mining the position of N(im)-benzylation in compounds containing a histidine moiety. This is especially valuable in cases where the cross-ring coupling information is not available.

Experimental Section

Proton NMR Spectra were measured at 300 MHz. All spectra were recorded as methanol-d_4 solutions (10 mg/0.5 mL) containing Me_4Si as an internal reference. The solutions were degassed. Nuclear Overhauser enhanced difference spectra were obtained using standard software. The spectra were obtained at a spectral width of 4 kHz, using 16k data points resulting in a spectral resolution of 0.49 Hz per point. All experiments were performed at ambient temperature (298 K).

Acknowledgment. We thank Paula B. Rittgarn for supplying the model compounds and Dr. Christopher J. Turner, Columbia University, for the 300-MHz spectra.

Registry No. 1, 76712-82-8; 2, 99310-01-7; 3, 65717-64-8; histidine, 71-00-1; imidazole, 288-32-4.

Novel Route from Thiocarbamate to Isocyanate: 2,2,2-Trinitroethyl Isocyanate

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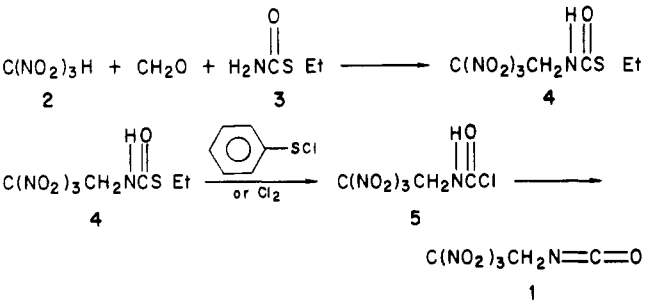
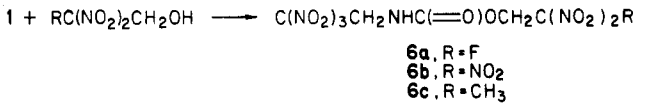
Standard methods for isocyanate synthesis are not suitable for the preparation of 2,2,2-trinitroethyl isocyanate (**1**), a compound that is of interest as an intermediate for energetic materials. The method employing an amine with phosgene[1] cannot be used because the required precursor, 2,2,2-trinitroethylamine, is not available.[2] An alternate method via the rearrangement of an acyl azide[3] is impractical since the required 3,3,3-trinitropropanoic acid is quite unstable and is only available in low yield from a relatively scarce starting material.[4] Therefore we have devised a route (Scheme I) to **1** starting from the readily available trinitromethane (**2**), *S*-ethyl thiocarbamate (**3**), and formaldehyde.

Finding a method to condense **2** with **3** and formaldehyde in good yield proved to be difficult. Although **2** has been shown to readily condense with *N*-methylol amides,[5] there has been only very limited success in similar reactions with carbamates[6] and there is no literature report

Scheme I



Scheme II



of a corresponding thiocarbamate condensation. Insignificant yields of **4** were obtained when base catalysis was used to attempt to form the *N*-methylol derivative of **3** before **2** was added.[7] Attempts to trap the *N*-methylol derivative of **3** as the trifluoroacetate[8] by treating **3** with paraformaldehyde in trifluoroacetic acid followed by later addition of trifluoroacetic anhydride gave instead the *N*-trifluoroacetyl derivative of **3**. Fusion of 2,2,2-trinitroethanol and **3** gave decomposition with only insignificant amounts of **4** being produced.

We did find that reasonable yields of **4** could be obtained if **2** was heated with **3** at 70–75 °C for 5 h in aqueous formaldehyde solution buffered with potassium acetate and acetic acid to control the pH. The elevated temperatures were necessary for the formation of **4** and increased reaction times gave lowered yields. When the reagents were heated without pH control (starting pH 4), only very low yields (<5%) of **4** were obtained. The pH fell during the reaction presumably due to decomposition of **2** at elevated temperatures.

The thiocarbamate **4** can be readily converted to the carbamyl chloride **5** and eventually to isocyanate **1** with either benzenesulfenyl chloride[9] or gaseous chlorine. When **4** was treated with chlorine in carbon tetrachloride, workup gave a mixture of **5** and **1**. By contrast, **4** with benzenesulfenyl chloride gave pure **5** and was the reagent of choice when isolation of the intermediate **5** was desired.[10]

Several derivatives (carbamates) were prepared from **1** by the addition of polynitro alcohols (Scheme II).

