Carbohydrate Research, 240 (1993) 245–252
Elsevier Science Publishers B.V., Amsterdam

Studies on the regioselectivity of cellulose sulfation in an N_2O_4–*N*,*N*-dimethylformamide–cellulose system

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(Received April 21st 1992; accepted in revised form August 26th, 1992)

ABSTRACT

Starting from a cellulose trinitrite solution prepared by dissolving the polymer in a N_2O_4–Me_2NCHO mixture, cellulose sulfation was investigated with different sulfating agents under homogeneous reaction conditions. At room temperature the degree of substitution (ds) increased in the order $H_2SO_4 \ll H_2NSO_3H \sim NOSO_4H < SO_2 < ClSO_3H < SO_3 < SO_2Cl_2$. Generally, the nitrite group in the 6-position was the preferential reaction site at +20°C. With SO_2Cl_2 the highest ds values are reached, and considerable sulfation in the 2-, and to some extent in the 3-position, was found by ^{13}C NMR spectroscopy after decomposition of the residual nitrite groups. At −20°C the secondary nitrite groups in the 2-position were definitely the preferred reaction site for sulfation of the cellulose trinitrite with SO_3. The results are discussed in relation to stability and availability of the nitrite groups.

INTRODUCTION

The problem of regioselectivity of substitution within the anhydroglucopyranose unit (AGU) is of actual interest in connection with cellulose derivatization under homogeneous conditions in nonaqueous solvents for cellulose that have been discovered during the past few decades[1–3]. In particular, the N_2O_4–Me_2NCHO system has been employed in recent years by us and other groups for a subsequent homogeneous conversion of cellulose to various esters of inorganic and organic acids (compare ref. 1) with the studies of our group being centered on sulfation[4,5] and phosphatation[6,7].

In comparing results of sulfation in the N_2O_4–Me_2NCHO–cellulose system, for example, those published in refs. 8–10, it is evident that the site of substitution within the AGU depends on the sulfating agent, as well as on the conditions of the reaction. Quite recently, we confirmed the existence of a cellulose trinitrite in the homogeneous systems cellulose–N_2O_4–Me_2NCHO and cellulose–N_2O_4–Me_2SO

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having an excess of N_2O_4 and a water content $\leqslant 0.02\%$, and we compared the stability of the nitrite ester groups in the different positions vs. temperature and content of protic additives[11]. The present study summarizes the experimental results from studies on the effect of sulfating agent and temperature on the ds and the distribution of sulfate half-ester groups introduced by reaction with a cellulose trinitrite in Me_2NCHO. Furthermore, these experimental results are correlated with the stability of the nitrite groups in different positions of the AGU.

EXPERIMENTAL

Preparation of cellulose trinitrite solution.—The starting material was a commercial cellulose powder with a dp_{Cuoxam} of 160 (Heweten 10HZ®, Zellstoff und Papierfabrik Weißenborn, Weißenborn, Sachsen). The air-dried powder was further dried for 15 h at 105°C and swollen overnight in dry Me_2NCHO (water content $\leqslant 0.02\%$). Then one-third of the liquid phase was distilled off in vacuo, and the cellulose was dissolved by adding 3.5 mol N_2O_4 per mol AGU, with stirring for 2 h at room temperature. The N_2O_4 was added as a 10% solution in dry Me_2NCHO. Usually cellulose samples of 10 g were employed and dissolved to a final volume of ~ 300 mL (compare ref. 11).

Homogeneous sulfation and isolation of the cellulose sulfates.—To 300 mL of the cellulose trinitrite solution, with a polymer content of about 3%, the sulfating agent (1–3 mol per mol AGU) was added as a 10% solution in dry Me_2NCHO. The reaction was then carried out for the time period and at the temperature given in Tables I and II. For the elimination of residual nitrite ester groups and precipitation of the H^+-cellulose sulfate, the reaction mixture was poured into acetone (water content $\sim 1\%$). The precipitate was washed free of acid components with acetone containing 30% EtOH and then neutralized with 4% NaOH in EtOH to obtain the Na cellulose sulfate, which was further purified by washing with EtOH. The product was then dried in vacuo at 50°C.

A somewhat different technique of precipitation and purification of cellulose sulfate was developed in our studies on the influence of temperature of sulfation. The reaction mixture was poured into ice-cold aq Na_2CO_3, precipitated with acetone, washed with MeOH containing 30% water to remove inorganic salts, washed with MeOH, and dried in vacuo at 50°C.

Characterization of the Na cellulose sulfates.—The ^{13}C NMR spectra were recorded on Bruker MSL 400 and AM 300 spectrometers, at frequencies of 100.63 and 75.47 MHz, respectively. Accumulations were between 100 and 500 scans; Me_4Si was the internal standard.

