

Photoreaction of 1-(o-Allyloxyphenyl)-2-pentamethyldisilanylethyne with Methanol or Acetone

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Irradiation of 1-(o-allyloxyphenyl)-2-pentamethyldisilanylethyne (**2**) in methanol yields two 1:1 photoaddition products (**3** and **4**) via silacyclopentene intermediate. Photolysis of (**2**) with acetone in deaerated methylene chloride yields site specific and regioselective 1:1 adducts (**7** and **8**) via silacyclopentene and 1-sila-1,2-propadiene intermediate, respectively.

Introduction

The photolysis of alkynyl-substituted disilanes affords a convenient route to the highly strained silacyclopentenes.¹ These silacyclopentenes react readily with methanol or acetone in the presence of methanol or acetone as trapping agents. Silacyclopentenes also react with unsaturated functional groups such as aldehydes, ketones, styrenes, conjugated terminal acetylenes, benzyne, terminal 1,3-dienes, and conjugated imines to give five-membered cyclic organosilicon products in which C=O, C=C, C≡C or C=N bonds are inserted into the Si-C bond of the silacyclopentene ring.² In connection with this silacyclopentene intermediates we have recently reported the photochemical behavior of some disilanyl diynes.³

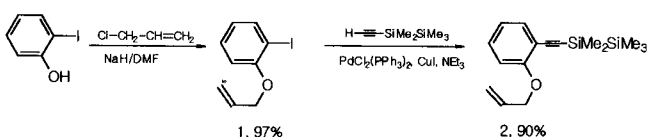
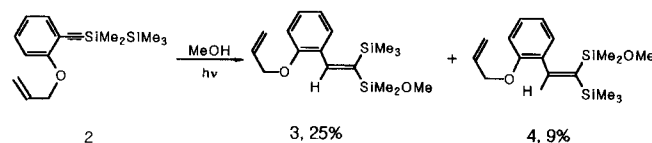
Although the chemical properties of silacyclopentenes have been extensively investigated,⁴ relatively few examples have been reported on the intramolecular photoreactions of the system. In order to check whether the C=C bond in the ortho substituent inserts intramolecularly into Si-C bond of the silacyclopentene ring, we have recently synthesized (**2**) which has the allyloxy group as ortho substituent to phenylethyne pentamethyldisilane and investigated the photolysis of (**2**) in the presence or absence⁵ of trapping agents such as methanol or acetone.

Results and Discussion

The starting 1-(o-allyloxyphenyl)-2-pentamethyldisilanylethyne (**2**) was prepared by the reaction of o-allyloxyiodobenzene (**1**) with ethynylpentamethyldisilane in the presence of bis(triphenylphosphine)palladium dichloride and copper(I) iodide in triethylamine at 40 °C (Scheme 1).

Photoreaction of 1-(o-allyloxyphenyl)-2-pentamethyldisilanylethyne (2**) with methanol.** Irradiation of (**2**) in methanol affords two 1:1 photoaddition products (**3** and **4**) but neither the expected reaction of the C=C bond in o-allyloxy group with Si-C bond of silacyclopentene intermediate (**6**) to give the compound (**5**) observed (Scheme 2) nor the photoproduct via [3,3] sigmatropic rearrangement of allyl group in (**2**) is observed in this photoreaction.

The structure of these photoproducts is determined by various physical methods such as ¹H NMR, ¹³C NMR, and mass spectrometry. The UV absorption spectra of both photoproducts are similar and the absorption patterns were significantly changed in (**3**) and (**4**) compared to that of (**2**). The molecular ion peaks (M⁺) of (**3**) and (**4**) indicate that the photoproducts are formed by the addition of one methanol molecule to (**2**). FT-IR spectra of (**3**) and (**4**) do not show the typical ethynyl absorption. The photoisomers (**3**) and (**4**) can be distinguished by comparison with the literature data.⁶ The chemical shifts for the vinylic protons of (**3**) and (**4**) are similar to those of (E) and (Z)-1-methoxydimethylsilyl-1-trimethylsilyl-2-phenylethyne.⁶ The structure of photoisomer (**3**) could also be distinguished from that of (**4**) on the basis of the ¹H NMR spectra of the isomer pair. The ¹H NMR of photoadduct (**4**) show a upfield shift for the dimethylmethoxysilyl group due to the ring current of the phenyl ring, while its isomer (**3**) shows the upfield shift for the trimethylsilyl group but not the dimethylmethoxysilyl group, and E structure to (**3**) and Z structure to (**4**) could be assigned.



