dene-D-*xylo*-pentofuranose, 12.65 g. of sodium pyrosulfite and 3.4 g. of sodium cyanide was prepared at 0°, and allowed to warm to room temperature. After three days the solution was heated at 90° for one hour, then treated with 7 g. of sodium carbonate, and refluxed for three hours. The solution was cooled in an ice-bath, and passed through a column containing 350 ml. of cation exchange resin[8] at ice temperature. The effluent, including washings, was delivered into a flask immersed in an ice-bath, containing 41.6 g. of barium hydroxide octahydrate. After removal of excess barium hydroxide by carbonation and filtration, one-tenth of the filtrate was set aside for analysis by an isotope dilution technique. The remainder of the solution was concentrated under vacuum to a sirup that yielded 7.77 g. of crude crystalline barium 1,2-*O*-isopropylidene-D-glucofururonate monohydrate. After removal of the barium salt, the mother liquor was passed through a column containing 75 ml. of cation exchange resin[8] at ice temperature. The effluent, including washings, was delivered into a flask containing 5 g. of calcium carbonate. The mixture was filtered, and the filtrate concentrated under vacuum. Calcium 1,2-*O*-isopropylidene-L-idofururonate-6-C^{14} dihydrate separated. The product, 4.2 g., was recrystallized from water with the addition of methanol.

Anal. Calcd. for Ca $C_{18}H_{26}O_{14}\cdot 2H_2O$: C, 39.8; H, 5.6; Ca, 7.4. Found: C, 39.8; H, 5.8; Ca, 7.2; $[\alpha]^{25}_D$ −11.8° (*c* 3, water).

Preparation of Calcium 1,2-*O*-Isopropylidene-L-idofururonate-6-C^{14} Dihydrate.—The original synthesis began with 0.005 mole of sodium cyanide-C^{14} (12.5 millicuries) and 1.11 g. of 5-aldo-1,2-*O*-isopropylidene-D-*xylo*-pentofuranose buffered with 0.005 mole of sodium hydroxide and 0.02 mole of acetic acid. The mother liquor that remained after separation of 6.75 millicuries of barium 1,2-*O*-isopropylidene-D-glucofururonate-6-C^{14} monohydrate from the cyanohydrin synthesis previously reported had been set aside for approximately two years before the work reported here was resumed.

The mother liquor was dissolved in 100 ml. of water, treated with 700 ml. of ethanol, and passed through a carbon-coated filter. Under vacuum the filtrate was concentrated to a 50-ml. volume. The concentrate was passed, ice-cold, into a column containing 30 ml. of cation exchange resin,[8] washed through with ice-water, and collected in a flask containing 0.3 g. of barium carbonate. The partially neutralized effluent was freeze-dried to remove the acetic acid present. Addition of methanol to an aqueous solution of the residue yielded 0.18 g. of crude barium 1,2-*O*-isopropylidene-D-glucuronate-6-C^{14} monohydrate.

The purified mother liquor was diluted with ice-water and passed through a column of 12 ml. of ice-cold cation exchange resin[8] into a flask containing 0.13 g. of calcium carbonate. Concentration of the solution under vacuum yielded calcium 1,2-*O*-isopropylidene-L-idofururonate-6-C^{14} dihydrate, which was separated and washed with a mixture of ethanol and water (6:1). Recrystallization from water and ethanol yielded 2.81 millicuries of the salt. By use of non-radioactive carrier, an additional 0.53 millicurie of this product was obtained. The radiochemical yield based on the 12.5 millicuries of cyanide-C^{14} originally used was 27%.

