

from the corresponding acids for both *meso* and *dl* compounds.

For the disubstituted succinic anhydrides, the same equality of chemical shift for protons *trans* and *cis* to X for X = Cl and X = Br has already been noted. It is not surprising, therefore, to find the same chemical shifts for all three members of the acyclic *meso* series, provided the same conformation (IIB) predominates in each case, as is indicated by the vicinal coupling constants. Furthermore, the very small difference in shifts between *meso*- and *dl*-dibromosuccinic acids and esters adds weight to the hypothesis that IIB predominates for the *meso* isomer while IIIA predominates for the *dl* isomer. In both cases each proton is *gauche* to both CO₂R and Br. This is particularly apparent for R = CH(CH₃)₂ (Table V), for which $J_{AB} = 10.3$ and 11.2 c.p.s. and the shifts are equal. By contrast, the difference in chemical shifts of the dichloro compounds is greater since conformation IIB still predominates for the *meso* isomer, while IIIA and IIIB probably both make important contributions for the *dl* isomer. In IIIB, each proton is *trans* rather than *gauche* to a chlorine and is thereby shifted further downfield. This conclusion is again consistent with that based on vicinal coupling constants. A similar difference between *meso*- and *dl*-dibromobutane chemical shifts has been reported. As for the acids and esters, the *meso* shifts are upfield from *dl* shifts.^{6,7} The effect of neutralization on chemical shifts of the acids can be accounted for on a similar basis. For example, all three of the *meso* salts, with both steric and electrostatic factors favoring conformation IIIB, should have almost identical chemical shifts as is observed (71 ± 1 c.p.s.).

Relative Steric Effects of Bromine Atom and Other Groups. On the basis of vicinal spin-coupling constants reported in this paper and those for other substituted dibromoethanes in the literature, it is possible to assign relative steric effects to several groups.

Confining the comparison to substituted dibromoethanes reduces the likelihood that electronegativity differences might be responsible for a significant part of the observed coupling constant differences. On the basis of two dibromoethanes, *erythro*-C₆H₅CHBr-CHDBr and *threo*-(CH₃)₃CCHBr-CHDBr, Buza and Snyder³⁹ concluded that the steric effect of (CH₃)₃C is greater than that of Br and that of C₆H₅ is less than that of Br. Similarly, the data of Anet⁶ and Bothner-By and Naar-Colin⁷ for *meso*- and *dl*-dibromobutane requires that CH₃ < Br and CH₃ < C₆H₅. The close similarity between vicinal coupling constants (10.4 and 11.3 c.p.s.) for two dibromomethanes studied by Gutowsky, *et al.*,⁸ which differ only by replacement of CH₃ by C₆H₅ at one carbon, is consistent with an assignment of similar steric effects for CH₃ and C₆H₅. Unfortunately, the configuration of these compounds, CH₃CHBr-CHBrCOC₆H₅ and C₆H₅-CHBr-CHBrCOC₆H₅, is not known. However, a Br-COC₆H₅ *gauche* interaction of magnitude similar to that we have estimated for Br-CO₂CH₃ (1200 cal./mole) would result in the conformation with protons *trans* being more stable for either of the two possible *dl* pairs. In summary, these results and those discussed earlier suggest the following order for steric effects in substituted ethanes: CO₂CH(CH₃)₂ > CO₂C₂H₅ > CO₂CH₃ > CO₂H=Br > C₆H₅ > CH₃, Cl with (CH₃)₃C and COC₆H₅ also > Br.

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(39) M. Buza and E. I. Snyder, Abstracts, 148th National Meeting of the American Chemical Society, Chicago, Ill., Aug. 1964.

Electron Paramagnetic Resonance Study of Radicals Produced in Irradiated Amides^{1,2}

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An e.p.r. study of the radicals produced by electron irradiation of a series of polycrystalline amides, *N*-alkylamides, and *N,N*-dialkylamides at low temperatures has been made. The isotropic hyperfine interactions with the protons usually permit identification of the radical species. For the *N*-alkyl- and *N,N*-dialkylamides the radiation damage consists of loss of a proton from the

carbon atom of the alkyl group adjacent to nitrogen. In the amides and carboxylic acids a proton is lost from the carbon atom adjacent to the carbonyl group. When there are no hydrogen atoms on the carbons adjacent to nitrogen or carbonyl, other bonds may be broken. Thus, trimethylacetic acid and trimethylacetamide give the *t*-butyl radical. The hyperfine splitting constants tend to be lower when the radical site is adjacent to nitrogen, presumably as a result of some delocalization of the odd electron onto nitrogen.

