Spiropentyl Cations Formed by Solvolysis Reactions

Douglas E. Applequist* and Gary W. Nickel

Department of Chemistry, University of Illinois, Urbana, Illinois 61801

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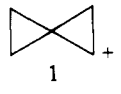
Reinvestigation of the hydrolysis of spiropentyl chloride has confirmed that the product is primarily 2-(hydroxymethyl)-1,3-butadiene, but with some β-cyclopropylideneethanol formed as well. To test the possibility that these products differ from those of diazotization of spiropentylamine (2- and 3-methylenecyclobutanol) because of a simple leaving-group effect, spiropentanol and some sulfonate esters of it were synthesized. The *p*-nitrobenzenesulfonate hydrolyzes to give just 2-(hydroxymethyl)-1,3-butadiene, much like the chloride. The trifluoromethanesulfonate, however, gives not only 2-(hydroxymethyl)-1,3-butadiene, but also 3-methylenecyclobutanol and 1-methylcyclopropanecarboxaldehyde, showing that the hydrolysis products and mechanism approach those of diazonium ion decomposition as the leaving group improves. 1-Bromo-1-phenylspiropentane was also synthesized and found to hydrolyze to give mainly unrearranged 1-phenylspiropentanol. Minor products isolated were those of ring opening analogous to those of spiropentyl chloride and *p*-nitrobenzenesulfonate.

The spiropentyl cation **1** is unique among carbonium ions



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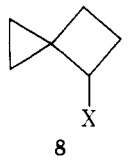
in that the rearrangement products formed from the cation generated by deamination with nitrous acid show no overlap with those observed when the cation is produced by hydrolysis of chlorospiropentane.[1] Specifically, the deamination reaction proceeds through an initial cyclopropylcarbinyl–cyclobutyl ring enlargement, with subsequent rearrangements leading to 2- and 3-methylenecyclobutanol (Scheme I). On the other hand, hydrolysis of chlorospiropentane proceeds by a typical cyclopropyl–allyl ring opening sequence, with 2-(hydroxymethyl)-1,3-butadiene as the primary product (Scheme II). Similar duality of cation behavior does not appear to have been observed in other systems, even the closely related 4-spirohexyl system (**8**),[2] although the products from deamination reactions are generally different in quantitative distribution from solvolysis products and often more numerous than the latter, as well.[3]



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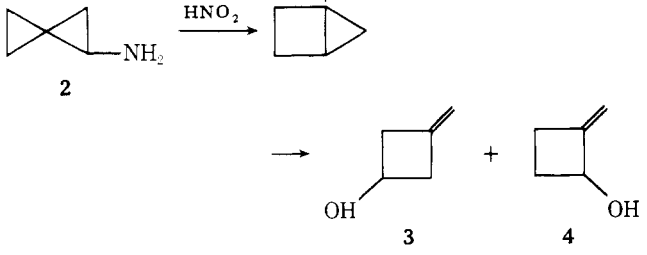
The most economical explanation of the mechanistic dichotomy in the spiropentyl case is that the process changes from a k_Δ process (neighboring carbon participation) when the leaving group is relatively poor (chloride) to a k_c process (unassisted carbocation formation) when the leaving group becomes very good (nitrogen). The k_Δ process involves opening to the allyl cation (Scheme II), while the unrearranged cation from the k_c process prefers the ring enlargement route of Scheme I. While intuition might suggest that the rearrangement of spiropentyl cation should most easily follow the pathway which provides anchimeric assistance in the k_Δ solvolysis, that situation is not required by theory, and one can easily construct energy surfaces for a reaction coordinate diagram to permit different pathways for k_Δ solvolysis and rearrangement of the k_c cation.

Alternatively, one must consider the possibility that the product differences are caused by some previously unsuspected mechanistic difference between solvolysis and deamination, and not by differences in the leaving-group abilities. To test this possibility, we report here the synthesis and solvolysis of spiropentyl sulfonates with intermediate leaving-group abilities to see if intermediate product behavior can be detected.

The previously unknown spiropentanol (**10**) was prepared by the method of Schöllkopf and Paust[4] from methylenecyclopropane via the spiropentyl β-chloroethyl ether (**9**) (Scheme III). The structure of **10** was confirmed by its NMR spectrum, which showed six cyclopropyl hydrogens at δ 0.7–1.0, a one-proton pattern of four lines at δ 3.5 (typical X portion of an ABX system), and the OH singlet at δ 4.4. The *p*-nitrobenzenesulfonate and trifluoromethanesulfonate (triflate) of **10** were prepared by the standard methods. Unlike most triflates, spiropentyl triflate was found to be stable enough to be isolated in pure form (by chromatography on silica gel). Its NMR spectrum closely resembled that of **10**.

