Solvolysis of *cis*-Pinocarvyl *p*-Bromobenzenesulfonate and Related Esters[1]

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The solvolyses of *cis*-pinocarvyl *p*-bromobenzenesulfonate in 55% aqueous acetone and in methanol gave *trans*-pinocarveol and myrtenol and their methyl ethers, respectively. Allylic rearrangement was also observed in the solvolyses of 2-methylenecyclohexyl brosylate. Rate measurements and product distributions were consistent with unimolecular mechanisms. The isopropylidene bridge in *cis*-pinocarvyl brosylate has virtually no effect on the rate of solvolysis; it does, however, prevent formation of *cis*-pinocarveol or its methyl ether. Alkaline methanolysis of the related saturated brosylates of isopinocampheol and *trans*-2-methylcyclohexanol gave primarily elimination products. The allylic brosylate esters gave high yields (89% or greater) of substitution products and no detectable elimination products.

Solvolysis reactions of allylic systems have long been of considerable interest.[3] Evidence, in many cases, has supported pathways involving the formation of intermediate carbonium ions or ion pairs which subsequently combine with solvent to give both normal and rearranged substitution products. In other cases, characteristics of bimolecular processes (SN2 or SN2′) have been noted. Acyclic allylic halides, in particular, have been thoroughly studied. Bicyclic allylic systems, however, have apparently not been examined in detail.

The terpene alcohol, *cis*-pinocarveol, combines the interesting structural features of a bicyclic allylic alcohol. We sought to determine the effects of these features by studying solvolysis reactions of *p*-bromobenzenesulfonate esters of *cis*-pinocarveol (I) and 2-methylenecyclohexanol (II). Related cyclic but nonallylic esters were also investigated. The importance of elimination in such esters has been previously demonstrated.[4,5]

Experimental Section

All melting points of new compounds are corrected. Infrared spectra were run on a Perkin-Elmer, Model 21, infrared recording spectrophotometer. Solid samples were run as potassium bromide pellets, unless stated otherwise. Liquid samples were run neat between salt plates. Carbon, hydrogen, and nitrogen analyses were performed by Geller Laboratories, Charleston, W. Va. All *p*-nitrobenzoate derivatives were prepared by the method of Schenck and co-workers[6] and were recrystallized twice from methanol.

Reagent and Solvent Purification.—β-Pinene and lead tetraacetate were purified by procedures reported earlier.[7] All other reagents were reagent grade. Magnesium sulfate was used as a drying agent.

Methanol,[8] isopropyl alcohol,[8] and diglyme[9] were purified by procedures reported earlier. Reagent grade pyridine (800 ml) was refluxed for 0.5 hr over barium oxide (5 g) and then distilled, with the exclusion of moisture, through a 40-cm Vigreux column.[10]

Preparation of Alcohols.—*trans*-Pinocarveol and myrtenol were prepared by lead tetraacetate oxidation of β-pinene in benzene and subsequent transesterification of the monoacetate fraction.[7] The *p*-nitrobenzoate derivative of *trans*-pinocarveol was prepared, mp 93–94° (lit. mp 93.5–94.5°[6] and 91–92°[11]).

cis-Pinocarveol was prepared by selenium dioxide oxidation of β-pinene in pyridine[12] and subsequent aluminum isopropoxide reduction of pinocarvone.[13] The infrared spectrum of *cis*-pinocarveol showed O–H absorption at 3378 and disubstituted alkene absorption at 1655 and 888 cm^{-1}. The *p*-nitrobenzoate derivative was prepared, mp 103.5–104.5° (lit.[11] mp 104°).

2-Methylenecyclohexanol and 1-cyclohexenemethanol were prepared by lithium aluminum hydride reduction of 2-carbethoxycyclohexanone.[14] The *p*-nitrobenzoate derivative of 2-methylenecyclohexanol was prepared, mp 63.5–64.5° (lit.[14] mp 61–62.5°). The *p*-nitrobenzoate derivative of 1-cyclohexenemethanol, mp 64.5–65.5°, has not been previously reported.

Anal. Calcd for $C_{14}H_{15}NO_4$: C, 64.35; H, 5.78; N, 5.36. Found: C, 64.45; H, 5.59; N, 5.36.

Isopinocampheol was prepared by hydroboration of α-pinene in diglyme and subsequent hydrogen peroxide oxidation of the product.[15] The *p*-nitrobenzoate derivative, mp 90.5–91.5°, has not been previously reported.

Anal. Calcd for $C_{17}H_{21}NO_4$: C, 67.31; H, 6.98; N, 4.62. Found: C, 67.24; H, 6.93; N, 4.87.

trans-2-Methylcyclohexanol was prepared by hydroboration of 1-methylcyclohexene in diglyme and subsequent hydrogen peroxide oxidation of the product.[16] The *p*-nitrobenzoate derivative was prepared, mp 63.5–64.5° (lit.[17] mp 63.7–64.2°).

