products. All other nitrated and oxidized compounds found in the end products, particularly of low temperature nitrations are the result of secondary reactions. The nitration products can be converted to 1-nitro-1-olefins or to 1-nitro-2-alcohols as the predominant products.

Registry No.—1-Hexadecene, 629-73-2; 1-nitro-1-octene, 4550-05-4; 1-octene, 111-66-0.

Acknowledgment.—We wish to thank Dr. Ming Nan Sheng of our Department for many interesting discussions during the preparation of this paper.

Mass Spectrometric and Thermal Fragmentation of 1-Substituted 3-Phenyl-2-thioureas[1]

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The mass spectra of 12 1-substituted and 11 1,1-disubstituted 3-phenyl-2-thioureas have been measured. Deuterium labeling and high-resolution mass spectrometry enabled general fragmentation modes for these compounds to be elucidated. The mass spectra obtained were critically dependent on the method of introduction of the sample into the ion source. Using an all-glass heated (150°) inlet system the mass spectra represented the products of thermal fission. Reproducible spectra of the thioureas were obtained by the direct insertion of the sample into a comparatively cool (70–100°) ion source.

During the past few years much information has been obtained on the ability of many of the functional groups of organic chemistry to direct and control the electron impact induced fragmentation of organic molecules.[2] The concept of charge localization[2,3] at specific sites in a molecule has lead to mechanistic interpretations of the fragmentation of relatively simple molecules[2] and, furthermore, these principles would also appear to be valid when applied to more complex structures.[4]

It was of interest to examine the electron impact induced fragmentation of 3-phenyl-2-thioureas since the initial charge localization may be expected to reside preferentially at either nitrogen, sulfur, or the aromatic ring. Indeed evidence has been presented[5] from a study of the ionization potentials of N-methylated thioureas that the positive charge in the molecular ion of these compounds is primarily localized on sulfur. Consequently, the distribution of the various fragments in the mass spectra of thioureas should reflect, at least in part, the localization of the charge at specific sites within this class of compounds.

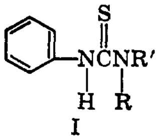
In an attempt to measure the mass spectra of substituted 3-phenyl-2-thioureas with sample introduction by a heated (150°) all-glass inlet system we obtained spectra of amines and isothiocyanates from which the thioureas were prepared. In addition a product resulting from the elimination of hydrogen sulfide from 1-substituted 3-phenyl-2-thioureas was also observed. Proof that these fragmentations were thermal and not electron impact promoted was secured by obtaining the mass spectra of these compounds by direct sample insertion into the ion source. Spectra obtained in this manner were characterized by intense peaks corresponding to the molecular ions of the parent compounds, whereas analogous peaks were absent or at best very weak in the spectra obtained using a heated inlet system.

A comparison of the thermal spectra (heated inlet) with the mass spectra (direct inlet) of 3-phenyl-2-thioureas revealed, in addition to some marked differences, several similarities in the distribution of the fragmentation products. Isotopic labeling and high-resolution techniques were employed as an aid in elucidating the fragmentation pathways. The results from previous investigations have also shown similarities and differences of fragmentation reactions caused by heat and electron impact. Most notable among these comparative studies are the similarities observed with some aromatic anhydrides[6] and the differences observed with Michael adducts.[7]

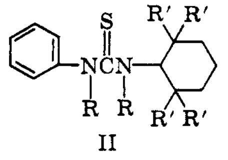
In the sequel we shall first discuss the electron impact promoted fragmentation of 3-phenyl-2-thioureas and then the thermal fragmentation observed using a heated (150°) all glass inlet system.

Electron Impact Fragmentation.—The mass spectra of phenylthiourea, 12 of its 1-substituted (I, R = H) and 11 of its 1,1-disubstituted derivatives have been measured using the direct inlet procedure. All the compounds examined yielded easily recognizable molecular ions and the principal fragmentation peaks for each class of thioureas are tabulated in Tables I and II.

A. 1-Substituted 3-Phenyl-2-thioureas (I, R = H).—This class of thioureas exhibit in their mass spectra



I



II

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[1] We are indebted to the Petroleum Research Fund of American Chemical Society (Grant No. 2829-A4 to the University of Colorado) and to the U. S. Public Health Service (Grants No. GM-11309 and AM 04257 to Stanford University) for financial support. The purchase of the Atlas CH-4 mass spectrometer was made possible through Grant No. NsG 81-60 from the National Aeronautics and Space Administration.

(2) H. Budzikiewicz, C. Djerassi, and D. H. Williams, "Interpretation of Mass Spectra of Organic Compounds," Holden-Day, Inc., San Francisco, Calif., 1964.

(3) F. W. McLafferty, "Determination of Organic Structures by Physical Methods," F. C. Nachod and W. D. Phillips, Ed., Academic Press Inc., New York, N. Y., 1962, p 93.

(4) H. Budzikiewicz, C. Djerassi, and D. H. Williams, "Structure Elucidation of Natural Products by Mass Spectrometry," Vol. 1 and 2, Holden-Day, Inc., San Francisco, Calif., 1964.

(5) M. Baldwin, A. Maccoll, A. Kirkien-Konasiewicz, and B. Saville, *Chem. Ind.* (London), 286 (1966).

(6) M. P. Cava, M. J. Mitchell, D. C. DeJongh, and R. Y. Van Fossen, *Tetrahedron Letters*, 2947 (1966).

(7) C. F. H. Allen and G. P. Happ, *Can. J. Chem.*, **42**, 641, 650, 655 (1964).

Table I[a]

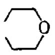
Principal Peaks Present in the Mass Spectra of Some 1-Substituted 3-Phenyl-2-thioureas

