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Intermolecular Photoreactions of Phthalimide-Alkene Systems. Regio- and Stereoselective Oxetane Formation from *N*-Methylphthalimide and *N*-Acetylindole Derivatives[1)]

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Upon irradiation of *N*-methylphthalimide (**1**) in the presence of *N*-acylindole derivatives (**2** or **11**), [2+2]cycloaddition occurred to give sterically hindered oxetanes (**5**) in moderate yields. Some reactions of these imide-oxetanes, such as formation of benzoxazepines (**8** and **12**) and eight-membered lactams (**9** and **10**), are also described.

Keywords——intermolecular photoreaction; *N*-methylphthalimide; *N*-acylindole; oxetane; [2+2]cycloaddition; imide-oxetane; benzoxazepine; Paterno–Büchi reaction

In the photochemistry of imide-alkene systems,[1)] oxetane formation has been one of the important objectives of a number of studies to delineate its scope and mechanism. However, there have been no examples of the efficient formation of imide-oxetane, probably because competing processes such as photocyclization (k_{ET}), photoreduction (k'_{ET}), and photoaddition (k_{CN}) dominate the oxetane formation process (Paterno–Büchi reaction, k_{PB}), even though the latter is a representative photoreaction of carbonyl compounds[2)] (Chart 1). As reported in a preceding paper,[1)] we have found the first example of efficient oxetane formation in a phthalimide system by intramolecular photolysis of *N*-(ω-indol-3-ylalkyl)phthalimides. Further, as an extension of this reaction, we have already reported, in a preliminary communication,[3)] that photolysis of *N*-methylphthalimide (**1**) with a series of *N*-acetylindole derivatives (**2**) efficiently gave the corresponding oxetanes (Paterno–Büchi product). In the present paper, we wish to report the detailed results on the regio- and stereoselective oxetane formation by intermolecular photolysis of the imide-indole system.

A solution of equimolecular amounts of **1** and **2** in acetone was irradiated with a 500 W high-pressure mercury lamp through Pyrex glass under a nitrogen atmosphere. The results are listed in Table I.

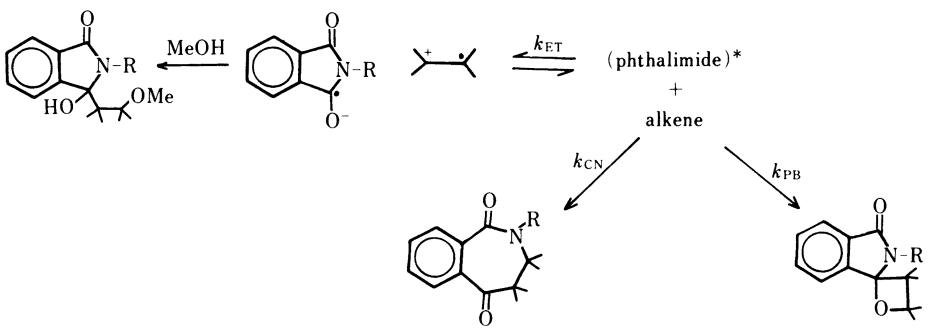


Chart 1

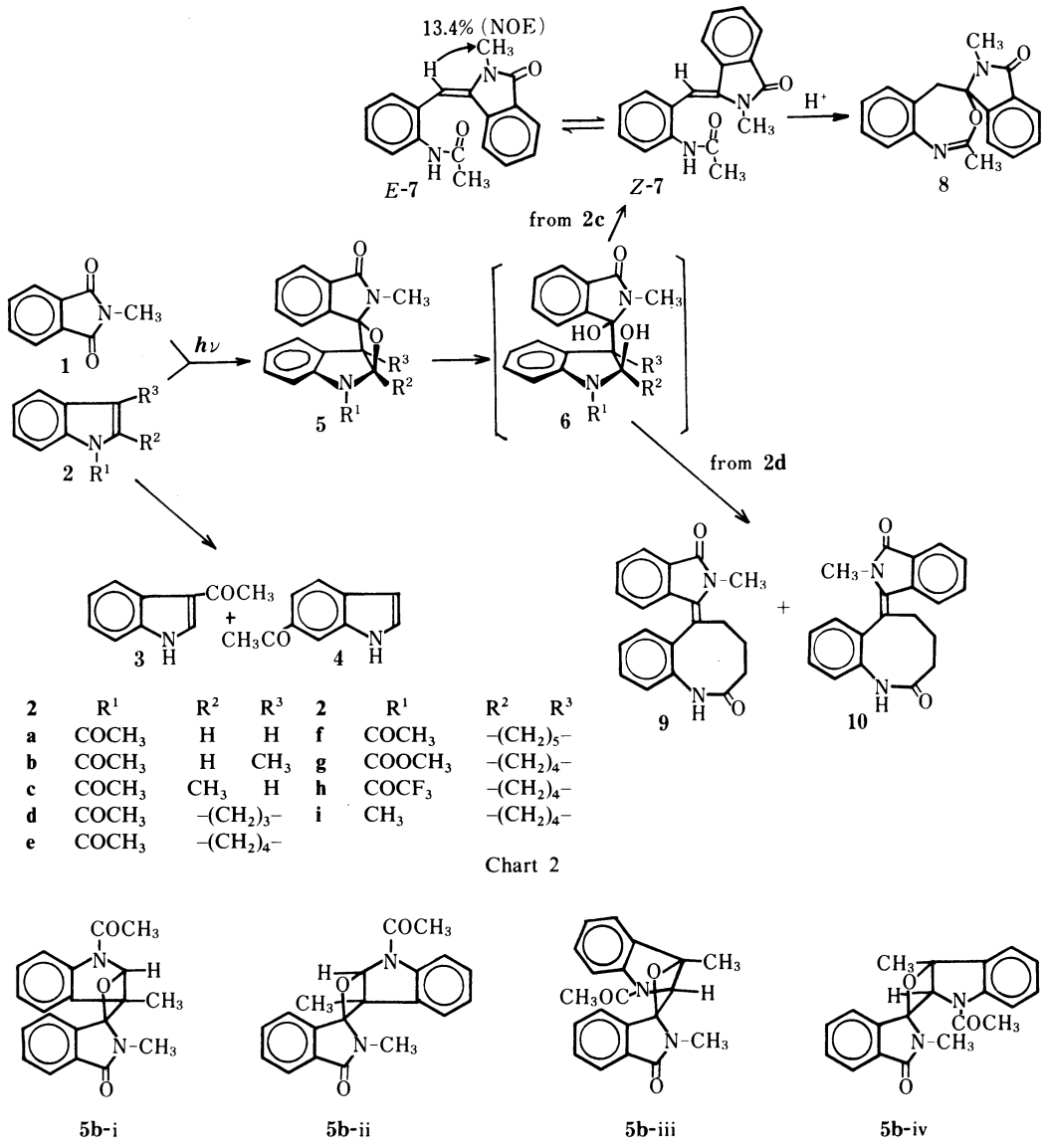
TABLE I. Photolysis of **1** in the Presence of **2** or **11**