Preparation of Brosylate Esters.—The brosylate derivatives of *cis*-pinocarveol, 2-methylenecyclohexanol, isopinocampheol, and *trans*-2-methylcyclohexanol were prepared by a modification of the procedure reported by Chloupek and Zweifel[18] for the preparation of isopinocamphyl mesylate. The appropriate alcohol (2.0 g) was dissolved in pyridine (20 ml), and the solution was cooled to −40°. *p*-Bromobenzenesulfonyl chloride (10% excess) was added, and the temperature was maintained at −40°. The esterifications of *cis*-pinocarveol and 2-methylenecyclohexanol were terminated after 2 days, while isopinocampheol and *trans*-2-methylcyclohexanol were allowed to react for 3 days. The reaction mixtures were poured into equal volumes of 6 *N* hydrochloric acid and ether in a cold room (3°). The brosylate esters were extracted with ether and the ether extracts were washed with 6 *N* hydrochloric acid and water until neutral. The dried, ether extracts were concentrated on a rotary evaporator with ice–water cooling. The products were recrystallized twice from pentane–ether (10:3) at −40°.

cis-Pinocarvyl brosylate, mp 42–44° dec, was stable when stored under pentane at −40°. The infrared spectrum (Nujol mull) showed disubstituted alkene absorption at 1655 and 870 cm^{-1}. Strong bands characteristic of aryl sulfonate esters[19] appeared at 1182 (S–O) and 827 cm^{-1} (*para*-disubstituted benzene).

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Bromine and sulfur analyses were run.[20-23] The instability of the compound made it impractical to have carbon and hydrogen analyses run.

Anal. Calcd for $C_{16}H_{19}BrO_3S$: Br, 21.53; S, 8.64. Found: Br, 21.74; S, 8.70.

2-Methylenecyclohexyl brosylate was crystalline and moderately stable at 3° but rapidly decomposed at room temperature. The compound was stable for 3 to 4 weeks when stored under pentane at −40°. The infrared spectrum, run in 25% carbon tetrachloride solution in a fixed cell (0.0265 mm), showed disubstituted alkene absorption at 1660 and 884 cm^{-1}. Strong bands appeared at 1187 (S–O) and 822 cm^{-1} (*para*-disubstituted benzene).

Anal. Calcd for $C_{13}H_{15}BrO_3S$: Br, 24.13; S, 9.67. Found: Br, 24.73; S, 9.67.

Isopinocamphyl brosylate, mp 53–54° dec, was stable when stored under pentane at −40°. The infrared spectrum (Nujol mull) showed strong bands at 1186 (S–O) and 822 cm^{-1} (*para*-disubstituted benzene).

Anal. Calcd for $C_{16}H_{21}BrO_3S$: Br, 21.41; S, 8.59. Found: Br, 21.34; S, 8.54.

trans-2-Methylcyclohexyl brosylate, mp 52–53°, was stable at room temperature. The infrared spectrum (Nujol mull) showed strong bands at 1183 (S–O) and 823 cm^{-1} (*para*-disubstituted benzene).

Anal. Calcd for $C_{13}H_{17}BrO_3S$: C, 46.85; H, 5.14; Br, 23.98; S, 9.62. Found: C, 46.71; H, 4.92; Br, 24.00; S, 9.62.

Preparation of Methyl Ethers.—The methyl ether derivatives of *cis*-pinocarveol, *trans*-pinocarveol, myrtenol, 2-methylenecyclohexanol, and 1-cyclohexenemethanol were prepared by methylation of the sodium salts of the alcohols. The appropriate alcohol (2.0 g) was treated with metallic sodium (50% excess) in ether (20 ml) for 1 day at room temperature. Methyl iodide (20% excess) was added to the reaction mixtures and the methylations were run for 3 days at room temperature. The reaction mixtures were washed with water to remove sodium iodide. The dried ether extracts were concentrated by slow distillation of ether. The reaction products were distilled *in vacuo* through an 18-in. spinning-band column. The boiling points of the methyl ethers were as follows: *trans*-pinocarvyl, 57–60° (6 mm); *cis*-pinocarvyl, 70° (6 mm); myrtenyl, 65° (7 mm); 2-methylenecyclohexyl, 58–59° (43 mm); and 1-cyclohexenemethyl, 64–66° (32 mm).

The methyl ethers were further purified by preparative gas chromatography on a hyprose column. The pure compounds were characterized by infrared spectra and elemental analyses.

The infrared spectrum of *cis*-pinocarvyl methyl ether showed strong bands at 2830 (methoxy C–H), 1115 (ether C–O), and 1655 and 888 cm^{-1} (disubstituted alkene). The compound became very viscous upon standing for several days at room temperature. Satisfactory carbon and hydrogen analyses were not obtained.

The infrared spectrum of *trans*-pinocarvyl methyl ether showed strong bands at 2830 (methoxy C–H), 1092 (ether C–O), and 1650 and 896 cm^{-1} (disubstituted alkene).

Anal. Calcd for $C_{11}H_{18}O$: C, 79.45; H, 10.93. Found: C, 79.57; H, 10.86.

The infrared spectrum of myrtenyl methyl ether showed strong bands at 2830 (methoxy C–H), 1110 (doublet, ether C–O), and 1660 and 800 cm^{-1} (trisubstituted alkene).

Anal. Calcd for $C_{11}H_{18}O$: C, 79.45; H, 10.93. Found: C, 79.43; H, 10.95.

The infrared spectrum of 2-methylenecyclohexyl methyl ether showed strong bands at 2830 (methoxy C–H), 1096 (ether C–O), and 1660 and 896 cm^{-1} (disubstituted alkene).

Anal. Calcd for $C_8H_{14}O$: C, 76.12; H, 11.20. Found: C, 76.00; H, 11.10.

The infrared spectrum of 1-cyclohexenemethyl methyl ether showed strong bands at 2837 (methoxy C–H), 1102 (doublet, ether C–O), and 1675 and 801 cm^{-1} (trisubstituted alkene).

