(9) Turek, A. B.; Tirrell, D. A.; Wilkinson, D. A.; Merajver, S. D., manuscript in preparation.
(10) Klotz, I. M.; Royer, G. P.; Sloniewsky, A. R. *Biochemistry* **1969**, *8*, 4752.
(11) Chen, S. C.; Sturtevant, J. H.; Gaffney, B. J. *Proc. Natl. Acad. Sci. U.S.A.* **1980**, *77*, 5060.
(12) Mabrey, S.; Sturtevant, J. In "Methods in Membrane Biology"; Korn, E. D., Ed.; Plenum Press: New York, 1978; Vol. 9, p 237.
(13) This distance is calculated from the data of Watts et al. (Watts, A.; Harlos, K.; Marsh, D. *Biochim. Biophys. Acta* **1981**, *645*, 91) assuming hexagonal packing of the lipid head groups. Known crystal structures of phosphatidylcholines and phosphatidylethanolamines (Hauser, H.; Pascher, I.; Pearson, R. H.; Sundell, S. *Biochim. Biophys. Acta* **1981**, *650*, 21) suggest that this calculation overestimates the charge separation.
(14) This distance is calculated from the bond lengths and bond angles given by Chatani et al. (Chatani, Y.; Tadokoro, H.; Saegusa, T.; Ikeda, H. *Macromolecules* **1981**, *14*, 315) assuming a planar zigzag conformation and complete ionization of the PEI. The validity of the latter assumption is open to question, as the titration behavior of PEI in the presence of DPPG has not been determined.
(15) Klotz, I. M.; Sloniewsky, A. R. *Biochem. Biophys. Res. Commun.* **1968**, *31*, 421.
(16) Chapman, D.; Cornell, B. A.; Eliasz, A. W.; Perry, A. *J. Mol. Biol.* **1977**, *113*, 517.
(17) Van Zoelen, E. J. J.; van Dijck, P. W. M.; de Kruijff, B.; Verkleij, A. I.; van Deenen, L. L. M. *Biochim. Biophys. Acta* **1978**, *514*, 9.
(18) Boggs, J. M.; Moscarello, M. A. *Biochemistry* **1978**, *17*, 5734.
(19) Gomez-Fernandez, J. C.; Goni, F. M.; Bach, D.; Restall, C. J.; Chapman, D. *Biochim. Biophys. Acta* **1980**, *598*, 502.
(20) Lentz, B. R.; Clubb, K. W.; Barrow, D. A.; Meissmer, G. *Proc. Natl. Acad. Sci. U.S.A.* **1983**, *80*, 2917.
(21) Freire, E.; Markello, T.; Rigell, C.; Holloway, P. W. *Biochemistry* **1983**, *22*, 1675.
(22) Alonso, A.; Restall, C. J.; Turner, M.; Gomez-Fernandez, J. C.; Goni, F. M.; Chapman, D. *Biochim. Biophys. Acta* **1982**, *689*, 283.
(23) Faucon, J.-F.; Dufoureq, J.; Bernard, E.; Duchesneau, L.; Pezolet, M. *Biochemistry* **1983**, *22*, 2179.
(24) Curatolo, W.; Sakura, J. D.; Small, D. M.; Shipley, G. G. *Biochemistry* **1977**, *16*, 2313.
(25) Klotz, I. M.; Royer, G. P.; Scarpa, I. S. *Proc. Natl. Acad. Sci. U.S.A.* **1971**, *68*, 263.
(26) Kiefer, H. C.; Congdon, W. I.; Scarpa, I. S.; Klotz, I. M. *Proc. Natl. Acad. Sci. U.S.A.* **1972**, *69*, 2155.
(27) Lege, C. S.; Deyrup, J. A. *Macromolecules* **1981**, *14*, 1629.
(28) Lege, C. S.; Deyrup, J. A. *Macromolecules* **1981**, *14*, 1634.
(29) Fendler, J. H. "Membrane Mimetic Chemistry"; Wiley: New York, 1982.
(30) Similar negative-stain electron micrographs were recorded for dried polymer solutions which contained no lipid. These control micrographs showed no evidence of discoidal particles similar to those in Figure 6B.
(31) Epand, R. M.; Epand, R. F.; Orlowski, R. C.; Schlueter, R. J.; Boni, L. T.; Hui, S. W. *Biochemistry* **1983**, *22*, 5074.
(32) Walsh, M. T.; Atkinson, D. *Biochemistry* **1983**, *22*, 3170.

Ene Reaction of (*S*)-(−)-4-(α-Methylbenzyl)-1,2,4-triazoline-3,5-dione with Propylene. X-ray Diffraction Analysis of a Single Crystal of the Brominated Adduct

Shadpour E. Mallakpour and George B. Butler*

Center for Macromolecular Science and Engineering and Department of Chemistry, University of Florida, Gainesville, Florida 32611

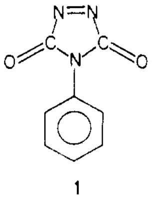
Hossein Aghabozorg and Gus J. Palenik

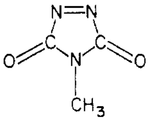
Center for Molecular Structure and Department of Chemistry, University of Florida, Gainesville, Florida 32611. *Received June 5, 1984*

ABSTRACT: Optically pure (*S*)-(−)-4-(α-methylbenzyl)-1,2,4-triazoline-3,5-dione was synthesized and its ene reaction with propylene carried out in order to obtain a model compound for further study in the modification of polydienes. The product was brominated to demonstrate that the absolute configuration of the dione had been retained and to study the N–H hydrogen bonding. The compounds were fully characterized by using ^{1}H NMR, ^{13}C NMR, and mass spectroscopy. A structural analysis of (*S*)-(−)-4-(α-methylbenzyl)-1-(2,3-dibromopropyl)urazole was performed via single-crystal X-ray diffraction. It crystallizes in space group $P2_12_12_1$ with four molecules in a unit cell of the following dimensions: $a = 5.985$ (2) Å, $b = 10.758$ (3) Å, $c = 23.063$ (3) Å, and $V = 1484.8$ (6) Å^3. The structure was solved by the heavy-atom method and refined by least-squares techniques to give a final $R = 0.066$. The dihedral angle between the phenyl ring and the five-membered ring is 65.8°, and oxygen is joined by the hydrogen bond to the N–H group [N(4)–H(4)—O(1)].

