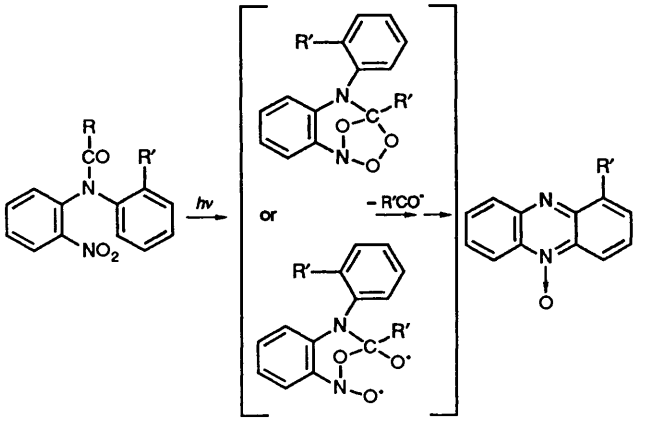
Photochemical Reaction of 2,4-Dinitrodiphenylacetamide and Related Compounds: Spectroscopic and Chemical Identification of Intermediates

Elisa Fasani,[a] Mariella Mella[a] and Angelo Albini*[,b]
[a] *Department of Organic Chemistry, The University, V. Taramelli 10, 27100 Pavia, Italy*
[b] *Institute of Organic Chemistry, The University, V. Giuria 7, 10125 Torino, Italy*

2,4'-Dinitrodiphenylacetamide **1b** reacts *via* the triplet state to give 3-nitrophenazine 5-oxide **2b**. The initial step is addition of the nitro group to the C=O bond. This intermediate **7** rearranges in the ms time scale to yield an *O*-acylnitro derivative **8**. This, in turn, undergoes heterolytic cleavage (rate dependent upon solvent polarity) and the aminium cation thus formed cyclizes to **2b**. Intermediate **7** is sensitive to acid-catalysed hydrolysis, and the cleavage of **8** and subsequent cyclization are influenced by various additives. Thus, with triphenylphosphine a phosphoranylidenamino derivative is obtained, and 2,6-di-*tert*-butylphenol gives 4-nitro-2-nitrosodiphenylamine. Two other amides are compared.

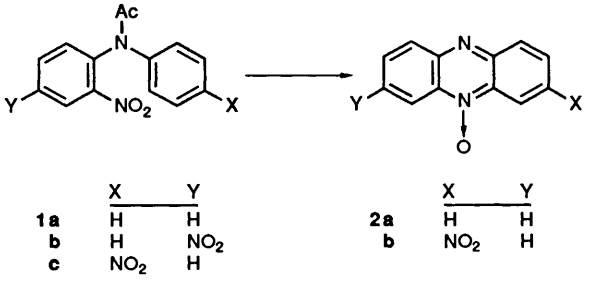
The radical character of the triplet state of aromatic nitro compounds has been evidenced in many hydrogen abstraction reactions, both inter- and intra-molecular,[1] as well as in the addition to alkenes to yield 1,3,2-dioxazolidines.[2] Relevant to this context is a reaction reported some years ago by Maki *et al.* (Scheme 1).[3] They found that some derivatives of 2-nitrodiphenylacetamide photochemically cyclize to give phenazine *N*-oxides. This is interesting both as a synthetic path to substituted phenazine *N*-oxides and in view of the mechanism proposed, which envisages an intramolecular attack of the nitro on the amide C=O group to yield a 1,2,4,3-trioxazolidine or a diradical as the first step. Our continuing interest in the photochemistry of *N*-oxides and nitro heterocycles led us to reconsider this reaction.[4–6]