(1) (a) Roberts, J. D.; Caserio, M. C. "Basic Principles of Organic Chemistry"; W. A. Benjamin, Inc.: New York, 1964; p 685. (b) Adolph, H. G. *J. Org. Chem.* **1972**, *37*, 747.

(2) The only isolable and reasonable stable 2-substituted 2,2-dinitroethylamine is 2-fluoro-2,2-dinitroethylamine. The other dinitroethylamines of this type cannot be isolated because the reverse Mannich reaction predominates: $ZC(NO_2)_2CH_2NH_2 \rightleftharpoons ZC(NO_2)_2^- + [CH_2{=}NH_2]^+$. Where Z = F, this equilibrium is shifted to the left because fluorodinitromethide ion is less stable and more nucleophilic than the other dinitro carbanions. (Adolph, H. G.; Kamlet, M. J. *J. Org. Chem.* **1969**, *34*, 45).

(3) (a) Reference 1a, p 685. (b) Gold, M. H.; Frankel, M. B.; Linden, G. B.; Klager, K. *J. Org. Chem.* **1962**, *27*, 334.

(4) The trinitropropanoic acid is prepared in 33% yield from 1,1,1,3-tetranitropropane. The hydrogen of the methylene group of the acid exhibit a very high reactivity. For example, the acid reacts with water even at room temperature to form 2-hydroxy-3,3-dinitropropanoic acid. (Golod, E. L.; Novatskii, G. N.; Bagal, L. I. *Zh. Org. Khim.* **1973**, *9*, 1111.)

(5) (a) Feuer, H.; Lynch-Hart, U. E. *J. Org. Chem.* **1961**, *26*, 391. (b) Kranyuskin, M. M.; Andreeva, T. G.; Shvarts, I. Sh.; Sevost'yanova V. V.; Yarovenko, V. N.; Novikov, S. S. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1980**, *3*, 642.

(6) The only literature report is: Klager, K.; Frankel, M. B. "A Review of Nitroform and 2,2,2-Trinitroethanol"; Aerojet Report No. 494, 13 Feb, 1951, p 36, 52. It is stated that methyl *N*-(trinitroethyl)carbamate and ethyl *N*-(trinitroethyl)carbamate were prepared from 2,2,2-trinitroethanol and the corresponding alkoxy carbamate by fusion at 120–130 °C. Yields were not given. It is also stated that condensation of **2** with ethyl *N*-(hydroxymethyl)carbamate was unsuccessful.

(7) A procedure analogous to that in ref 5b was followed.

(8) The thiocarbamate–formaldehyde reaction should be reversible as is the reaction of an amide and formaldehyde. (Lamberton, A. H.; Lindley, C.; Owston, P. G.; Speakman, J. C. *J. Chem. Soc.* **1949**, 1641). Trapping the methylol derivative as the trifluoroacetate might allow reaction of it with the potassium salt of **2** to give **4**.

(9) The conversion of **4** to **5** by benzenesulfonyl chloride is analogous to the reaction: $CH_3C(=O)SCH_3 + CH_3SCl \rightarrow CH_3C(=O)Cl + CH_3SSCH_3$. (Douglass, I. B. *J. Org. Chem.* **1959**, *24*, 2004.) Benzenesulfenyl chloride was chosen for our studies because of convenience but obviously any sulfenyl chloride (RSCl, R = alkyl, aryl) of similar reactivity could be used.

(10) The loss of HCl from **5** is very facile and is presumably due to the electron-withdrawing trinitroethyl group which increases the acidity of the hydrogen attached to nitrogen. Thus, removal of the volatiles from the reaction mixture is sufficient to sweep away HCl with formation of **1**. The reaction with benzenesulfenyl chloride can be run conveniently at high concentration and thus considerable less volatiles have to be removed during workup.

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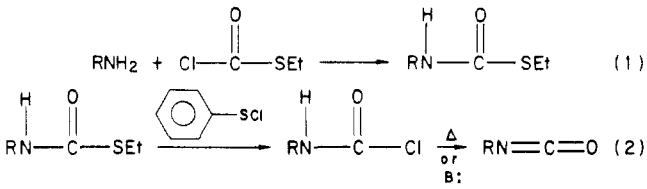
The conversion of thiocarbamates to isocyanates is not restricted to the preparation of **1**. Ordinary thiocarbamates such as S-ethyl *N*-ethylthiocarbamate and S-ethyl *N*-phenylthiocarbamate were readily obtained from the reaction of the appropriate amine with ethyl chlorothiolformate (eq 1)[11] and then converted to isocyanates by



procedures similar to those used to prepare **1** from **4** (eq 2) (see Experimental Section). Thus the new method (thiocarbamate to isocyanate) would be of interest to chemists who wish to prepare an isocyanate from an amine precursor but yet want to avoid the use of hazardous phosgene gas.

