of the protonation of *tert*-butyl carbanions, but not as a proton source for the carbanion itself. A qualitatively similar result was seen in a study involving a primary alkyl halide;[10] the electrolysis of 0.0025 M 1-iododecane at −1.70 V in dimethylformamide containing 0.1 M tetramethylammonium perchlorate, 0.002 M water, and 0.25 M $CD_2(COOC_2H_5)_2$ gave decane as the major product, of which only 17% was deuterated. It should be noted that the extent of deuterium incorporation is an upper limit because scrambling of the isotopic label between diethyl malonate and water could occur on the time scale of an electrolysis and because the same molecule of water might undergo more than one set of deprotonation–protonation reactions.

In conclusion, at potentials corresponding to its second polarographic wave, *tert*-butyl bromide undergoes reduction to yield the *tert*-butyl carbanion; the primary reaction of the carbanion is protonation, with adventitious water supplying the majority of protons. For low concentrations of water (<0.015 M), both tetramethylammonium and tetraethylammonium cations furnish substantial quantities of protons, whereas the solvent and the unreduced starting material donate few if any protons to the *tert*-butyl carbanion. In the presence of tetraethylammonium perchlorate, a significant portion of the *tert*-butyl carbanions react with dimethylformamide to form pivalaldehyde.

Acknowledgment. Appreciation is expressed to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research.

Registry No. *t*-BuBr, 507-19-7; *t*-Bu·, 1605-73-8; *t*-Bu⁻, 65114-21-8; $(CH_3)_3CH$, 75-28-5; $CH_3C(CH_3)=CH_2$, 115-11-7; $(CH_3)_3CC(CH_3)_3$, 594-82-1; $(CH_3)_3CCHO$, 630-19-3; $Me_4N^+ClO_4^-$, 2537-36-2; $Bu_4N^+ClO_4^-$, 1923-70-2; $Et_4N^+ClO_4^-$, 2567-83-1.

First Electron Spin Resonance Spectroscopic Study of Aliphatic RCONSR′ Radicals. ^{17}O and ^{33}S Hyperfine Splittings[1]

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The first ESR study of aliphatic RCONSR′ radicals is described. The ESR parameters for the amidyls in benzene or toluene from +18 to −50 °C are a_N = 8.0–8.55 G, $a_{^{33}S}$ = 10.5–10.8 G, and g = 2.0091–2.0094. ^{17}O-Enriched PhCONS-*t*-Bu radical has also been generated, and the value $a_{^{17}O}$ = 2.70 G (in benzene at 18 °C) has been determined. These ESR parameters confirm a higher π-orbital spin density on the nitrogen and sulfur, whereas a very low π-orbital spin density on the oxygen. In addition, the ESR parameters for the structurally interesting PhCONSS-*t*-Bu radical are also reported.

N-Alkylcarboxamidyl radicals (RCONR′) are among the most important intermediates in photochemical reactions.[2] Although a considerable amount of experimental and theoretical work has been devoted to determine the electronic structure in the ground state of RCONR′[3-5] and related radicals, *N*-alkoxycarboxamidyls[6] (RCONOR′), it has recently clearly demonstrated by variable-temperature ESR spectra of RCONSR′ radicals that they must have a π electronic structure in the ground state.[4c,d] While RCONR′ radicals are transient in lifetime,[4f,g] RCONOR′ radicals would be substantially stabilized by conjugative electron delocalization from the nitrogen to the alkoxy oxygen reinforced by the neighboring carbonyl group having an ability to accept the electrons.[6] Accordingly, the later radicals would be more long-lived. In this view, sulfur analogues, *N*-thiocarboxamidyls (RCONSR′) are also expected to be substantially stabilized in a similar manner, namely, conjugative electron delocalization from the nitrogen to the sulfur. In fact, we found in an earlier work that aromatic *N*-thiocarboxamidyl radicals persist over a long period, even in the presence of oxygen.[7] However, in contrast to a large body of the ESR work on RCONR′ and RCONOR′ radicals, only little attention has been paid to RCONSR′ radicals and much has remained unsolved.[7]

In the present paper we report the first ESR spectroscopic study of structurally simple aliphatic RCONSR′ radicals, **2**. In this work, fortunately, we could observe ^{17}O and ^{33}S hyperfine splittings (hfs) for some **2** and could estimate the π-orbital spin density distribution in **2** on the basis of ESR parameters. In addition, we also report the ESR parameters for the structurally interesting *N*-dithiocarboxamidyl radical (RCONSSR′).