Scheme 1

Results

Maki *et al.*[3] reported that irradiation of 2-nitrodiphenylacetamide **1a** gave a 5% yield of phenazine 5-oxide **2a**, while with 2'-methoxy-2-nitrodiphenylacetamide and some other 2'-substituted derivatives yields ranged between 3 and 85%. We observed that the yield of **2a** was 80% of consumed **1a** when the irradiation of dilute (10^{-4} mol dm^{-3}) solutions was interrupted at *ca.* 25% conversion (Table 1). However, **2a** is photolabile[7] and since it absorbs more strongly than **1a** over the range of mercury-lamp emission, continuing the irradiation up to complete conversion accumulated the known photoproducts from **2a**,[7] rather than the *N*-oxide itself. We then turned to 2,4-dinitrodiphenylacetamide **1b**, and found that its irradiation gave 3-nitrophenazine 5-oxide **2b** in excellent (≥95%) chemical yield (Scheme 2). The same photoproduct was obtained, again in high chemical yield, from the isomeric 2,4'-dinitrodiphenylacetamide **1c**. This result was due to the known photostability of *N*-oxide **2b** (quantum yield for reaction in acetonitrile 3×10^{-3}, ref. 8) in comparison of the photoreactivity of **2a**. Therefore, the dinitroamines seemed to be well suited for a mechanistic investigation. Furthermore, preliminary experiments showed that during the photoreaction of **1b** (but not of **1c**) a red colour was formed, which faded after several minutes to give place to the yellow colour of the end product **2b**. Thus the investigation was centred particularly on **1b**.



	X	Y
1a	H	H
b	H	NO_2
c	NO_2	H

	X	Y
2a	H	H
b	NO_2	H

Scheme 2

The amides **1a–c** showed neither fluorescence (at room temperature) nor phosphorescence (in ether–pentane–alcohol glass at 77 K). Quantum yields for the photoconversion into the corresponding phenazine *N*-oxides upon direct irradiation both of a deaerated and of an air-equilibrated solution in benzene, irradiation in the presence of benzophenone (90% of the light absorbed by the latter), and irradiation in the presence of the low-energy quencher 3,3,4,4-tetramethyldiazetine 1,2-dioxide are reported in Table 2.

In all these cases the reaction gave practically only the phenazine *N*-oxides. The reaction was further investigated with the amide **1b**. It was found that the course of the reaction was the same also in dichloromethane, acetonitrile, and methanol and that the *N*-oxide **2b** remained by far the main product also in isopropyl alcohol. However, in benzene containing trifluoroacetic acid (TFA) (10^{-2} mol dm^{-3}) (see Table 2) **2b** was only a minor product and gave place to 2,4-dinitrodiphenylamine **3**. Also in the presence of 1,4-diazabicyclo[2.2.2]octane (DABCO) the yield of *N*-oxide was diminished and **3** was formed in preference. Experiments in the presence of triphenylphosphine

Table 1 Preparative irradiation in deaerated benzene

Substrate[a]	Additive (mol dm^{-3})	Irradiation time/min	Substrate conversion (%)	Product [yield (%)]
1a[b]		5	25	**2a** (80)
1b		35	95	**2b** (95)
1b[c]		35	95	**2b** (98)
1b	TFA (10^{-2})	35	95	**2b** (15), **3** (80)
1b	DABCO (5×10^{-3})	35	95	**2b** (45), **3** (40)
1b	TPP (10^{-2})	30	82	**2b** (50), **4** (6), **5** (25)
1b	DTBP (3×10^{-2})	30	82	**2b** (58), **4** (27), **6** (9)
1c		60	90	**2b** (88)

[a] 5×10^{-3} mol dm^{-3}, unless otherwise stated. [b] 1×10^{-4} mol dm^{-3}. [c] Not deaerated.

Table 2 Quantum yield for the photochemical conversion of amides **1** into phenazine *N*-oxides **2** in degassed benzene

Substrate[a]	Additive (mol dm^{-3})	Φ
1a		0.1
1a[b]	Ph_2CO (10^{-2})	0.07
1b		0.06
1b[c]		0.06
1b[b]	Ph_2CO (10^{-2})	0.04
1b	TMDD[d] (10^{-2})	0.05
1c		0.025
1c[b]	Ph_2CO (10^{-2})	0.018

[a] 1×10^{-4} mol dm^{-3}. [b] 5×10^{-5} mol dm^{-3}. [c] Not degassed. [d] 3,3,4,4-Tetramethyldiazetine 1,2-dioxide.