(1) This research was supported through a contract with the Atomic Energy Commission.

(2) Abstracted in part from the Ph.D. Thesis of S. K. Bolte, Michigan State University, 1963.

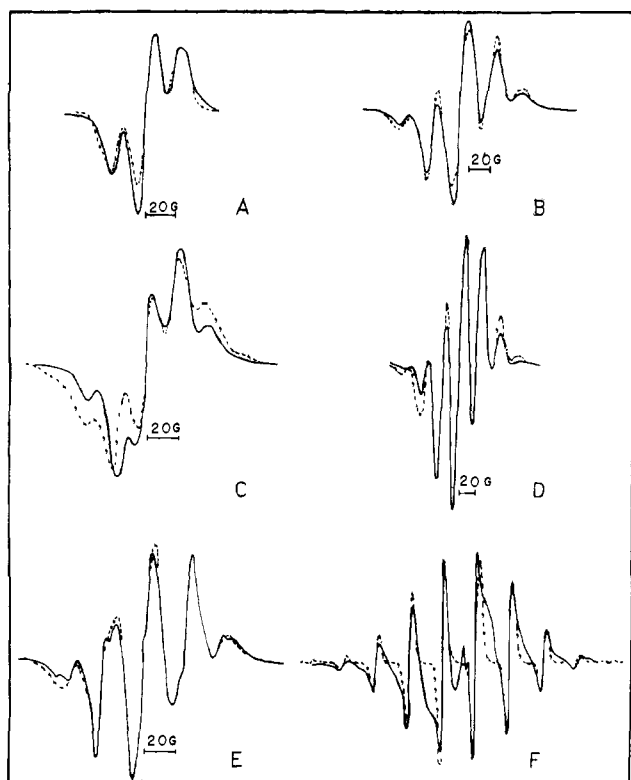


Figure 1.—Experimental (—) and calculated (---) e.p.r. spectra of amides irradiated with 1-Mev. electrons at liquid air temperature (cavity temperature about -140°): (A) N,N-dimethylbutyramide; (B) N,N-diethylacrylamide; (C) N,N-di-*n*-propylacetamide; (D) N,N-diisopropylacetamide; (E) propionamide; (F) trimethylacetamide. The scale along the magnetic field axis is indicated in each case by a line 20 gauss wide.

Introduction

Many amides give rise to free radicals of considerable stability when the solid material is irradiated with X-rays or electrons. A number of studies of these radicals have been made by electron paramagnetic resonance (e.p.r.) spectroscopy and it has been shown that in some cases the anisotropic effects do not interfere with the identification of the radical even when polycrystalline material is used. Burrell³ studied a series of N-substituted aliphatic amides and found that on irradiation a hydrogen atom was usually removed from the carbon atom adjacent to nitrogen; if the α -positions were substituted, a β -hydrogen was removed. In only one case (N-neopentylpropionamide) did he also find a second radical in which a hydrogen atom had been removed from the carbon adjacent to carbonyl. When there is no substituent on nitrogen, however, a hydrogen atom is apparently removed from the carbon atom adjacent to the carbonyl group.⁴ Analogous radicals have been observed in irradiated aliphatic alcohols,⁵ and it was noted that an α -hydrogen was preferentially removed. Whiffen and co-workers⁶ have made extensive studies of the radicals from irradiated carboxylic acids, which appear to be analogous to those obtained from irradiated amides,

(3) E. J. Burrell, Jr., *J. Am. Chem. Soc.*, **83**, 574 (1961), and earlier references cited there.

(4) C. F. Luck and W. Gordy, *ibid.*, **78**, 3240 (1956); I. Miyagawa and W. Gordy, *ibid.*, **83**, 1036 (1961).

(5) M. C. R. Symons, *et al.*, *J. Chem. Soc.*, 263, 269, 277 (1959).