Introduction

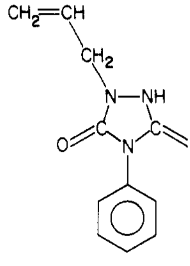
There is recent interest in the 4-substituted-1,2,4-triazoline-3,5-diones, first synthesized by Thiele[1] in 1894. They are among the most powerful dienophiles and enophiles known. For example, 4-phenyl-1,2,4-triazoline-3,5-dione (1) has been shown to be 10^3 times more reactive with 2-chlorobutadiene than tetracyanoethylene (TCNE) and 2×10^3 times more reactive than maleic anhydride (MA).[2] Also, 4-methyl-1,2,4-triazoline-3,5-dione (2) has been found to undergo the Diels–ene reaction with cyclohexene at least 3×10^4 times faster than ethylazodicarboxylate.[3] We have investigated the reaction of 1 with a variety of organic substrates including enol ethers,[4] styrenes,[5] enol esters,[6] enols,[7] alkenes,[8] allyl silanes,[9] and poly(1,3-dienes).[10,11] Most of these reactions occur very rapidly at room temperature.


1


2

During the latter studies, it was found that poly(1,3-dienes) which had been modified to the extent of 1–5% by the ene reaction of the allylic function with 1 or 2 showed dramatic changes in their solubility character, thermal behavior, and tensile properties.[11] For example, these modified polymers exhibited dramatic decreases in molecular size in solution along with an increase in tensile strength, properties which were associated with a strong intermolecular association between the urazole structures on neighboring polymer chains. The observance of two N–H stretching absorption bands in the infrared (IR) spectra of these modified polymers, one around 3400 cm^{-1} attributed to free N–H stretching, and the other around 3170 cm^{-1} attributed to bonded N–H stretching, led to a probable explanation of these unexpected properties. The latter interaction was postulated to be responsible for the dramatic reduction in hydrodynamic volume (V_h) of the modified polymers, as well as the increase in tensile strength.

The versatility of the triazoline moiety which permits introduction of a wide variety of functional groups into organic substrates or diene polymers under mild conditions prompted us to initiate a study of the effect of the 4-chiral substituent on the properties of stereoregular polymers, as well as the possibility of utilizing such modified polymers in resolving racemic modifications of certain organic compounds. For example, the NH proton of 1-allyl-4-phenyl-1,2,4-triazolidine-3,5-dione (**3**) has been shown to be quite acidic, the pK_a of **3** being 4.71.[12] Thus, cross-linked diene polymers, when swollen with a suitable solvent, undergo rapid reaction with the triazolinedione moiety to introduce the triazolidinedione structure.[13]



3

Optically pure triazolinediones have been synthesized, their ability to discriminate between diastereomeric Diels–Alder transition states has been demonstrated, and their levels of enantioselection have been determined.[14] During the course of our study, the synthesis of (*S*)-(−)-4-(α-methylbenzyl)-1,2,4-triazoline-3,5-dione (**9**) was reported.[14b] However, the retention of the chirality during the synthetic pathways was not demonstrated. Since the parent dione (**9**) is a low melting solid, we prepared the dibromo adduct so that the retention of chirality could be unequivocably proven.

The present study describes a single-crystal X-ray diffraction determination of the structure, absolute configuration, and intermolecular N–H hydrogen bonding in a chiral urazole. The aims of our investigation were to relate the N–H hydrogen bonding to the change in the properties of modified polymers and to confirm that no racemization or inversion of the chiral substituent on the 4-position had occurred during the synthesis.

Results and Discussion

Although the (*S*)-(−)-4-(α-methylbenzyl)-1,2,4-triazoline-3,5-dione (**9**) has been reported before,[14b] some modifications in the reported procedure were necessary in order to obtain adequate quantities for our studies. Thus, (*S*)-(−)amine (**4**) was allowed to react with dry hydrogen chloride gas in one cycle, and a quantitative yield of the amine salt was collected. This amine salt (**5**) was converted to the (*S*)-(−) isocyanate (**6**) via passing phosgene gas through a slurry mixture of hot toluene, resulting in a high yield of the compound (**6**). This isocyanate was led to react with ethyl carbazate to afford semicarbazide (**7**) in a quantitative yield. The (*S*)-(−)-semicarbazide (**7**) had been reported[14b] as an oily substance; however, in our case it was isolated as a white solid, having a melting point of 87.0–89.0 °C. Cyclization of **7** was performed by heating at 250–260 °C. The product (**8**) was isolated from a hot solution of benzene rather than trituration in petroleum ether[14b] (the residue becomes very tough after pyrolysis, is difficult to triturate, and a poor yield is obtained). Oxidation of (*S*)-(−)urazole (**8**) with dinitrogen tetraoxide gave an excellent yield of the (*S*)-(−)triazolinedione (**9**) with a higher melting point than previously reported.[14b] All of the above compounds were fully characterized by using IR, ^{1}H NMR, ^{13}C NMR, and mass spectroscopy (Scheme I).

Table I
Pseudo-First-Order Kinetics for Decomposition of (*S*)-(−)-4-(α-Methylbenzyl)-1,2,4-triazoline-3,5-dione (9) in Different Solvents at 25 °C

solvent	K,[a] s^{-1}	$t_{1/2}$, h	COC
DMF	3.83×10^{-5}	5.02	0.9909
THF	5.64×10^{-6}	34.10	0.9926
Me_2SO	2.53×10^{-6}	76.20	0.9961

[a] Calculated by the method of least squares.

Table II
Visible Absorption of (*S*)-(−)-4-(α-Methylbenzyl)-1,2,4-triazoline-3,5-dione in Selected Solvents at 25 °C

solvent	λ_{max}, nm	ϵ
toluene	565, 542, 525 (sh)	148, 185, 149
CH_2Cl_2	566, 538, 526 (sh)	116, 146, 114
acetone	540 (sh), 525	100, 122
THF	540 (sh), 530	105,[a] 116[a]
Me_2SO	530 (sh), 520	117,[a] 137[a]
DMF	540 (sh), 520	76,[a] 84[a]

[a] Estimated value. Because of the instability of (*S*)-(−)-triazolinedione in THF, Me_2SO, and DMF.

The stability of (*S*)-(−)-4-(α-methylbenzyl)-1,2,4-triazoline-3,5-dione (**9**) in solvents such as methylene chloride, toluene, acetone, tetrahydrofuran, *N*,*N*-dimethylformamide (DMF), and dimethyl sulfoxide (Me_2SO) was studied via visible spectroscopy. These results show that **9** is quite stable in solvents such as methylene chloride, acetone, and toluene, but it decomposes slowly in Me_2SO, THF, and DMF. Rate constants for such decomposition are given in Table I. The λ_{max} values are shown in Table II.

