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The Distribution of Acetyl Groups in a Technical Acetone-Soluble Cellulose Acetate[1]

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The *p*-toluenesulfonyl (tosyl) esters of primary, as opposed to secondary, alcoholic groups in carbohydrates are quantitatively converted to the corresponding halides by heating with sodium iodide dissolved in a suitable solvent.[3] This analytical method made it possible to determine the molar amount of unsubstituted primary hydroxyl group in the sixth positions of acetone-soluble cellulose acetate, to estimate the corresponding rate of tosylation under standard conditions and to obtain, by difference, the total amount of secondary alcoholic groups distributed in the second and third positions of the anhydroglucose residues.[4] More recent work with a partly ethylated cellulose showed that hydroxyl groups in the second position were tosylated very much more rapidly than those in the third and that a mathematical analysis of their combined tosylation rate plot gave the molar amount of each.[5] The improved experimental and mathematical methods developed in this ethylcellulose study have now been applied to the high grade, commercial acetone-soluble cellulose acetate II used in the previous work.[4]

Experimental

Materials.—Acetyl analysis of the cellulose acetate by a modification of a standard method,[6] as yet unpublished, gave values of 39.73, 39.72, 39.79, 39.60%, corresponding to an average substitution of 2.44. The substitution value of 2.33 formerly accepted as correct for du Pont sample II was accordingly too low.[7] All samples were dried before use or before analysis over phosphorus pentoxide *in vacuo* at 65°.

High grade pyridine was dried over barium oxide and redistilled shortly before use. Commercial *p*-toluenesulfonyl chloride was purified by washing the benzene solution with cold water, drying and decolorizing with carbon. After recovery, the acid chloride was recrystallized from ether–petroleum ether until the colorless product melted at 69°.

The acetonylacetone was freshly distilled under diminished pressure and the sodium iodide was a carefully dried C. P. specimen.

Rate of Tosylation.—The experiment was carried out as formerly[4] but on a four-fold scale. The mixture of 80 g. of the cellulose acetate (1 mole hydroxyl) and 424 g. of tosyl chloride (13.1 moles), dissolved in a total of 1420 ml. of pyridine, was contained in a large, glass stoppered bottle kept in the dark at 20 ± 0.5°. Discoloration of the solution set in very slowly. From time to time a 30 to 50 ml. sample was withdrawn in a glass dipper and the tosylated product was isolated and prepared for analysis as previously described.[4] The first samples were colorless and fibrous but those withdrawn after one week, when replacement of tosyl by chlorine began to be apparent (Notes *e*, *f*, *g*, Table I) had a little color and gave light brown solutions in acetone.

Sulfur analyses were conveniently carried out on the semi-micro scale by a recently published method.[8] Acetyl was determined by the modified technique, in which the carefully shredded sample was heated in alcoholic sodium methylate before the mixture was acidified with excess *p*-toluenesulfonic acid and acetyl was recovered in the form of methyl acetate by distillation. The analyses in Table I, columns 3 and 4, are the mean of closely concordant duplicates and obvious simultaneous equations made it possible to calculate the moles of acetyl present at each stage of the tosylation. The data (column 5) show that the acetyl substitution did not change during the first five days from the original value of 2.44 and the reliability and accuracy of the analytical methods were thereby confirmed. After seven days, when the presence of combined chlorine rendered the acetyl values high, an acetyl content of 2.44 was assumed and the total substitution was calculated from the sulfur and halogen values (Table I, notes *f* and *g*). The last sample isolated (eighty days) was a light brown fibrous material that was soluble in pyridine, acetonylacetone and acetone. Tests for nitrogen were negative. The assumption that this sample had the usual acetyl substitution of 2.44 was justified because on this basis the 1.65% of chlorine and 3.89% of sulfur gave a combined acetyl, chloro and tosyl substitution of 2.99 where theory was 3.00. A Staudinger viscosity determination made with this sample dissolved in glacial acetic acid at 25 ± 0.1°, gave an η_{sp}/c value of 54.8. This value checked very well with those of 53.3 and 52.5 previously found for a 6-chlorotosyl acetate and for the original cellulose acetate II.[4,9] The absence of degradation during prolonged tosylation and the consistency of the acetyl analyses justified the calculation of the molar tosyl substitution (column 6) from the observed sulfur content (column 4) and the average acetyl substitution of 2.44 (column 5).

(1) Presented before the Division of Cellulose Chemistry at the Memphis Meeting of the American Chemical Society, April, 1942.

(2) du Pont Cellulose Research Fellow, 1941–1942.

(3) Oldham and Rutherford, THIS JOURNAL, **54**, 366 (1932).

(4) Cramer and Purves, *ibid.*, **61**, 3458 (1939).

(5) Mahoney and Purves, *ibid.*, **64**, 9 (1942).