(6) Y. D. Tsvetkov, J. R. Rowlands, and D. H. Whiffen, to be published.

and Ayscough and Thompson⁷ have obtained similar radicals in α -irradiated polycrystalline alkyl halides.

We have carried out studies on the e.p.r. spectra of radicals produced on irradiating polycrystalline samples of several N,N-disubstituted amides of the general type RCONR'R'', where R, R', and R'' are aliphatic groups or hydrogen; a few monosubstituted and unsubstituted amides and two carboxylic acids were also studied. In most of the cases reported here the spectra appear to arise from a single radical, and identification along conventional lines can be made. In a few cases an unambiguous assignment of structure to the radical will require isotopic substitution or single crystal data; the latter present experimental difficulties for substances liquid at room temperature.

No studies of these substituted amides seem to have been made, although some early work on acetamide and propionamide has been reported.⁴ Since most of the substituted amides are liquids at room temperature, both irradiation and examination of spectra must be carried out at low temperatures.

Experimental

Spectrometer. Some of the e.p.r. spectra were observed using a conventional X-band spectrometer employing a transmission cavity. This system has been described previously.⁸ The sample was cooled by passing dry nitrogen through a copper coil dipped in liquid air then over the sample. Temperatures down to -140° could be maintained in this way. The magnet and power supply permitted a resolution of about 0.1 gauss, and the sensitivity was about 10^{16} spins.

Some spectra were also measured using a Varian V-4501 e.p.r. spectrometer with 100-kc. modulation, along with a V-4531 multipurpose cavity and V-4547 variable temperature accessory. Regulated temperatures to -170° could be achieved. A V-4012-3B 12-in. rotating magnet system and V-2100B regulated power supply provided fields of adequate homogeneity (about 20 mgauss). Fields were measured with a proton magnetic resonance probe⁹ and a Hewlett-Packard 524C electronic counter. The klystron frequency was measured by beating it with a harmonic of a Micro-Now Model 101 frequency calibrator and tuning the difference with a communications receiver. The g values for all these radicals were found to be near 2.003 and are not reported in detail.

Most of the samples were reagent grade Eastman chemicals, but several were prepared in these laboratories for n.m.r. studies. The purification and properties of the latter have been described.^{10,11}

Irradiation. The liquids were placed in sealed polyethylene sample tubes or in sealed thin-wall Kimax capillary tubes and frozen in liquid air. The frozen solids were irradiated, while cooled to liquid air temperature, with 1-Mev. electrons from a General Electric resonant transformer. Dosages were 3×10^6 to $5 \times 10^7 r$. The samples were transferred to the

(7) P. B. Ayscough and C. Thompson, *Trans. Faraday Soc.*, **58**, 1477 (1962).

(8) R. J. Faber and M. T. Rogers, *J. Am. Chem. Soc.*, **81**, 1249 (1959).

(9) L. Buss and L. Bogart, *Rev. Sci. Instr.*, **31**, 204 (1960).

(10) J. C. Woodbrey and M. T. Rogers, *J. Am. Chem. Soc.*, **84**, 13 (1962).

(11) L. LaPlanche and M. T. Rogers, *ibid.*, **85**, 3728 (1963); **86**, 337 (1964).

cavity of the spectrometer without allowing them to warm appreciably and e.p.r. spectra were taken at about -140° .

Calculations. A MISTIC computer program was employed to compute the first derivative spectrum to be expected for a given set of spectral lines with gaussian line shape. The ratio of the hyperfine splitting to the line width was adjusted by trial and error until the computed spectrum gave the best approximation to the experimental spectrum. The relative intensities employed were the binomial coefficients appropriate to the given multiplet. A few spectra were also obtained as second derivative plots; this was found to improve the resolution and precision of measurement of splittings.

Results

Experimental e.p.r. first-derivative spectra (solid lines), and the matching computed spectra (dashed lines), are shown in Figures 1 and 2 for some of the radicals. The number of hyperfine components, the line widths, and the hyperfine splittings obtained from a comparison of the computed spectra and the experimental spectra are listed in Table I (to an accuracy of ± 1 gauss). Our results are in satisfactory agreement with previous work where such is available (compounds no. 20 and 21, Table I).