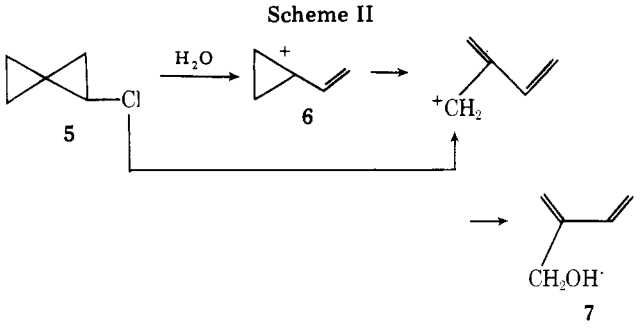
The hydrolysis of spiropentyl *p*-nitrobenzenesulfonate in 50% aqueous dioxane at 100 °C with potassium carbonate to maintain basicity gave 2-(hydroxymethyl)-1,3-butadiene (**7**) as the only identifiable product. If insufficient potassium carbonate was used, the product consisted partly of tiglaldehyde from the acid-catalyzed rearrangement of **7**. The sol-

Scheme I



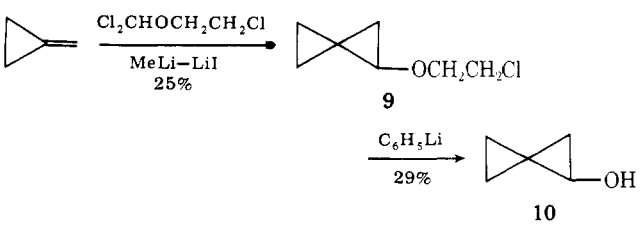
2 **3** **4**

Scheme II



5 **6** **7**

Scheme III



9 **10**

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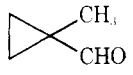
volysis reaction thus closely resembles the previously reported hydrolysis of chlorospiropentane.

Hydrolysis of spiropentyl triflate in aqueous potassium carbonate at 25 °C gave a 47% yield of the (hydroxymethyl)-butadiene (**7**), 16% of 3-methylenecyclobutanol (**3**), and 5% of 1-methylcyclopropanecarboxaldehyde (**11**). A nearly



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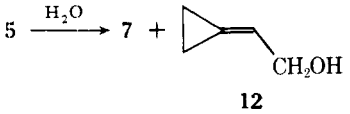
identical mixture was obtained when the reaction was run at 50 °C, so a comparison with the products from the chloride and *p*-nitrobenzoate at 100 °C can probably be done without concern that a temperature effect is responsible for major product variations. The triflate thus provides the intermediate case sought, one in which the cyclopropyl-type behavior (to give **7**) and the cyclopropylcarbinyl-type behavior (to give **3**) are competitive. The product **11** probably arises from unrearranged **10** under the basic conditions.[5] Another possibility would be a rearrangement of **4** to **11**, but this reaction is known to occur with acid, not base, catalysis.[6] The absence of detectable **4** in the reaction mixture is not a cause for concern, since **4** is formed in much smaller amounts than **3** in the deamination reaction also.

The apparent formation of unrearranged spiropentanol (observed as **11**) could represent some sulfur–oxygen cleavage, but it may also mean that unrearranged spiropentyl cation had a transient existence. It is of interest that deamination of spiropentylamine in acetic acid has recently been reported by Gajewski and Chang[7] to give some spiropentyl acetate. Both observations of unrearranged products lend support to the theory that a very good leaving group leads to a k_c process for solvolysis.

The details of the k_Δ process for hydrolysis of spiropentyl chloride (Scheme II) have been revealed in part by a reinvestigation of the products. A previously unanswered question was whether the rings opened sequentially, with cation **6** as an intermediate, or whether both rings opened in concert. It has now been found that the products include not only the dienol **7** but also β-cyclopropylideneethanol (**12**). Yields were variable, but in a typical run at 90 °C in aqueous lithium carbonate for 70 days the products identified were dienol **7** (21%) and **12** (9%). The NMR spectrum of **12** was essentially

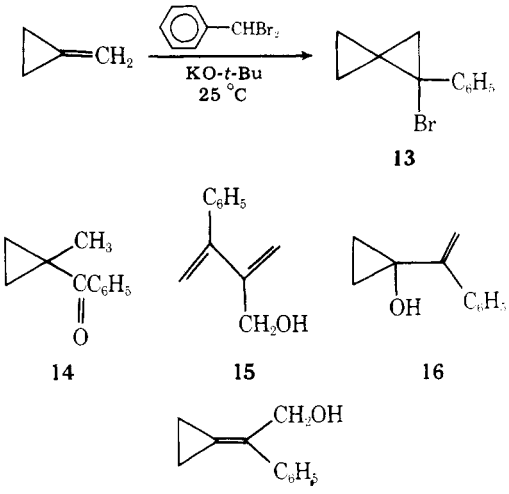


12

identical with that reported by Bottini and Christensen.[8] The simplest interpretation of the formation of **12** is that it comes from the reaction of cation **6** with water and that the two rings therefore open sequentially on the path to **7**. Repeated control reactions showed that **12** was not formed from **7** under the reaction conditions. There is a precedent for the capture of a 1-vinylcyclopropyl cation prior to ring opening,[9] and other substituents also stabilize cyclopropyl cations in the cyclic form.[10]

If the two distinct patterns of products from the spiropentyl cation do indeed represent k_Δ and k_c solvolysis processes as proposed above, then another approach to altering the balance between the two (in addition to leaving-group variation) would be to put a cation-stabilizing substituent at the 1 position. To test this approach, we have prepared 1-bromo-1-phenylspiropentane (**13**) by the reaction of methylenecyclopropane with benzal bromide and potassium *tert*-butoxide.

