of 21.

Other Type II products were also detected. N,N-dihexylacetamide was the other Type II product from the generation of 1-butene. N-hexylhexanoamide, 1, was generated in the Type II process which yielded 1-hexene. N-hexylacetamide, the product of two Type II reactions, was also detected. Since N-hexylacetamide is not a major product in the photodecomposition of 1, it is unlikely that 1 is the intermediate in its formation here. The N-hexylacetamide is probably a secondary Type II product of N,N-dihexylacetamide. Relative quantities of the Type II products were not measured.

The Type I reaction was still important. Although 2, 3, 4, and 5 were identified, they were not the predominant sole products of the previous N-alkylamide and unsubstituted amide reactions. Another factor afforded by N,N-dialkylamides is the increased stability of the amine radical produced by initial Type I reaction. In the 13 and 20

hour samples N,N-dihexylamine was detected as a major product. From this evidence N,N-dihexylamine is the only initial Type I product to be directly identified.

The reaction scheme depicting the photodecomposition of 21 is shown. The identified products are underlined.





Photolysis of the unsymmetrical amide $\stackrel{22}{\sim}$ verified the previous results obtained from irradiation of 21. A solution of 4 g 22 in 210 ml dioxane was irradiated to nearly complete decomposition in 48 hours with the Hanovia lamp. Samples were taken at $\frac{9}{2}$, $\frac{18}{2}$, $\frac{31}{2}$, and $\frac{48}{2}$ hours and immediately analyzed by glpc. Volatile products 1-butene and pentane were again identified. This time, however, the 1-butene could be produced by either initial Type II reaction of $\overset{22}{\sim}$ or initial Type I followed by secondary Type II reaction of the aldehyde.

CH₃CHO-

Other Type II products were also identified in the reaction mixture. Identification of N-methylhexanoamide showed that part of the 1-butene was being produced via Type II reaction. Strangely N-butylhexanoamide, which would require generation of a methyl radical, was also produced. N-methyl-N-butylacetamide, which would yield l-butene as the alternate product, was also identified.

N-methyl-N-butylamine was identified as an initial Type I product. Other products arising from initial Type I reactions were also identified as $\stackrel{2}{\sim}$, $\stackrel{3}{\sim}$, $\stackrel{4}{\sim}$, $\stackrel{5}{\sim}$, pentane, and

l-butene. The following reaction scheme is proposed for the photodecomposition of 22 and identified products are underlined.





The results obtained from the two amides can be summarized as follows. Type I reactions are accelerated by the inductive effect of the extra alkyl group on nitrogen. The amides decompose too rapidly for solvent decomposition to be significant. Thus, 2, 3, 4, and 5 are not the predominant products as they are in N-alkylamides and unsubstituted amides. Pentane and 1-butene (in part) are produced in a similar fashion to the other amides. The best evidence for initial Type I reactions is identification of the secondary amines.

There may be several reasons for the increased Type II reactivity of the amides. From a purely electronic consideration the electron donation of the extra alkyl group should decrease σ withdrawal and increase the Π donation of nitrogen. The previous arguments indicate that this combination should decrease Type II reactivity by making the oxygen more nucleophilic. The reason for the increased Type II reactivity then must not be electronic.

It has been stated on page 49 that Padwa⁴⁹ observed cases where ability or tendency to attain the proper geometry had great effect on Type II reaction rates. The previous observation was that N-alkylamides should be able

to attain the proper geometry for Type II reaction. In the dialkylamide shown the R-CH₂ group forces the other groups



from the carbonyl and amine side toward the oxygen for a larger fraction of the time than these groups spend with H in that position. This geometric, albeit steric factor, may then be the cause of increased Type II reaction in N,N-dialkylamides.

Photolysis of Aniline Imides

One way to increase the Type II reactivity of amides would be to decrease the ability of the nitrogen to Π donate. A withdrawing group on nitrogen would prevent the lone pair from being donated to the carbonyl, and the oxygen would be more electrophilic. Mazzocchi and Jameson⁷² found that dialkylimides would indeed undergo Type II reactions more readily than amides. Kanaoka⁷³ showed that Nalkyl succinimides, and glutarimides would undergo Yhydrogen abstraction (Type II reaction) followed by closure to yield cyclobutanols.

The reactions observed by Mazzocchi and Jameson⁷² showed two types of Type II cleavage.



*This reaction will be discussed at greater length in Part II.

The type of cleavage evidently depends on the geometry of the compound. For example, the top rotamer can undergo two possible Type II reactions while the bottom rotamer has only one Type II possibility. The combined quantum yield from the singlet and triplet state for N-acetyl-N-4-methylvaleramide was 0.08, which is much less than that measured for the corresponding ketone.¹³ Determination of the rate constant shows it to be much smaller (0.05) than that of the corresponding ketone.¹³

Mazzocchi and Bodurgil⁶⁴ irradiated a series of N-alkyl-N,N-diacetamides where the alkyl group was varied. The Y-position on the nitrogen chain was varied from primary to secondary, tertiary, and benzylic. The products observed were N-alkylamides, which were produced as Type I products from the initial C-N bond scission or by the Type II reaction shown by Mazzocchi and Jameson.⁷² N-alkyl-N-acetylhexanoamides were also irradiated, and Type II reaction of the carbonyl chain was promoted to yield N-alkyl-N,N-diacetamides. In no case, however, when Type II reaction of the amine group was possible, was Type II cleavage of that group detected. It also appeared, as expected, that the N-alkyl groups reduced Type II reactivity, presumably as in previously cited cases, by making the carbonyl oxygens more nucleophilic.

N,N-diacylanilines were selected for study in order to further reduce the Π donation of nitrogen. The aromatic ring would serve as an additional Π system for delocali-

zation of the nitrogen lone pair, and donating and withdrawing groups on the ring would afford an excellent insight on Hammett correlation for Type II reactions.

The imides were prepared by a method analogous to that of Heyns and Pyrus⁷⁴ where the anion of an amide is generated with a Grignard reagent. Reaction of the anion with an acid chloride yields the imide. The imide is purified generally by distillation after unreacted amide is removed with a saturated K_2CO_3 solution.



Other methods, which were attempted to prepare the imides, were largely acyl exchanges and had very low yields of the desired products in complex mixtures. In all imide preparations N,N-diacetylaniline was a contaminant. N-acetylvaleranilides, after detection in the reaction mixture, could not be purified. Apparently the heat of distillation or glpc passage caused loss of propene to yield the diacetyl

conjugation in one direction.

compound. Similar, although lesser, loss of ethylene from the N-acetylbutyranilide accounts for diacetylaniline as well as acetanilide and butyranilide impurities.

The photochemistry of anilides, amides and imides is best described by the Photo-Fries reaction. This reaction is the same as the ground state Fries rearrangement, which uses a Lewis acid catalyst.



Kanaoka and Hatanaka⁷⁷ showed that certain phenyl heterocyclic esters photodegrade as above to yield o and p-ketophenols in combined yields ranging from 25 to 60%.



The photoanilide reaction was discovered by D. Elad, D. Rao, and V. Stenberg,⁷⁸ who irradiated acetanilide, proprionanilide, butyranilide, and benzanilide. The results were analogous to those for esters. The para and ortho isomers of the ketoanilines were isolated as well as aniline in combined yields ranging from 30-70%.



The obvious radical formation necessary to form these products is clearly subject to the cage effect due to the high rate of recombination and lesser solvent participation.

The analogous reaction also occurs for N-phenyl lactams in moderate yields according to Fischer.⁷⁹



The following intermediates were proposed for the reaction, which could only be characterized as Type I.



The generated diradicals formed are forced to recombine inter or intramolecularly independent of the "cage effect".

Kan and Furey⁸⁰ investigated the photodecomposition of N,N-dibenzoylaniline. Ω



Any of these reactions could hardly be construed as Type II reactions, due to the lack of γ -hydrogens. Katsuhara and coworkers⁸¹ expanded on the work of Kan.⁸⁰ They irradiated N,N-diacetylaniline and N-acetyl-N-benzoylaniline.



It is interesting to note here that no secondary photoproducts such as o-acetoaniline, p-acetoaniline, or aniline were detected. The explanation for the absence of these products was that the acetophenone moiety would be excited by the light rather than the acetanilide moiety.

There is the possibility of Type II reaction in the diacetyl compound with the proper geometry.



N-acetyl-N-benzoylaniline yielded 2-(8%) and 4-acetaminobenzophenone (16%), acetanilide (54%), benzanilide (18%), and benzoic acid (15%). These results suggest that the predominant dissociation is to benzoyl and acetanilide radicals rather than acetyl and benzanilide radicals, despite the possibility for Type II dissociation in the latter case.

N-acetylbutyranilide can undergo three possible Type II reactions depending on the geometry.



A recent NMR study on the geometry of imides, which was conducted by Noe and Raban,⁸² indicated, as expected, that the C-N bonds in the imides were not freely rotating. This restriction to rotation is due to the overlap of the nitrogen lone pair with the two carbonyl systems. One may expect the favored conformation to be the trans-trans, which is called the Z,Z form. This form would be expected because the I overlap would

Η Н Н H

allow the resonance at the right to increase stability similar to aromatic systems. NMR data on diformamide showed no evidence for the iminol forms possibly due to the decreased II donating ability of the nitrogen. The major contributing structure by NMR in diformamide is the E,E (R, R', R'' = H).



In this work and a study by Pellessier⁸³ most substituted imides preferred the E,Z form. For example, N,N-diacetylp-chloroaniline and N,N-diacetyl-p-toluidine exist solely as the E,Z form to the point that the bond rotation energies have been measured for conversion to the other forms. The reported compound which relates best to the imides of this study is N-acetyl-N-2,2-dimethylproprionylaniline, which also exists in the E,Z form. The compound has two possible E,Z forms. The dipole moment study by Pellissier suggests that 23 predominates over 24.



Substituted N-acetylbutyranilides then have the proper geometry to undergo Type II reactions. The possible Type II reactions and products are shown. All three can be detected



apart from starting material by glpc. When an impure sample of N-acetylbutyranilide was irradiated in dioxane for 104 hours (2537Å), three major products were generated. Butyranilide, 27, was not detected, and the other Type II products, 26 and 28, which were impurities in the starting material, decreased during the course of the reaction rather than accumulated (as if being generated by decomposition of starting material).

The three major products were isolated by preparative glpc. The first peak was characterized as o-acetoaniline by glpc coinjection and comparison with spectra from literature and authentic samples. The para isomer may be assumed to be present although it was not isolated. The second product was o-butyroaniline isolated and characterized in the same fashion as the previous product. The para isomer could not be isolated because its retention time was equal to the starting material. The third and major product was actually a mixture of four products: o-acetobutyranilide and o-acetanilide, p-acetobutyranilide and p-butyroacetanilide. The NMR was difficult to interpret except to say that there was a mixture. In the mass spec m⁺/e 205 indicated the proper mass. IR showed the presence of ketone and amide C=0 stretch. These products could not be separated by glpc or TLC.

A purified sample of N-acetylbutyranilide was irradiated in dioxane for 42 hours with 2537\AA light. Samples were taken at 0, 3, 6, 14, 25, and 42 hours and analyzed by glpc. The same three major products of the previous reaction were present. In contrast, the three Type II products, 26, 27, and 28 were only minor products of the reaction.

The reaction can be proposed as follows:









A second purified imide with a strong electron withdrawing group on the phenyl ring was irradiated. Theoretically, the withdrawing group should increase Type II reactions by making the carbonyl oxygens more electrophilic. Of the possible strong withdrawing groups only the trifluoromethyl would not interfere by absorbing light and fostering secondary reactions. The large multitude of products generated by the photodecomposition of N-acetyl-N-butyryl-m- α, α, α -trifluoromethylaniline was not identified. The projected Type II products were prepared. When coinjected with the samples taken from the reaction mixture, it was obvious that these Type II products were only minor.

This study has thus shown that anilide imides do not undergo Type II reactions efficiently despite the extra withdrawing group on nitrogen and the presence of the phenyl ring with an additional withdrawing group. The benzene ring is the determining factor as it alters the UV spectra of the compounds causing reactions not characteristic of N-alkyl imides. The predominant reactions were Photo-Fries reactions, which were shown to be Type I by previous investigators. The Type II processes may be even less important than observed since only N,N-diacetylaniline can be unequivocally traced to a Type II reaction. These anilide systems were not investigated further since only the Photo-Fries reaction and not the Type II reaction was shown to be important.

