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Photochromic spin traps. Part 3.[1,2] A new phosphorylated spiro[indoline-naphthoxazine] †

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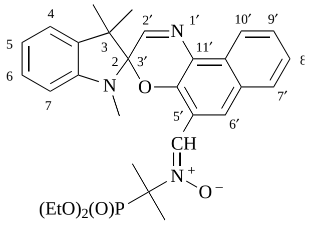
The synthesis and characterisation of a new phosphorylated nitrone belonging to the spiro[indoline-naphthoxazinic] family are described. The results of spin trapping experiments which indicate the ability of this photochromic nitrone to react with carbon-, oxygen- and sulfur-centred radicals are also reported.

Photochromic derivatives are exploited for many applications of relevant industrial impact,[3] and particular attention has been focused on those compounds belonging to the spiro[indoline-naphthoxazinic] family.[4] The photochromic activity of these compounds is the result of their ability to undergo a reversible opening of the oxazinic ring: in fact in solution these compounds exist in equilibrium between the nearly colourless form of the spiro structure and the deeply coloured open form, the merocyanine, ring opening being mainly induced by light and ring closure by temperature. Unfortunately these species may undergo irreversible degradation under repeated light–dark cycles, and indeed one major problem in their use is associated with their tendency to fatigue. It is thought that radical reactions may play an important role in these degradation processes,[5,6] and it is therefore important that new additives are devised, capable of halting them or slowing them down.

In order not to spoil the performance of the photochromic compounds, it is also important that the additives be as structurally similar as possible to the photochromes themselves. In this light we are presently investigating photochromic compounds capable of acting as spin traps, and the preparation and characterisation of some photochromic nitrones have already been described.[1,2] It has been recently reported that the insertion of a phosphoryl group into the molecule largely improves the properties of nitrones commonly used for spin trapping experiments, such as *N*-*tert*-butyl-α-phenylnitrone (PBN)‡ or 5,5-dimethyl-4,5-dihydro-3*H*-pyrrole *N*-oxide (DMPO),[7–10] the advantages being particularly evident in the trapping of oxygen-centred species such as the superoxide radical anion or the hydroperoxyl radical.

Because oxygen derived radicals appear to have serious relevance in the degradation of photochromic spiro[indoline-naphthoxazine] and its derivatives,[6] we have endeavoured to prepare some phosphoryl-substituted nitrones of this family, and we report here the synthesis, characterisation and spin trapping properties of 5′-{*N*-[2-(diethoxyphosphoryl)propan-2-yl]-*N*-oxidoazaniumylidenemethyl}-1,3,3-trimethylspiro-{indoline-2,3′-naphtho[2,1-*b*][1,4]oxazine}, **1**, the first member of this new class of compounds.



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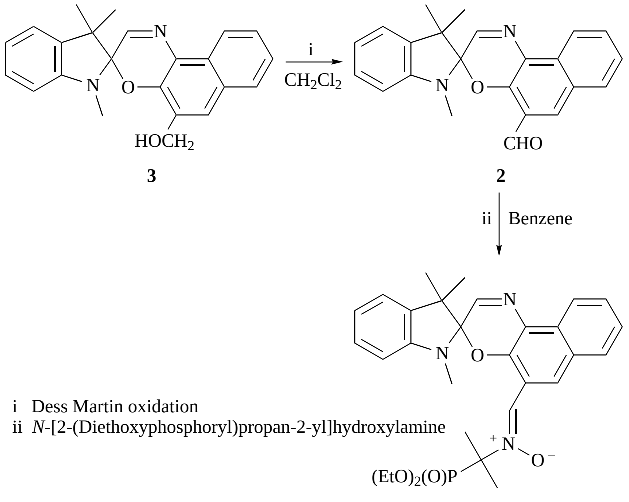
Results and discussion

Synthesis and characterisation

Nitrone **1** was prepared through the reaction sequence outlined in Scheme 1, the key step being the condensation of *N*-[2-(diethoxyphosphoryl)propan-2-yl]hydroxylamine[11] with the spiro[indoline-naphthoxazinic] aldehyde **2**,[2] obtained by oxidation of the hydroxymethyl compound **3** according to the Dess Martin procedure.[12]



i Dess Martin oxidation
ii *N*-[2-(Diethoxyphosphoryl)propan-2-yl]hydroxylamine

Scheme 1

Nitrone **1** was characterised by means of ^{1}H, ^{13}C and ^{31}P NMR. In particular, the proton decoupled ^{31}P spectrum consisted of a single line at δ 23.12 (measured with respect to 85%

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‡ IUPAC name: *N*-benzylidene-*tert*-butylamine *N*-oxide.