(6) Freudenberg and Harder, *Ann.*, **433**, 230 (1923).

(7) We are indebted to Doctors J. W. Hill and F. Schulze, of the du Pont Company, for the gift of this acetate. The quoted acetyl content was 39.3%. Cramer and Purves[4] found 38.6%.

(8) Mahoney and Michell, *Ind. Eng. Chem., Anal. Ed.*, **14**, 97 (1942).

(9) Cramer and Purves' η_{sp}/c values[4] become 54.0 and 53.3 when based on an acetyl substitution of 2.44 instead of 2.33.

TABLE I

ANALYTICAL DATA OF TOSYLATION AND IODINATION REACTIONS

	Tosylation					Iodination					
Sample (1)	Tosylated, hours (2)	Acetyl, % (3)	Sulfur, % (4)	Acetyl,[a] moles (5)	Tosyl,[a] moles (6)	Iodine, % (7)	Sulfur, % (8)	Calcd.[b] S, % (9)	Iodine, moles (10)	Tosyl, moles (Z_S) (11)	Calcd. tosyl[c] moles ($Z_A + Z_B$) (12)
1	0.25	37.85	0.92	2.443	0.079	3.76	0.10	0.00	0.081		0.007
2	0.50	36.52	1.66	2.441	.149	5.98	.28	.20	.133	0.016	.015
3	0.75	35.78	2.02	2.437	.185	6.94	.42	.31	.157	.028	.021
4	1.00	35.43	2.26	2.448	.210	7.60	.55	.45	.170	.040	.029
5	2.00	34.43	2.69	2.428	.255	8.51	.65	.61	.198	.057	.052
6	3.00	34.05	2.94	2.439	.290					.092[d]	.071
7	4.00	33.97	3.01	2.445	.291	8.42	1.08	.95	.200	.093	.088
8	5.00	33.92	3.09	2.457	.301					.103[d]	.100
9	6.00	33.76	3.17	2.449	.310					.112[d]	.112
10	7.00	33.73	3.22	2.464	.316					.118[d]	.122
11	8.00	33.66	3.27	2.468	.322	8.05	1.25	1.33	.194	.124[d]	.129
12	9.00	33.57	3.38	2.483	.336					.138[d]	.136
13	10.00	33.38	3.42	2.469	.338					.140[d]	.143
14	11.00	33.07	3.49	2.443	.347					.149[d]	.149
15	12.00	32.73	3.65	2.444	.366					.168[d]	.153
	Days										
16	0.71	32.48	3.72	2.428	.374	7.98	1.73	1.81	.196	.176[d]	.174
17	1.11	32.23	3.84	2.427	.389					.191[d]	.192
18	1.57	31.97	3.97	2.425	.405					.207[d]	.210
19	2.08	31.56	4.17	2.422	.430	7.95	2.39	2.38	.203	.232[d]	.228
20	2.58	31.52	4.26	2.453	.444					.246[d]	.243
21	3.08	31.33	4.33	2.432	.451					.253[d]	.257
22	5.16	30.90	4.59	2.440	.487					.289[d]	.299
23	7.08	30.95[e]	[4.60]	2.448	.489					.291[d]	.322
24	9.12	31.60[e]	[4.51]	2.493	.471					....	...
25	11.12		[4.42]		....					.323[d]	.361
26[f]	21.12		4.17		.521[f]					.355[d]	.362
27[g]	80.12		3.89		.553[g]						

[a] Calcd. from columns (3) and (4) by means of simultaneous equations. [b] Calcd. from % iodine and acetyl substitution of 2.44. [c] Calcd. by $(0.56 - 0.198) = Z_S = Z_A + Z_B$; $\log 0.139/(0.139 - Z_A) = 2.16t$; $\log 0.223/(0.223 - Z_B) = 0.106t$. [d] Column 11 was obtained by subtracting a constant iodine substitution of 0.198 (average value) from column 6. [e] Replacement of tosyl by chlorine gives high acetyl values. [f] % Cl = 0.93, giving 0.434 mole of tosyl and 0.087 mole of chlorine, and if acetyl is 2.44; total = 2.961 moles. [g] % Cl = 1.65, giving 0.400 mole of tosyl, and 0.153 mole of chlorine, and if acetyl is 2.44 moles; total = 2.993 moles.

Chlorine in later tosylated acetates was determined by heating 20–30 mg. samples under reflux for two hours with 100 ml. of 95% ethanol containing 2 g. of chloride-free sodium hydroxide (made from metallic sodium). Nitrite-free, 6 *N* nitric acid was used to acidify the mixture before the halogen was estimated by the Volhard method[10] with nitrobenzene to coagulate the silver chloride.