The carbonate-buffered hydrolysis of **13** at temperatures from 25 to 100 °C gave two principal products, ketone **14** and dienol **15**, and very small amounts, usually less than 1%, of two allylic alcohols, **16** and **17**. The yields of **16** and **17** were enhanced to 15 and 5%, respectively, by running the reaction in 10% aqueous sodium hydroxide at 100 °C. The four compounds were identified from their NMR and IR spectra (see Experimental Section). Compound **14** was previously known,[11] and a comparison with the published NMR spectrum confirmed the identity. The yields under the various conditions are summarized in Table I.



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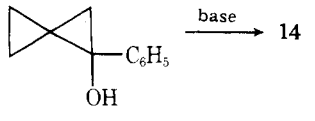
14 **15** **16**

17

A likely origin of ketone **14** is unrearranged 1-phenylspiropentanol (**18**), which would be expected to undergo base-



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catalyzed ring opening to **14**. In fact, when the hydrolysis of **13** was carried out in unbuffered distilled water at 25 °C, the products were **18** and **15** in the same 93:7 ratio as **14** and **15** under basic conditions. Compound **18** was identified by its NMR and IR spectra, which were typical of substituted spiropentanes, and by the fact that in aqueous potassium carbonate at 25 °C it rearranged completely to **14**.

The mechanistic scheme consistent with all of the observed products is shown in Scheme IV. The process is a k_c process to give unrearranged spiropentyl cation **19**, which is either captured by water or opens to allyic cation **20**, the latter process having an activation enthalpy about 4 kcal/mol higher

Scheme IV

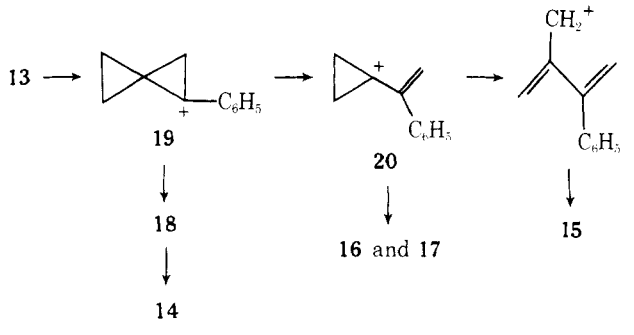
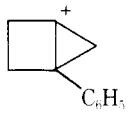


Table I. Hydrolysis Products of 1-Bromo-1-phenylspiropentane (13)

reaction conditions	product composition, % 14	15	16	17	total yield, %
K_2CO_3, 100 °C	75	24	<1	1	100
K_2CO_3, 60 °C	80	17	<1	2	81
K_2CO_3, 25 °C	92	7	<1	<1	100
NaOH, 100 °C	70	10	15	5	68

than the solvent capture of **19** (from the temperature dependence of the product mixture, Table I). Further ring opening in **20**, however, is faster than solvent capture in water, but in 10% sodium hydroxide most of the **20** can be diverted to products **16** and **17** before the second ring opening can occur.

Cation **19** appears to be one of the more stable cyclopropyl cations known, probably because the cationic site is conjugatively stabilized by both a phenyl group and the other three-membered ring. It is interesting that the cation, when it does rearrange, acts as a cyclopropyl cation (electrocyclic ring opening), whereas the unstabilized spiropentyl cation gives exclusively ring enlargement, according to the interpretation presented above. It may be noted that cation **20** still enjoys some conjugative stabilization from phenyl, whereas the cation from ring enlargement, **21**, would not.



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Experimental Section

All boiling points and melting points are uncorrected. Infrared spectra were obtained on a Beckman IR-12 instrument, and ultraviolet spectra were recorded on a Perkin-Elmer Model 202 UV-vis spectrophotometer. The NMR spectra were recorded with Varian A-56/60, A-60-A, or EM-390 spectrometers. Analytical, and some preparative, GLC work was done on an Aerograph Autoprep Model A700. The following columns were employed: column A, 6 ft × 0.25 in. 20% tricresyl phosphate on Chromosorb P, and column F, 12 ft. × 0.25 in. 10% Apiezon L on Chromosorb P. Microanalyses were performed by the Microanalytical Laboratory of the University of Illinois.

(2-Chloroethoxy)spiropentane (9). An ether solution of CH_3Li–LiI (~1 mol in 800 mL) was prepared from lithium metal (23 g, 3.3 mol) and methyl iodide (240 g, 1.7 mol) and was transferred to an addition funnel by syringe. A crude preparation of methylenecyclopropane[12] (89.9 g, ~1.3 mol) and dichloromethyl 2-chloroethyl ether[13] (142 g, 0.87 mol) were mixed at −40 °C in a 2-L flask equipped with a dry ice condenser. The ether solution of CH_3Li–LiI was added over 3.5 h while the reaction temperature remained at −40 °C. The solution was stirred for 1 h longer at 0 °C and hydrolyzed with water (500 mL). The layers were separated, and the aqueous phase was extracted with ether (100 mL). The combined ether phases were extracted repeatedly with saturated $NaHCO_3$ and water until the water washes were neutral, dried over $MgSO_4$, and concentrated. Distillation yielded 31.1 g (25% yield) of the product **9** at 48–62 °C/4 mm. The distillate rapidly discolored to a dark green, and the sample was stored at −25 °C because it decomposed after several days at room temperature. Compound **9** could be further purified by chromatography on silica gel (36 × 2 cm column) with elution by hexane followed by ether–hexane mixtures. A pure sample of **9** was collected by preparative GLC on column F (200 °C, 60 mL/min He flow, injector 225 °C): IR (neat) 670, 750, 850, 925, 1050, 1100, 1145, 1175, 1205, 1300, 1325, 1430, 1445, 1540, 1735, 2880, 2970–3000, 3080 cm^{-1}; NMR (CCl_4) δ 0.65–1.3 (m, 6 H), 3.3–3.9 (m, 5 H).

