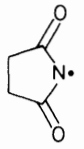
Cyclisation of ω-(Isocyanatocarbonyl)alkyl Radicals: Acyclic Precursors of Imidyl Radicals

Parveen Kaushal and Brian P. Roberts *
Christopher Ingold Laboratories, University College London, 20 Gordon Street, London WC1H 0AJ

Imidyl radicals, generated by photolysis of, or halogen-atom abstraction from, *N*-halogenoimides, are efficiently trapped by $Bu^t_2C{=}CH_2$ to give relatively persistent adducts which have been studied by e.s.r. spectroscopy. Bromine-atom abstraction from $BrCH_2CH_2C(O)NCO$ (**2**) yields $H_2\dot{C}CH_2C(O)NCO$ (**1**) which undergoes rapid 1,5-*endo* cyclisation to give the succinimidyl radical. This cyclisation has been investigated using e.s.r. spectroscopy in conjunction with spin-trapping by $Bu^t_2C{=}CH_2$ and $Bu^tN{=}O$. The rate coefficient for cyclisation of (**1**) has been estimated to be 3.7×10^6 s^{-1} at 328 K in cyclohexane from analysis of the products from the radical-chain reaction between (**2**) and triethylgermane. E.s.r. and product-analysis studies show that $H_2\dot{C}CMe_2C(O)NCO$ (**14**) cyclises, more rapidly than (**1**), to give the 2,2-dimethylsuccinimidyl radical which subsequently undergoes ring opening to yield $Me_2\dot{C}CH_2C(O)NCO$ (**15**). The overall rearrangement of (**14**) to (**15**) represents a 1,2-shift of the –C(O)NCO group *via* an intermediate imidyl radical. The glutarimidyl radical is formed by 1,6-*endo* cyclisation of $H_2\dot{C}CH_2CH_2C(O)NCO$. It is proposed that the rapid cyclisation of ω-isocyanatoalkyl radicals provides strong evidence that the unpaired electron occupies a σ-orbital in the product imidyl radicals.

The reactions of imidyl radicals and the nature of their electronic configurations are subjects of continuing interest to both experimentalists and theoreticians. The succinimidyl radical (S•) has been at the centre of many controversies over

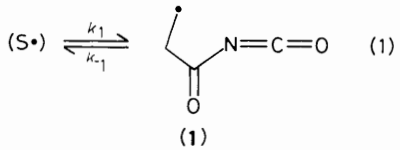


(S•)

the 45 years since it was first proposed[1] as an intermediate in allylic bromination by *N*-bromosuccinimide (NBS) in CCl_4 under reflux. Halogenation under these (Ziegler[2]) conditions was later shown[3] to follow a radical-chain mechanism involving hydrogen-atom abstraction by a bromine atom rather than by (S•), but subsequently a number of genuine bimolecular reactions of the succinimidyl radical were identified.[4–7]

It is now firmly established that (S•) and related imidyl radicals can act as chain carriers in hydrocarbon halogenation by *N*-halogenoimides, provided that steps are taken to suppress competing halogen-atom chains.[8] However, the electronic state of (S•) which participates in these reactions is still uncertain and disagreement remains as to whether an excited state of the imidyl radical is involved in thermal reactions of *N*-halogenosuccinimides and of other *N*-halogenoimides.[9–12] Certainly, mechanistic studies in this area are fraught with severe experimental difficulties which can readily lead to erroneous conclusions being drawn.

Over thirty years ago, it was proposed[13,14] that the rearrangement of NBS to 3-bromopropanoyl isocyanate involves thermally induced ring opening of (S•) to form the 2-(isocyanatocarbonyl)ethyl radical (**1**) as the key step [equation (1)]. Skell and co-workers[15] have proposed that this ring opening is also readily reversible, with $k_1 \approx k_{-1} \approx 2 \times 10^7$ s^{-1} at around room temperature, although kinetic data obtained by Walling *et al.*[16] require that $k_1 \leqslant 2 \times 10^4$ s^{-1} under similar



(1)

conditions. While our own work was in progress, a further report from Skell's group appeared which gave a revised value for k_{-1} of *ca.* 5×10^8 s^{-1} at 288 K and cast doubt on the validity of their earlier conclusion that k_1 and k_{-1} are approximately equal.[17]

Whilst no e.s.r. spectrum of (S•) (or indeed of any imidyl radical) in solution has ever been detected, one assigned to this radical trapped in a rigid matrix has been interpreted in terms of an electronic ground state ($S^{\bullet}_{\pi}$) in which the SOMO is antisymmetric with respect to reflection in the plane containing the heavy atoms and in which the unpaired electron is centred mainly on nitrogen.[18] This conclusion receives support from high-level *ab initio* MO calculations which predict ($S^{\bullet}_{\pi}$) to be the ground state, although this is separated from the excited state ($S^{\bullet}_{\sigma}$) by only 21.5 kJ mol^{-1}.[19]† However, it has been pointed out[21,22] that the ring-opening process shown in equation (1) is stereoelectronically allowed only from ($S^{\bullet}_{\sigma}$) and it follows that cyclisation of (**1**) should lead to this electronic state. Dewar and Olivella[22] have calculated that the ring opening of ($S^{\bullet}_{\sigma}$) to give (**1**) is exothermic by 30 kJ mol^{-1} and have estimated k_1 to be *ca.* 2.4×10^4 s^{-1} at 298 K, close to the maximum value proposed by Walling *et al.*,[16] although on the basis of these calculations endothermic cyclisation of (**1**) to give ($S^{\bullet}_{\sigma}$) would be very slow under normal conditions. Symmetry-forbidden ring opening of ($S^{\bullet}_{\pi}$) was predicted to be extremely slow at ambient temperature[22] and it has even been suggested[10] that, whilst the

† Other recent theoretical work,[20] while agreeing that ($S^{\bullet}_{\pi}$) is the ground state, predicts the first excited state to be a σ-radical, less stable by 49.0 kJ mol^{-1}, in which the unpaired electron is centred mainly on the oxygen atoms ($^2B_2$ in C_{2v}). The $^2A_1$ state ($S^{\bullet}_{\sigma}$) was predicted to be less stable than ($S^{\bullet}_{\pi}$) by 66.9 kJ mol^{-1}.

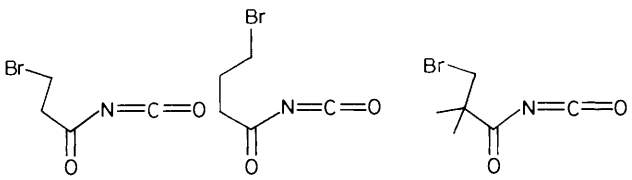
Table 1. E.s.r. parameters for the adducts $Bu^t_2\dot{C}CH_2Im$ (**10**) in [$^2H_9$]acetonitrile.

		Hyperfine splittings/G[a]		
(Im•)	T/K	$a(2H_\beta)$	$a(^{14}N_\beta)$	$a(18H_\gamma)$
Succinimidyl	305	13.65	6.88	0.38
	259	13.56	6.95	0.38
2,2-Dimethylsuccinimidyl	290	13.50	6.88	0.38
	248	13.48	7.00	0.38
Glutarimidyl	332	15.38	5.25	0.34
	244	15.31	5.50	0.33
3,3-Dimethylglutarimidyl	324	15.00	5.40	0.33
	244	14.90	5.64	0.33
Phthalimidyl	330	13.63	7.28	0.38
	270	13.50	7.36	0.37

[a] All *g*-factors are 2.0025.

electronic ground state is indeed ($S^\bullet_\pi$), the reported chemistry of (S•) may be that of ($S^\bullet_\sigma$). Of course, the calculations refer to isolated molecules in the gas phase and medium effects could be critically important since imidyl radicals are undoubtedly very polar species.

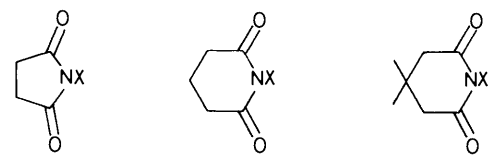
Whilst we were reluctant to venture into this mechanistic minefield a second[4] time, we nevertheless felt it important to investigate the formation of imidyl radicals by cyclisation of ω-(isocyanatocarbonyl)alkyl radicals such as (**1**) thus avoiding some of the complications associated with the use of *N*-halogenoimides. Indeed, before this work no direct evidence for the cyclisation of (**1**) existed because (S•) had never been generated from acyclic reagents. Thus, we set out to use a combination of e.s.r. spectroscopic techniques and product analysis to study the cyclisation of ω-(isocyanatocarbonyl)alkyl radicals derived by bromine-atom abstraction from the ω-bromoalkanoyl isocyanates (**2**)–(**4**). Part of this research has been reported in a preliminary communication.[23]



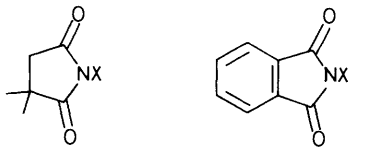
(**2**) (**3**) (**4**)

Results and Discussion

Authentic sources of imidyl radicals were derived from the *N*-halogenoimides (**5**–**9**; X = Cl or Br), which were prepared from the corresponding imides by reaction with Bu^{t}OCl in methanol or with bromine in aqueous sodium hydrogencarbonate.