Table 3 Kinetic data for the intermediate absorbing at 520 nm from the photolysis of amides **1**

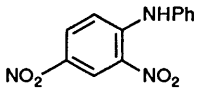
Substrate[a]	Solvent	Additive	k_f/s^{-1}	k_I/s^{-1}	k_{II}/dm^3 mol^{-1} s^{-1}
1b	C_6H_6		250	0.04	
1b	C_6H_6	TPP	250		15
1b	CH_2Cl_2		320	0.2	
1b	MeCN		300	125	
1b	MeOH		*b*	~500	
1a	C_6H_6		*b*	200	
1b	C_6H_6		8000	4	

[a] 2×10^{-5} mol dm^{-3}. [b] Signal too weak for accurate evaluation.

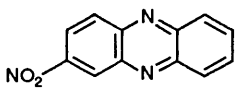
(TPP) gave **2b** as the main product, but this was accompanied by some 2-nitrophenazine **4** and by 2-triphenylphosphoranylidenamino-4-nitrodiphenylamine **5**.

Finally, when the irradiation was carried out in the presence of 2,6-di-*tert*-butylphenol (DTBP), **2b** was obtained together with substantial amounts of compound **4** and of another product, 4-nitro-2-nitrosodiphenylamine **6** which was smoothly oxidized to product **3** by hydrogen peroxide under basic conditions.

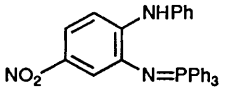
The irradiation of the amide **1b** caused the solution to turn red. When the irradiation was interrupted, at whatever stage of the conversion, the red colour faded completely in about 20 min. Examination of the UV–VIS spectrum showed the formation of a broad band with a maximum at 520 nm. This decreased in the dark to be replaced by absorptions at 457 and at 434 nm characteristic of the *N*-oxide **2b**. If, after every irradiation, the spectra were measured after *ca.* 20 min in the dark, the time evolution of the reaction showed a clean conversion of **1b** into



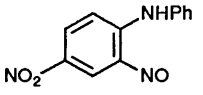
3



4



5



6

2b conserving the isosbestic points. Under conditions of steady state irradiation the red absorption never accumulated beyond a certain point (this corresponded to a few percent of **2b** after the dark reaction had taken place). Since the proportionality between the decrease of the 520 nm absorption and the amount of **2b** generated was always maintained, the red species was a photoproduct from **1b** capable of being transformed to the end product **2b** through some path. This was a first-order process, with a rate of 4×10^{-2} s^{-1} in benzene. Comparison of the decrease of the amide after 1 min irradiation and the increase of the *N*-oxide after the completion of the dark reaction confirmed that at least 90% of **1b** converted into the end-photoproduct *via* this path.

Flash photolysis experiments showed that the red intermediate was not formed instantaneously but was generated through a first-order process, with a rate of 250 s^{-1} in benzene. Changing the solvent affected both the rate of formation, and, more strongly, the rate of consumption of this species. Furthermore, flash photolysis revealed that a similarly absorbing transient was generated also from the amides **1a** and **1c**, though in these cases it was not persistent enough to accumulate during steady-state irradiation. Repeating the experiment in the presence of the additives considered above strongly affected the observed kinetics. Thus, the lifetime of the red species was shortened in the presence of TPP, DTBP, and DABCO, while no transient absorption was observed with TFA (in the last case, formation of the end product, the amine **3**, was instantaneous on the time scale of the experiment). Rate constants for the formation of the red species (k_f), for its decay (k_I) as well as for its reaction with TPP (k_{II}, with DTBP and DABCO the reaction is too slow to be accurately measured) are reported in Table 3.