Table 1 Hyperfine spectral parameters for the radical adducts between X· radicals and nitrone **1**[a]

X	a_N	a_H(CH)	a_P	g	T/K
CH_3	13.89	3.44	47.68	2.0061_0	343
CH_2CH_3	13.88	3.58	43.93	2.0054_7	343
$CH(CH_3)_2$	13.44	3.87	40.93	2.0055_3	296
$C(CH_3)_3$	13.33	3.23	37.57	2.0056_0	296
C_6H_5[b]	13.72	3.55	40.35	2.0060_0	343
$OC(O)CH_3$	13.37	2.02	37.97	2.0061_8	343
OCH_2CH_3	14.02	1.86	38.34	2.0062_0	343
$OC(CH_3)_3$	13.60	1.58	37.08	2.0061_8	343
SCH_3	13.37	2.88	43.51	2.0065_6	292
$SCH(CH_3)_2$	13.53	3.83	40.61	2.0064_6	292
$SC(CH_3)_3$	14.10	4.00	33.81	2.0065_1	292

[a] Coupling constants in G = 10^{-4} T. [b] An additional doublet of 0.98 G is also observed.

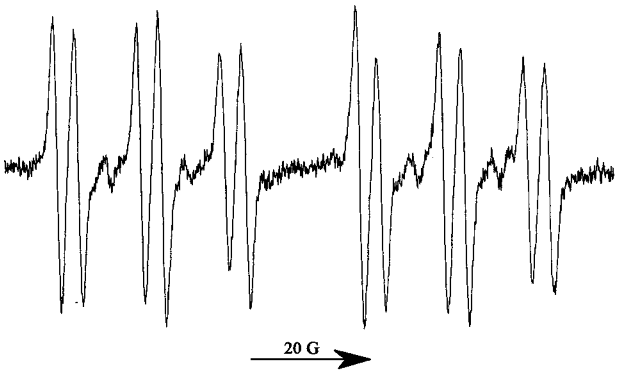

Fig. 1 EPR spectrum of the methyl adduct of nitrone **1** observed after UV irradiation of a benzene solution of **1** and IBDA (iodobenzene diacetate) at room temperature

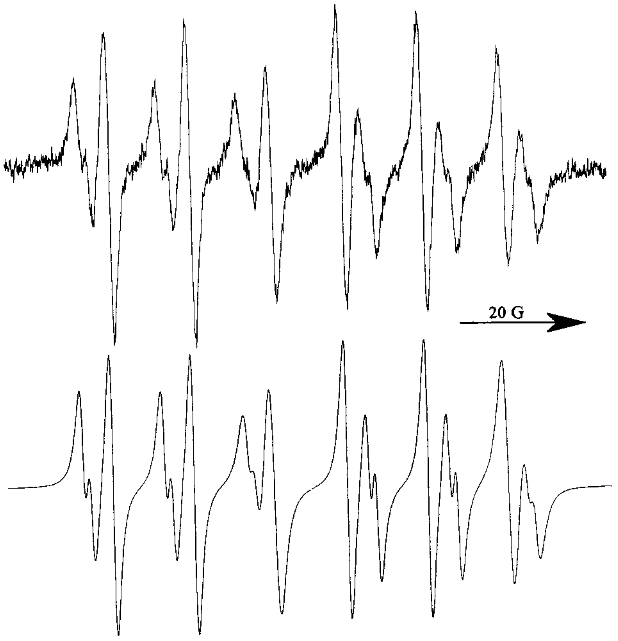

Fig. 2 Experimental (top) and computer simulated EPR spectra observed upon prolonged irradiation of a solution of isopropyl bromide, hexabutylditin and **1** in benzene at room temperature

H_3PO_4), typical of phosphorylated nitrones of similar structure. Being a photochromic compound, nitrone **1** in toluene solution exhibits two different absorption spectra depending on whether the sample is being illuminated or not while the spectra are recorded. Thus, under illumination the λ_{max} is 597 nm, a value typical of the merocyanine (open form), whereas under dark conditions the spectrum shows absorption at much lower wavelengths, with four peaks at 304, 335, 352 and 389 nm.

As is the case for other spiro[indoline-naphthoxazinic] compounds, the rate constant for light induced opening of **1** is very fast, but the actual value has not been determined; on the other hand, the rate constant for ring closure has been measured as $k_{clos} = 3.48\ 10^{-1}\ s^{-1}$, a value similar to that of the unsubstituted spiro[indoline-naphthoxazine].