Yield of the L-Iduronate Epimer in a Bisulfite-buffered Cyanohydrin Reaction.—The portion of the solution from the preparation of non-radioactive calcium 1,2-*O*-isopropylidene-L-idofururonate dihydrate kept for the isotope dilution analysis was diluted with a tracer consisting of 95.2 microcuries of calcium 1,2-*O*-isopropylidene-L-idofururonate-6-C^{14} dihydrate (10.68 mg.). After separation of the D-glucuronate epimer as the barium salt, the solution was passed through 15 ml. of cation exchange resin[8] into a flask containing 0.75 g. of calcium carbonate. The excess calcium carbonate was removed, and the calcium salt was crystallized as already described. After two recrystallizations, the air-dried salt had a specific radioactivity of 0.151 μc./mg. This activity corresponds to dilution of the tracer by 620 mg. of calcium 1,2-*O*-isopropylidene-L-idofururonate dihydrate or a 34.3% yield of this substance from the cyanohydrin reaction.

Radioactivity Measurements.—Determinations of C^{14} were made by direct count of the materials in formamide or aqueous formamide solutions.[9] Samples were counted to a probable error of 1%, and the results converted to microcuries by a factor based on the C^{14}-standard issued by the National Bureau of Standards.

The authors express their appreciation to R. A. Paulson and L. Tregoning for the microanalyses.

(8) Amberlite IR-120 H, Resinous Products Division of Rohm and Haas Co., Philadelphia, Pa.

(9) A. Schwebel, H. S. Isbell and J. D. Moyer, *J. Research Natl. Bur. Standards*, **53**, 221 (1954).

WASHINGTON 25, D. C.

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY OF THE OHIO STATE UNIVERSITY]

Acyl Migration in the D-Galactose Structure

BY M. L. WOLFROM, A. THOMPSON[1] AND M. INATOME[1]

RECEIVED JANUARY 17, 1957

When 2,3,4-tri-*O*-acetyl-1,6-anhydro-β-D-galactose is treated successively with titanium tetrachloride and mercuric acetate, there are obtained two crystalline tetraacetates of D-galactose. The one (isomer A) is convertible to the other (isomer B) by traces of alkali. Both are convertible to β-D-galactopyranose pentaacetate on mild acetylation. Isomers A and B are resistant toward triphenylmethylation. Isomer A yields a *p*-toluenesulfonate which in turn forms a methyl tri-*O*-acetyl-*O*-*p*-toluenesulfonyl-β-D-galactopyranoside, both of which derivatives are different from known isomers believed to have the *p*-toluenesulfonyl group in the sixth position. Both isomers A and B yield tetra-*O*-acetyl-3-*O*-methyl-β-D-galactopyranose on methylation. Positions 2, 3 or 4 are assignable for the open hydroxyl group in each of the two D-galactopyranose tetraacetates, but the present evidence disallows definite allocations.

No tetraacetate of D-galactose is known in which the terminal primary hydroxyl group is unsubstituted. An attempt to prepare such a derivative by a procedure suitable for the synthesis of the analogous D-glucose structure, led to a crystalline D-galactose tetraacetate, m.p. 138–138.5°, $[\alpha]_D$ +37° (chloroform), herein designated isomer A.[2] This substance was considered to have its position six substituted by an acetate group since it was recovered unchanged on treatment with triphenylmethyl chloride and pyridine.[2] Isomer A had been prepared[2] by the successive action of titanium tetrachloride and mercuric acetate on 2,3,4-tri-*O*-acetyl-1,6-anhydro-β-D-galactopyranose. A second isomer has now been isolated, by chromatographic techniques, from the same reaction mixture. The substance, m.p. 140–141.5°, $[\alpha]_D$ +25.5° (chloroform), designated isomer B, possesses essentially the same melting point as isomer A but the mixed

(1) Research Associate (A. T.) and Fellow (M. I.) of the Corn Industries Research Foundation.

(2) A. Thompson, M. L. Wolfrom and M. Inatome, THIS JOURNAL, **77**, 3160 (1955).

melting point exhibits a marked depression; rotations and crystal X-ray powder diffraction data are different.