The amount of this intermediate accumulated during steady state irradiation was too low to allow the study of its chemistry. However, it was found that submitting a 10^{-4} mol dm^{-3} solution of **1b** to a series (7–8) of flashes consumed *ca.* 50% of the substrate and enabled us to explore directly the chemical reaction of the intermediate. Thus, when the prepared red solution was further flashed with $\lambda > 450$ nm, the rate of conversion of the intermediate into **2b** was not affected. Furthermore, Table 4 compares the results (determined by HPLC) obtained by flashing a solution containing various additives, and those obtained by adding the same amount of such compounds to the previously flashed solution. One can see that there is little difference between the two experiments when DTBP and TPP are used, but that completely different results are obtained with TFA and DABCO. In fact, while flashing **1b** in the presence of these additives leads to the amine **3**, in accordance with the result of preparative irradiations, adding TFA and DABCO to the pre-flashed solution of **1b** causes the immediate discharge of the red colour to yield the *N*-oxide **2b**, *i.e.* the same product formed, though more slowly, in their absence.

Finally, some experiments were carried out concerning the temperature dependence of the reaction. Thus, it was observed that the quantum yield for the reaction of **1b** in ethanol–

Table 4 Product distribution in flash photolysed solution of amide **1b** in benzene[a]

Additive		
added before	added after	Product [yield (%)]
—	—	**2b** (90)
TPP[b]	—	**2b** (50), **5** (35)
—	TPP[b]	**2b** (50), **5** (30)
TFA[b]	—	**2b** (10), **3** (80)
—	TFA[b]	**2b** (90), **3** (trace)
DABCO[c]	—	**2b** (50), **3** (40)
—	DABCO[c]	**2b** (90)
DTBP[b]	—	**2b** (60), **6** (10)
—	DTBP[b]	**2b** (60), **6** (10)

[a] 10^{-4} mol dm^{-3}. [b] 10^{-2} mol dm^{-3}. [c] 5×10^{-3} mol dm^{-3}.

methanol solution did not appreciably change by lowering the temperature until, around −40 °C, it dropped rapidly to zero.