	R	$M\cdot^+$	M − 1	M − SH	M (R − 1)	M − R	M − SH (R − 1)	C_6H_5S	$C_6H_5NH_2$
Hydrogen[b]	H	152 (100)	151 (25)	119 (30)	. . .	. . .	. . .	109 (8)	93 (79)
Methyl[c]	CH_3	166 (100)	165 (7)	133 (18)	152	151 (3)	119 (3)	109 (0)	93 (24)
Ethyl[d]	CH_2CH_3	180 (100)	179 (7)	147 (25)	152 (1)	151 (8)	119 (15)	109 (9)	93 (24)
Isopropyl[e]	$CH(CH_3)_2$	194 (100)	193 (6)	161 (7)	152 (1)	151 (14)	119 (31)	109 (10)	93 (98)
sec-Butyl[f]	$CH(-CH_3)CH_2CH_3$	208 (100)	207 (14)	175 (6)	152 (8)	151 (23)	119 (15)	109 (8)	93 (17)
t-Butyl[g]	$C(CH_3)_3$	208 (100)	207 (20)	175 (3)	152 (13)	151 (54)	119 (56)	109 (15)	93 (68)
Neopentyl[h]	$CH_2C(CH_3)_3$	222 (100)	221 (7)	189 (11)	152 (2)	151 (11)	119 (17)	109 (15)	93 (25)
n-Hexyl[i]	$(CH_2)_5CH_3$	236 (100)	235 (15)	203 (24)	152 (4)	151 (36)	119 (18)	109 (9)	93 (70)
Cyclohexyl[j]		234 (52)	233 (7)	201 (2)	152 (11)	151 (44)	119 (15)	109 (5)	93 (100)
α-Phenylethyl[k]	$CH(-CH_3)C_6H_5$	256 (100)	255 (4)	223 (3)	152 (4)	151 (20)	119 (11)	109 (4)	93 (35)
β-Phenylethyl[l]	$CH_2CH_2C_6H_5$	256 (100)	255 (1)	223 (2)	152 (27)	151 (41)	119 (14)	109 (5)	93 (30)
γ-Phenylpropyl[m]	$CH_2CH_2CH_2C_6H_5$	270 (100)	269 (10)	237 (47)	152 (3)	151 (20)	119 (16)	109 (8)	93 (50)
Benzyl[n]	$CH_2C_6H_5$	242 (100)	241 (5)	209 (4)	152 (1)	151 (1)	119 (3)	109 (4)	93 (8)

[a] Figures in parentheses refer to per cent relative abundance and are uncorrected for isotope peaks. [b] Registry no.: 103-85-5; [c] 2724-69-8; [d] 2741-06-2; [e] 15093-36-4; [f] 15093-37-5; [g] 14327-04-9; [h] 15093-39-7; [i] 15153-13-6; [j] 722-03-2; [k] 15093-41-1; [l] 15093-42-2; [m] 15093-43-3; [n] 726-25-0.

Table II[a]

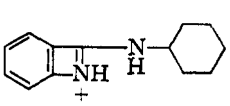
Important Peaks in the Mass Spectra of Some 1,1-Disubstituted 3-Phenyl-2-thioureas

			m/e							
	R	R′	$M\cdot^+$	M − 1	M − SH	M − 135 $\frac{R_1}{R_2}>NH$	M − $\left(\frac{R_1}{R_2}>NH\right)$	C_6H_5-HNCS	M − SH (R − 1)	M − SH (R′ − 1)
Dimethyl[c]	CH_3	CH_3	180 (100)	179 (28)	147 (56)	45 (4)	135 (18)	136 (27)		
Di-*n*-propyl[d]	$CH_2CH_2CH_3$	$CH_2CH_2CH_3$	236 (100)	235 (17)	203 (15)	101	135 (4)	136 (13)	161 (14)	
Di-*n*-butyl[e]	$CH_2CH_2CH_2CH_3$	$CH_2CH_2CH_2CH_3$	264 (100)	263 (20)	231 (18)	129	135 (7)	136 (11)	175 (7)	
Diisobutyl[f]	$CH_2CH(-CH_3)CH_3$	$CH_2CH(-CH_3)CH_3$	264 (100)	263 (16)	231 (4)	129 (7)	135 (10)	136 (18)	175 (5)	
Dicyclohexyl[g]			316 (80)	315 (20)	283 (64)	181 (85)	135 (79)	136 (44)	201 (5)	
Methyl phenyl[h]	CH_3	C_6H_5	242 (100)	241 (43)	209 (9)	107 (50)	135 (19)	136 (20)		133 (51)
Ethyl phenyl[i]	CH_2CH_3	C_6H_5	256 (100)	255 (23)	223 (8)	121 (13)	135 (5)	136 (19)	195 (6)	147 (71)
Benzyl phenyl[j]	$CH_2C_6H_5$	C_6H_5	318 (100)	317 (12)	285 (3)	183[b] (23)	135[b] (10)	136 (7)	195[b] (8)	209[b] (26)
Dibenzyl[k]	$CH_2C_6H_5$	$CH_2C_6H_5$	332 (100)	331 (2)	299 (1)	197 (38)	135 (50)	136 (35)	107 (30)	
Morpholino[l]			222 (100)	221 (5)	189 (11)	87	135 (18)	136 (15)	. . .	. . .
Piperidino[m]			222 (100)	219 (12)	187 (18)	85	135 (8)	136 (12)	. . .	. . .

[a] Figures in parentheses refer to per cent relative abundance and are uncorrected for isotope peaks. [b] These compositions were verified by high-resolution mass measurements. [c] Registry no.: 705-62-0; [d] 15093-46-6; [e] 15093-47-7; [f] 15093-48-8; [g] 15093-49-9; [h] 4949-93-3; [i] 15093-51-3; [j] 3053-39-2; [k] 15093-53-5; [l] 15093-54-6; [m] 2762-59-6.

weak M − 1 fragments (Table I) which in the case of the N,N′-dideuterated cyclohexyl analog (II, R = D; R′ = H) surprisingly retained both deuterium atoms.[8a] Moreover, an M − 1 ion was also detected (Table I) in the spectra of 1-methyl-3-phenyl-2-thiourea (I, R = CH_3; R′ = H) and 1-phenyl-2-thiourea (R = R′ = H). Since loss of hydrogen from N-methylated amines is known [8b] not to involve the N-methyl group, the evidence in hand suggests that the expelled hydrogen may originate in the phenyl ring.

The mass spectra of all the 1-substituted 3-phenyl-2-thioureas examined (Table I) contain a peak corresponding to the loss of 33 mass units (M − SH). This peak remained at M − 33 in the spectrum of the dideuterated cyclohexyl analog (II, R = D; R′ = H) as well as that of the corresponding tetradeuterated derivative (II, R = H; R′ = D). Thus rearrangement of the molecular ion to the thiol form and then loss of a sulfhydryl radical can be discounted as a contributing mechanism in this ion's formation. The evidence suggests that the labile hydrogen eliminated with the sulfur atom may originate in the phenyl ring and the resulting ion can be represented (in the case of the cyclohexyl analog) as a, *m/e* 201.



a

An ion of mass 152 (M − 82) in the spectrum (Figure 1a) of 1-cyclohexyl-3-phenyl-2-thiourea (II, R = R′ = H) corresponds to $C_7H_8N_2S$ (high-resolution mass measurement) and the origin of this ion can best be accommodated by expulsion of cyclohexene from the molecular ion. Recognition of a metastable ion at mass 98.8 ($152^2/234 = 98.8$) verified the genesis of this ion from a one-step decomposition of the molecular ion. Furthermore, the source of hydrogen transferred was found to be the β position of the cyclohexyl ring as determined by the spectrum of the 2,2,6,6-d_4-cyclohexyl analog (II, R = H; R′ = D). Mechanistically this can be envisaged as occurring by way of a McLafferty rearrangement[9] (II → b, *m/e* 152). Corresponding peaks were also observed in the spectra of other 1-alkyl-3-phenyl-2-thioureas containing a γ-hydrogen atom (relative to the thiocarbonyl group) in the alkyl

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(8) (a) The retention of deuterium in the M − 1 fragment was quantitative or nearly quantitative. Small isotopic impurities prevented an exact determination. (b) A. M. Duffield, H. Budzikiewicz, D. H. Williams, and C. Djerassi, *J. Am. Chem. Soc.*, **87**, 810 (1965).