Compound **9** was allowed to react with propylene gas at room temperature to yield the "ene" adduct (**10**). This compound was needed as a model compound for another study which involved modification of polydienes via the "ene" reaction with chiral enophiles. In order to determine absolute configuraiton as well as the extent of hydrogen bonding via solid state analysis, it became necessary to brominate the "ene" adduct (**10**). Thus, bromination of compound **10** was performed with a solution of Br_2 in CCl_4 at room temperature to give compound **11**. A single crystal was obtained from methanol solution, and an X-ray analysis was carried out. From the X-ray analysis, it is clear that the absolute configuration is *S* and that no racemization had occurred during the course of the seven-step synthesis. Also, there is strong support from this study for the postulate that carbonyl oxygen is bonded by hydrogen bonding to the N–H group [N(4)–H(4)···O(1)]; this postulate was advanced to account for the observation of pronounced thermoplastic elastomer properties in triazolinedione modified polydienes[11] (Scheme II). Previous evidence in support of this postulate was based on

Table III
Crystal Data for
(*S*)-(−)-4-(α-Methylbenzyl)-1-(2,3-dibromopropyl)urazole

formula	$C_{13}H_{15}O_2N_3Br_2$
mol wt	405.10
space group	$P2_12_12_1$
a, Å	5.985 (2)
b, Å	10.758 (3)
c, Å	23.063 (3)
α, deg	90^a
β, deg	90^a
γ, deg	90^a
vol, $Å^3$	1484.8 (6)
Z	4
D_m, g cm^{-3}	1.807
D_c, g cm^{-3}	1.812
crystal size, mm	0.27 × 0.27 × 0.13
μ, cm^{-1}	54.1
radiation used	Mo Kα, graphite monochromator
2θ range	0–45°
no. of measd reflections	1183
no. of reliable reflections	966
K [in $I < K\sigma(I)$]	2.0
goodness of fit	0.257
R	0.066

[a] Required by symmetry of space group.

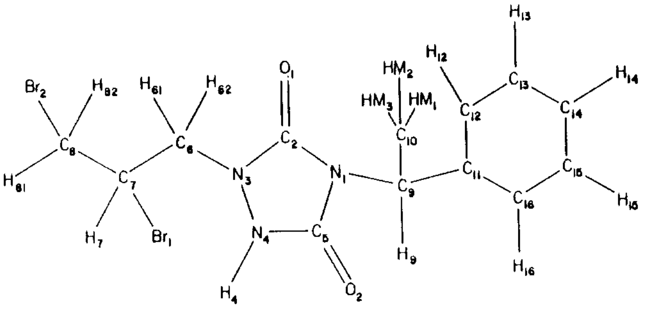


Figure 1. Numbering scheme used in the X-ray analysis of (*S*)-(−)-4-(α-methylbenzyl)-1-(2,3-dibromopropyl)urazole.

the observation of infrared bands for both bonded and nonbonded N–H stretching frequencies which occur around 3400 and 3170 cm^{-1}, respectively.

(*R*)-(+)-4-(α-Methylbenzyl)-1,2,4-triazoline-3,5-dione has also been prepared and characterized in these laboratories. Optically pure samples of both (*R*)-(+) and (*S*)-(−) forms of compound **9** have been used to modify a variety of diene polymers and copolymers, including cross-linked polymers, to produce the corresponding optically active modified polymer. The results of these studies will be reported in succeeding papers.

X-ray Crystallographic Study. Crystals suitable for X-ray studies were grown by slow evaporation of a methanol solution. All measurements were carried out by using a P$\bar{1}$ diffractometer with Zr-filtered Mo radiation; $\lambda\alpha_1$ = 0.70926, and $\lambda\alpha_2$ = 0.71354 Å. Pertinent crystal data and other details are given in Table III. The crystal structure was solved by the heavy-atom method and refined by least-squares techniques. The absolute configuration was determined by using the anomalous dispersion effect of the two bromine atoms. After three cycles of least-squares using isotropic thermal parameters, the R values ($R = \sum||F_o| - |F_c||/\sum|F_o|$) for the two possible configurations were 0.106 and 0.096. With anisotropic thermal parameters for only the two Br atoms, the R value was 0.073. Least-squares refinement using the block approximation and anisotropic thermal parameters for all atoms gave a final R value of 0.066. The final positional parameters are given in Table IV. A difference Fourier synthesis gave reasonable positions for 12 of the 15 hydrogen atoms in the molecule. The hydrogen atom positions, the thermal parameters for the heavy atoms, and tables of observed and calculated structure factors are available as supplementary material.

Table IV
Final Positional Parameters (×10^4) and Their Estimated Standard Deviations for
(*S*)-(−)-4-(α-Methylbenzyl)-1-(2,3-dibromopropyl)urazole

atom	x	y	z
Br(1)	−6454 (4)	−1255 (2)	−1688 (1)
Br(2)	−724 (4)	−3104 (2)	−663 (1)
O(1)	−4346 (25)	−1840 (12)	−3089 (5)
O(2)	−9442 (24)	−4954 (12)	−2742 (6)
N(1)	−7339 (27)	−3226 (14)	−3030 (6)
N(3)	−4513 (27)	−3523 (16)	−2429 (7)
N(4)	−6193 (29)	−4338 (13)	−2256 (6)
C(2)	−5306 (33)	−2750 (17)	−2877 (7)
C(5)	−7910 (33)	−4264 (16)	−2695 (8)
C(6)	−3059 (32)	−3008 (18)	−1987 (8)
C(7)	−4250 (35)	−2535 (19)	−1442 (8)
C(8)	−2713 (39)	−1839 (19)	−1018 (8)
C(9)	−8903 (38)	−2798 (18)	−3478 (7)
C(10)	−8947 (42)	−1288 (23)	−3520 (9)
C(11)	−8569 (35)	−3415 (17)	−4053 (7)
C(12)	−6560 (36)	−3319 (20)	−4325 (8)
C(13)	−6247 (43)	−3872 (20)	−4912 (8)
C(14)	−8002 (44)	−4515 (21)	−5131 (8)
C(15)	−10010 (42)	−4653 (17)	−4865 (8)
C(16)	−10323 (35)	−4118 (18)	−4292 (9)

Table V
Bond Distances (Å) with Their Estimated Standard Deviations for
(*S*)-(−)-4-(α-Methylbenzyl)-1-(2,3-dibromopropyl)urazole

C(11)–C(12)	1.361 (29)	N(3)–N(4)	1.393 (23)
C(12)–C(13)	1.491 (26)	N(4)–C(5)	1.444 (25)
C(13)–C(14)	1.355 (34)	C(5)–N(1)	1.400 (23)
C(14)–C(15)	1.358 (34)	C(2)–O(1)	1.236 (22)
C(15)–C(16)	1.454 (28)	C(5)–O(2)	1.185 (23)
C(16)–C(11)	1.406 (28)	N(3)–C(6)	1.451 (24)
C(11)–C(9)	1.495 (24)	C(6)–C(7)	1.532 (26)
C(9)–C(10)	1.627 (32)	C(7)–C(8)	1.538 (28)
C(9)–N(1)	1.469 (25)	C(7)–Br(1)	1.990 (21)
N(1)–C(2)	1.366 (25)	C(8)–Br(2)	1.985 (21)
C(2)–N(3)	1.408 (24)		

The numbering scheme used is shown in Figure 1, and a stereoview in the correct absolute configuration is given in Figure 2. Bond distances and angles for the non-hydrogen atoms are presented in Tables V and VI, respectively. Selected torsion angles are given in Table VII.