Discussion

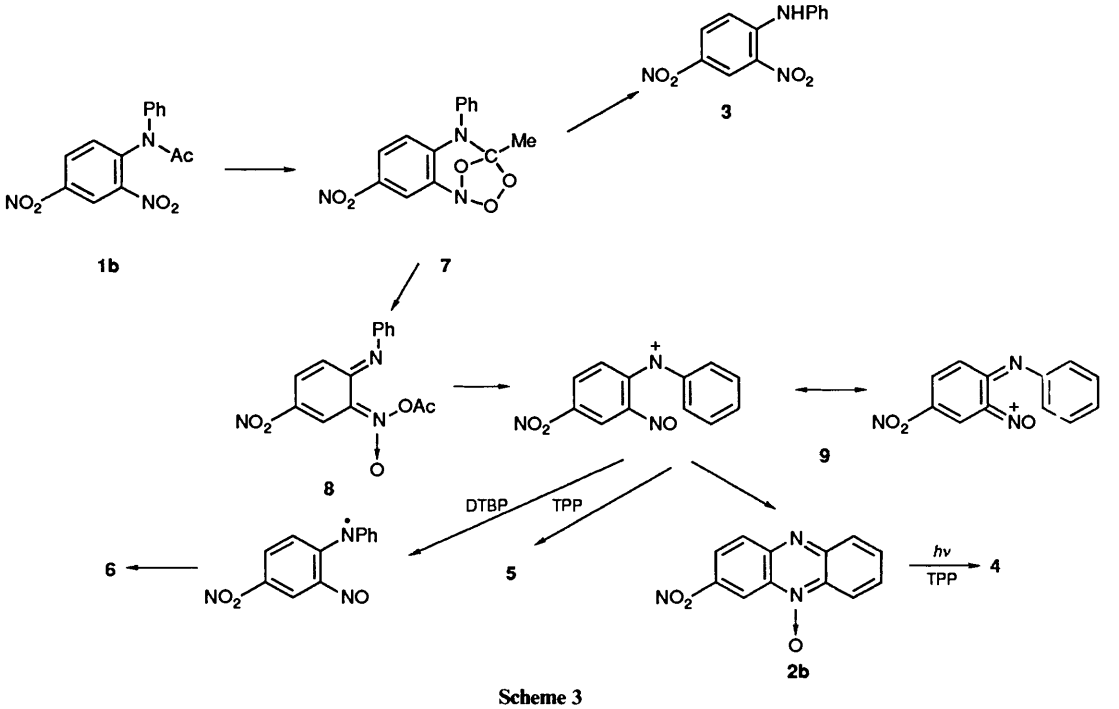
The nitrodiphenylacetamides are expected to have low-lying internal change transfer (ICT) states. Indeed, the absorption spectrum shows strong ($\varepsilon > 10^3$) bands due to the lowest singlet with a bathochromic shift in the series **1c** < **1a** < **1b**. As for the lower triplet, the absence of phosphorescence excludes that it is a ππ* state similar to that of diphenylacetamide, and leaves the alternative that is either a nπ* state localized on the nitro group or a ππ* ICT state; since the nπ* state would not be expected to be much lower than *e.g.* in nitrobenzene, it is expected that the latter one is isoenergetic or lower than the former one. The successful benzophenone sensitization (under the conditions of Table 2; the sensitizer absorbs 90% of the light) suggests a triplet path. This is a short lived triplet, and it neither emits nor is appreciably quenched by 10^{-2} mol dm^{-3} 3,3,4,4-tetramethyldiazetine 1,2-dioxide (TMDD); this is expected due to the fast intramolecular reaction.

The most interesting finding is that two intermediates lie in the path leading to the *N*-oxide, one with a lifetime in the range of ms, and the other one of min. In fact, the evidence discussed shows that the *N*-oxide is formed through a dark reaction from the longer lived (red) intermediate. The latter, in turn, does not directly arise from excited **1b** since flash photolysis shows that it appears in a few ms. We did not detect an absorption corresponding to this first-formed intermediate but the TFA experiments clearly involve the trapping of a species which is a precursor of the red intermediate. The structures assigned to these species are shown in Scheme 3, where some features of the earlier proposal are confirmed.[3]

The first step is addition of the nitro group to the C=O bond. Since the formation of phenazine *N*-oxide is monophotonic and there is no indication that any of the following steps is reversible, nor are there significant by-paths (the chemical yield of the end product is high from all three amines), the quantum yield for the overall reaction depends on the efficiency of the primary step. As it appears from the data in Table 2, quantum yields are in the order **1a** > **1b** > **1c**, *i.e* they follow the order of the amide basicity. This is expected for attack by the nitro group, if this has some nπ* radical character. Molecular mechanics calculations show that in these amides the nitro group is coplanar with the ring with a strong barrier to rotation, while the plane of the amide group is tilted *ca.* 30°. The conformation with the minimal distance between the oxygen of the nitro group and the carbon atom of the imide is somewhat more tilted than that corresponding to the energy minimum. The sharp inhibition of the reaction below −40 °C apparently indicates that a suitable conformation is required for reaction.

The intermediate thus formed has some stability (ms lifetime) and therefore is not a diradical but rather the polycyclic azaozonide **7**. This undergoes a bond rearrangement to give compound **8**. The reaction apparently is a concerted rearrangement, not affected by the nature of the medium (Table 3). However this relatively long-lived intermediate undergoes both TFA and DABCO catalysed cleavage to give the nitroamine **3**. Facile protonation and heterolytic cleavage is expected for this heterocycle, and DABCO may act either through base or electron transfer catalysis.