§4. CONCLUSIONS

The assertions of Norrish² and Moore⁹ that Type II reactions are important in amide photochemistry are false. Neither their experimental evidence nor evidence obtained from the photolysis of N-alkylphthalimides and unsubstituted amides substantiates the efficiency of the Type II mechanism. Our results are consistent with those of Leermakers¹² who found Type I reactions to be the significant photodecomposition pathway for amides. The significant products identified in the reactions were due to the interaction of radicals from initial Type I reaction with solvents such as dioxane and cyclohexane.

Solvent effects on the rate of photodecomposition of amides were not significant. Polar solvents do not promote Type II reactions in amides as in ketones. Significantly, dioxane, which has been a solvent of choice in many photochemical reactions, undergoes partial decomposition and subsequent product formation when irradiated for the long periods required for amide decomposition.

There are two possible reasons for decreased Type II reactivity in amides. The I donation of the nitrogen lone pair makes the carbonyl oxygen nucleophilic where Type II reactions in ketones require the oxygen to be electrophilic. Type II reactivity and decomposition were apparently not affected by changes in γ -hydrogen bond strengths. A steric consideration may also be necessary since Type II reactions were observed with N,N-dialkylamides, where the side chains are forced toward the carbonyl.

PART II

Photochemistry of Phthalimides

§1. INTRODUCTION

It has been shown in the previous section that most amides and imides studied underwent Type II reaction only inefficiently. Alkyl imides had low quantum yields, and reaction constants for Type II reactions were much lower than those in the corresponding ketones. Anilide imides were shown to undergo Photo-Fries reactions predominantly.

Kanaoka⁸⁴ asserted that N-alkylphthalimides in a variety of solvents would undergo efficiently γ-hydrogen abstraction and subsequent ring closure to yield an azacyclobutanol. Due to the instability of the intermediate, the azacyclobutanol cleaved to yield a series of substituted, 3,4-benzo-6,7-dihydroazepine-2,5-diones. In order to determine the efficiency of the reaction a series of N-alkylphthalimides was synthesized and irradiated, and the quantum yields were measured for the ring expansion products of each phthalimide.

An optically active phthalimide was synthesized and irradiated in order to elucidate the mechanism. This reaction determined the irreversibility of the γ -hydrogen abstraction. In addition, a dibenzoyl amine was irradiated to determine whether the γ -hydrogen abstraction was peculiar to the phthalimide system alone, and whether the reaction had other synthetic implications.

Quenching studies on the phthalimides revealed an interesting reaction. New products were produced when the phthalimides were irradiated in the presence of 1,3-pentadiene. The products were isolated for the reaction of several other alkenes and N-methylphthalimide. The mechanism of the product formation is proposed to be a 2+2 cycloaddition followed by ring expansion to yield substituted 1-methyl-3,4-benzo-6,7-dihydroazepine-2,5-diones.

§2. HISTORICAL

The predominance of photochemical investigations on phthalimides was conducted by Kanaoka and co-workers in a series of papers. Until the first paper was published, there was no conclusive evidence to substantiate the assertion that Type II reactions were efficient for amide and imide systems. High efficiency of Type II reactions for phthalimides would be contrary to the observations made for many amides and imides.⁷²

Initial investigations were made by Kanaoka⁸⁵ on Nphthaloyl derivatives of α amino acids. Irradiation of a series of these compounds was shown to promote decarbonylation. The product yields were observed to be very solvent dependent, that is, protic solvents lowered the yield of decarbonylation product. The meaning of this observation is clearly that the acid hydrogen must interact with one of the carbonyl oxygens.

In addition to the decarbonylation products, several other products were also isolated. For example, vinylphthalimide was isolated from N-phthaloylserine in 30% yield and from diphthaloylcysteine in 20% yield.^{*} An addition product can be isolated in acetone from N-phthaloylleucine at 3% yield, which verifies the diradical character of the intermediate. On the basis of the experimental evidence, Kanaoka proposed the following mechanism:

[&]quot;N-vinylphthalimide could be considered as evidence for a dipolar intermediate.



The question of a dipolar versus a diradical intermediate was not resolved in this paper but was addressed in a later publication. Initial γ -hydrogen transfer was necessary, however, in either case. It may be argued that the O-H bond energy is not equal to the C-H bond energy or that the hydrogen transfer is not diradical in nature, and thus comparison with ketone Type II reactions would not be valid.

The first evidence for C-H bond cleavage was presented by Kanaoka and Koyama.⁸⁶ Irradiation of o-N-phthaloyltoluene yielded products which could only arise via benzylic hydrogen abstraction. As shown in the mechanism, a sevenmembered transition state is required. The molecule studied had no γ -hydrogens available for abstraction. Wagner³⁴ showed that δ -hydrogen abstraction would in some cases predominate over γ -hydrogen abstraction in ketones. The diradical intermediate that was proposed would account for the secondary solvent addition product, which was also observed.

The solvent would also act as a hydrogen source to yield the photoreduction product 29. Additional evidence for the diradical intermediate was isolation of 30, the product of diradical cyclization. The structure of 30 was verified following acid treatment to yield the dehydration product. The following diradical mechanism was proposed to account for formation of the three products.



"Yields of 30 were increased when tert-butanol was the solvent because only ethanol and methanol formed the solvent addition products.

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The hydrogen abstraction is affected by neighboring groups on the alkyl chain. Kanaoka and Migita⁸⁷ irradiated a number of N-alkylphthalimides with oxygen in different positions on the alkyl chain. In contrast to other carbonyl compounds, Kanaoka states that δ -hydrogen abstraction was preferred over γ -abstraction in phthalimides. From the series of compounds selected for study such a conclusion would be hard to substantiate since not all compounds studied contained γ -hydrogens, and the presence of an oxygen activating group alters the usual pattern of hydrogen abstraction. The following scheme shows the evidence Kanaoka's conclusion was based on:





(1)

12%



In the first three reactions there were only δ -hydrogens, no γ -hydrogens. Reactions (4) and (5) were the main substance of Kanaoka's conclusion. Despite "activated" γ -hydrogens no azacyclobutanol was isolated, and only small quantities of unidentified products were observed, presumably due to an absence of δ -hydrogens. Reaction (5) shows almost quantitative product formation due to δ -hydrogen abstraction despite the presence of Y-hydrogens and apparently activated ζ -hydrogens. The explanation is clearly that in (5) the eight-membered transition state required is too difficult to attain due to entropy considerations and added ring strain. The δ -hydrogens have been activated for abstraction in reaction (5) more than the γ -hydrogens. The results from reaction (4) could be explained by the instability of azacyclobutanols formed in the reaction mixture or under the analysis conditions.

Kanaoka proposed that the increased yields for the cyclopentanol products could be predicted by the increased stability of radicals formed after the δ -hydrogen transfer. For example, in reaction (3) a benzyl radical leads to a 65% product compared with 30% product from a secondary radical and 12% product from a primary radical. At this point, significantly, some control of hydrogen abstraction and reactivity could be demonstrated.

Studies on heteroatom control over reactivity and hydrogen abstraction were extended to sulfides by Kanaoka and coworkers.⁸⁸ This study showed that not only γ and δ -hydrogen abstractions take place but also that hydrogens could be abstracted from more remote parts of the chain with the proper adjacent substituent. Characteristically, Type II hydrogen abstractions in ketones have progressed in the order $\gamma > \delta > \varepsilon$. Kanaoka was able to show abstraction not only from the ε -position but also for the first time from the ζ -position. This diradical closes to yield a cycloheptanol. Several points are illustrated in the following reaction scheme:








Reaction (1) illustrates the general reaction for Nalkylphthalimides containing sulfur. These reactions show that the products of γ or δ -hydrogen abstraction often do not form when ε and ζ -hydrogen abstraction products are equally favored due to the position of the sulfur. For example, in reactions (4) and (5) the starting materials

have both γ and ε -hydrogens adjacent to the sulfur. In those reactions only products arising from ε -hydrogen abstraction are formed. In reactions (8), (9), (10), and (11) ζ -hydrogen abstraction was favored over δ -hydrogen abstraction. The larger ringed products were formed almost quantitatively in reactions (8) and (9).

Reactions (3) and (7), which started with tert-butyl sulfides, formed smaller rings since there was no hydrogen more remote adjacent to sulfur. Unlike previous cases, such as phthalimide ethers, increased yield could not correspond to the stability of the incipient diradical as in reaction (11), where the yield of azacyclothioheptanol is 54% for a benzylic radical. In comparison, in reactions (8) and (9) the yields were 86% and 80% respectively for the corresponding products from primary and secondary radicals.

Reaction (12) appears to be an exception since the δ hydrogen abstraction product is preferred over the ζ -hydrogen abstraction product by 2:1. In other reactions, however, only one product was formed. The fact that both products were formed in significant quantities alone makes reaction (12) different.

Reaction (2) shows that the elimination product N-methylphthalimide is favored over the product of δ -hydrogen abstraction. This observation is decidedly in opposition to the observations made on the phthalimide ethers when the oxygen was in the γ -position (δ -hydrogen abstraction possible). Although a five-membered ring was produced in reaction (12),

the sulfur was not included in the ring. The low yield of ring closure product then may be a result of the large size or the electronic configuration of the sulfur atom, which would have a greater effect in formation of rings with less than five members.

It is obvious that the mechanism proposed for other phthalimide decompositions was inconsistent at best for describing the photodecomposition of phthalimide sulfides. The mechanism, as well as scope of the sulfide reaction, was further studied by Kanaoka and co-workers.⁸⁹ It was shown that the hydrogen abstraction was indeed regioselective and that rings as large as sixteen members could be formed fairly efficiently. In light of the entropy factor and torsional strain involved, these products were unlikely. The irradiations yielded two products of the type that were shown in the general reaction (1). A dehydrated product as well was also isolated.



The mechanism for the sulfide reaction must be different than that proposed for the phthalimides for several reasons. When sulfur is replaced with oxygen in the longer chain compounds, the large ring products do not form. No reaction is efficient with an ether when hydrogen abstraction is required from further than the δ -position. Secondly, product yields for the sulfide reactions were significantly higher

than those observed for the o-tolylphthalimides, where only a seven-membered transition state was required. The difference in the mechanism must be due to the sulfur atom, either its size or electronic structure. On this basis, Kanaoka proposed the following mechanism:



The proposed dipolar intermediate could account for the formation of large rings in several ways. The proton transfer would be accelerated by the proximity of the methylmercapto cation and imide anion due to electrostatic forces. This donor-acceptor complex in the excited state is analogous to the amide case and observations by Ditchfield and Pople⁴⁸ on other hetero double bond excited states. Kanaoka was unable to show any intramolecular interactions with the sulfides, but in the UV, a solution of N-methylphthalimide and butylsulfide in ethanol was observed to have a chargetransfer band. This band shows that there is some degree of intermolecular interaction in the ground state. Smaller ring products may not be formed due to the inability of the radical to bend with the sulfur, or steric interference of sulfur to radical recombination.

These reactions do have significant synthetic ramifications since the Type II reaction appears to occur without interfering with other chromophores. For example, reaction (10) on page 123 shows the Type II adjacent to sulfur without interference from the ester group. The following example from Kanaoka's paper shows the photopreparation of cyclic amides:



This reaction shows the formation, in good yield, of eight and ten-membered rings, which contain an amide chromophore. The required geometry of the amide apparently does not interfere with the ring formation, which might be expected in rings this large. Apparently the hydrogens adjacent to nitrogen were not activated for abstraction. The reaction does, however, show the versatility of the sulfide photoreaction.

Hydrogen abstraction adjacent to nitrogen was shown by Roth and Schwarz⁹⁰ to occur in bis(phthalimidomethyl) methylamine by the following reaction:



The reaction is actually a double reaction that shows the preference of hydrogen abstraction adjacent to .nitrogen. Initial abstraction from the methyl group is preferred, presumably for steric reasons. The second hydrogen abstraction occurred only between the two nitrogens rather than between nitrogen and the hydroxy group formed in the initial reaction. An additional observation, not made by Kanaoka in the previously cited papers, is that secondary reactions will occur when possible.

