Reversible Photorearrangement of N-Substituted Phthalimides: a Flash Photolysis Study

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Phosphorescence and fluorescence studies of a series of N-substituted phthalimides suggest that the photochemical cyclization reaction of dialkylaminoalkyl substituted compounds probably occurs through the (n,π^*) singlet excited state. Flash photolysis of these and other, simpler phthalimides reveals an unrelated reaction involving two types of transient intermediate. One is a triplet state and the other a much longer-lived species which is postulated to be an isomer of the imide produced by a 1,3-shift. The isomer reverts to the imide, and the effect of substituent and of solvent on the decay is discussed.

THE photochemistry of N-substituted phthalimides [1] and other imides [2] has been a subject of considerable interest because of applications in the synthesis of normal, medium, or large heterocyclic ring systems. The nature of the imide excited states and the mechanism of cyclization are less well established, although we have recently proposed [3] that N-(dialkylaminomethyl)phthalimides have a fluorescent $S_2(\pi,\pi^*)$ excited state, a non-fluorescent $S_1(n,\pi^*)$ state, and a phosphorescent $T_1(\pi, \pi^*)$ state (the latter in ethanol at 77 K). The mechanism of cyclization for these particular imides is thought to involve initial electron transfer from the amine nitrogen atom to the excited carbonyl group, and a very similar proposal has been put forward [4] for the reaction of N-(methylthioalkyl)phthalimides.

During the course of our mechanistic studies some observations were made that could not easily be accommodated in the proposed reaction scheme, and we now present these findings.
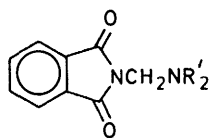
RESULTS AND DISCUSSION

The compounds chosen for intensive study were N-methyl- and N-propyl-phthalimide (1a, b), three N-(dialkylaminomethyl)phthalimides (2a—c), and N-(2-diethylaminoethyl)phthalimide (3).
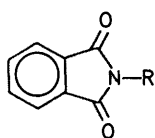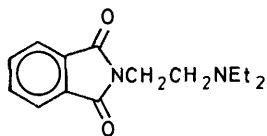

(1)
a; R = Me
b; R = Pr

(2)
a; R' = Me
b; R' = Pr
c; R' = CH₂Ph

(3)

All the imides phosphoresce quite strongly at 77 K, and in ethanol as solvent the lifetimes are quite close to 1 s (Table 1). Insofar as electron transfer in the amino-alkyl compounds would be expected to cause a significant reduction in lifetime as compared with the lifetime of the N-alkylphthalimides (1), and insofar as results from a

TABLE 1

Fluorescence and phosphorescence of phthalimides

Compound	τ_f/ns [a]	ϕ_f [b]	τ_p/s [c]
(1a)			1.02
(1b)	3.0	0.008	1.04
(2a)	3.7	0.016	0.97
(2b)	3.7	0.013	0.99
(2c)	3.7	0.017	1.02
(3)			0.92

[a] Fluorescence lifetime (± 0.25 ns) in ethanol at 20 °C. [b] Quantum yield for fluorescence, using aniline in ethanol as standard. [c] Phosphorescence lifetime in ethanol at 77 K.

rigid glass at 77 K can be extrapolated to fluid solution at normal temperature, it seems that the phosphorescent (π,π^*) triplet state [3] is not the reactive excited state in the photochemical cyclization of (2).

On a similar basis the fluorescent (π,π^*) singlet state is probably not the reactive state, since the fluorescence lifetime for imides (2) is no shorter than that for (1).† From this negative evidence the most likely candidate for the reactive excited state in the photocyclization is $S_1(n,\pi^*)$, although a short-lived upper triplet state is also a possibility. Because S_1 (or T_n) cannot be observed directly, it is not possible to say whether it reacts by way of ' conventional ' hydrogen atom transfer, or by way of electron transfer followed by proton transfer.