Anal. Calcd for $C_7H_{11}ClO$: C, 57.34; H, 7.57; Cl, 24.18. Found: C, 57.32; H, 7.56; Cl, 24.21.

Spiropentanol (10). A solution of about 0.2 mol of phenyllithium in 275 mL of ether was added dropwise over 1 h to a solution of (2-chloroethoxy)spiropentane (7.5 g, 51 mmol) in 50 mL of ether at 25 °C. The mixture was stirred for 1 h at 25 °C and poured into 300 mL of saturated aqueous $NaHCO_3$ at 0 °C. The layers were separated, and the aqueous phase was extracted with ether (4 × 50 mL). The ether layers were washed with two 50-mL portions of cold 5% aqueous NaOH and brine until neutral. The ether was dried ($MgSO_4$) and evaporated at 25 °C to yield a residue of ~11 g. Column chromatography of the residue on 110 g of silica gel with an eluent of 20% diethyl ether–80% petroleum ether separated the aromatic impurities and gave 1.23 g (14.6 mmol, 29%) of **10**. A second column chromatography was performed, and the middle fractions were evaporated at 25 °C on a rotary evaporator to yield pure spiropentanol: NMR (CCl_4) δ 0.7–1.0 (m, 6 H), 3.5 (m, 1 H, four lines, X part of ABX pattern with J_{AX} = 3 Hz, J_{BX} = 6 Hz), 4.4 (broad s, -OH); IR (neat) 810, 855, 880, 920, 960, 1000, 1135, 1175, 1325, 3020, 3090, 3200–3500 cm^{-1}.

Anal. Calcd for C_5H_8O: C, 71.38; H, 9.60. Found: C, 71.53; H, 9.70.

Spiropentyl *p*-Nitrobenzenesulfonate. To a solution of **9** (4.5 g, 31 mmol) in 50 mL of ether was added an ether solution of phenyllithium (~120 mmol) over 1 h at 25 °C, and the combined mixture was stirred for 1 h longer at 25 °C. The crude spiropentanol resulting from the extraction scheme and concentration of the ether phases (as above) was mixed with 50 mL of dry pyridine at 0 °C, and *p*-nitrobenzenesulfonyl chloride (9 g, 40 mmol) was added. The mixture was stored at 0 °C for 1 day and poured into a mixture of 200 mL of water and 40 mL of concentrated HCl at 0 °C. The solution was extracted with an ether–benzene mixture, which was then washed with saturated $NaHCO_3$ and brine, dried ($MgSO_4$), and evaporated. The *p*-nitrobenzenesulfonate remained as a crude crystalline mass in a total yield of 1.67 g (mp 87–89 °C, 6.2 mmol, 20% yield from **9**). The product was recrystallized four times from benzene–low petroleum ether at room temperature to yield a small sample (mp 93–94 °C) of pure spiropentyl *p*-nitrobenzenesulfonate: IR (KBr) 568, 615, 685, 733, 747, 778, 840, 851, 864, 929, 958, 998, 1047, 1080, 1095, 1198 (sulfonate), 1292, 1309, 1350 (nitro), 1367 (sulfonate), 1402, 1537 (nitro), 1608, 3019, 3078, 3114 cm^{-1}; NMR ($CDCl_3$) δ 0.93 (s, 4 H), 1.13 (s, 1 H), 1.20 (d, 1 H, J = 1 Hz), 4.35 (t, 1 H, J = 4.5 Hz), 8.28 (q, AA′BB′, 4 H, aromatic).

Anal. Calcd for $C_{11}H_{11}O_5NS$: C, 49.06; H, 4.12; N, 5.20; S, 11.91. Found: C, 49.28; H, 4.14; N, 5.24; S, 12.12.

Spiropentyl Trifluoromethanesulfonate.[14] Phosphorus pentoxide (9 g) was added to trifluoromethanesulfonic acid (14 g, 91 mmol), and the mixture was kept at 25 °C for 1 h. Trifluoromethanesulfonic anhydride (9.2 g, 32.6 mmol, 72%) was distilled from the mixture at 75–82 °C. Spiropentanol (1.23 g, 14.6 mmol) was mixed with 30 mL of dry pyridine at 0 °C. The anhydride, dissolved in 10 mL of CCl_4, was added dropwise over 30 min to the stirred pyridine solution at 0 °C. The mixture was stirred for 1 h longer and stored at 0 °C overnight. The reaction mixture was poured into a solution of 30 mL of concentrated HCl in 150 mL water at 0 °C. The acidic solution was extracted with ether (5 × 75 mL). The ether extracts were washed with cold saturated aqueous $NaHCO_3$ and brine, dried ($MgSO_4$), and evaporated at 25 °C to leave 1.40 g of liquid. Column chromatography on 75 g of silica gel with petroleum ether eluent gave 0.52 g (2.4 mmol, ~17%) of spiropentyl triflate. A second column chromatography was performed, and the middle fractions were evaporated on a rotary evaporator at 25 °C to yield pure spiropentyl triflate: IR (neat) 610, 880, 940, 955, 1040, 1080, 1150, 1210, 1250, 1420, 3020, 3090 cm^{-1}; NMR (CCl_4) δ 0.8–1.2 (m, 4 H), 1.2–1.6 (m, 2 H), 4.60 (m, 1 H, four lines, X part of ABX pattern with J_{AX} = 3 Hz, J_{BX} = 6 Hz); ^{19}F NMR ($CFCl_3$) δ 75.75 (s).