The five-membered triazoline ring is distorted from planarity toward the envelope conformation. The puck-

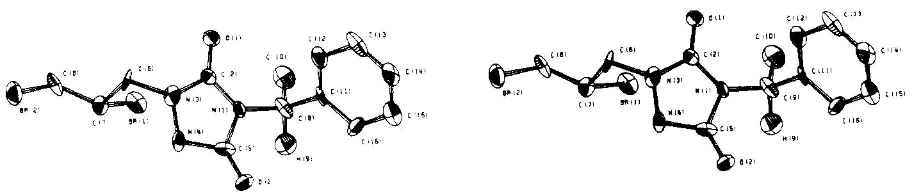
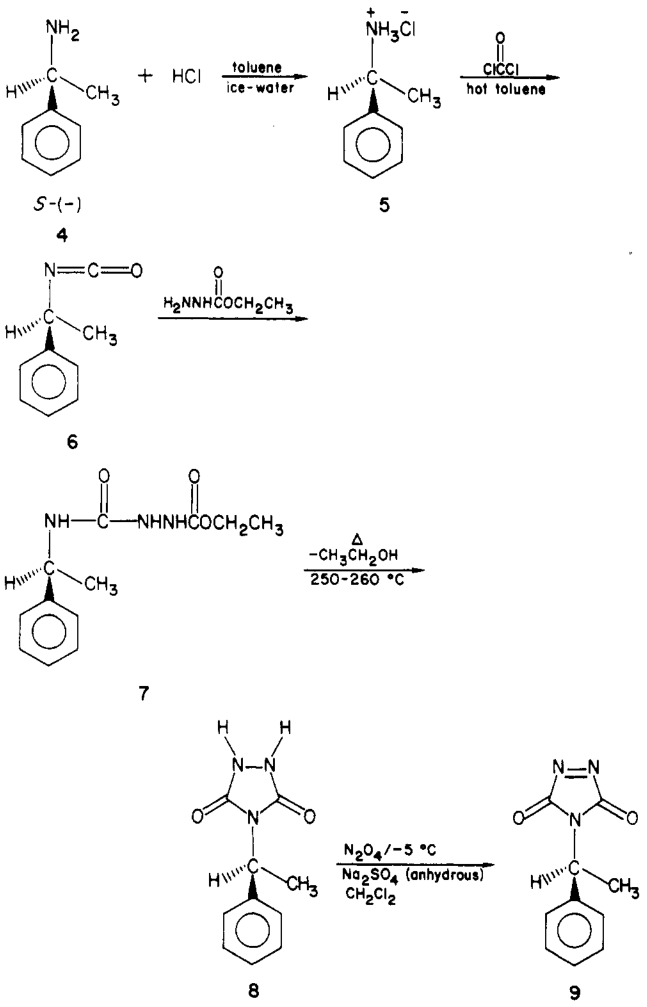
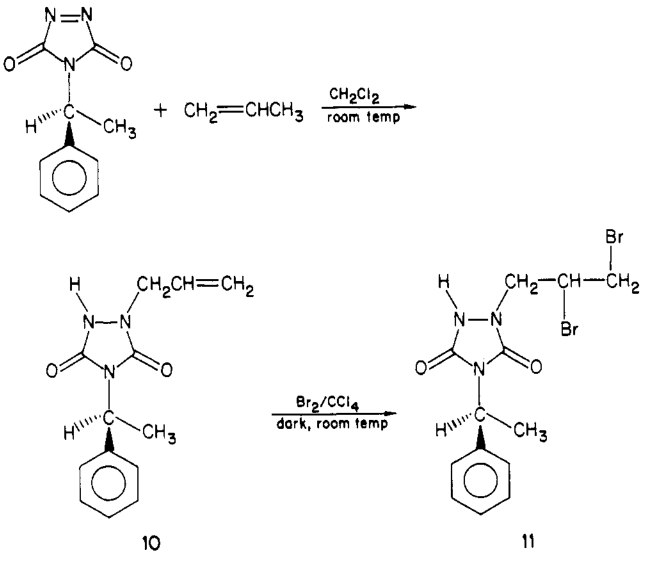


Figure 2. Stereoscopic view of (*S*)-(−)-4-(α-methylbenzyl)-1-(2,3-dibromopropyl)urazole showing the atomic numbering and thermal ellipsoids (50% probability level). Only the hydrogen atom on C(9) is shown, with the other hydrogen atoms being omitted for clarity.

Scheme I



Scheme II



ering amplitude[15] was estimated to be 0.086 Å from the observed torsion angle. The small puckering angle is undoubtedly due to the two C=O groups which tend to limit the puckering of the ring. The two Br atoms are essentially trans relative to the C(7)–C(8) bond as would be expected on steric grounds. The dihedral angle between phenyl ring and five-membered ring is 65.8°.

Table VI
Bond Angles (Deg) with Their Estimated Standard Deviations for (*S*)-(−)-4-(α-Methylbenzyl)-1-(2,3-dibromopropyl)urazole

C(11)–C(12)–C(13)	120.0 (18)	N(1)–C(2)–N(3)	105.5 (15)
C(12)–C(13)–C(14)	116.4 (20)	C(2)–N(3)–N(4)	109.8 (15)
C(13)–C(14)–C(15)	125.0 (21)	N(3)–N(4)–C(5)	106.1 (14)
C(14)–C(15)–C(16)	118.8 (19)	N(4)–C(5)–N(1)	104.9 (15)
C(15)–C(16)–C(11)	118.2 (18)	C(5)–N(1)–C(2)	112.0 (15)
C(16)–C(11)–C(12)	121.3 (18)	O(1)–C(2)–N(3)	127.0 (17)
C(12)–C(11)–C(9)	119.6 (17)	O(2)–C(5)–N(4)	125.4 (17)
C(16)–C(11)–C(9)	119.1 (17)	C(2)–N(3)–C(6)	119.5 (15)
C(11)–C(9)–C(10)	113.2 (16)	N(4)–N(3)–C(6)	118.1 (15)
C(11)–C(9)–N(1)	113.6 (16)	N(3)–C(6)–C(7)	115.1 (16)
C(10)–C(9)–N(1)	111.4 (16)	C(6)–C(7)–C(8)	113.9 (16)
C(9)–N(1)–C(2)	129.2 (15)	C(6)–C(7)–Br(1)	107.7 (13)
C(9)–N(1)–C(5)	118.9 (15)	C(8)–C(7)–Br(1)	104.0 (13)
N(1)–C(2)–O(1)	127.5 (17)	C(7)–C(8)–Br(2)	106.7 (13)
N(1)–C(5)–O(2)	129.7 (17)		