Of particular interest for our present study is that all the imides appear to undergo a reversible photoreaction from the lowest triplet state that is unrelated to the photochemical cyclization and occurs for N-alkyl- as well as N-(dialkylaminoalkyl)-phthalimides. Flash photolysis reveals that presence of two observable transient species for each imide.‡,§ The first transient
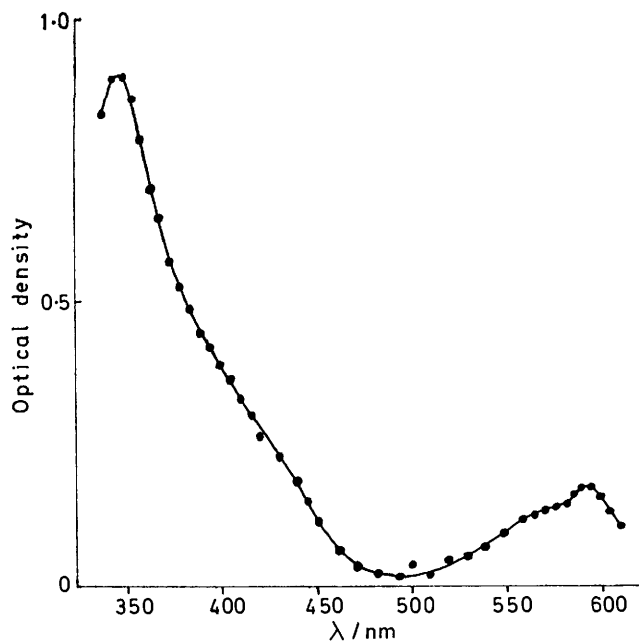
FIGURE 1 Triplet absorption spectrum from imide (1b) in ethanol (100 ns delay)

(spectrum in Figure 1; the spectra for the other imides are very similar) is formed directly after excitation and is the triplet state of the imide. The spectrum is not greatly affected by solvent (MeOH, EtOH, Pr^{i}OH,

cyclohexane), and the transient is quenched at near the diffusion-controlled rate by oxygen or by a conjugated diene [for imide (1b) and oxygen, $k_q \sim 3.5 \times 10^9$ 1 mol^{-1} s^{-1}]. In air-equilibrated solutions no transient is observed.

Under all conditions the decay of the triplet state is exponential, and the lifetimes (τ_T) are given in Table 2.

TABLE 2

Transients in the flash photolysis of phthalimides

Compound	Solvent	$\tau_T/$ μs	$k_D{}^T/$ 10^4s^{-1}	$k_R/$ 10^4s^{-1}	$k_1/$ s^{-1}	$k_1'/$ s^{-1}
(1a)	EtOH	43	2.3 [a]	2.0 [b]	0.85 [b]	0.23 [b]
(1a)	C$_6$H$_{12}$	10	10	1.6	354	70
(1b)	MeOH	40	2.5	1.8	1.10	0.18
(1b)	EtOH	40	2.5	1.6	1.04	0.16
(1b)	Pr^{i}OH	37	2.7	1.8	1.10	0.20
(1b)	C$_6$H$_{12}$	12	8.3	1.4	385	68
(2a)	EtOH	10	10	6.5	4.16	0.18
(2b)	EtOH	10	10	2.5	2.16	0.19
(2c)	EtOH	12	8.3	3.4	1.12	0.16
(3)	EtOH	42	2.3	1.3	1.20	0.23

[a] $k_D{}^T = (\tau_T)^{-1}$. [b] Monitored at 380 and 620 nm.

A second transient is observed that builds up with a rate constant smaller than that for the decay of the triplet state. It is very likely that this transient is formed directly from the triplet state, and Table 2 shows the rate constant (k_R) for its formation from the triplet. The spectra of this longer-lived transient for imides (1b) and (2a) are shown in Figures 2 and 3 (the spectra are not noticeably different in cyclohexane solvent). The
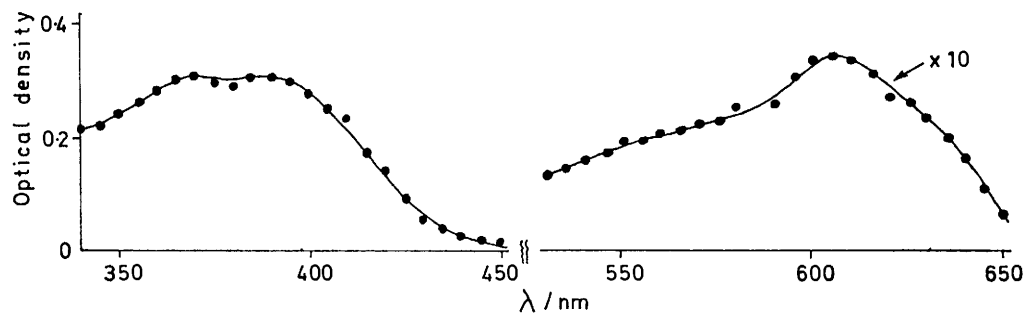