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(2) For reviews on the chemistry of amidyls, see: Neale, R. S. *Synthesis* **1971**, 1. Mackiewicz, P.; Furstoss, R. *Tetrahedron* **1978**, *34*, 3241.

(3) For reviews on ESR studies of amidyls, see: (a) Nelsen, S. F. In "Free Radicals"; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. 2, Chapter 21. (b) Danen, W. C.; Neugebauer, F. A. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 783.

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Table I. ESR Parameters for Radicals 2 and 4[a]

radical	temp, °C	solvent[b]	a_N	a_H[c]	a_{other}	g
2a	−50	A	8.1	1.3 (3)		2.0094
2b	−50	A	8.0	2.1 (2)		2.0092
2c	18	B	8.5	1.3 (1)		2.0091
2d	18	B	8.55		10.5 (^{33}S)	2.0091
2e	18	B	8.04		2.70 (^{17}O), 10.8 (^{33}S)	2.0092
4e	18	B	7.1			2.0109
PhCONSPh[d]	24	benzene	7.09	1.68 (3)[e]		2.0081

[a] Hyperfine splitting constants are given in Gauss. [b] A, 1:4 (v/v) *t*-BuOO-*t*-Bu–toluene; B, 1:4 (v/v) *t*-BuOO-*t*-Bu–benzene. [c] Numbers in parentheses refer to the number of equivalent protons. [d] Taken from ref 7. [e] Ortho and para protons of the phenylthio benzene ring.

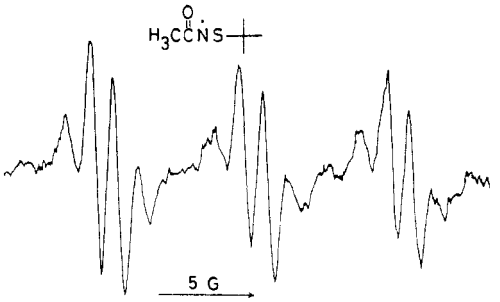


Figure 1. ESR spectrum of **2a** recorded during photolysis of a solution of **1a** in 1:4 (v/v) di-*tert*-butyl peroxide–toluene at −50 °C.

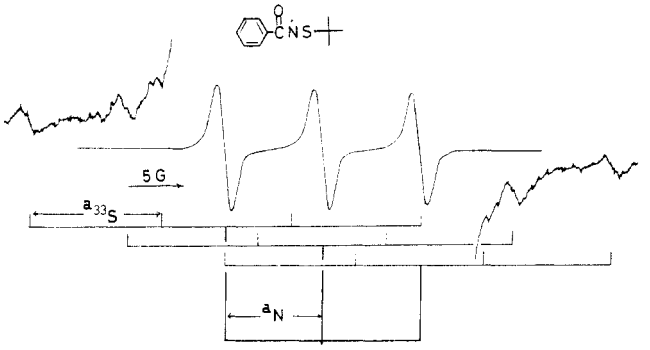
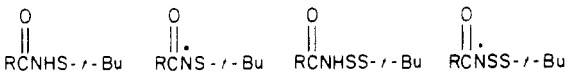


Figure 2. ESR spectrum of **2e** recorded during photolysis of a solution of **1e** in 1:4 (v/v) di-*tert*-butyl peroxide–benzene at 18 °C. The wings are shown at high gain (100 times). The stick diagram represents the theoretical reconstruction of splittings due to N and ^{33}S. The experimentally observed satellite lines due to ^{33}S are shown by the full lines and those lost in the main spectrum are shown by the dotted lines.

Results and Discussion

Amidyl radicals **2** were generated by photolysis of **1** in benzene or toluene in the presence of di-*tert*-butyl peroxide. Precursors **1** were obtained in 12–31% yields by



a, R = Me
b, R = Et
c, R = *i*-Pr
d, R = *t*-Bu
e, R = Ph

reaction of sodium amides (RCONHNa) with *t*-BuSCl in THF. Interestingly, the reaction also gave, besides **1**, small amounts (1.9–9.3%) of *N*-dithioamides **3**. It is well-known that when alkanesulfenyl chlorides are prepared from aliphatic disulfides by treating them with chlorine at low temperatures, small amounts of alkanethiosulfenyl chlorides (RSSCl) are simultaneously formed.[8] It is therefore

(8) Himel, C. M. U.S. Patent 2 807 615, 1957; *Chem. Abstra.* **1958**, *52*, 14706*a*.