(**5**) (**6**) (**7**)



(**8**) (**9**)

Johnson and Bublitz[13] prepared 3-bromopropanoyl isocyanate (**2**) by treatment of 3-bromopropanoyl bromide with silver cyanate in the absence of solvent [equation (2)]. However,

$$BrCH_2CH_2C(O)Br + AgNCO \longrightarrow BrCH_2CH_2C(O)NCO + AgBr \quad (2)$$

this reaction is heterogeneous and the treatment had to be repeated four times to achieve complete conversion of the acid bromide; we prepared compound (**2**) in a single step using the same reagents by ultrasonication of the reaction mixture. 4-Bromobutanoyl isocyanate (**3**) was prepared in low yield by a similar procedure starting from 4-bromobutanoyl chloride. Acyl isocyanates which do not have hydrogen attached at C-2 can be readily prepared from the corresponding amide and oxalyl dichloride[24] [equation (3)] and this method worked well

$$RC(O)NH_2 + ClC(O)C(O)Cl \longrightarrow RC(O)NCO + CO + 2HCl \quad (3)$$

for synthesis of (**4**). All acyl isocyanates were colourless liquids which were very sensitive to water and, especially in the case of (**2**), light sensitive and subject to polymerisation during storage. In common with unsubstituted acyl isocyanates, they react smoothly with methanol in diethyl ether to give crystalline *N*-acylurethanes [equation (4)], which were used for characterisation and quantitative determination of these reactive compounds.

$$RC(O)NCO + MeOH \longrightarrow RC(O)NHCO_2Me \quad (4)$$

E.S.R. Experiments.—Our initial approach was to use the technique of spin-trapping[25] to intercept imidyl radicals and convert them into relatively persistent adducts which would be readily detectable by e.s.r. spectroscopy. We reasoned[23] that 1,1-di-t-butylethylene[26] (DTBE) would function as a selective trap for imidyl radicals (Im•) [equation (5)] and that uncyclised ω-(isocyanotocarbonyl)alkyl radicals would not undergo addition at a detectable rate.

$$(Im^\bullet) + Bu^t_2C{=}CH_2 \longrightarrow \underset{\textbf{(10)}}{Bu^t_2\dot{C}{-}CH_2Im} \quad (5)$$

Authentic imidyl adducts (**10**) were generated directly in the microwave cavity of an e.s.r. spectrometer[27] by u.v. photolysis of the *N*-chloroimide (*ca.* 0.2 mol dm^{-3}) [equation (6)] in the

$$ImCl \xrightarrow{h\nu} (Im^\bullet) + Cl^\bullet \quad (6)$$

presence of DTBE (*ca.* 0.5 mol dm^{-3}). The solvent was usually CD_3CN, which gave rather better quality spectra than CH_3CN, although other solvents such as EtCN, PrCN, and CH_2Cl_2 were also satisfactory. Under these conditions, the adduct[26] formed between the chlorine atom to DTBE was not readily detected. Strong spectra of the adducts (**10**) were observed for all the *N*-chloroimides (**5**–**9**; X = Cl) (see Figure 1 and the spectrum reproduced in ref. 23) in the temperature range 230–300 K; the spectroscopic parameters are collected in Table 1. All these spectra exhibited temperature-dependent line broadening attributable to out-of-phase modulation of the splittings from instantaneously non-equivalent β-protons. Thus, the lines corresponding to $M_I(2H_\beta) = 0$ broadened selectively as the temperature was lowered. These lineshape effects were particularly pronounced for (**10**) derived from glutarimidyl or 3,3-dimethylglutarimidyl radicals and for the adduct derived from (**7**; X = Cl) at *ca.* 235 K, the central multiplet of the β-proton triplet was broadened almost beyond the limit of detection [see Figure 1(*a*)]. Hindered rotation about the N–C_β

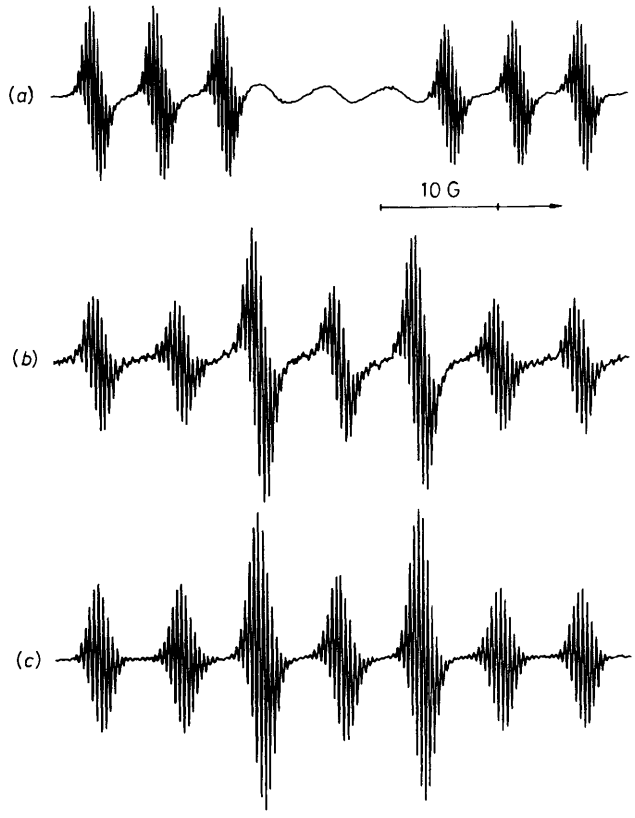
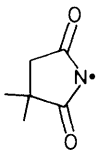
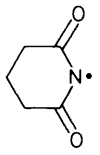


Figure 1. E.s.r. spectra of radicals (**10**) formed by addition of imidyl radicals to $Bu^t_2C{=}CH_2$ in CD_3CN. (*a*) (Im$^\bullet$) from photolysis of (**7**; X = Cl) at 245 K. (*b*) (Im$^\bullet$) from photolysis of (**8**; X = Cl) at 293 K. (*c*) (Im$^\bullet$) produced during thermolysis of TBHN in the presence of (**4**) and $Bu_3P{\rightarrow}BH_3$ at 294 K; the spectrum is essentially indistinguishable from that shown in (*b*).

bond is the probable cause of these lineshape effects[23] and the non-equivalence of the β-protons could be especially marked when the non-planar glutarimidyl moiety is present. Attempts to observe spectra of (**10**) in the slow-exchange region by working in CH_2Cl_2 at low temperatures were unsuccessful.

Ring opening of the 2,2-dimethylsuccinimidyl radical (DMS$^\bullet$) to give a tertiary alkyl radical would be expected to be more favourable thermodynamically and more rapid than ring opening of (S$^\bullet$). Despite this, u.v. photolysis of (**8**; X = Cl) in the presence of DTBE afforded very strong e.s.r. spectra of the (admittedly quite persistent) adduct (**10**; Im = DMS).


(DMS•)


(G•)

There have been suggestions that photochemical generation of imidyl radicals from *N*-halogenoimides can give rise to excited species different from those generated in thermal reactions.[12] Imidyl adducts of the type (**10**) were also detected by e.s.r. spectroscopy when dibutanoyl peroxide (*ca.* 0.2 mol dm^{-3}) was decomposed thermally (320–340 K) in the presence of an *N*-chloroimide (*ca.* 0.2 mol dm^{-3}) and DTBE (*ca.* 0.5 mol dm^{-3}) in ethano- or butano-nitrile solvent [equations (7) and (8)]. Once

$$PrC(O)OOC(O)Pr \xrightarrow{heat} 2\ Pr^\bullet + 2\ CO_2 \quad (7)$$

$$Pr^\bullet + ImCl \longrightarrow (Im^\bullet) + PrCl \quad (8)$$

generated, the persistent adducts (**10**) could still be detected at lower temperatures and their spectra were indistinguishable from those of the adducts produced photochemically.

Spin-trapping experiments with the three ω-bromoalkanoyl isocyanates (**2**)–(**4**) showed conclusively that the corresponding (isocyanatocarbonyl)alkyl radicals undergo cyclisation to give imidyl radicals. The most suitable halogen-abstracting radical proved to be $Bu_3P{\rightarrow}\dot{B}H_2$ [equations (9) and (10)],[28] although

$$Bu^tON{=}NOBu^t \xrightarrow{heat} 2\ Bu^tO^\bullet + N_2 \quad (9)$$

$$Bu^tO^\bullet + Bu_3P{\rightarrow}BH_3 \longrightarrow Bu_3P{\rightarrow}\dot{B}H_2 + Bu^tOH \quad (10)$$

trialkylstannyl and trialkylsilyl radicals were also effective. When a CD_3CN solution containing tributylphosphine–borane[28] (*ca.* 0.4 mol dm^{-3}), DTBE (*ca.* 0.5 mol dm^{-3}), di-t-butyl hyponitrite[29] (TBHN) (*ca.* 0.1 mol dm^{-3}), and a bromoacyl isocyanate (*ca.* 0.8 mol dm^{-3}) was heated in darkness at 290–320 K, the e.s.r. spectrum of the appropriate imidyl adduct (**10**) was observed. Thus, (**2**), (**3**), and (**4**) afforded adducts of (S$^\bullet$), the glutarimidyl radical (G$^\bullet$), and (DMS$^\bullet$), respectively [*e.g.* equations (11) and (12)], and the spectroscopic parameters were the same within experimental error as those of the adducts derived from the *N*-chloroimides [see Figure 1(*c*)]. 2,2,5,5-Tetramethyltetrahydrofuran (TMTHF) was also used as a solvent for these trapping experiments.

$$Bu_3P{\rightarrow}\dot{B}H_2 + BrCH_2CH_2CH_2C(O)NCO \longrightarrow {}^\bullet CH_2CH_2CH_2C(O)NCO + Bu_3P{\rightarrow}BH_2Br \quad (11)$$

$${}^\bullet CH_2CH_2CH_2C(O)NCO \longrightarrow (G^\bullet) \quad (12)$$

Spin-trapping with 2-Methyl-2-nitrosopropane (MNP).—This nitroso compound is known to form persistent adducts with both imidyl[30–32] and alkyl[25] radicals, although the nitroxides formed by addition of primary alkyl radicals are much shorter lived than those derived from tertiary radicals. Rate coefficients are available[33] for the trapping of alkyl radicals by MNP and we initially hoped to determine quantitative rates of cyclisation and ring opening, although in the event this was not possible.