FIGURE 2 Absorption spectrum of long-lived transient from imide (1b) in ethanol (1 ms delay). Imide (1a) gives a very similar result
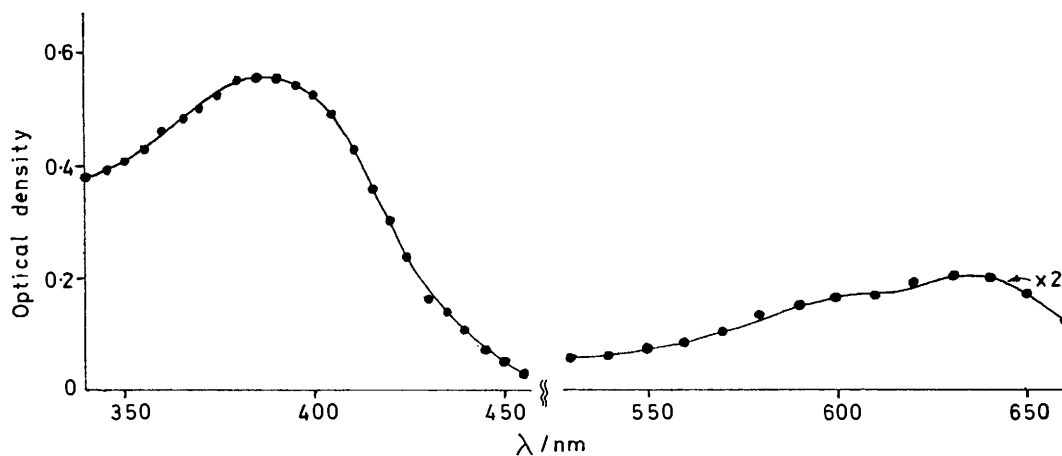

FIGURE 3 Absorption spectrum of long-lived transient from the imide (2a) in ethanol (1 ms delay). Imides (2b), (2c), and (3) give very similar results

second transient decays to the ground state of the original phthalimide. The kinetics of decay can be simulated by a summation of two first-order processes, one considerably slower than the other. The rate constants for the processes (k_1, k_1') are given in Table 2, and ca. 80% of the decay occurs by the faster of the two processes. The features of these results that call for comment are (i) the enhanced rate of triplet reaction for imides (2), (ii) the effect of N-substituent on the rate constant (k_1) for the major decay pathway of the long-lived transient, and (iii) the influence of solvent on the rate constants, particularly on k_1.

It is very unlikely that the long-lived species is a biradical or zwitterion of the type proposed in photocyclization, since these would not have a lifetime in the range 0.1—1 s and imide (1a) would be unable to form such a species readily. A radical species is also unlikely, since it would be expected to decay by a second-order process or, if it reacted with solvent, by a process whose rate constant was markedly dependent on the solvent (MeOH, EtOH, Pr^{i}OH). This is not the case, and we propose that the species is an isomer of the imide formed by a 1,3-migration. Two possibilities are an isoimide
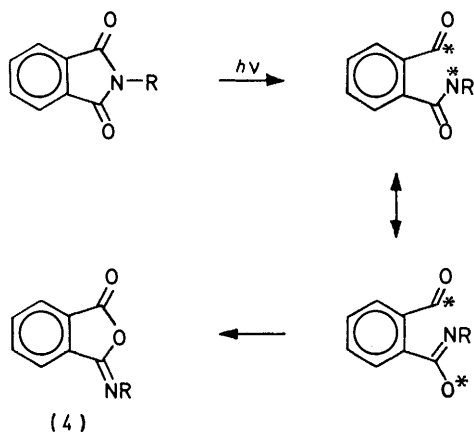

(4) formed by α-cleavage in the triplet state followed by bond rotation and recombination, or the product (5) of a 1,3-alkyl shift that could occur by way of radical or ionic species.
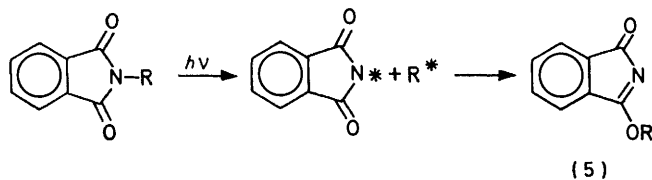