In certain cases additional weaker lines indicative of a second radical could be seen, but these have been ignored since their intensities were too low to permit study.

Discussion

It has been shown by studies of aliphatic carboxylic acids⁶ and amides³ that irradiation of substances of this type usually leads to production of radicals by loss of a hydrogen atom which is able to diffuse away from the radical site, preventing recombination. There are exceptions to this rule and various other bonds may be broken.^{3,6} The mechanism of the radiation damage is not known, but the evidence appears to be consistent with a direct bond rupture at the final site, and hydrogen transfer does not appear to take place along the aliphatic chains.³ In rare cases two radicals are produced and it is sometimes possible to make use of the differential rate of decay to identify each.

The identification of the trapped radicals in polycrystalline materials from the e.s.r. spectra is based on observations of the number of hyperfine lines resulting from interaction of the odd electron with various magnetic nuclei in the molecule, their relative intensities, the line widths, and the g factors. The isotropic hyperfine interactions only are considered here, the anisotropic components not being resolvable. It is known^{6,7} that a proton attached to the carbon atom on which the odd electron is centered (an α -proton) produces an isotropic splitting of 17–22 gauss in aliphatic radicals whereas the β -protons may produce isotropic splittings of from 0 to about 45 gauss depending on the orientation between the $C-H_{\beta}$ bond and the axis of the p -orbital on the α -carbon atom in which the odd electron spends most of its time. When the β -protons are equivalent by rapid reorientation as in the case of a β -methyl group, the splitting is close to the value for α -protons (about 25 gauss for β -methyl groups). In other cases, as noted below, when there is

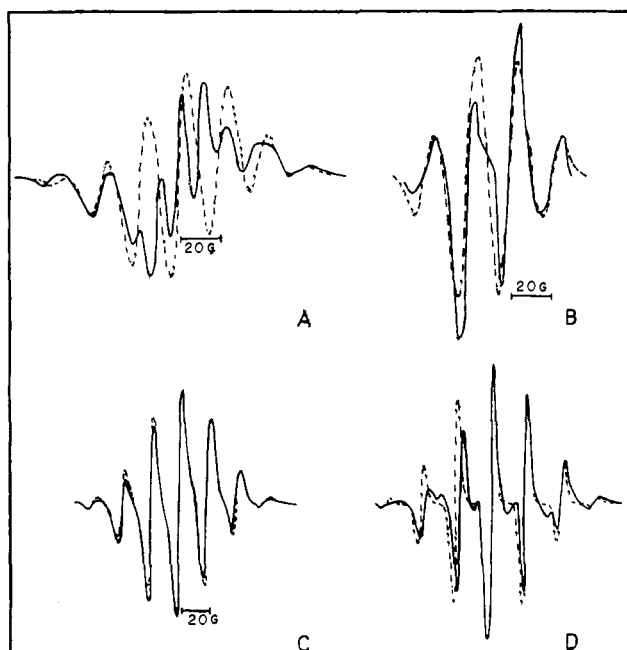


Figure 2. Experimental (—) and calculated (---) e.p.r. spectra of isobutyramide and isobutyric acid irradiated with Mev. electrons at liquid air temperature: (A) isobutyramide immediately after irradiation, at about -140° , and the calculated seven-line spectrum; (B) the difference (—) between the experimental and calculated spectra shown in A, which is taken as the experimental spectrum for the second radical, and the calculated (---) four-line spectrum of the second radical; (C) isobutyramide after warming or aging; (D) isobutyric acid.

a β -CH or β -CH₂ group, the splitting must be deduced from the spectrum since the radicals may have the β -protons fixed in orientation and the arrangement depends on the particular material being studied (and perhaps temperature).

Orientation. It frequently happens that the n α -protons and the m β -protons produce isotropic splittings, A , which are nearly equal (20 ± 5 gauss); since the line widths are large (5–15 gauss), this results in a spectrum of $(n + m + 1)$ lines with intensities given more or less by the usual binomial coefficients.