Irradiation of bis (phthalimidomethyl) isobutylamine showed, in addition to hydrogen abstraction adjacent to nitrogen, an elimination to yield phthalimide.



The other reaction, to yield the polycyclic product, required formation of a secondary radical adjacent to nitrogen from the δ -position rather than a tertiary radical from the ϵ -position. The secondary reaction showed preference for a secondary radical from the δ -position to be favored over a tertiary radical from the δ -position.

Irradiation of bis (phthalimidomethyl) benzylamine showed a different elimination product as well as the polycyclic products.



This reaction also clearly shows that there is preference in hydrogen abstraction for the δ -position and adjacent to nitrogen.

Roth, Schwarz, and Hundeshagen⁹¹ showed that the proposed elimination product was actually a radical recombination. Photolysis of N- (morpholinomethyl) phthalimide in methanol yielded two products of radical recombination.





Irradiation of N- (dimethylaminomethyl) phthalimide in methanol yielded two recombination products, a primary photoproduct and a secondary photoproduct, $\stackrel{31}{\sim}$.



Irradiation of N- (diisobutylaminomethyl) phthalimide in methanol resulted in formation of two products. The first primary photoproduct was hard to explain except by an elimination mechanism. The secondary photoproduct was $\frac{31}{\sim}$.





The stability of the phthalimide moiety may be questioned. No products of phthalimide decomposition have been isolated. Scharf and Fuchs⁹² investigated the photoreactivity of dihydrophthalimide indirectly and isolated five products.



25%





Irradiation of the tricyclic imide yielded the five products, hence, dihydrophthalimide was proposed as an intermediate. A mechanism was also proposed for the formation of the products.



It is unlikely that these reactions, which require long irradiation periods, would interfere with the primary reactions on the alkyl chain, which require comparatively brief irradiation periods.

Kanaoka and co-workers⁸⁴ did the most significant work on Type II hydrogen abstraction of phthalimides by studying N-alkylphthalimides. The alkyl chains from which the hydrogens were abstracted were not activated by hetero atoms or phenyl systems. The predominant abstraction was from the γ -position, with minor amounts of δ -hydrogen abstraction.

The abstraction was not observed through direct ring closure but rather by inference through isolation of secondary and tertiary photoproducts. The initial γ-hydrogen abstraction was undoubtedly followed by ring closure to yield a cyclobutanol as proposed by Yang¹⁴ and Wagner¹³ for Type II reactions in ketones. The azacyclobutanols formed in this case, however, are unstable and undergo retrotransannular ring opening to yield ring expansion products, namely substituted 3,4-benzo-6,7-dihydro(1H)azepine-2,5-diones. The following series of reactions illustrates the various types of products attained by irradiating N-alkylphthalimides.





It may be clearly seen that all photoproducts except one in reaction (4) arise via initial γ -hydrogen abstraction. That product arises via δ -hydrogen abstraction and closure. Reactions (2), (3), and (4) each contain major alkene products, which presumably are formed by secondary δ -hydrogen transfer rather than ring closure. These alkene products were observed when the reaction was conducted in acetonitrile and acetone but not in tert-butanol. In reactions (3), (4), and (6) parts of the alkyl chain were eliminated, and no ring-expansion product containing all of the chain was isolated. This observation could be rationalized as a secondary Type II elimination in the ketone moiety of the ring-expansion product. Kanaoka proposed the following mechanism to account for the product formation:





The bottom series of reactions shows that starting materials with ε -hydrogens undergo, as predicted, the Type II elimination following ring opening. This elmination from a ketone is presumably more efficient than the initial Y-hydrogen abstraction and ring closure, hence, no azepinediones with groups larger than methyl α to the ketone have been isolated.

Reaction (5) opened the possibility for synthesis of a series of spiro compounds in one step. A degree of synthetic control could be introduced with a hetero atom. Kanaoka and co-workers⁹³ demonstrated that various δ -tertiary hydrogen abstractions in chains containing oxygen were more efficient than normal γ or δ -tertiary hydrogen abstractions from hydrocarbon chains had been found to be highly efficient⁸⁴ and afford prod-

ucts only in small yields. The oxygen greatly enhanced the product yield (33-53%) for five to eight-membered rings in the following general reaction.



The reaction shows that the excited state of the phthalimide carbonyl is similar to a regular triplet carbonyl. The versatility of the phthalimide reaction is shown by the spiro products formed. These products would be difficult to prepare by conventional means due to steric interference.

Although tertiary hydrogens were difficult to abstract (unless adjacent to oxygen) from the standpoint of spiroproduct formation, secondary hydrogens⁸⁴ afforded increased product yields in hydrocarbon chains. The possibility for fused polycyclic systems was studied by Kanaoka and coworkers.⁹⁴ The following reaction illustrates the principle:





The benzazepinedione product was formed in yields of 30-50% only when the ring contained five, six or eight members.

The product isolated with a cycloheptane ring was different from the others, with IR bands characteristic of an alcohol rather than the ketone present in the other cases. The product was characterized by NMR, and the structure of the O-acetylated derivative was verified by x-ray studies as 1,2,2a,3,4,9b-hexahydro-9b-acetoxy-1,3-propano-5H-cyclobuta[d][2] benzazepin-5-one. Formation of this product was explained by the following reactions:



As in the reactions observed by Padwa,⁴⁹ Padwa and Eastman,⁵⁰ and Wagner¹³ the geometry of Type II reactions is very important. The γ -hydrogen must have been in the proper geometry for Type II reaction only in the fused cycloheptyl product. The high yield of this product, 55%, is further evidence of the increased efficiency of ketone Type II reactions when proper geometry is attained. Similar secondary reactions to form more complex products did

not occur with the spiro compounds⁹³ because there was only an amide moiety after the cyclopentanol formation. Kanaoka and co-workers^{95,96} extended their original study of N-aryl and N-alkylphthalimides. Synthetic control was exhibited due to electronic considerations. Photochemically unreactive substituents on the aromatic rings influenced the position of hydrogen abstraction from the alkyl chain⁹⁵ and could determine which carbonyl would be excited and undergo Type II reaction.⁹⁶ Both processes were naturally investigated through product analysis. Investigation of substituted terminal phenylalkyl-

phthalimides 95 showed that the optimum ring size for these phthalimide reactions was n = 4 for a series of aryl substituted compounds where n was 3,4, and 5.



This conclusion was reached because the series n = 3afforded significantly lower product yields than the n = 4series, and except for the formation of the p-methoxy product, the n = 5 series did not cyclize. It is significant to note that the preferred transition state for these phthalimides (from ε -hydrogen abstraction) was eightmembered as opposed to the preferred six-membered transition state in ketones.³⁴

The yields obtained with the methyl and methoxy substituents far exceed the yield obtained for the unsubstituted starting material. Donating groups, as predicted by ³⁴Wagner, make the hydrogen to be abstracted more nucleophilic and, hence, enhance ketone Type II reactivity. In this respect the Type II reactivity of phthalimides corresponds to that of ketones.

The second study of Kanaoka⁹⁶ on substituted o-tolylphthalimides extended the investigation of electronic effects on Type II reactions in phthalimides. Substitution on the o-tolyl ring gave somewhat ambiguous results. No trend in product yield was observed with donating groups. A nitro substituted compound, however, was the only phthalimide which did not undergo cyclization.

Substitution on the phthalimide ring would be expected to favor abstraction by one carbonyl over the other. Stronger donating groups do not form cyclized products, while withdrawing groups cyclized, but the products were mixtures of isomers. Stonger withdrawing groups did not increase product yields but were consistent with the observations for ketones. The withdrawing groups would remove electron density from oxygen making it electrophilic. Lack of cyclization in phthalimides with donating groups would indicate extra electron density in oxygen. The electronic considerations in phthalimides are consistent with those for ketones as observed by Wagner.³⁴

Another early observation by Kanaoka⁸⁶ was further investigated by his and other groups. The original observation was that acetone would add to the diradical formed in the photolysis of phthalimide derivatives of amino acids. In addition, Kanaoka had observed the addition of certain alcohols to form hemiacetals in a type of photoreduction of the N-o-phthaloyltoluenes.⁸⁵

Another addition reaction was discovered by Tanabe, Dehn, and Bramhill.⁹⁷ Irradiation of imidan, O,O-dimethyl-S-phthalimidomethylphosphorodithioate, in diethyl ether, produced two products in low yields, N-methylphthalimide and N-methoxymethylphthalimide. The following mechanism explains the product formation:



In this case no hydrogen abstraction and subsequent closure is likely. One of the primary products, N-methylphthalimide, was shown to undergo subsequent photoreaction to yield three products. The first product was due to photoreduction while the second and third were the diastereomeric addition products of methylphthalimide and

diethyl ether. The following mechanism illustrates their formation:



Roth and Schwarz⁹⁸ found that another ether, tetrahydrofuran, would photochemically add to phthalimide and to phthalimidoyl acetic acid. Photoreduction and radical recombination products were also observed for phthalimide. Irradiation of the acetic acid in acetone yielded only the decarbonylation product. Products of addition and photoreduction were isolated following irradiation of N-methoxymethylphthalimide in THF. In addition, thalidomide was observed to undergo photoreduction in THF. These points are illustrated in the following scheme:





















Roth and Hundeshagen 99 expanded the previous work on solvent photointeraction with phthalimide. Ethanol added to phthalimide to yield 21% product while isopropanol yielded 45% of the product obtained through acetone addition, $^{33}_{\sim}$. Phthalimide underwent only photoreduction and radical recombination with methanol. A dioxane addition product analogous to that with THF was isolated in 20% yield from the irradiation of phthalimide in dioxane/acetone. The following scheme illustrates Roth's findings:



Kanaoka and Hatanaka¹⁰⁰ showed that olefins as well as ethers would add to N-methylphthalimide. THF formed products with N-methylphthalimide analogous to those observed by Roth for phthalimide arising via photoreduction and solvent addition.



Similar results were observed for diethyl ether and dioxane. N-methylphthalimide, when irradiated in a 2M solution of cyclohexene or cyclopentene in acetonitrile, afforded addition products in small yields.



The oxetane formation observed in the photoreaction of ketones and alkenes, Paterno-Buchi reaction, did not occur with phthalimides and olefins. Kanaoka and co-workers¹⁰¹ showed that amines and toluenes would also add to N-methylphthalimide. Intramolecular hydrogen abstraction from an o-tolyl substituted phthalimide was already reported.⁸⁵ The addition reaction as well as photoreduction was observed for a number of alkyl substituted toluenes as illustrated by the following reaction:



The two amines investigated, N,N-dimethylaniline and N,N-dimethylcyclohexylamine, added to N-methylphthalimide in acetonitrile to yield a variety of addition and reduction products.





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The product, 34, was isolated only with N,N-dimethylcyclohexylamine and unfiltered mercury arc light for 10 hours. The photoreduction product, dihydromethylphthalimide, was not detected with N,N-dimethylaniline. All products but 34 were observed with N,N-dimethylaniline. The following mechanism was proposed by Kanaoka to explain the product formation:







It can be seen that solvent addition and interaction are important factors in phthalimide photochemistry. The photochemical addition of a variety of types of compounds to phthalimides is synthetically useful and perhaps will aid in the elucidation of the mechanism of substituted phthalimide decomposition.

Phthalimides were not the only imide systems to undergo Type II reactions. As previously mentioned,⁷³ substituted glutarimides and succinimides also undergo γ -hydrogen abstraction. The scope of this reaction is probably as vast as for phthalimides. Some of the applications can be seen below:





The reactions show formation of activated spiro compounds as well as the fused rings analogous to the phthalimide reactions. The mechanism proposed for these photodecompositions by Kanaoka and Hatanaka is similar to that proposed for alkylphthalimide decomposition. The products require formation of a diradical via γ -hydrogen abstraction followed by closure to yield an azacyclobutanol intermediate. The intermediate, due to its instability, undergoes ring cleavage to yield the ring-expanded product.



It was not established how efficient these Type II and addition reactions were in phthalimides and other imidic compounds studied. Quantum yield determination of these reactions is necessary for comparison with other carbonyl compounds. The reversibility of the individual steps could be verified by irradiation of specific compounds.