In agreement with previous work,[30–32] irradiation with filtered light from a high-pressure mercury arc lamp* of a CD_3CN solution containing NBS (*ca.* 1.0 mol dm^{-3}) and MNP (*ca.* 0.04 mol dm^{-3}) at 290–315 K, afforded the e.s.r. spectrum of the nitroxide (**11**; Im = S). Other *N*-bromoimides were more

$$(Im^\bullet) + Bu^tNO \longrightarrow Bu^tN(\dot{O})Im \quad (13)$$
(**11**)

soluble than NBS and similar experiments could be carried out in TMTHF solvent. Glutarimidyl radicals undergo ring opening more slowly than succinimidyl radicals,[34] and both (G$^\bullet$) and the 3,3-dimethylglutarimidyl radical were readily trapped by MNP during photolysis of (**6**; X = Cl) in CD_3CN or (**7**; X = Br) in TMTHF, respectively. The e.s.r. parameters of all nitroxide spin adducts are given in Table 2.

Trial experiments were carried out to determine the optimum conditions for trapping of ω-(isocyanatocarbonyl)alkyl radicals using ethyl 3-bromopropanoate as a model for the bromoacyl isocyanates. The phosphine–boryl radical $Bu_3P{\rightarrow}\dot{B}H_2$

* The beam from the mercury discharge lamp used to generate transient radicals[27] was attenuated with a 3% transmittance metal gauze screen and passed through a 4 mm thick sheet of Pyrex glass.

Table 2. E.s.r. parameters for t-butyl nitroxides Bu^{t}N(Ö)Im (**11**) and Bu^{t}N(Ö)R.

Nitroxide	Solvent	T/K	g-Factor	Hyperfine splittings/G	
				a(N)	Others
(**11**; Im = succinimidyl)	CD_3CN	294	2.0058	16.38	1.81 (N_γ)
(**11**; Im = glutarimidyl)	CD_3CN	295	2.0059	15.88	1.91 (N_γ), 0.27 (nH)[a,b]
(**11**; Im = 3,3-dimethylglutarimidyl)	TMTHF	294	2.0058	15.63	1.85 (N_γ), 0.27 (nH)[b,c]
(**13**)	TMTHF	293	2.0060	15.30	0.53 ($2H_\delta$)[b]
Bu^{t}N(Ö)$CH_2CH_2CO_2$Et	TMTHF	294	2.0060	15.38	12.25 ($2H_\gamma$), 0.63 ($2H_\delta$)

[a] Splitting into an even number (≥ 8) of lines spaced by 0.27 G. [b] Splitting pattern unchanged, but better resolved, for the nitroxide derived from [$^2H_9$]MNP. [c] Splitting into an even number (≥ 10) of lines spaced by 0.27 G.

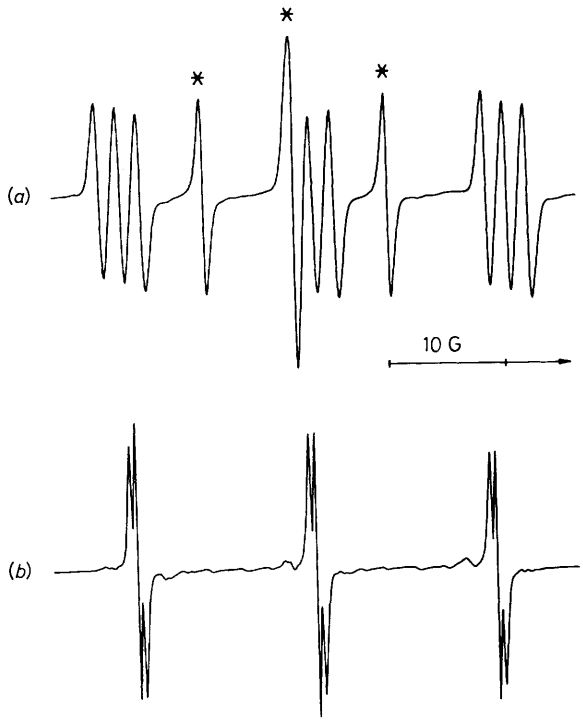


Figure 2. (*a*) E.s.r. spectrum of the nitroxide (**11**; Im = S) obtained during thermolysis of TBHN in the presence of (**2**), MNP, and Et_3SiH in CD_3CN at 328 K. The asterisks mark lines assigned to an acyl t-butyl nitroxide (see the text). (*b*) E.s.r. spectrum of the nitroxide (**13**) obtained during thermolysis of TBHN in the presence of (**4**), [$^2H_9$]MNP, and Et_3SiH in TMTHF at 302 K.

abstracted bromine more slowly than it added[35] to MNP under normal conditions and $Et_3Si^\bullet$ proved to be the most suitable halogen abstractor. When CD_3CN or TMTHF solutions which contained (**2**) (*ca.* 1.0 mol dm^{-3}), MNP (*ca.* 0.05 mol dm^{-3}), triethylsilane (*ca.* 1.2 mol dm^{-3}), and TBHN (*ca.* 0.05 mol dm^{-3}) were heated in darkness to temperatures of 290–315 K, an intense composite e.s.r. spectrum from two nitroxides was detected [see Figure 2(*a*)]. The stronger spectrum arises from (**11**; Im = S) and the weaker three-line spectrum [a(N) 7.8 G, g 2.0067 in CD_3CN at 328 K] is assigned to an acyl t-butyl nitroxide, probably Bu^{t}N(Ö)C(O)CH_2CH_2Br formed by trapping of acyl radicals derived from a trace of 3-bromopropanoyl bromide present in (**2**) (*cf.* ref. 36). No spin adduct of the uncyclised 2-(isocyanatocarbonyl)ethyl radical (**1**) was detected, even when the concentration of MNP was increased to *ca.* 1.2 mol dm^{-3}.† although we note that the resulting nitroxide would be expected to be much shorter-lived than (**11**) under the same conditions.

In similar experiments with (**4**), again no spectrum of the primary alkyl spin-adduct (**12**) was observed, but neither could a signal from (**11**; Im = DMS) be conclusively identified. The spectrum was dominated by an intense signal which we assign to the very persistent di-t-alkyl nitroxide (**13**), produced by trapping of the t-alkyl radical formed by overall 1,2-shift of the C(O)NCO group which follows abstraction of bromine from

Bu^{t}N(Ö)$CH_2CMe_2C(O)NCO$ Bu^{t}N(Ö)$CMe_2CH_2C(O)NCO$
(**12**) (**13**)

(**4**). Variation of the MNP concentration from *ca.* 0.04–1.2 mol dm^{-3} did not lead to the detection of nitroxides other than (**13**) [apart from variable concentrations of Bu^{t}N(Ö)OBu^t]. Since (**11**; Im = DMS) would be expected to be as persistent as the (S$^\bullet$) adduct, its absence is presumably related to the greater rate of ring opening of the methylated imidyl radical.

Direct Detection of Imidyl and (Isocyanatocarbonyl)alkyl Radicals.—Despite numerous attempts under a variety of conditions of solvent and temperature, we have been unable to observe any e.s.r. spectra attributable to imidyl radicals during u.v. irradiation of the *N*-halogenoimides (**5**–**9**; X = Cl or Br) either alone or in the presence of R_3SnSnR_3 (R = Me or Bu) which might scavenge halogen atoms more rapidly than imidyl radicals, especially at low temperatures. Sometimes, very weak and poorly defined signals were detected, but these appeared to be associated with the formation of solid deposits in the sample tubes. Even the *N*-halogenoimides (**6**), (**7**), and (**9**), which would yield imidyl radicals with less tendency to undergo ring opening than (S$^\bullet$) or (DMS$^\bullet$), did not afford e.s.r. spectra. In particular, no spectra were obtained from (**7**; X = Cl or Br) in CH_2Cl_2 at 160 K.

E.s.r. spectra were detected during the u.v. irradiation of cyclopropane solutions containing di-t-butyl peroxide (DTBP) (*ca.* 15% v/v), trimethyl- or triethyl-silane (*ca.* 10% *v/v*), and one of the bromoacyl isocyanates (**2**) or (**4**) (*ca.* 1.0 mol dm^{-3}). This is a well-known method for the generation of specific alkyl radicals for e.s.r. study[37] and involves bromine-atom abstraction by a trialkylsilyl radical. The experiments were technically difficult because of the high reactivities of (**2**) and (**4**) and the small quantities involved. We were well aware that chemical modification of the NCO group (*e.g.* by hydrolysis) might pass undetected and samples were prepared under stringently anhydrous conditions; the reagents were frozen in layers at 77 K in the sample tube and only allowed to mix at *ca.* 170 K in an ethanol slush bath immediately before insertion into the microwave cavity.

No e.s.r. spectra attributable to imidyl radicals were observed from either (**2**) or (**4**), although these radicals would abstract

† This would be the concentration of monomeric MNP if the dimer dissociates fully in solution. The extent of dissociation will be solvent dependent and will be smaller in CD_3CN than in TMTHF.