Experimental Section

The compounds described herein are energetic materials and should be handled with care. Elemental analyses were performed by Galbraith Laboratories, Inc., Knoxville, TN. The melting points are uncorrected and NMR chemical shifts are relative to Me_4Si as an internal standard.

S-Ethyl thiocarbamate **3** was prepared by treating ethyl chlorothiolformate (Aldrich Chemical Co., technical grade 95%) in methylene chloride (ice bath) with gaseous ammonia.[12] Benzenesulfenyl chloride was prepared by treating thiophenol with chlorine gas.[13]

***S*-Ethyl *N*-(2,2,2-Trinitroethyl)thiocarbamate (4).** To 21 g (0.116 mol) of 2,2,2-trinitroethanol in 110 mL of water was added 10 g of potassium acetate, 15 mL of acetic acid, 9 mL of 36% aqueous formaldehyde, and 12.2 g (0.116 mol) of *S*-ethyl thiocarbamate. The mixture was heated in an oil bath at 70–75 °C for 5 h before it was cooled in an ice bath and the insoluble oil (18 g) was extracted into methylene chloride. The oil was chromatographed on silica gel 40 (115 g) using methylene chloride as eluent to give 8.6 g (28%) of crystals, mp 61–63 °C: ^{1}H NMR ($CDCl_3$) δ 1.29 (t, 3 H), 2.98 (q, 2 H), 4.98 (d, 2 H), 6.00 (br, 1 H); IR (KBr) 3280 (NH), 1665 (C=O), 1595 (NO_2) cm^{-1}. Anal. Calcd for $C_5H_8N_4O_7S$: C, 22.39; H, 3.01; N, 20.89; S, 11.95. Found: C, 22.50; H, 2.99; N, 20.79; S, 12.07.

***N*-(2,2,2-Trinitroethyl)carbamyl Chloride (5).** To a stirred solution of 1.01 g (6.9 mmol) of benzenesulfenyl chloride in 2 mL of dry 1,2-dichloroethane was added 1.80 g (6.9 mmol) of **4**. After 30 min the volatiles were removed at 25 °C with a stream of nitrogen, 5 mL of hexane was added (oil separates), and the mixture was cooled to −10 °C to yield a solid. The solution was decanted from the solid which was then washed with hexane and quickly dried in a vacuum desiccator over drierite to give 1.36 g (84%), mp 56–58 °C: ^{1}H NMR ($CDCl_3$) δ 4.90 (d, 2 H), 6.43 (br, 1 H); IR (film) 3420, 3320 (NH), 1765 (C=O), 1600 (NO_2) cm^{-1}. Upon standing overnight in the vacuum desiccator, an appreciable amount of the solid had turned to an oil. The IR spectrum then showed a large isocyanate absorption at 2275 cm^{-1}.

5 from Chlorine Gas. Compound **4** (2.0 g, 7.5 mmol) was added to 15 mL of carbon tetrachloride containing 1.2 g (16 mmol) of chlorine gas. After 10 min the volatiles were removed at 25 °C with a stream of nitrogen to give a residual oil which did not solidify upon stirring with cold hexane. The hexane solution was decanted from the insoluble oil (1.22 g) whose IR spectrum showed it to be **5** containing an appreciable amount of **1**.

2,2,2-Trinitroethyl Isocyanate (1). A solution of **5** (1.36 g, 5.6 mmol) in 15 mL of dry carbon tetrachloride was heated in an oil bath at 75 °C for 3 h. During the heating period a slow stream of nitrogen was swept over the solution and out the condenser (protected by a drierite drying tube) to remove evolved hydrogen chloride and force the reaction to completion.[14] After the 3-h heating period, the volatiles were removed with a rapid stream of nitrogen to give 1.0 g (87%) of **1** as oil: ^{1}H NMR (C_6D_6) δ 5.40 (s); IR (film) 2380, 2275 (N=C=O), 1600 (NO_2) cm^{-1}.