Iodination.—The dry, tosylated sample, 1 g., sodium iodide, 2 g., and acetonylacetone, 75 ml., were heated together to 120°, when solution was complete in all cases. After two hours at that temperature, which was again shown to be sufficient[4,5] for maximum iodination, the solution was cooled, poured into 1 liter of ice water, allowed to stand for one hour and filtered. The residue was washed with distilled water, dried and purified by reprecipitation from aqueous acetone. A final drying at 65° *in vacuo* over phosphorus pentoxide preceded the analyses for sulfur and for iodine. Iodine analyses were carried out as described in the work on ethylcellulose.[5]

The assumption that iodination replaced a portion of the tosyl groups by iodine without altering the original acetyl substitution was checked by calculating the per cent. of sulfur in the iodinated specimens from the observed iodine content (Table I, column 7) and an assumed acetyl substitution of 2.44. Calculated sulfur values (column 9) agreed well with the observed ones (column 8) except with the first four samples, in which the sulfur content was too small to be estimated accurately. The corresponding data for the molar substitution of iodine (column 10) were therefore accepted as reliable. All attempts to iodinate later specimens containing chlorine gave dark colored products which were not amenable to purification and were not further examined.

(10) Kolthoff and Sandell, "Textbook of Quantitative Inorganic Analysis," The Macmillan Company, New York, N. Y., 1938, p. 543

Results

The molar amount of tosyl groups replaced by iodine (Z) corresponded to the primary hydroxyl groups that had been esterified at any given time. Reference to Table I, column 10, shows that a total of 0.198 mole of hydroxyl was originally present in the sixth position of the cellulose acetate and that all were tosylated within two hours. The total agreed excellently with the earlier value of 0.197 mole,[4] and, as the cellulose acetate averaged 0.56 mole per glucose unit, about 35% of the hydroxyl groups were primary. The earlier work showed that the amount lay between one-third and one-half. Substitution in the first order rate

equation, $\log 0.198/(0.198 - Z) = kt$, of the data in columns 2 and 10 gave values for k of (21.4), 23.2, 21.9 and 25.0 corresponding to (0.25), 0.50, 0.75 and 1.00 hour, respectively. The average rate constant for the last three samples was 23.4 when reckoned in days and decimal logarithms. Calculation by the method of least squares, using the same time intervals, gave 24.9 when most weight was given to the hour interval. No advantage was gained by assuming a second order rather than a first order equation for the tosylation.

Subtraction of 0.198 from 0.56 gave 0.362 as the total moles of hydroxyl group in the second and third positions of the cellulose acetate. Subtraction of the data in column 10 from those in column 6 gave the amount of tosylation, Z_S, in both of these secondary positions at various times. Points corresponding to the function $\log 0.362/(0.362 - Z_S)$ were plotted against time t (in days) and those within the limits 0.71 to 3.08 days inclusive were found to lie about a straight line whose position was determined by the method of least squares[5] (Fig. 1). The conclusion was that the amount of tosylation, Z_B, of 0.223 mole of the secondary hydroxyl groups at any time was given by the equation

$$\log 0.223/(0.223 - Z_B) = 0.106\, t \qquad (1)$$

The remaining 0.139 mole was esterified at a faster rate. If Z_A represented the amount of this more rapid tosylation at any time, $Z_A + Z_B = Z_S$. By the use of Eq. 1, the amount of Z_B was calculated for times between 0.125 and 0.5 days and was subtracted from Z_S (column 11). The values of Z_A so obtained were found to fit the following first order rate equation

$$\log 0.139(0.139 - Z_A) = 2.16\, t \qquad (2)$$

In order to check the data, the sums $Z_A + Z_B$, as calculated from Eqs. 1 and 2, were tabulated in Table I, column 12. The agreement with the observed values of Z_S (column 11) was always within 0.02 mole, and usually within 0.01 mole, until the replacement of tosyl by chlorine became appreciable from sample 23 onward. It is interesting to note that no such replacement complicated the equally prolonged tosylation of the ethylcellulose.[5]

Discussion

The above work was an experimental duplicate of that on the ethylcellulose, when it was demonstrated that hydroxyl groups in the sixth, second and third positions of the anhydroglucose units were tosylated at rates in the approximate ratio of 15:2.3:0.07. Rates for acetone-soluble cellulose acetate were 23.4 for the sixth position with 2.16 and 0.106 for the two kinds of hydroxyl groups occupying the other two positions. Comparison with ethylcellulose values justified the conclusion that the faster rate (2.16) was characteristic of the second position in the acetyl cellulose and the slower one (0.106) pertained to the third. There was no reason to expect that the rates for ethylcellulose and acetyl cellulose would be absolutely the same in magnitude, because steric and other effects caused by the different substituents would not necessarily be the same in the two cases. These effects, however, could hardly be large enough to obliterate or reverse a ratio of rates, one of which was twenty or thirty times the other. It therefore appeared that the deacetylation of cellulose triacetate to the acetone-soluble condition removed 0.223 mole of acetyl from the third position and only 0.139 mole from the second, which was more than twenty times as reactive in tosylation. While it is possible that the reactivities displayed toward acetylation and deacetylation may be reversed, it seems probable that the original "triacetate" contained a few unacetylated hydroxyl groups in the sluggishly reacting position three. Further experiments are required to decide between the alternative explanations.