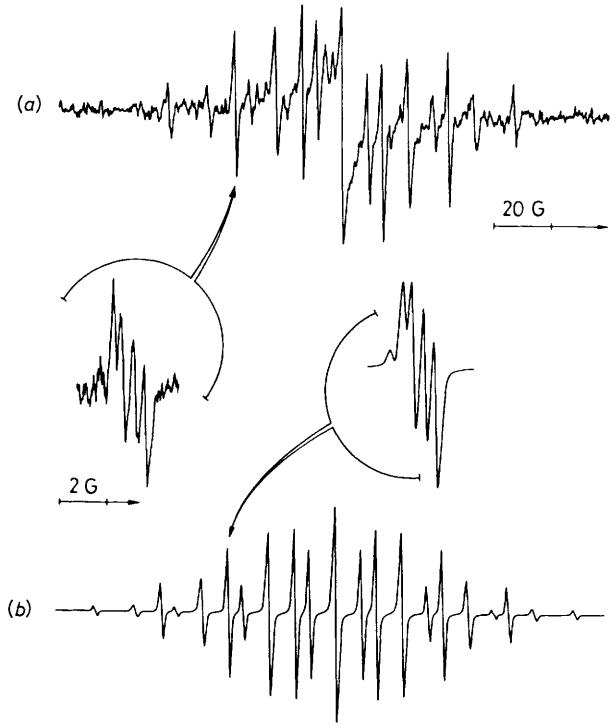
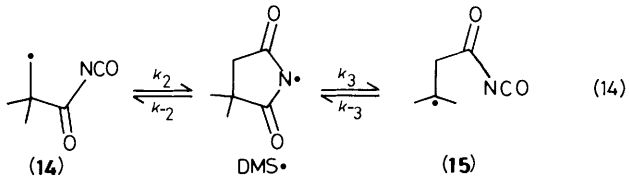


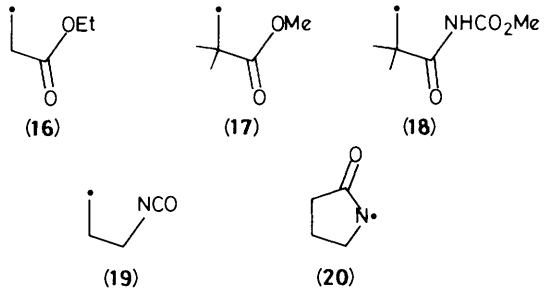
Figure 3. (*a*) E.s.r. spectrum of the alkyl radical (**15**) produced by photolysis of DTBP in the presence of (**4**) and Me_3SiH in cyclopropane at 149 K. The spectrum shows selective line broadening (see the text); further fine structure due to nitrogen and second-order proton splittings is resolvable for the unbroadened 'lines.' (*b*) Computer simulation using the parameters given in Table 3; ΔB_{P-P} for the lines corresponding to $M_I(2H_\beta) = 0$ is 1.08 G, for other lines it is 0.70 G.

hydrogen from the silane rapidly even at low temperatures leading to chain consumption of the reagents (see below). At *ca.* 165 K in cyclopropane, the e.s.r. spectrum obtained from (**2**) was very weak and although an alkyl-type radical was probably present, it could not be identified with any certainty.

More definitive results were obtained from (**4**) and the spectrum recorded during the u.v. irradiation of DTBP, Me_3SiH, and (**4**) is reproduced in Figure 3. The spectrum can be analysed in terms of a 23.0 G splitting from six equivalent protons and a 14.0 G splitting from two protons, although the central lines of the triplets arising from the latter coupling are broadened relative to the wing lines, indicating the existence of a dynamic process which acts to exchange two protons which are instantaneously non-equivalent on the e.s.r. timescale.[38] Under conditions of higher resolution, it was possible to detect further splitting of the sharper lines which arises from a combination of second-order effects and long-range coupling of 0.51 G to ^{14}N. We assign this spectrum to the tertiary radical (**15**), produced by ring opening of (DMS•), itself formed by cyclisation of the primary radical (**14**) [equation (14)]. The temperature range over which (**15**) could be detected was restricted at the lower end by reagent solubility and above *ca.* 150 K rapid consumption of reagents and precipitation of a white solid occurred. The low value of $a(2H_\beta)$ for (**15**) indicates[38] that the eclipsed conformation about the C_α–$CH_2C(O)NCO$ bond is preferred; the selective line broadening probably arises because of hindered rotation about the CH_2–C(O) bond. Detection of only radical (**15**) at 149 K implies[39] that both k_2 and k_3 are $> ca.\ 10^3\ s^{-1}$ and that $(k_3/k_{-3}) \gg 1$ at this temperature; (k_2/k_{-2}) would be expected to be > 1.[8,12] If an *A*-factor of $10^{11}\ s^{-1}$ applies to the unimolecular ring closure and opening, a rate coefficient of $> 10^3\ s^{-1}$ at 149 K implies an activation energy $< 23\ kJ\ mol^{-1}$.



For comparative purposes a number of related substituted alkyl radicals were generated by halogen-atom abstraction from the corresponding bromides.[37] These radicals are shown in (**16**)–(**19**) and their e.s.r. parameters are included in Table 3. 3-Bromopropyl isocyanate[40] afforded the radical (**19**) and the



complications found with (**2**) and (**4**) were absent, such that a clean e.s.r. spectrum could be observed over a wide range of temperatures. The same spectrum was detected when Et_3SiH was replaced with Bu^iSnMe_3 (*cf.* ref. 41) and when the silane and DTBP were replaced with $Me_3SnSnMe_3$. Between 173 and 300 K the spectrum of (**19**) exhibited selective broadening of the lines associated with $M_I(2H_\beta) = 0$, indicating out-of-phase modulation of the β-proton splittings probably because of hindered rotation about the C_β–C_γ bond.[38] No spectroscopic evidence for cyclisation of (**19**) to give the amidyl radical (**20**) could be found up to 300 K, when the spectrum of (**19**) was still observed. The radical (**19**) was detectable for extended periods of time at high temperatures, indicating that the amidyl (**20**) was not being formed and removed by a fast reaction with silane or stannane which would result in chain consumption of reagents.

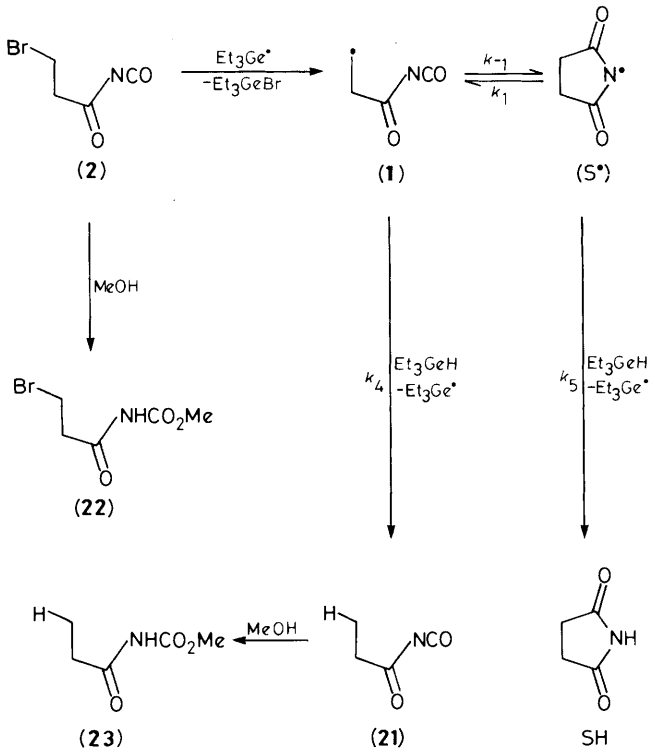
A number of possible reasons may be advanced to explain the slower cyclisation of (**19**) compared with 2-(isocyanatocarbonyl)alkyl radicals. Amidyl radicals similar to (**20**) are known to be π radicals[42] in their electronic ground states and any excited σ radical would be expected to be less close in energy than ($S^\bullet_\sigma$) is to ($S^\bullet_\pi$). Cyclisation of (**19**) to (**20**) would thus be stereoelectronically forbidden if the heavy atoms are coplanar and even for non-planar rings the activation energy could still be relatively large. The same reasoning would account for the fact that β-scission of cyclic or acyclic amidyl radicals has never been observed. It is also possible that replacement of the CH_2NCO group in (**19**) by a C(O)NCO moiety reduces strain in the transition state for ring closure or accelerates cyclisation because of polar effects which favour addition of nucleophilic alkyl radicals to acyl, as opposed to alkyl, isocyanates, in the same way as they favour analogous addition of nucleophilic alkyl radicals to vinyl ketones as compared with simple alkenes.

Product Analysis.—In order to support and extend the conclusions reached from the e.s.r. spectroscopic studies, we have determined quantitatively the products from radical-chain reductive debromination of (**2**) and (**4**) with triethylgermane in cyclohexane at 328 K. In the absence of spin-traps and provided that heterolytic processes do not intervene, (**2**) and (**4**) would be expected to react with a number of metal or metalloid hydrides by radical-chain mechanisms[43] to give the corresponding

Table 3. E.s.r. parameters for carbon-centred radicals derived from bromo compounds.

Radical	Solvent	T/K	g-Factor	Hyperfine splittings/G	
				$a(2H_\alpha)$	Others
(15)	Cyclopropane	149	2.0028	—	23.0 ($6H_\beta$), 14.0 ($2H_\beta$), 0.51 (1N)
(16)[a]	Cyclopropane	178	2.0028	22.5	31.3 ($2H_\beta$)
(17)	Cyclopropane	194	2.0027	22.1	0.53 ($6H_\gamma$)
(18)	Oxirane	195	2.0027	22.1	0.49 ($6H_\gamma$), 0.49 (1N), 0.49 (NH)[b]
(19)	Cyclopropane	193	2.0027	22.3	27.5 ($2H_\beta$), 0.50 ($2H_\gamma$)

[a] Previously reported by R. M. Haigh, A. G. Davies, and M.-W. Tse, *J. Organomet. Chem.*, 1979, **174**, 163. [b] Pattern of equally spaced lines with the predicted intensity distribution.