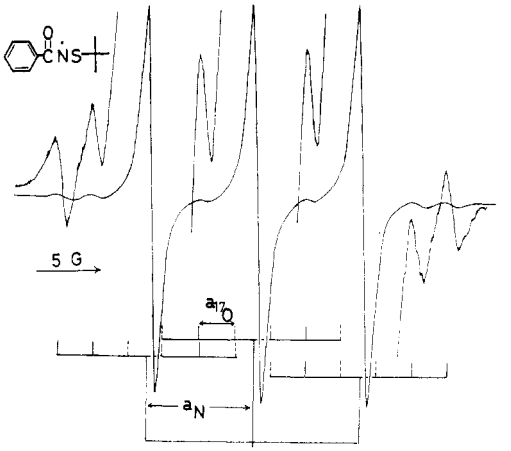


Figure 3. ESR spectrum of ^{17}O-enriched **2e** recorded during photolysis of a solution of ^{17}O-enriched **1e** in 1:4 (v/v) di-*tert*-butyl peroxide–benzene at 18 °C. The wings are shown at high gain (20 times). The stick diagram represents the theoretical reconstruction of splittings due to N and ^{17}O. The experimentally observed satellite lines due to ^{17}O are shown by the full lines, and those lost in the main spectrum are shown by the dotted lines.

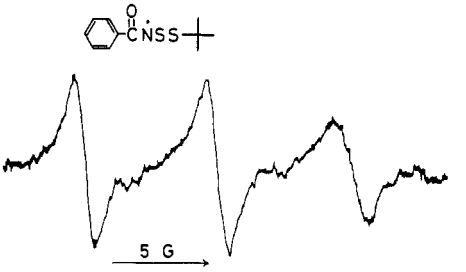


Figure 4. ESR spectrum of **4e** recorded during photolysis of a solution of **3e** in 1:4 (v/v) di-*tert*-butyl peroxide–benzene at 18 °C.

likely that the *N*-dithioamides **3** were yielded by reaction of sodium amides with the *t*-BuSSCl which was generated as a byproduct on chlorination of di-*tert*-butyl disulfide.

Some ESR spectra are shown in Figures 1–4, and the ESR parameters are summarized in Table I. As found in Figure 1, the ESR spectrum of **2a** is split into 1:3:3:1 quartets of an 1:1:1 triplet, indicating that it is split by the interaction with the nitrogen nucleus and the three protons in the acetyl group. The ESR spectra of **2b** and **2c** were split into 1:2:1 triplets of a 1:1:1 triplet or 1:1 doublets of a 1:1:1 triplet by the interaction with the nitrogen nucleus and the two or one γ protons in the acetyl group. On the other hand, **2d** and **2e** gave a simple 1:1:1 triplet spectrum.

Although radicals **2a–c** are transient and the ESR signals disappeared immediately upon interruption of UV irradiation, **2d** and **2e** persisted in solution over a long period. For example, the half-life time of **2d** in 1:4 (v/v) di-*tert*-buty peroxide–benzene at 18 °C is ~30 min and that of **2e** in the same solvent at 18 °C is far longer than 1 day.[9] Furthermore, it was found that introduction of

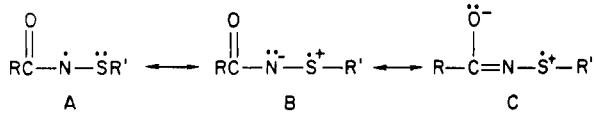
air into the degassed ESR samples had no effect other than to broaden the ESR lines, and the radicals were as persistent as in the degassed solution.[10] Accordingly, the aliphatic *N*-thiocarboxamidyls, as well as aromatic types of radicals, still retain the resistance to oxygen, and this result strickingly contrasts with the ready conversion of RCONR' radicals to the corresponding nitroxides in the presence of oxygen.[4b]

Owing to the great persistence of **2e**, it could be readily shown, by raising and lowering the temperature, that **2e** (and probably other **2** also) exists in equilibrium with a diamagnetic dimer. The enthalpy of dissociation ($\Delta H°$) for the dimer in 1:4 (v/v) di-*tert*-butyl peroxide–benzene, which was calculated from a plot of ln (cT) *vs.* $1/T$, where c is the relative radical concentration and T is the absolute temperature,[11,12] is 17.2 ± 0.5 kcal/mol.[13] This relatively low $\Delta H°$ value, as well as the persistence of **2** and the resistance of **2** to oxygen, is interesting with regard to the hypothesis concerning captodative stabilization or merostabilization: synergistic effect of resonance electron-donating and electron-withdrawing groups.[14]

Fortunately, we could observe ^{33}S hfs in the spectra of **2d** and **2e**, without any enrichment of ^{33}S atoms, on recording at high gain. As found in Figure 2, four satellite lines are completely resolved, and from the spectrum the value $a_{^{33}S}$ = 10.8 G was obtained (for **2d** the value was 10.5 G).