(9) F. W. McLafferty, *Anal. Chem.*, **31**, 82 (1959).

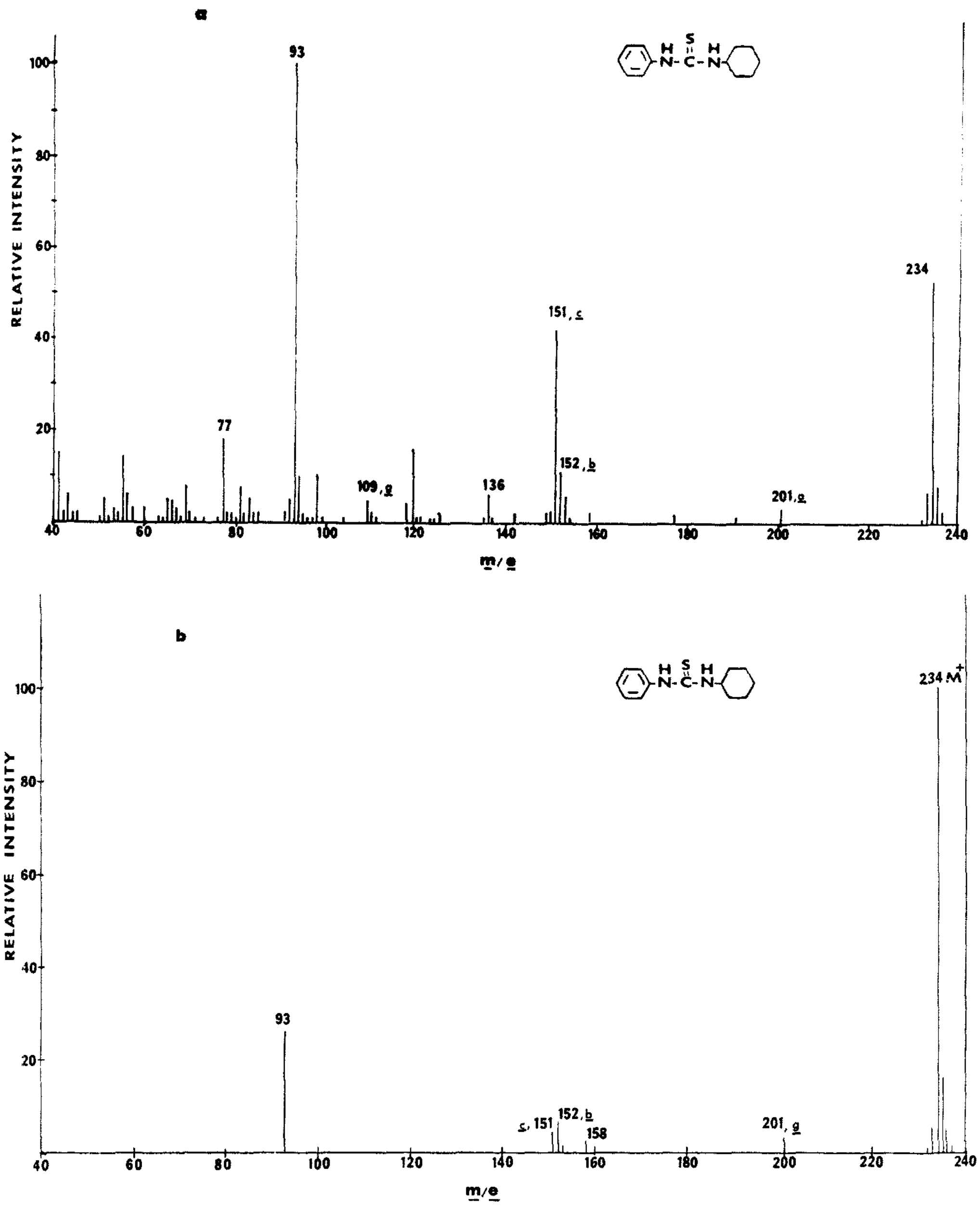
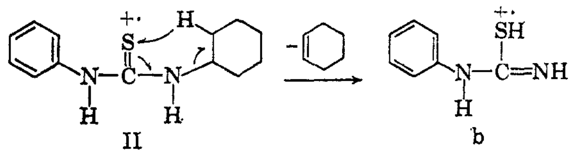
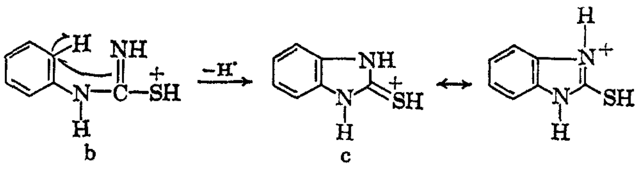


Figure 1.—Mass spectra of 1-cyclohexyl-3-phenyl-2-thiourea: (a) at 70 ev; (b) at 15 ev.

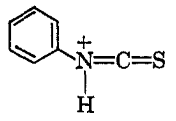
group (Table I), although in most instances it was of low abundance.



A strong metastable ion at mass 150.0 ($151^2/152 = 150.0$) testified to the loss of a hydrogen atom from the ion b affording the fragment of mass 151 ($C_7H_7N_2S$ by high-resolution mass measurement) in the spectrum (Figure 1a) of II (R = R′ = H). As shown by deuterium labeling the expelled hydrogen atom was not originally attached to nitrogen (peak was shifted to *m/e* 153 in II (R = D; R′ = H)) nor was it the hydrogen atom originating on the cyclohexyl ring and transferred to sulfur in the genesis of species b [peak was transposed to *m/e* 152 in II (R = H; R′ = D)]. Thus the hydrogen atom lost from the species b must originate from the phenyl group and the ion at mass 151 can be depicted by c. Low electron energy studies (15 ev, Figure 1b) substantiated the conclusion that the ion at mass 151 originated from secondary fragmentation as its intensity dropped markedly at 15 ev. That is, in contrast to the 70-ev spectrum (Figure 1a), the 15-ev spectrum showed that the peak at *m/e* 152 is more intense than that at *m/e* 151. This datum affords additional support for the sequence b → c + H·.