Scheme.

imide. If the hydride is also capable of donating a hydrogen atom sufficiently rapidly to an isocyanatocarbonyl(alkyl) radical, acyl isocyanate will be produced competitively. Quenching of the reaction mixture with methanol will convert any acyl isocyanates into the corresponding urethanes. The pertinent reactions for reductive debromination of (**2**) by triethylgermane are summarised in the Scheme.

Triethylgermane was chosen as the reducing agent after a number of trial experiments. Tributylstannane reacted exothermically with (**2**) and with (**4**) after being mixed in cyclohexane at room temperature in the absence of an initiator. Addition of the Sn–H function across the isocyanate group is probably involved, by analogy with the (slower) reaction which is known to take place between tin hydrides and alkyl or aryl isocyanates.[44] Radical-chain debromination of (**2**) could be brought about by treatment with either $Bu_3P{\rightarrow}BH_3$ or Et_3SiH in the presence of TBHN at 320–330 K, but although succinimide was formed in moderate yield none of the urethane (**23**) was detected after quenching with methanol. As expected,[23,28,45] hydrogen-atom abstraction from $Bu_3P{\rightarrow}BH_3$ or Et_3SiH is too slow to compete with cyclisation of (**1**) to give (S•), even when these hydrides are present in relatively high concentration (1–2 mol dm^{-3}). Alkyl radicals abstract hydrogen more rapidly from trialkylgermanes[46,47] and by the use of Et_3GeH small amounts of (**23**) were detected along with succinimide. Triethylgermane was used in preference to Bu_3GeH because the greater volatility of the former allowed it to be removed from the product mixture immediately after it had been quenched with methanol, which prevents any complication which might arise because of subsequent reactions of the germane, such as reduction of the bromourethane (**22**) (derived from any unchanged bromoacyl isocyanate) to form (**23**).

However, triethylgermane was also found to react with the acyl isocyanates (**2**) and (**21**) at the C(O)NCO function, probably by addition of the Ge–H group to give (**24**) and/or (**25**), products analogous to those formed between tin hydrides and alkyl or aryl isocyanates.[44] Hence, propanoyl isocyanate

$$\mathrm{RC(O)NCO} + \mathrm{Et_3GeH} \begin{cases} \rightarrow \mathrm{RC(O)N(GeEt_3)CHO} \quad (15a) \\ \quad\quad (\mathbf{24}) \\ \rightarrow \mathrm{RC(O)NHC(O)GeEt_3} \quad (15b) \\ \quad\quad (\mathbf{25}) \end{cases}$$

formed by the homolytic pathway shown in the Scheme will be subsequently destroyed by reaction with Et_3GeH. It might also be argued that reaction of (**2**) with Et_3GeH at the C(O)NCO group could give a product which might undergo homolytic debromination to give a compound capable of reacting with methanol to form the urethane (**23**). This would provide a source of (**23**) other than that from (**21**) produced from (**1**) *via* hydrogen abstraction from the germane. Whilst it is difficult to eliminate this alternative source completely, we believe it is a very unlikely pathway since (**24**) and (**25**) will probably react with methanol to give *N*-formylamides RC(O)NHCHO.[48]

Despite all the technical problems encountered, by working at 328 K and by carrying out appropriate control experiments, we have obtained a value for k_{-1} in which we have reasonable confidence, although the precision will clearly not be as high as would be expected for rate coefficients derived using similar techniques with simple systems.

A known amount of 3-bromopropanoyl isocyanate (**2**) was added quickly from a calibrated microsyringe to a rapidly stirred solution of Et_3GeH and TBHN in cyclohexane maintained at 328 ± 0.5 K. The reaction flask was equipped with a water-cooled condenser and a septum inlet and its contents were maintained under an atmosphere of dry argon. After a known time, the reaction was stopped by plunging the flask into an ice–water bath. An excess of methanol was added to convert acyl isocyanates into the *N*-acylurethanes (**22**) and (**23**) during 10 min rapid stirring at 273 K, before all material volatile at room temperature was quickly pumped into a cold trap under reduced pressure (0.1 Torr).* A known weight of methyl phenyl sulphone was added as internal standard to the residual solid and the mixture was dissolved in [$^2H_8$]tetrahydrofuran

* 1 Torr = 133.322 Pa.

Table 4. Products obtained from reactions of 3-bromopropanoyl and propanoyl isocyanates with triethylgermane in cyclohexane in the presence of TBHN.[a]

Entry	T/K	Reaction time/min	Product yields[b]/mmol		
			SH	(22)	(23)
1[c]	328	10	0.412	0.0273	0.0109
2	328	30	0.465	0.0015	0.0017
3	273	0[d]	0.0037	0.554	*e*
4[f]	328	10	*e*	*e*	0.227

[a] Reaction mixtures contained Et_3GeH (2.36 mmol), the acyl isocyanate (0.664 mmol), and TBHN (*ca.* 0.033 mmol) in cyclohexane (1.0 cm^3). For entries 1–3, $[Et_3GeH]_0$ is 1.63 mol dm^{-3}, for entry 4 it is 1.64 mol dm^{-3}. After reaction, isocyanates were converted into urethanes by the addition of dry methanol (0.10 cm^3). [b] Obtained by h.p.l.c. analysis; those obtained by ^1H n.m.r. spectroscopy were similar but are considered rather less accurate. [c] Et_3GeH (1.3 mmol) was recovered by trap-to-trap distillation after reaction (see the text). [d] Reaction mixture was quenched with methanol immediately after addition of (**2**). [e] Not detected. [f] Reaction of propanoyl isocyanate with Et_3GeH.

and examined by high field ^1H n.m.r. spectroscopy to determine product yields. Yields were determined more accurately by reverse-phase h.p.l.c. analysis, using the sulphone as an internal standard; the results are collected in Table 4. The cold trap contained mainly excess Et_3GeH, cyclohexane, and methanol.

The possibility that (**22**) might be reduced to (**23**) after the addition of methanol but before removal of the excess germane, was examined using a reaction mixture which had been prepared as usual but maintained at 273 K before being quenched (Table 4, entry 3). Although a high yield of the bromourethane (**22**) was obtained, no (**23**) was detected and only a trace of succinimide was found. Since both (**2**) and (**21**) react with Et_3GeH at their C(O)NCO groups and because the conversion of isocyanates to urethanes might be somewhat less than quantitative, the final yield of (**23**) will be less than the total amount of propanoyl isocyanate produced during the reaction (see above). A control experiment (entry 4) was carried out in which (**2**) was replaced with an equal quantity of (**21**) and the yield of (**23**) was determined after the reaction mixture had been quenched with methanol in the usual way. Since the reaction between (**21**) and Et_3GeH is likely to be first order in isocyanate, the value of [amount (**21**) taken/yield (**23**)] (2.9) obtained from this experiment was used to scale-up the yield of (**23**) obtained from (**2**) (entry 1). Comparison of entries 1 and 2 shows that increasing the reaction time from 10 to 30 min leads to almost complete destruction of the product propanoyl isocyanate by reaction with excess germane.

The succinimidyl radical is a potent hydrogen abstractor which yields succinimide, it even abstracts a hydrogen atom from cyclopropane at a rate sufficient to make halogenation of this hydrocarbon by *N*-halogenosuccinimides a viable reaction.[6,17] It is, therefore, reasonable to assume that hydrogen-atom transfer to the electrophilic (S$^\bullet$) from Et_3GeH will be extremely rapid, making the cyclisation of (**1**) effectively irreversible under our experimental conditions. At 300 K, the rate coefficient for abstraction of hydrogen from Bu_3GeH by t-butoxyl radicals[49] is *ca.* 9×10^7 dm^3 mol^{-1} s^{-1}. Assuming that $Bu^tO^\bullet$ and (S$^\bullet$) are similarly reactive towards trialkylgermanes, it is likely that k_5 is *ca.* 10^8 dm^3 mol^{-1} s^{-1} at 328 K. Since $[Et_3GeH]$ is *ca.* 1.5 mol dm^{-3} in our experiments, cyclisation of (**1**) will be effectively irreversible provided that k_1 is $< ca.$ 10^8 s^{-1}. This would accord with our previous work[4] in which we have shown that tetra-alkylstannanes react with *N*-halogenosuccinimides at 308 K by a radical-chain mechanism [equations (16) and (17)] to give *N*-trialkylstannylsuccinimide and not products derived from ring opening of (S$^\bullet$), although k_6 is only *ca.* 10^4 dm^3 mol^{-1} s^{-1}.

$$(S^\bullet) + R_4Sn \xrightarrow{k_6} R_3SnS + R^\bullet \quad (16)$$

$$R^\bullet + SHal \longrightarrow RHal + (S^\bullet) \quad (17)$$

Based on the Scheme, it follows that after a reaction time *t* equation (18) will hold. Because of the difficulties with side

$$d[SH]/d[(21)] = k_{-1}/k_4[Et_3GeH]_t \quad (18)$$

reactions described previously, it is only worthwhile to integrate equation (18) with the assumption that the germane concentration remains constant at an average value of $[Et_3GeH]_0 - 0.5[(2)]_0$, to obtain equation (19). The data from

$$\text{Yield SH/Yield (21)} = k_{-1}/k_4[Et_3GeH]_{avg} \quad (19)$$

entry 1, if the yield of (**21**) is assumed to be 2.9 times the yield of (**23**), together with the value of $[Et_3GeH]_{avg}$ (1.40 mol dm^{-3}) lead to $(k_{-1}/k_4) = 18.2$ mol dm^{-3}. The rate coefficient for hydrogen-atom abstraction from Bu_3GeH by the primary hex-5-enyl radical (**26**) has been measured[46] and, by using the published Arrhenius parameters, we calculate it to be 2.04×10^5 dm^3 mol^{-1} s^{-1} at 328 K. Assuming that (**1**) abstracts hydrogen from Et_3GeH at a similar rate, we obtain $k_{-1} = 3.7 \times 10^6$ s^{-1} at 328 K in cyclohexane.