Anal. Calcd for $C_8H_{14}O$: C, 76.12; H, 11.20. Found: C, 76.40; H, 11.05.

Gas Chromatography.—A Wilkens Aerograph A-90-S gas chromatograph with a Sargent SR recorder was used for qualitative and quantitative analysis of the solvolysis products. Helium was used as the carrier gas. Four column types were used: (1) 20% by weight of hyprose on hexamethyldisilazane (HMDS)-treated Chromosorb W (60–80 mesh) packed into a 10 ft × 0.25 in. stainless steel (ss) column, (2) preparative hyprose which was identical with the hyprose column above except that the packing was contained in a 10 ft × 0.375 in. aluminum column, (3) 15% β,β'-oxydipropionitrile (ODPN) on HMDS-treated Chromosorb W (60–80 mesh) packed into a 10 ft × 0.25 in. ss column, and (4) 25% didecyl phthalate on HMDS-treated Chromosorb W (60–80 mesh) packed into a 6.5 ft × 0.25 in. ss column.

Retention times of the solvolysis products were compared with those of known compounds on two different columns. The products were isolated from the reaction mixtures by gas chromatography and compared with known compounds by infrared and, in some cases, refractive index analyses.

Solvolysis reaction product mixtures were analyzed quantitatively by the internal standardization method, and peak areas were determined by the method of approximating triangles.[24] A known amount of the internal standard was added to the entire volume of the reaction mixture. The absolute amount of each product, G_u, was determined from the weight of internal standard, G_i; the ratio of product response, A_u, to internal standard, A_i; and a weight response correction factor, F.

$$G_u = (A_u/A_i)(F)(G_i) \quad (1)$$

Weight response factors, shown in Table I, were determined by analysis of methanol solutions of the internal standard and the known products from the equation

$$F = (a_i/g_i)/(a_u/g_u) \quad (2)$$

where a_i = response of internal standard (cm^2), g_i = weight of internal standard (μg), a_u = response of known product (cm^2), and g_u = weight of known product (μg). The factors were determined at gas chromatographic conditions identical with those used for the quantitative analyses of the reaction products. Anisole and borneol were used as internal standards, respectively, for all methanolysis and hydrolysis reaction product analyses.

TABLE I

WEIGHT RESPONSE FACTORS FOR SOLVOLYSIS REACTION PRODUCTS[a]

Compd	Weight response factor[b]
trans-Pinocarvyl methyl ether	1.49 ± 0.07[c]
Myrtenyl methyl ether	1.28 ± 0.08[c]
2-Methylenecyclohexyl methyl ether	1.11 ± 0.03[d]
1-Cyclohexenemethyl methyl ether	1.15 ± 0.03[d]
trans-Pinocarveol	1.13 ± 0.02[e]
Myrtenol	1.17 ± 0.02[e]
cis-Pinocarveol	1.02 ± 0.01[e]
2-Methylenecyclohexanol	0.77 ± 0.02[f]
	1.05 ± 0.04[e]
1-Cyclohexenemethanol	0.79 ± 0.02[f]

[a] Two to three concentrations of internal standard relative to reaction product concentration, and three to four analyses at each concentration. [b] Response of anisole relative to methyl ethers and response of borneol relative to alcohols. [c] ODPN column at 90° and 75 ml/min. [d] Didecyl phthalate column at 105° and 100 ml/min. [e] Hyprose column at 145° and 100 ml/min. [f] Didecyl phthalate column at 145° and 100 ml/min.

The total yield of solvolysis products was calculated from the known amount of material solvolyzed and the total amount of products. The relative product proportions were calculated from the ratio of the amount of each product to the total product. Duplicates were run at each reaction condition and three or four analyses were run on each reaction product. The product proportions could be determined within ±2% (based on total product).

Product Analysis. Solvolysis of *cis*-Pinocarvyl Brosylate.—*cis*-Pinocarvyl brosylate (I, R = Bros; 0.50 g) was treated with 0.1 *M* methanolic sodium methoxide (20 ml) for 1 week at 3°. The brosylate was not entirely soluble. The neutralized (methanol–concentrated hydrochloric acid, 12:1, w/w) reaction mixture

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TABLE II

ALKALINE METHANOLYSIS OF *cis*-PINOCARVYL BROSYLATE[a]

Area, cm²			Product, g			Relative amount, %	
trans-Pinocarvyl methyl ether	Myrtenyl methyl ether	Anisole[b]	*trans*-Pinocarvyl methyl ether	Myrtenyl methyl ether	Total % yield	*trans*-Pinocarvyl methyl ether	Myrtenyl methyl ether
21.09	13.57	23.09	0.136	0.075	94.2	64.5	35.5
22.14	13.18	22.26	0.148	0.076	100.0	66.1	33.9
22.80	14.30	23.80	0.143	0.077	98.2	65.0	35.0

[a] ODPN column at 90° and 75 ml/min. [b] 0.1002 g.