The structure assigned to the red intermediate is that of an anhydride of the nitro derivative in the *aci* form **8**. Extended delocalization and ICT explain the colour. This compound



Scheme 3

suffers heterolytic, rather than homolytic, cleavage to yield the aminium cation **9**, as shown by the strong dependence of its lifetime on solvent polarity. This reaction too is subjected to acid catalysis (see the effect of TFA on preformed **8**). TPP also reacts with this intermediate (and not with **7**, see Tables 3 and 4), and has two effects, *viz* first it accelerates the heterolysis (reasonably acting as an electron donor) and secondly it intercepts the cation (competitively with its cyclization, see below). The product resulting from the trapping is the phosphoranylidene amine **5**, not dissimilarly from what had been previously observed with nitrenes,[9] *i.e.* the trapping is accompanied by deoxygenation, reasonably by a second molecule of TPP.

DTBP has a similar, but less strong effect. Thus decomposition of **8** is somewhat accelerated and a new product **6** is formed. Though the latter is obtained in low yield, its structure is a useful support to the identification of the cation **9** as an intermediate. This is apparently reduced to the corresponding radical and abstracts a hydrogen from the phenol giving the nitroso derivative **6**.

Finally, cyclization of the cation **9** to a phenazine *N*-oxide may be viewed either as an electrophilic substitution by the charged NO^+ group or as a nucleophilic substitution by the neutral NO group *ortho* to the positively charged amine nitrogen. The corresponding radical is probably involved in the reported thermal cyclization of 2-nitrodiphenylamines by reduction with hydrazine, metals or metal salts.[10–14] The small amount of 2-nitrophenazine isolated in the presence of TPP and DTBP is apparently due to a secondary photoreaction from **2b**, similarly to the previously reported reduction with amines.[6]

The present findings substantiate in an intramolecular case the attack of triplet nitroaromatic onto a C=O bond and, through the detailed investigation of the intermediates involved, offers mechanistic information about what seems to be a fairly general photochemical synthesis of phenazine *N*-oxides.[15]

Experimental

The amides **1a–c** were prepared by treatment of the corresponding amines with acetic anhydride–zinc chloride according to the literature procedures.[16,17]

Preparative Irradiation.—A solution of 2,4-dinitrodiphenylacetamide **1b** (376 mg, 1.25 mmol) in benzene (250 cm^3) in an immersion well apparatus was brought to boiling point and then cooled under an argon stream and irradiated for 35 min by means of a 125 W high pressure mercury arc through Pyrex. Evaporation of the solvent and chromatography of the residue on silica gel gave unchanged **1b** (19 mg, 5%) and 3-nitrophenazine 5-oxide **2b** (272 mg, 95%) (identical with an authentic sample).[18] The other reactions were carried out similarly, as detailed in Table 1.

2-*Triphenylphosphoranylidenamino*-4-*nitrodiphenylamine* **5**. Dark red crystals, m.p. 173–174 °C (EtOH) (Found: C, 76.6; H, 5.2; N, 8.6. Calc. for $C_{30}H_{24}N_3O_2P$: C, 76.61; H, 4.94; N, 8.58%); $\delta_H(CDCl_3)$ 7.0–8.0 (m, 23 H) and 8.25 (s, 1 H, exch.); *m/z* 489 (M^+); ν/cm^{-1} 1560, 1470 and 1300.

4-*Nitro*-2-*nitrosodiphenylamine* **6**. Orange–red crystals, m.p. 138–140 °C (toluene) (Found: C, 59.3; H, 3.7; N, 17.2. Calc. for $C_{12}H_9N_3O_3$: C, 59.26; H, 3.73; N, 17.28%); $\delta_H(CDCl_3)$ 7.15 (d, *J* 9.5, 6-H), 8.15 (dd, *J* 2.5, 9.5, 5-H), 9.8 (d, *J* 2.5, 3-H), 7.25 (m, 2 H), 7.35 (m, 1 H), 7.45 (m, 1 H) and 11.9 (s, 1 H, exch.); ν/cm^{-1}(KBr) 1610, 1590, 1580 and 1315.