§3. RESULTS AND DISCUSSION

The Type II reactions that were proposed by Kanaoka and other investigators for phthalimides and related compounds have been shown in the first section to be important in the photodecomposition processes of other carbonyl compounds. Relative quantum yield measurements provide a quantitative handle for comparison of Type II reactions in phthalimides with those in the other compounds. The quantum yield of each compound can be related to starting material disappearance to give the efficiency of the reaction. Wagner¹³ showed that the Type II quantum yields in substituted butyrophenones did not correlate with Type II reactivity.

The series of compounds selected for study could not undergo the secondary Type II reaction shown on page 137 for N-alkylphthalimides with ϵ -hydrogens. The accurate measurement of quantum yields requires isolation of all Type II products as well as determination of the quantity of light absorbed by the reaction mixture. The trends shown by the quantum yields would allow further comparison of electronic and geometric effects with those from other carbonyl compounds.

It has been stated that other alkyl imides do not undergo Type II reactions for a variety of reasons.⁷² Irradiation of a dibenzoyl amine would show whether the Type II reactivity of phthalimides is due to conjugation with the benzene system or the specific geometry of the

phthalimide, which allows extended I overlap of the two carbonyls as well as the benzene ring. A Type II reaction analogous to the phthalimides would have further synthetic implications.

The several step mechanism proposed by Kanaoka for the decomposition of N-alkylphthalimides has not been verified. Several of the proposed steps may be reversible, and experiments can be designed to show the reversibility. The actual excited state of the phthalimides proposed by Kanaoka had been determined by quenching studies, which should be repeated.

In general the primary and secondary N-alkylphthalimides were prepared by the action of potassium phthalimide on the appropriate alkyl bromide or iodide in refluxing DMF.



Tertiary phthalimides like tert-butylphthalimide were prepared indirectly from the corresponding urea.¹⁰² A mixture of tert-butanol, urea, and concentrated sulfuric acid was stirred overnight at room temperature. The reaction mixture was neutralized, and substituted urea was recovered. Pyrolysis of the urea and phthalic anhydride followed by recrystallization from water/ethanol yielded pure tert-butylphthalimide.



Preparative irradiations in general were conducted through a quartz well with a 450W medium pressure mercury Hanovia lamp unless otherwise stated. The solutions irradiated generally contained 1% by weight of the phthalimide in spectrograde solvent. In general, zero-hour samples were compared by TLC with irradiated samples.

Photolysis of N-propylphthalimide

Irradiation of propylphthalimide in acetonitrile yielded two products, as expected on the basis of Kanaoka's work 84 , which were isolated by preparative TLC. The product with the higher $R_{\rm f}$ was assigned the structure of 3dihydrophthalimidopropene on the basis of the NMR and IR data and Kanaoka's assignments. 84

The second product was also isolated by TLC and purified by recrystallization from benzene/Skelly B. The compound, 36, was assigned the structure 3,4-benzo-6,7dihydro-6-methyl(1H)azepine-2,5-dione on the basis of spectral data.⁸⁴



36

The irradiation was repeated in tert-butanol. Only one product, 3_{0}^{6} , was identified in the reaction mixture and isolated.

Photolysis of N-ethylphthalimide

Solutions of N-ethylphthalimide in acetonitrile and tert-butanol were irradiated. In both cases only one product was present, which was isolated by preparative TLC. IR and NMR were consistent for Kanaoka's reported product, 3,4-benzo-6,7-dihydro(1H)azepine-2,5-dione, 37.



Photolysis of N-isobutylphthalimide

Irradiation of a solution of N-isobutylphthalimide in acetonitrile yielded three products. Silica gel column chromatography afforded a white solid with methylene chloride, which was characterized by IR, NMR, and m.p.(130°) as phthalic anhydride (~15%). A further discussion of the formation of phthalic anhydride will be given in the photolysis of N-2-methylbutylphthalimide section.

The second product isolated was purified by preparative TLC. The IR was analogous to the dihydrophthalimide alkene isolated in the photolysis of N-propylphthalimide. The NMR of the solid (m.p. 78-80°) showed an alkyl singlet, which was consistent for one of the two products proposed by Kanaoka. The structure was assigned as 3-dihydrophthalimido-2-methyl-propene, 38.

The third product was isolated by column chromatography and purified by preparative TLC and by recrystallization from acetonitrile. The IR was analogous to those proposed for the two previously proposed azepinediones. The NMR contained three signals, a six hydrogen alkyl singlet, a two hydrogen doublet, and a five hydrogen multiplet containing the phenyl and N-H signals. The IR and NMR were consistent with 3,4-benzo-6,7-dihydro-6,6-dimethyl(lH)azepine-2,5-dione 39, which would explain the dimethyl singlet and alkyl doublet of two hydrogens adjacent to N-H.



Irradiation of the phthalimide in tert-butanol yielded only 39. The dihydrophthalimide alkene was not observed in this reaction. Presence of phthalic anhydride was not confirmed or disproved.

Photolysis of N-isopropylphthalimide

Irradiation of N-isopropylphthalimide in acetonitrile and tert-butanol yielded only one product, which was isolated by preparative TLC. The reason for the absence of an alkene product was obviously due to the absence of δ -hydrogens. The IR was analogous to those for the previous benzazepinediones. The NMR contained an alkyl doublet and was consistent with the product proposed by Kanaoka, 3,4-benzo-6,7-dihydro-7-methyl(lH)azepine-2,5-dione, 40.



Photolysis of N-tert-butylphthalimide

Irradiation of solutions of N-tert-butylphthalimide in acetonitrile and tert-butanol yielded only one product which was isolated by preparative TLC and purified by recrystallization from benzene/Skelly B. On the basis of the spectral data this material was assigned the structure of 41 (3,4-benzo-6,7-dihydro-7,7-dimethyl(1H)azepine-2,5-dione), which was consistent with Kanaoka's assignment.⁸⁴


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Photolysis of N-butylphthalimide

Irradiation of a solution of N-butylphthalimide in acetonitrile yielded three products. This phthalimide was of interest for two reasons. The major product reported by Kanaoka was 37, which could be produced only in small quantities by irradiation of N-ethylphthalimide. Pure 37 in substantial quantities was necessary for the quantum yield determination. The second reason would be to observe the secondary Type II reaction previously mentioned on page 137. N-butylphthalimide was not used for quantum yield determination because the secondary Type II cleavage by the ketone moiety would complicate the results.

The products were isolated by silica gel column chromatography. The IR and NMR spectra of the first two products were analogous to those of the dihydrophthalimide alkenes observed for the photolysis of isobutylphthalimide and propylphthalimide. On the basis of the spectra and Kanaoka's observations, the compounds were assigned as the cis and trans isomers of 4-dihydrophthalimido-2-butene.

The third product was isolated and purified by preparative TLC and recrystallization from benzene/Skelly B. The spectra and melting point match those for 37. Isolation of 37 shows that the secondary Type II reaction does occur very efficiently in N-alkylphthalimides with both γ and ε -hydrogens. None of the intermediate to formation of 37 was observed, that is, the substituted 6-ethylazepinedione. This is qualitative evidence in one experiment that Type II reactions in ketones are probably more efficient than in phthalimides.



Photolysis of N-sec-butylphthalimide

Irradiation of this phthalimide allows comparison of primary versus secondary hydrogen abstraction in the same molecule because sec-butylphthalimide has both in the γ position. In ketones, Wagner¹³ showed that secondary hydrogens were easier to abstract than primary hydrogens due to the increased nucleophilicity of the hydrogen³¹ from the electron donating power of the methyl group. Theoretically, several products could result from the photolysis via initial γ -hydrogen abstraction:





43 cis and trans

The secondary hydrogen abstraction due to the diradical intermediate would yield the cis and trans isomers of the 6,7-dimethylazepinedione (43) as well as the dihydrophthalimide alkene, which as previously shown, arises via secondary δ -hydrogen transfer. The 7-ethyl compound, 42, may be isolated or undergo a secondary Type II reaction and subsequent cyclization to yield a secondary product. This would be analogous to Kanaoka's multicyclic system synthesis. Product analysis would determine which one or if both processes operate.

Irradiation of the phthalimide yielded two main products, which were isolated by preparative TLC. The product with the highest R_f was further purified by preparative TLC. The IR of the compound was analogous to those of previous dihydrophthalimide alkenes. The NMR showed an alkyl doublet at ~1.458 as well as an OH signal and vinyl signals. The structure of the compound was assigned as 3-dihydrophthalimido-l-butene on the basis of the spectral data.

The second and major product was isolated as an oil, purified by preparative TLC, and recrystallized from benzene/Skelly B. The IR had the characteristics of the other benzazepinediones rather than the single carbonyl of 43. The alkyl region of the NMR was complex, but no ethyl group pattern characteristic of 42 was observed.

The melting point, NMR, IR, and mass spec match those obtained for cis and trans- 3,4-benzo-6,7-dihydro-6,7dimethyl(1H)azepine-2,5-dione by Koch¹⁰³ in the photochemical addition of 2-butene to ethoxyisoindolene. Under the reaction conditions it is apparent that secondary hydrogen abstraction is preferred over primary hydrogen abstraction.

Photolysis of Inactive N-2-methylbutylphthalimide

Irradiation of N-2-methylbutylphthalimide in acetonitrile served as a model for the optically active material. This phthalimide would also be expected to undergo a secondary Type II elimination to yield 36, and its reactivity should be similar to that of isobutylphthalimide. The alkyl halide required to prepare this phthalimide would be the simplest to have an asymmetric carbon in the γ -

position.

The phthalimide was prepared by the general procedure, but the alkyl bromide had to be prepared from the alcohol via the tosylate by a method analogous to that of Kjer and Friis 104 .



The reaction of inactive 2-methylbutanol and tosyl chloride (Skelly B) in pyridine at 0° required 24 hours for quantitative conversion to the tosylate. The tosylate was quantitatively converted to the bromide with lithium bromide in acetone under reflux. After distillation the bromide was converted to the phthalimide by the general procedure.

Photolysis of the inactive phthalimide in acetonitrile yielded two products, which were isolated by silica gel column chromatography. One product was identified by its spectra and melting point as phthalic anhydride. The second product was purified by preparative TLC and identified by its spectra and lc retention time as 36.





It is apparent from the formation of 36 that the secondary Type II ketone process is occurring as it did with the intermediate product of N-butylphthalimide. Type II reactions in ketones had been shown to be quenched with cis-1,3-pentadiene by investigators. It is possible that 44 could be isolated when a quencher was added to the photolysis mixture (see page 207).

An irradiation was conducted through a Corex filter with the inactive phthalimide and quencher in sodium dried tert-butanol. Two products were formed, and the minor product was identified as 36 by TLC and NMR. The major product was isolated by preparative TLC, having a much higher R_f than 36 but slightly less than the starting material. The NMR of the product would be expected to show an alkyl singlet and an ethyl pattern. The alkyl region of the NMR had characteristics of the starting material as well as additional signals and a vinyl pattern. The IR showed no bands in the OH, NH region. Lc analysis showed the presence of more than one product. Further purification was not attained.

The presence of phthalic anhydride in the original reaction could be explained by the following mechanism:



In most cases, Type I reactions would not be observed either because the Type II reaction is much more efficient or because the incidence of the reverse reaction is much higher than rotation, rehybridization, and closure. The imine compound 45 is not observed because the slightly acidic condition of the silica gel column hydrolyzes the imine, and the heat of the workup completes the conversion to phthalic anhydride. This product is observed only when the γ -hydrogen is tertiary. Quantum yield determination will show if this observation is due to the inefficiency of the Type II reaction for tertiary γ -hydrogen abstraction.

Quantum Yield Determination in Alkyl Phthalimides

The quantum yield of a photochemical reaction provides common ground for comparison with other photochemical reactions. Quantum yields can be measured for starting material disappearance or any process where there is a product or detectable evidence of product formation. Although the quantum yield does not necessarily imply the reactivity of a compound, ¹³ the quantum yields for Type II reactions in a series of alkyl phthalimides could show trends in reactivity as well as how phthalimide Type II reactivity compares with that of ketones, esters, acids, etc.

The quantum yield Φ is defined as the quotient of the moles of the product formed and the einsteins of light incident to the reaction mixture. The moles of product formed can usually be measured by glpc using an internal standard. There are numerous ways to measure the light quantity, which include monitoring a reaction of known quantum yield (actinometry).