Isomer A is convertible to isomer B by traces of alkali, statements to the contrary[2] being in error. Mild acetylation of both isomers yielded β-D-galactopyranose pentaacetate. Methylation of either resulted in a crystalline monomethyl ether without acetyl loss, and this on deacetylation afforded 3-*O*-methyl-α-D-galactose[3] of established structure. Esterification of isomer B with *p*-toluenesulfonic acid failed to yield a crystalline product but like treatment of isomer A did. This tetra-*O*-acetyl-*O*-*p*-toluenesulfonyl-β-D-galactopyranose was converted to methyl tri-*O*-acetyl-*O*-*p*-toluenesulfonyl-β-D-galactopyranoside through its glycosyl bromide derivative.

While the complete structures of the isomeric D-galactose tetraacetates A and B cannot be established on the basis of the present evidence, some data may be advanced as to their partial structures. Their rotatory powers, method of synthesis and ease of conversion to β-D-galactopyranose pentaacetate would indicate that both contain the pyranose ring and possess an acetate group on carbon one in the β-D-anomeric form. Acyl migrations are catalyzed by both acids and bases and the direction of acyl movement is considered to favor a shift from a secondary to a primary hydroxyl group.[4,5]

Both isomers were resistant to etherification with triphenylmethyl chloride. It is accordingly probable that carbon six is acetylated in both tetraacetates. This conclusion is supported by the nature of the *p*-toluenesulfonate derivative of isomer A. This substance did not react with sodium iodide in acetonylacetone as a primary *p*-toluenesulfonate should, and it was not identical with either of the two known forms of tetra-*O*-acetyl-6-*O*-*p*-toluenesulfonyl-β-D-galactose recorded by Ohle and Thiel[6] (Table I). These workers acetylated the two anomeric forms of D-galactopyranose 6-*p*-toluenesulfonate, prepared in turn from 1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose. There is no established case of *p*-toluenesulfonyl migration, and it is believed that this group, possessing no function quite analogous to a carbonyl, does not migrate. In the case of the β-D-anomer, Ohle and Thiel obtained two products which they considered to be ring isomers. If the *p*-toluenesulfonate group in our isomer A was on position 6, it should have been identical with one of the two ring forms of the β-D-derivatives of Ohle and Thiel. Since this is not the case, position 6 must be occupied by an acetyl group in the *p*-toluenesulfonate ester of isomer A. This conclusion is supported by the fact that the methyl β-D-glycoside of the *p*-toluenesulfonate is not identical with the recorded anomeric forms of methyl tri-*O*-acetyl-6-*O*-*p*-toluenesulfonyl-D-galactopyranoside (Table II).

TABLE I

ISOMERIC FORMS OF TETRA-*O*-ACETYL-*O*-*p*-TOLUENESULFONYL-D-GALACTOSE

Tetra-*O*-acetyl-	M.p., °C.	$[\alpha]^{20\pm5}D$, $CHCl_3$, $c < 5$	Reference
O-*p*-Toluenesulfonyl-β-D-galactopyranose (from isomer A)	154–155	+43°	This work
6-*O*-*p*-Toluenesulfonyl-α-D-galactose	117	+89	6
6-*O*-*p*-Toluenesulfonyl-β-D-galactose, ring isomer 1	126–127	+ 9.3	6
6-*O*-*p*-Toluenesulfonyl-β-D-galactose, ring isomer 2	147	+16	6

TABLE II

ISOMERIC FORMS OF METHYL TRI-*O*-ACETYL-*O*-*p*-TOLUENESULFONYL-D-GALACTOPYRANOSIDE

Methyl tri-*O*-acetyl-	M.p., °C.	$[\alpha]^{20\pm5}D$, $CHCl_3$, $c < 5$	Reference
O-*p*-Toluenesulfonyl-β-D-galactopyranoside (from isomer A)	129–130	+25°	This work
6-*O*-*p*-Toluenesulfonyl-β-D-galactopyranoside	Sirup	*ca.* +2.5	7
	Sirup	−3	8
6-*O*-*p*-Toluenesulfonyl-α-D-galactopyranoside	128	+102	6