Table VII
Selected Torsion Angles (Deg) for (*S*)-(−)-4-(α-Methylbenzyl)-1-(2,3-dibromopropyl)urazole

atoms	angle	atoms	angle
N(1)–C(2)–N(3)–N(4)	−8.8	Br(1)–C(7)–C(8)–Br(2)	172.1
C(2)–N(3)–N(4)–C(5)	13.0	C(5)–N(1)–C(9)–C(10)	142.7
N(3)–N(4)–C(5)–N(1)	−12.0	C(5)–N(1)–C(9)–C(11)	−88.1
N(4)–C(5)–N(1)–C(2)	7.0	C(12)–C(11)–C(9)–N(1)	−59.0
C(5)–N(1)–C(2)–N(3)	0.8	C(16)–C(11)–C(9)–N(1)	119.1
N(4)–N(3)–C(6)–C(7)	−45.3	C(12)–C(11)–C(9)–C(10)	69.3
N(3)–C(6)–C(7)–C(8)	−172.2	C(16)–C(11)–C(9)–C(10)	−112.7

The distances in the triazoline are similar to the dimensions observed in semicarbazones and related compounds.[16] There is a lengthening of the C(2)–O(1) bond compared to that of C(5)–O(2) which could be related to the N–H···O hydrogen bond to O(1). The ring distances appear to reflect the difference in substitution on N(3) vs. N(4) as well as the lengthening of the C(2)–O(1) bond.

The N(4)–H(4)···O(1) hydrogen bond is confirmed by the appearance of H(4) in the difference Fourier synthesis. The distances of N(4)–H(4) of 0.90 Å, H(4)···O(1) of 2.013 Å, and the N(4)–H(4)···O(1) angle of 151° are typical for an N–H···O hydrogen bond. The effect of this hydrogen bond on the distances in the triazoline ring is not unequivocal, however. The longer C(2)–O(1) and shorter C(2)–N bond distances compared to those involving C(5) are as one would expect for a hydrogen bond involving O(1) but not O(2). However, the differences in the bond distances in the triazoline ring are not statistically significant at the 95% level because of the presence of the two bromine atoms.

Experimental Section

Equipment and Data. All temperatures are reported uncorrected. Melting points were determined in open capillary tubes by using a Thomas-Hoover melting point apparatus. Pressures are expressed as millimeters of mercury. Carbon-13 NMR (25 MHz, 75 MHz) and proton nuclear magnetic resonance (100 MHz, 300 MHz) were obtained on either a JEOL JNM-FX-100 or Nicolet NT-300 instrument. All chemical shifts are relative to tetramethylsilane. In cases where no internal reference was added, spectra were calibrated via a characteristic signal of the deuterated solvent used.[17] Infrared (IR) spectra were obtained by using a Perkin-Elmer Model 281 infrared spectrophotometer. Mass spectra [low resolution (LRMS) and high resolution (HRMS)] were recorded on an Associated Electronic Industries (AEI) Model MS-30 spectrometer. Elemental analyses were performed by either Atlantic Microlab, Inc., Atlanta, GA, or the University of Florida Department of Chemistry, Gainesville, FL. Optical rotations were measured by either a Rudolph Research Autopol III Automatic or a Perkin-Elmer Model 141 polarimeter. All concentrations are reported in mg/mL.

(*S*)-(−)-α-Methylbenzylamine Hydrochloride. Into a 1000-mL, three-necked round-bottomed flask equipped with a gas-inlet tube and a mechanical stirrer (all glassware was flame-dried prior to use) were charged 26.19 g (0.2161 mol) of

(*S*)-(−)-α-methylbenzylamine ($[\alpha]^{20}_{\mathrm{D}}$ −30 ± 2° (*c* 10, ethanol) and 700 mL of dry toluene. The mixture was cooled in an ice–water bath, and dry hydrogen chloride gas was passed through the solution for 15 min. A white crystalline solid was formed. The HCl flow was discontinued, and the ice–water bath was removed. Dry nitrogen gas was passed through the slurry mixture for 1 h, and the excess HCl was trapped with a 20% NaOH solution. After the white solid was filtered using suction filtration, washed with 500 mL of anhydrous diethyl ether, and dried overnight in a vacuum desiccator, 33.45 g (98.2%) of a white crystalline solid was obtained; mp 169.0–170.0 °C; IR (KBr) 2920 (s, br), 2725 (sh), 2675 (sh), 2630 (sh), 2570 (sh), 2480 (m), 2030 (m), 1600 (m), 1505 (s), 1450 (s), 1380 (m), 1357 (w), 1332 (w), 1312 (w), 1289 (w), 1225 (m), 1087 (m), 1064 (m), 1028 (w), 986 (w), 920 (w), 758 (s), 745 (m), 694 (s) cm^{-1}; ^{1}H NMR ($\mathrm{Me_2SO}$-d_6) δ 1.55 (d, 2 H, *J* = 7.0 Hz), 4.38 (q, 1 H, *J* = 7.0 Hz), 7.5 (m, 5 H), 8.83 (s, br, 3 H) which exchanges with $\mathrm{D_2O}$; ^{13}C NMR ($\mathrm{Me_2SO}$-d_6) 20.88, 50.08, 126.89, 128.20, 128.54, 139.51 ppm; $[\alpha]^{25}_{\mathrm{D}}$ −19.8° (*c* 10.0, $\mathrm{CH_2Cl_2}$).