Substrate	R^1	R^2	R^3	React. time (h)	Product	Yield (%)	mp (°C)	Appearance (Solvent)	Formula	Analysis (%) Calcd (Found) C	H	N
2a	$COCH_3$	H	H	11.5	**3**	25	190—191.5[a]					
					4	3	121—122[a]					
2b	$COCH_3$	H	CH_3	2	**5b**	18	196—198	Colorless prisms (AcOEt–hexane)	$C_{20}H_{18}N_2O_3$	71.84 (71.90)	5.43 (5.47)	8.38 (8.42)
2c	$COCH_3$	CH_3	H	3	*E*-**7**[b]	17	265—266.5	Colorless needles (EtOH)	$C_{18}H_{16}N_2O_2$	73.95 (73.79)	5.52 (5.58)	9.58 (9.39)
					8[b]	34	123.5—124.5	Colorless needles (AcOEt–hexane)	$C_{18}H_{16}N_2O_2$	73.95 (74.08)	5.52 (5.56)	9.58 (9.40)
2d	$COCH_3$	$-(CH_2)_3-$		3	**9**	41	273.5—275.5	Colorless prisms (EtOH)	$C_{20}H_{18}N_2O_2$	75.45 (75.55)	5.70 (5.77)	8.80 (8.93)
					10	6	286—287	Colorless needles (EtOH)	$C_{20}H_{18}N_2O_2$	75.45 (75.59)	5.70 (5.69)	8.80 (8.82)
2e	$COCH_3$	$-(CH_2)_4-$		2	**5e**	62	184—186	Colorless needles (AcOEt–hexane)	$C_{23}H_{22}N_2O_3$	73.78 (73.90)	5.92 (5.99)	7.48 (7.50)
2f	$COCH_3$	$-(CH_2)_5-$		2	**5f**	39	198—204	Colorless needles (AcOEt–hexane)	$C_{24}H_{24}N_2O_3$	74.20 (74.11)	6.23 (6.26)	7.21 (7.12)
2g	$COOCH_3$	$-(CH_2)_4-$		4	**5g**	34	185—187.5	Colorless prisms (AcOEt–hexane)	$C_{23}H_{22}N_2O_4$	70.75 (70.82)	5.68 (5.59)	7.18 (7.19)
11a	OCH_3	H		6	**12**	21	237—238	Colorless needles (AcOEt–$CHCl_3$)	$C_{24}H_{24}N_2O_4$	71.27 (71.44)	5.98 (5.96)	6.93 (6.95)

a) A 1 kW high-pressure mercury lamp. *b*) Treatment with *p*-toluenesulfonic acid after photolysis.

Irradiation of **1** in the presence of *N*-acetylindole (**2a**) resulted only in rearrangement of an *N*-acetyl group to the 3- and 6-positions on the indole ring, although it has been reported[4] that irradiation of **2a** with benzophenone gave the corresponding oxetane. Occurrence of the rearrangement is consistent with the results of the photorearrangement of *N*-substituted indoles in the absence of **1**.[5]

In order to investigate the effects of substituents on the indole ring upon oxetane formation, photoreactions of 2- and 3-substituted *N*-acetylindoles were examined. Photolysis of **1** with *N*-acetyl-3-methylindole (**2b**) gave, as expected, the oxetane (**5b**) due to [2+2]photocycloaddition. In the mass spectrum (MS) of **5b** the molecular ion peak ($M^+ = 334$) indicated the addition of **1** to **2b**. The infrared (IR) spectrum showed the presence of two carbonyl groups, an amide and a lactam at 1670 and 1705 cm^{-1}, respectively (assignments may be interchanged). In the proton nuclear magnetic resonance (^{1}H-NMR) spectrum of **5b** a characteristic singlet appeared at 6.40 ppm, suggesting the presence of a methine proton, whose chemical shift value is close to that of the methine proton adjacent to the nitrogen and oxygen atoms in the previously reported oxeto[2,3-*b*]indole system.[4] Three singlet peaks at 1.60, 2.37, and 3.37 ppm indicated the presence of *C*-methyl, acetyl, and *N*-methyl groups, respectively. Two doublets with the coupling constants of $J = 7.5$ Hz appeared at 5.95 and 6.54 ppm, upfield from the normal benzene proton region, showing a pronounced shielding effect due to the anisotropy of the benzene rings. In the carbon-13 nuclear magnetic resonance (^{13}C-NMR) spectrum, a doublet at 94.5 ppm and a singlet at 103.3 ppm indicated the presence of the methine carbon and a newly formed spiro carbon in the oxetane ring, respectively. As illustrated in Chart 3, although four isomers (**5b**-i, **5b**-ii, **5b**-iii, and **5b**-iv) are possible for the