Anal. Calcd for $C_6H_7O_3SF_3$: C, 33.33; H, 3.27; S, 14.83. Found: C, 33.50; H, 3.35; S, 14.92.

Solvolysis of Spiropentyl *p*-Nitrobenzenesulfonate. A solution of 0.7 g (2.6 mmol) of the *p*-nitrobenzenesulfonate (mp 90–91 °C) and 0.72 g (5.2 mmol) of potassium carbonate in 100 mL of 50% aqueous dioxane was heated under reflux in a nitrogen atmosphere for 110 h. The solution (pH >7) was cooled, saturated with salt, and extracted with ether (5 × 25 mL). The dried ($MgSO_4$) ether was distilled at 35 °C, and the dioxane was distilled at 40 °C/47 mm to leave 0.77 g of oil. Investigation of the product by GLC and NMR spectroscopy showed dioxane and only 2-(hydroxymethyl)-1,3-butadiene[15] in ~45% yield. The NMR (CCl_4) showed signals at δ 2.28 (s, 1 H, hydroxyl), 4.34 (s, 2 H, $-CH_2OH$), 5.27 (m, 4 H), and 6.47 (m, four lines, 1 H, $J_{AX} + J_{BX}$ = 29 Hz).

Solvolysis of Spiropentyl Triflate. Purified spiropentyl triflate (0.2 g, 0.94 mmol), K_2CO_3 (0.42 g, 3 mmol), and 50 mL of distilled water were mixed at 25 °C for 48 h. The solution pH ranged from 11 to 10.5. The solution was saturated with salt and extracted with ether (5 × 25 mL). The dried ($MgSO_4$) ether extracts were evaporated carefully at 25 °C to leave 0.053 g of oil. Investigation of the oil by GLC on column A (115 °C, 60 mL/min He flow) showed three products with retention times of 6.4, 13.2, and 16.6 min. The three products were identified by comparison of their NMR spectra with those of authentic samples. Yields were determined by NMR integration of the weighed product mixture. The major product in 47% yield was 2-(hydroxymethyl)-1,3-butadiene (16.6 min). The second product (13.2 min) in 16% yield was 3-methylenecyclobutanol:[16] NMR (CCl_4) δ 2.55–2.85 (m, 4 H), 4.20 (quint., 1 H, J = 6 Hz), 4.71 (quint., 2 H, J = 2 Hz). The third component (6.4 min) in 5% yield was 1-methylcyclopropanecarboxaldehyde: NMR (CCl_4) δ 0.6–1.2 (m, 4 H), 1.3 (s, 3 H, methyl), 8.5 (s, 1 H). The NMR spectrum was identical with that of an authentic sample.[17]

Hydrolysis of Spiropentyl Chloride (5). Spiropentyl chloride (0.65 g, 6.3 mmol), Li_2CO_3 (0.69 g, 9.4 mmol), and 110 mL of distilled

water were sealed in a Carius tube and heated at 95–100 °C for 34 days. The tube was cooled and opened, and the contents (pH 7) were saturated with salt, filtered, and extracted with ether (6 × 25 mL). The ether phase was dried ($MgSO_4$), and the ether was removed by distillation to leave a residue of 0.23 g of oil. The oil was shown by GLC (column A, 115 °C, 60 mL/min He flow) to contain six components as follows: peak 1 (1.8 min, 2.7% of total); 2 (4.5 min, 3.8% of total); 3 (9.0 min, 26.8% of total); 4 (12.2 min, 2.2% of total); 5 (16 min, 24.6% of total); and 6 (19.5 min, 39.9% of total). The total recovery of products was 43%. Peak 2 was identified as spiropentyl chloride and peak 3 as tiglaldehyde by comparison with the retention times of authentic samples. Peaks 5 and 6 could be collected by preparative GLC, and peak 5 was identified as 2-(hydroxymethyl)-1,3-butadiene (**7**) by NMR spectroscopy. Peak 6 was identified by comparison of the NMR spectrum with an authentic spectrum[8] as cyclopropylideneethanol (**12**): NMR (CCl_4) δ 1.10 (m, 4 H, cyclopropyl), 4.24 (d, 2 H, J = 6 Hz, $-CH_2OH$), 6.05 (m, >9 lines, 1 H).

Three other runs (runs 2–4) were made under closely similar conditions, except that in run 3 the reaction temperature was 90 °C for 70 days and in run 4 the buffer was 2.0 g (19 mmol) of sodium carbonate. The respective yields of recovered spiropentyl chloride were 31, 4, and 19%; the yields of **7** were 30, 21, and 7%; and the yields of **12** were 1, 9, and 7%.