(**26**) (20)

Our value for k_{-1} is considerably smaller than that recently proposed by Skell and co-workers[17] (5×10^8 s^{-1} at 288 K), which extrapolates to 8×10^8 s^{-1} at 328 K if we use the *A*-factor ($10^{10.42}$ s^{-1}) determined for cyclisation of (**26**) [equation (20)]. One contributing reason for this discrepancy could be the invalidity of Skell's assumption that (**1**) and the cyclopropylmethyl radical both abstract bromine from NBS at the same rate. Although both are primary alkyl radicals, the cyclopropylmethyl radical could be appreciably more nucleophilic than (**1**) (the cyclopropylmethyl cation is relatively stabilised) and polar effects would result in the former abstracting bromine more rapidly than (**1**) [equation (21)]. Taking our value for k_{-1},

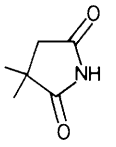
$$\underset{(1)}{{}^\bullet CH_2CH_2C(O)NCO} + SBr \xrightarrow{k_7} \underset{(2)}{BrCH_2CH_2C(O)NCO} + (S^\bullet) \quad (21)$$

extrapolated to 288 K assuming an *A*-factor of $10^{10.42}$ s^{-1}, in conjunction with Skell's value[17] of (k_{-1}/k_7) (0.035 mol dm^{-3} at 288 K) gives $k_7 = 3.1 \times 10^7$ dm^3 mol^{-1} s^{-1} at 288 K, much smaller than the value proposed by Skell[17] ($1.3–1.6 \times 10^{10}$ dm^3 mol^{-1} s^{-1}). The lower value would be more in line with the rate coefficient for abstraction of bromine from NBS by the (albeit stabilised) benzyl radical obtained previously by us[4] (*ca.* 5×10^5 dm^3 mol^{-1} s^{-1} at 308 K).

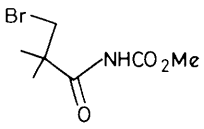
We have also examined the products of the reaction between triethylgermane and 3-bromo-2,2-dimethylpropanoyl isocyanate (**4**) using the same techniques. After the reaction mixture had been quenched with methanol, the yields of 2,2-dimethylsuccinimide (DMSH) and of the three *N*-acylurethanes (**27**)–(**29**) were determined by reversed-phase h.p.l.c. The imide

DMSH and the urethanes (**28**) and (**29**) arise because the initially formed radical (**14**) undergoes cyclisation to give DMS• which ring opens to (**15**) [equation (14)], all in competition with hydrogen abstraction from the germane. As mentioned before, cyclisation of (**14**) to (DMS•) is evidently much faster than the corresponding cyclisation of (**1**) to give (S•), because of the presence of the two methyl groups on C-2 (*gem*-dimethyl effect[50]). A similar acceleration of ring closure is brought about by 2,2-dimethylation of the hex-5-enyl radical [equation (20)].[51]

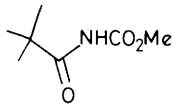
In cyclohexane at 328 K under the same conditions as described above for the reactions of (**1**) (Table 4, entry 1), (**4**) (0.679 mmol) and triethylgermane (2.36 mmol, initially 1.60 mol dm^{-3}) yielded, after being quenched with methanol, DMSH (0.590 mmol), (**28**) (0.004 mmol), and (**29**) (0.062 mmol); the bromoacyl urethane (**27**) was not detected. In view of the complexity of the reaction kinetics and the number of unknown rate coefficients, we did not consider that any attempt to interpret the data quantitatively would be justified. However,



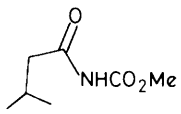
DMSH



(**27**)



(**28**)



(**29**)

the results serve to confirm that the (isocyanatocarbonyl)alkyl radical (**14**) undergoes rapid cyclisation to give (DMS•) which then readily opens to form the tertiary radical (**15**). Overall this represents a particularly rapid 1,2-shift of the C(O)NCO group by way of the intermediate cyclic imidyl radical. The rearrangement contrasts with the 1,2-homolytic shift undergone by β-acyloxyalkyl radicals such as (**30**) which are believed[52] to proceed in a concerted fashion, usually[53,54] through a five-

$$\underset{\textbf{(30)}}{MeC(O)OCMe_2\dot{C}H_2} \longrightarrow Me_2\dot{C}CH_2OC(O)Me \quad (22)$$

membered cyclic transition state and not *via* the stereoelectronically disfavoured pathway involving a discrete 1,3- dioxolanyl radical intermediate.

The very rapid cyclisation of the three ω-(isocyanatocarbonyl)alkyl radicals studied in this work to give imidyl radicals and the facility with which (S•) and (DMS•) undergo ring opening surely requires the involvement of σ-imidyl radicals. It seems likely that these are the electronic ground states (at least under our conditions), but if not, then the σ state must be very close in energy to the π ground state for each radical.

Cyclisation of (isocyanatocarbonyl)alkyl radicals has potential in synthesis, since it represents an efficient method for increasing the length of a carbon chain by one atom, through reaction of bromoacyl isocyanates with reagents such as silanes, phosphine–boranes, germanes, and probably[5] hexamethyldistannane.

Experimental

E.S.R. Spectroscopy.—Spectra were obtained using a Varian E-109 instrument operating at *ca.* 9.1 GHz. The techniques used have been described previously;[27,55] samples containing MNP were prepared and handled in darkness or subdued light.[55]

Materials.—^{1}H N.m.r. spectra were recorded using Varian XL-200 or VXR-400 instruments; the solvent was $CDCl_3$ and the internal standard was tetramethylsilane.

1,1-Di-t-butylethene,[56] di-t-butyl hyponitrite,[29] dibutanoyl peroxide,[57] trimethyl(isobutyl)stannane,[41] and 2,2-dimethylsuccinimide[15,58] were prepared as described previously. [$^2H_9$]-MNP was prepared as described by Holman and Perkins[59a] from [$^2H_9$]Bu^{t}NH$_2$, itself prepared[59b] from [$^2H_9$]Bu^{t}OD (Aldrich). Triethylgermane[60] (b.p. 121–122 °C at 760 Torr) was prepared in 55% yield by reduction of chlorotriethylgermane (Strem) (5.0 g) with $LiAlH_4$ in diethyl ether using the procedure described for the preparation of tributylgermane.[61] Methyl 3-bromo-2,2-dimethylpropanoate[62] (b.p. 55–57 °C at 5 Torr was prepared by esterification of 3-bromo-2,2-dimethylpropanoic acid (Riedel) in benzene–methanol (1:1 v/v) under reflux with concentrated sulphuric acid as catalyst.

The *N*-halogenoimides (**5**–**9**; X = Cl or Br) which were not available commercially were prepared from the corresponding imides and either t-butyl hypochlorite[63] in methanol (or in water–t-butyl alcohol[64]) or bromine in aqueous sodium hydrogencarbonate.[65] The compounds (**6**; X = Cl), (**7**; X = Cl or Br),[34] (**8**; X = Cl or Br),[15] and (**9**; X = Cl)[64] were prepared *via* these routes; the preparation of (**6**; X = Cl) is described below. t-Butyl hypochlorite (2.00 g, 17 mmol) was added dropwise to a stirred solution of glutarimide (1.87 g, 17 mmol) in methanol (20 cm^3) cooled in an ice-bath. The temperature was allowed to rise to ambient and stirring was continued for 1 h. Removal of the methanol under reduced pressure left the crude product which was purified by flash chromatography on silica (pentane–ethyl acetate 2:1 v/v eluant) to yield *N*-chloroglutarimide (1.85 g, 76%), m.p. 150 °C. (Found: C, 40.8; H, 4.0; N, 9.4; Cl, 23.9. $C_5H_6ClNO_2$ requires C, 40.7; H, 4.1; N, 9.5; Cl, 24.0%). δ_H 2.03 (quintet, 2 H, *J* 6.5 Hz) and 2.88 (t, 4 H, *J* 6.5 Hz).

All the isocyanates used in this work were very moisture sensitive and were prepared and handled under an atmosphere of dry argon with anhydrous conditions rigorously maintained.

3-*Bromopropanoyl Isocyanate* (**2**).—Silver cyanate[66] was thoroughly dried at 30 °C for 9 h under reduced pressure (0.05 Torr) and then finely powdered. Silver cyanate (14.0 g, 93 mmol) was added in three approximately equal portions to mechanically stirred 3-bromopropanoyl bromide[13] (10.0 g, 46 mmol) cooled in an ice-water bath. After each addition, the flask was immersed in a water-filled ultrasonic cleaning bath (Decon FS200) and the contents was stirred and sonicated for 30 min at room temperature. Benzene (10 cm^3) was added after the second portion of silver cyanate in order to keep the reaction mixture mobile. After centrifugation, benzene was removed from the supernatant liquid under reduced pressure and the residual oil was distilled to yield 3-bromopropanoyl isocyanate (4.5 g, 55%), b.p. 69 °C at 10 Torr (lit.,[13] 68–70 °C at 10 Torr). δ_H 3.08 (t, 2 H, *J* 6.5 Hz) and 3.56 (t, 2 H, *J* 6.5 Hz). Preparations in which the benzene was replaced by diethyl ether were usually rather more successful, although occasionally some ethyl 3-bromopropanoate was produced along with (**2**) (presumably by silver-assisted reaction of ether with residual acyl bromide) and the ester was difficult to remove by distillation.