2	R^1	R^2	R^3	2	R^1	R^2	R^3
a	$COCH_3$	H	H	f	$COCH_3$	$-(CH_2)_5-$	
b	$COCH_3$	H	CH_3	g	$COOCH_3$	$-(CH_2)_4-$	
c	$COCH_3$	CH_3	H	h	$COCF_3$	$-(CH_2)_4-$	
d	$COCH_3$	$-(CH_2)_3-$		i	CH_3	$-(CH_2)_4-$	
e	$COCH_3$	$-(CH_2)_4-$					

Chart 2

Chart 3

structure of **5b**, the regioisomers (**5b**-iii and **5b**-iv) were excluded on the basis of ^{1}H- and ^{13}C-NMR data of the methine moiety as described above. Two stereoisomers (**5b**-i and **5b**-ii) are still possible, and the stereochemical structure was assigned as **5b**-i on the basis of the spectral data, in which the signal of the *N*-methyl group (3.37 ppm; in the normal region) is unaffected by the anisotropy of the benzene ring and the signals of the benzene rings (5.95 and 6.54 ppm; upfield) indicate overlapping between them.[6] The above spectral data also show similarities with those of the Paterno–Büchi products reported in the preceding paper.[1]

In the case of *N*-acetyl-2-methylindole (**2c**), although the oxetane (**5c**) formation was observed by thin layer chromatography (TLC), the oxetane (**5c**) was very sensitive to the conditions of column chromatography on alumina, and was easily transformed into the enamides (*E*-7 and *Z*-7). The mixture (ratio, $E:Z=2:1$) of *E*–*Z* isomers in chloroform was

refluxed in the presence of *p*-toluenesulfonic acid. The enamide *E*-**7** and spiro-oxazepine (**8**) were obtained in 17 and 34% yields, respectively, together with the *E*–*Z*-**7** mixture. The conversion of *Z*-**7** into **8** seems faster than that of *E*-**7** judging from their behavior on TLC. On standing in a chloroform solution at room temperature, the isolated *E*-**7** was easily convertible to *Z*-**7**, reaching an equilibrium. This interconversion was observed on TLC, and confirmed by ^{1}H-NMR spectroscopy of the mixture of stereoisomers *E*-**7** and *Z*-**7**. Probably the enamides **7** arise from the initially formed imide-oxetane (**5c**) by hydrolysis followed by subsequent opening of the hydroxyindoline (**6c**), and lead to **8** by acid-catalyzed cyclization (Chart 2). In fact, a diol compound such as **6c** was isolated, supporting its involvement in the hydrolysis of oxetane in an imide-oxetane system, as previously reported.[1] Thus, a stepwise process (**5**→**6**→**7**) involving hydrolysis of the oxetane **5c** seems likely for the formation of **7**, although a concerted process (**5**→**7**, not involving an intermediate) could not be ruled out.

The structures of *E*-**7** and **8** were assigned on the basis of elemental analyses and spectral data. The MS of *E*-**7** showed the molecular ion peak at $m/z=292$. In the IR spectrum, bands at 1640, 1675, and 3290 cm^{-1} indicated the presence of two amide groups and an NH group. In the ^{1}H-NMR spectrum of *E*-**7** three singlet peaks appeared at 1.98, 3.35, and 6.56 ppm, suggesting the presence of acetyl, *N*-methyl, and one proton of a vinyl group, respectively; this was also supported by the ^{13}C-NMR data. In the ^{1}H-NMR spectrum of the *E*–*Z* mixture, the *N*-methyl signal in *E*-**7** appeared at 3.35 ppm, at lower field than that of *Z*-**7** ($\delta=2.88$ ppm). Further, the stereochemistries of *E*-**7** and *Z*-**7** were supported by nuclear Overhauser effect (NOE) studies.[7] In the case of *E*-**7**, irradiation of the olefinic proton ($\delta=6.563$ ppm) resulted in enhancement (13.4%) of the *N*-methyl signal. Similarly, irradiation of the *N*-methyl group ($\delta=3.337$ ppm) also gave a slight enhancement of the intensity of the olefinic proton signal. However, in the case of *Z*-**7** in the *E*–*Z*-**7** mixture, irradiation of either the olefinic proton or the *N*-methyl group did not cause any enhancement of the intensity of the *N*-methyl or the olefinic proton signal. For the product **8**, the MS showed the molecular ion peak at m/z 292, the same as that of **7**. The ^{1}H-NMR spectrum of **8** showed two singlet peaks at 1.53 and 2.86 ppm due to two methyl groups, and an AB quartet with the coupling constant of 17.7 Hz at 3.38 and 3.72 ppm, suggesting the presence of a methylene group in a cyclic structure. The ^{13}C-NMR spectrum of **8** also showed peaks due to two methyl groups at 23.5 and 23.9 ppm. A triplet at 42.0 ppm and a singlet at 84.0 ppm indicated the presence of the methylene carbon and a newly formed spiro carbon adjacent to the oxygen and nitrogen atoms. Signals at 166.3 (s) and 169.8 (s) were assigned to the carbons of a carbon–nitrogen double bond and a lactam, although these assignments may be interchanged. Therefore, the oxazepine structure was tentatively assigned for **8**.