As found in Table I, the a_N and g values for **2** are both somewhat higher than the corresponding values for PhCONSPh (by 1.1 G for a_N and by 0.0011 for g). These increases in a_N and g are obviously due to the absence of the phenyl ring on sulfur that removes some spin from the nitrogen and sulfur in PhCONSPh.

The large a_N and large $a_{^{33}S}$ values found for **2** confirm that the unpaired electron resides mainly on the nitrogen and sulfur. Accordingly, radicals **2** can be best represented by the three principal canonical structures A–C, and the large g values of **2** reflect the substantially high spin density on the sulfur having a large spin–orbit coupling parameter.[15]

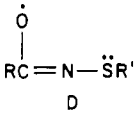


In a previous paper[7] we reported that in aromatic *N*-thiocarboxamidyl radicals there might be little delocalization of the unpaired electron to the carbonyl group on the basis of the ESR parameters (a_N, a_H, g) obtained. However, this cannot be unequivocally elucidated until the ^{17}O hfs constant due to the carbonyl oxygen has been evaluated. For this reason, ^{17}O-enriched (5.9 atom %) **2e** radical was generated by photolysis of ^{17}O-enriched **1e** in benzene containing di-*tert*-butyl peroxide. An ESR spectrum is illustrated in Figure 3. As found in the figure, six ^{17}O satellite lines are clearly seen on record at high gain, and from the spectrum the value $a_{^{17}O}$ = 2.70 G was obtained. This value is considerably smaller than that (4.0 G) for the carbonyl oxygen of the structurally close oxygen analogue, PhC^{17}ONOEt, which was previously reported by Forrester et al.[6f] The a_N value is also lower than that (9.9 G) for the oxygen analogue. We therefore account for these reductions in a_N and $a_{^{33}S}$ found on going from **2e** to the oxygen analogue in terms of the greater ability of RS– groups to groups.[16]

There is a simple relationship between the ^{17}O hfs constant and the π-orbital spin density at the oxygen neucleus, which has been established by Silver[17] through an investigation of the ^{17}O hfs of organic and inorganic oxygen-containing π radicals. If Silver's equation

$$\rho_O^\pi = a_{^{17}O}/Q_O = a_{^{17}O}/-41 \text{ G}$$

is applied to **2e**, the π-orbital spin density on the oxygen will be 0.066.[18] This value is very small and indicates that the π-orbital spin is only slightly delocalized onto the carbonyl oxygen. Accordingly, we can say that contribution of the canonical structure D to the structure of **2** is not important.



The π-orbital spin density at the sulfur nucleus can also be estimated from the ^{33}S hfs constant by using a simple relationship of the McConnell type, similar to the case of the ^{17}O hfs:[19]

$$\rho_S^\pi = a_{^{33}S}/Q_S = a_{^{33}S}/23 \text{ G}$$

In a previous paper,[20] we demonstrated, from a plot of the ^{33}S hfs constants for a variety of *N*-thioaminyls (RNSR') vs. the calculated π-orbital spin densities on the sulfurs, that the value Q_s = 23 G is valid in *N*-thioaminyls. On employment of this equation, we obtain the π-orbital spin density of 0.47 on the sulfur of **2e**. These values of π-orbital spin density then leave the value ρ_N^π = 0.46, provided that delocalization of the π-orbital spin onto the carbonyl carbon, the *tert*-butyl group, and the benzene ring can be neglected. Accordingly, the π-orbital spin is distributed equally between the nitrogen and sulfur.

Finally, we studied *N*-dithiocarboxamidyl radicals, **4**, by ESR spectroscopy. Although they have an interesting structure of –CONSS–, there has appeared no ESR study of these radicals in the literature.

Attempts to generate the radicals by direct photolysis of the solutions containing **3** and di-*tert*-butyl peroxide in

(9) The radicals were generated by photolysis of **1d** or **1e** in benzene in the presence of di-*tert*-butyl peroxide with 100-W high-pressure mercury lamp.

(10) It was reported that *N*-*tert*-butoxycarboxamidyl radicals were also inactive toward oxygen. See ref 6b.

(11) Vincow, G.; Dauben, H. J., Jr.; Hunter, F. R.; Volland, W. V. *J. Am. Chem. Soc.* **1969**, *91*, 2823.