The first method for determination of light quantity to be discussed is that of Dunion and Trumbore,¹⁰⁵ which uses cyclopentanone actinometry. Cyclopentanone was observed to photodegrade to yield 4-pentenal by a number of investigators.¹⁰⁶ The quantum yield has been accurately measured and documented at 0.37 ± 0.02 . Samples of cyclopentanone containing an internal standard are irradiated at the same time and under the same conditions as the com-

pound whose quantum yield is to be determined. The quantity of 4-pentenal produced could be determined from the glpc ratio of 4-pentenal area to an internal standard area and the molar response factor of 4-pentenal. The exact method is discussed in the experimental section dealing with quantum yields. The light quantity incident on the samples, measured in einsteins, is the ratio of the moles of 4-pentenal and the quantum yield for the reaction, 0.37.

A second method for measuring light quantity is ferrioxalate actinometry. The method of Parker and Hatchard¹⁰⁷ is the most popular due to the ease of operation and employs the photochemical redox reaction of potassium ferrioxalate solution in an acidic aqueous medium. The oxalate is oxidized to carbon dioxide, and the iron is reduced from the ferric to the ferrous state. The quantum yield of this reaction has been measured accurately for irradiation in the range of wavelengths of interest, 250-255 nm.

After the acid solution of ferrous ions is buffered, the ions form an orange complex with 1,10-phenanthrolene solution. The intensity of the orange color in solution is dependent on the original ferrous ion concentration. The concentration of ferrous ion can then be calculated from the uv absorbance of the solution at 510 nm as related by Beer's Law.

 $A = \varepsilon \times b \times c$ where b = 1 cm and ε at 254 nm $= 1.1 \times 10^4$.

The actual procedures used in the determination of light quantities by ferrioxalate actinometry were a refinement of those designed by J.J. Thomas.¹⁰⁸ Two adaptations of the procedure were used. In order to understand the theory and explanation of the procedures, the apparatus used must be defined.



- 1. Monochromator
- 2. Quartz collimating lens
- 3. Optically clear quartz reflector
- 4. Sample cell
- 5. Reference cell
- 6. Backup cell

Figure 5. Black Box Photolysis Apparatus

Figure 5 shows the apparatus used for the determination of light quantity by ferrioxalate actinometry. There are two methods for the determination, split ratio and direct irradiation. Both methods use the same apparatus with a number of modifications. It is assumed in both methods that the monochromator produces light of a constant intensity, however, measures can be taken in both cases to correct for inconsistency.

In the split ratio determination the quartz reflector splits the light beam into two unequal components (according to the reflector angle) with the small beam, i.e. 5%, diverted to the reference cell. The sample, reference, and backup cells were filled with the actinometer solution and irradiated with stirring for 30 minutes. Each solution was treated with phenanthrolene solution and buffer solution in preparation for uv analysis as discussed in the experimental section. The split ratio is defined as follows:

The moles of Fe²⁺ that were produced in each cell are directly related to the absorbance of each at 510 nm as are the dilutions used in the sample preparations in the following fashion from Beer's Law:

$$C = \frac{A}{1.1 \times 10^4} \quad \text{and} \quad C = \frac{\text{moles Fe}^{2+}}{\frac{V_1 V_3}{V_2}}$$

 V_1 is the volume of actinometer photolyzed, V_2 is the volume of the aliquot of the photolyte, V_3 is the total dilution volume.

moles
$$Fe^{2+} = \frac{A}{1.1 \times 10^4} \times \frac{V_1 V_3}{V_2}$$

In this equation all quantities are known or can be easily measured.

The actual quantity of light or moles of light particles/unit time is defined as the intensity and can be expressed in terms of the moles of ferrous ions produced by the following quantum yield expression:

$$I = \frac{\text{moles Fe}^{2+}}{\Phi \times t}$$

where Φ = 1.25 at 254 nm and t = time of irradiation in seconds. Intensity of light can then be expressed in all known or measured quantities.

$$I = \frac{A}{\frac{1.1 \times 10^4}{t}} \times \frac{\frac{V_1 V_3}{V_2}}{v_2}$$

The split ratio can then be calculated in terms of known and measurable quantities from the following equation:

Split Ratio =
$$\frac{A_{\text{Sample}} \times \frac{V_{1}V_{3}}{V_{2}} - A_{\text{Backup}} \times \frac{V_{1}V_{3}}{V_{2}}}{A_{\text{Reference}} \times \frac{V_{1}V_{3}}{V_{2}}}$$

In all cases it was experimentally determined that the absorbance in the backup cell was 0, hence, the split ratio was merely:

Split Ratio =
$$\frac{A_{\text{Sample}} \times \frac{V_1 V_3}{V_2}}{A_{\text{Reference}} \times \frac{V_1 V_3}{V_2}}$$

The split ratio was measured before and after each quantum yield irradiation. In all cases the split ratio was the same before and after irradiations, within experimental limits.

While samples were irradiated, a reference and a backup cell were maintained with actinometer solution. The absorbance of each solution was measured following complexation. With the absorbance the quantity of light absorbed by the sample can be expressed by the following equations:

Einsteins = $\frac{\text{moles Fe}^{2+} \text{Reference}}{\Phi}$ × Split Ratio - moles Fe²⁺ Backup

where again Φ = 1.25 or

Einsteins = $\frac{A_{\text{Reference}} \times \frac{V_1 V_3}{V_2} - A_{\text{Backup}} \times \frac{V_1 V_3}{V_2}}{1.1 \times 10^4 \times 1.25}$

It is easily seen from the split ratio that a known constant fraction of the light is diverted to the reference cell. (The quantity of light absorbed by the sample is then the product of the quantity of light, which passed through and was measured in the backup cell, and the split ratio.) The added advantage of this method is that any deviation in light intensity during the quantum yield irradiation could be detected by constant monitoring. A number of light quantity calculations using the split ratio and split ratio calculations as well as detailed derivation of the previous equation is given in the experimental section on pages 361 - 365.

It was observed in the split ratio determination that the light intensity was constant. The light source, a Bausch and Lomb monochromator, is known to produce light of constant intensity for 200 hours. The procedure for determination of light quantity could be simplified to eliminate the split ratio.

An intensity measurement before and after each quantum yield irradiation was conducted without the quartz reflector. Actinometer solution in the sample and backup cells was irradiated for an accurately measured interval. Irradiation of the sample whose quantum yield is to be determined was accompanied with a backup cell, once again, to measure the light passing through the sample cell. The light quantity for the sample irradiations could be calculated from the intensity measured for the short period. The light quantity measured by this direct irradiation method can be expressed in terms of known and measurable quantities, since the absorbance of the backup cell was negligible.

Einsteins =
$$t_{I} \times \frac{A}{\varepsilon \times \Phi \times t_{0}} \times \frac{V_{I} \times V_{3}}{V_{2}}$$

t₀ = time in seconds of irradiation for intensity measurement

t_I = time in seconds of irradiation for quantum yield determination

Since the denominator of the quantum yield expression has been determined, a method must be devised to determine the product yield. It is necessary to choose substituted phthalimides for the quantum yield study, which cannot undergo secondary processes. In order to eliminate this obvious problem no compound with ε -hydrogens can be used.

In order to compare primary, secondary, and tertiary hydrogen abstraction, compounds with δ -hydrogens are necessary. As previously stated, δ -hydrogen transfer occurs to an unspecified degree in acetonitrile. Wagner¹⁰⁹ studied the effect of solvent on hydrogen transfer and found that Type II reactions, which proceed through a diradical, could lead to products by three routes:



It was shown that product distribution could be altered by changing the polarity of the solvent. The following scheme illustrates the effect:



It can be seen here that polar solvents prevent the reverse reaction to starting material. Relative distribution of the yields of the isomeric cyclobutanols was also changed with tert-butanol. It was proposed that the alcohol complexes with the γ -hydrogen that was transferred. The complex would then prevent back transfer of the hydrogen to yield starting material and hinder closure to cyclobutanol in the case of the methyl group trans to phenyl. We had observed, as well as Kanaoka,⁸⁴ that only ring expansion products were formed when the photolysis of the phthal-

imides was conducted in tert-butanol.

Solutions of the phthalimides to be studied containing an internal standard in tert-butanol were purged by freezepump-thaw degassing. Loss of starting material could be monitored by glpc with the internal standard. Unfortunately, the products were not detectable by glpc. The analytical TLC separation showed that the products would be readily distinguishable by high pressure liquid chromatography. Only external standards could be used to monitor product formation since the hydrocarbon internal standard would not be uv detectable, and any detectable standard present during irradiation would absorb light. An aliquot of the photolyte and an aliquot of the standard solution were mixed for the product analysis, while the photolyte alone was sufficient to monitor starting material loss by glpc.

In order to determine the exact product yield lc response factors for each product were determined. The product yield can be calculated from known and measured quantities by the following equation:

Moles Product = Response Factor × Moles Standard × Area Product Area Standard

The response factors for the products of the phthalimides studied were calculated in the experimental section and shown in Table XXIV on page 370. The results of the quantum yield calculations are shown in Table VII.

Table VII

Quantum Yields of N-alkylphthalimides

Ъу	Cyclopentanone Actinometry	-

Starting Material	Moles Product	Moles Light (einsteins)	Quantum Yield
N-propylphthalimide	6.68 ×10 ⁻⁶	9.35 ×10 ⁻⁴	0.0071
N-ethylphthalimide	2.5×10^{-6}	9.35 ×10 ⁻⁴	0.0027
N-isobutyl- phthalimide	7.8×10^{-6}	9.35 ×10 ⁻⁴	0.0083
N-isopropyl- phthalimide	7.38 ×10 ⁻⁶	9.35 ×10 ⁻⁴	0.0079
N-tert-butyl-	2.31 ×10 ⁻⁵	9.35 ×10 ⁻⁴	0.0247
N,N-dibenzoyl- isobutylamine	0	9.35 ×10 ⁻⁴	0

The irradiation was with 2537Å light, and the light quantity was measured by cyclopentanone actinometry. Duplicate tubes of each phthalimide were irradiated simultaneously. The actual quantity of light from the cyclopentanone was determined in a separate irradiation in which the quantum yield for N-ethylphthalimide was measured and found to be consistent with the second irradiation. Irradiation for 12 hours resulted in between 9 and 24% starting material conversion. The quantum yield for N-tert-butylphthalimide, 0.0247, was checked by potassium ferrioxalate actinometry and determined to be 0.023 (within experimental limits).

Another measure of the effectiveness of the Type II reaction is the percent efficiency, which is defined to be the moles of product formed divided by the moles of starting material decomposed. Table VIII shows these relative efficiencies as well as the quantities necessary for their determination.

The trends in quantum yields and efficiencies appear to be the reverse of the observations made for primary versus secondary versus tertiary hydrogen abstraction in ketones and esters. Several possible reasons are given in the section on geometric and electronic effects.

Table VIII

Efficiency of Ring Expansion for N-alkylphthalimides

Phthalimides	Moles Product	% Starting Material Conversion	Moles Starting Material	Moles Starting Material Decomposed	% Effi- ciency
N-propyl- phthalimide	6.68×10 ⁻⁶	14.7	1.35×10 ⁻⁴	1.99×10 ⁻⁵	33.6
N-ethyl- phthalimide	2.52×10 ⁻⁶	8.9	1.47×10 ⁻⁴	1.12×10 ⁻⁵	22.5
N-isobutyl- phthalimide	7.8×10 ⁻⁶	21.1	1.26×10 ⁻⁴	2.66×10 ⁻⁵	29.3
N-isopropyl- phthalimide	7.38×10 ⁻⁶	9.6	1.35×10 ⁻⁴	1.29×10 ⁻⁵	57.2
N-tert-butyl- phthalimide	2.31×10 ⁻⁵	23.9	1.26×10 ⁻⁴	3.01×10 ⁻⁵	76.7
N,N-dibenzoyl isobutylamine	- 0	0(<.2)	1.39×10 ⁻⁴	0	0

Irreversibility of Y-Hydrogen Abstraction

In addition to the difference observed for Y-hydrogen abstraction, the quantum yields were quite low in comparison to other types of compounds. Wagner¹⁰⁹ stated, as noted in the previous section, that the hydrogen abstracted may be transferred back from oxygen to carbon as a possible decomposition pathway of the 1,4-diradical intermediate. Reversible hydrogen abstraction does not lead to products and, hence, is a quantum wasting step.