Likewise, photoreactions of 2,3-disubstituted indoles (**2d**—**f**) such as carbazole and its analogs having various ring sizes were examined. In the case of **2e**, **f**, the oxetane (**5e**, **f**) were isolated in 62 and 39% yields, respectively, but with **2d** two stereoisomeric lactams (**9** and **10**) were obtained in 41 and 6% yields, respectively. Presumably these benzene-fused eight-membered lactams (**9** and **10**) were derived from the initially formed imide-oxetane (**5d**). Although the formation of **5d** was observed on thin layer chromatography, which showed only a single product, the oxetane (**5d**) was very sensitive to the conditions of column chromatography on alumina, like **5c**, and was easily transformed into the lactams (**9** and **10**). In comparison with the case of **7**, geometric isomerization of the lactams (**9**⇌**10**) was not observed during the column chromatography. Therefore this preferential formation of **9** over **10** seems to reflect the stereochemistry of the fused ring structure of the oxetane (**5d**). From the above results, it is suggested that the transformation of **5d** into the lactams (**9** and **10**) proceeds in a stepwise process involving an intermediate such as **6d** derived from a benzylic-type cation. Such a process involving a carbonium cation is often found in the acid-catalyzed hydrolysis of the oxetane ring.[2,8] If the transformation of the oxetane (**5d**) to the lactam

TABLE II. Spectral Data for Photoproducts

Compound	IR (Nujol) cm^{-1}	MS (M^+) m/z	^{1}H-NMR ($CDCl_3$) δ, ppm	^{13}C-NMR ($CDCl_3$) (OFR) δ, ppm
5b	1705, 1670	334	1.60 (3H, s, CH_3), 2.37 (3H, s, $COCH_3$), 3.37 (3H, s, N-CH_3), 5.95 (1H, d, J=7.5 Hz, aromatic H), 6.40 (1H, s, N-CH-O), 6.54 (1H, d, J=7.5 Hz, aromatic H), 6.8—7.5 (4H, m, aromatic H), 7.63 (1H, d, J=7.5 Hz, aromatic H), 8.1—8.4 (1H, m, aromatic H)	17.7 (q), 23.7 (q), 27.5 (q), 59.5 (s), 94.5 (d), 103.3 (s), 117.3 (d), 122.5, 124.6, 125.5, 129.7, 130.3, 131.2, 133.3 (s), 141.3 (s), 142.6 (s), 168.2 (s), 168.9 (s)
E-**7**[a]	3290, 1675, 1640	292	1.98 (3H, s, $COCH_3$), 3.35 (3H, s, N-CH_3), 6.56 (1H, s, HC=C-), 6.9—7.9 (8H, m, aromatic H), 9.2—9.4 (1H, m, NH)	23.6 (t), 28.8 (q), 33.5 (t), 35.7 (t), 120.3 (s), 123.7, 125.5, 127.7, 128.8, 129.0, 129.9, 130.4, 132.1, 133.5 (s), 135.7 (s), 140.5 (s), 167.8 (s), 176.2 (s)
8	1690, 1665	292	1.53 (3H, s, C-CH_3), 2.86 (3H, s, N-CH_3), 3.38 and 3.72 (2H, AB q, J=17.7 Hz, benzylic H), 7.0—7.7 (6H, m, aromatic H), 7.7—7.9 (1H, m, aromatic H), 8.1—8.3 (1H, m, aromatic H)	23.5 (q), 23.9 (q), 42.0 (t), 84.0 (s), 117.3 (d), 121.3 (d), 123.8 (d), 124.0 (d), 124.2 (d), 126.1 (s), 128.3 (d), 129.9 (d), 131.3 (s), 133.1 (d), 143.5 (s), 147.0 (s), 166.3 (s), 169.8 (s)
9	3200, 1690, 1650	318	1.9—2.5 (5H, m), 3.60 (3H, s, N-CH_3), 3.5—3.8 (1H, m), 5.43 (1H, d, J=7.8 Hz, aromatic H), 6.9—7.8 (7H, m, aromatic H), 7.62 (1H, s, NH)	26.4 (t), 29.8 (q), 32.9 (t), 34.0 (t), 119.9 (s), 122.7 (d), 123.0 (d), 126.0 (d), 128.1, 129.0, 129.2, 130.1, 131.6, 134.5 (s), 135.5 (s), 136.3 (s), 141.0 (s), 168.0 (s), 175.6 (s)
10	3260, 1690, 1655	318	2.0—2.6 (5H, m), 2.47 (3H, s, N-CH_3), 3.6—3.9 (1H, m), 6.7—7.0 (1H, m, aromatic H), 7.0—8.0 (7H, m, aromatic H), 8.5—8.6 (1H, m, NH)	23.6 (t), 28.8 (q), 33.5 (t), 35.7 (t), 120.3 (s), 123.7, 125.5, 127.7, 128.8, 129.0, 129.9, 130.4, 132.1, 133.5 (s), 135.7 (s), 140.5 (s), 167.8 (s), 176.2 (s)
5e	1705, 1660	374	1.0—1.4 (1H, m), 1.5—2.1 (4H, m), 2.43 (3H, s, $COCH_3$), 2.2—2.8 (3H, m), 3.43 (3H, s, N-CH_3), 6.3—6.6 (2H, m, aromatic H), 6.7—7.4 (4H, m, aromatic H), 7.6 (1H, d, J=7.5 Hz, aromatic H), 8.22 (1H, d, J=7.5 Hz, aromatic H)	17.8 (t), 18.1 (t), 24.8 (q), 25.1 (t), 28.5 (q), 32.5 (t), 60.6 (s), 98.6 (s), 102.8 (s), 116.8 (d), 122.5 (d), 123.6 (d), 124.3 (d), 124.8 (d), 129.6 (d), 129.8 (d), 130.1 (d), 131.2 (s), 131.6 (d), 143.1 (d), 145.7 (s), 168.8 (s), 170.0 (s)
5f	1710, 1665	388	0.7—2.2 (7H, m), 2.2—2.8 (2H, m), 2.43 (3H, s, $COCH_3$), 2.8—3.1 (1H, m), 3.43 (3H, s, N-CH_3), 6.2—6.5 (2H, m, aromatic H), 6.7—7.4 (4H, m, aromatic H), 7.59 (1H, d, J=7.5 Hz, aromatic H), 8.23 (1H, d, J=8.1 Hz, aromatic H)	24.1 (t), 25.3 (q), 25.5 (t), 28.7 (q), 28.7 (t), 30.9 (t), 36.2 (t), 66.3 (s), 100.0 (s), 103.6 (s), 117.1 (d), 122.5, 123.7, 124.0, 124.8, 129.5 (d), 129.8 (d), 130.4 (s), 131.5 (d), 143.2 (s), 146.2 (s), 168.8 (s), 170.2 (s)
5g	1710, 1685	390	1.0—2.1 (5H, m), 2.2—2.9 (3H, m), 3.40 (3H, s, N-CH_3), 3.87 (3H, s, OCH_3), 6.2—6.6 (2H, m, aromatic H), 6.7—7.4 (4H, m, aromatic H), 7.57 (1H, d, J=7.5 Hz, aromatic H), 7.87 (1H, d, J=8.4 Hz, aromatic H)	17.9 (t), 18.1 (t), 25.1 (t), 28.3 (q), 30.4 (t), 52.9 (q), 60.2 (s), 99.0 (s), 102.7 (s), 114.9 (d), 122.4 (d), 123.7 (d), 124.0 (d), 124.8 (d), 129.6 (d), 130.1 (s), 131.3 (d), 131.6 (s), 143.1 (s), 144.6 (s), 153.2 (s), 168.7 (s)
12	1710, 1690, 1670	404	1.1—2.2 (6H, m), 1.43 (3H, s, N=C-CH_3), 2.3—2.7 (2H, m), 2.59 (3H, s, N-CH_3), 3.79 (3H, s, OCH_3), 6.60 (1H, d, J=3 Hz, aromatic H), 6.80 (1H, dd, J=9 Hz, 3 Hz, aromatic H), 7.5—7.8 (3H, m, aromatic H), 7.8—8.2 (3H, m, aromatic H)	21.8 (t), 24.1 (q), 26.1 (q), 26.6 (t), 41.1 (t), 42.3 (t), 55.6 (q), 65.6 (s), 87.7 (s), 111.6 (d), 114.3 (d), 117.0 (d), 124.2 (d), 124.6 (d), 130.7 (d), 132.3 (d), 133.3 (s), 133.5 (s), 135.8 (s), 144.0 (s), 156.4 (s), 167.3 (s), 169.0 (s), 205.2 (s)

