## A Probe for Homolytic Reactions in Solution. Part IV.<sup>1</sup> The Succinimidyl Radical

By G. R. Chalfont and M. J. Perkins,\* Department of Chemistry, King's College, London W.C.2 A. Horsfield, Varian Associates, Ltd., Walton-on-Thames, Surrey

The nitroso-scavenging technique has been used to seek evidence for the formation of succinimidyl and phthalimidyl radicals. During this work nitroxides have been detected which are attributable to the formation of a secondary diamagnetic scavenger, N-t-butyl methylene nitrone. This nitrone has been independently synthesised and shown to be a useful radical scavenger, and has been employed to investigate reactions of several precursors for succinimidyl or phthalimidyl radicals. It is argued that in the photoinduced decomposition of t-butyl succinimide percarboxylate in toluene succinimide is formed by hydrogen abstraction from toluene by succinimidyl radicals.

In an attempt to employ the radical-scavenging technique<sup>1</sup> to reactions which are less clearly understood, we examined the succinimidyl radical (S·).<sup>2</sup> The literature contains several studies of allylic bromination by N-bromosuccinimide, all of which support the Goldfinger mechanism in which hydrogen abstraction is by a bromine atom and not S.<sup>3</sup> Much of the evidence, while compelling, is somewhat circumstantial. The arguments are largely based on competition experiments in which the reactivity pattern exhibited by N-bromosuccinimide closely parallels that shown by molecular bromine. Further, one of the few non-circumstantial arguments, that the N-H bond of succinimide is too weak for S. to be a candidate for the hydrogen-abstracting species,<sup>3b</sup> can be discounted. One estimate now suggests that the strength of this bond may be as high as 100 kcal. mole<sup>-1</sup>.<sup>2</sup>

Hedaya <sup>2</sup> and Koenig <sup>4,5</sup> and their co-workers have investigated alternative precursors which might unambiguously generate S, but these investigations proved inconclusive. Indeed, Hedaya *et al.*, while acknowledging that certain addition <sup>6</sup> and rearrangement <sup>7</sup> reactions appear to be best rationalised by invoking succinimidyl radicals, nonetheless open their paper with the statement that 'Succinimidyl radical has not been unequivocally characterised.'

With this background of uncertainty, we studied reactions of N-bromosuccinimide and of t-butyl succinimideperoxycarboxylate in the hope of securing additional evidence for the existence of succinimidyl radicals, and possibly also of establishing whether these radicals can abstract allylic or benzylic hydrogen atoms.

In a brief examination of the mechanism of homolytic phenylation by nitrosoacetanilide, we have demonstrated that phenylacetamido-radicals will add to C-nitroso-compounds<sup>8</sup> [reaction (1)]. In analogy with

<sup>3</sup> (a) F. L. J. Sixma and R. H. Riem, Proc. k. Ned. Akad. Wetenschap, 1958, B, **61**, 183; B. P. McGrath and J. M. Tedder, Proc. Chem. Soc., 1961, 80; G. A. Russell and K. M. Desmond, J. Amer. Chem. Soc., 1963, **85**, 3139; R. E. Pearson and J. E. Martin, *ibid.*, p. 3142; (b) C. Walling, A. L. Rieger, and D. D. Tanner, *ibid.*, p. 3129.

<sup>4</sup> T. Koenig and W. Brewer, J. Amer. Chem. Soc., 1964, 86, 2728.

this we examined the reaction of N-bromosuccinimide with 2-methyl-2-nitrosopropane in deoxygenated benzene. An e.s.r. spectrum showing nine lines of equal

$$Ph\dot{N}COMe + RN=O \longrightarrow \begin{vmatrix} R-N-O \cdot \\ | \\ Ph-N-COMe \end{vmatrix}$$
(1)

intensity (triplet of triplets with  $a_N = 15.9$  and 1.75 G) was observed when the reaction mixture was exposed to visible light. This spectrum is consistent with the nitroxide structure (I), generated as shown in reactions (2)—(4). [The values of  $a_N$  are very similar to those found<sup>8</sup> in the spectrum of MeCO·N(Ph)·N(Bu<sup>t</sup>)O·. The only plausible alternative structure for the radical responsible for this spectrum appears to be Bu<sup>t</sup>N(NO)O<sup>•</sup>, but a similar spectrum could not be observed during the reaction which occurs between Bu<sup>t</sup>N=O and NO. We have found no clear evidence for radicals derived from nitric oxide in our scavenging experiments with nitrosocompounds.] A similar spectrum was obtained with N-bromophthalimide in place of N-bromosuccinimide.

$$Bu^{t}N=O \longrightarrow Bu^{t} + NO$$
 (2)

$$Bu^{t} + NBS \longrightarrow Bu^{t}Br + S^{t}$$
(3)

$$S + Bu^{t}N=O \longrightarrow S-N-O$$
 (4)

$$NBS = N$$
-Bromosuccinimide.