The first seven compounds of Table I are of the type $RCONRCH_3$ and give rise to three-line spectra with relative intensities 1:2:1 and values of $A = 18.5 \pm 1.5$ gauss. Since the values of A for radicals of the type $-CH_2CO-$ are normally⁶ 20–23 gauss (as for acetamide), it seems likely that all these radicals are of the class $R-CO-NR'CH_2$ and that the somewhat lower values of A are associated with some delocalization of the odd electron onto nitrogen. It is perhaps not surprising that the lines from interaction with the nitrogen nucleus are not seen since the coupling should be small (< 10 gauss) and the line widths are ~ 15 gauss here; the nitrogen interactions would serve only to help broaden the lines. It has been previously noted¹² that the nitrogen hyperfine splitting is small in a radical of the type $-NH-CH-$. The NH proton likewise produced no detectable hyperfine interaction¹²; we have similarly not found any evidence for hyperfine splitting by the $-NH-$ proton in the monosubstituted amides although it is a β -proton.

(12) I. Miyagawa, Y. Kurita, and W. Gordy, *J. Chem. Phys.*, **33**, 1599 (1960).

Table I. Parameters for the E.p.r. Spectra of Radicals Obtained on Irradiating Amides and Carboxylic Acids

Code	Amide or acid	Probable radical	No. of hyperfine components	Line width, ^{a,e} gauss	Hyperfine splitting, ^a A, gauss
1	N-Methylacetamide	CH ₃ CONCH ₂ ·	3		(18) ^b
2	N,N-Dimethylacetamide	CH ₃ CON<CH ₃ CH ₂ ·	3		(18) ^b
3	N-Methylpropionamide	CH ₃ CH ₂ CONHCH ₂ ·	3	14.5	17.1
4	N,N-Dimethylpropionamide	CH ₃ CH ₂ CON<CH ₃ CH ₂ ·	3	14.2	17.5
5	N,N-Dimethylbutyramide	CH ₃ CH ₂ CH ₂ CON<CH ₃ CH ₂ ·	3	14.0	16.8
6	N-Methylisobutyramide	(CH ₃) ₂ CHCONHCH ₂ ·	3	14.7	19.6
7	N,N-Dimethylacrylamide	CH ₂ =CHCON<CH ₃ CH ₂ ·	3		
8	N,N-Dimethylchloroacetamide	CH ₂ ClCON<CH ₃ CH ₂ ·	3		(18) ^b
9	N-Ethylformamide	HCONHCH ₂ CH ₃	5		(22) ^b
10	N,N-Diethylformamide	HCON<CH ₂ CH ₃ CHCH ₃	5	16.7	20.4
11	N-Ethylacetamide	CH ₃ CONHCH ₂ CH ₃	5		(22) ^b
12	N,N-Diethylacetamide	CH ₃ CON<CH ₂ CH ₃ CHCH ₃	5		(22) ^b
13	N,N-Diethyl- <i>n</i> -butyramide	CH ₃ CH ₂ CH ₂ CON<CH ₂ CH ₃ CHCH ₃	5	15.2	20.1
14	N-Ethylisobutyramide	(CH ₃) ₂ CHCONHCH ₂ CH ₃	5		
15	N,N-Diethylacrylamide	CH ₂ =CHCON<CH ₂ CH ₃ CHCH ₃	5	15.5	20.6
16	N,N-Diethylchloroacetamide	CH ₂ ClCON<CH ₂ CH ₃ CHCH ₃	5		(22) ^b
17	N,N-Di- <i>n</i> -propylacetamide	CH ₃ CON<CH ₂ CH ₂ CH ₃ CHCH ₂ CH ₃	5	17.5	18.4
18	N-Isopropylacetamide	CH ₃ CONHĊ(CH ₃) ₂	7		(19) ^b
19	N,N-Diisopropylacetamide	CH ₃ CCN<CH(CH ₃) ₂ ·C(CH ₃) ₂	7	15.4	22.4
20	Acetamide	·CH ₂ CONH ₂	3		(23) ^c
21	Propionamide	CH ₃ ĊHCONH ₂	5	17.3	24.7
22	Isobutyramide	(CH ₃) ₂ ĊCONH ₂ or CH ₃ >CHCONH ₂ ·CH ₂	7 4	15.3 9.6	23.6 21.6
23	Isobutyramide (aged)	(CH ₃) ₂ CĊONH ₂	7	6.5	19.6
24	Trimethylacetamide	(CH ₃) ₃ C·	10		
25	Isobutyric acid	(CH ₃) ₂ ĊCOOH	7		
26	Trimethylacetic acid (pivalic acid)	(CH ₃) ₃ C·	10		(23) ^d

^a In some cases only the number of hyperfine lines is reported since precise values of hyperfine splittings and line widths were not measured. The values are similar (± 2 gauss), however, to those reported for analogous radicals. ^b Approximate values. ^c Value is taken from ref. 4. ^d Value from ref. 6 for ammonium pivalamide. ^e Line widths were taken as the separation between the maximum and minimum of the first derivative curves.