The most logical way to determine the reversibility of the reaction would be to irradiate a compound where the γ carbon is asymmetric. The proposed initial γ -hydrogen abstraction to yield a 1,4-diradical would show partial racemization after rotation of the radical and back transfer to yield starting material.

Wagner, Kelso, and Zepp¹¹⁰ irradiated (4S)-(+)-4methyl-l-phenyl-l-hexanone in a variety of solvents. Rapid racemization was observed in irradiations done in non-polar solvents such as benzene. As tert-butanol concentration in the solvent was increased, the photoelimination and photocyclization increased. Accordingly, back transfer and, hence, racemization decreased. The original rotation of the starting material $[\alpha]_D^{25}$ + 9.81° is greatly decreased in the substituted cyclobutanol isolated from irradiation in tert-butanol $[\alpha]_{548}^{25}$ -0.25°. This small angle would indicate that the diradical lifetime is not sufficient to permit

complete racemization, either through loss of radical chirality or bond rotation.

Yang, Elliot, and Kim¹¹¹ irradiated (S)-(+)-5-methyl-2-heptanone in hexane and in tert-butanol, with and without quencher. Racemization was observed in both solvents without quencher. As with Wagner racemization of starting material was decreased in tert-butanol. No analysis was done on the optical activity of the cyclobutanones. Irradiation in the presence of quencher showed no racemization, which indicates decomposition from the singlet (as well as predominating triplet state without quencher) state and radical lifetime shorter than that required for bond rotation or spin inversion.

Mazzocchi, Danisi, and Thomas¹¹² irradiated the optically active N-2-methylbutylpyrrolidone in isopropanol in order to determine if polyvinylpyrrolidones were photodegradable. As an analogy to Guillet's observation for poly-(methyl vinyl ketone)¹ the following Type II mechanism was investigated:



The reaction to yield alkene and iminol was not observed. In order to determine if the γ -hydrogen abstraction was reversible, the starting material was recovered after 50% conversion. Racemization was not observed as the rotation

was $[\alpha]_{213}^{20} = -6.3^{\circ} \pm .2$ in the unirradiated sample and was $[\alpha]_{313}^{20} = -6.2^{\circ} \pm .2$ after irradiation. Consequently, reversible γ -hydrogen abstraction and, hence, Type II processes were not important in the photodegradation of poly (vinyl-pyrrolidones).

Two irradiations were conducted on the optically active N-2-methylbutylphthalimide with an internal standard in tertbutanol. According to Yang¹¹¹ reversible hydrogen transfer would be impaired but not stopped. The first irradiation was conducted for 21 hours to a 11-12% starting material conversion. Unreacted starting material was recovered by preparative glpc. The optical rotation of unirradiated starting material, purified in the same manner, showed $\left[\alpha\right]_{370}^{25} = +8.68^{\circ}$ at 0 hours and $\left[\alpha\right]_{370}^{25} = +8.64^{\circ}$ at 21 hours. Similar consistency of rotation was also observed at 390 nm.

The second irradiation was conducted in the same manner, however, samples were taken at 10, 15, 20, 25, and 31 hours. Starting material disappearance was monitored by glpc. The ORD of each sample was measured. The low difference in starting material conversion rendered accurate $[\alpha]_{-}^{20}$ calculations impossible. The individual lines were concentric and nearly parallel diverging at the low wavelength end of the spectrum, as was observed in the first irradiation.

Product analysis for 36 was conducted on aliquots of each sample. The calculations and numbers for starting It may be noted here that the alcohol solvent may prevent the reverse hydrogen transfer according to Wagner.109,110 material disappearance and product generation are shown in the experimental section in Tables XXVIII and XXIX. Figure 6 shows the starting material disappearance and product generation versus time. It is apparent from these studies that the initial Y-hydrogen abstraction is not reversible in tert-butanol. The argument of reversible Y-hydrogen abstraction to explain the quantum wasting and the low quantum yields for substituted phthalimides in tert-butanol does not apply.



Photolysis of N,N-dibenzoylisobutylamine

Kanaoka asserted in a number of his papers that the rigid geometry as well as the overlap with the additional carbonyl and benzene ring contributed to the Type II reactivity of phthalimides. Kanaoka and Hatanaka⁷³ showed in their irradiation of substituted succinimides and glutarimides that the extra carbonyl and the rigidity of structure may be a factor in Type II reactivity. Photolysis of an N,N-dibenzoylamine could show the role of the benzene moiety and rigidity of the imide structure in determining reactivity.

In phthalimides and other imide compounds studied by Kanaoka,⁷³ the nitrogen lone pair and ring structure of the starting materials prevent complete cleavage after the proposed cyclobutanol formation.



It may be interesting to study a compound where ring cleavage yields dissociation to an alkyl chain rather than a ring. If Type II reactions are efficient for N,N-dibenzoyl compounds (assuming reaction operates by the same mechanism) the cleavage of the cyclobutanol intermediate would yield a substituted β-ketoamide.



The reaction may then have significant synthetic utility, and substituent effects on the benzene and amine chain could be observed. Phenacylamines were shown by Hyatt⁶³ to undergo Type II reaction, presumably, according to Wagner^{34,31} and Walling,³⁵ due to the increased electron density on the hydrogen with the neighboring nitrogen's lone pair. In the case of 45 the carbonyl is further removed, and the lone pair is less able to donate due to the electron withdrawing carbonyl. As an amide and as a ketone without easily abstractable γ -hydrogens, 45 or its cyclobutanol precursor should show a buildup and hence be detected during the course of the reaction.

Irradiation of N,N-dibenzoylisobutylamine yielded one minor product, N-isobutylbenzamide. The photolyses in both tert-butanol and acetonitrile required considerably longer periods of irradiation than any of the substituted phthali-mides. Irradiation at 2537\AA showed no starting material

disappearance or product formation. Glpc and TLC analysis of samples taken during the quartz-filtered irradiation showed only the one product present in more than trace amounts.



Quantum yield measurements attempted under the same conditions, where substituted phthalimide decomposition was measured, failed to show product formation on 0.2% starting material disappearance. The quantum yield must thus be less than 0.0003, (on the basis of 22% versus 0.2% starting material conversion for the same quantity of light), which is much less than that observed for the corresponding N-isobutylphthalimide. It is then obvious that one of the determining factors in the increased Type II reactivity may include the rigidity of the structure in phthalimides. Since Type II reactivity was low and the compound apparently decomposed by Type I reaction, there was no further interest in these compounds.

Electronic and Geometric Effects in Type II Reactions of Phthalimides

Presumably, the same conditions stated in Part I, which inhibit Type II reactions in amides, would determine Type II reactivity in substituted phthalimides. When comparison with the Type II quantum yields of ketones and esters was attempted, the Type II quantum yields measured for phthalimides were considerably lower. The pattern of increase in the Type II quantum yields was also different for phthalimides than for ketones. It had been asserted by Kanaoka in a number of his works that the Type II reactivity was due to the rigid geometric structure and the molecular electronic configuration.

The largest electronic effect in Type II reactions, according to Wagner,^{31,34} is the electrophilicity of the carbonyl oxygen and the nucleophilicity of the hydrogen to be abstracted. This electronic consideration in phthalimides can be defined by the electronic configurations, which were predicted by dipole moment studies. The following resonance structures can be drawn on the basis of the dipole studies.





In a dipole moment study of monosubstituted phthalimides, Caswell and coworkers ll3 originally assumed that the molecule was planar, the vectors of the group moments were in the plane, the imide moiety was electron withdrawing, and the benzene as a perfect hexagon made no contribution to the total dipole moment. When the dipole moments of a number of monosubstituted phthalimides were calculated, using the above assumptions, the experimental results only coincided with the calculations in a few cases. It was then determined that the interaction from the benzene moiety in the resonance forms shown above accounted for the difference. Resonance in the planar structure would predict a great degree of I overlap in any free imide group. 114 The dipolar resonance form often shown for amides would leave a positive charge on nitrogen. In order to stabilize the charge, some donation from the other carbonyl would be expected, which would make the oxygen of that carbonyl more electrophilic. In other words, the extra carbonyl would make the nitrogen a poorer Π donor as well as a better σ withdrawer.



Other carbonyl compounds have shown increased Type II reactivity when electrophilicity of oxygen was increased. Wagner also showed that Type II reactivity in ketones was increased by raising the nucleophilicity of the hydrogen to be abstracted with extra donating groups. In substituted phthalimides the increased nucleophilicity of the γ-hydrogen did not result in higher Type II quantum yields, and even with the extra carbonyl, no compound had a Type II quantum yield of the magnitude of most ketones.

In conjunction with the electronic factors, a number of geometric considerations should promote Type II reactivity. In the freely rotating alkyl imides the cis-trans rotamer is the most stable, hence the most prevalent. Only one form is possible in the case of substituted phthalimides, the cis-cis. In the rigid planar cis-cis form, 360° rotation of the nitrogen-carbon bond brings prospectively reactive γ -hydrogens in proximity to two reactive sites. The extra reactive site does not increase Type II quantum yields over those of aldehydes, ketones, and esters (pages 30-32), which have been shown to efficiently undergo Type II reaction.

In other compounds, restriction of bonds or steric hindrance produced a distorted six-membered transition state and decreased Type II reactivity. As opposed to the amide case, for most carbonyl compounds six-membered transition states are known to prefer Type II reactions to interaction with solvent.¹¹⁵ Although Kanaoka⁸⁶ and Roth⁹⁹ showed that

certain alcohols would react with the diradical intermediates, neither acetonitrile nor tert-butanol had been observed to combine with the phthalimides. It must be assumed that other quantum wasting processes must be occurring, which do not lead to Type II products and do not appreciably decompose starting material.

Valid comparison cannot be made with other carbonyl compounds since alkylphthalimides are actually semi-conjugated dicarbonyls. A comparison with α -ketoesters, α -ketoacids, α -diketones, and α -methylene ketones may be more valid. These types of compounds also have extra carbonyls or double bonds either in conjugation with the chromophore of interest or in a position to delocalize any radicals or charges formed. These compounds, in general, were observed like the alkylphthalimides to undergo Type II ring closure to yield cyclobutanols.

Hemperly, Wolff, and Agosta¹¹⁶ irradiated 2-methylenecyclododecanone, an α -methylene ketone. The only product, which was obtained in high yield, was 12-methylene-cisbicyclo[8.2.0]dodecan-l-ol. The following Type II mechanism would be assumed to operate:



The initial Y-hydrogen abstraction would be promoted by the rigid starting material structure. The intermediate diradical contained ostensibly an allyl radical. Alternate closure to a cyclobutyl ketone did not occur due to the restricted bond rotation. In this case, no quantum yield was measured for the Type II reaction; however, the irradiation period required for the conversion to the cyclobutanol would indicate a low Type II quantum yield.

Irradiation of isomesityl oxide by Yang and Thap¹¹⁷ showed another interaction of an alkene in the photochemistry of a ketone. The double bond was not conjugated with the carbonyl, and the products isolated were due either to fragmentation followed by recombination or Type II cleavage to yield 1-methyl-3-methylenecyclobutanol. No Type II elimination products were observed, and the quantum yield for cyclobutanol formation was measured at 0.05.

Results with α-ketoesters were ambiguous. Yang and Morduchowitz¹¹⁸ found no Type II products in the irradiation of ethyl pyruvate, despite the hydrogen Y to the ketone and adjacent to the oxygen. The products observed were diethyl dimethyl tartrate and a small amount of ethyl lactate. Leermakers, Warren, and Vesley,¹¹⁹ in contradiction to Yang,¹¹⁶ found aldehyde products for a variety of substituted pyruvates. The aldehydes could only be attained by Type II processes. Type II reactions contributed to the only significant product formation, and the ketone carbonyl was again the hydrogen abstracting moiety. The quantum

yields for the reactions measured 0.06 to 0.19 (much higher than any of the quantum yields measured for the alkylphthalimides).

Investigation of the photochemistry of a number of α-diketones by Urrey and Trecker¹²⁰ showed one similarity. In most of the cases studied only one major product was formed, substituted 2-hydroxycyclobutanones. In order to explain the product formation the following mechanism was proposed:



The mechanism suggested that besides the known transoid conformation of the carbonyls that carbons 4, 5, 6, and 7 were essentially coplanar, and the bond between carbons 5 and 6 had a substantial double bond character. Despite another possible Y-hydrogen abstraction, the only abstraction observed required a transition state where the second ketone participated. Due to the formation of a number of products, including cleavage products, by different Y-hydrogen abstractions, it is obvious that the second carbonyl by its participation governs the photochemical decomposition path-

way.