Both these possibilities are consistent with the fact that the chemical reaction must be a feature of the imide ring system and does not involve the side-chain nitrogen atom of imides (2) or (3), since the transient appears also for imides (1). The reaction seems not to occur for lactam [6; R = CH$_2$N(CH$_2$Ph)$_2$]. The triplet state of this amide is quite short-lived ($\tau_T = 0.4$ μs), but no long-lived transient is formed from it. For the amide, (O=)C–N or N–R cleavage is less favourable than for

the corresponding imide (2c) because there is less resonance stabilisation in the nitrogen radical or ion.
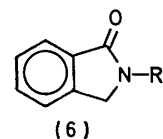
A precedent for the α-cleavage reaction is found in the photoisomerization of indan-1,3-diones (7), although the isomer in this case is much more stable thermally.[5] In a recent report [6] of the photoaddition of conjugated dienes to N-methylphthalimide, the absence of isomer (8) amongst the photoproducts was used as an argument against an α-cleavage mechanism, although its presence would not have been detected if its lifetime were around 1 s.
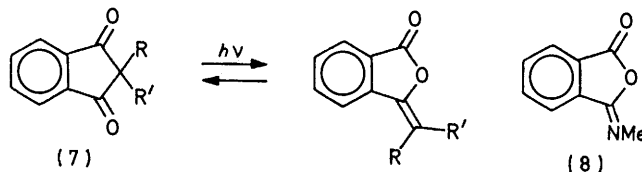
N-Substituted isomaleimides (4-iminobut-2-en-4-olides) have been prepared; [7] the alkyl derivatives are colourless, and the aryl derivatives yellow. N-Phenyl-isophthalimide (3-phenyliminophthalide) has been reported [8] as a yellow crystalline compound. The implied u.v./visible spectral characteristics and the relative stability of these isoimides lead us to prefer structure (5) of the two proposed for the flash photolysis transient. The absorption spectrum of indenone (9) shows a strong band at 380 nm.[9] The transients we have observed show an absorption band in this region, and also a weaker band at much longer wavelength. The latter could arise from the presence of an alkoxy-substituent in the system, but we have no model compounds to show whether or not such a large effect could be expected (in acyclic enone systems, shifts of only ca. 35 nm are found).
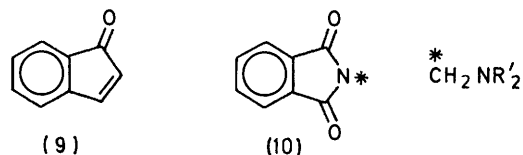
In ethanol solution the rate constant (k_R) for reaction of the triplet state is enhanced when the substituent on nitrogen is dialkylaminomethyl [imides (2a—c)]. This may reflect the ability of an adjacent nitrogen to stabilise the reactive centre if cleavage occurs at the β-position relative to the carbonyl group (10). Such an effect would be absent for imide (3). This rate constant (k_R) is much the same in cyclohexane as in ethanol, although triplet decay (k_D^T) is faster in cyclohexane. Most probably the effect of solvent is on the rate constant (k_{isc}) for intersystem crossing to ground state, and since k_D^T can be represented as $(k_{isc} + k_R + k_Q[O_2])$, where

$k_Q[O_2]$ represents quenching by residual oxygen and is estimated to be $\leqslant 10^3$ s^{-1}, k_{isc} increases by a factor of 7—8 for imide (1b) in going from ethanol to cyclohexane.

The long-lived transient species decays to imide ground state mainly by a pathway whose rate constant (k_1) is significantly affected by the substituent on nitrogen only for imides (2a) and (2b). Since the decay process must involve a reversal of the bond cleavage and bond formation that led from the triplet state to the transient, it is not surprising that a similar substituent effect is observed. The rate constant (k_1') for the slower decay process is not affected in the same way. The effect of cyclohexane on the rate of decay (k_1) is quite dramatic, and it is consistent with stabilisation of the transient (4) or (5) by hydrogen-bonding in alcohol solvents. Such stabilisation would an inhibit isomerisation process in the hydroxylic solvents provided that the reaction occurs by way of radical rather than ionic species.

EXPERIMENTAL

The *N*-substituted imides (1) and (3) were prepared from phthalic anhydride and the appropriate amine. Imides (2) were prepared by a Mannich reaction from phthalimide. Phosphorescence and fluorescence measurements were taken using a Perkin-Elmer MPF4 instrument with Hitachi S10 photomultiplier. Conventional flash-photolysis equipment [10] was employed to generate and detect the transients. In all cases thorough degassing was achieved by a sequence of freeze–pump–thaw cycles, and the rate constants are the average of values from two or three separate experiments.

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