(12) In the present work the relative radical concentrations were measured from the areas under the absorption curves of the singly integrated ESR spectra that were obtained on a JEOL JES-ID-2 integrator. The ESR measurement was carried out at four different temperatures between 4 and 36 °C, and the temperatures of the ESR cavity were measured with a copper-constantan thermocouple.

(13) The $\Delta H°$ measurement was repeated four times and averaged. Errors are standard deviations.

(14) Viehe, H. G.; Merényi, R.; Stella, L.; Janousek, Z. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 917. Viehe, H. G.; Janousek, Z.; Merényi, R.; Stella, L. *Acc. Chem. Res.* **1985**, *18*, 148. Leigh, W. O.; Arnold, D. R. *Can. J. Chem.* **1981**, *59*, 609.

(15) Sulfur spin–orbit coupling parameter is 382 cm^{-1}: McClure, D. S. *J. Chem. Phys.* **1949**, *17*, 905.

(16) Block, E. In "Reactions of Organosulfur Compounds"; Blomquist, A. T., Wasserman, H. H., Eds.; Academic Press: New York, 1978; p 189.

(17) Melamud, E.; Silver, B. L. *J. Phys. Chem.* **1973**, *77*, 1896. Also, see: Camaioni, D. M.; Walter, H. F.; Pratt, D. W. *J. Am. Chem. Soc.* **1973**, *95*, 4057. Camaioni, D. M.; Walter, H. F.; Jordan, J. E.; Pratt, D. W. *Ibid.* **1973**, *95*, 7978.

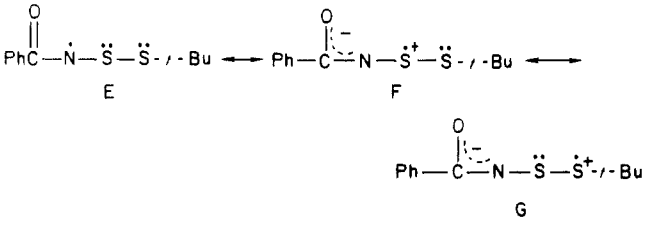
(18) The ^{17}O hfs constant is taken to have the negative sign. See ref 17.

(19) Sullivan, P. D. *J. Am. Chem. Soc.* **1968**, *90*, 3618. Bramwell, F. B.; Haddon, R. C.; Wudl, F.; Kaplan, M. L.; Marshall, J. H. *Ibid.*, **1978**, *100*, 4612. Kwan, C. L.; Carmark, M.; Kochi, J. K. *J. Phys. Chem.* **1976**, *80*, 1786.

(20) Miura, Y.; Asada, H.; Kinoshita, M.; Ohta, K. *J. Phys. Chem.* **1983**, *87*, 3450.

the cavity of an ESR instrument at +18 to −50 °C with a high-power xenon lamp (1 kW) gave a weak and broad 1:1:1 triplet spectrum in the case of **3e** only (Figure 4). The other afforded no ESR signals. We assign the radical structure **4e** on the basis of the unusually high g value (2.0109) and assume that the difficulty in obtaining ESR spectra of **4** is attributable mainly to facile fission of the S–S bond in **4**.

We are interested in the unusually high g value of **4e** and assume that this is due to an additional contribution of the canonical structure G. This assumption is in accord with some reduction (0.9 G) in the magnitude of a_N, relative to that of **2e**. In this view, we have been eager to know the ^{33}S hfs constants for the two sulfur atoms. However, the ESR signal was not so strong as to permit us to observe them.



Experimental Section

All melting points were taken on a Yanagimoto micro melting point apparatus and are uncorrected. Infrared (IR) spectra were run on a Jasco A-200 spectrophotometer. ^1H nuclear magnetic resonance (NMR) spectra were recorded with a JEOL JNM PS-100 spectrometer, and chemical shifts (δ) are expressed relative to internal tetramethylsilane.

Acetamide, propionamide, isobutyramide, pivalamide, and benzamide were commercially obtained and used without any purification.

General Procedure for Preparation of *N*-(*tert*-Butylthio)amides (1). Di-*tert*-butyl disulfide (5.58 g, 31.3 mmol) was dissolved in 20 mL of dry hexane, and chlorine was bubbled into the solution at a rate of ~40 mL/min for 30–40 min at 30 ± 3 °C, the solution turning yellow or orange. After the unreacted chlorine dissolved was removed by bubbling nitrogen into the solution, it was concentrated to ca. 5 mL under reduced pressure.