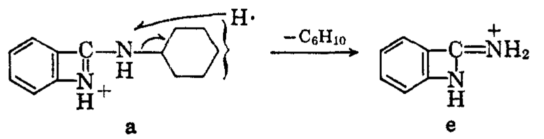


A peak of moderate to weak intensity at *m/e* 136 in the mass spectra of the 1-substituted 3-phenyl-2-thioureas was shown, in the case of the 1-cyclohexyl derivative, to correspond to C_7H_6NS. This peak was located at *m/e* 137 in II (R = D; R′ = H) consistent with the assignment of structure d (*m/e* 136) to this fragment.

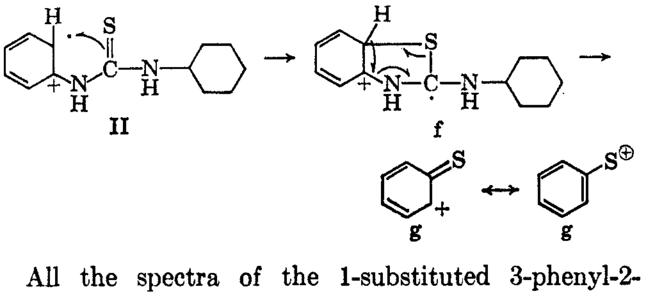


d

Without exception all the spectra of the 1-substituted 3-phenyl-2-thioureas examined contain a peak of moderate intensity at *m/e* 119 (Table I). In the case of the 1-cyclohexyl derivative II (R = R′ = H) a strong metastable ion at mass 70.4 ($119^2/201 = 70.4$) establishes the origin of this ion, at least partially, from decomposition of the species a, *m/e* 201. Furthermore, a low-voltage (15 ev) spectrum (Figure 1b) lacks an ion of mass 119 suggesting that this fragment arises from a secondary fragmentation process. High-resolution mass spectrometry established the empirical composition $C_7H_7N_2$ for this ion. Deuterium labeling (II, R = D; R′ = H) established that the hydrogen atoms attached to nitrogen were retained in the charged species while the labels in the tetradeuterated analog II (R = H; R′ = D) were lost. A rationalization, consistent with the results from deuterium labeling, is depicted by a → e, *m/e* 119, although the hydrogen transfer originating from the 3 and 4 positions of the cyclohexyl ring and hence the nature of the neutral species is only speculative.



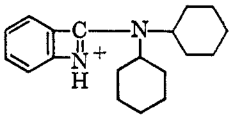
A peak at *m/e* 109 in the mass spectra (Table I) of the majority of the 1-substituted-3-phenyl-2-thioureas was shown in the case of the cyclohexyl compound to correspond to C_6H_5S. The phenyl group must, subsequent to electron impact, migrate to sulfur and a possible mechanistic rationalization for the formation of this species is depicted by II → f → g (*m/e* 109). A similar mechanism has been postulated to explain the presence of an ion of composition C_6H_5S in the spectrum of a phenyl-substituted thiuramdisulfide.[10]



All the spectra of the 1-substituted 3-phenyl-2-thioureas examined contain a peak corresponding to the ubiquitous phenyl cation (*m/e* 77) together with a peak at *m/e* 93 which corresponds to the molecular ion of aniline. The source of the hydrogen atom transferred in the origin of the species of mass 93 follows from deuterium labeling to be N-1. In addition a recorded metastable ion at mass 37.0 ($93^2/234 = 36.9$) affords evidence that the ion in question is at least partially formed by a single-step decomposition from the molecular ion. This assignment was reinforced by the low energy spectrum (Figure 1b) of 1-cyclohexyl-3-phenyl-2-thiourea in which the ion of mass 93 was still present suggesting its genesis was a primary decomposition mode. It is interesting to note that in the 1,1-disubstituted 3-phenyl-2-thiourea spectra discussed below no peak occurs at *m/e* 93. This is conveniently explained by the absence of a hydrogen atom on N-1 in these compounds.

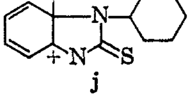
B. 1,1-Disubstituted 3-Phenyl-2-thioureas.—Examples (eleven) of this class thiourea have been included in the present investigation and the principal peaks in their mass spectra are tabulated in Table II. All display recognizable molecular ion peaks and the relative intensity of each is apparently dependent on the sample temperature. Thus on minimal heating 1,1-dicyclohexyl-3-phenyl-2-thiourea (III) produced a spectrum with the molecular ion having 80% relative abundance while with further heating this dropped to 3% relative abundance. The spectrum from the latter determination is reproduced in Figure 2a. In subsequent paragraphs the electron impact induced fragmentation reactions of 1,1-disubstituted 3-phenyl-2-thioureas are discussed using the dicyclohexyl compound as an example.

The first fragment ion of any significance in the spectrum (Figure 2a) of 1,1-dicyclohexyl-3-phenyl-2-thiourea (III) corresponds to the loss of a sulfhydryl radical (M − 33) which can be represented by h, *m/e* 283 from analogy with the 1-substituted compounds discussed above.



h

An ion of mass 233 (M − 83) occurs in the spectrum of 1,1-dicyclohexyl-3-phenyl-2-thiourea (III) and a metastable ion appearing at mass 171.8 ($233^2/316 = 171.8$) establishes its origin as a one-step fragmentation of the molecular ion. One possible representation of this ion is j, *m/e* 233, which is analogous to c, *m/e* 151, resulting from the 1-cyclohexyl derivative which first loses cyclohexene followed by a hydrogen atom in yielding an ion at mass M − 83.



j

High-resolution mass spectrometry established the composition $C_{12}H_{23}N$ for the prominent ion of mass 181 (M − 135) in the spectrum (Figure 2a) of 1,1-dicyclohexyl-3-phenyl-2-thiourea. In addition at low electron energy (15 ev) this peak was still of high relative abundance (Figure 2b) indicating that it arises from a primary fragmentation process. One representation is depicted by III → k, *m/e* 181, the neutral species corresponds to phenyl isothiocyanate, the molecular ion of which (m, *m/e* 135) contributes strongly to the ion current (Figure 2a). At low electron energy the species m emerges as the base peak. A peak of *m/e*

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(10) J. Ø. Madsen, S. O. Lawesson, A. M. Duffield, and C. Djerassi, *J. Org. Chem.*, **32**, 2054 (1967).