was poured into water and extracted with ether. The dried ether extract was concentrated by slow distillation of ether. The infrared spectra of the isolated products were identical with those of known *trans*-pinocarvyl methyl ether (II, R′ = CH_3) and myrtenyl methyl ether (III, R′ = CH_3). The gas chromatographic retention times were comparable with those of *trans*-pinocarvyl and myrtenyl methyl ether on the ODPN and prep hyprose columns. The refractive indices were similar to those of the known compounds. Gas chromatographic analysis gave no indication of elimination products or *cis*-pinocarvyl methyl ether (I, R = CH_3). The retention time ratios for *trans*-pinocarvyl methyl ether–myrtenyl methyl ether–*cis*-pinocarvyl methyl ether on the ODPN column were 1.00:1.16:1.34. A similar neutralized reaction mixture was partially concentrated by slow distillation of methanol. After addition of internal standard, the reaction products were analyzed directly. The data for a typical quantitative analysis are shown in Table II. The two methyl ethers were obtained in 97% yield. The ratio of *trans*-pinocarvyl to myrtenyl methyl ether was 65.4:34.6.

cis-Pinocarvyl brosylate (0.50 g) was treated with dry methanol (20 ml) for 1 week at 3°. The reaction mixture was neutralized with 10% methanolic sodium hydroxide. The products were the same as those found in the alkaline methanolysis of the brosylate. Addition of known *trans*-pinocarvyl methyl ether and myrtenyl methyl ether to the reaction product caused an increase in the gas chromatographic peak heights and no new peaks. The two methyl ethers were obtained in 98% yield and in the same ratio as that found for alkaline methanolysis (65.4:34.6).

cis-Pinocarvyl brosylate (0.50 g) was treated with a methanolic solution of 0.1 *M* sodium methoxide and 0.1 *M* lithium perchlorate (20 ml) for 1 week at 3°. The neutralized reaction product gave a 99% yield of *trans*-pinocarvyl methyl ether and myrtenyl methyl ether with a ratio of 62.1:37.9. The reaction was repeated with 0.5 *M* lithium perchlorate. The two methyl ethers were obtained in 89% yield with a ratio of *trans*-pinocarvyl to myrtenyl methyl ether of 49.6:50.4.[25]

cis-Pinocarvyl brosylate (0.25 g) was treated with 55% aqueous acetone (11 ml) at 25° for 26 hr. The brosylate completely dissolved. Acetone was slowly removed from the neutralized reaction mixture with a rotary evaporator. Sodium chloride (5% by weight) was added, and the product was extracted with ether. The dried ether extract was concentrated on a rotary evaporator. The infrared spectra of the isolated products were identical with those of known *trans*-pinocarveol (II, R′ = H) and myrtenol (III, R′ = H). The gas chromatographic retention times were comparable to those of *trans*-pinocarveol and myrtenol on the hyprose and didecyl phthalate columns. Gas chromatographic analysis gave no indication of elimination products or *cis*-pinocarveol (I, R = H). The retention time ratios for *trans*-pinocraveol–*cis*-pinocarveol–myrtenol on the hyprose column were 1.00:1.51:1.63. A similar concentrated ether extract of the reaction mixture was diluted with methanol. After addition of the internal standard, the reaction product was quantitatively analyzed. The two alcohols were obtained in 94% yield. The ratio of *trans*-pinocarveol to myrtenol was 49.9:50.1.

Solvolysis of 2-Methylenecyclohexyl Brosylate.—2-Methylenecyclohexyl brosylate (IV, R = Bros; 0.50 g) was treated with 0.1 *M* methanolic sodium methoxide (22.5 ml) for 1 week at 3°. The system was heterogeneous. The work-up and analysis procedures were identical with those employed for alkaline methanolysis of *cis*-pinocarvyl brosylate. The infrared spectra of the isolated products were identical with those of known 2-methylenecyclohexyl methyl ether (V, R′ = CH_3) and 1-cyclohexenemethyl methyl ether (VI, R′ = CH_3). The gas chromatographic retention times were comparable with those of 2-methylenecyclohexyl methyl ether and 1-cyclohexenemethyl methyl ether on the ODPN, prep hyprose, and didecyl phthalate columns. The refractive indices of the two products were similar to those of the known compounds. Gas chromatographic analysis gave no indication of elimination products. The two methyl ethers were obtained in 94% yield. The ratio of 2-methylenecyclohexyl to 1-cyclohexenemethyl methyl ether was 43.8:56.2.

2-Methylenecyclohexyl brosylate (0.50 g) was dissolved in 55% aqueous acetone (18 ml) and allowed to react for 1 week at 3°. The work-up and analysis procedures were identical with those employed for hydrolysis of *cis*-pinocarvyl brosylate. The infrared spectra of the isolated products were identical with those of known 2-methylenecyclohexanol (V, R′ = H) and 1-cyclohexenemethanol (VI, R′ = H). The gas chromatographic retention times were comparable with those of 2-methylenecyclohexanol and 1-cyclohexenemethanol on the hyprose and didecyl phthalate columns. Gas chromatographic analysis gave no indication of elimination products. The two alcohols were obtained in 91% yield. The ratio of 2-methylenecyclohexanol to 1-cyclohexenemethanol was 42.4:57.6.

Product Stability.—The products of hydrolysis and alkaline methanolysis of *cis*-pinocarvyl and 2-methylenecyclohexyl brosylate were individually carried through the reaction and work-up procedures at conditions comparable with those used for the solvolysis product analyses. *p*-Bromobenzenesulfonic acid, a product of the solvolysis reactions, was dissolved in the reaction mixtures. No new peaks appeared in the gas chromatographs after reaction. The reaction conditions caused no isomerization.