a) DMSO-d_6.

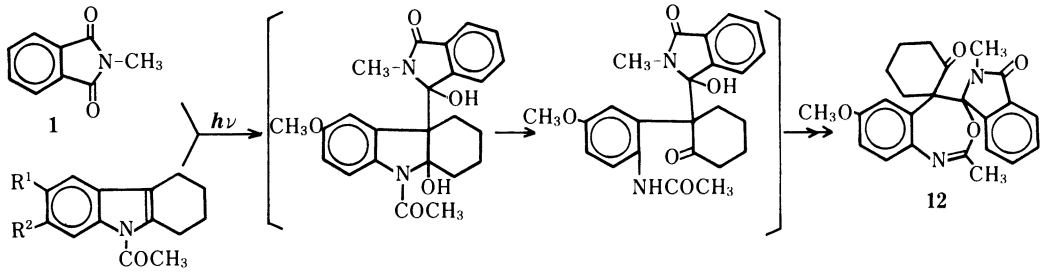
proceeds in a concerted process, the formation of only a single isomer (**9**) of the lactams would be expected.

Further, in order to investigate the effects of *N*-substituents on the properties as Paterno–Büchi acceptors (oxetane-forming partners), tetrahydrocarbazoles with various *N*-substituents were examined. Methoxycarbonylcarbazole (**2g**) gave the oxetane (**5g**) in decreased yield (34%) in comparison with that (62%) of **5e**, whereas in the case of *N*-trifluoroacetylcarbazole (**2h**) no oxetane was obtained after prolonged irradiation for 37 h, and unchanged **1** was recovered. When *N*-methyltetrahydrocarbazole (**2i**) was used, only the adduct of **1** with acetone was isolated.

The ^{1}H-NMR spectra of the oxetanes **5e**, **f**, **g** showed similarities to that of **5b**. In the ^{13}C-NMR spectra of **5e**, **f**, **g** three singlet peaks at 60.2—66.3, 98.6—100.0 and 102.7—103.6 ppm indicated the presence of a normal quaternary carbon and two quaternary carbons adjacent to the oxygen and nitrogen atoms, suggesting that regioselective photocycloadditions of **1** to **2e**, **f**, **g** have occurred between one carbonyl and the olefinic carbons of the 2- and 3-positions of the indole ring. Their stereochemical structures were confirmed on the basis of the spectral data as well as that of **5b**. Also, the spectral data (MS, IR, and NMR) of the stereoisomeric lactams **9** and **10** were very similar to each other. However, the signal of the *N*-methyl protons in **10** appeared at 2.47 ppm, being shifted upfield compared with that of **9** (3.60 ppm). This can be explained in terms of the anisotropic effects of the benzene ring. Thus, the stereoisomers **9** and **10** could be easily discriminated by the ^{1}H-NMR spectroscopy.[9]