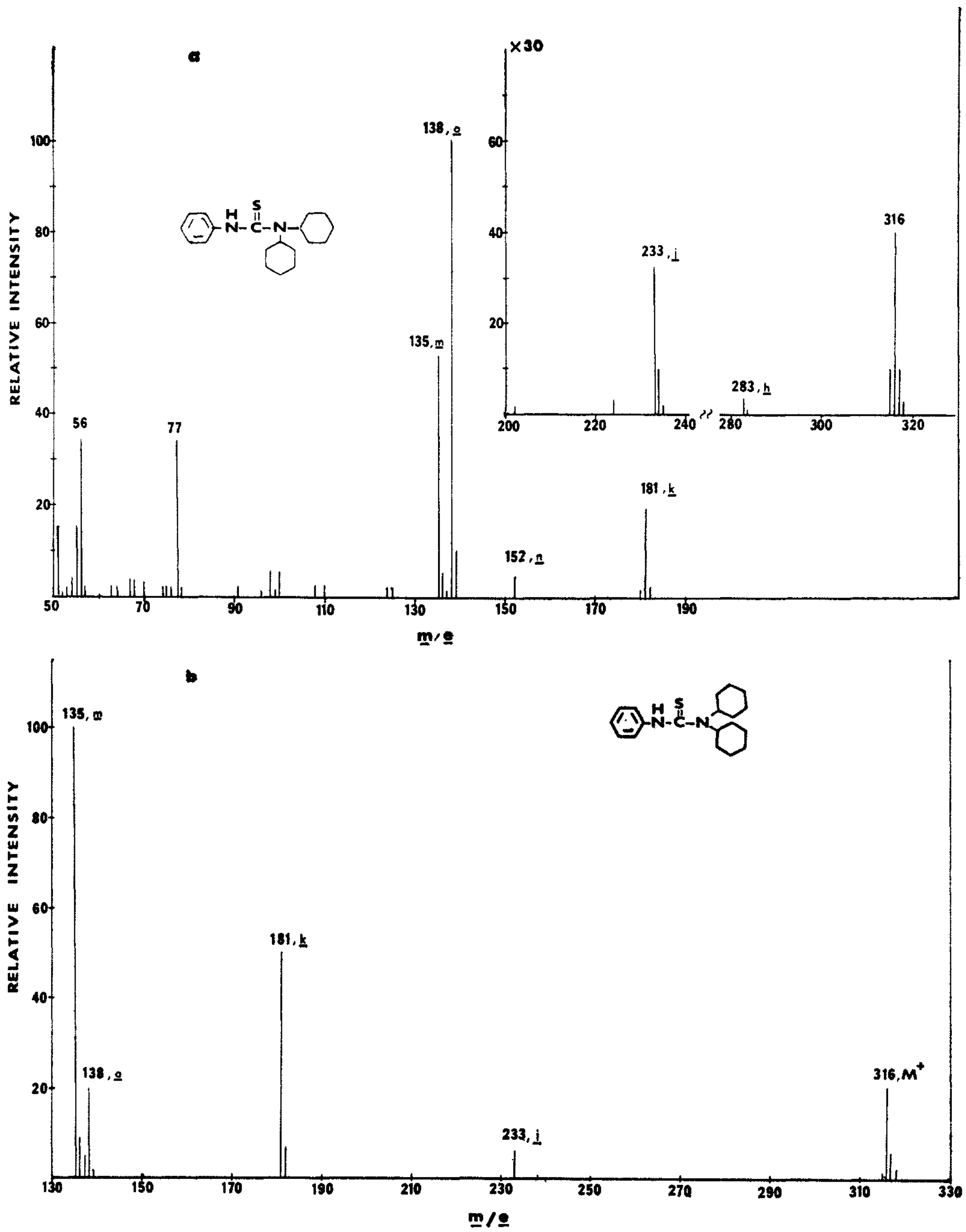
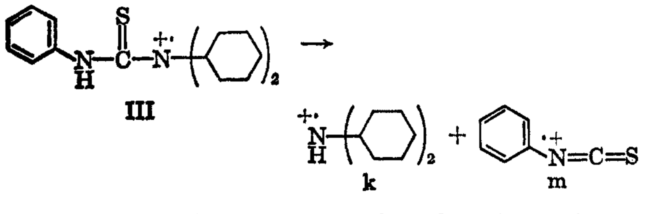
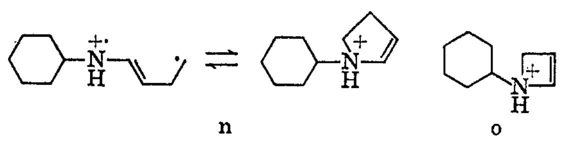


Figure 2.—Mass spectra of 1,1-dicyclohexyl-3-phenyl-2-thiourea: (a) at 70 ev; (b) at 15 ev.

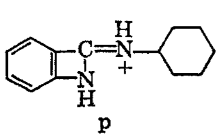
136 is present in the spectra of all the 1,1-disubstituted 3-phenyl-2-thioureas examined (Table II) and this fragment is best attributed to the ion d, *m/e* 136.



Loss of 29 and 43 mass units from k, *m/e* 181 (metastable ions at mass 127.6 ($152^2/181 = 127.6$) and 105.2 ($138^2/181 = 105.2$) yield ions of mass 152 (n) and 138 (o) respectively, the latter being the base peak at 70 ev. As would be predicted the ions corresponding to n and o are either absent or of low intensity in the low electron volt spectrum (Figure 2b). High-resolution mass spectrometry indicated that the peaks at *m/e* 152 and 138 had the compositions $C_{10}H_{18}N$ and $C_9H_{16}N$, respectively.



A weak peak at *m/e* 201 (M − 115) in the spectrum (Figure 2a) of 1,1-dicyclohexyl-3-phenyl-2-thiourea corresponds to the ion e, *m/e* 119, present in the spectrum of the 1-cyclohexyl analog and can be represented by p, *m/e* 201.