Scheme 1

Scheme 2

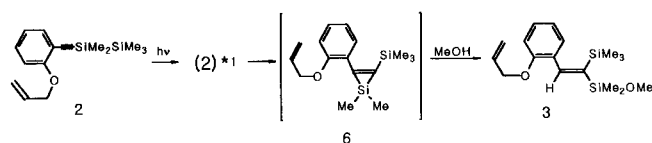
Photochemical reactions of phenylethynylpentamethyldisilane in the presence of methanol were reported to give mainly photoaddition products through the silacyclopentene intermediates in the singlet excited states.⁷ The major addition product has E configuration between the phenyl and dimethylmethoxysilyl groups and isomerize to give Z isomer on further irradiation. The silacyclopentene intermediate cannot be isolated in general because of the high reactivity toward air and moisture except for some cases. In the photoreaction of (2) in methanol, no silacyclopentene intermediate was isolated as expected. After irradiation of (2) (0.5 mM) in 5 mL of dry methylene chloride in the absence of methanol for 5 mins, 0.5 mL (12.3 mmol) of methanol was added to the reaction mixture to identify the formation of silacyclopentene as the intermediate. The addition product (3) having a E configuration was detected by HPLC from (2), strongly supporting the formation of silacyclopentene intermediate. The photoreaction of (2) in methanol is not quenched by oxygen suggesting the photoreaction to proceed *via* silacyclopentene intermediate in the singlet excited state as shown in Scheme 3.

From these results, we conclude that a silacyclopentene intermediate is formed from the singlet excited state of (2) and reacts with methanol to give a photoproduct (3). Geometrical C=C bond photoisomerization of (3) yields (4) upon irradiation of (3).

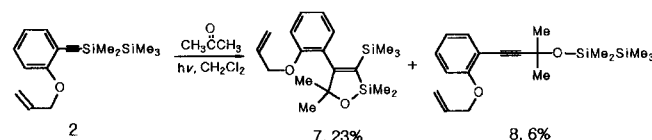
Photoreaction of 1-(*o*-allyloxyphenyl)-2-pentamethyldisilanylethyne (2) with Acetone. Irradiation of (2) with acetone in deaerated methylene chloride yields site specific and regioselective 1:1 photoadducts (7 and 8) but expected compound (5) is not observed (Scheme 4). A few other photoproducts of unknown structure are observed in trace amounts as byproducts in the reaction.

The UV absorption spectrum of photoproduct (8) is similar to that of (2) indicating that the conjugation system is sustained. The UV absorption maximum of photoproduct (7) is blue-shifted compared with that of (2).

The FT-IR spectrum of photoproduct (8) shows the ethy-



Scheme 3



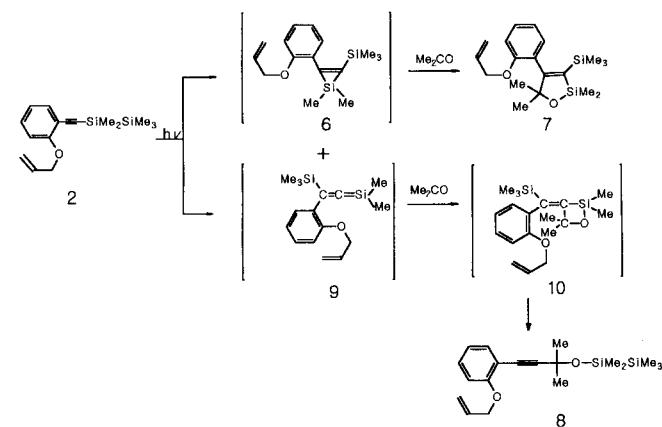
Scheme 4

nyl absorption at 2151 cm^{-1} but not in the photoproduct (7). Mass spectra of (7) and (8) show the molecular ion (M^+) peaks indicating that the photoproducts are formed by the addition of one acetone molecule to (2). The ^{13}C NMR spectrum of photoadduct (7) shows the characteristic dimethyl substituted sp^3 carbons at δ 88.9 supporting the 1-oxa-2-silacyclopent-3-ene moiety. The location of the dimethylmethylene group on the five-membered ring was confirmed by comparison with the results reported by Shizuka.⁸ The chemical shifts for the dimethylmethylene group of (7) are similar to those of 2,2,5,5-tetramethyl-3-trimethylsilyl-4-phenyl-1-oxa-2-silacyclopent-3-ene.⁸ The ^{13}C NMR spectrum of photoadduct (8) shows an ethynyl carbon at δ 103.7, 97.9 indicating that the C(1)-C(2) triple bond remains intact.⁹