Ethyl Isocyanate. Benzenesulfenyl chloride (7.0 g, 0.0481 mol) was added dropwise to 6.4 g (0.0481 mol) of *S*-ethyl *N*-ethylthiocarbamate[15] stirred under a nitrogen atmosphere. After the addition was complete the IR spectrum of the reaction mixture showed no absorption at 1655 cm^{-1} (starting thiocarbamate) but a large peak at 1755 cm^{-1}, corresponding to the carbamyl chloride, was present. The reaction mixture was cooled in ice and triethylamine (6 mL) was added dropwise with good stirring (after the mixture became thick with precipitated amine salt the ice bath was removed and the remainder of the amine was added without cooling). The mixture was warmed to 40 °C for 20 min and then was cooled to 25 °C and a cold trap (dry ice) was attached. The pressure was reduced to 5 mm and the product collected was 2.1 g (62%) of ethyl isocyanate which was identified by comparison of the IR and ^{1}H NMR spectra with an authentic sample.

Phenyl Isocyanate. To a solution of 8.76 g (0.048 mol) of *S*-ethyl *N*-phenylthiocarbamate[16] in 50 mL of carbon tetrachloride at ambient temperature was added dropwise a solution of 7.0 g (0.048 mol) of benzenesulfenyl chloride in 50 mL of carbon tetrachloride over 30 min. During the addition, phenylcarbamyl chloride came out of solution as a second liquid phase. After the mixture was refluxed for 16 h to expel hydrogen chloride, the IR spectrum of the resulting homogeneous solution showed a strong absorption at 2278 and 2260 cm^{-1} (partially resolved doublet) with a shoulder at 2203 cm^{-1}. There was no absorption due to the carbamyl chloride carbonyl.

The phenyl isocyanate was characterized as the 1,3-diphenylurea as follows: 50 mL of dry methylene chloride was added to the isocyanate solution and then 4.93 g (0.053 mol) of aniline in 50 mL of methylene chloride was added over 15 min. The slurry was stirred for 2 h and the solids were then removed by filtration and washed with hexane. The solids were combined with additional product obtained by concentration of the filtrate and addition of hexane. Crystallization from ethanol gave a first crop (8.97 g, mp 240–242 °C) and a second drop (0.97 g, mp 239–242 °C) (total yield is 97.5%). The IR and ^{1}H NMR spectra were the same as for an authentic sample.

2-Fluoro-2,2-dinitroethyl *N*-(2,2,2-Trinitroethyl)carbamate (6a). To 1.1 g (5.3 mmol) of **1** in 15 mL of dry 1,2-dichloroethane was added 1.2 g (7.5 mmol) of 2-fluoro-2,2-dinitroethanol followed by 6 mg of iron(III) 2,4-pentanedionate. The solution was heated at 80 °C for 2 h before the solvent was removed to give a semisolid residue which was stirred with 10 mL of water. The water-insoluble product was crystallized from chloroform to give 1.90 g (93%) of crystals, mp 114.5–116 °C: ^{1}H NMR (CD_2Cl_2) δ 4.90 (d, 2 H), 5.22 (s, 2 H), 5.90 (br, 1 H); IR (KBr) 3450, 3515 (NH), 1777 (C=O) cm^{-1}. Anal. Calcd for $C_5H_5FN_6O_{12}$: C, 16.68; H,

(11) Conversion of amines to isocyanates using phosgene gas requires that phosgene be kept in appreciable excess to prevent formation of the urea derivative. Urea formation does not readily occur when ethyl chlorothioformate is reacted with amines.

(12) The procedure is essentially that reported by: Salmon *J. Prakt. Chem.* **1873**, *7*, 256 (Beilstein, III, 138).

(13) Lecher, H.; Holschneider F. *Chem. Ber.* **1924**, *57*, 755. *N*-chlorosuccinimide can also be used as the chlorinating agent. (Hopkins, P. B.; Fuchs, P. L. *J. Org. Chem.* **1978**, *43*, 1208.)

(14) Often a base is used to facilitate the removal of HCl from carbamyl chlorides. When weak base was used with **5**, total decomposition occurred and no **1** was formed. This is not too surprising since trinitromethyl compounds are known to be sensitive to base.