In addition, photoreaction of tetrahydrocarbazole derivatives (**11a**—**c**) with a substituent on the benzene ring was investigated. Irradiation of 6-methoxy-tetrahydrocarbazole (**11a**) gave a product (**12**) in 21% yield. However, in the cases of **11b**, **c**, products were not isolated, apparently due to photochemical and/or thermal instability. The MS of **12** showed the molecular ion peak at *m/z* 404 corresponding to the molecular weight of the addition product of **1** to **11a**. The IR spectrum of **12** suggested the presence of a ketone (1710 cm^{-1}), a lactam and a carbon–nitrogen double bond (1690 and 1670 cm^{-1}, interchangeable assignment). In the ^{1}H-NMR spectrum three singlets were observed at 1.43 (3H, N=C–CH_3), 2.59 (3H, N–CH_3), and 3.79 (3H, O–CH_3) and a multiplet signal at 2.3—2.7 was assigned to a methylene group adjacent to the carbonyl. The ^{13}C-NMR spectrum showed the signals of a ketone at 205.2 ppm, a lactam at 167.3 or 169.0 ppm (either peak could be due to a carbon–nitrogen double bond), a normal spiro carbon at 65.6 ppm and a spiro carbon adjacent to the nitrogen and oxygen atoms at 87.7 ppm. Although the stereochemistry of **12** is not clear, the structure was tentatively assigned to be an oxazepine derivative **12**. Further, photoreactions of substrates (**13**—**15**) having an enamide moiety were tested, but the expected oxetanes and the related products were not isolated. In the case of **15**, the adducts (**17** and **18**) were obtained although their structures are still not clear.

In general, inter- and intramolecular photochemical [2+2]cycloadditions of heterocyclic compounds are of synthetic interest.[10] It is well known that photocycloadditions between carbonyl compounds and certain heterocycles such as furans and pyrroles (the Paterno–Büchi reaction) regioselectively give oxetanes (**5b**-i or **5b**-ii type) such as 2,7-dioxabicyclo[3.2.0]hept-3-ene derivatives and related compounds.[4,11–13] The Paterno–Büchi reaction described in the present work also affords regio- and stereoselectively the isolable oxetane derivatives **5**, which are presumably derived from the biradical intermediate generated by addition of carbonyl oxygen to the 2-position of the indole nucleus. This regioselective addition mode (the formation of N–C–O linkage) can be explained in terms of the biradical intermediate generated due to the stability of the benzylic position (Chart 6).[14] In addition, it is noteworthy that in spite of the 1 : 1 molar ratio of **1** and **2** this reaction afforded efficiently and exclusively the more sterically hindered oxetane **5** as a single stereoisomer, in which the aromatic rings of the isoindolone and the indoline moieties overlap each other. Such a



11a–c

11a: $R^1=CH_3O$, $R^2=H$
11b: $R^1=CH_3O$, $R^2=CH_3O$
11c: $R^1=NO_2$, $R^2=H$

Chart 4

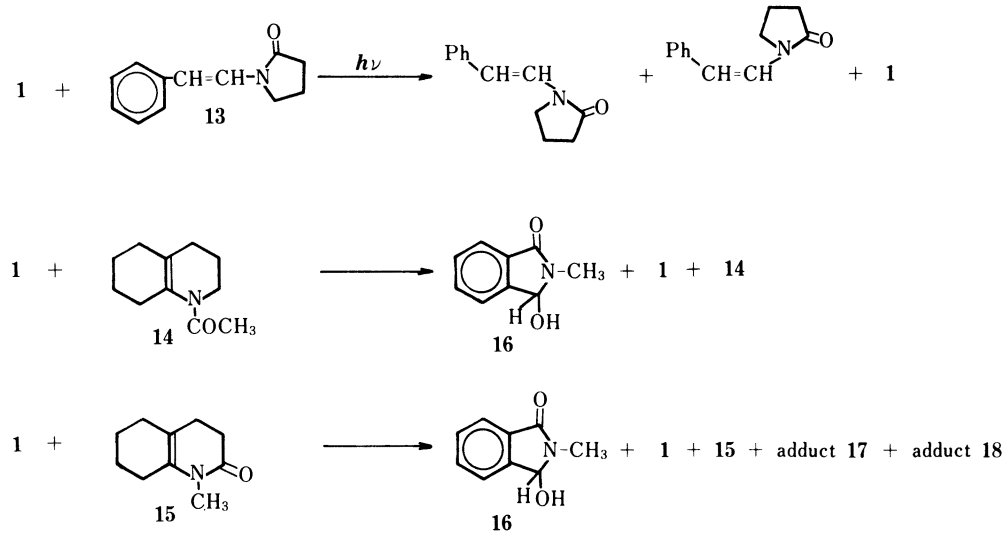


Chart 5

hindered oxetane formation was also observed in the naphthalic anhydride-indene system,[15] resulting from the excited complex that has the same configuration with π-overlapping as the ground state complex. These results would suggest a possible involvement of stacking interaction, such as an excited complex, between the aromatic rings of phthalimide **1** (a good electron acceptor)[16] and the indole derivatives **2**, although no spectroscopic evidence has so far been obtained. Certain indole derivatives could serve as good Paterno–Büchi acceptors, but the enamide structure seems not to be essential for the Paterno–Büchi reaction. It was reported that *N*-acylindoles undergo the Paterno–Büchi reaction to give oxetanes, whereas other heterocycles such as 1*H*-pyrroles, oxazoles, and isoxazoles do not, due to a quenching effect on the excited ketone of the nonbonded electrons on the heteroatom.[4] No simple explanation for the reactivity of the 2,3-carbon–carbon double bond in *N*-acetylindole toward the imide systems, in comparison with the lack of reactivity of other *N*-substituted indoles such as **2h** and **2i**, can be offered at the present time. The intermolecular photocycloaddition reactions of the imides and various possible Paterno–Büchi acceptors would lead to interesting nitrogen-heterocycles by way of the intermediate imide-oxetanes.