The photolysis of (2) seems to proceed in two different routes simultaneously. The main route involves the production of 1-silacyclopentene (6), and the minor route involves the formation of a new type of intermediate, 1-sila-1,2-propadiene (9) (Scheme 5) as observed in the photoreaction of phenylethynyl-pentamethyldisilane with acetone.⁶ Insertion of acetone into the silicon-carbon bond in silacyclopentene (6) generates five membered ring compound (7). The cycloaddition of acetone to intermediate (9) to afford silaoxetane (10) followed by migration of trimethylsilyl group to dimethylsilyl position will give the compound (8).

Experimental

General Methods. ^1H and ^{13}C NMR spectra were recorded on Bruker AM-300 and Bruker AC-200 spectrometers with chemical shifts being referenced against TMS as an internal standard or the signal of the solvent CDCl_3 . UV absorption spectra were recorded on a Hewlett-Packard 8453 spectrophotometer. Mass spectra were determined at 70eV with a Hewlett-Packard 5985A GC-MS by the electron impact (EI) method. FT-IR spectra were recorded on a Bomem MB-100 spectrometer in KBr pellets and NaCl cell. High-performance liquid chromatography was performed on a Waters Associates Model 244 liquid chromatograph (Mildford, MA) equipped with a Model 6000A solvent delivery system, Model 440 UV absorbance detector fixed at 254 nm, and Model U6K universal injector. Lichrosorb SI-60 column was used for preparative analyses. Methylene chloride was dried with P_2O_5 followed by fractional dis-



Scheme 5

tillation prior to use. Acetone was dried with K_2CO_3 followed by fractional distillation immediately prior to use. Solvents of reagent grade for chromatography were used without further purification. Spectroscopic grade solvents (Tedia) were used for HPLC and UV absorption spectra.

Synthesis of o-allyloxyiodobenzene (1)

A solution of 2-iodophenol (3 g, 13.6 mmol) in N,N-dimethyl formamide (20 mL) was added to a solution of NaH (0.36 g, 14.9 mmol) in DMF (40 mL) at room temperature under nitrogen atmosphere. Allyl chloride (1.7 mL, 20.4 mmol) was added dropwise to the resulting solution and the mixture was stirred at room temperature for 2 hrs. Water (30 mL) was added to the solution and was extracted with ethyl acetate (3×30 mL). The combined ethyl acetate solution was washed with water (20 mL), brine (20 mL) and dried ($MgSO_4$), and concentrated *in vacuo* to give the crude product. Flash column chromatography (10% ethyl acetate/n-hexane) gave the o-allyloxyiodobenzene (1) (3.44 g, 97% yield).

Colorless oil; 1H NMR ($CDCl_3$, 300 MHz) δ_H 4.58 (2H, dt, $J=4.8$, 1.6 Hz, $-CH_2-CH=CH_2$), 5.31 (1H, dq, $J=7.4$, 1.5 Hz, $-CH_2-CH=CH_2$), 5.53 (1H, dq, $J=13.9$, 1.8 Hz, $-CH_2-CH=CH_2$), 6.02 (1H, m, $-CH_2-CH=CH_2$), 6.70 (1H, td, $J=7.7$, 1.4 Hz, ArH), 6.79 (1H, dd, $J=7.7$, 1.4 Hz, ArH), 7.27 (1H, td, $J=7.7$, 1.4 Hz, ArH), 7.77 (1H, dd, $J=7.7$, 1.4 Hz, ArH); ^{13}C NMR ($CDCl_3$, 75 MHz) δ_C 69.60, 86.63, 112.46, 117.54, 122.60, 129.30, 132.52, 139.45, 157.04; UV (CH_2Cl_2) λ_{max} 278 nm ($\epsilon=2126 M^{-1}cm^{-1}$), 286 nm ($\epsilon=1979 M^{-1}cm^{-1}$); FT-IR (NaCl) 3061.7, 2988.6, 1472.1, 1017.5, 747.7 cm^{-1} ; MS (70 eV) m/z 260 (M^+).