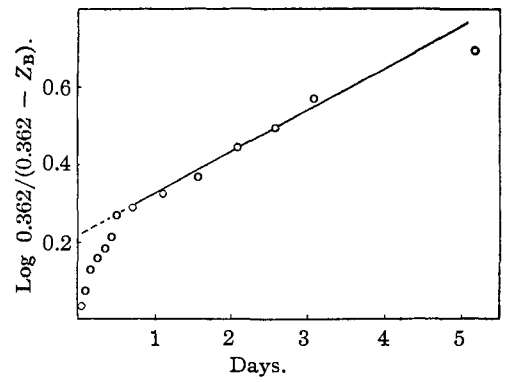

Fig. 1.—Logarithmic plot of rate of tosylation of 0.362 mole of secondary hydroxyl group. Solid line is calculated relationship $\log 0.223/(0.223 - Z_B) = 0.106$ day.

If secondary hydroxyl groups in the acetone-soluble cellulose acetate were distributed in random order but with uniform average density along the length of the macromolecules, the probability of a particular glucose residue containing a completely unsubstituted 2,3 glycol group was 0.139 ×

0.223 or 0.031.[11] If the hydroxyl groups occurred in sharply localized patches along the macromolecule, the probability of a glycol grouping was obviously 0.139 and if deacetylation in one position tended to preclude deacetylation in the other, the probability was 0.139 + 0.223 − 1 or zero.[5]

The oxidation of the cellulose acetate with lead tetraacetate was carried out as before[5] and the results (Table II) showed that 0.0071 to 0.0079, or almost zero, moles of glycol were actually present. This confirmation of the earlier low value of 0.0067 to 0.01 mole[11] supports the inference that the number of 2,3 glycol groups in acetone soluble cellulose acetate, as well as in the partly ethylated cellulose,[5] is depressed by factors still unknown. It also suggests that the partial deacetylation of the triacetate was carried out in a practically homogeneous system and that the loss of acetyl from one of the two secondary alcoholic positions had a marked tendency to stabilize the adjacent group in the same anhydroglucose residue.

TABLE II

OXIDATION OF 0.01 MOLE OF CELLULOSE ACETATE WITH EXCESS LEAD TETRAACETATE AT 20°

Hours (t)	0.01 N Thio., ml.	Moles $Pb(OAc)_4$ $\times 10^2$	$\Delta M/\Delta t$ (10^6y)	Moles glycol[a] (10^3x)
0	0			
24	0.81	0.41		
48	1.50	0.75		
72	2.07	1.04		
82.5	2.42	1.21		
102	2.65	1.33	6.2	7.9
120	2.76	1.38	(2.7)	7.4
168	3.22	1.61	4.7	7.1
192	3.45	1.73	5.0	7.1
		Average	5.3	7.4

[a] Per glucose residue. Calcd. as previously described.[5]

(11) Cramer, Hockett and Purves, THIS JOURNAL, 61, 3463 (1939).

Summary

1. A technical cellulose acetate, averaging 2.44 acetyl and 0.56 hydroxyl groups per glucose residue, was esterified by *p*-toluenesulfonyl chloride. Analyses of samples removed at intervals showed that 0.198 mole of hydroxyl groups was present in the sixth or primary positions of the original cellulose acetate.

2. The data in (1) give, by difference, a value of 0.362 mole of total secondary hydroxyl in the cellulose acetate and mathematical analyses of the rate of esterification showed that there was a first order, fairly rapid tosylation of 0.139 mole of hydroxyl, on which was superimposed a slow tosylation of 0.223 mole. The 0.139 mole was assigned to the second position and the 0.223 mole to the third by analogy with previous experience on an ethylated cellulose.

3. The first order rate constants for the tosylation of unsubstituted hydroxyl groups in the cellulose acetate were found to be in the ratio of 2.16 for the second, 0.106 for the third and 23.4 for the sixth position.

4. Lead tetraacetate oxidation of the cellulose acetate indicated that 7.4×10^{-3} mole of unsubstituted 2,3 glycol was present per glucose residue. The amount calculated for a random distribution of hydroxyl groups in the two positions was 3.1×10^{-2} mole and for localized concentrations of hydroxyl, 13.9×10^{-2} mole. If deacetylation in either the second or third position of cellulose triacetate stabilized the adjacent acetyl group, the probability of 2,3 glycol groups in the resulting acetone-soluble acetate was zero.

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