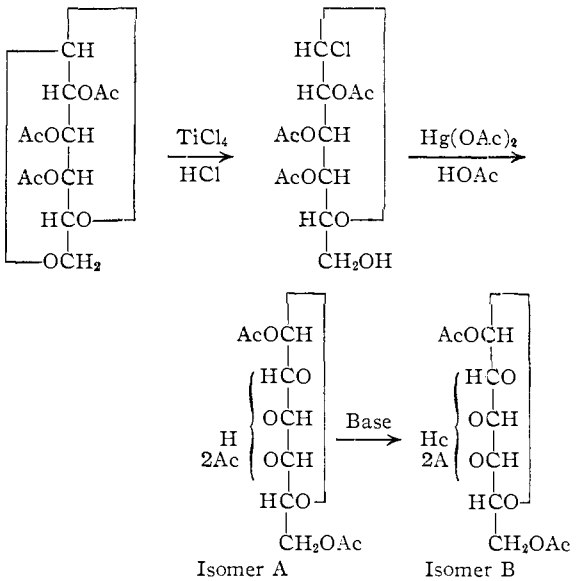
The *p*-toluenesulfonate ester of isomer B failed to crystallize but was obviously different from the corresponding derivative of isomer A. On the other hand, 3-*O*-methyl-α-D-galactose was obtained from both isomers on methylation and deacetylation.

The following reaction is established.

$$\text{A} \xrightarrow{\text{Base}} \text{B}$$

Thus, isomer B is the more stable form.

2,3,4-Tri-*O*-acetyl-α-D-galactopyranosyl chloride has been prepared in crystalline form by Zemplén, Gerecs and Flesch[9] and was utilized by them



(3) F. Reber and T. Reichstein, *Helv. Chim. Acta*, **28**, 1164 (1945).
(4) J. M. Sugihara, *Advances in Carbohydrate Chem.*, **8**, 4 (1953).
(5) J. S. D. Bacon, D. J. Bell and H. W. Kosterlitz, *J. Chem. Soc.*, 1248 (1939).
(6) H. Ohle and H. Thiel, *Ber.*, **66**, 525 (1933).
(7) W. N. Haworth, J. Jackson and F. Smith, *J. Chem. Soc.*, 620 (1940).
(8) I. A. Forbes and E. G. V. Percival, *ibid.*, 1844 (1939).
(9) G. Zemplén, A. Gerecs and Hedwig Flesch, *Ber.*, **71**, 774 (1938).

in their synthesis of robinobiose, 6-*O*-β-L-rhamnopyranosyl-D-galactose. Thus, the *O*-acylglycosyl chloride must have its terminal primary hydroxyl group unsubstituted. Isomer A was obtained by us on reaction of this halide with mercuric acetate in acetic acid solution. It is then probable that an acetyl shift occurred in this replacement reaction.

The collective evidence then would appear to establish the presence of acetate groups on positions 1 and 6 of the β-D-galactopyranose ring structure, but an assignment of the remaining two acetate groups on positions 2, 3 and 4 in the two isomeric tetraacetates cannot be made on the basis of the present evidence.

Experimental[10]

Isomer A from 2,3,4-Tri-*O*-acetyl-α-D-galactopyranosyl Chloride.—An amount of 1.7 g. of 2,3,4-tri-*O*-acetyl-α-D-galactopyranosyl chloride[9] (m.p. 134°) was dissolved in 25 ml. of acetic acid containing 4 g. of mercuric acetate and allowed to stand for 1 hr. Isomer A was isolated from the reaction mixture by the procedure described previously[2]; yield 1.2 g., m.p. 133–135°. Pure material was obtained on crystallization from chloroform–ether; m.p. 140–140.5° undepressed on admixture with an authentic specimen of isomer A.