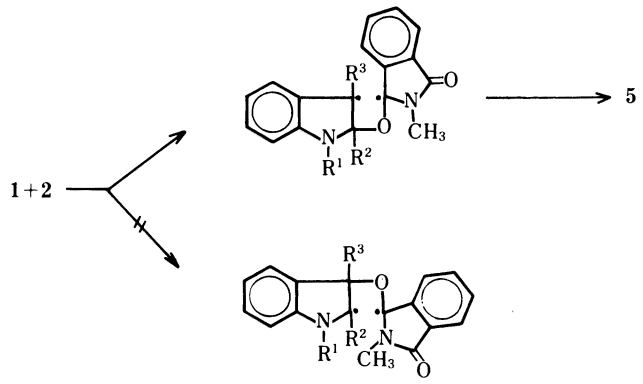


Chart 6

Experimental

All melting points were determined on Yamato MP-21 melting point apparatus and are uncorrected. IR spectra were recorded on a Shimadzu IR-400 spectrometer and a JASCO A-102 spectrometer. NMR spectra were taken on Hitachi R-40 and JEOL FX 60 and 90Q spectrometers. Chemical shifts are reported in parts per million (δ) relative to tetramethylsilane (TMS, 0.0 ppm) as an internal standard. The abbreviations used are as follows: s, singlet; d, doublet; t, triplet; m, multiplet; br, broad. MS were determined with a gas chromatograph-mass spectrometer (JEOL JMS-QH-100) with a direct inlet system.

Irradiations of substrates were conducted using a 500 W high-pressure mercury lamp and a water-cooled quartz immersion well (Eikosha PIH-500) at room temperature. Stirring of the reaction mixture was effected by the introduction of a stream of nitrogen at the bottom of the outer jacket. All column chromatography was conducted using silica gel (Merck, Kieselgel 60, 70—230 mesh) or alumina (Merck, Aluminium oxide 90, activity II—III).

N-Methylphthalimide (**1**) was prepared from phthalic anhydride and *N*-methylamine in a usual manner. 2-Methylindole and 3-methylindole are commercially available. Other indole derivatives were prepared from phenylhydrazine and the corresponding cycloalkanones; cyclopentanone, cyclohexanone, and cycloheptanone by means of the Fischer indole synthesis.[17] 1,2-Dihydrocyclopent[*b*]indole, mp 103—105 °C (lit.,[18] mp 108 °C); 1,2,3,4-tetrahydrocarbazole, mp 119.5—120.5 °C (lit.,[17] mp 115—116 °C); 5,6,7,8,9,10-hexahydrocyclohept[*b*]indole, mp 145—145.5 °C (lit.,[19] mp 140—141 °C).

Preparation of 2a—f: General Procedure——Compounds **2a—f** were prepared by refluxing a mixture of the corresponding indole derivatives and acetic anhydride in the presence of K_2CO_3 in *N*,*N*-dimethylformamide. **2a**: bp_{15} 152—160 °C (lit.,[20] bp_{12} 140—150 °C); **2b**: mp 64—66 °C (lit.,[21] mp 66—67 °C); **2c**: bp_{15} 163—164 °C (lit.,[22] bp_{40} 200—210 °C); **2d**: mp 116—117 °C (lit.,[18] mp 117 °C); **2e**: mp 75—78.5 °C (lit.,[23] mp 77 °C); **2f**: mp 36—37.5 °C. *Anal.* Calcd for $C_{15}H_{17}NO$: C, 79.26; H, 7.54; N, 6.16. Found: C, 79.38; H, 7.57; N, 6.06.

***N*-Methoxycarbonyl-1,2,3,4-tetrahydrocarbazole (2g)**——A solution of 1,2,3,4-tetrahydrocarbazole (13.7 g, 80 mmol) in tetrahydrofuran (THF) (100 ml) was added dropwise to a stirred suspension of KH (3.8 g, 95 mmol) in THF (120 ml) at room temperature. Stirring was continued for 30 min, then ClCOOMe (9.1 g, 96 mmol) was added dropwise to the above mixture and the whole was further stirred for 2 h. After removal of the solvent, the residue was treated with AcOEt and water, and the extract was washed with saturated brine, dried (Na_2SO_4) and concentrated. The residue was subjected to column chromatography on silica gel, and elution with hexane–acetone (6 : 1, v/v) gave 12.3 g (67%) of **2g**, colorless needles from hexane, mp 39—40 °C (lit.,[24] mp 35 °C).

***N*-Trifluoroacetyl-1,2,3,4-tetrahydrocarbazole (2h)**——The title compound was prepared from tetrahydrocarbazole and trifluoroacetic anhydride, mp 67—70 °C (hexane).

***N*-Methyl-1,2,3,4-tetrahydrocarbazole (2i)**——The title compound **2i** was prepared from tetrahydrocarbazole and methyl iodide in the presence of KH in THF, mp 48—49 °C (lit.,[25] mp 51 °C).

***N*-Acetyl-6-methoxy-1,2,3,4-tetrahydrocarbazole (11a)**——6-Methoxy-1,2,3,4-tetrahydrocarbazole was prepared from anhydrous $MgCl_2$, anisidine, and 2-*p*-anisidinocyclohexanone (prepared from *p*-anisidine and 2-chlorocyclohexanone) according to the method of Campaigne and Lake.,[26] mp 104.5—105.5 °C (lit.,[26] mp 107.5—108.5 °C). Next, the resulting tetrahydrocarbazole was acetylated with acetic anhydride to give **11a** (85%) in the manner described above, mp 100—101.5 °C. *Anal.* Calcd for $C_{15}H_{17}NO_2$: C, 74.05; H, 7.04; N, 5.76. Found: C, 73.96; H, 7.11; N, 5.66.