Synthesis of 1-(o-allyloxyphenyl)-2-pentamethyl-disilanylethyne (2)

To a deaerated solution of o-allyloxyiodobenzene (1) (1 g, 3.8 mmol), bis(triphenylphosphine)palladium dichloride (27 mg, 0.038 mmol) and copper(I) iodide (7.3 mg, 0.038 mmol) in anhydrous triethylamine (30 mL) was added dropwise ethynylpentamethyldisilane (0.66 g, 4.2 mmol) at room temperature. The reaction mixture was heated at 40 °C for 5 hrs. To this solution saturated ammonium chloride solution (20 mL) was added and the reaction mixture was extracted with ethyl acetate (3×20 mL). The combined ethyl acetate solution was washed with H_2O (10 mL), brine (10 mL), and dried ($MgSO_4$), and concentrated *in vacuo* to give the crude product. Flash column chromatography with 5% ethyl acetate/n-hexane as eluents gave (2) (1.1 g, 90% yield).

Colorless oil; 1H NMR ($CDCl_3$, 200 MHz) δ_H 0.15 (9H, s, $-Si(CH_3)_3$), 0.25 (6H, s, $-Si(CH_3)_2$), 4.57 (2H, dt, $J=4.8$, 1.6 Hz, $-CH_2-CH=CH_2$), 5.30 (1H, dq, $J=7.4$, 1.5 Hz, $-CH_2-CH=CH_2$), 5.48 (1H, dq, $J=17.2$, 1.6 Hz, $-CH_2-CH=CH_2$), 6.03 (1H, m, $-CH_2-CH=CH_2$), 6.86 (2H, m, ArH), 7.22 (1H, td, $J=7.7$, 1.7 Hz, ArH), 7.40 (1H, dd, $J=7.5$, 1.7 Hz, ArH); ^{13}C NMR ($CDCl_3$, 50 MHz) δ_C -2.94, -2.51, 69.17, 97.49, 103.30, 112.40, 113.39, 117.09, 120.53, 129.56, 133.04, 133.85, 159.48; UV (CH_2Cl_2) λ_{max} 306 nm ($\epsilon=9620 M^{-1}cm^{-1}$), 298 nm ($\epsilon=9560 M^{-1}cm^{-1}$), 261 nm ($\epsilon=18457 M^{-1}cm^{-1}$); FT-IR (NaCl) 2953.0, 2151.9, 1488.7, 1246.5, 749.4 cm^{-1} ; MS (70 eV) m/z 288 (M^+); HRMS (M^+) calcd for $C_{16}H_{24}OSi_2$ 288.1366, found 288.1352.

Irradiation of 1-(o-allyloxy phenyl)-2-pentameth-

ylidisilanylethyne (2) in methanol.

Deaerated solution (5×10^{-4} M) of 1-(o-allyloxyphenyl)-2-pentamethyldisilanylethyne (144 mg) in methanol (1 L) was irradiated in a Rayonet photochemical reactor, model RPR-208, equipped with RUL 300 nm lamps. After irradiation for 5 minutes, the resulting photoreaction mixture was concentrated *in vacuo*. The photoadducts (3 and 4) were isolated in (40 mg, 25% yield) and (14 mg, 9% yield), respectively, by column chromatography with n-hexane/ethyl acetate (60/1) as an eluent followed by normal phase HPLC using n-hexane/ethyl acetate (60/1, v/v) as an eluent.