Although we had successfully scavenged phenylacetamido-radicals with nitrosobenzene, we could not obtain any reproducible spectra from nitrosobenzene and N-bromosuccinimide, a negative result also noted by Forrester.<sup>9</sup> On the other hand, Lagercrantz and Forshult have very recently reported an independent study of the N-bromosuccinimide reaction, using nitrosobutane as a scavenger, in which they, too, observed the nine-line spectrum attributed to radical (I).<sup>10</sup> They

<sup>5</sup> T. Koenig and L. Lam, J. Org. Chem., 1969, **34**, 956. <sup>6</sup> L. H. Zalkow and C. D. Kennedy, J. Org. Chem., 1964, **29**,

<sup>6</sup> L. H. Zalkow and C. D. Kennedy, J. Org. Chem., 1964, 29, 1290.

3150. <sup>8</sup> G. R. Chalfont and M. J. Perkins, J. Amer. Chem. Soc., 1967, 89, 3054.

<sup>9</sup> A. R. Forrester, Chem. and Ind., 1968, 1483.

<sup>10</sup> C. Lagercrantz and S. Forschult, Acta Chem. Scand., 1969, 23, 708.

<sup>&</sup>lt;sup>1</sup> Part III, preceding paper.

<sup>&</sup>lt;sup>2</sup> E. Hedaya, R. L. Hinman, V. Schomaker, S. Theodoropulos, and L. M. Kyle, J. Amer. Chem. Soc., 1967, **89**, 4875. This reference contains a summary of the succinimidyl problem, and an MO description of this radical.

<sup>&</sup>lt;sup>7</sup> P. D. Bartlett and J. C. Martin, *J. Amer. Chem. Soc.*, 1957, 79, 2533; H. W. Johnson and D. E. Bublitz, *ibid.*, 1958, **80**, 3150.

extended their investigations by conducting the reaction in the presence of certain olefinic solvents, whereupon nitroxides which incorporated solvent-derived radicals were detected. However, it was emphasised that these observations did not help to identify the hydrogenabstracting species involved.

Our efforts to extend this research followed a different approach. An attempt was made to scavenge succinimidyl radicals from the thermal and/or photochemical decomposition of t-butyl succinimideperoxycarboxylate (II).<sup>2,5</sup> (Kinetic studies <sup>2,5</sup> have shown that no more than 10% of the thermal decomposition involves a homolytic mechanism.) Although no immediately useful information was obtained from the photochemical reaction with 2-methyl-2-nitrosopropane as scavenger, the thermal reaction with the same scavenger (chlorobenzene, 110°) gave a mixture of nitroxides, one of which was identified as t-butyl methyl nitroxide.<sup>1</sup> However, when this reaction mixture was cooled a different radical was the predominant paramagnetic species present, and the spectrum of this is shown in the Figure. This exhibits coupling to two nitrogen nuclei and to two equivalent protons ( $a_{\rm N} = 14.6$  and 1.4;  $a_{\rm H} = 11.2$  G). From these observations it seemed possible that the new radical was formed in a secondary reaction. Structure (V) suggested itself. Structure (V) could have arisen as in the annexed Scheme: nitroxides have been isolated from radical additions to nitrones,<sup>11</sup> and, since the present work was carried out, the general utility of nitrones as diamagnetic scavengers has been discussed.<sup>12,13</sup> The postulated intermediate (IV), with a terminal methylene group, might be particularly reactive in this respect. As a test for structure (V), succinimidylmethyl radicals



were generated in the presence of 2-methyl-2-nitrosopropane<sup>1</sup> and a 27-line spectrum was obtained identical with that shown as the Figure.

A Referee has questioned the interpretation of the 27-line spectrum, pointing out that the magnitude of the  $\alpha$ -nitrogen splitting is comparable with that in nitroxides having a nitrogen atom attached directly to the nitroxide function [e.g., (I)]. This does not seem too surprising, as the same situation is found for hydrogen, and probably results from the operation of different coupling mechanisms between the nucleus and the unpaired electron in the two situations. Two examples of  $\alpha$ -nitrogen splittings in the e.s.r. spectra of the radical anions of aliphatic nitro-compounds have recently been found. These were 0.96 and 2.21 G.<sup>14</sup>

Methylene nitrones are available in quantitative yield from the reaction between diazomethane and tertiary nitrosoalkanes.<sup>15</sup> The key nitrone (IV) <sup>16</sup> was obtained as a colourless oil by use of this reaction. It has now been investigated as an alternative nitroxide-producing radical scavenger, particularly in the context of succinimidyl radical chemistry. As a typical example,



E.s.r. spectrum of the radical C4H4O2N·CH2N(But)O·

when the nitrone (IV) was warmed with a solution of lauryl peroxide in benzene, a nitroxide was produced whose spectrum was indistinguishable from that obtained from lauryl peroxide and 2-methyl-2-nitrosopropane. In fact the nitroxides should differ by one methylene unit in the n-alkyl chain.