An amide (20 mmol) was dissolved in 100 mL of dry tetrahydrofuran. To the solution was added 1.05 g (26 mmol) of NaH (60 wt %), and the mixture was stirred for 3–12 h at room temperature, giving a suspension. The hexane solution of 2-methyl-2-propanesulfenyl chloride was added, in one portion, to the suspension at 0–5 °C, and the resulting colorless or light yellow thick solution was stirred at the same temperature for 4 h. Then, 4 mL (29 mmol) of triethylamine was added, and the resultant solution was stirred for an additional 0.5 h. After NaCl formed was removed by filtration, the solution was concentrated under reduced pressure and the residue was chromatographed on alumina (Merck, art 1097; column size 3.5 × 7 cm). Elution with benzene gave di-*tert*-butyl disulfide, and subsequent elution with ether gave a mixture of *N*-(*tert*-butylthio)amides (**1a–e**) and *N*-(*tert*-butyldithio)amides (**3a–e**).[21] The mixtures were rechromatographed on alumina (column size 3.5 × 20 cm) as described below to separate the mixtures into the two components.

***N*-(*tert*-Butylthio)acetamide (1a) and *N*-(*tert*-Butyldithio)acetamide (3a).** Chromatography of the mixture of **1a** and **3a** with ether as eluant first gave **3a**, and further elution with the same solvent gave **1a**.

1a: Colorless needles, mp 51–52.5 °C (from hexane); yield 12% (0.35 g, 2.4 mmol); IR (KBr) 3200 (NH), 1660 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.30 (s, *t*-Bu, 9 H), 2.17 (s, Me, 3 H), 6.90 and 7.58 (each br s, NH, 1 H). Anal. Calcd for $C_6H_{13}NOS$: C, 48.95; H, 8.90; N, 9.51. Found: C, 48.84; H, 9.01; N, 9.19.

3a: Colorless needles, mp 77–78 °C (from hexane); yield 1.3% (45 mg, 0.25 mmol); IR (KBr) 3220 (NH), 1665 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.40 (s, *t*-Bu, 9 H), 2.15 (br s, Me, 3 H), 6.73 (br s, NH, 1 H). Anal. Calcd for $C_6H_{13}NOS_2$: C, 40.20; H, 7.31; N, 7.81. Found: C, 40.02; H, 7.24; N, 7.70.

***N*-(*tert*-Butylthio)propionamide (1b) and *N*-(*tert*-Butyldithio)propionamide (3b).** Chromatography of the mixture of **1b** and **3b** with 1:100 (v/v) ethanol–benzene as eluant gave **3b**, and subsequent elution with ether gave **1b**.

1b: Colorless needles, mp 38.5–39 °C (from hexane); yield 13% (0.41 g, 2.6 mmol); IR (KBr) 3200 (NH), 1655 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.20 (t, J = 8 Hz, CH_3CH_2, 3 H), 1.27 (s, *t*-Bu, 9 H), 2.38 (br q, J = 8 Hz, CH_3CH_2, 2 H), 6.40 and 6.70 (each br s, NH, 1 H). Anal. Calcd for $C_7H_{15}NOS$: C, 52.14; H, 9.38; N, 8.69. Found: C, 51.92; H, 9.47; N, 8.67.

3b: Colorless needles, mp 46–47 °C (sublimation); yield 6.1% (0.23 g, 1.2 mmol); IR (KBr) 3230 (NH), 1660 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.17 (t, J = 8 Hz, CH_3CH_2, 3 H), 1.44 (s, *t*-Bu, 9 H), 2.38 (br s, CH_3CH_2, 2 H), 6.78 (br s, NH, 1 H). Anal. Calcd for $C_7H_{15}NOS_2$: C, 43.49; H, 7.82; N, 7.25. Found: C, 43.60; H, 7.90; N, 7.30.

***N*-(*tert*-Butylthio)isobutyramide (1c) and *N*-(*tert*-Butyldithio)isobutyramide (3c).** Chromatography of the mixture of **1c** and **3c** with benzene as eluant gave **3c**, and subsequent elution with ether gave **1c**.

1c: Colorless needles, mp 120–120.5 °C (from hexane); yield 18% (0.62 g, 3.6 mmol); IR (KBr) 3240 (NH), 1670 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.18 (d, J = 7 Hz, Me_2CH, 6 H), 1.26 (s, *t*-Bu, 9 H), 2.57 (sept, J = 7 Hz, Me_2CH, 1 H), 6.77 (br s, NH, 1 H). Anal. Calcd for $C_8H_{17}NOS$: C, 54.82; H, 9.77; N, 7.99. Found: C, 54.95; H, 9.84; N, 8.01.