A series of ethyl derivatives (no. 9 to 16) give rise to five-line spectra with relative intensities 1:4:6:4:1 which are attributed to radicals $R-\text{CONR}'\dot{\text{C}}\text{HCH}_3$ with the one α -proton and three β -methyl protons producing an average value of A of about 20.2 gauss. For propionamide, where the five-line spectrum is presumably due to the radical $\text{CH}_3\dot{\text{C}}\text{HCONH}_2$, the value of A is higher, again suggesting that in the $-\text{N}-\dot{\text{C}}\text{H}_2$ type of radical there is some delocalization of the odd electron onto nitrogen. A splitting of 22 gauss has been reported for the radical $\text{CH}_3\dot{\text{C}}\text{HOH}$ from irradiated propanol.⁵

The five-line spectrum for *N,N*-di-*n*-propylacetamide has intensities more nearly approaching 1:2:2:2:1 and may tentatively be assigned to the radical $\text{CH}_3-\text{CON}(n-\text{C}_3\text{H}_7)\dot{\text{C}}\text{HCH}_2\text{CH}_3$ where the α -proton and one β -proton produce splittings of ~ 18.5 gauss and the second β -proton a splitting of ~ 37 gauss. Radicals with the proton removed from a β - or γ -position should give rise to more lines and different relative intensities. It should be noted that the four-line spectra in irradiated *N*-(*n*-propyl)propionamide and *N*-(*n*-propyl)butyramide reported by Burrell³ indicate a radical of the same structure as the one postulated above but with the α - and both β -couplings equal.

Compounds with isopropyl groups attached to nitrogen (no. 18 and 19) or attached to carbonyl carbon (no. 22, 23, and 25) give rise to radicals of the type $(\text{CH}_3)_2\dot{\text{C}}-\text{X}$ with seven-line spectra indicative of six equivalent methyl protons. Irradiated isobutyramide shows, in addition to this radical, a second one, and we have attempted to determine the spectrum of this radical by subtracting a seven-line spectrum (built up from the outer four lines of Figure 2A) from the complex one of Figure 2A. The difference (Figure 2B) is a fairly good four-line spectrum with binomial

intensities and might be the methyl radical or the radical $\dot{\text{C}}\text{H}_2\text{CH}(\text{CH}_3)\text{CONH}_2$ in which the α - and β -couplings are about equal. The latter is favored since we do not see any lines attributable to $\dot{\text{C}}\text{H}(\text{CH}_3)-\text{CONH}_2$ which should remain if methyl were produced. The four-line spectrum disappears rapidly on aging or warming.

Trimethylacetamide and trimethylacetic acid appear to give rise to the *t*-butyl radical, the ten-line spectrum with binomial intensities indicating nine equivalent protons. The radical $(\text{CH}_3)_3\dot{\text{C}}$ has also been reported in irradiated ammonium trimethylacetate.⁶

Some empirical rules may be deduced which make it possible to predict the site of radiation damage in many aliphatic amides. An alkyl substituent on nitrogen is the most favored site for loss of a proton, the alkyl group attached to carbonyl being attacked only in the amides themselves. In the amides and *N*-substituted amides *N*-H bonds never appear to be broken. It is a C-H bond adjacent to the nitrogen atom or the carbonyl group which is preferentially broken. When there is no hydrogen atom on the carbon atoms adjacent to N or to CO, another bond will break; thus trimethylacetamide gives the *t*-butyl radical.

The carboxylic acids appear to give the same radicals as the amides and again there is a preference for loss of a hydrogen atom from the carbon adjacent to nitrogen or carbonyl.

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