β-D-Galactopyranose Tetraacetate (Isomer B).—The sirup from the concentration of the mother liquors obtained in the preparation[2] of isomer A, from 7.8 g. of tri-*O*-acetyl-1,6-anhydro-β-D-galactopyranose, was chromatographed, following the general directions of McNeely, Binkley and Wolfrom.[11] The sirup (4.7 g.) was dissolved in a small amount of benzene and placed on a Magnesol[12]–Celite[13] (5:1 by wt.) column (250 × 75 mm., diam.) using 3500 ml. of benzene–*t*-butyl alcohol (100:1 by vol.) as the developer. After the column was extruded and streaked with indicator (1% potassium permanganate in 10% sodium hydroxide), two zones appeared. They were numbered from the bottom to the top of the column.

Zone I, located 125–155 mm. from the top, was eluted with acetone, evaporated to a sirup under reduced pressure and the residue was crystallized from an ether–petroleum ether (b.p. 30–60°) solution; yield 640 mg., m.p. 70–73°, unchanged on admixture with 2,3,4-tri-*O*-acetyl-1,6-anhydro-β-D-galactopyranose.

Zone II, located 24–75 mm. from the top, was eluted with acetone, the eluate evaporated to a sirup and crystallized from ether; yield 0.37 g., m.p. 138–141°. Pure β-D-galactopyranose tetraacetate (isomer B) was obtained on further recrystallization from ether; m.p. 140–141.5° depressed to 116–122° on admixture with isomer A of m.p. 138–138.5°, $[\alpha]^{32}D$ +25.5° (*c* 2.94, chloroform); X-ray powder diffraction data: 9.77[14] vs,[15] 7.76m, 5.55vw, 4.99vs, 4.60w, 4.36m, 4.21s, 3.82m, 3.69s, 3.56m, 3.40m, 3.27m.

Anal. Calcd. for $C_6H_8O_6(CH_3CO)_4$: C, 48.27; H, 5.79; CH_3CO, 11.48 ml. of 0.1 *N* NaOH per 100 mg. Found: C, 48.40; H, 5.76; CH_3CO, 11.65 ml.

The substance was recovered unchanged after treatment with pyridine and triphenylmethyl chloride.

Conversion of Isomer A to Isomer B by Alkali.—Following the general directions of Helferich and Klein,[16] 0.2 g. of isomer A was shaken for 1 hr. in 20 ml. of 0.001 *N* sodium hydroxide whereupon the solution was extracted with chloroform. The sirup obtained on solvent removal, under reduced pressure, from the dried chloroform extract, was dissolved in ether and crystallization ensued on seeding with isomer B; yield 10 mg., m.p. 138–141° unchanged on admixture with isomer B and depressed to 115–120° on admixture with isomer A, X-ray powder diffraction lines identical with those of isomer B.

The isomer B was obtained in better yield when 0.1 g. of isomer A was shaken for 3.5 hr. with 10 ml. of water and 0.2 g. of Amberlite IR-4B.[17] The resin was removed by filtration and the aqueous solution was extracted with chloroform. The sirup obtained on solvent removal, under reduced pressure, from the dried extract, was crystallized from ether; yield 70 mg., m.p. 140–141.5° unchanged on admixture with isomer B and depressed to 114–125° on admixture with isomer A.

Conversion of Isomers A and B to β-D-Galactopyranose Pentaacetate.—An amount of 100 mg. of isomer A was treated for 18 hr. at 0° with acetic anhydride (1 ml.) and pyridine (2 ml.). The reaction was completed on being maintained at room temperature for 12 hr. The crystalline product that formed on pouring the reaction mixture into ice and water was removed by filtration and recrystallized from ethanol; yield 100 mg., m.p. 137–139° unchanged on admixture with authentic β-D-galactopyranose pentaacetate; X-ray powder diffraction data[14,15] (identical with that of authentic material): 12.93vw, 8.10m, 6.93s, 6.18s, 5.62w, 5.06m, 4.28m, 4.00vs, 3.83s, 3.66vw, 3.42vw, 3.29vw, 3.17vw, 3.08w, 3.03w, 2.94vw, 2.87w, 2.81vw, 2.72vw.

β-D-Galactopyranose pentaacetate was likewise identified on the acetylation of isomer B effected in the same manner.