Solvolysis of Isopinocamphyl Brosylate.—Isopinocamphyl brosylate (VII, 0.50 g) was treated with 0.1 *M* methanolic sodium methoxide (20 ml) for 1 week at 25°. The work-up procedure was identical with that employed for alkaline methanolysis of *cis*-pinocarvyl brosylate. Gas chromatographic comparison with known compounds on the didecyl phthalate column (110° and 100 ml/min) and ODPN column (68° and 50 ml/min) showed that α-pinene, β-pinene, camphene, and limonene were present in the reaction product. Two other unidentified peaks appeared in the hydrocarbon region on the ODPN column. Three peaks, assumed to be substitution products, appeared at retention times longer than those of the hydrocarbons. The ratio of elimination to substitution products was approximately 74:26. The peak areas were measured by the method of approximating triangles and were uncorrected.

Solvolysis of *trans*-2-Methylcyclohexyl Brosylate.—*trans*-2-Methylcyclohexyl brosylate (VIII, 0.50 g) was treated with 0.1 *M* methanolic sodium methoxide (22.5 ml) for 1 week at 25°. The work-up procedure was identical with that employed for alkaline methanolysis of *cis*-pinocarvyl brosylate. Gas chromatographic comparisons with a known compound on the didecyl phthalate column (110° and 100 ml/min) and ODPN column (68° and 30 ml/min) showed that 1-methylcyclohexene was present in the reaction product. Two other unidentified peaks appeared in the hydrocarbon region on the didecyl phthalate column. Two peaks, assumed to be substitution products, appeared at retention time longer than those of the hydrocarbons. The ratio of elimination to substitution products was approximately 94:6.

Solvolysis of *p*-Nitrobenzoates.—*cis*-Pinocarvyl (I, R = *p*-NB; 0.50 g), *trans*-pinocarvyl (II, R′ = *p*-NB; 0.50 g), and 2-methylenecyclohexyl (IV, R = *p*-NB; 0.50 g) *p*-nitrobenzoates were treated with 0.1 *M* methanolic sodium methoxide (25 ml) for 24 hr at 50° in a nitrogen atmosphere. The neutralized reaction mixtures were partially concentrated by distillation of methanol. The reactions gave only the parent alcohols in

(25) In this case, direct analysis of the products was complicated by a large peak at retention time near that of the products. A similar peak was obtained from a methanolic solution of *p*-bromobenzenesulfonic acid in 0.1 *M* sodium methoxide and 0.5 *M* lithium perchlorate. The reaction mixture was poured into water (containing 5% sodium chloride) and extracted with ether. The ether extract was concentrated and diluted with methanol. Quantitative analyses were run on this solution.

quantitative yields (96–102%). The infrared spectra and gas chromatographic retention times (on two columns) of the products were comparable to those of the known alcohols. Methyl *p*-nitrobenzoate was also isolated and identified by infrared analysis.

Alkaline methanolysis of *cis*-pinocarvyl *p*-nitrobenzoate in the presence of oxygen yielded two compounds. The reaction product gave a positive carbonyl test. In addition to *cis*-pinocarveol, pinocarvone was tentatively identified by gas chromatographic and infrared analyses. The ratio of *cis*-pinocarveol to suspected pinocarvone was approximately 3:1.

Solvolysis Rate Measurements.—All solvolysis rate measurements were carried out at 5.1 ± 0.1°. The reactions were carried out in 10% methanolic acetone solutions (10% acetone, by volume) since *cis*-pinocarvyl brosylate was not very soluble in pure methanol.

Pseudo-first-order rate constants for methanolysis of *cis*-pinocarvyl and 2-methylenecyclohexyl brosylate were determined titrimetrically by a procedure used for the ethanolysis of allyl benzenesulfonate.[26] The brosylate (0.45–0.50 g), weighed at 3°, was dissolved in acetone (10 ml) and placed in a constant temperature bath. A stop watch was started when methanol was added. The solution was diluted to 100 ml and thoroughly mixed. Aliquots (10 ml) were removed at various times and pipetted into cold carbon tetrachloride (20 ml) to quench the reaction. Cold water (25 ml) was added to extract the liberated *p*-bromobenzenesulfonic acid. The mixtures were quickly titrated to the phenolphthalein end point with 0.03875 *M* sodium hydroxide solution. The initial ester concentration was obtained by titration of an aliquot of the reaction mixture at long reaction time (6 hr). Nine or ten titrations were made for each run, and duplicate runs were made with both brosylates.

The pseudo-first-order rate constants were graphically determined from a form of the integrated rate equation for a first-order reaction

$$\log c = -k_1 t/2.303 + \text{constant} \quad (3)$$

where c = brosylate concentration at time (t) and k_1 = pseudo-first-order rate constant. The data for a typical run with *cis*-pinocarvyl brosylate are shown in Table III. A plot of eq 3 for the same data is shown in Figure 1. The pseudo-first-order rate constants for *cis*-pinocarvyl brosylate and 2-methylenecyclohexyl brosylate were 9.6×10^{-4} sec^{-1} and 9.7×10^{-4} sec^{-1}, respectively. The reactions followed good first-order kinetics to approximately 85% reaction.

TABLE III

METHANOLYSIS OF *cis*-PINOCARVYL BROSYLATE AT 5.1°[a]

Time, min	0.03875 *M* NaOH, ml,[b]	Ester concn, moles/100 ml × 10⁴	Reaction, %
2.25	0.64	10.85	18.6
8.50	1.56	7.28	45.4
13.00	1.97	5.70	57.2
18.67	2.36	4.18	68.6
24.00	2.60	3.25	75.5
30.25	2.86	2.25	83.1
37.50	2.99	1.74	86.9
54.33	3.16	1.08	91.9
91.00	3.35	0.35	97.4
6 hr	1.72[c]	13.33	100

[a] Brosylate (0.5069 g) in 100 ml of 10% acetone–methanol solution. [b] Corrected for 0.02-ml reagent blank, 10-ml aliquots. [c] A 5-ml aliquot.