p

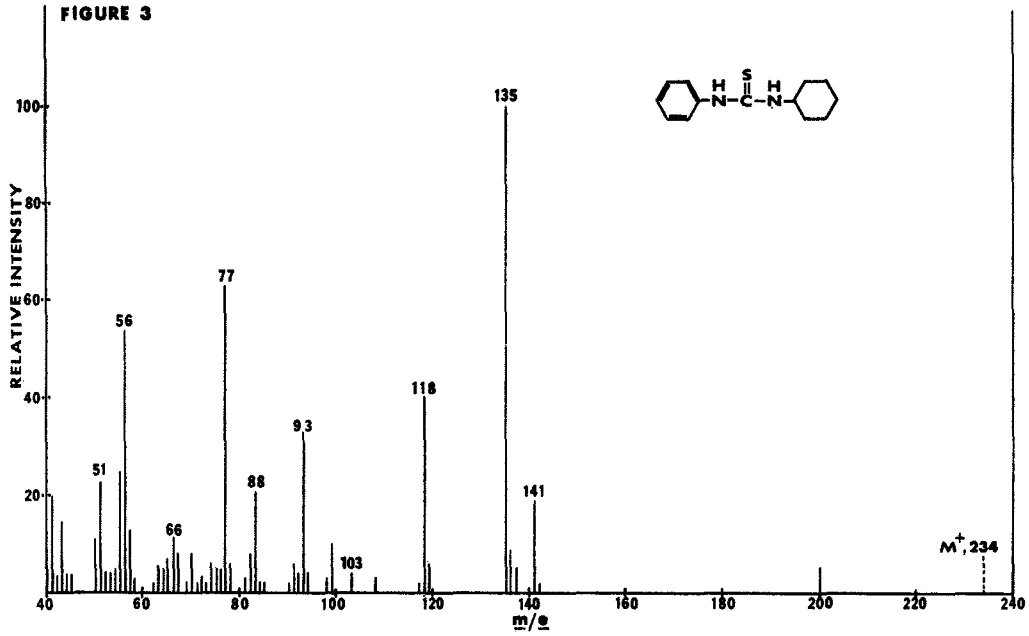
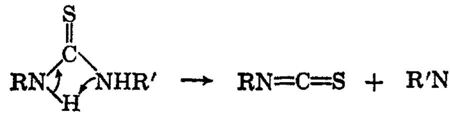


Figure 3.—Thermal spectrum of 1-cyclohexyl-3-phenyl-2-thiourea.

Thermal Fragmentations.—Introduction of 1-substituted and 1,1-disubstituted 3-phenyl-2-thioureas into the mass spectrometer by way of a heated (150°), evacuated inlet system led to complete or nearly complete destruction of the sample and mass spectra of thermal fragmentation products were obtained. Pyrolysis of the disubstituted derivatives in this manner led to mass spectra of phenyl isothiocyanate[11] and the corresponding secondary amine, *i.e.*, the compounds from which the thiourea was synthesized. The monosubstituted phenylthioureas thermally decomposed to two amines, two isothiocyanates, and a hydrogen sulfide elimination product.

As demonstrated by deuterium labeling the production of amines and isothiocyanates from 1-substituted 3-phenyl-2-thioureas involves a hydrogen transfer from one nitrogen atom to the other with simultaneous cleavage of a central carbon–nitrogen bond. Since both amines and isothiocyanates are produced thermally the reaction can be initiated on either side of the thiocarbonyl group. Thus thermal fragmentation of 1-cyclohexyl-3-phenyl-2-thiourea-1,3-d_2 (II, R = D; R′ = D) in the heated inlet system led to the superimposed mass spectra of aniline-N,N-d_2 and cyclohexylamine-N,N-d_2, as well as those of unlabeled phenyl isothiocyanate and cyclohexyl isothiocyanate. Therefore the mechanism leading to these products probably proceeds by way of a four-membered cyclic transition



R,R′ = alkyl, aryl, or hydrogen

state and is not unlike that operative in the thermolysis of simple thioureas in aqueous acid.[12]

The thermal fragmentation reactions could also be conducted in a hot (250°) injector port of a gas chromatograph and the amount of cleavage on each side of the thiocarbonyl group could then be measured accurately. Thus the ratio of cyclohexylamine to aniline observed in the pyrolysis of 1-cyclohexyl-3-phenyl-2-thiourea was 1:4 as determined by gas chromatography. The thermal cleavage was quantitative and instantaneous as demonstrated by the sharp peaks which were recorded in the chromatograms. At 150° the reactions were not complete in the injection port as they were in the heated inlet system of the mass spectrometer; the lower pressures in the latter apparently favored the formation of gaseous products. The direction of the dominant hydrogen migration was reversed in the inlet system of the mass spectrometer, *i.e.*, cyclohexylamine formation was preferred in the thermal spectrum of 1-cyclohexyl-3-phenyl-2-thiourea (Figure 3). This was measured in the following way. 1,3-Diphenyl-2-thiourea (thiocarbanilide) was allowed to decompose in the inlet system and the spectrum of the resulting aniline and phenyl isothiocyanate was measured. Because of the symmetry of the molecule the amount (in molecules) of aniline produced equals the amount of phenyl isothiocyanate and the relative intensity of the molecular ions of each of these compounds is a measure of the mode of response of the mass spectrometer to each compound. Several runs disclosed that the molecular ions had the same relative intensity within 3%. Using this result, the intensity of the molecular ion of aniline was compared to that of the molecular ion of phenyl isothiocyanate in the thermal spectrum of 1-cyclohexyl-3-phenyl-2-thiourea, since the amount of phenyl isothiocyanate produced in this reaction is the same as that of cyclohexylamine. By this method the ratio of cyclohexylamine to aniline was found to be 5:1. Apparently the lower temperatures and pressures of the heated inlet system have a great effect on the site of cleavage.

The elimination of hydrogen sulfide also involves the two hydrogen atoms attached to nitrogen. That is the elements of deuterium sulfide are lost in the thermal

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[11] A. Kjaer, M. Ohashi, J. M. Wilson, and C. Djerassi, *Acta Chem. Scand.*, **17**, 2143 (1963).

[12] W. H. R. Shaw and D. G. Walker, *J. Am. Chem. Soc.*, **79**, 3683 (1957), and references contained therein.