1,2,4,6-Tetra-*O*-acetyl-3-*O*-methyl-β-D-galactose.—The general procedure of Haworth, Hirst and Teece[18] was followed. An amount of 1.0 g. of isomer A, 50 ml. of methyl iodide and 7 g. of silver oxide was maintained at 50–60° under reflux for 5 hr. Ether was then added and the mixture was filtered. The filtrate was concentrated under reduced pressure and the resultant sirup was crystallized from ether; yield 400 mg., m.p. 118–120°. Recrystallization from ethanol gave pure 1,2,4,6-tetra-*O*-acetyl-3-*O*-methyl-β-D-galactose, m.p. 119–120°, mixed m.p. with isomer A 105–111°, $[\alpha]^{25}D$ +41° (*c* 3, chloroform); X-ray powder diffraction data[14,15]: 10.72s, 8.93m, 7.53m, 6.99m, 6.60vw, 6.23m, 5.53m, 5.13w, 4.93w, 4.44s, 3.97m, 3.90m, 3.69m, 3.46m.

Anal. Calcd. for $C_6H_7O_5(CH_3CO)_4(OCH_3)$: C, 49.71; H, 6.12; OCH_3, 8.57; CH_3CO, 11.00 ml. of 0.1 *N* NaOH per 100 mg. Found: C, 49.70; H, 6.01; OCH_3, 8.61; CH_3CO, 11.01 ml.

Methylation of Isomer B.—The general procedure of Richtmyer and Hudson[19] was followed. An amount of 400 mg. of isomer B, 5 g. of silver oxide and 25 ml. of methyl iodide were shaken in a closed flask for 3 hr. at room temperature. The product was processed in a manner similar to that described for the methylation of isomer A. Crystals were obtained from an ethanolic solution; yield 70 mg., m.p. 119–120° unchanged on admixture with 1,2,4,6-tetra-*O*-acetyl-3-*O*-methyl-β-D-galactoside, the methylation product of isomer A. The X-ray powder diffraction patterns of crystals from the two sources were identical.

3-*O*-Methyl-α-D-galactose.—The 1,2,4,6-tetra-*O*-acetyl-3-*O*-methyl-β-D-galactose was deacetylated by an adaptation of the method of Zemplén and Pacsu.[20] An amount of 500 mg. of the substance was dissolved, under exclusion of moisture, in 10 ml. of dry methanol, and 1.5 ml. of a sodium methoxide solution, prepared by treating 500 mg. of sodium with 100 ml. of methanol, was added. After 30 min., 50 ml. of water was added and the solution was passed successively over Amberlite IR-120[17] and Duolite A-4.[21] The neutral, aqueous solution was concentrated under reduced pressure, and the resultant sirup was crystallized from methanol by seeding with 3-*O*-methyl-α-D-galactose[22]; yield 100 mg., m.p. 146–148° (recorded[3] 144–147°) unchanged on admixture with an authentic specimen of 3-*O*-

(10) All melting points herein reported were taken in Pyrex capillary tubes and are uncorrected.

(11) W. H. McNeely, W. W. Binkley and M. L. Wolfrom, THIS JOURNAL, **67**, 527 (1945).

(12) A synthetic magnesium silicate produced by the Westvaco Chemical Division of the Food Machinery and Chemical Corp., South Charleston, W. Va.

(13) No. 535, a siliceous filter-aid produced by the Johns-Manville Co., New York, N. Y.

(14) Interplanar spacing, CuK_α radiation.

(15) Relative intensity, estimated visually; vs, very strong; s, strong; m, medium; w, weak; vw, very weak.

(16) B. Helferich and W. Klein, *Ann.*, **455**, 173 (1927).

(17) A product of the Rohm and Haas Co., Resinous Products Division, Philadelphia, Pa.

(18) W. N. Haworth, E. L. Hirst and E. G. Teece, *J. Chem. Soc.*, 1405 (1930).

(19) N. K. Richtmyer and C. S. Hudson, THIS JOURNAL, **63**, 1727 (1941).