Pseudo-first-order rate constants for reaction of *cis*-pinocarvyl and 2-methylenecyclohexyl brosylate with 0.02 *M* methanolic sodium methoxide were titrimetrically determined by a procedure used for the alkaline ethanolysis of allyl benzenesulfonate.[26] The brosylate (0.50–0.55 g), weighed at 3°, was dissolved in acetone (10 ml) and placed in the bath. A stop watch was started when standard methanolic sodium methoxide was added. The reaction solution was diluted to 100 ml with dry methanol and thoroughly mixed. Aliquots (10 ml) were removed at various times and pipetted into a cold mixture of carbon tetrachloride (20 ml), excess 0.01993 *M* hydrochloric acid (10.0 ml) and phenolphthalein. The excess hydrochloric acid was quickly titrated with 0.03875 *M* sodium hydroxide solution. The pseudo-first-order rate constants, determined from a graphical plot of eq 3, for *cis*-pinocarvyl brosylate and 2-methylenecyclohexyl brosylate were 8.5×10^{-4} sec^{-1} and 9.4×10^{-4} sec^{-1}, respectively. The reactions followed good first-order kinetics to approximately 80% reaction.

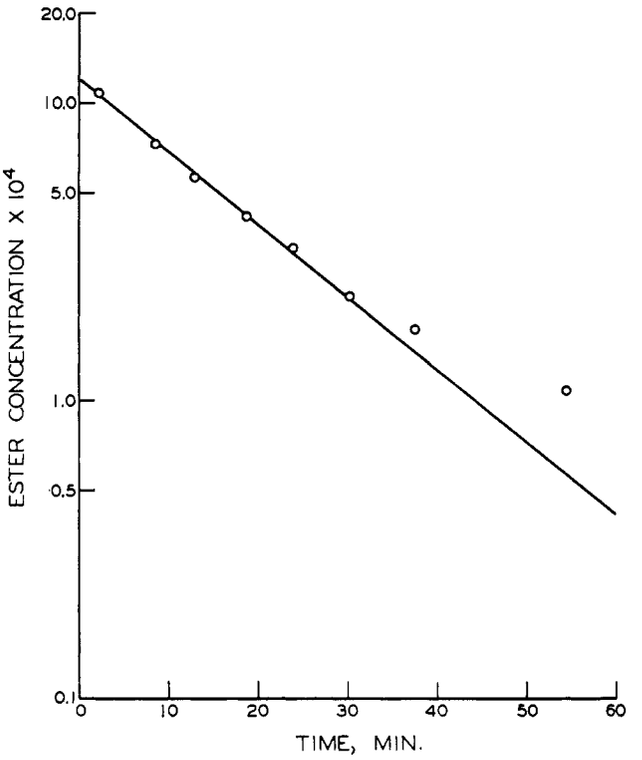
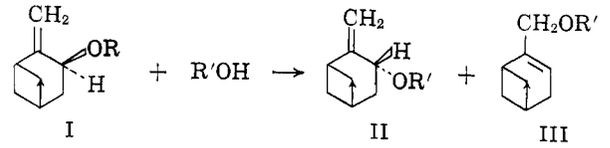


Figure 1.—Titrimetric rate constant determination–methanolysis of *cis*-pinocarvyl brosylate at 5.1°.

The pseudo-first-order rate constant for reaction of *cis*-pinocarvyl brosylate with 0.5 *M* lithium perchlorate in methanolic sodium methoxide (0.02 *M*) was determined. The brosylate (0.5 g) was dissolved in acetone (10 ml) and placed in the bath. A stop watch was started when a methanolic lithium perchlorate solution was added. The reaction solution was diluted to 100 ml with methanolic sodium methoxide (25 ml, 0.0842 *M*) and dry methanol. Aliquots (10 ml) were titrated by the procedure used for alkaline methanolysis of the brosylate. The pseudo-first-order rate constant, determined from a graphical plot of eq 3, was 19.95×10^{-4} sec^{-1}. The reaction followed good first-order kinetics to approximately 85% reaction.

Discussion

Methanolysis of *cis*-pinocarvyl brosylate (I, R = Bros), with or without sodium methoxide, was found to give a nearly quantitative yield of methyl ethers. The ratio of *trans*-pinocarvyl methyl ether (II, R′ = CH_3) to myrtenyl methyl ether (III, R′ = CH_3) was



I II III

65:35. The proportion of rearranged product increased on going to more polar systems (Table IV) such as 0.5 *M* lithium perchlorate in methanol or 55% aqueous acetone.

The monocyclic sulfonate ester, 2-methylenecyclohexyl brosylate (IV, R = Bros), was also found to yield normal and rearranged products under the con-

(26) C. G. Bergstrom and S. Siegel, *J. Am. Chem. Soc.*, **74**, 254 (1952).