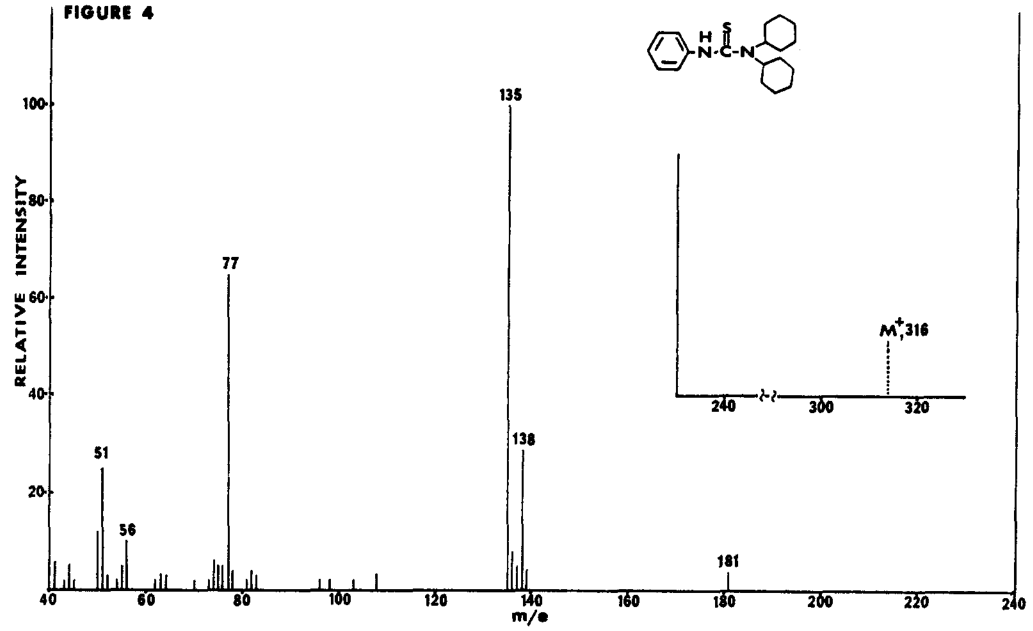


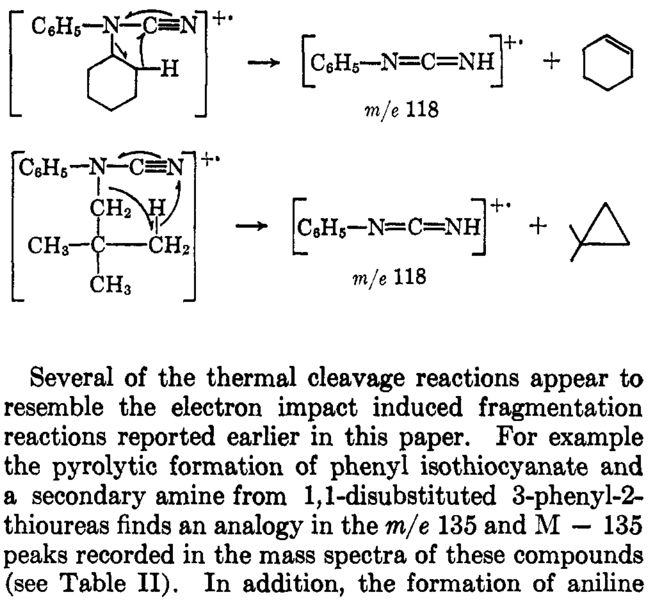
Figure 4.—Thermal spectrum of 1,1-dicyclohexyl-3-phenyl-2-thiourea.

spectrum of 1-cyclohexyl-3-phenyl-2-thiourea-1,3-d_2 (Figure 4) (II, R = D; R′ = H). The product from this reaction decomposes upon electron impact to give a very abundant ion of mass 118 in the spectra of all the 1-substituted 3-phenyl-2-thioureas in which the substituent contains a β- or γ-aliphatic hydrogen. This ion results from the elimination of a neutral olefin or its elemental equivalent from the molecular ion of the hydrogen sulfide expulsion product. An *m/e* 118 peak was not detected in the thermal spectra of 1-methyl-, 1-phenyl-, or 1-benzyl-3-phenyl-2-thiourea, even though the molecular ion of the hydrogen sulfide elimination product was recorded.

The thermal elimination of hydrogen sulfide and subsequent electron impact induced olefin elimination do not appear to be restricted to phenylthioureas, since 1,3-dicyclohexyl-2-thiourea displays analogous behavior, *i.e.*, in the thermal spectrum the peak at highest mass number corresponds to the hydrogen sulfide elimination product and this decomposes upon electron impact to an intense peak at *m/e* 124 resulting from the expulsion of cyclohexene.

Although it is well known that 1,3-disubstituted thioureas give carbodiimides upon heating in the presence of heavy metal oxides and other oxidizing agents[13] it appears that the hydrogen sulfide elimination product behaves more like the rearranged cyanamide. For example, the mass spectrum of dicyclohexyl carbodiimide is dominated by an *m/e* 125 (elimination of a cyclohexyl radical) as well as an *m/e* 124 peak, whereas no peak at *m/e* 125 is recorded in the thermal spectrum of 1,3-dicyclohexyl thiourea. In addition the thermal spectrum of 1-ethyl-3-phenyl-2-thiourea was compared to the mass spectrum of ethyl phenyl cyanamide[14] and aside from the peaks attributable to the amines and isothiocyanates in the former, the two spectra were essentially identical.

In the thermal spectrum of 1-(2,2,6,6-d_4-cyclohexyl)-3-phenyl-2-thiourea (II, R = H; R′ = D) the peak corresponding to cyclohexene elimination was partially (about 50%) shifted to *m/e* 119. Therefore the expulsion of the alkyl group with a back-transfer of one hydrogen atom is not a specific process and some of the migrating hydrogen atoms must originate at the γ or δ position. The thermal spectrum of 1-neopentyl-3-phenyl-2-thiourea (which has no β-aliphatic hydrogens) led to a similar conclusion since an intense *m/e* 118 peak was recorded. This peak could result from an expulsion of a cyclopropane.



Several of the thermal cleavage reactions appear to resemble the electron impact induced fragmentation reactions reported earlier in this paper. For example the pyrolytic formation of phenyl isothiocyanate and a secondary amine from 1,1-disubstituted 3-phenyl-2-thioureas finds an analogy in the *m/e* 135 and M − 135 peaks recorded in the mass spectra of these compounds (see Table II). In addition, the formation of aniline from the monosubstituted derivatives by either mode of decomposition appears to follow an identical pathway including the origin site of the migrating hydrogen atom. However, the thermally induced expulsion of hydrogen sulfide which is overtly similar to the electron impact induced elision of sulfhydryl radical occurs by a completely unrelated mechanism as proved by deuterium labeling.

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[13] H. G. Khorana, *Chem. Rev.*, **53**, 145 (1953).

[14] J. V. Braun, *Ber.*, **33**, 1449 (1900); R. Scholl and W. Norr, *ibid.*, 1554 (1900).

Experimental Section[15]

Phenylthioureas.—All of the phenylthioureas were prepared by the following procedure. To a solution of 10 mmoles of phenyl isothiocyanate in 10 ml of 95% ethanol were added 11 mmoles of the appropriate amine or amine hydrochloride. In cases where the hydrochloride was used, a slight excess of triethylamine was added. The mixture was allowed to stir at ambient temperature for 1-2 hr. In some cases the product crystallized from the reaction mixture and in others it was necessary to dilute the solution with a small amount of water and/or scratch the sides of the reaction vessel with a glass rod. Each phenylthiourea so produced was recrystallized from 60 to 90% ethanol and all melted within 2° of the reported value.