Spin trapping

The ability of nitrone **1** to act as spin trapping agent was investigated by means of EPR spectroscopy. When argon-purged benzene solutions of **1** were photolysed or heated up to the solvent boiling point inside the cavity of the EPR spectrometer no signal could be observed. On the other hand, addition of substances amenable to produce free radicals either photolytically or thermally led to the observation of spectra that could be attributed to aminoxyls originating from addition of the *in situ* generated radicals to the –CH=N(O)– group of **1**. In Table 1 are collected the hyperfine spectral parameters measured for some representative adducts from carbon, oxygen and sulfur centred species.

From the data collected in Table 1 it emerges that in the adducts of carbon-centred radicals the phosphorus splitting decreases with the increasing size of the trapped species. It also appears that oxygen centred radicals are characterised by smaller β-hydrogen and phosphorus hyperfine coupling constants than exhibited by alkyl radical adducts, while thiyl radical adducts appear to be on the borderline between the two kinds of adducts. It should also be pointed out that the phosphorus splitting of all the adducts exhibits a negative temperature dependence. While in most cases just one radical adduct at a time was observed in the initial stage of the reaction, in some instances two or more adducts were simultaneously detected, owing to the fact that under the reaction conditions the initially formed radicals evolved to other radical species that could also be trapped. In particular, this was the case of the addition of *tert*-butoxyl radical to **1** which resulted in the overimposition of the spectra of the methyl and of the *tert*-butoxyl adducts. This implies that to some extent the attacking species undergoes cleavage to acetone and methyl radicals and, by extrapolation, that addition of rather large radicals to the phosphorylnitrone under examination may not be easy. This behaviour is similar to that observed in the addition of radicals to DMPO bearing a bulky substituent in position 2.[9]

On the other hand, in nearly all cases where the attacking radicals were generated through UV irradiation of the appropriate precursor(s), after prolonged photolysis an additional radical species could be observed (see Fig. 2). As that additional spectrum was the same independent of which radical was being generated, it was assigned to an adduct resulting from the trapping of a radical fragment formed in the photodegradation of compound **1** itself by another nitrone molecule. This adventitious species exhibits coupling of the unpaired electron with a hydrogen (a_H = 1.57 G), a nitrogen (a_N = 14.31 G) and a phosphorus nucleus (a_P = 38.34 G). The values of the β-hydrogen and phosphorus splittings suggest that the trapped species be identified as an oxygen-centred radical, an hypothesis in line with reports of the involvement of such radicals in the photodegradation of naphthoxazinic photochromes.[6]

In some instances, upon prolonging irradiation or heating, the reaction resulted in the detection of one more aminoxyl, which only exhibited coupling of the unpaired electron with the nitrogen (*ca.* 13.5 G) and one phosphorus atom (*ca.* 30 to 40 G). We identify these adducts as species resulting from double radical addition, although we cannot be certain about the nature of the attacking species. Indeed two molecules of the radical adduct might be envisaged to disproportionate to an hydroxylamine and a substituted nitrone, which by further radical addition would give a new adduct without any hydrogen atoms on the carbon adjacent to the aminoxyl function.

The additional doublet splitting observed in the spectrum of the phenyl adduct is rather disturbing. We tentatively assign it to one hydrogen of the aromatic ring which would be conformationally blocked due to extensive steric hindrance.

Experimental

J Values are given in Hz.

Synthetic procedure

Compounds **2** and **3** were prepared as already described.[2]