3: 1H NMR ($CDCl_3$, 500 MHz) δ_H -0.04 (9H, s, $-Si(CH_3)_3$), 0.29 (6H, s, $-Si(CH_3)_2$), 3.46 (3H, s, $-OCH_3$), 4.53 (2H, dt, $J=4.9$, 1.5 Hz, $-CH_2-CH=CH_2$), 5.24 (1H, dq, $J=10.7$, 1.5 Hz, $-CH_2-CH=CH_2$), 5.41 (1H, dq, $J=17.3$, 1.5 Hz, $-CH_2-CH=CH_2$), 6.02 (1H, m, $-CH_2-CH=CH_2$), 6.82 (1H, dd, $J=7.8$, 1.5 Hz, ArH), 6.89 (1H, td, $J=6.8$, 1.5 Hz, ArH), 7.12 (1H, dd, $J=6.8$, 1.5 Hz, ArH), 7.23 (1H, td, $J=7.8$, 1.5 Hz, ArH), 7.83 (1H, s, vinylic H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ_C -0.89, 1.4, 14.1, 22.6, 31.6, 50.3, 68.7, 111.7, 116.5, 120.0, 128.7, 129.6, 131.9, 133.4, 153.8, 155.8; UV (CH_2Cl_2) λ_{max} 283, 251, 229 nm; FT-IR (NaCl) 2953.9, 1599.5, 1482.1, 1246.5, 1087.0 cm^{-1} ; MS (70 eV) m/z 320 (M^+); HRMS (M^+) calcd for $C_{17}H_{28}O_2Si_2$ 320.1628, found 320.1625.

4: 1H NMR ($CDCl_3$, 500 MHz) δ_H -0.02 (6H, s, $-Si(CH_3)_2$), 0.20 (9H, s, $-Si(CH_3)_3$), 3.29 (3H, s, $-OCH_3$), 4.53 (2H, dt, $J=4.4$, 2.0 Hz, $-CH_2-CH=CH_2$), 5.25 (1H, dq, $J=10.7$, 1.5 Hz, $-CH_2-CH=CH_2$), 5.42 (1H, dq, $J=17.3$, 1.5 Hz, $-CH_2-CH=CH_2$), 6.03 (1H, m, $-CH_2-CH=CH_2$), 6.81 (1H, dd, $J=7.3$, 2.0 Hz, ArH), 6.89 (1H, td, $J=7.3$, 2.0 Hz, ArH), 7.15 (1H, dd, $J=7.3$, 2.0 Hz, ArH), 7.22 (1H, td, $J=7.3$, 2.0 Hz, ArH), 7.77 (1H, s, vinylic H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ_C 0.2, 0.3, 14.1, 22.6, 31.6, 49.8, 68.7, 111.8, 116.4, 120.1, 128.8, 129.7, 131.8, 133.4, 145.0, 152.4, 155.8; UV (CH_2Cl_2) λ_{max} 283, 252, 229 nm; FT-IR (NaCl) 2953.5, 1599.3, 1482.3, 1246.1, 1091.9 cm^{-1} ; MS (70 eV) m/z : 320 (M^+); HRMS (M^+) calcd for $C_{17}H_{28}O_2Si_2$ 320.1628, found 320.1639.

Irradiation of 1-(o-allyloxyphenyl)-2-pentameth-ylidisilanylethyne (2) with acetone.

Deaerated solution (5×10^{-4} M) of 1-(o-allyloxyphenyl)-2-pentamethyldisilanylethyne (144 mg) and acetone (34 mM) in methylene chloride (1 L) was irradiated in a Rayonet photochemical reactor, Model RPR-208, equipped with RUL 300 nm lamp. After irradiation for 5 minutes, the resulting photoreaction mixture was concentrated *in vacuo*. The photoadducts (7 and 8) were isolated in (39 mg, 23% yield) and (10 mg, 6% yield), respectively, by silica gel column chromatography with n-hexane/ethyl acetate (60/1, v/v) as an eluent. The products were purified by normal phase HPLC using n-hexane/ethyl acetate (60/1, v/v) as an eluent.

7: 1H NMR ($CDCl_3$, 300 MHz) δ_H 0.23 (9H, s, $-Si(CH_3)_3$), 0.32 (6H, s, $-Si(CH_3)_2$), 1.28 (3H, s, methyl), 1.33 (3H, s, methyl), 4.46 (2H, dt, $J=4.4$, 2.0 Hz, $-CH_2-CH=CH_2$), 5.23 (1H, dq, $J=10.7$, 1.5 Hz, $-CH_2-CH=CH_2$), 5.42 (1H, dq, $J=17.3$, 1.5 Hz, $-CH_2-CH=CH_2$), 6.00 (1H, m, $-CH_2-CH=CH_2$), 6.82 (1H, dd, $J=6.8$, 1.5 Hz, ArH), 6.87-6.97 (2H, m, ArH), 7.24 (1H, td, $J=6.8$, 1.5 Hz, ArH); ^{13}C NMR ($CDCl_3$, 50 MHz) δ_C -0.33, 0.02, 0.36, 2.4, 28.9, 30.2, 68.0, 88.9, 111.3, 116.6, 119.9, 128.6, 130.7, 133.3, 136.9, 155.5, 172.9; UV (CH_2Cl_2) λ_{max} 282, 275, 230 nm; FT-IR (NaCl) 2967.4, 1650.

