accurate. The calculated NOE factor, η, from dipolar spectral densities and Eq. (11) agrees well with that measured from the spectrum.

From Eq. (19) we calculated the bond angle ∠HCH (105.1°) and the elements of diffusion tensor for CH_2Cl group in the molecule-fixed coordinates shown in Figure 5 by making use of the spectral densities listed in Table 2, assuming that the molecular frame is rigid. The bond angle ∠HCH was found to be somewhat less than the tetrahedral angle 109.5°, which is reasonable considering that the strong repulsions between electrons in the chlorine atom of CH_2Cl and in the dichlorophenyl group can narrow this angle. D_x was found to be several times larger than D_y, and D_z, which means the overall molecular shape and interactions are such that the rotation about the x-axis is more facile than those about the other two axes. The magnitude of these diffusion tensor components also confirms that the extreme narrowing condition is well valid for our case.

Acknowledgment. This research was supported by the SNU-Daewoo Research Fund during the fiscal year of 1993-1994.

References

1. Werbelow, L. G.; Grant, D. M. *J. Chem. Phys.* **1975**, *63*, 544.
2. Mayne, C. L.; Alderman, D. W.; Grant, D. M. *J. Chem. Phys.* **1975**, *63*, 2514.
3. Fuson, M. M.; Prestegard, J. H. *J. Am. Chem. Soc.* **1983**, *105*, 168.
4. Fuson, M. M.; Brown, M. S.; Grant, D. M.; Evance, G. T. *J. Chem. Soc.* **1985**, *107*, 6695.
5. Hu, S. B. *M. S. Thesis*, S. N. U. **1990** "A study of methyl carbon-13 spin-lattice relaxation in 2,6-dichlorotoluene."
6. Wang, C. H.; Grant, D. M. *J. Chem. Phys.* **1976**, *64*, 1522.
7. Mayne, C. L.; Grant, D. M.; Alderman, D. W. *J. Chem. Phys.* **1976**, *65*, 1684.
8. Werbelow, L. G.; Grant, D. M. *Adv. Magn. Reson.* **1977**, *9*, 189.
9. Chenon, M. T.; Bernassau, J. M.; Mayne, C. L.; Grant, D. M. *J. Phys. Chem.* **1982**, *86*, 2733.
10. Fang Liu; Horton, W. J.; Mayne, C. L.; Tian-xiang Xiang; Grant, D. M. *J. Am. Chem. Soc.* **1992**, *114*, 5281.
11. Grant, D. M.; Mayne, C. L.; Fang Liu; Tian-xiang Xiang, *Chem. Rev.* **1991**. *91*, 1591.
12. Vold, R. L.; Vold, R. R.; Canet, D. *J. Chem. Phys.* **1977**, *66*, 1202.
13. Kratchowill, A.; Vold, R. L.; Vold, R. R. *J. Chem. Phys.* **1979**, *71*, 1319.
14. Kratchowill, A.; Vold, R. L. *J. Magn. Reson.* **1980**, *40*, 197.
15. Vold, R. L.; Vold, R. R. *Prog. in NMR Spectrosc.* **1978**, *12*, 76.
16. Canet, D. *Prog. in NMR Spectrosc.* **1989**, *21*, 237.
17. Bain, A. D.; Lynden-Bell, R. M. *Mol. Phys.* **1975**, *33*, 325.
18. Bloch, F. *Phys. Rev.* **1956**, *102*, 104.
19. Wangsness, R. K.; Bloch, F. *Phys. Rev.* **1953**, *89*, 728.
20. Redfield, A. G. *Adv. Magn. Reson.* **1965**, *1*, 1.
21. Bloembergen, N.; Purcell, E. M.; Pound, R. V. *Phys. Rev.* **1948**, *73*, 1679.
22. Pyper, N. C. *Mol. Phys.* **1970**, *19*, 161; **1971**, *21*, 1.
23. Favro, L. D. *Phys. Rev.* **1960**, *119*, 53.
24. Solomon, I. *Phys. Rev.* **1955**, *99*, 559.