(20) G. Zemplén and E. Pacsu, *Ber.*, **62**, 1613 (1929).

(21) A product of the Chemical Process Co., Redwood City, Calif.

(22) Nuclei were kindly furnished by Prof. T. Reichstein of the University of Basel.

methyl-α-D-galactose; X-ray powder diffraction data[14,15] (identical with those of authentic 3-*O*-methyl-α-D-galactose): 8.85m, 6.93s, 5.74s, 4.98w, 4.56vs, 3.90vw, 3.76s, 3.62vw, 3.49m, 3.39s, 3.31m, 2.88w, 2.83w, 2.66m, 2.41w, 2.32w, 2.26w.

Tetra-*O*-acetyl-*O*-*p*-toluenesulfonyl-β-D-galactopyranose from Isomer A.—The general experimental procedure followed was that of Helferich and Klein.[16] An amount of 500 mg. of isomer A was treated with 200 mg. of *p*-toluenesulfonyl chloride in 3 ml. of dry pyridine. After 24 hr., the mixture was poured into ice and water. The precipitate that formed was filtered and dissolved in ethanol. Crystals appeared upon concentration of the solution; yield 500 mg., m.p. 153–155°. The product was recrystallized from an acetone–ether–petroleum ether (b.p. 30–60°) mixture; m.p. 154–155°, $[\alpha]^{25}D$ +43° (*c* 3, chloroform); X-ray powder diffraction data[14,15]: 10.52s, 8.44vw, 5.72m, 5.31w, 4.76w, 4.48m, 4.19vw, 4.00vw, 3.53w, 3.45m, 3.14w.

Anal. Calcd. for $C_{21}H_{28}O_{12}S$: C, 50.19; H, 5.21; S, 6.38. Found: C, 50.10; H, 5.30; S, 6.33.

Similar treatment of isomer B with *p*-toluenesulfonyl chloride and pyridine failed to yield a crystalline product.

The *p*-toluenesulfonate (150 mg.) from isomer A yielded a negligible precipitate (5 mg.) of sodium *p*-toluenesulfonate on heating at 100° with 70 mg. (1.5 molar ratio) of sodium iodide in 3 ml. of acetonylacetone for 48 hr. A like experiment utilizing 400 mg. of tetra-*O*-acetyl-6-*O*-*p*-toluenesulfonyl-β-D-glucopyranose, 180 mg. of sodium iodide and 8 ml. of acetonylacetone yielded 141.2 mg. (88%) of sodium *p*-toluenesulfonate.

Methyl Tri-*O*-acetyl-*O*-*p*-toluenesulfonyl-β-D-galactopyranoside from Isomer A.—The general procedure of Haworth, Jackson and Smith[7] was followed. An amount of 500 mg. of tetra-*O*-acetyl-*O*-*p*-toluenesulfonyl-β-D-galactopyranose (from isomer A) was treated for 1 hr. with 5 ml. of a solution containing 30% hydrogen bromide in anhydrous acetic acid:acetic anhydride (1:1 by vol.). Chloroform was then added to the solution and the extract was washed four times with water and dried over sodium sulfate. The dried solution was concentrated under reduced pressure, and the resulting sirup was dissolved in 25 ml. of dry methanol, and 10 g. of freshly prepared silver carbonate was added. The mixture was shaken for 5.5 hr. whereupon it was filtered, and the filtrate was concentrated under reduced pressure. Crystals of the methyl tri-*O*-acetyl-*O*-*p*-toluenesulfonyl-β-D-galactopyranoside appeared during the concentration; yield 240 mg., m.p. 129–130°, $[\alpha]^{25}D$ +24° (*c* 3, chloroform); X-ray powder diffraction data[14,15]: 9.77vs, 6.20w, 5.84m, 5.24s, 4.88m, 4.46w, 4.23w, 4.01s, 3.79vw, 3.65m, 3.51m, 3.37m.