Control Reaction on 2-(Hydroxymethyl)-1,3-butadiene (7). A GLC-collected sample of **7** (0.2 g, 2.4 mmol), Li_2CO_3 (0.70 g, 9.4 mmol), 60 mL of 0.1 N HCl (6 mmol), and 50 mL of distilled water were sealed in a glass tube and heated at 95 °C for 35 days. The tube was cooled and opened. The liquid (pH 7) was saturated with salt and extracted with ether (6 × 25 mL). The dried ether ($MgSO_4$) was distilled through a glass-helices-packed column to leave 0.625 g of oil. The residue was shown by GLC (column A, 115 °C, 60 mL/min He flow) to contain ether, unchanged **7** at 17 min, and something at greater than 27 min that gave a peak that trailed. The NMR spectrum was consistent with **7**, but also showed three other unidentified peaks at δ 3.9, 4.0, and 5.6. No cyclopropylideneethanol was observed by GLC or NMR spectroscopy. The recovery of **7** was ~75%.

In another test, **7** (0.2 g, 2.4 mmol), Li_2CO_3 (0.7 g, 9.4 mmol), 0.75 mL of concentrated HCl (~7 mmol), and 100 mL of distilled water (solution pH 9) were sealed in a glass tube and heated at 100 °C for 70 days. The tube was cooled and opened, and the liquid (pH 8.5) was saturated with salt and extracted with ether (5 × 25 mL). The dried ether ($MgSO_4$) was evaporated to leave 0.198 g of oil. The product was examined by GLC and NMR spectroscopy and shown to contain ether, unchanged **7** (~60%), and the decomposition product at a retention time greater than 30 min. No cyclopropylideneethanol was observed.

1-Bromo-1-phenylspiropentane (13). A screw-top glass Carius tube (Fisher-Porter Co., ~0.75 × 18 in.) was cooled to −78 °C and filled with crude methylenecyclopropane[12] (25 g, ~0.46 mol), benzal bromide (43 g, 0.17 mol), and t-BuOK (27 g, 0.24 mol). The tube was sealed, fastened into a rocker apparatus, and rocked at 25 °C for 16 days. The tube was cooled to −78 °C, opened, and rinsed out with 250 mL of ether and 300 mL of water. The phases were separated, and the ether was washed with 100 mL each of 1 N HCl, water, saturated $NaHCO_3$, and water. The ether was dried ($MgSO_4$) and evaporated to leave 35.6 g of oil. The oil was stirred with 50 mL of 10% aqueous NaOH at reflux for 3 h. The oil was reisolated by extraction into ether and evaporation of the dried ether to yield 34.4 g of oil. The product **13** was collected by distillation (9.0 g, at 75–80 °C/1 mm). More product was isolated (another 8.6 g) from column chromatography of the undistilled pot material on silica gel with petroleum ether eluent (R_f 0.5). The total yield of 17.6 g of impure **13** represented (by NMR integration) ~3 g of benzal bromide and ~14.5 g of **13** (0.065 mol, 38% based on the starting amount of benzal bromide). A pure sample of **13** was obtained after a second aqueous NaOH treatment followed by column chromatography on silica gel twice: IR (neat) 610, 700, 750, 760, 785, 1015, 1035, 1060, 1450, 1490, 3000, 3040, 3070 cm^{-1}; NMR (CCl_4) δ 1.1 (sharp m, 4 H), 1.8 (q, AB, J = 7 Hz, 2 H), 7.2 (m, 5 H, aromatic).

Anal. Calcd for $C_{11}H_{11}Br$: C, 59.21; H, 4.98; Br, 35.81. Found: C, 58.99; H, 4.97; Br, 35.85.

Hydrolysis of 1-Bromo-1-phenylspiropentane (13). Compound **13** (0.5 g, 2.2 mmol), K_2CO_3 (1 g, 7.2 mmol), and 100 mL of distilled water were stirred and refluxed at 100 °C under nitrogen for 120 h. The basic solution (pH 10.5) was cooled, saturated with salt, and extracted with ether (5 × 25 mL). The ether was distilled to leave 0.46 g (~100%) of oil. The product was shown by GLC on column F (230 °C, 60 mL/min He flow, injector 230 °C) to consist of benzaldehyde at 2.3 min from traces of benzal bromide and four components at 3.2, 4.2, 5.6, and 6.5 min of area 1:1:75:24. The two major components were collected by preparative GLC. The component at 5.6 min was identified by comparison of the spectral data with the literature values[11] as 1-methylcyclopropyl phenyl ketone: IR (neat) 700, 720, 780, 930, 985, 1025, 1180, 1210, 1340, 1390, 1450, 1580, 1600, 1680 (carbonyl), 2885, 2940, 2980, 3015, 3070, 3090 cm^{-1}; NMR (CCl_4) δ 0.67, 1.2 (m, A_2B_2, 4 H), 1.41 (s, 3 H, methyl), 7.4, 7.7 (m, 5 H, aromatic). The component at 6.5 min was assigned, by its spectral similarity to **7**, to be 2-(hydroxymethyl)-3-phenyl-1,3-butadiene (**15**): IR (neat) 705, 780, 910, 1050, 1100, 1130, 1380, 1450, 1495, 1595, 1660, 2940, 2985, 3030, 3060, 3090, 3200–3600 cm^{-1}; NMR (CCl_4) δ 2.5 (s, 1 H, hydroxyl), 4.2 (s, 2 H, $-CH_2OH$), 5.0–5.4 (m, 4 H), 7.25 (s, 5 H, aromatic); UV (diethyl ether) λ_{max} 246 mμ.