5′-{*N*-[2-(diethoxyphosphoryl)propan-2-yl]-*N*-oxidoazanium-ylidenemethyl}-1,3,3-trimethylspiro[indoline-2,3′-naphtho[2,1-*b*][1,4]oxazine] 1. A solution of **2** (0.09 g, 0.25 mmol) in benzene (10 ml) was added dropwise under argon to a refluxing solution of *N*-[2-(diethoxyphosphoryl)propan-2-yl]hydroxylamine (0.08 g, 0.38 mmol) in benzene (10 ml) and the resulting mixture was further refluxed for 1 h 10 min. After evaporating the solvent the residue was flash-chromatographed on silica (with a gradient from 0 to 60% Et_2O). Evaporation of the solvent left 0.13 g of pure **1** as a yellow powder (92%), mp 137 °C. δ_H(400 MHz, $CDCl_3$) 1.24 (6H, t, 2 × CH_3CH_2O), 1.34 (3H, s, CH_3 on C-3), 1.38 (3H, s, CH_3 on C-3), 1.61 (3H, d, CH_3 β to phosphorus, $J_{H\text{-}P}$ 4.1), 1.65 (3H, d, CH_3 β to phosphorus, $J_{H\text{-}P}$ 4.1), 2.68 (3H, s, N-CH_3), 4.08 (4H, m, 2 × CH_3CH_2OP), 6.54 (1H, d, H-7, $J_{7\text{-}6}$ 7.7), 6.87 (1H, dt, H-5, $J_{5\text{-}6}$ 7.6, $J_{5\text{-}4}$ 7.4, $J_{5\text{-}7}$ 0.8), 7.07 (1H, dd, H-4, $J_{4\text{-}5}$ 7.4, $J_{4\text{-}6}$ 0.8), 7.18 (1H, dt, H-6, $J_{6\text{-}7}$ 7.7, $J_{6\text{-}5}$ 7.6), 7.39 (1H, dt, H-8′, $J_{8'\text{-}9'}$ 8.2, $J_{8'\text{-}7'}$ 8.3), 7.58 (1H, dt, H-9′, $J_{9'\text{-}10'}$ 8.5, $J_{9'\text{-}8'}$ 8.2), 7.78 (1H, s, H-2′), 7.83 (1H, d, H-7′, $J_{7'\text{-}8'}$ 8.3), 7.93 (1H, d, H-6′, $J_{6'\text{-}P}$ 2.5), 8.48 (1H, d, H-10′, $J_{10'\text{-}9'}$ 8.5), 9.82 (1H, s, CH bound to C-5′); δ_C(100 MHz, $CDCl_3$) 16.60 (CH_3CH_2O, $J_{C\text{-}P}$ 5.5), 21.30 (CH_3 on C-3), 23.08 (CH_3 β to phosphorus), 23.11 (CH_3 β to phosphorus), 25.09 (CH_3 on C-3), 29.79 (CH_3 on nitrogen), 51.57 (C-3), 63.37 (d, CH_2OP, $J_{C\text{-}P}$ 6.8), 63.43 (d, CH_2OP, $J_{C\text{-}P}$ 6.8), 73.43 (d, C α to phosphorus, $J_{C\text{-}P}$ 153.1), 99.25 (C-2), 107.21 (C-7), 118.40 (C-5′), 120.09 (C-5), 121.32 (C-10′), 121.43 (C-4), 122.67 (C-11′), 124.89 (C-9′), 126.12 (d, C-6′, $J_{C\text{-}P}$ 5), 128.08 (C-6), 128.54 (C-8′), 128.90 (C-6′a), 129.66 (C-7′), 130.17 (CH on C-5′), 131.62 (C-10′a), 135.88 (C-4a), 141.25 (C-4′a), 147.29 (C-7a), 150.50 (C-2′).

Photodegradation experiments

UV–VIS spectra were recorded in toluene solution on a Beckman DU 7500 spectrometer. When necessary, the sample was irradiated with the light from a diaphragm-equipped 150 W Oriel high-pressure xenon lamp filtered with water to remove most of the infrared component. The polychromatic light intensity was determined by means of an Oriel quantum photoradiometer (sample concentration 10^{-4} M, $T = 25$ °C, flux = 220 W m^{-2}).

The bleaching rate constant was measured by means of the spectrometric apparatus DEGRAPHOT.[13]

Spin trapping experiments

EPR spectra were recorded on a Bruker ER200 D spectrometer equipped with a dedicated data system, a standard temperature controller, an NMR-gaussmeter for magnetic field calibration, and a frequency counter for the determination of *g*-factors that were corrected with respect to that of perylene radical cation in conc. sulfuric acid.

In a typical spin trapping experiment, the precursor(s) of the transient radicals was (were) added to a *ca.* 10^{-2} M solution of nitrone **1** in benzene or *tert*-butylbenzene, and the sample tube was irradiated with the unfiltered light from a 1 kW high pressure mercury lamp (Hanovia) focused onto the EPR cavity.

Alkyl radicals were obtained by photocleavage of the appropriate organomercury compound R_2Hg (methyl, ethyl, phenyl), by bromine abstraction from the alkyl bromide by *in situ* generated tributylstannyl radicals (isopropyl, *tert*-butyl), or by Norrish 1 photocleavage of the ketene $R_2C{=}O$ (*tert*-butyl and *tert*-butylcarbonyl). Alkoxyl radicals were obtained by photo- or thermal-decomposition of ethyl nitrite (ethoxyl) or *tert*-butyl hyponitrite (*tert*-butoxyl). Alkylthiyl radicals were obtained by photodecomposition of dimethyl and di-*tert*-butyl disulfide. All the radical precursors were commercially available, with the exception of *tert*-butyl hyponitrite that was prepared as already described.[14]

Acknowledgements

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