Compound **6** (20 mg) was dissolved in 5% methanolic NaOH (3 cm^3) and treated with an excess of 35% hydrogen peroxide. After 3 h the solution was diluted with water and extracted with chloroform to give quantitatively 2,4-dinitrodiphenylamine.

Quantum Yield Measurements.—These were carried out on benzene solutions of the amide (1×10^{-4} mol dm^{-3}, ε_{366} 2.8×10^3) in spectrophotometric cuvettes (opt. path 1 cm) irradiated by means of a focussed 150 W super high pressure mercury arc through an interference filter (λ_{max} 366 nm) after degassing by five freeze–degas–thaw cycles. Chemical reaction was determined by HPLC. The incident flux was measured by ferrioxalate actinometry to be *ca.* 1×10^{-6} einstein min^{-1} cm^{-2}.

Flash Photolysis Experiments.—These were carried out by means of a commercial (Applied Photophysics) apparatus. A solution of the amide (2×10^{-5} mol dm^{-3}) in a 10 cm optical path cylindrical cuvette was used. The intensity of the discharge was *ca.* 200 J. In the experiments in Table 4 (10^{-4} mol dm^{-3} starting substrate concentration) seven such flashes were discharged on the cuvette (total time required, *ca.* 2 min) and the solution was treated as detailed in the Table and then analysed by HPLC. Substrate conversion was in every case *ca.* 50%.

Acknowledgements

Support of this work by MURST, Rome is gratefully acknowledged.

References

1 D. Döpp, *Top Curr. Chem.*, 1975, **55**, 49.
2 J. L. Charlton, C. C. Liao and P. de Mayo, *J. Am. Chem. Soc.*, 1971, **93**, 2463.
3 Y. Maki, M. Suzuki, T. Hosokami and T. Furuta, *J. Chem. Soc., Perkin Trans. 1*, 1974, 1354.
4 A. Albini and M. Alpegiani, *Chem. Rev.*, 1984, **84**, 43.
5 A. Albini, G. Bettinetti, E. Fasani and G. Minoli, *J. Chem. Soc., Perkin Trans. 1*, 1978, 299.
6 S. Pietra, G. Bettinetti, A. Albini, E. Fasani and G. Minoli, *J. Chem. Soc., Perkin Trans. 2*, 1978, 185.
7 A. Albini, G. Bettinetti and S. Pietra, *Tetrahedron Lett.*, 1972, 3657.
8 A. Albini, A. Barinotti, G. Bettinetti and S. Pietra, *J. Chem. Soc., Perkin Trans. 2*, 1977, 238.
9 Y. Gololobov, G. Zhmurova and L. F. Kasukhin, *Tetrahedron*, 1981, **37**, 437.
10 B. Cross, P. J. Williams and R. E. Woodall, *J. Chem. Soc. C*, 1971, 2085.
11 H. C. Waterman and D. L. Vivian, *J. Org. Chem.*, 1949, **14**, 289.
12 R. W. G. Preston, S. H. Tucker and J. M. L. Cameron, *J. Chem. Soc.*, 1942, 500.
13 R. A. Abramovitch and B. A. Davis, *J. Chem. Soc. C*, 1968, 119.
14 R. G. R. Bacon, S. D. Hamilton, *J. Chem. Soc., Perkin Trans. 1*, 1972, 2391.
15 E. Fasani, S. Pietra and A. Albini, *Heterocycles*, 1992, **33**, 573.
16 F. Kehrmann and E. Baumgartner, *Helv. Chim. Acta*, 1926, **9**, 675.
17 B. Menke, *Recl. Trav. Chim. Pays-Bas*, 1925, **44**, 141.
18 H. Otomasu, *Pharm. Bull.*, 1954, **2**, 667.

Paper 2/02664C
Received 21*st May* 1992
Accepted 23*rd June* 1992