0, 1600.0, 1555.7 cm^{-1} ; MS (70 eV) m/z : 346 (M^+); HRMS (M^+) calcd for $\text{C}_{19}\text{H}_{30}\text{O}_2\text{Si}_2$ 346.1784, found 346.1787.

8: ^1H NMR (CDCl_3 , 300 MHz) δ_{H} 0.16 (9H, s, $-\text{Si}(\text{CH}_3)_3$), 0.28 (6H, s, $-\text{Si}(\text{CH}_3)_2$), 1.26 (3H, s, methyl), 1.57 (3H, s, methyl), 4.59 (2H, dt, $J=4.9$, 1.6 Hz, $-\text{CH}_2\text{CH}=\text{CH}_2$), 5.28 (1H, dq, $J=10.6$, 1.6 Hz, $-\text{CH}_2\text{CH}=\text{CH}_2$), 5.50 (1H, dq, $J=17.2$, 1.6 Hz, $-\text{CH}_2\text{CH}=\text{CH}_2$), 6.06 (1H, m, $-\text{CH}_2\text{CH}=\text{CH}_2$), 6.82-6.90 (2H, m, ArH), 7.24 (1H, td, $J=7.1$, 1.8 Hz, ArH), 7.42 (1H, dd, $J=7.1$, 1.8 Hz, ArH); ^{13}C NMR (CDCl_3 , 50 MHz) δ_{C} -2.52, -2.08, 30.1, 69.5, 77.6, 97.9, 103.7, 112.7, 117.6, 120.9, 130.0, 133.4, 134.3, 159.9, 162.7; UV (CH_2Cl_2) λ_{max} 306, 298, 261 nm; FT-IR (NaCl) 2953.7, 2151.8, 1488.6, 1246.5 cm^{-1} ; MS (70 eV) m/z : 346 (M^+); HRMS (M^+) calcd for $\text{C}_{19}\text{H}_{30}\text{O}_2\text{Si}_2$ 346.1784, found 346.1785.

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The chemical shifts for the ethynyl carbons of (2) and (8) appear at (δ 97.49, 103.30) and (δ 97.9, 103.7), respectively. From this results, it is thought that the C(1)-C(2) triple bond of (2) remains intact in this photoreaction.

Synthesis of Carbobenzoxy-alanyl-thiaarginine (thialysine) benzyl ester and Kinetic Studies with Trypsin

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Carbobenzoxy-alanyl-thiaarginine benzyl ester and carbobenzoxy-alanyl-thialysine benzyl ester were synthesized in solution. Kinetic studies were carried out using three different analytical methods, semi-classical method, progress curve analysis and competitive spectrophotometry. In competitive spectrophotometry, carbobenzoxy-valyl-glycyl-arginyl-*p*-nitroaniline was used as a detector. Kinetic constants such as K_m and V_{max} measured by competitive spectrophotometry are almost the same as those values measured by semi-classical method. Colorimetric Ellman's assays showed the thio-peptide mimetics to be a suitable substrates for trypsin. Kinetic studies with trypsin gave K_m of 2.33 mM and k_{cat} of $1.50 \times 10^5 \text{ min}^{-1}$ for carboxy-alanyl-thiaarginine benzyl ester and K_m of $3.41 \times 10^{-3} \text{ mM}$ and k_{cat} of $520 \times 10^2 \text{ min}^{-1}$ for carbobenzoxy-alanyl-thialysine benzyl ester, respectively. Kinetic constants ($K_m=2.04 \times 10^{-2} \text{ mM}$, $K_{\text{cat}}=4.42 \times 10^3 \text{ min}^{-1}$) for natural substrate, carbobenzoxy-alanyl-lysine benzyl ester, were also evaluated by competitive spectrophotometry in order to compare the mode of binding on trypsin.

Introduction

The breakdown of the alpha-substituted glycine¹⁻⁵ pep-

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tides yields a nucleophilic substituent along with ammonia and glyoxylate. If the substituent had been linked to the glycine residue through sulfur, decomposition lead to a compound with free sulfhydryl group. Its appearance can be