(*S*)-(−)-α-Methylbenzyl Isocyanate. In a 1000-mL three-necked round-bottomed flask equipped with a mechanical stirrer, water-cooled condenser, and gas inlet tube were placed 29.05 g (0.1843 mol) of (*S*)-(−)-α-methylbenzylamine hydrochloride salt and 600 mL of dry toluene. The slurry mixture was heated to the reflux temperature. Phosgene gas was bubbled into the mixture until all solid had completely dissolved (~3 h) and then again for an additional hour. The phosgene gas was routinely passed through two traps and towers containing cottonseed oil, concentrated sulfuric acid, and $\mathrm{CaSO_4}$ prior to passing into the reaction vessel. The HCl from the reaction and excess $\mathrm{COCl_2}$ gas were trapped in a 20% NaOH solution. The hot, clear solution was flushed with dry nitrogen gas for 1 h. Toluene was removed via simple distillation at atmospheric pressure, and the residue was distilled under vacuum to yield 23.3 g of a clear liquid (85.9%): bp 104–106 °C (30 mmHg); IR (neat) 3660 (m), 3087 (m), 3068 (m), 3038 (m), 2980 (m), 2936 (m), 2260 (s), 1950 (w), 1880 (w), 1820 (w), 1750 (w), 1620 (w), 1605 (m), 1495 (m), 1452 (m), 1375 (m), 1348 (m), 1310 (m), 1280 (m), 1205 (m), 1064 (m), 1028 (m), 910 (m), 830 (m), 758 (m), 697 (s) cm^{-1}; ^{1}H NMR ($\mathrm{CDCl_3}$) δ 1.59 (d, 3 H, *J* = 6.8 Hz), 4.8 (q, 1 H, *J* = 6.8 Hz), 7.3 (s, 5 H); ^{13}C NMR ($\mathrm{CDCl_3}$) 25.97, 54.58, 125.30, 127.78, 128.71, 142.40 (C=O carbon is overlapped with aromatic carbons); $[\alpha]^{25}_{\mathrm{D}}$ −13.9° (*c* 10.05, $\mathrm{CH_2Cl_2}$) lit.[18] $[\alpha]^{20.5}_{\mathrm{D}}$ −10.1°; mass spectrum, calcd *m/e* 147.0684, obsd 147.0676. Anal. Calcd for $\mathrm{C_9H_9NO}$: C, 73.45; H, 6.16; N, 9.52. Found: C, 73.55; H, 6.20; N, 9.49.

(*S*)-(−)-4-(α-Methylbenzyl)-1-(ethoxycarbonyl)semicarbazide. In a 250-mL three-necked flask fitted with a constant-pressure dropping funnel, magnetic bar, reflux condenser attached to a drying tube containing silica gel, and a thermometer was placed a solution of 16.27 g (0.1563 mol) of ethylhydrazine carboxylate[19] in 60 mL of dry toluene. To this mixture was added a solution of 23.00 g (0.1563 mol) of (*S*)-(−)-α-methylbenzylisocyanate in 60 mL of dry toluene dropwise over a period of 1.5 h. The temperature was kept below 40 °C. After addition was complete, the mixture was heated at reflux temperature for 8 h (2 h will be enough). The mixture was cooled and stirred at room temperature for 60 h to effect crystallization. (Solidification also can occur in a shorter period of time, ~4 h, if a few previously formed crystals are added.) The white solid was filtered by using suction filtration, washed with 500 mL of petroleum ether (bp 37–58 °C), and then dried in a vacuum desiccator for 24 h to give 38.21 g of a white solid (97.3%): mp 87.0–89.0 °C; IR (KBr) 3350 (s), 3280 (s), 3110 (w), 3060 (w), 3037 (w), 2980 (m), 2940 (w), 2910 (w), 2870 (w), 1700 (s), 1650 (s), 1600 (w), 1548 (s), 1480 (w), 1475 (w), 1450 (w), 1435 (w), 1379 (m), 1349 (m), 1335 (m), 1320 (m), 1280 (m), 1228 (m), 1140 (m), 1070 (s), 1028 (w), 1000 (w), 990 (w), 915 (w), 780 (w), 758 (m), 695 (s), 660 (w) cm^{-1}; ^{1}H NMR ($\mathrm{Me_2SO}$-d_6) δ 1.16 (t, 3 H, *J* = 7.0 Hz), 1.35 (d, 3 H, *J* = 7.0 Hz), 4.03 (q, 2 H, *J* = 7.0 Hz), 4.80 (p, 1 H, *J* = 7.0 Hz), 6.73 (d, 1 H, *J* = 8.0 Hz), 7.29 (m, 5 H), 7.67 (s, 1 H), 8.78 (s, br, 1 H); ^{13}C NMR ($\mathrm{Me_2SO}$-d_6) 14.50, 22.88, 48.57, 60.36, 125.86, 126.46, 128.10, 145.31, 156.96, 157.45; $[\alpha]^{25}_{\mathrm{D}}$ −3.7° (*c* 10.0, $\mathrm{CH_2Cl_2}$); mass spectrum, calcd *m/e* 251.1269, obsd 251.1288. Anal. Calcd for $\mathrm{C_{12}H_{17}N_3O_3}$: C, 57.35; H, 6.82; N, 16.73. Found: C, 57.80; H, 6.86; N, 16.75.

(*S*)-(−)-4-(α-Methylbenzyl)urazole. Into a 250-mL round-bottomed flask equipped with a magnetic stirring bar, distillation head, thermometer, and a water-cooled condenser was placed 36.83 g (0.1466 mol) of (*S*)-(−)-(α-methylbenzyl)-1-(ethoxycarbonyl)-semicarbazide. The flask was heated at 250–260 °C using a sand bath for 1.5 h. The distillate was collected between 80–95 °C and was discarded. The residue was cooled, 200 mL of benzene was added, and the mixture was heated to the boiling point of the solvent. The hot mixture was filtered and cooled to give 21.25 g (70.6%) of a white solid. Recrystallization from benzene furnished a white crystalline solid: mp 126.0–127.5 °C; IR (KBr) 3160 (sh), 3030 (s), 2972 (s), 2800 (s, br), 1760 (sh), 1675 (s), 1490 (m), 1450 (s), 1375 (m), 1310 (w), 1280 (w), 1238 (m), 1217 (m), 1207 (m), 1160 (w), 1140 (w), 1110 (w), 1080 (m), 1055 (m), 1025 (m), 1003 (w), 980 (w), 919 (w), 775 (s), 695 (s), 665 (w), 623 (w) cm^{-1}; ^{1}H NMR ($\mathrm{Me_2SO}$-d_6) δ 1.76 (d, 3 H, *J* = 7.4 Hz), 5.17 (q, 1 H, *J* = 7.4 Hz), 7.33 (m, 5 H), 9.97 (s, br, 2 H); ^{13}C NMR ($\mathrm{Me_2SO}$-d_6) 17.37, 49.34, 126.59, 127.37, 128.40, 140.92, 154.71; $[\alpha]^{25}_{\mathrm{D}}$ −43.4° (*c* 10.0, $\mathrm{CH_2Cl_2}$); mass spectrum calcd *m/e* 205.0851, obsd 205.0842. Anal. Calcd for $\mathrm{C_{10}H_{11}N_3O_2}$: C, 58.52; H, 5.40; N, 20.48. Found: C, 58.67; H, 5.44; N, 20.42.