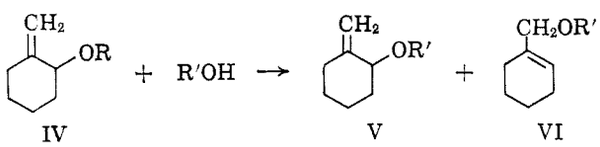
TABLE IV

QUANTITATIVE ANALYSIS ON SOLVOLYSIS OF *cis*-PINOCARVYL AND 2-METHYLENECYCLOHEXYL BROSYLATE[a]

Brosylate	Solvent	Added salt or base	Products and relative amounts, %	Yield, %
I	CH_3OH	...	II, R′ = CH_3 + III, R′ = CH_3 65.4 ± 0.8 34.6 ± 0.8	98 ± 2
I	CH_3OH	0.1 *M* $NaOCH_3$	II, R′ = CH_3 + III, R′ = CH_3 65.4 ± 0.6 34.6 ± 0.6	97 ± 2
I	CH_3OH	0.1 *M* $NaOCH_3$ 0.1 *M* $LiClO_4$	II, R′ = CH_3 + III, R′ = CH_3 62.1 ± 0.2 37.9 ± 0.2	99 ± 1
I	CH_3OH	0.1 *M* $NaOCH_3$ 0.5 *M* $LiClO_4$	II, R′ = CH_3 + III, R′ = CH_3 49.6 ± 0.6 50.4 ± 0.6	89 ± 2
I[b]	H_2O + CH_3COCH_3[c]	...	II, R′ = H + III, R′ = H 49.9 ± 0.5 50.1 ± 0.5	94 ± 1
IV	CH_3OH	0.1 *M* $NaOCH_3$	V, R′ = CH_3 + VI, R′ = CH_3 43.8 ± 0.9 56.2 ± 0.9	94 ± 3
IV	H_2O + CH_3COCH_3[c]	...	V, R′ = H + VI, R′ = H 42.4 ± 0.6 57.6 ± 0.6	91 ± 4

[a] Reactions run at 3° except in one case. [b] Reaction run at 25°. [c] 55% acetone (by volume).

ditions studied. Here the degree of rearrangement was greater than that observed for the bicyclic analog and did not differ significantly in the two solvent systems.



IV V VI

The allylic brosylates are solvolyzed much faster than similar saturated sulfonate esters. The pseudo-first-order rate constants for ethanolysis of isopinocamphyl tosylate[5] at 30° and for methanolysis of *trans*-2-methylcyclohexyl tosylate[4] at 60° are 1.26×10^{-5} and 4.45×10^{-6} sec^{-1}, respectively. The pseudo-first-order rate constants for methanolysis of *cis*-pinocarvyl and 2-methylenecyclohexyl brosylate at 5° are 9.6×10^{-4} and 9.7×10^{-4} sec^{-1}, respectively. The rate difference would be even greater if the comparison could be made at the same temperature.

The formation of stable normal and rearranged products and the accelerated rates observed show the importance of unsaturation and rule out simple SN2 displacement. The combination of SN2 and SN2′ pathways,[3] however, remains a possibility.

Further information was gained by examining the effect of methoxide ion on the rates of solvolysis of the brosylates. Since the distribution of products is the same from the methanolysis of *cis*-pinocarvyl brosylate with or without sodium methoxide present, there is apparently no change in the mechanism of solvolysis.

In contrast to a unimolecular reaction, the rate of a bimolecular reaction is markedly increased when the nucleophilicity of the attacking group is increased. Table V shows that the presence of sodium methoxide (0.02 *M*) causes a slight decrease in the rate of methanolysis of *cis*-pinocarvyl brosylate. Similarly, the rate of methanolysis of 2-methylenecyclohexyl brosylate is slightly lower in the presence of sodium methoxide (0.02 *M*). The lack of an increase in rate of reaction in the presence of lyate ion is evidence that bimolecular pathways do not contribute significantly to the methanolysis mechanisms of the brosylates.[26-28]

(27) C. A. Vernon, *J. Chem. Soc.*, 4462 (1954).
(28) A. Streitweiser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, p 34.

TABLE V

RATE CONSTANTS FOR SOLVOLYSIS OF *cis*-PINOCARVYL AND 2-METHYLENECYCLOHEXYL BROSYLATE AT 5°

Brosylate	Solvolysis medium	$k_1 \times 10^4$, sec^{-1}
cis-Pinocarvyl	CH_3OH	9.6 ± 0.2
cis-Pinocarvyl	CH_3OH + 0.02 *M* $NaOCH_3$	8.5 ± 0.1
cis-Pinocarvyl	CH_3OH + 0.02 *M* $NaOCH_3$ + 0.5 *M* $LiClO_4$	19.95 ± 0.03
2-Methylenecyclohexyl	CH_3OH	9.7 ± 0.1
2-Methylenecyclohexyl	CH_3OH + 0.02 *M* $NaOCH_3$	9.4 ± 0.1

There is additional evidence that methanolysis of the allylic brosylates does not proceed by a bimolecular mechanism. The kinetic expression[28] for reaction of a sulfonate ester with a hydroxylic solvent and with the lyate ion is

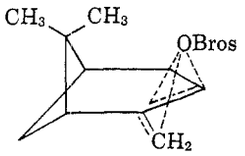
$$dx/dt = k_1(a - x) + k_2(a - x)(b - x) \quad (4)$$

where a = initial ester concentration, b = initial lyate ion concentration, x = ester concentration reacted at time (t), k_1 = first-order rate constant for reaction with solvent, and k_2 = second-order rate constant for substitution by lyate ion. The first-order rate constant (k_1) is a measure of the unimolecular and bimolecular reaction with the solvent.