In a second example, the nitrone was employed to scavenge (5) phenyl radicals from the thermal or photochemical decomposition of benzoyl peroxide. The principal nitroxide obtained was indistinguishable from that formed when nitrosobutane is employed to scavenge benzyl radicals.<sup>1</sup> A second nitroxide, formed under the photochemical conditions, was attributed to the scavenging of benzoyloxy-radicals and had  $a_{\rm H} = 4.1$  and  $a_{\rm N} =$ 12.9 G. A nitroxide with the same splitting constants was obtained by hydrogen abstraction from methyl benzoate in the presence of nitrosobutane (cf. ref. 12).

$$(IV) \xrightarrow{Ph} PhCH_2 \xrightarrow{N} O \xrightarrow{PhCH_1} Bu^t NO$$
(5)  
Bu<sup>t</sup>

It was concluded that a valuable new scavenger was to hand, and thus equipped we returned to the succinimidyl

14 H. Zeldes and R. Livingston, J. Amer. Chem. Soc., 1968, 90,

4540. <sup>15</sup> J. E. Baldwin, A. K. Qureshi, and B. Sklarz, J. Chem. Soc. (C), 1969, 1073.
<sup>16</sup> J. E. Baldwin, R. G. Pudussery, A. K. Qureshi, and B.

<sup>&</sup>lt;sup>11</sup> M. Iwamura and N. Inamoto, Bull. Chem. Soc. Japan, 1967,

<sup>40, 702.</sup> <sup>12</sup> E. G. Janzen and B. J. Blackburn, J. Amer. Chem. Soc., 1968, **90**, 5909.

<sup>&</sup>lt;sup>13</sup> E. G. Janzen and J. L. Gerlock, J. Amer. Chem. Soc., 1969, **91**, 3108.

Sklarz, J. Amer. Chem. Soc., 1968, 90, 5325.

problem. Under conditions either of thermal or photochemical ( $\lambda > 300$  nm.) decomposition in the presence of (IV), the perester (II) was found to generate the now familiar nitroxide (V). [The nitrone PhCH=N(Bu<sup>t</sup>) $\rightarrow$ O (VI) (refs. 11–13) seems appreciably less reactive than (IV), and no useful information could be obtained with it and the succinimidyl precursors.] In the photochemical reaction the spectrum of (V) was superimposed on a nine-line spectrum attributable to Bu<sup>t</sup>OCH<sub>2</sub>-(Bu<sup>t</sup>)NO• ( $\alpha_N = 13.7$ ;  $\alpha_H = 4.4$  G). Evidence for the structure of this second nitroxide was obtained when an identical nine-line spectrum was found by thermolysis of t-butyl peroxyoxalate or photolysis of di-t-butyl peroxide in benzene solutions of (IV). Ultraviolet irradiation of solutions of the nitrone (IV) alone, with unfiltered light, also produced a nitroxide whose spectrum showed the characteristic couplings to nitrogen and two  $\alpha$ -protons ( $\alpha_N = 13.1$ ;  $\alpha_H = 7.0$  G). This is readily distinguishable from spectra observed during the irradiation of the perester. The radical responsible remains unidentified.

The thermal decomposition of perester (II) in the presence of synthetic nitrone (IV) was effected in chlorobenzene. The photochemical reaction was carried out in benzene, and there was a rapid build-up of the two nitroxide spectra as irradiation progressed. The latter result could be reproduced in toluene. Now in the published work on photolysis of perester (II) in toluene it was found that almost quantitative yields of succinimide could be isolated. However it was suggested that the photolysis would first produce the carboxylate radical (III), and that this might react by hydrogen abstraction from solvent before a non-radical decarboxylation. If a carboxylate radical of sufficient longevity to abstract hydrogen from toluene before decarboxylation were involved, it might reasonably be expected to be trapped as is the butoxyl radical. As noted above, photolysis of benzoyl peroxide in toluene in the presence of comparable concentrations of nitrone gives spectra attributable to scavenging of both phenyl and benzoyloxy-radicals. The fact that in the photoreaction of the succinimidyl perester in toluene succinimidyl radicals, but apparently not carboxylate radicals, are scavenged, strongly suggests that the succinimidyl radical rather than the hypothetical carboxylic acid, S·CO<sub>2</sub>H, is the immediate precursor of succinimide formed in the preparative reactions. We therefore conclude that in these preparative experiments succinimide is largely formed as a result of hydrogen abstraction from toluene by succinimidyl radicals.