(*S*)-(−)-4-(α-Methylbenzyl)-1,2,4-triazoline-3,5-dione. Anhydrous sodium sulfate (40.0 g) was placed into a 300-mL round-bottomed flask with 6.00 g (0.0292 mol) of (*S*)-(−)-4-(α-methylbenzyl)urazole and 160 mL of methylene chloride. The slurry mixture was stirred by a magnetic stirrer and cooled to −5 °C with an ice–salt bath. Dinitrogen tetraoxide gas was bubbled slowly through the mixture for 10 min, while keeping the temperature below 0 °C. After a few minutes, a deep red color developed. The red solution was stirred for 30 min and then filtered into a 250-mL round-bottomed flask. The excess $\mathrm{N_2O_4}$ was flushed with dry nitrogen gas (~3 h), and the solvent was removed by rotoevaporation to give a deep pink viscous liquid. Upon scratching the interior part of the flask, a dark pink crystalline solid was formed. The pink crystals were dried overnight under vacuum at room temperature to give 5.67 g (95.6%) of pink crystals: mp 74–78 °C. Sublimation was accomplished at 60–70 °C under a vacuum of less than 0.6 mm: mp 78–81 °C (lit.[14b] mp 57–61 °C). The pink solid was stored in the absence of light in a desiccator until it was used: IR (KBr) 3580 (w), 3090 (w), 3070 (w), 3048 (w), 2990 (m), 2942 (w), 2078 (w), 1985 (w), 1960 (w), 1915 (w), 1760 (s), 1665 (sh), 1588 (w), 1520 (w), 1495 (m), 1460 (m), 1385 (s), 1375 (s), 1345 (se, 1285 (m), 1215 (m), 1180 (s), 1160 (m), 1115 (w), 1080 (w), 1060 (w), 1020 (m), 980 (m), 935 (m), 840 (w), 780 (s), 770 (m), 735 (s), 700 (s), 680 (s), 650 (w), 640 (m) cm^{-1}; ^{1}H NMR ($\mathrm{Me_2SO}$-d_6) δ 1.75 (d, 3 H, *J* = 7.2 Hz), 5.25 (q, 1 H, *J* = 7.3 Hz), 7.40 (m, 5 H); ^{13}C NMR ($\mathrm{Me_2SO}$-d_6) 17.13, 52.56, 126.93, 128.01, 128.45, 138.44, 159.69 ppm; $[\alpha]^{25}_{\mathrm{D}}$ −61° (*c* 2.0, $\mathrm{CH_2Cl_2}$) [lit.[14b] $[\alpha]^{20}_{\mathrm{D}}$ −48.6° (*c* 3.7, $\mathrm{CH_2Cl_2}$)].

(*S*)-(−)-4-(α-Methylbenzyl)-1-allylurazole. (*S*)-(−)-4-(α-Methylbenzyl)-1,3,5-triazoline-2,4-dione (1.5 g, 0.0073 mol) was placed in a 50-mL round-bottomed flask with 15 mL of methylene chloride. The dark pink solution was stirred by a magnetic stirrer, and propylene was bubbled slowly through the solution until all the pink color had disappeared (~4 h). Methylene chloride was removed by rotoevaporation, and a pale yellow viscous oil remained. Ether was added (5 mL), and slow evaporation gave a white solid, 1.81 g (100%). Purification was performed by sublimation at 80 °C under a vacuum of less than 0.3 mm: mp 73.5–75.0 °C; IR (KBr) 3450 (w), 3170 (s, br), 3017 (w), 2990 (w), 2940 (w), 2910 (w), 1770 (s), 1685 (s), 1600 (sh), 1580 (w), 1490 (m), 1440 (s), 1414 (s), 1380 (s), 1345 (m), 1305 (m), 1235 (m), 1190 (w), 1160 (w), 1110 (w), 1090 (w), 1045 (m), 1025 (m), 1000 (m), 980 (m), 930 (s), 895 (m), 845 (w), 780 (s), 760 (s), 712 (s), 695 (s), 620 (m), 610 (m) cm^{-1}; ^{1}H NMR ($\mathrm{Me_2SO}$-d_6) δ 1.77 (d, 3 H, *J* = 7.5 Hz), 4.03 (d, 3 H, *J* = 6.0 Hz), 5.2 (m, 3 H), 5.79 (tt, 1 H, *J* = 6.0 Hz), 7.30 (m, 5 H), 1049 (s, 1 H); ^{13}C NMR ($\mathrm{Me_2SO}$-d_6) 17.3, 48.4, 49.8, 119.0, 126.5, 128.3, 127.4, 131.5, 140.6, 153.6, 153.4 ppm; $[\alpha]^{25}_{\mathrm{D}}$ −34.8° (*c* 10.0, $\mathrm{CH_2Cl_2}$), mass spectrum calcd *m/e* 245.1164, obsd 245.1157. Anal. Calcd for $\mathrm{C_{13}H_{15}N_3O_2}$: C, 63.66; H, 6.16; N, 17.13. Found: C, 63.75; H, 6.17; N, 17.09.

(*S*)-(−)-4-(α-Methylbenzyl)-1-(2,3-dibromopropyl)urazole. Into a 25-mL three-necked round-bottomed flask, which had been wrapped with foil and equipped with a drying tube containing anhydrous $\mathrm{Ca_2SO_4}$ and an addition funnel, were placed 0.30 g (0.0012 mol) of (*S*)-(−)-4-(α-methylbenzyl)-1-allylurazole and 7 mL of carbon tetrachloride. A solution of 0.19 g (0.0012 mol) of bromine in 5 mL of $\mathrm{CCl_4}$ was added dropwise to the stirred mixture. At the end of addition, the mixture was stirred at room temperature for 2 h. The pale yellow solid was filtered, washed with cold CCl$_4$, and dried under vacuum to give 0.40 g (82%) of product. Recrystallization twice from methanol gave colorless crystals: mp 178.0–179.0 °C; IR (KBr) 3140 (s, br), 2992 (w), 2940 (w), 1765 (s), 1680 (s), 1495 (w), 1470 (s), 1450 (s), 1435 (s), 1388 (m), 1380 (m), 1370 (m), 1338 (w), 1280 (w), 1252 (m), 1232 (m), 1218 (m), 1200 (w), 1150 (m), 1080 (m), 1070 (w), 1050 (w), 1030 (w), 1010 (w), 1005 (w), 950 (w), 930 (m), 800 (m), 790 (m), 760 (s), 725 (m), 700 (s), 688 (m), 648 (m) cm^{-1}; ^{1}H NMR (Me$_2$SO-d_6) δ 1.76 (d, 3 H, J = 7.5 Hz); 3.84 (dd, 2 H, J = 4.5 Hz), 4.00 (m, 2 H), 4.62 (m, 1 H), 5.20 (q, 1 H, J = 7.5), 7.31 (m, 5 H), 10.52 (s, 1 H); ^{13}C NMR (Me$_2$SO-d_6) 17.20, 35.47, 49.45, 49.73, 50.62, 126.48, 127.32, 128.25, 140.30, 153.40, 153.53 ppm; $[\alpha]^{25}{}_{D}$ −23.0° (c 9.9 Me$_2$SO); mass spectrum calcd for M$^+$ − HBr 323.0264, obsd 323.0267.