Anal. Calcd. for $C_{20}H_{26}O_{11}S$: C, 50.62; H, 5.52; S, 6.77. Found: C, 50.42; H, 5.71; S, 6.67.

COLUMBUS 10, OHIO

[CONTRIBUTION FROM THE GENERAL ELECTRIC RESEARCH LABORATORY]

Deuterium-isotope Effects in the Autoxidation of Aralkyl Hydrocarbons. Mechanism of the Interaction of Peroxy Radicals[1]

BY GLEN A. RUSSELL

RECEIVED FEBRUARY 1, 1957

α-Phenethylperoxy radicals interact to form non-radical products 1.9 times as readily as their α-deutero derivatives. This is taken as evidence that the termination reaction is $2C_6H_5CH(D)CH_3COO\cdot \rightarrow C_6H_5COCH_3 + C_6H_5CH(D)OH(D)\text{-}CH_3 + O_2$. Yields of hydroperoxide and acetophenone produced in the autoxidation of ethylbenzene at various kinetic chain lengths are consistent with the indicated termination reaction. Evidence is presented that this reaction involves a cyclic transition state and excluding an alternate process proceeding by the formation and disproportionation of alkoxy radicals. The deuterium-isotope effect in the reaction of a peroxy radical with cumene and α-*d*-cumene is $k_H/k_D = 5.5$. The magnitudes of deuterium-isotope effects in the reactions of atoms and radicals with carbon–hydrogen and carbon–deuterium bonds are considered. Reactivities of the attacking atoms or radicals and polar effects in the reaction are discussed.

Despite the fact that the autoxidation of hydrocarbons has been studied intensively,[2] evidence is lacking as to the mechanism and products of the reaction wherein two peroxy radicals are converted to non-radical products. We have, therefore, investigated the products of this termination reaction in the oxidation of ethylbenzene and have demonstrated its detailed mechanism by a study of deuterium-isotope effects. The deuterium-isotope effect in the reaction of a peroxy radical with α-*d*-cumene has been measured, and its magnitude confirms our earlier conclusions in regard to the extent of bond-breaking in the transition state for this reaction.

Results

Autoxidations of cumene, ethylbenzene and various deuterated derivatives were performed at 60° in the liquid phase in the presence of α,α′-azodiisobutyronitrile (AIBN). The rates of oxidation were independent of the oxygen pressure over the range 200–760 mm. indicating that only peroxy radicals were involved in the termination reaction.[2] The kinetics of the reaction under these conditions indicate that the following sequence of events is involved.

$$\text{AIBN} \xrightarrow{k_d} (CH_3)_2\dot{C}CN \xrightarrow{O_2} \text{ROO}\cdot \ (\text{Rate} = R_i)$$

$$\text{ROO}\cdot + \text{RH} \xrightarrow{k_3} \text{ROOH} + \text{R}\cdot$$

$$\text{R}\cdot + O_2 \xrightarrow{\text{fast}} \text{ROO}\cdot$$

$$2\text{ROO}\cdot \xrightarrow{k_6} \text{non-radical products} + O_2$$

Under steady-state conditions the rate of oxygen consumption is calculated to be

$$-d[O_2]/dt = k_3[RH](R_i)^{1/2}/(2k_6)^{1/2} + R_i/2 \quad (1)$$

The rate of initiation, R_i, is equal to $2k_d e[\text{AIBN}]^{1/2}$ where *e* represents the fraction of catalyst molecules that produce two free radicals. In Table I the rates of oxidation of cumene and ethylbenzene are presented as a function of hydrocarbon concentration, AIBN concentration and oxygen pressure. The data of column 6 indicate that (1) is obeyed and the rate of oxidation is independent of

(1) Directive Effects in Aliphatic Substitutions. IX. Presented before the Division of Organic Chemistry at the Atlantic City meeting of the American Chemical Society, September, 1956.

(2) J. L. Bolland, *Quart. Revs.*, **3**, 1 (1949); L. Bateman, *ibid.*, **8**, 147 (1954).