Attention was again turned to N-bromosuccinimide, and it was found that when it was mixed with a benzene solution of the methylene nitrone (IV) in the dark, a nitroxide was produced which again exhibited the characteristic 27-line spectrum of the Figure.

Our principal achievement is the preliminary evaluation of t-butyl methylene nitrone as a diamagnetic scavenger. The nitrone appears to be much more reactive towards oxygen- and nitrogen-centred radicals than are the nitroso-compounds discussed previously. It is transparent to light of wavelengths greater than 300 nm. and can therefore be used to monitor photochemical reactions which employ such light. It is, however, destroyed (with formation of an unidentified nitroxide) by light of shorter wavelengths. The possibility that the nitrone can accept triplet energy, or otherwise react with photoexcited molecules is under active investigation. The nitrone is appreciably soluble in water and therefore lends itself to scavenging studies in aqueous systems.<sup>17</sup> The  $\alpha$ -proton splittings in the nitroxides derived from (IV) are generally larger and show a much wider spread of values than those observed when the benzylidene nitrone (VI)<sup>11-13</sup> is employed as a diamagnetic

scavenger. This is clearly an advantage in the interpretation of spectra though, as with (VI), there are seldom any resolved splittings due to magnetic nuclei in the scavenged radical. (The succinimidyl radical is an obvious exception.) The relative merits of the different nitrones and nitroso-compounds discussed in this and the accompanying paper are being further assessed.

A second significant outcome is the new evidence for the succinimidyl radical, and for the participation of this radical in hydrogen abstractions, even though the results do not allow further comment on the mechanism of allylic bromination with N-bromosuccinimide. Further information may not be forthcoming until an unambiguous means of generating succinimidyl radicals in the absence of other initiator radicals is discovered. As a step towards this, we have examined photolysis of



the tetrazene (VII), which, in the presence of methylene nitrone (IV), gives a 27-line spectrum analogous to that in the Figure. The results of preparative photolyses of this tetrazene will be described later. Our attempts to synthesise it by the oxidation of N-aminophthalimide were unsuccessful. We learnt, however, of its isolation as a by-product from some oxidations of the same compound in Professor Rees's laboratory, and we thank him for a sample.

In the preceding paper,<sup>1</sup> some difficulties and uncertainties in the use of diamagnetic scavengers were discussed. One of these is the possibility that some of the observed nitroxides might arise by routes other than radical scavenging. A case is the observation of nitroxide (V) from the *dark* reaction between N-bromosuccinimide and methylene nitrone. The nature of this

<sup>&</sup>lt;sup>17</sup> M. J. Perkins, unpublished observations.

reaction is obscure. It is difficult to concede any immediate analogy between it and the dark nitroxideproducing reaction between the benzylidene nitrone (VI) and various aromatic amines noted by Janzen and Gerlock.<sup>13</sup> In that case it seems plausible that electron transfer from amino-compound to nitrone might initiate a radical sequence. We do not consider that similar uncertainty exists in the photochemical decompositions of perester (II). In these reactions nitroxide concentration built up only whilst the sample was exposed to u.v. light.

## EXPERIMENTAL

The general experimental procedure has been indicated.<sup>1</sup> Thermal and photochemical decomposition of peroxides was effected by heating or irradiating samples in the cavity of the spectrometer.

t-Butyl succinimideperoxycarboxylate was obtained as described by Hedya *et al.*,<sup>2</sup> except that, in our hands, isolation of the product was greatly facilitated by use of methanol in place of pentane. t-Butyl methylene nitrone was obtained by the general procedure outlined by Baldwin *et al.*<sup>15</sup> After removal of excess of diazomethane and solvent, the nitrone was dissolved in a little carbon tetrachloride, and portions of the resulting solution (*ca.* 10%) were then added in the nitrone scavenging experiments. Benzylidene t-butyl nitrone was prepared by condensation of t-butylhydroxylamine and benzaldehyde. Other materials were obtained as described.<sup>1</sup>

The reaction between N-bromosuccinimide and methylene nitrone was carried out as follows. A portion of nitrone solution was diluted with an excess of benzene, and the resulting solution degassed in a quartz tube. It was then frozen in liquid air, and solid N-bromosuccinimide was added The tube was then placed in the darkened cavity of the spectrometer, and allowed to warm to room temperature. As the benzene melted, and the N-bromosuccinimide settled through the solution a strong 27-line signal rapidly developed (Figure).

We thank Varian Associates Ltd for a Summer Visitorship (to M. J. P.) and the S.R.C. for a Studentship (to G. R. C.).

[9/1340 Received, August 6th, 1969]