If a solvolysis reaction follows the rate law shown in eq 4, a plot of $[1/(a - x)][dx/dt]$ against $(b - x)$ is linear. The titrimetric data for methanolysis of *cis*-pinocarvyl and 2-methylenecyclohexyl brosylate in the presence of 0.02 *M* sodium methoxide was not linear when eq 4 was plotted. If k_1 is much greater than k_2, the rate law is that of a pseudo-first-order reaction. The titrimetric data fit this rate law (eq 3).

Solvolysis Mechanisms.—An SN1 reaction mechanism involving either ion-pair or carbonium-ion formation is in accord with both the product and kinetic data. Addition of lithium perchlorate causes a two-fold increase in rate. This salt should have no effect other than to increase the ionic strength of the system. Such an increase should aid in charge development and thus accelerate an SN1 reaction.

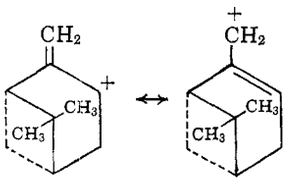
An allylic ion-pair mechanism is proposed for solvolysis of *cis*-pinocarvyl brosylate in the relatively poor ionizing solvent, methanol. The intermediate shown would be rather well protected from nucleophilic



ion-pair intermediate

attack on one side because of the combined steric effects of the isopropylidene bridge and the leaving group.

In 55% aqueous acetone and in methanol containing 0.5 *M* lithium perchlorate, however, an essentially free carbonium ion intermediate may be formed. The greater amount of rearranged product (50% compared with 35% in methanol) would be accounted for by the increased availability of the exocyclic carbon. Alternatively, the ion pair may also be the intermediate in the more polar media. Here, partitioning of the



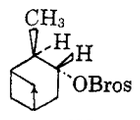
intermediate to give more rearranged product could occur because of the greater charge separation (and, therefore, lesser hindrance between the leaving group and the nucleophile) in the product-determining step.

The same mechanisms are believed to operate in the solvolysis of 2-methylenecyclohexyl brosylate. This is supported by the general similarity in product distributions and the fact that the reaction rates are virtually identical for the bicyclic and monocyclic brosylates.

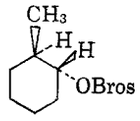
The steric effect of the isopropylidene bridge shows up in the product-determining step by the absence of *cis*-pinocarveol or its methyl ether in the product mixtures. It also shows up in the observation that the product distribution is the same in methanol and acetone–water for the monocyclic system (56–58% rearranged) but is not the same in the two solvents for the bicyclic system. The leaving group interferes with attack on one side of the ring in the methanolysis of 2-methylenecyclohexyl brosylate. The more polar intermediate, however, would make *each* end of the allylic system more available for attack. This is not the case with the terpene because the isopropylidene bridge still blocks[29] one mode of attack at the ring carbon—no *cis*-pinocarvyl products are formed.

An excess of rearranged product (56–58%) was found in the solvolyses of 2-methylenecyclohexyl brosylate; only 35–50% of the product from *cis*-pinocarvyl brosylate, however, was the rearranged isomer. The higher degree of rearrangement for the monocyclic system may primarily be due to the greater relative stability of the transition state leading to rearrangement because of the development of the incipient double bond *within* the ring. 1-Methylcyclohexene has been reported[30] to be more stable than methylenecyclohexane. This stability difference would undoubtedly be greater than the analogous terpene situation since there the double bond within the ring would give rise to increased strain or rigidity.

Saturated Brosylates.—Alkaline methanolysis of isopinocamphyl brosylate (VII) and *trans*-2-methylcyclohexyl brosylate (VIII) yielded a large proportion of elimination products estimated at 74 and 94%, respectively. α-Pinene, β-pinene, camphene, and limonene were identified as products of the reaction of the terpene ester, and 1-methylcyclohexene was identified as a product of the reaction of the other brosylate. This is in accord with the findings of Hückel and Nag[5] who identified α-pinene, camphene, and limonene in the reaction product of isopinocamphyl tosylate with ethanolic sodium ethoxide. They also found isopinocamphyl ethyl ether and other unidentified ethers. Hückel and co-workers[4] identified 1- and 3-methylcyclohexene and three methyl ethers in the reaction product of *trans*-2-methylcyclohexyl tosylate with methanolic sodium methoxide.



VII



VIII

The high degree of elimination found for these sulfonate esters contrasts markedly with the reactions of the allylic esters which gave no detectable elimination products. Acyclic, allylic halides have been found[27,31–34] to yield elimination products in addition to substitution products, at least in the presence of high base concentrations. Many other studies[35–39] have given no indication of elimination products, but reported product yields were below 80%. It is possible that ring strain in the cyclic diene systems makes the pathway leading to their production less energetically favorable, but further work will be necessary to determine whether this is true.

Leaving Group.—Because of their lower basicity, sulfonate groups are better leaving groups than carboxylate groups.[40] As might be expected, the *p*-nitrobenzoate esters of *cis*-pinocarveol and 2-methylenecyclohexanol did not give rise to allylic ion formation but underwent acyl oxygen cleavage when subjected to alkaline methanolysis; no rearrangement was detected.

(29) The isopropylidene bridge should not block *cis* attack at the exocyclic carbon because the nearest methyl of the *gem*-dimethyl pair is nearly 4.0 A away as revealed by molecular models.

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(40) E. S. Gould, "Mechanism and Structure in Organic Chemistry," Henry Holt and Co., Inc., New York, N. Y., 1959, p 261.