Methyl N-(3-*Bromopropanoyl*)*carbamate* (**22**).—Methanol (1.0 cm^3) was added dropwise to a stirred solution of 3-bromopropanoyl isocyanate (0.20 g, 1.12 mmol) in diethyl ether (2 cm^3) cooled in an ice bath. After 15 min, the ether and excess methanol were removed under reduced pressure and the residual solid was recrystallised from methanol to give (**22**) (0.20 g, 85%), m.p. 138–139 °C (lit.,[13] 137–138 °C). δ_H 3.42 (t, 2 H, *J*

Table 5. Melting points and analytical data for *N*-acylurethanes $RC(O)NHCO_2Me$.

R	Solvent for recryst.	M.p./°C	Lit. m.p./°C	Ref.	Elemental analysis [% Found (% calc.)] C	H	Br	N
$BrCH_2CH_2$	Methanol	138–139	132–134.5 137–138	3(*d*), 13	28.5 (28.6)	3.7 (3.8)	37.8 (38.0)	6.5 (6.7)
$BrCH_2CH_2CH_2$	Benzene	118–119			32.4 (32.2)	4.4 (4.5)	35.8 (35.7)	6.3 (6.3)
$BrCH_2CMe_2$	Benzene	107–108			35.7 (35.3)	5.1 (5.1)	33.4 (33.6)	5.8 (5.9)
Et	Benzene–hexane	134–136	132–133	70	45.9 (45.8)	7.1 (6.9)		10.6 (10.7)
Bu^i	Benzene	97–98			52.5 (52.8)	8.4 (8.2)		8.7 (8.8)
Bu^t	Benzene	110–111			52.9 (52.8)	8.3 (8.2)		8.8 (8.8)

6.5 Hz), 3.64 (t, 2 H, *J* 6.5 Hz), 3.80 (s, 3 H), and 7.60 (br s, 1 H). This general procedure was used to prepare *N*-acylurethanes from all acyl isocyanates; the solvent for recrystallisation differed for other compounds. Data for all urethanes are given in Table 5; the ^1H n.m.r. spectra were in accord with expectation.

4-*Bromobutanoyl Isocyanate* (**3**).—This was prepared from 4-bromobutanoyl chloride (Aldrich) (10.0 g, 54 mmol) and silver cyanate (16.2 g, 108 mmol) using the method described for (**2**) and adding diethyl ether to maintain mobility. The acyl isocyanate was obtained in low yield (1.0 g, 10%), b.p. 63 °C at 0.75 Torr. δ_H 2.19 (quintet, 2 H, $\bar{J}$ 6.7 Hz), 2.72 (t, 2 H, *J* 7.1 Hz), and 3.48 (t, 2 H, *J* 6.3 Hz).

3-*Bromo*-2,2-*dimethylpropanoyl Isocyanate* (**4**).—This was prepared in three steps from 3-bromo-2,2-dimethylpropanoic acid. Thionyl chloride (7.7 g, 65 mmol) was added dropwise to a stirred solution of 3-bromo-2,2-dimethylpropanoic acid (10.0 g, 55 mmol) in benzene (10 cm^3) which was warmed in an oil bath maintained at 35–40 °C. The resulting mixture was heated under reflux for 30 min, allowed to cool, and the benzene and excess thionyl chloride were removed under reduced pressure to leave crude acid chloride. This was added cautiously, dropwise to vigorously stirred aqueous ammonia (55 cm^3, specific gravity 0.880) contained in an open beaker surrounded by an ice–water bath. When the addition was complete, the mixture was stirred for a further 30 min before the precipitated amide was removed by filtration, washed with cold water, dried under reduced pressure (30 °C, 0.01 Torr), and recrystallised from benzene to yield 3-bromo-2,2-dimethylpropanamide, m.p. 117–118 °C (lit.,[67] m.p. 113–115 °C). δ_H 1.36 (s, 6 H), 3.53 (s, 2 H), and 5.82 (br s, 2 H).

Oxalyl dichloride (4.9 g, 39 mmol) in 1,2-dichloroethane (10 cm^3) was added dropwise to a stirred slurry of 3-bromo-2,2-dimethylpropanamide (5.0 g, 28 mmol) in 1,2-dichloroethane (10 cm^3) cooled in an ice–water bath. The mixture was allowed to warm to room temperature and was then stirred and heated under reflux for 24 h, during which time all the solid dissolved. The solvent was removed under reduced pressure and the residual oil was distilled to yield 3-bromo-2,2-dimethylpropanoyl isocyanate (4.7 g, 81%), b.p. 60–61 °C at 5 Torr. δ_H 1.34 (s, 6 H) and 3.47 (s, 2 H). The isocyanate was further characterised as the urethane after treatment with methanol (see Table 5). t-Butyl isocyanate[24] was prepared from 2,2-dimethylpropanamide using the same procedure.

Propanoyl and 3-methylbutanoyl isocyanates were prepared from the corresponding acyl chlorides and tri-n-butylstannyl isocyanate.[68,69] Propanoyl chloride (2.2 g, 24 mmol) and added to magnetically stirred tributylstannyl isocyanate (10.0 g, 38 mmol) at room temperature. The mixture was heated slowly to 50 °C and stirred for 30 min at this temperature. Distillation of the mixture yielded propanoyl isocyanate (1.0 g, 42%), b.p. 44–46 °C at 100 Torr (lit.,[70] 40–50 °C at 100–110 Torr). δ_H 1.17 (t, 3 H, *J* 7.4 Hz) and 2.54 (q, 2 H, *J* 7.4 Hz). The same procedure was used to prepare 3-methylbutanoyl isocyanate, b.p. 35 °C at 15 Torr (lit.,[71] 52 °C at 40 Torr). δ_H 0.99 (d, 6 H, *J* 6.5 Hz), 2.20 (nonet, 1 H, $\bar{J}$ 6.6 Hz), and 2.36 (d, 2 H, *J* 6.8 Hz).

3-Bromopropyl isocyanate was prepared as described previously.[40]

H.P.L.C. Analyses.—Analyses were carried out using a Gilson binary gradient liquid chromatograph with u.v. detection at 254 nm. The stationary phase was Spherisorb ODS2 (5 μm) and the eluting solvents were water–acetonitrile (90:10 v/v) for the reaction products from (**4**) and water–methanol (90:10 v/v) followed by a linear gradient to 40% methanol for the reaction products from (**2**). Mixtures containing known amounts of the reaction products were stirred with the eluting solvents for 30 min (comparable to the time required for h.p.l.c. analysis) at room temperature, the solvents removed under reduced pressure, and the residue subjected to analysis. The relative product concentrations were unchanged within experimental accuracy by such treatment.

Acknowledgements

We are grateful to Mr. S. T. Corker for carrying out the h.p.l.c. analyses and we thank Mrs. E. J. Ryan for a number of the initial experiments. The e.s.r. work with 3-bromopropyl isocyanate was carried out by Dr. J. A. Baban.

References

1 G. Bloomfield, *J. Chem. Soc.*, 1944, 114.
2 K. Ziegler, A. Späth, E. Schaaf, W. Schumann, and E. Winkelmann, *Justus Liebigs Ann. Chem.*, 1942, **551**, 80.
3 (*a*) J. Adam, P. Goselain, and P. Goldfinger, *Nature* (*London*), 1953, **171**, 704; (*b*) P. A. Goselain, J. Adam, and P. Goldfinger, *Bull. Soc. Chim. Belg.*, 1956, **65**, 533; (*c*) R. E. Pearson and J. C. Martin, *J. Am. Chem. Soc.*, 1963, **85**, 354; (*d*) C. Walling, A. L. Rieger, and D. D. Tanner, *ibid.*, p. 3129.
4 A. G. Davies, B. P. Roberts, and J. M. Smith, *J. Chem. Soc., Chem. Commun.*, 1970, 557; *J. Chem. Soc., Perkin Trans. 2*, 1972, 2221.
5 P. M. Digiacomo and H. G. Kuivila, *J. Organomet. Chem.*, 1973, **63**, 251.
6 J. G. Traynham and Y. S. Lee, *J. Am. Chem. Soc.*, 1974, **96**, 3590.
7 J. C. Day, M. J. Lindstrom, and P. S. Skell, *J. Am. Chem. Soc.*, 1974, **96**, 5161.
8 U. Lüning and P. S. Skell, *Tetrahedron*, 1985, **41**, 4289.
9 D. D. Tanner, D. W. Reed, S. L. Tan, C. P. Meintzer, C. Walling, and A. Sopchik, *J. Am. Chem. Soc.*, 1985, **107**, 6576 and references therein.