3c: Colorless needles, mp 105–105.5 °C (from hexane); yield 5.9% (0.24 g, 1.2 mmol); IR (KBr) 3200 (NH), 1670 cm^{-1} (C=O); ^1H NMR (CDCl) δ 1.16 (d, J = 7 Hz, Me_2CH, 6 H), 1.39 (s, *t*-Bu, 9 H), 2.42 (br s, CH, 1 H), 6.54 (br s, NH, 1 H). Anal. Calcd for $C_8H_{17}NOS_2$: C, 46.34; H, 8.26; N, 6.76; S, 30.92. Found: C, 46.22; H, 8.19; N, 6.70; S, 30.77.

***N*-(*tert*-Butylthio)pivalamide (1d) and *N*-(*tert*-Butyldithio)pivalamide (3d).** Chromatography of the mixture of **1d** and **3d** with benzene as eluant gave **3d**, and subsequent elution with ether gave **1d**.

1d: Colorless needles, mp 147–148 °C (from hexane); yield 31% (1.19 g, 6.3 mmol); IR (KBr) 3290 (NH), 1665 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.27 (s, *t*-Bu, 18 H), 6.47 (br s, NH, 1 H). Anal. Calcd for $C_9H_{19}NOS$: C, 57.10; H, 10.12; N, 7.40. Found: C, 57.10; H, 10.21; N, 7.20.

3d: Colorless needles, mp 149–150 °C (from hexane); yield 9.3% (0.42 g, 1.9 mmol); IR (KBr) 3270 (NH), 1660 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.21 (s, *t*-Bu, 9 H), 1.38 (s, *t*-Bu, 9 H), 6.97 (br s, NH, 1 H). Anal. Calcd for $C_9H_{19}NOS_2$: C, 48.83; H, 8.65; N, 6.33; S, 28.96. Found: C, 48.68; H, 8.59; N, 6.37; S, 29.05.

***N*-(*tert*-Butylthio)benzamide (1e) and *N*-(*tert*-Butyldithio)benzamide (3e).** Chromatography of the mixture of **1e** and **3e** with benzene as eluant gave **3e**, and subsequent elution with ether gave **1e**.

1e: Colorless needles, mp 177–178 °C (from benzene–hexane); yield 26% (1.07 g, 5.1 mmol); IR (KBr) 3190 (NH), 1650 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.32 (s, *t*-Bu, 9 H), 7.14 (br s, NH, 1 H), 7.43–7.87 (m, aromatic, 5 H). Anal. Calcd for $C_{11}H_{15}NOS$: C, 63.12; H, 7.22; N, 6.69. Found: C, 63.26; H, 7.32; N, 6.46.

3e: Colorless needles, mp 137–139 °C (from hexane); yield 8.0% (0.38 g, 1.6 mmol); IR (KBr) 3210 (NH), 1655 cm^{-1} (C=O); ^1H NMR ($CDCl_3$) δ 1.41 (s, *t*-Bu, 9 H), 7.27–7.84 (m, NH and aromatic, 6 H). Anal. Calcd for $C_{11}H_{15}NOS_2$: C, 54.47; H, 6.26; N, 5.80; S, 26.57. Found: C, 54.51; H, 6.24; N, 5.79; S, 26.32.

^{17}O-Enriched *N*-(*tert*-Butylthio)benzamide. ^{17}O-Enriched benzamide was prepared according to the procedure of Bender;[22,23] 0.70 g (5.7 mmol) of benzoic acid was dissolved in a mixture of 2 mL of 2 N hydrochloric acid and 1 mL of water containing 20 atom % of ^{17}O (purchased from Japan Radioisotope Association), and the mixture was refluxed for 1 day under nitrogen. After the mixture was cooled in an ice bath, the solid mass (0.70 g) was

(21) Chromatography was quickly conducted (usually finished in ~1 h) so as to suppress decomposition of products **1** and **2** occurring during chromatography. However, if the products were once subjected to chromatography, they showed no decomposition in repeated chromatography, in spite of a long time taken to separate the products.

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filtered and dried under vacuum.

The ^{17}O-enriched benzoic acid (0.70 g) and 0.20 mL of thionyl chloride were mixed and refluxed for 3 h under nitrogen. The excess thionyl chloride and hydrogen chloride were completely removed under vacuum. The resulting residue (oil) was dissolved in 10 mL of dry benzene, and the resulting solution was added to a stirred benzene solution (ca. 150 mL) containing a large excess of ammonia at 0–5 °C. After filtration, the mixture was evaporated under reduced pressure to leave a crystalline mass, which was crystallized from benzene: colorless needles, mp 128.5–129.5 °C; yield 79% (0.55 g, 4.5 mmol). The ^{17}O atom percent of the amide was determined from its mass spectrum to be 5.9.