***N*-Acetyl-6,7-dimethoxy-1,2,3,4-tetrahydrocarbazole (11b) and *N*-Acetyl-6-nitro-1,2,3,4-tetrahydrocarbazole (11c)**——Dimethoxy-tetrahydrocarbazole was prepared according to the method described for the preparation of **11a**, mp 101—103 °C (lit.,[27] mp 98 °C). The 6,7-dimethoxy-1,2,3,4-tetrahydrocarbazole was acetylated with acetic anhydride to give **11b**, mp 136—137 °C (lit.,[27] mp 136 °C). *Anal.* Calcd for $C_{16}H_{19}NO_3$: C, 70.31; H, 7.01; N, 5.13.

Found: C, 70.46; H, 7.02; N, 5.14. 6-Nitrotetrahydrocarbazole was prepared from *p*-nitrophenylhydrazine and cyclohexanone according to the modification of the Fischer indole synthesis,[17] mp 168—171 °C (lit.,[28] mp 177 °C). Similarly, the 6-nitrocarbazole was acetylated with acetic anhydride to give **11c**, mp 245—247 °C (lit.,[23] mp 244 °C). *Anal.* Calcd for $C_{14}H_{14}N_2O_3$: C, 65.10; H, 5.46; N, 10.85. Found: C, 65.18; H, 5.45; N, 10.67.

Compounds 13, 14, and 15——*N*-Styrylpyrrolidone (**13**),[29] *N*-acetyl-1,2,3,4,5,6,7,8-octahydroquinoline (**14**),[30] and 1-methyl-3,4,5,6,7,8-hexahydro-2(1*H*)-quinolone (**15**)[31] were prepared according to the reported procedures.

Irradiation of 1 in the Presence of 2 or 11: General Procedure——A solution of **1** and **2** (**1**:**2** = 1:1, molar ratio) (or **11**) in acetone (10 mM) was irradiated using a 500 W high-pressure mercury lamp through Pyrex glass in a stream of nitrogen at room temperature for 2—11.5 h. After removal of the solvent, the photolysate was subjected to column chromatography on alumina. The column chromatography was carried out using the following solvent systems. **5b**, AcOEt : hexane = 1 : 1, v/v; **3**, **4**, **5e**, **f**, **g**, **9**, **10**, and **12**, AcOEt : hexane = 1 : 2, v/v. In the case of the photolysate of **1** and **2c**, the eluates with AcOEt : $CHCl_3$ = 2 : 1 afforded **7** as an *E*–*Z* (2 : 1) isomeric mixture in 62% yield together with **1** (29%) and **2c** (26%). The chloroform solution (30 ml) of **7** (812 mg) was refluxed in the presence of *p*-toluenesulfonic acid (200 mg) for 24 h. After removal of the solvent *in vacuo*, AcOEt was added to the residue and insoluble *E*-**7** was isolated in 17% yield. The remainder was again subjected to column chromatography on silica gel and elution with AcOEt : hexane = 1 : 1 afforded the oxazepine **8** in 34% yield together with *E*–*Z* mixture (5%). Selected data for compound *Z*-**7** in the *E*–*Z* mixture **7**: ^{1}H-NMR (DMSO-d_6) δ: 2.02 (3H, s, $COCH_3$), 2.88 (3H, s, N-CH_3), 6.82 (1H, s, HC=C–), 7.0—8.0 (8H, m, aromatic H), 9.2—9.4 (1H, br s, NH). In the irradiation of **1** in the presence of **2i**, an adduct of **1** with acetone was isolated in 14% yield, mp 173—174.5 °C [lit.,[32] mp 172.5—173.5 °C, 2,3-dihydro-3-hydroxy-3-(1-hydroxy-1-methylethyl)-2-methyl-1*H*-isoindol-1-one]. The melting point and ^{1}H-NMR data were identical with those of an authentic sample.[32] ^{1}H-NMR (DMSO-d_6) δ: 0.92 (3H, s, CH_3), 1.19 (3H, s, CH_3), 2.97 (3H, s, N-CH_3), 4.76 (1H, s, OH exchanged with D_2O), 6.40 (1H, s, OH exchanged with D_2O), 7.3—7.7 (4H, m, aromatic H).

Irradiation of 1 in the Presence of 13, 14 or 15——A solution (10 mM) of **1** and **13**—**15** (1 : 1 molar ratio) was irradiated using a 500 W high-pressure mercury lamp as described above. In the case of **13**, upon irradiation in an acetone solution for 2 h, *N*-methylphthalimide **1** was recovered quantitatively and a *cis–trans* mixture (*cis–trans* = 1.8 : 1 by ^{1}H-NMR spectroscopy) of **13** was obtained in 84% yield. Irradiation of **14** in benzene for 1.5 h gave the reduction product (**16**, mp 133—134 °C, 25%) of **1** and **1** (26%) together with a trace of **14**. The melting point and ^{1}H-NMR spectrum of **16** were identical with those of an authentic sample (lit., mp 130—131 °C).[33] Photolysis of **1** in the presence of **15** in MeOH for 21 h gave the adducts **17** [MS *m/z*: 326 (M^+), 308 ($M^+ - 18$)] and **18** [MS *m/z*: 326 (M^+), 308 ($M^+ - 18$)] in 24 and 24% yields, respectively, and **16** (7%), **1** (17%) and **15** (10%). The structures of the adducts **17** and **18** are not clear.

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