The total ds of the sulfate half-ester groups was calculated from the sulfur content determined on an elemental analysis apparatus (Carlo Erba). Partial degrees of substitution in the different positions of the AGU were obtained from the ^{13}C NMR spectra of the samples of Na cellulose sulfate dissolved in D_2O by integration of the signal areas, and comparing the signal integrals of the "sub-

TABLE I

Influence of sulfating agent on the distribution of sulfate ester groups

Sulfating agent	Mol per mol AGU	Temperature (°C)	Time of reaction (h)	ds	ds [a]	Distribution of sulfate ester groups at position			
						C-2	C-3	C-6	% C-2
SO_3	1	20	3	0.56	0.55	0.12		0.43	21.8
	2	20	3	1.06	0.92	0.26		0.66	28.3
SO_2	1.5	30	3	0.40	0.36			0.36	0
	2	30	3	0.60	0.58	0.19		0.39	32.8
	3	30	3	0.93	0.94	0.26		0.68	27.7
$NOSO_4H$	2	20	4	0.30	0.35	0.04		0.31	11.4
SO_2Cl_2	1	20	2	0.55	0.53	0.16		0.37	30.2
	2	20	2	1.02	1.00	0.30		0.70	30.0
	3	20	2	1.56	1.91	0.69	0.22	1.0	36.1
$ClSO_3H$	2	20	2	0.71	0.87	0.31		0.56	35.6
H_2NSO_3H	2	20	3	0.40	0.40	0.10		0.30	25.0
H_2SO_4	3	20	3	<0.1					

[a] Determined by NMR spectroscopy. See Experimental for details.

stituted" and "non-substituted" C-atoms. It must be emphasized that the proton decoupling (nuclear Overhauser effect) influences the signal intensity of each of the various C-atoms of the AGU to a different degree; therefore, only a comparison of the signal integral at one and the same C-atom in the "substituted" and "non-substituted" state is valid. Signal integrals of different C-atoms should not be compared for quantitative evaluation of spectra recorded with normal decoupling routines. Further details of our procedure for determining partial ds values are given in refs. 11 and 12.

RESULTS

Influence of sulfating agent on substituent distribution.—Our results on sulfation of cellulose trinitrite in Me_2NCHO with different agents are summarized in Table I. Most notably, there is good agreement between total ds determined by elemental analysis and the sum of the partial ds obtained via ^{13}C NMR spectroscopy.

Under comparable conditions of reaction, the total ds increases, as expected, with the amount of sulfating agent per AGU, but the ds is also shown to depend on the structure of the sulfating agent according to the order of reactivity $H_2SO_4 \ll H_2NSO_3H \sim NOSO_4H < SO_2 < ClSO_3H < SO_3 < SO_2Cl_2$. Note that the total ds obtained with SO_2Cl_2 exceeds all the other values, which remain below 1.2 (compare refs. 9 and 13).

Regarding the distribution of the sulfate half-ester groups within the AGU, the 6-position is generally preferred in the range of temperature (20–30°C) used in these experiments. A sulfation in the 3-position was found only with SO_2Cl_2 at a higher amount of sulfating agent per AGU.

Noteworthy is the sulfation with H_2NSO_3H. This agent does not react to a detectable ds with free cellulosic OH groups at room temperature, as demonstrated by our experiments with partially substituted cellulose acetates dissolved in Me_2NCHO (compare ref. 14). Cellulose trinitrite in Me_2NCHO, on the other hand, is obviously able to react with aminosulfonic acid according to

$$\text{Cell-O-NO} + H_2NSO_3H \rightarrow \text{Cell-O-SO}_3H + N_2 + H_2O$$

But sulfation to a high ds is obviously impeded by the water formed, which decomposes nitrite ester groups, resulting in the regeneration of OH groups, which are not sulfated by H_2NSO_3H under the conditions employed. Thus two counteracting effects have to be considered: (*i*) a probably very fast sulfation by reaction between the NO- and the NH_2-group, and (*ii*) an inhibition of this reaction by destruction of the reactive sites.

These considerations are in agreement with experimental observations and results, i.e., (*i*) the color change from yellow (water-free system) via greenish-blue to nearly colorless, accompanied by gas evolution upon addition of the aminosulfonic acid; (*ii*) the rather moderate ds of sulfate groups in comparison to the action of, for example, $ClSO_3H$.