There is one notable exception where an adjacent carbonyl group is not proposed to interact in the excited state, but rather the opposite. Irradiation of α -ketoacids like α -ketodecanoic acid by Leermakers and Evans¹²¹ yielded mainly Type II cleavage products. Again the other carbonyl was proposed to participate in the reaction. Two Type II decompositions were possible:


The products observed in the reaction exclusively arose via Path A. In this case the alkene and pyruvic acid were produced as the only major products. From the possible products predicted by the mechanism, it is obvious that the chromophore promoting the reaction is the ketone function. In a reversal from the α -diketones, I was proposed as a better representation of the intermediate than II.

The quantum yield was high for aliphatic carboxylic acids, 0.21, but not for ketones. Formation of 1-heptene was completely quenched ^{*} in the presence of sufficient 1,3-cyclohexadiene. Since Type II reactions are not completely quenched for ketones, α -ketoacids must be assumed to be a special case in the photochemistry of α -ketocarbonyl compounds.

More recently, Wagner and Turro¹²² reopened the investigation of α -diketones. Spectroscopic studies had altered their concept of the relative positions of the excited state energy levels in α -diketones. One reaction not observed by Urrey and Trecker¹²⁰ was 1,4-hydrogen transfer:

* Further definition of quenching will be given in the next section.



This reaction was observed due to the stability of the oxyallyl radical.

The l,2-carbonyl diradicals observed in excited ketones were actually radicals electronically, however, in α diketones, a number of valence bond structures can be drawn in which the excited state could be depicted in a dipolar



From the structure at the left 1,4-hydrogen abstraction would be envisioned as the initially dipolar process shown below:



Lewis and Heine¹²³ also asserted that there was ionic character in Type II reactions although not as much as in the Type I. Alkyl phthalimides can be shown as a resonance form analogous to the α -diketones.

On the basis of the observations made on other compounds, several statements can be made regarding the quantum yields and the mechanism of decomposition of N-alkylphthalimides. The quantum yields for the series of compounds were low in comparison with other types of simple carbonyl compounds and α -ketocarbonyls with the exception of α -ketoacids. The efficiencies of the reactions (moles of Type II product formed/moles of phthalimide decomposed) were higher than expected from the quantum yields. Only the high efficiency of the reaction allowed measurement of such small quantum yields.

Comparison of the quantum yields and Type II efficiencies of the compounds showed that tert-butylphthalimide has the highest quantum yield and had the most efficient Type II decomposition. Isobutylphthalimide had the second highest quantum yield but the fourth efficiency. The quantum yield of isopropylphthalimide was nearly equal to that of isobutylphthalimide, however, the efficiency was much higher, second in the series and double that of the isobutyl. Propylphthalimide was fifth in both measurements.

On the basis of Wagner's observations on butyrophenones, the isobutyl having a 3° γ-hydrogen would be expected to have the highest quantum yield followed by n-propylphthalimide (2°), and finally tert-butyl, isopropyl, and ethylphthalimide (due to the number of γ-hydrogens), which all

had primary γ-hydrogens. The observed order in quantum yields was l° (t-butyl) > 3° (isobutyl) > 1° (isopropyl) > 2° (propyl) > 1° (ethyl). The series of efficiencies was 1° (tert-butyl) > 1° (isopropyl) > 2° (n-propyl) > 3° (isobutyl) > 1° (ethyl). There are several possible explanations for the orders of the series.

The number of γ -hydrogens involved in each case does not explain the large differences in the two measurements. Within the series of primary γ -hydrogens, it can be seen that the tert-butyl has a methyl group in position to react three times as often as the ethyl and 1.5 times as often as the isopropyl.



The difference in quantum yield and efficiency was too large to be accounted for by this superficial observation.

In addition to the greater number of Y-hydrogens, several geometric considerations may be important in phthalimide photochemistry. In tert-butylphthalimide, not only are the Y-hydrogens in the proper position for virtually the entire N-C bond rotation, but the geometry of the diradical intermediate is also important. Inspection of the various diradicals will illustrate the point.







The two radical sites in the tert-butyl case would be forced in closer proximity by the two methyl groups adjacent to nitrogen, which should appreciably increase the amount of cyclobutanol formed. It is obvious that once the cyclobutanol undergoes retrotransannular ring opening, reclosure from the azepinedione is impossible. The same forced closing of the diradical should be true to a lesser extent for isopropylphthalimide.

The closure of the ethyl and n-propylphthalimide diradicals should remain unaffected. Probably, the 2° Y-hydrogen abstraction is easier in the n-propylphthalimide than the primary Y-hydrogen abstraction in the ethylphthalimide, but the subsequent closure is subject to no substantial difference in geometric effects. Isobutylphthalimide is a special case. In contrast to the other phthalimides, isobutylphthalimide appears to be photochemically reactive but not to yield the azepinedione. The γ -hydrogen abstraction should be favored either by the stability of the tertiary radical formed or the increased nucleophilicity of the hydrogen to be abstracted, due to the two methyl groups. The methyl groups, however, sterically hinder the diradical closure to the cyclobutanol.

Only in the case of isobutylphthalimide and 2-methylbutylphthalimide was phthalic anhydride isolated. This product was previously attributed as the only recognizable product of Type I reaction. Observation of 46 in the reaction mixture of N-methylphthalimide and dienes in acetonitrile by Mazzocchi and Narain¹²⁴ would be evidence of Type I cleavage followed by rehybridization, rotation, and reclosure, however, 46 was not observed.



It was shown in the photolysis of optically active 2-methylbutylphthalimide that there is no reverse hydrogen transfer in tert-butanol. Other hydrogen transfers such as δ -hydrogen transfer were also not observed in this solvent. Thus, when the γ -hydrogen has been initially transferred to yield the diradical, the diradical must close to yield the cyclo-

butanol or proceed by another route to yield some as yet undetected and unidentified product.

An alternate explanation for the relative order of the quantum yields was given by $Agosta^{125}$ with regard to the electronic configuration of the excited state. The excited oxygen proposed would be partially anionic and would abstract most efficiently the γ -hydrogen which would give the most stable carbanion.



A similar proposal had been noted earlier in the case of α diketones.¹²² Such a proposal would account for the 1° γ hydrogen abstraction having the highest quantum yield over 2° and 3° hydrogen abstraction. (Formation of the cis and trans-6,7-dimethyl azepinedione in the photolysis of secbutylphthalimide would tend to refute this electronic argument).

Type II reactions in N-alkylphthalimides are inefficient. The high efficiency of these reactions combined with the low quantum yield indicates that either some reversible process, such as the Type I process shown on page 166 or a photophysical decay process (fluorescence, phosphorescence) must be wasting the available light. On the basis of Kanaoka's⁸⁴ work, analogy with other types of compounds, and

the experimental evidence the following mechanism can be proposed for the photochemical decomposition of N-alkylphthalimides.



Quenching Studies of N-alkylphthalimides

In order to confirm or reject this mechanism, some definition of the excited state is required. Kanaoka observed significant quenching by cis-1,3-pentadiene in the photolysis of N-phthaloyl amino acids.⁸⁵ In preliminary studies, the photocyclization of tolylphthalimides was significantly quenched by isoprene.⁸⁶

In order to explain the information obtained in a quenching study, certain terms must be defined. Quenching implies inhibition of a process, in this case a photochemical process, by a transfer of energy from the excited molecule, to the quenching agent, usually a diene. Detection of the quenching process is conducted by analyzing the product to be quenched over a series of quencher concentrations. A decreasing product yield as the diene concentration is increased indicates the quenching of the process that leads to the product.

The quenching process allows some definition of the nature of the excited state studied. Dienes specifically quench one type of excited state, the triplet. Irradiation of a ground state ketone, for example, produces the singlet excited state, where one electron of a pair is promoted and retains its spin (the electrons have opposite spin). The singlet state is converted to the triplet state, where the spins of both electrons are the same, by a radiationless decay process called intersystem crossing. It is the for-

mation of products from the triplet state that is quenched by the diene.

An alternate means to prove a quenching process is occurring would be to plot Φ/Φ_0 versus [Q]. Each point on the graph is determined with the ordinate as the ratio of the quantum yield of the reaction at a given quencher concentration to the quantum yield of the reaction at 0 quencher concentration and the abscissa as that quencher concentration. When the resulting plot, called a Stern-Volmer plot, is a straight line, the evidence suggests that a competition exists with the normal reaction.¹¹⁵ The competition is then the quenching process.

A quenching process with dienes is evidence that whatever fraction of the reaction was quenched came from the triplet state. Ketone Type II reactions have been shown to be partially quenched by diene. The Type II process in α ketodecanoic acid was completely quenched by 1,3-cyclohexadiene.¹²¹ Kanaoka's investigations^{85,86} suggested that a substantial portion of the Type II photocyclizations were being produced from the triplet state.

Solutions of tert-butylphthalimide and isobutylphthalimide with internal standards were irradiated in sodiumdried tert-butanol. Three quencher concentrations, 0.1M, 1M, and 10M were used for each phthalimide. Two tubes of each quencher concentration for both phthalimides were irradiated. A quenching study check on isobutylphthalimide was conducted to verify the results from the first study.

Starting material disappearance was measured by glpc and product analysis was conducted by lc. The results of these studies are shown in Figure 7.

In general, the results show that the Type II reaction to yield the azepinediones was being quenched. It was then hoped that perhaps the intermediate product 44 of the photolysis of N-2-methylbutylphthalimide might be isolated by the quenching of the secondary ketone Type II reaction to yield 36. The glpc analysis of starting material disappearance, however, showed that an increase in the quencher concentration resulted in an increase in the starting material disappearance. In addition, lc product analysis showed formation of a second product. It was assumed that any triplet state formed in the photoreaction of N-alkylphthalimides could not be quenched with diene because the diene reacted with starting material. The reaction of the phthalimides with dienes was investigated further.



Photochemical 2+2 Addition Reaction to N-alkylphthalimides

It was assumed in the previous section that the new products observed in the tert-butyl and isobutylphthalimide quenching studies were formed by the reaction of the diene with the starting material. Alkenes and dienes have been shown to photochemically add to alkenes, carbonyls, and even to amides.¹²⁶ The addition is usually a 2+2 reaction yielding a cyclobutane or other substituted four-membered rings.

The addition of an alkene to a ketone, the Paterno-Buchi reaction, yields an oxetane.



The reaction also covers intramolecular additions as shown by Meinwald and Hamner.



Substituted acrylamides were shown by Chapman¹²⁸ to undergo intramolecular 2 + 2 photoreactions to yield β -lactams.

2.5%



H N Ph

> 16% (cis and trans)

Alkenes and isolated dienes were shown by Elad^{129,130} to undergo photoamidation with formamide.



 $\operatorname{RCH=CH}_{2}$ + $\operatorname{CH}_{3}\operatorname{CONHCH}_{3} \xrightarrow{h\nu} \operatorname{CH}_{3}\operatorname{CONHCH}_{2}\operatorname{CH}_{2}\operatorname{CH}_{2}^{R}$ major

+ RCH₂CH₂CH₂CONHCH₃ minor

Photoalkylation of 2-pyrrolidone is initiated by acetone, which acts as a sensitizer.



It has thus been seen that the amide and carbonyl alone are capable of undergoing photoreaction with alkenes. The intermediate resonance structure of the phthalimide would be an iminol, and the photochemistry of this form should be analogous to that of imino ethers, which have been studied by a number of investigators.

Paquette, Barton, and Whipple¹³² began the study of 2methoxyazabullvalene with the β -lactam, which was converted to the imino ether with $(CH_3)_3 0^+ BF_4^-$. The NMR of the ether on heating to 150° showed that certain peaks coalesced, which could only be rationalized via a combination of two rapid Cope rearrangements. Paquette and Krow¹³³ then studied the photochemistry of this fluctuating system with the result that no intramolecular 2 + 2 cycloaddition was observed with the imino ether double bond. Paquette and Malpass¹³⁴ and Paquette, Malpass, and Krow¹³⁵ investigated the photochemical and thermal transformations of an imino ether to yield a benzazabullvalene (3-methoxy-4-aza-6,7-benzotricyclo-[3.3.2.0]deca-3,6,9-triene). Similar results were observed in a photolysis of the β -lactam followed by treatment of the products with trimethyl oxonium fluoroborate.