1-Cyclohexyl-3-phenyl-2-thiourea-1,3-d_2 (II, R = D; R′ = H).—A solution of cyclohexylamine (99 mg, 1 mmole) in methanol-*d* (2 ml) and deuterium oxide (1 ml) was heated at reflux for 2 hr. After cooling the mixture to room temperature phenyl isothiocyanate (135 mg, 1 mmole) was added and the mixture was heated to boiling. Cooling to 0° resulted in the deposition of fine crystals which were collected by filtration and twice recrystallized from methanol-*d*–D_2O: yield 150 mg (65%), mp 147–148°. The isotopic purity was 90% d_2 and 10% d_1 as determined from the mass spectrum.

1-(2,2,6,6-d_4-Cyclohexyl)-3-phenyl-2-thiourea (II, R = H; R′ = D).—A solution of cyclohexanone (300 mg, 3 mmoles) and sodium methoxide (300 mg) in methanol-*d* (3 ml) and deuterium oxide (10 ml) was heated at reflux for 2 hr. After cooling, the mixture was extracted with ether, the ether layer was dried, and the solvent was evaporated. The resulting product was subjected to the exchange procedure a second time under the same conditions. After the reflux period, hydroxylamine hydrochloride (200 mg, 3.3 mmoles) was added and the mixture was allowed to stand for several hours. The oxime was isolated with ether in the usual way and reduced, without purification, with excess $LiAlH_4$ (200 mg) in ether. The resulting amine was treated with phenyl isothiocyanate (135 mg, 1 mmole) in methanol and the deuterated product IV, collected by filtration, showed mp 146–148°. The mass spectrum showed that the isotopic purity was 95% d_4 and 5% d_3.

Thermal Fragmentation of 1-Cyclohexyl-3-phenyl-2-thiourea in Gas Chromatograph.—A saturated solution (0.3 ml) of 1-cyclohexyl-3-phenyl-2-thiourea in methanol was injected into a Varian Aerograph Hi-Fi III gas chromatograph. The injection port was maintained at 250° and the column (5 ft × $^1/_8$ in. 20% Dowfax 9N9, 2% KOH on Chromsorb W) at 180°. The methanol peak was recorded within a few seconds. The retention times for the cyclohexylamine and aniline were 0.75 and 2.05 min relative to methanol. The cyclohexyl isothiocyanate and phenyl isothiocyanate were not separated under these conditions and appeared as a broad composite peak with a retention of 4.05 min relative to methanol.

Registry No.—II (R = D; R′ = H), 15093-56-8; II (R = H; R′ = D), 15093-57-9.

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[15] Mass spectra were determined using an Atlas CH-4 mass spectrometer equipped with the TD-4 ion source. High-resolution mass measurements were kindly performed by Dr. J. K. MacLeod of Stanford University on an AEI MS-9 mass spectrometer operating at a resolution of 20,000. The thermal measurements were determined with a CEC 21-103C mass spectrometer equipped with an all-glass heated (150°) inlet system. 1,3-Dicyclohexyl-2-thiourea was kindly donated by Abbott Laboratories, North Chicago, Ill.

Chemiluminescence from Reactions of Electrophilic Oxamides with Hydrogen Peroxide and Fluorescent Compounds

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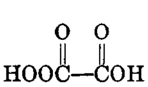
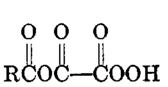
Chemiluminescence has been observed from the reactions of electrophilic oxamides with hydrogen peroxide in the presence of fluorescers. A general relationship was found between the efficiency of the light emission and the reactivity of the oxamide toward hydrogen peroxide. The intensity of chemiluminescence varied substantially with the solvent, catalyst, fluorescer, and peroxide. The emitting species in the chemiluminescent reactions was shown to be the first excited singlet state of the fluorescer.

Oxalyl chloride[1,2] and certain oxalic anhydrides[3] and esters[4] react with hydrogen peroxide in the presence of fluorescent compounds to generate light with unusual efficiency. Chemiluminescence quantum yields for such reactions have been reported to be as high as 5, 13, and 23%, respectively,[2-4] in contrast to yields on the order of 1% reported for earlier chemiluminescent reactions such as the 3-aminophthalhydrazide (luminol[4]) reaction with hydrogen peroxide.[5,6] Mechanism studies of oxalate chemiluminescent systems have tentatively indicated that peroxyoxalate derivatives such as I–III can be formed, depending on the reactants and reaction conditions, and that concerted multiple bond cleavage decomposition of such intermediates is the source of the large and synchronous energy release required for electronic excitation of the emitting fluorescer.[2-4]



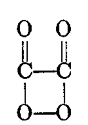
$$HOO\overset{O}{\overset{\|}{C}}-\overset{O}{\overset{\|}{C}}OH$$

I



$$R\overset{O}{\overset{\|}{C}}O\overset{O}{\overset{\|}{C}}-\overset{O}{\overset{\|}{C}}OOH$$

II



III

These earlier studies indicated that the oxalic starting material must have a high order of reactivity toward hydrogen peroxide to exhibit appreciable chemiluminescent activity. Although oxamides in general are less active toward nucleophiles than oxalic esters, a series of oxamide–hydrogen peroxide–fluorescer reactions has been examined to define the limits of the peroxyoxalate chemiluminescent system.

Results

A variety of oxamides was treated with hydrogen peroxide and the fluorescer 9,10-diphenylanthracene under several reaction conditions and the reactions were examined visually for chemiluminescence. Typical results are summarized in Table I. Simple oxa-

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[1] E. A. Chandross, *Tetrahedron Letters*, No. 12, 761 (1963).

[2] M. M. Rauhut, B. R. Roberts, and A. M. Semsel, *J. Am. Chem. Soc.*, **88**, 3604 (1966).

[3] L. J. Bollyky, R. H. Whitman, B. G. Roberts, and M. M. Rauhut, *ibid.*, **89**, 6523 (1967).

[4] M. M. Rauhut, L. J. Bollyky, B. G. Roberts, M. Loy, R. H. Whitman, A. V. Iannotta, and A. M. Semsel, *ibid.*, **89**, 6515 (1967).

[5] J. Lee and H. H. Seliger, *Photochem. Photobiol.*, **4**, 1015 (1965); M. M. Rauhut, A. M. Semsel, and B. G. Roberts, *J. Org. Chem.*, **31**, 2431 (1966).

[6] For recent reviews on chemiluminescence, see: F. McCapra, *Quart. Rev.* (London), **20**, 485 (1966); K. D. Gunderman, *Angew. Chem. Intern. Ed. Engl.*, **4**, 566 (1965); E. J. Bowen, *Pure Appl. Chem.*, **9**, 423 (1964).