Fig. 1 shows the data for some cellulose sulfates obtained with additional components in the sulfation process. As already mentioned[10], an addition of 27 mol of H_2O per mol AGU to a reaction mixture of cellulose, N_2O_4 and SO_3 in Me_2NCHO subsequent to the main reaction leads to a considerable post-sulfation,

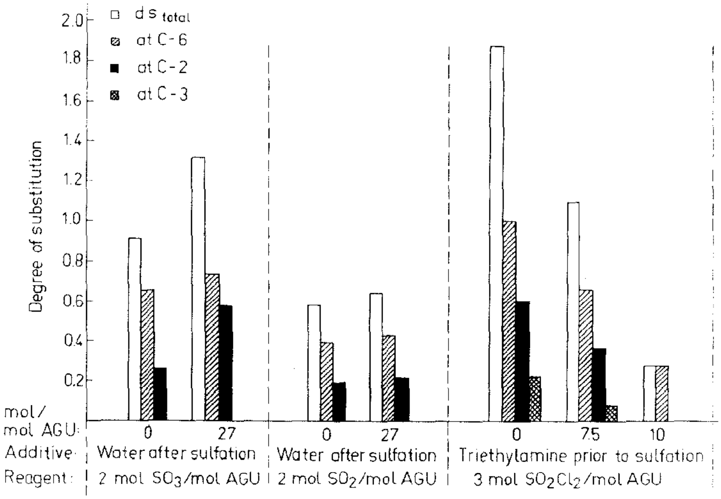

Fig. 1. Distribution of sulfate half-ester groups in the AGU vs. additives to the homogeneous reaction system.

TABLE II

Effect of temperature of sulfation with SO_3 on distribution of substituents

Mol SO_3 per mol AGU	Temperature (°C)	Time of reaction (h)	ds	ds [a]	Distribution of sulfate ester groups at position			
					C-2	C-3	C-6	% C-2
1	20	3	0.56	0.55	0.12		0.43	21.8
2	−20	1.5	0.65	0.55	0.45		0.10	81.8
2	20	3	1.06	0.92	0.26		0.66	28.3
4	−20	3	1.06	0.99	0.56	0.16	0.27	56.6
2	0	3	1.39	1.29	0.73		0.56	56.6
4	−20/+20	3/1.5	1.61	1.50	0.73		0.77	48.7

[a] Determined by NMR spectroscopy. See Experimental for details.

especially at the 2-position, while practically no post-sulfation occurs under similar conditions with SO_2 as the sulfating agent. As can be seen in Table I, no significant sulfation is achieved by sulfuric acid in the system considered here, a fact that largely rules out a post-sulfation by H_2SO_4 formed by hydrolysis of SO_3. A post-sulfation in the presence of water by the hydrolytically rather stable $SO_3 \cdot Me_2NCHO$ complex at the sites of nitrite groups just at the stage of decomposition by water seems to be more probable. On the other hand, addition of triethylamine to the cellulose trinitrite solution prior to the reaction with the very active sulfation agent SO_2Cl_2 leads to a partial inactivation of the agent, which becomes complete at a mol ratio of 4 mol of triethylamine per 1 mol SO_2Cl_2. The relative amount of substitution at the 2-position decreases here with the decreasing total ds.

Influence of temperature of reaction on sulfation of cellulose trinitrite with SO_3.—Table II gives a comparison of three sets of samples of the cellulose sulfate, one pair of samples each having the same level of total ds, but obtained with variation of the temperature of reaction. At a total ds ~ 0.6 or ~ 1, respectively, a lowering of the reaction temperature from 20 to −20°C definitely results in a preferential transesterification of nitrite groups in the 2-position. At a higher mol ratio of 4 mol SO_3 per mol AGU, a small number of half-ester groups in the 3-position was found, in contrast to sulfation at 20°C. An increase of the reaction temperature from −20 to 20°C during sulfation leads to a higher value of total ds by a strong increase of substitution in the 6-position and a small increase in substitution at the 2-position. At 0°C we found the highest ds with 2 mol SO_3 per mol AGU, along with a moderate preference for sulfation at the 2-position.

DISCUSSION

Before an attempt is made to correlate the distribution of the sulfate half-ester groups with the stability of the nitrite groups previously occupying the reaction sites, some remarks on the course of the sulfation and on the reaction components