A second solvolysis was conducted with a mixture of **13** (0.5 g, 2.2 mmol), K_2CO_3 (1 g, 7.2 mmol), and 100 mL of distilled water stirred and heated at 60 °C for 135 h. A residue of 0.34 g (~81%) of oil was isolated by the procedure described above, and it contained benzaldehyde and the same four products described above in a ratio of 1:2:80:17.

A third solvolysis was conducted with a mixture of **13** (0.5 g, 2.2 mmol), K_2CO_3 (1 g, 7.2 mmol), and 100 mL of distilled water stirred at 25 °C for 142 h under nitrogen. A residue of 0.367 g (~100%) of oil was isolated and shown by GLC to consist of the same four products described above in a ratio of 1:1:180:14.

Unbuffered Hydrolysis of 1-Bromo-1-phenylspiropentane at 25 °C. Compound **13** (2 g, 9 mmol) and 150 mL of distilled water were stirred at 25 °C for 100 h under nitrogen. The acidic solution (pH 1.5) was saturated with salt and extracted with ether (5 × 25 mL). The dried ($MgSO_4$) ether solution was evaporated at 25 °C on a rotary evaporator to yield 1.41 g of oil (~8.8 mmol, 98%). An NMR spectrum of the crude product indicated the presence of 1-phenylspiropentanol (**18**) and **15** in a ratio of 93:7 by integration. The thermally sensitive **18** was isolated by column chromatography on silica gel with 25% ether–75% petroleum ether eluent and identified by the obvious spectral similarity to **13** except for the alcohol function: IR (neat) 700, 765, 1010, 1020, 1075, 1100, 1130, 1175, 1280, 1450, 1495, 1600, 3000, 3040, 3070, 3200–3600 (hydroxyl) cm^{-1}; NMR (CCl_4) δ 0.93 (s, 4 H), 1.2–1.6 (m, 2 H), 2.7 (s, 1 H, hydroxyl), 7.1 (m, 5 H, aromatic).

Hydrolysis of 1-Bromo-1-phenylspiropentane in Aqueous Sodium Hydroxide. Compound **13** (3.5 g, 15.5 mmol) and 150 mL of 10% aqueous NaOH were stirred and refluxed at 100 °C for 9 h under nitrogen. The mixture was cooled and extracted with CH_2Cl_2 (5 × 25 mL). The dried CH_2Cl_2 ($MgSO_4$) was evaporated to yield a residue of 1.88 g (68%) of oil. The ratio of products determined by GLC (column F, 230 °C) at 3.2, 4.2, 5.4, and 6.5 min was 46:14:210:30. The sample was fractionated by column chromatography on silica gel (75 g) with petroleum ether–ether solvent mixtures into six fractions. Each fraction was fractionated again by chromatography and checked by NMR spectroscopy and TLC for purity. Six components were isolated, and these will be considered by the order of elution (nonpolar first). An unidentified compound eluted with petroleum ether could represent 1-phenylspiropentene: IR (neat) 705, 760, 780, 910, 1030, 1075, 1145, 1420, 1450, 1500, 2880, 2940, 2970, 3010, 3040, 3080, 3100 cm^{-1}; NMR (CCl_4) δ 1.1–1.5 (m, A_2B_2, ~4 H), 5.4 (d, J = 7 Hz, ~1 H), 6.9–7.6 (m, 5 H, aromatic). The second product, eluted with 10% ether–90% petroleum ether, was 1-methylcyclopropyl phenyl ketone (**14**). The third product, eluted with 10% ether–90% petroleum ether, was unidentified: IR (neat) 700, 765, 790, 1455, 1500, 1605, 1670, 1720 (carbonyl), 2940, 2980, 3040, 3070 cm^{-1}; NMR (CCl_4) δ 1.0 (t, J = 7 Hz, ~3 H), 2.3 (q, J = 7 Hz, ~2 H), 3.5 (s, ~2 H), 7.1 (s, ~10 H). The fourth compound was eluted with 25% ether–75% petroleum ether (GLC retention time 3.2 min) and assigned the structure 1-(α-styryl)cyclopropanol (**16**): IR (neat) 700, 770, 890, 910, 960, 1030, 1070, 1090, 1140, 1270, 1360, 1380, 1440, 1490, 1600, 2980, 3030, 3060, 3080, 3200–3600 (hydroxyl) cm^{-1}; NMR (CCl_4) δ 1.3 (s, 4 H, cyclopropyl), 1.8 (s, 1 H, hydroxyl), 5.1 (q, AB, J = 2 Hz, 2 H), 7.2 (s, 5 H, aromatic). The fifth compound was the previously identified 2-(hydroxymethyl)-3-phenyl-1,3-butadiene (**15**). The sixth compound was eluted with 33% ether–67% petroleum ether (GLC retention time 3.2 min) and tentatively assigned the structure 2-phenylcyclopropylideneethanol (**17**): NMR (CCl_4) δ 1.3 (m, 4 H, cyclopropyl), 2.1 (s, 1 H, hydroxyl), 4.5 (s, 2 H, $-CH_2OH$), 7.2 (m, 5 H, aromatic).