A Facile Synthesis of p-Nitrophenyl Glycosides

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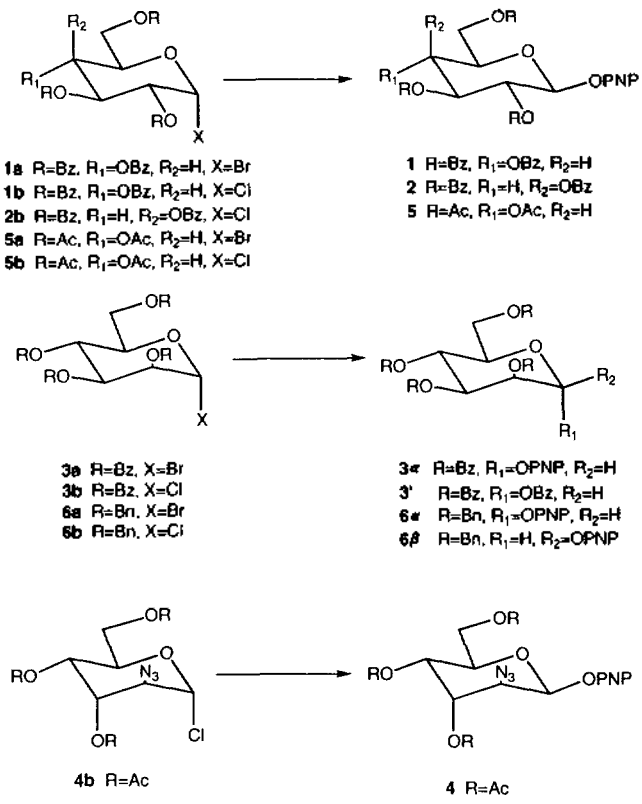
Received March 2, 1994

Glycosylation of benzoylated glycosyl halides of glucose, galactose and mannose with potassium p-nitrophenoxide and 18-crown-6 complex in chloroform resulted in the stereospecific formation of 1,2-trans p-nitrophenyl glycopyranosides in good yields. The same reaction with benzylated mannopyranosyl chloride gave the α-and β-p-nitrophenyl mannopyranosides in 3 : 1 ratio. However, acetylated 2-azido-altropyranosyl chloride gave β-p-nitrophenyl altropyranoside only.

Introduction

p-Nitrophenyl glycosides are widely used as chromogenic substrates in the study of glycosidase enzymes[1,2], and as linkage arms to couple oligosacchride epitopes to carrier proteins in producing immunogens[2-5]. In the latter, glycosidic p-nitrophenyl groups are converted, *via* an amino function, into a number of groups, such as isothiocyanate, diazo, and N-bromoacetate, capable of reacting with nucleophilic amino acid residues of a protein carrier[1-7]. Such a covalent attachment increases immunogenicity of carbohydrate epitopes. In addition, the coupling may be controlled for the specific synthesis of well-defined antigens, that may enable to elucidate mechanisms of antigen-antibody interaction.

However, conventional methods such as Helferich or Koenig-Knorr reaction have been reported to give p-nitrophenyl



Scheme Reactions with potassium p-nitrophenoxide/18-crown-6/ molecular sieve 4 Å in refluxing $CHCl_3$.

glycosides in poor yields[5,6,8-12]. Reaction of phenyl trimethylsilyl ethers with 1-O-trimethylsilyl peracetyl or perbenzyl glucopyranose in the presence of TMS-triflate has limitation of initial preparation of silyl ethers and control of stereochemistry[13]. Furthermore benzyl protecting groups tend to be vulnerable to TMS-triflate. Glycosidation of perbenzoylated or perbenzylated phenyl thioglycoside in the presence of thiophilic cations also showed no reaction with p-nitrophenol [14].