At this point, no additions to the imino ether moiety had been observed. Odum and Schmall¹³⁶ showed that the integrity of the imino ether was not disturbed in the photoreaction of the non-fluxional molecule shown.



Koch and Brown,¹³⁷ however, showed in the following conjugated imino ether that although in most solvents the compound would not react, in certain solvent systems or with a sensitizer intramolecular addition to the imino ether bond would occur.



In the following reaction, Koch, Geigel, and Tsai¹³⁸ showed that intramolecular insertion did not work in some cases. OCH_3



The quantum yields measured showed that formation of the azepine was not dependent on which sensitizer was used, but the dimerization and decomposition quantum yields depended to a great degree on whether the investigator used acetophenone or triphenylamine as a sensitizer. The reaction shows that intramolecular addition to the double bond of the imino ether is not universal but may depend on the substituents of the other double bond as well as the photolysis conditions.

More recently, Koch, Olesen, and DeNiro¹³⁹ investigated the photochemistry of the imine shown, which underwent photodimerization in isopropanol.



Koch originally studied the compound due to the unusually low bond strength of the C-C bond in the dimer. The most important concept shown is the photoreactivity of the imine. Koch and Rodehorst¹⁴⁰ irradiated 2-phenyl-2-oxalin-4-one under various conditions. When the compound was irradiated in glyme, the initial product was an isocyanate, which rearranged as shown on silica gel.



The compound was, however, shown to undergo 2+2 cycloaddition in high yield when alkenes were present.



It was determined by Howard and Koch¹⁰³ that an analogous isocyanate product was produced in the photolysis of 2-ethoxypyrrolin-5-one.



The interest in this molecule is that it closely represents the dipolar resonance form of a substituted phthalimide. Studies on the photochemistry of 3-ethoxyisoindolene and alkenes would exactly show the photochemistry of the dipolar resonance form of the phthalimide with alkenes. A number of alkenes were shown to add to 3-ethoxyisoindolene by a 2+2 cycloaddition as well as by other mechanisms:







The ring expansion products produced by acid hydrolysis of the 2+2 adduct are the benzazepinediones observed in the photolysis of N-alkylphthalimides. The first three reactions proceed via 2+2 cycloaddition exclusively, but the ring expansion product from the photoaddition of furan and secondary hydrolysis was not observed because the intermediate decomposed to starting material with heat. The last four reactions contained products not produced by 2+2 cycloaddition. Isolation of 53 in the reaction of N-methylphthalimide with tetramethylethylene was unique and could only be explained by the following mechanism:







+









The process common to reactions (4)-(7) to yield 50, 51, 52, and 55 (on pages 215 to 216) was called the "ene reaction" and is analogous to the secondary δ -hydrogen transfer observed in the photolysis of N-alkylphthalimides containing δ -hydrogens in acetonitrile.

The presence of 5,3 gave insight to the process occurring in the attempted quenching of N-alkylphthalimides by indicating a degree of double bond character in the CO-N bond. It was certain in the quenching studies that a product was being formed with the diene. A number of alkenes were photoreacted with N-methylphthalimide and phthalimide. N-methylphthalimide was chosen due to the lack of γ-hydrogens necessary to form the (lH)azepinedione products, described earlier. Reaction with furan and N-methylphthalimide failed to yield a product. Other alkenes such as cyclohexene, which did not undergo the "ene reaction" with 3-ethoxyisoindolene, had been observed by Kanaoka¹⁰⁰ to add to the carbonyl in N-methylphthalimide by photoreduction. (See page 146). Several alkenes, such as trimethylethylene and tetramethylethylene, with N-methylphthalimide produced too many products to be isolated and identified. The intermediate azacyclobutanol would be assumed to open retrotransannularly to a 1-methylazepinedione analogous to the azepinediones observed earlier. For example, assuming only 2 + 2 cycloaddition, the photoreaction of cis 1,3-pentadiene with Nmethylphthalimide would yield four inseparable products since there are two double bonds in the diene.









(There was no observed 2 + 2 addition of alkenes to phthalimide with isobutylene and cyclohexene).

It was hoped that an intramolecular 2 + 2 photocycloaddition would be produced in the photolysis of 2-propenylphthalimide.



After prolonged irradiation, however, no product formation was detected by analytical TLC or by NMR. Three alkenes were observed to add in a 2+2 fashion to N-methylphthalimide giving one or two products.

Photolysis of N-methylphthalimide and Isobutylene

Irradiation of a chilled solution of N-methylphthalimide and a large excess of isobutylene in acetonitrile for 4 hours yielded only one product by analytical TLC and NMR of the residue of the evaporated reaction mixture. Following isolation by preparative TLC and purification by recrystallization, the mass spec of the product showed a parent ion at m⁺/e 217, which indicated the isobutylene had added. In the IR of the product absence of a band at 3150- 4000 cm^{-1} indicated no amide or alcohol was present. The NMR of the product showed three singlets of 6, 3, and 2 hydrogens besides the phenyl signals, which would be consistent for either 2 + 2 adduct, 56 or 57.



The chemical shift of the two-hydrogen singlet was greater than that for the N-CH₃ group, which indicated the only product of the reaction was 56. The apparent regioselective alkene addition makes several demands on the process by which the product was formed. Although stereoselectivity could not be tested in this case, regioselectivity without stereoselectivity implies a diradical intermediate as invoked in the 2+2 cycloaddition to 3-ethoxyisoindolene. Turro had previously observed the mechanism in the photochemical addition of olefins to ketones¹⁴¹ and the photochemical addition of aromatic thiones to multiple bonds.¹⁴² On the basis of the above information the following mechanism was proposed for the photochemical addition of isobutylene to N-methylphthalimide.







Photolysis of N-methylphthalimide and 1,3-butadiene

Irradiation of a chilled solution of N-methylphthalimide and a large excess of 1,3-butadiene in acetonitrile yielded two products. Addition of butadiene, if it proceeds through the same mechanism earlier proposed for 1,3-pentadiene and isobutylene, would yield only two products, where 1,3-pentadiene would yield four possible products. The products of this reaction would then show the course followed by the attempted quenching reaction.

The products were not equally produced in the reaction. The relative amounts of the two products in the evaporated residue of the reaction mixture were analyzed by NMR. The product ratio was 2:1 when the irradiation was conducted through a Corex filter and 4:1 with quartz-filtered light. The major product was isolated by preparative TLC and puri-

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hν

fied by recrystallization. Mass spec of the product had a parent ion at m⁺/e 215, which indicated that the 1,3-butadiene had added. The IR of the products was analogous to that observed for 56. The NMR of the product showed a doublet at $1.9-2.1\delta$ as an allyl signal adjacent to one hydrogen. There are four possible products of the 2+2 cycloaddition:



Besides the N-methyl singlet at 3.1-3.2 δ a second singlet of two hydrogens at 4.2δ indicates that 5.8 and 5.9 are more likely. The chemical shifts expected for methylene hydrogens in 60 and 61 as a combination of α to a ketone and allylic would be much less than the observed shift. The vinyl quartet had a chemical shift of $6.9-7.3\delta$ in the major product and $6.2-6.7\delta$ in the minor product. In structure 5.8 the chemical shift of the vinyl signal would be higher than in 5.9. The final products may arise via secondary photoconjugation with the ketone. Steric considerations would make 58 more favorable than 59. Thus, the major product of the reaction is 58, and the minor product, 59. The products must arise via the following mechanism:



More recent work by Mazzocchi and Narain¹⁴³ verified the above mechanism in the irradiation of isoprene and N-methylphthalimide. Due to the methyl group on the seven-membered ring, the double bond cannot photoconjugate. The compound with the unconjugated double bond was isolated, as well as the conjugated product from photoaddition to the other double bond.



Photolysis of N-methylphthalimide and Ethyl Vinyl Ether

Irradiation of N-methylphthalimide and excess ethyl vinyl ether in acetonitrile yielded two products, which were isolated by preparative TLC. The product, analogous to 56, was purified by recrystallization. Mass spec of the product showed a parent ion with m⁺/e 189. The IR was analogous to 56. The NMR showed two multiplets at 36 and 3.66, which correspond to the signals in 37. Evidence of an ethoxy pattern was conspicuously absent. The secondary Type II ketone reaction was possible as shown and accounts for one of the products, 3,4-benzo-6,7-dihydro-1-methylazepine-2,5-dione, 62.



The other product was considerably more difficult to isolate and identify. Repeated preparative TLC showed contamination with starting material. Mass spec of the product showed a small amount of starting material (m⁺/e 161) and a parent ion for the product at m⁺/e 159. The IR showed no amides or alcohol bands, and the NMR was quite simple. Besides the phenyl and N-CH₃ singlet there were a pair of doublets in the vinyl region corresponding to one hydrogen each. The doublets were shown to be coupled in a decoupling experiment, and the coupling constant of 2Hz was indicative of geminal coupling in a terminal methylene group. On the basis of spectral data the structure of 63, 3-methylene-2methyl-2-azaindanone, was assigned.



Generation of the indanone could only be explained by direct addition to the carbonyl, a Paterno-Buchi reaction. Such a reaction had not been observed by Kanaoka.¹⁰⁰ The following mechanism would explain the formation of the indanone:



The reverse reaction to N-methylphthalimide is probably important, but because no product is seen, it is not detected. (The odor of triethylorthoformate was present in the reaction mixture.) This is the only observed case of a Paterno-Buchi reaction in the photochemistry of N-alkylphthalimides and shows that the carbonyl also retains some double bond character.

The general mechanism proposed for the photochemical addition of certain alkenes and dienes to N-methylphthalimide involves the dipolar resonance structure. The alkene or diene adds to the dipole via a non-concerted diradical, which promotes the regioselectivity. Closure of the diradical to the unstable azacyclobutanol is followed by ring expansion to the azepinediones as shown.



Photoconjugation will occur, when possible, if dienes are added. Secondary Type II ketone processes will also occur when possible. Addition to the carbonyl may also occur.

§4. CONCLUSIONS

The products isolated in the photolysis of N-alkylphthalimides were those identified by Kanaoka.⁸⁴ The Type II reaction proposed by Kanaoka was not as efficient as Type II reactions in aldehydes, ketones, and esters. The magnitude of the quantum yield at 0.023 (tert-butyl) was very low for several reasons. The high efficiencies of the reactions allowed determination of these low quantum yields. Reversible Type I reactions would be quantum wasting. In addition, the usual fluorescence and phosphorescence would account for the quantum wasting.

Irradiation of a phthalimide optically active in the γ -position showed that the initial hydrogen abstraction was not reversible in tert-butanol (the solvent for the quantum yield determination). This process would have been a well documented quantum waster.

Kanaoka, in his study of alkylphthalimides⁸⁴ and rigid cyclic imides,⁷³ asserted that the rigid geometry and the I-overlap with the additional carbonyl were responsible for their Type II reactivity. Photolysis of non-rigid N,Ndibenzoylisobutylamine showed this to be the case.

Kanaoka asserts that phthalimide Type II reactivity is determined by the stability of the intermediate diradical without measuring the quantum yields. The relative quantum yields indicate that this approach is oversimplified. Steric hindrance may prevent the intermediate closure of the tertiary diradical to an azacyclobutanol.

Additional evidence shows that the excited state may be dipolar in nature. Attempted quenching of tert-butylphthalimide and isobutylphthalimide triplet states showed decreased Type II product formation and increased starting material disappearance with increased quencher concentrations. It was determined that 1,3-butadiene, isobutylene, and ethyl vinyl ether would add to N-methylphthalimide by a variety of 2 + 2 cycloadditions. The additions were shown to be regioselective, which implies a diradical intermediate. The alkene addition is due to the dipolar character of the phthalimide and proceeds via diradical, closure to an azacyclobutanol, and retrotransannular ring opening to yield substituted 3,4-benzo-6,7-dihydro-l-methylazepine-2,5diones. The intermediate diradical and unstable azacyclobutanol can only be shown as dipolar structures. Photoconjugation and secondary ketone Type II reaction occur when possible. In addition, we isolated in impure form the first evidence of a Paterno-Buchi reaction in phthalimides.