(15) The thiocarbamate was prepared as follows: a mixture of 53 mL of 70% ethyl amine in water and 100 mL of methylene chloride was stirred in an ice bath while 31.2 mL (0.3 mol) of ethyl chlorothiolformate (Aldrich Chemical Co.) was added dropwise. Water (150 mL) was added and the methylene chloride layer was separated and washed with dilute hydrochloric acid and water. The solution was dried (magnesium sulfate) and the solvent was removed by distillation. The residual liquid was distilled under reduced pressure (water aspirator) and the product [34.0 g (85%), bp 116–118 °C] was collected.

(16) The thiocarbamate was prepared as follows: 20.8 mL (0.2 mol) of ethyl chlorothiolformate (Aldrich Chemical Co.) was added dropwise to a solution of 18.2 mL (0.2 mol) of aniline and 17.8 mL (0.22 mol) of pyridine in 200 mL of methylene chloride stirred in an ice bath. The methylene chloride solution was washed with dilute hydrochloric acid and water and then was dried (sodium sulfate) and the solvent was removed to give 34.2 g (94%) of solid, mp 69–71 °C. Crystallization from methylene chloride–hexane gave 32.4 g, mp 70–71 °C.

1.40; F, 5.28; N, 23.34. Found: C, 16.71; H, 1.59; F, 5.30; N, 23.14.

2,2,2-Trinitroethyl *N*-(2,2,2-Trinitroethyl)carbamate (6b) and 2,2-Dinitropropyl *N*-(2,2,2-Trinitroethyl)carbamate (6c). Substitution of 2,2,2-trinitroethanol and 2,2-dinitropropanol for 2-fluoro-2,2-dinitroethanol in the above procedure gives **6b** (mp 165–167 °C) and **6c** (mp 125–126 °C), respectively, in similar yield. For **6b**: ^{1}H NMR [$(CD_3)_2C{=}O$] δ 5.28 (s, 2 H), 5.88 (s, 2 H), 8.22 (br, 1 H); IR (KBr) 3445 (NH), 1770 (C=O) cm^{-1}. Anal. Calcd for $C_5H_5N_7O_{14}$: C, 15.51; H, 1.30; N, 25.33. Found: C, 15.48; H, 1.32; N, 25.04.

For **6c**: ^{1}H NMR (CD_2Cl_2) δ 2.20 (s, 3 H), 4.90 (d, 2 H) 5.02 (s, 2 H), 5.85 (br, 1 H); IR (KBr) 3445, 3380 (NH), 1760 (C=O) cm^{-1}. Anal. Calcd for $C_6H_8N_6O_{12}$: C, 20.23; H, 2.26; N, 23.60. Found: C, 20.37; H, 2.28; N, 23.47.

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Photoisomerization of 2-(Trimethylsilyl)pyrroles

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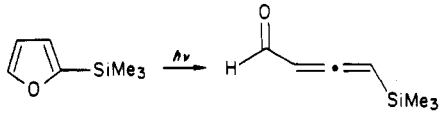
Received July 15, 1985

Recently we reported the remarkable effect of silicon substitution on the photochemistry of furans.[1] Thus, the irradiation of silyl-substituted furans leads to unprecedented exclusive formation of acylallenes in high yield.

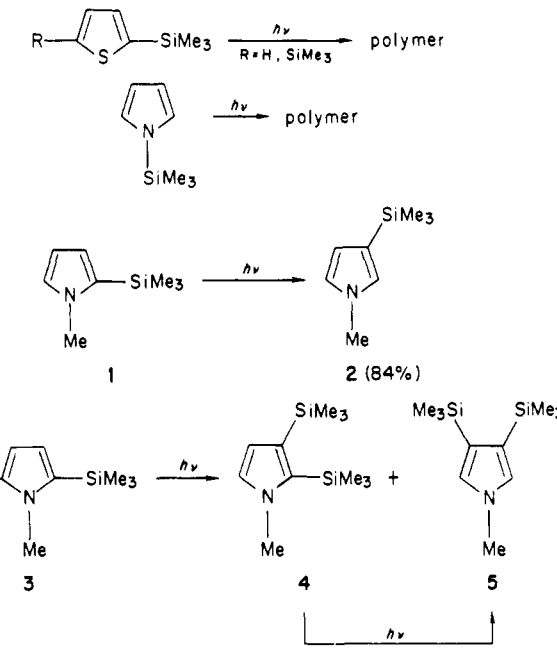


The obvious extensions to the photochemistry of silylthiophenes and silylpyrroles have now been investigated and are reported here. We find that silyl substitution has no apparent positive effect on the photochemistry of thiophenes. Irradiation of either 2-(trimethylsilyl)-thiophene or 2,5-bis(trimethylsilyl)thiophene in degassed pentane yields only intractable polymer.