^{17}O-enriched **1e** was obtained in 23% yield (0.10 g, 0.48 mmol) from 0.25 g (2.1 mmol) of the ^{17}O-enriched benzamide by the same procedure as described above.

ESR Measurements. A 5–20-mg portion of amide **1** or **3** and 0.40 mL of 1:4 (v/v) di-*tert*-butyl peroxide–benzene (or toluene) were placed in an ESR cell. The cell was degassed by three freeze–pump–thaw cycles using a high-vacuum line and sealed off. It was then set in the cavity of an ESR instrument and irradiated directly with an 100-W high-pressure mercury (JEOL JES-UV-1) or an 1-kW xenon lamp (Wacom Xenon UV-10X). ESR spectra were recorded during irradiation or in the dark after irradiation of a few minutes with a JEOL JES-ME-3X or JEOL JES-FE-2XG spectrometer equipped with an X-band microwave unit and 100-kHz field modulation. Hyperfine splitting constants and g values were determined by comparison with Fremy's salt in K_2CO_3 aqueous solution (a_N 13.09 G,[24] g 2.0057[25]). Estimated accuracy was as follows: ±0.1 G for a_N, a_H, and $a_{^{17}O}$, ±0.2 G for $a_{^{33}S}$, and ±0.0002 for g.

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Registry No. **1a**, 100682-56-2; **1b**, 100682-58-4; **1c**, 100682-60-8; **1d**, 100682-62-0; **1e**, 100682-64-2; **2a**, 100682-69-7; **2b**, 100682-70-0; **2c**, 100682-71-1; **2d**, 100682-72-2; **2e**, 100682-73-3; **3a**, 100682-57-3; **3b**, 100682-59-5; **3c**, 100682-61-9; **3d**, 100682-63-1; **3e**, 100682-65-3; **4e**, 100682-74-4; *z*-BuSCl, 52322-55-1; ^{17}O-enriched benzoic acid, 100682-66-4; ^{17}O-enriched benzamide, 100682-67-5; ^{17}-enriched *N*-(*tert*-butylthio)benzamide, 100682-68-6; acetamide, 60-35-5; propionamide, 79-05-0; isobutyramide, 563-83-7; pivalamide, 754-10-9; benzamide, 55-21-0; benzoic acid, 65-85-0.

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Use of Proton Spin–Lattice Relaxation and Nuclear Overhauser Effect Data in Structure Analysis of Alkaloids

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The diagnostic potential of ^1H spin–lattice relaxation measurements has been evaluated for seven morphine, four cinchona, and four tropane alkaloids. Using an approach that stresses examination of specific relaxation pathways, analyzed with the aid of calculations on model structures, it has been shown that ^1H spin–lattice relaxation can provide detailed information on molecular structure and relative stereochemistry of alkaloids.

Analysis of ^1H spin–lattice relaxation is now routinely used to gain insight into the primary structure of organic molecules in solution. The most commonly used methods involve spin–lattice relaxation rate (R_1) measurements,[1] determination of nuclear Overhauser effect[2] (NOE) enhancements, or combinations of these. It has been shown previously that qualitative analysis of spin–lattice relaxation can be useful for determination of certain details of the three-dimensional solution structure (e.g., ref 3 and 4), whereas precise, highly accurate data are required for three-dimensional structures at the angstrom level (e.g., ref 5, 6, and 7). The approach used in our studies involves detailed calculation of relaxation pathways from model structures and qualitative experimental measurement of nonselective R_1 values and NOE enhancements, from which it is possible to determine solution structures at a level sufficient to characterize primary structure and relative stereochemistry.[8,9] Experimental procedures have been examined in detail,[10,11] and the diagnostic potential has been surveyed for carbohydrates[12] and steroids.[4] In this report, our investigations of the potential of ^1H R_1 values for the determination of the structure and stereochemistry of natural products are extended, by examining spin–lattice relaxation in some typical alkaloids, and are refined by the addition of NOE experiments to examine specific relaxation pathways. A summary of studies on some strychnos alkaloids has been described elsewhere.[9]

With appropriate sample preparation,[10,11] spin–lattice relaxation of protons in organic molecules is dominated by intramolecular dipolar interactions with other protons. For a molecule tumbling isotropically in the extreme narrowing limit (molecular weight up to about 1000 for field strengths in common use today), the rate (R_1) whereby a proton, j, relaxes is given by (1), where K is the

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