Use of 18-crown-6 has been found to facilitate modifications of carbohydrates in terms of good yields and mild reaction conditions[15]. This paper describes the reactions of potassium p-nitrophenoxide and 18-crown-6 complex with glycopyranosyl halides of glucose, galactose, mannose, and altrose, respectively. The condensation has been examined with varying substituents on C-2 with O-acetyl, O-benzoyl and O-benzyl groups, and also with different halides on C-1 (Scheme).

Results and Discussions

Perbenzoylated glycosyl α-halides of glucose **1a** and **1b**, galactose **2b**, mannose **3a** and **3b** were refluxed with potassium p-nitrophenoxide and 18-crown-6 in the presence of molecular sieves 4 Å in chloroform. 1,2-Trans p-nitrophenyl glycopyranoside tetrabenzoates **1**, **2**, and **3α** were obtained as the major product respectively (Table 1). It is noteworthy that the reaction with perbenzoylated mannopyranosyl halide, **3a** and **3b** produced 1,2,3,4,6-penta-O-benzoyl-α-D-mannopyranose(**3'**) as the side product, in 3 : 1 and 3 : 2 ratio respectively. ^{13}C-NMR spectrum of **3'** showed the peaks at δ 91.34, 71.16, 69.97, 69.40, 66.13, and 62.30 which are corresponding to the chemical shift values of the authentic **3'**. ^{1}H-NMR data of **3'** were also identical to the reported values[16]. Peaks of the anomeric proton at δ 6.6 as a doublet, H-4 at δ 6.3 as a triplet, and H-3 at δ 6.1 as a double doublets are characteristics of **3'**. The formation of 1,2,3,4,6-penta-O-benzoyl-β-D-glucopyranose as a side product has been reported in the phase-transfer catalyzed aryl glycosidation of perbenzoylated glucopyranosyl bromide **1a** by Loganathan and Trivedi[17]. The reaction of perbenzoylated glycosyl bromides, **1a** and **3a** proceeded in a half of the reaction times required for the corresponding chlorides, **1b** and **3b** (Table 1). In case of mannose, more reactive bromide **3a** was found to reduce the proportion of the side product α-pentabenzoate **3'** to 3 : 1, compared with 3 : 2 of perbenzoylated mannopyranosyl α-chloride (**3b**).

Table 1. Reaction with potassium p-nitrophenoxide/18-crown-6/ molecular sieves 4 Å in refluxing $CHCl_3$

Reactants	Time (h)	Products	Yield (%)
1a	21	**1**	89
1b	42	**1**	80
2b	35	**2**	89
3a	11	3α, 3'	75*
3b	26	3α, 3'	89**
4b	8	**4**	95
6b	15	6α, 6β	50***

*3α/3' = 3/1
**3α/3' = 3/2
***from 1-O-acetyl derivative, 6α/6β = 3/1

It has been reported that treatment of perbenzylated α-D-mannopyranosyl bromide **6a** with an excess of methanol gives methyl 2,3,4,6-tetra-O-benzyl-β-D-mannopyranoside, *i.e.*, S_N2 product[18]. However, the reaction of potassium p-nitrophenoxide and 18-crown-6 with perbenzylated α-D-mannopyranosyl chloride **6b** gave the benzylated p-nitrophenyl α-D-mannopyranoside **6α** as the major product and its β-anomer **6β** as the minor product. ^{13}C-NMR of the produced mixture showed two sets of peaks, *i.e.*, δ 96.6, 79.5, 75.1, 74.4, 73.2, 72.9, and 66.8 ppm for the α-mannopyranoside **6α** and δ 98.6, 82.0, 76.2, 73.5, 72.2, 69.2 for the β-anomer **6β** in 3 : 1 ratio. Although 2-O-benzyl group is nonparticipating on the reaction of the anomeric carbon, and the reaction condition is favourable for **6β** *via* S_N2 pathway, the result shows that the β-attack by potassium p-nitrophenoxide and 18-crown-6 complex is severely retarded probably due to its bulkiness and the repulsive electronic environment which is exerted by the axial 2-O-benzyl group of **6b**. The reaction appears to be governed by the relative thermodynamic stability of **6α** to **6β**. The mannopyranosyl chloride **6b** was prepared by the treatment of 1-O-acetyl-2,3,4,6-tetra-O-benzyl-α-D-mannopyranose with $TiCl_4$, which resulted in partial de-O-benzylation. The overall yield of p-nitrophenyl glycosidation of **6b** was 50% from the 1-O-acetyl derivative.