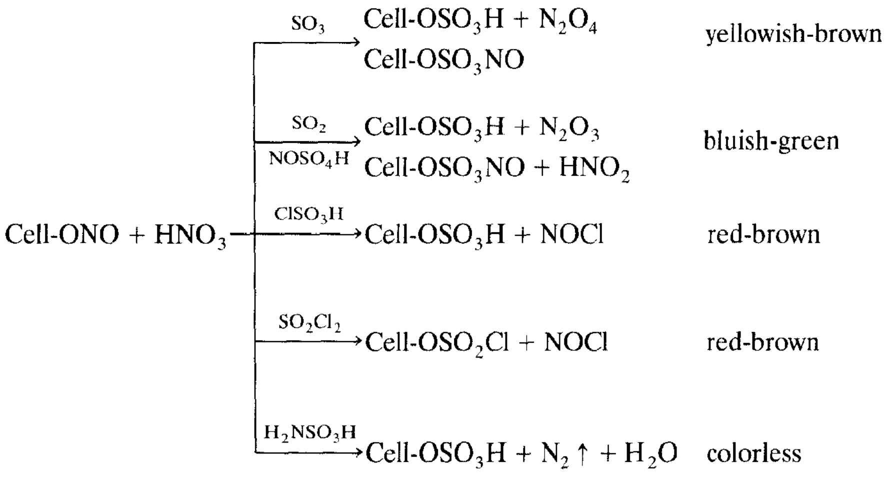

Fig. 2. Scheme of possible reactions in the system cellulose–N_2O_4–Me_2NCHO on addition of different sulfating agents.

involved are justified: (*i*) The acidic reaction mixture is already rather complex prior to sulfation, containing besides cellulose trinitrite and Me_2NCHO, an excess of N_2O_4 and nitric acid. (*ii*) The formulae given in Table I for the sulfating agents are a simplification, as the sulfating agents are complexed by Me_2NCHO. (*iii*) Sulfation can proceed either via transesterification eliminating nitrite ester groups, such as, N_2O_4, N_2O_3, HNO_2, NOCl, or N_2 (compare Fig. 2) or via a direct sulfation of cellulosic OH groups formed by a previous decomposition of nitrite ester groups, for example, by the action of water.

Sulfur dioxide (SO_2) may be oxidized to $NOSO_4H$ by an excess of nitric acid formed by reaction of cellulose with N_2O_4 to give cellulose trinitrite, or it can be oxidized by a larger excess of N_2O_4 to SO_3. As already mentioned, the aminosulfonic acid can react, not only directly with nitrite ester groups of cellulose, but also with free N_2O_4 forming elemental N_2, water, sulfuric acid, and nitric acid.

Sulfation with SO_2Cl_2 may possibly proceed via an ionic dissociation of the acid chloride that is facilitated by formation of an ionic complex $[SO_2Cl \cdot Me_2NCHO]^+Cl^-$, analogous to $SOCl_2$[15], which then displaces an NO^+ cation and forms a chlorosulfate of cellulose that is subsequently hydrolyzed to cellulose sulfate in the process of isolating the reaction product. The NO^+ is probably converted to NOCl.

Considering the distribution of sulfate groups, we find in any case only a limited (as opposed to an absolute) selectivity. In the range of 20–30°C, the nitrite groups in the 6-position are obviously the preferred reaction site with all the sulfating agents studied here. We assume that, in spite of the stability for the nitrite groups in the order 6- $\gg$ 3- $>$ 2-position against the action of water (compare ref. 11), the reactivity in the primary 6-position for transesterification is high at room temperature due to good steric accessibility in reaction with voluminous sulfating agent · Me_2NCHO complexes. At a reaction temperature of −20°C, on the other hand, the stability of the nitrite groups in the 6-position is already too high for a rapid transesterification, and sulfation with SO_3–Me_2NCHO occurs predominantly at the still rather labile nitrite ester group in the 2-position. An alternative mechanism, assuming a trans-sulfation from the 2- to the 6-position on raising the temperature, is largely ruled out by the fact that, on increasing the temperature of sulfation from −20 to +20°C, the partial ds at the 2-position does not decrease, but it is shown to increase by a small, but significant, amount, while the degree of sulfation in the 6-position rises remarkably. In contrast to sulfation via transesterification taking place in a water-free cellulose trinitrite system, we must consider a direct esterification of free OH groups in the presence of even a small amount of water due to decomposition of nitrite ester groups. It seems plausible that, in this case, the most labile nitrite groups in the 2-position are decomposed first, before the $SO_3 \cdot Me_2NCHO$ complex is hydrolyzed to $H_2SO_4 \cdot Me_2NCHO$. The sulfation of free OH groups is a rather fast reaction, as shown by our results with partially substituted cellulose acetate in Me_2NCHO[14].

CONCLUSIONS

From our experiments it can be concluded that in a water-free system the sulfation of cellulose trinitrite occurs by transesterification, only, while in the presence of water, reactions with free OH groups also must be considered. In this case, and also in a water-free system at low temperature, the different stabilities of the specific nitrite groups obviously determine the regioselectivity of sulfation, while at room temperature in the absence of water, the high steric accessibility of the 6-nitrite groups predominates in determining the distribution of sulfate half-ester groups.

ACKNOWLEDGMENT

The financial support of this work by the Fonds der Chemischen Industrie of Germany is gratefully acknowledged.

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