In contrast to these unremarkable results, photolysis of silyl-substituted pyrroles cleanly affords rearrangement products in high yields. Photolysis of 2-(trimethylsilyl)-*N*-methylpyrrole (**1**) in degassed pentane with a medium-pressure mercury lamp yielded 3-(trimethylsilyl)-*N*-methylpyrrole (**2**, 84%) as the only volatile product. A similar irradiation of 2,5-bis(trimethylsilyl)-*N*-methylpyrrole (**3**) initially afforded two products: 2,3-bis(trimethylsilyl)-*N*-methylpyrrole (**4**, 39%) and 3,4-bis-(trimethylsilyl)-*N*-methylpyrrole (**5**, 41%). Continued irradiation of this reaction mixture, or irradiation of pure **4**, resulted in exclusive formation of **5**.

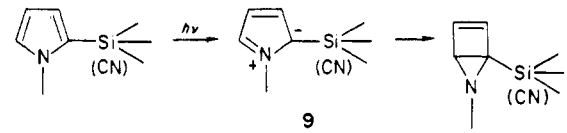
The necessity for silyl substitution to be at the 2-position is indicated by the photochemical inactivity of 3-silylpyrrole **2** and the observation that irradiation (1 h) of *N*-(trimethylsilyl)pyrrole produced only a yellow polymer. NMR and GC analysis of the photolysis solution revealed only unreacted starting material.

Although the photochemistry of pyrroles is usually rather complex,[2] this clean photorearrangement has precedent in the work of Hiraoka[3] who observed formation



of 3-cyano-*N*-methylpyrrole upon photolysis of 2-cyano-*N*-methylpyrrole. There is no reason to suspect actual silyl migration in the rearrangements **1** → **2**, **3** → **4**, and **4** → **5**, and we concur with Day[4] that the most reasonable mechanistic pathway (Scheme I) involves electrocyclic closure to a 5-azabicyclo[2.1.0]pentene **6** followed by 1,3-nitrogen shift and ring opening. Whether **5** is the thermodynamic sink on the energy surface, or whether it is simply the steric bulk of the trimethylsilyl groups that inhibit the back-reaction of **8** → **7** that controls the direction of the isomerization, our data do not reveal. A single attempt to trap a bicyclic intermediate was undertaken when **1** was irradiated in furan. Exclusive formation of **2** was found with no evidence of a furan/5-azabicyclo-[2.1.0]pent-2-ene adduct.

To our knowledge, such rearrangements of substituted pyrroles occur only when the 2-position is substituted by either cyano or silyl groups. The only obvious relationship between these two seemingly disparate groups is their pronounced ability to stabilize adjacent negative charges. Thus, a tentative suggestion is that CN or $SiMe_3$ 2-substitution favors the polarized structure **9** in the excited state and that cyclization occurs more readily from this form.



The photolyses of silicon-substituted pyrroles can be performed with gram quantities and taken to 100% conversion. Pyrroles disubstituted at the 3- and 4-positions are often not readily accessible,[5] and this route should allow for further manipulation at these positions. Investigations are continuing to examine the role of silyl substitution in heterocyclic photochemistry.

Experimental Section

All mass spectra were recorded at 70 eV. Gas chromatographic (GC) data were obtained on a Varian-Aerograph Model 3700, 1700,

(1) Barton, T. J.; Hussmann, G. *J. Am. Chem. Soc.* **1983**, *105*, 6316.
(2) For an excellent review see: Padwa, A. In "Rearrangements in Ground and Excited States"; Demayo, P., Ed.; Academic Press: New York, 1980; Vol. 3, p 501.
(3) Hiraoka, H. *J. Chem. Soc., Chem. Commun.* **1970**, 1306.
(4) Barltrop, J.; Day, A. C.; Moxon, P. D.; Ward, R. R. *J. Chem. Soc., Chem. Commun.* **1975**, 786. Barltrop, J. A.; day, A. C.; Ward, R. W. *J. Chem. Soc., Chem. Commun.* **1978**, 131.
(5) Anderson, H. J.; Loader, C. E. *Synthesis* **1985**, 353.

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