Recently, altroheptopyranose is reported to be a major constituent in the trisaccharide repeating units of the O-antigens of *Campylobacter jejuni* serotype O : 23 and O : 36[19]. This pro-

Table 2. Reactions with potassium p-nitrophenoxide/18-crown-6/Ag_2CO_3/molecular sieves 4Å in refluxing $CHCl_3$-CH_3NO_2

Reactants	Time (h)	Products	Yield (%)
5a	12	5	37
5b	54	5	82
1a	24	1	61
1b	41	1	52

mpted us to examine p-nitrophenyl glycosidation of D-altrose. Refluxing 3,4,6-tri-O-acetyl-2-azido-1-chloro-1,2-dideoxy-α-D-altropyranose (**4b**) with potassium p-nitrophenoxide and 18-crown-6 produced p-nitrophenyl 3,4,6-tri-O-acetyl-2-azido-2-deoxy-β-D-altropyranoside (**4**) as the sole product in 95% yield. Peaks of δ 96.92, 72.89, 67.03, 65.78, 62.81, and 58.92 in ^{13}C-NMR spectrum confirmed the formation of β-altropyranoside **4**. Nonparticipating 2-N_3 group, and the repulsive electronic environment for the α-side attack due to the axial 3-O-acetyl group appears to assist the exclusive formation of the β-altropyranoside **4**.

Silver salts such as carbonate, perchlorate, and triflate were reported to be effective catalysts for aryglycosidation[5,6,10-12]. CH_3NO_2 is also being used in mixture with toluene to enhance glycosidation[20]. Thus p-nitrophenyl glycosidation was studied using Ag_2CO_3 as a catalyst and $CHCl_3$-CH_3NO_2 as the solvent (Table 2). Reflux of acetobromoglucose (**5a**) with Ag_2CO_3 and potassium p-nitrophenoxide/18-crown-6 in $CHCl_3$-CH_3NO_2 yielded p-nitrophenyl 2,3,4,6-tetra-O-acetyl-β-D-glucopyranoside (**5**) in 37%, whereas acetochloroglucose (**5b**) produced the β-glucopyranoside **5** in 82% under the same reaction condition. Perbenzoylated α-1-bromoglucose **1a** was transformed to p-nitrophenyl 2,3,4,6-tetra-O-benzoyl-β-D-glucopyranoside (**1**) in 61%, contrasted with perbenzoylated α-1-chloroglucose **1b** giving **1** in 52%. Under the conditions that the formation of glycosyl oxonium ions can be facilitated, p-nitrophenyl glycosidation was most effective with acetochloroglucose (**5b**), but less effective with perbenzoylated glucopyranosyl bromide (**1a**). Combination of a poor leaving Cl^- and a better participating 2-O-acetyl group facilitated p-nitrophenyl glycosidation, while a better leaving Br^- showed a higher glycosidation turnover with a poorer participating 2-O-benzoyl group.

Phase-transfer catalyzed D-glucosylation of phenolic aglycons was reported on the synthesis of benzoylated aryl β-D-glucopyranosides from the reaction of **1a** in a CH_2Cl_2-aq. NaOH biphasic system employing cetyltrimethylammonium bromide as the phase transfer catalyst[17]. However their yields were less than 46%. Treatment of a peracetylated glycosyl bromide with Amberlyst A-26-p-nitrophenoxide was also reported to give the p-nitrophenyl β-D-glycoside, but had the limitation of low yields due to accompanying elimination, and of initial preparation of resin-bound phenoxides[6].