Rearrangement of 1-Phenylspiropentanol (18). A sample of **18** (0.124 g, 0.8 mmol), purified by column chromatography, K_2CO_3 (0.28 g, 2 mmol), and 50 mL of distilled water were stirred at 25 °C for 120 h under nitrogen. The solution was saturated with salt and extracted with ether (5 × 25 mL). The dried ($MgSO_4$) ether was evaporated at 25 °C on a rotary evaporator to yield 0.098 g of oil. The product was shown by NMR spectroscopy to contain only one component, 1-methylcyclopropyl phenyl ketone (**14**) in 79% yield.

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Registry No.—**3**, 68423-20-1; **7**, 13429-21-5; **9**, 68423-21-2; **10**, 68423-22-3; **11**, 4515-89-3; **12**, 28974-51-8; **13**, 68423-23-4; **14**, 26921-44-8; **15**, 68423-17-6; **16**, 68423-18-7; **17**, 68423-19-8; **18**, 68423-24-5; spiropentyl *p*-nitrobenzenesulfonate, 68423-25-6; spiropentyl trifluoromethanesulfonate, 68423-26-7; methylenecyclopropane, 6142-73-0; dichloromethyl 2-chloroethyl ether, 13830-34-7; tiglaldehyde, 497-03-0; benzal bromide, 618-31-5; 1-phenylspiropentene, 68438-62-0.

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Neighboring Group Participation by Hydroxyl Oxygen. Intramolecular Cyclization of [(*anti*-9-Hydroxybenzonorbornen-*exo*-2-yl)methyl]-(*p*-nitrophenyl)methylsulfonium Tetrafluoroborate in Water

Tadashi Irie and Hiroshi Tanida*

Shionogi Research Laboratory, Shionogi & Co., Ltd., Fukushima-ku, Osaka, 553 Japan

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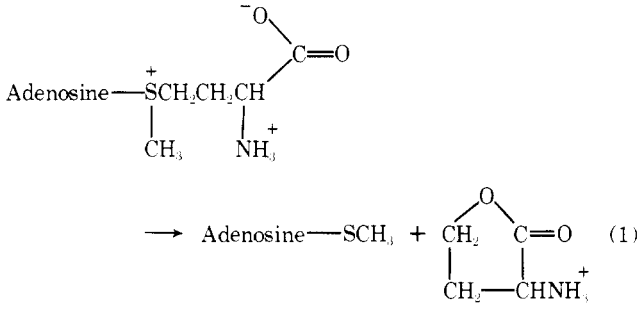
Gentle warming of the title sulfonium salt **1** in aqueous buffer medium afforded an intramolecularly cyclized ether **2** and *p*-nitro(methylthio)benzene, resulting from attack of the 9-hydroxyl oxygen on the *exo*-2-methylene carbon. This reaction pattern and the conditions required differ from the reported intermolecular nucleophilic attack on a series of aromatic-substituted phenyldimethylsulfonium salts and also, from the hydrolysis of the epimer, (*endo*-2-ylmethyl)sulfonium compound **16**. The reaction of **1**, which may be considered a model reaction of the biological alkylating agent *S*-adenosyl-L-methionine, was subjected to extensive kinetic studies over a wide pH range in aqueous buffered medium. Evidence was obtained for important participation of the *anti*-9-hydroxyl group and for catalysis effects of general bases. The water-catalyzed rate constant for **1** was $k_{H_2O} = 5.13 \times 10^{-7}$ s^{-1} at 25 °C. When this was compared to the rate evaluated for the hydrolysis of (*p*-nitrophenyl)dimethylsulfonium perchlorate (**18**), the effective molarity was calculated to be $\sim 5 \times 10^4$ M.

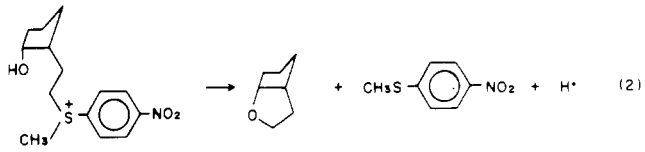
Nucleophilic attack at a carbon atom adjacent to electron-deficient trivalent sulfur (sulfonium compounds) is of biochemical importance. For example, *S*-adenosylmethionine, which is a principal coenzyme associated with biological methylation, undergoes not only methyl transfer, but also nucleophilic attack at the two methylene carbons attached to the sulfur atom.[1-3] An enzymatic reaction of the latter kind has been observed in the conversion of *S*-adenosylmethionine to α-amino-γ-butyrolactone (eq 1). This reaction presumably



(1)

proceeds by intramolecular nucleophilic attack of the carboxylate ion on the four-carbon chain attached to the sulfur.

Study of the enzyme mechanism is considerably aided by mechanistic studies on analogous nonenzymic chemical reactions of appropriate model compounds.[1-4] In studies of this kind, one of the preferred factors for understanding the enzyme reactions is neighboring group participation in intramolecular reactions. Model compounds for adenosylmethionine should undergo nucleophilic attack at the sp^3 carbon α to trivalent sulfur in aqueous media at moderate temperatures. Facile intramolecular nucleophilic substitution was expected, and many model compounds having a substituent capable of participation near the reaction center were synthesized, but the reactions did not proceed as expected.[3] The first success was communicated by Coward et al. in 1976, who found the reaction (eq 2) involving participation by the in-



(2)

tramolecular hydroxyl group. Until some years ago, we studied carbonium ion reactions of the benzonorbornenyl system, in which typical cases for aryl participation were obtained.[6]

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