Acknowledgment. We (S.E.M. and G.B.B.) gratefully acknowledge partial support of this work by the Procter & Gamble Co. We also thank Dr. Wallace Brey of the Department of Chemistry and Mr. Paul Kanyha for recording the 300-MHz ^{1}H NMR and 75-MHz ^{13}C NMR spectra. We (H.A. and G.J.P.) also thank the Center for Instructional and Research Computing Activities, University of Florida, for a grant of computer time.

Registry No. 4, 2627-86-3; **5**, 17279-30-0; **6**, 14649-03-7; **7**, 75600-65-6; **8**, 75600-66-7; **9**, 75600-67-8; **10**, 94427-70-0; **11**, 94427-71-1; ethyl carbazate, 4114-31-2; propylene, 115-07-1.

Supplementary Material Available: Tables of the hydrogen atom positions, the thermal parameters for the non-hydrogen atoms, and observed and calculated structure factors (9 pages). Ordering information is given on any current masthead page.

References and Notes

(1) Thiele, J.; Strange, O. *Justus Liebigs Ann. Chem.* **1894**, *283*, 1.

(2) Middleton, W. J.; Heckert, R. E.; Little, E. L. *J. Am. Chem. Soc.* **1958**, *80*, 2783.

(3) Pirkle, W. H.; Stickler, J. C. *Chem. Commun.* **1967**, 760.

(4) Turner, S. R.; Guilbault, L. J.; Butler, G. B. *J. Org. Chem.* **1971**, *36*, 2838.

(5) Wagener, K. B.; Turner, S. R.; Butler, G. B. *J. Polym. Sci., Part B* **1972**, *10*, 805.

(6) (a) Wagener, K. B.; Turner, S. R.; Butler, G. B. *J. Org. Chem.* **1972**, *37*, 1454. (b) Wagener, K. B.; Butler, G. B. *J. Org. Chem.* **1973**, *38*, 3070.

(7) Williams, A. G.; Butler, G. B. *J. Org. Chem.* **1980**, *45*, 1232.

(8) Ohashi, S.; Butler, G. B. *J. Org. Chem.* **1980**, *45*, 3472.

(9) Ohashi, S.; Ruch, W. E.; Butler, G. B. *J. Org. Chem.* **1981**, *46*, 614.

(10) Butler, G. B.; Williams, A. G. *J. Polym. Sci., Polym. Chem. Ed.* **1979**, *17*, 1117.

(11) Leong, K.-W.; Butler, G. B. *J. Macromol. Sci., Chem.* **1980**, *A14*, 287.

(12) Ohasi, S.; Leong, K.-W.; Matyjaszewski, K.; Butler, G. B. *J. Org. Chem.* **1980**, *45*, 3467.

(13) Butler, G. B., unpublished results.

(14) (a) Gardlik, J. M.; Paquette, L. A. *Tetrahedron Lett.* **1979**, 3597. (b) Paquette, L. A.; Doehner, R. F., Jr. *J. Org. Chem.* **1980**, *45*, 5105. (c) Klobucar, W. D.; Paquette, L. A.; Blount, J. F. *J. Org. Chem.* **1981**, *46*, 4021.

(15) Fuchs, B. "Topics in Stereochemistry"; Ehel, E. L., Allinger, M. L., Eds.; Wiley: New York, 1978; Vol. 10.

(16) Naik, D. V.; Palenik, G. J. *Acta Crystallogr., Sect. B* **1974**, *B30*, 2396.

(17) Merck & Co., Inc. "Deuterated NMR Solvents—Handy Reference Data"; Merck & Co., Inc.: Quebec, 1978.

(18) Kolomiets, V. F.; Gracheva, R. A.; Potapov, V. M.; Samusenko, A. L. *J. Org. Chem. USSR* **1980**, 854.

(19) Gillis, B. T.; Hagarty, J. D. *J. Org. Chem.* **1967**, *32*, 330. Cookson, R. C.; Gilani, S. S. H.; Stevens, I. D. R.; Watts, C. T. *Org. Synth.* **1971**, *51*, 121.

Molecular Weight Distribution and Relationship between Chemical Composition and Molecular Weight in High-Conversion Samples of Copoly(styrene–methyl acrylate) Prepared in Solution by Adding Initiator

Shinya Teramachi,* Akira Hasegawa, Fumiya Sato, and Nobuhiro Takemoto

Department of Industrial Chemistry, Kogakuin University, 2665-1 Nakano-cho, Hachioji, Tokyo 192, Japan. *Received April 4, 1984*

ABSTRACT: The molecular weight distributions and the relationships between chemical composition and molecular weight for the samples of statistical copolymer of styrene and methyl acrylate prepared by radical copolymerization in solution were determined by gel permeation chromatography with dual detectors and compared with those calculated by using simple copolymerization kinetics (negligible penultimate effects). Results obtained both experimentally and theoretically are in good agreement. The agreement between theory and experiment confirms the validity of simple copolymerization kinetics when the gel effect is negligible.

Introduction

Statistical copolymers prepared by radical copolymerization have distributions with respect to chemical composition (CC) and molecular weight. Along with these distributions, the relationship between molecular weight and CC is also important for practical uses of copolymers. These two distributions and also the relationship between CC and molecular weight can be experimentally determined and also calculated by using simple copolymerization kinetics. Chemical composition distributions (CCD) of copolymers determined experimentally were found to be in good agreement with those calculated by using simple copolymerization kinetics in all cases.[1–6] However, molecular weight distribution (MWD) and also the relationship between CC and molecular weight are not always in satisfactory agreement with theoretical calculations.

In our previous work,[7] MWD and the relationship between CC and molecular weight in several samples of styrene (S)–methyl acrylate (MA) statistical copolymer prepared by radical copolymerization *in bulk* were determined by gel permeation chromatography (GPC) equipped with dual detectors, and the data were compared with the theoretical calculations by using simple copolymerization kinetics. Agreement between the theoretical and experimental results was satisfactory for low-