10 P. S. Skell, U. Lüning, D. S. McBain, and J. M. Tanko, *J. Am. Chem. Soc.*, 1986, **108**, 121 and references therein.
11 J. C. Day, N. Govindaraj, D. S. McBain, P. S. Skell, and J. M. Tanko, *J. Org. Chem.*, 1986, **51**, 4959.
12 Y. L. Chow and D.-C. Zhao, *J. Org. Chem.*, 1987, **52**, 1931.
13 H. W. Johnson, Jr. and D. E. Bublitz, *J. Am. Chem. Soc.*, 1957, **79**, 753; 1958, **80**, 3150.
14 J. C. Martin and P. D. Bartlett, *J. Am. Chem. Soc.*, 1957, **79**, 2533.
15 R. L. Tlumak, J. C. Day, J. P. Slanga, and P. S. Skell, *J. Am. Chem. Soc.*, 1982, **104**, 7257.
16 C. Walling, G. M. El-Taliawi, and C. Zhao, *J. Am. Chem. Soc.*, 1983, **105**, 5119.
17 J. M. Tanko, P. S. Skell, and S. Seshadri, *J. Am. Chem. Soc.*, 1988, **110**, 3221.
18 A. Lund, P. O. Samskog, L. Eberson, and S. Lunell, *J. Phys. Chem.*, 1982, **86**, 2458.
19 M. J. Field, I. H. Hillier, S. A. Pope, and M. F. Guest, *J. Chem. Soc., Chem. Commun.*, 1985, 219.
20 C. Petrongolo and S. D. Peyerimhoff, *J. Mol. Struct. (Theochem)*, 1986, **138**, 69.
21 T. Koenig and R. A. Wielesek, *Tetrahedron Lett.*, 1975, 2007.
22 M. J. S. Dewar and S. Olivella, *J. Chem. Soc., Chem. Commun.*, 1985, 301.
23 P. Kaushal, B. P. Roberts, and E. J. Ryan, *J. Chem. Soc., Chem. Commun.*, 1987, 1587.
24 A. J. Speziale, L. R. Smith, and J. E. Fedder, *J. Org. Chem.*, 1965, **30**, 4306.
25 M. J. Perkins, *Adv. Phys. Org. Chem.*, 1980, **17**, 1.
26 D. Griller and K. U. Ingold, *J. Am. Chem. Soc.*, 1974, **96**, 6715.
27 V. Paul and B. P. Roberts, *J. Chem. Soc., Perkin Trans. 2*, 1988, 1183.
28 J. A. Baban and B. P. Roberts, *J. Chem. Soc., Perkin Trans. 2*, 1984, 1717.
29 H. Kiefer and T. G. Traylor, *Tetrahedron Lett.*, 1966, 6163.
30 C. Lagercrantz and S. Foschult, *Acta Chem. Scand.*, 1969, **23**, 708.
31 G. R. Chalfont, M. J. Perkins, and A. Horsfield, *J. Chem. Soc. B*, 1970, 401.
32 H. Singh, J. M. Tedder, and J. C. Walton, *J. Chem. Soc., Perkin Trans. 2*, 1980, 1259.
33 P. Schmid and K. U. Ingold, *J. Am. Chem. Soc.*, 1978, **100**, 2493; Y. Maeda and K. U. Ingold, *ibid.*, 1979, **101**, 4975; T. Doba, T. Ichikawa, and H. Yoshida, *Bull. Chem. Soc. Jpn.*, 1977, **50**, 3158.
34 U. Lüning, S. Seshadri, and P. S. Skell, *J. Org. Chem.*, 1986, **51**, 2071.
35 J. A. Baban, V. P. J. Marti, and B. P. Roberts, *Tetrahedron Lett.*, 1985, **26**, 1349.
36 J. Smith and J. M. Tedder, *J. Chem. Soc., Perkin Trans. 2*, 1987, 895.
37 A. Hudson and R. A. Jackson, *Chem. Commun.*, 1969, 1323
38 J. K. Kochi, *Adv. Free Radical Chem.*, 1975, **5**, 189.
39 J. A. Baban and B. P. Roberts, *J. Chem. Soc., Perkin Trans. 2*, 1981, 161.
40 A. Krantz and B. Hoppe, *Tetrahedron Lett.*, 1975, **9**, 695; E. Dyer and H. Scott, *J. Am. Chem. Soc.*, 1957, **79**, 672.
41 A. G. Davies, B. P. Roberts, and M.-W. Tse, *J. Chem. Soc., Perkin Trans. 2*, 1978, 145.
42 R. Sutcliffe, D. Griller, J. Lessard, and K. U. Ingold, *J. Am. Chem. Soc.*, 1981, **103**, 624.
43 B. Giese, 'Radicals in Organic Synthesis,' Pergamon Press, Oxford, 1986.
44 J. G. Noltes and M. J. Janssen, *J. Organomet. Chem.*, 1961, **1**, 346; D. H. Lorentz and E. I. Becker, *J. Org. Chem.*, 1963, **28**, 1707; A. J. Leusink and J. G. Noltes, *Recl. Trav. Chim.*, 1965, **84**, 585; Yu. I. Dergunov, A. V. Pavlycheva, V. D. Sheludyakov, I. A. Vostokov, Yu. I. Mushkin, V. F. Mironov, and V. P. Kosyukov, *Zh. Obshch. Khim.*, 1972, **42**, 2501.
45 J. M. Kanabus-Kaminska, J. A. Hawari, D. Griller, and C. Chatgilialoglu, *J. Am. Chem. Soc.*, 1987, **109**, 5267.
46 J. Lusztyk, B. Maillard, D. A. Lindsay, and K. U. Ingold, *J. Am. Chem. Soc.*, 1983, **105**, 3578.
47 J. Lusztyk, B. Maillard, S. Deycard, D. A. Lindsay, and K. U. Ingold, *J. Org. Chem.*, 1987, **52**, 3509.
48 I. Ojima and S.-I. Inaba, *J. Organomet. Chem.*, 1977, **140**, 97.
49 C. Chatgilialoglu, K. U. Ingold, J. Lusztyk, A. S. Nazran, and J. C. Scaiano, *Organometallics*, 1983, **2**, 1332.
50 E. L. Eliel, N. L. Allinger, A. J. Angyal, and G. A. Morrison, 'Conformational Analysis,' Wiley, New York, 1965, p. 191.
51 A. L. J. Beckwith and T. Lawrence, *J. Chem. Soc., Perkin Trans. 2*, 1979, 1535.
52 L. R. C. Barclay, D. Griller, and K. U. Ingold, *J. Am. Chem. Soc.*, 1982, **104**, 4399; L. R. C. Barclay, J. Lusztyk, and K. U. Ingold, *ibid.*, 1984, **106**, 1793; S. Saebo, A. L. J. Beckwith, and L. Radom, *ibid.*, 1984, **106**, 5119.
53 A. L. J. Beckwith and P. J. Duggan, *J. Chem. Soc., Chem. Commun.*, 1988, 1000.
54 H.-G. Korth, R. Sustmann, K. S. Gröninger, M. Leisung, and B. Giese, *J. Org. Chem.*, 1988, **53**, 4364.
55 V. P. J. Marti and B. P. Roberts, *J. Chem. Soc., Perkin Trans. 2*, 1986, 1613.
56 M. S. Newmann, A. Arkell, and T. Fukunaga, *J. Am. Chem. Soc.*, 1960, **82**, 2498. J. A. Baban and B. P. Roberts, *J. Chem. Soc., Perkin Trans. 2*, 1986, 1607.
57 J. K. Kochi and P. E. Mocadlo, *J. Org. Chem.*, 1965, **30**, 1134; I. G. Green, R. L. Hudson, and B. P. Roberts, *J. Chem. Soc., Perkin Trans. 2*, 1987, 1773.
58 J. R. Johnson, *Org. Synth.*, 1936, **16**, 75.
59 (*a*) R. J. Holman and M. J. Perkins, *J. Chem. Soc. C*, 1971, 2324; (*b*) R. Chiarelli and A. Rassat, *Tetrahedron*, 1973, **29**, 3639.
60 H. H. Anderson, *J. Am. Chem. Soc.*, 1957, **79**, 326.
61 H. G. Kuivila and O. F. Beumel, Jr., *J. Am. Chem. Soc.*, 1961, **83**, 1246; P. J. Stang and M. R. White, *ibid.*, 1981, **103**, 5429.
62 E. Wenkert, R. A. Mueller, E. J. Reardon, Jr., S. S. Sathe, D. J. Scharf, and G. Tosi, *J. Am. Chem. Soc.*, 1970, **92**, 7428.
63 M. J. Mintz and C. Walling, *Org. Synth.*, 1969, **49**, 9.
64 H. Zimmer and L. F. Audrieth, *J. Am. Chem. Soc.*, 1954, **76**, 3856.
65 R. E. Pearson and J. C. Martin, *J. Am. Chem. Soc.*, 1963, **85**, 3142.
66 R. G. Nevilie and J. J. McGee, *Inorg. Synth.*, 1966, **8**, 23.
67 H. H. Tan and E. L. Martin, U.S. 3,414,612/1968 (*Chem. Abstr.*, 1969, **70**, 57188s).
68 W. Stamm, *J. Org. Chem.*, 1965, **30**, 693.
69 H. Kodama, T. Kodama, Y. Hisada, O. Takashima, N. Koga, and N. Yagi, Japan 7,209,568/1972 (*Chem. Abstr.*, 1972, **77**, 5016j).
70 K. A. Nuridzhanyan, G. V. Kuznetsova, N. P. Bulanova, and L. M. Nesterova, *Biol. Atk. Soedin.*, 1968, 290 (*Chem. Abstr.*, 1969, **71**, 123768e).
71 V. D. Sheludyakov, A. S. Tkachev, S. V. Sheludyakova, V. P. Kozyukov, and V. F. Mironov, *J. Gen. Chem. USSR*, 1977, **47**, 2061.

Received 4*th January* 1989; *Paper* 9/00050J