Our method, the reaction of benzoylated glycosyl chlorides with potassium p-nitrophenoxide and 18-crown-6 provides a convenient and mild route for the synthesis of 1,2-trans p-nitrophenyl glycopyranosides.

Experimental

^{1}H-NMR and ^{13}C-NMR spectra were recorded with a Varian VXR-200 spectrometer on solutions in $CDCl_3$ with tetramethylsilane as the internal standard. Melting points were determined with an Edmund Buhlen 7400 SPA-1 and uncorrected. Organic solvents were dried and purified before use. Solutions were usually evaporated *in vacuo*. at temperatures below 40℃. Thin layer chromatography (t.l.c.) was conducted on aluminum sheets, precoated with 0.2 mm layers of silica gel 60F-254 (E. Merck, Darmstadt, Germany). The tlc plates were visualized by sparying with 5% sulfuric acid in ethanol and heating at 150℃. Column chromatography was performed with silica gel 60 (E. Merck, Art 7734, 70-230 mesh). Potassium p-nitrophenoxide was prepared from potassium hydroxide (0.51 g) and p-nitrophenol (1.39 g) in acetone (20 m*l*) and dried in vacuum oven at 50℃ over phosphorus pentoxide.

General procedure for the preparation of p-nitrophenyl D-glycosides. α-Chlorides (**1b, 2b, 3b, 4b, 5b,** and **6b**) were obtained by treatment of the corresponding 1-O-acetates or 1-O-benzoates with $TiCl_4$ in $CHCl_3$ at room temperature[20]. α-Bromides (**1a, 3a,** and **5a**) were prepared by the reactions of each methyl glycosides with HBr in acetic acid[21]. Each halides showed characteristic α-anomeric proton signals, *i.e.*, small coupling values and downfield chemical shifts in their ^{1}H-NMR spectra. The chemical shift/coupling constant of the anomeric proton of α-chloride **1b, 2b, 3b, 4b, 5b,** and **6b** in $CDCl_3$ was 6.6/4, 6.7/3.5, 6.3/<1, 6.0/<1, 6.3/4, and 5.64/2 (ppm/Hz), respectively. The chemical shift/coupling constant of the anomeric proton of α-bromide **1a, 3a,** and **5a** in $CDCl_3$ corresponded to 6.9/4, 6.6/<1, and 6.6/4 (ppm/Hz).

Reaction condition I. to obtain p-nitrophenyl glycosides **1, 2, 3α, 4, 6α,** and **6β**. The named glycosyl halide (0.35 mmol) was dissolved in alcohol-free $CHCl_3$ (5 m*l*). Potassium p-nitrophenoxide (0.71 mmol), a catalytic amount of 18-crown-6 (0.071 mmol), and molecular sieves powder (4 Å, 120 mg) were added into the solution. The suspension was refluxed with stirring for the reaction time given on Table 1 (when tlc showed the reaction to be complete). The reaction mixture was cooled and filtered on a Celite bed. The filtrate was washed with dilute sodium hydrogen carbonate solution, successively with cold water several times to remove the excess of phenoxide, dried over anhydrous sodium sulfate, and evaporated to a syrup, which was subjected to silica gel column chromatography eluting with 5 : 2 hexane /ethyl acetate or 5 : 3 toluene/ethyl acetate to afford the desired product. In some cases the products were crystallized from methanol.

Reaction condition II to obtain p-nitrophenyl glycosides **1** and **5**. The named glycosyl halide (0.26 mmol) was dissolved in a mixture of alcohol-free $CHCl_3$-CH_3NO_2 (9 m*l*, 2 : 1, v/v). Potassium p-nitrophenoxide (0.54 mmol), Ag_2CO_3 (0.32 mmol), molecular sieves powder (4 Å, 100 mg) and a catalytic quantity of 18-crown-6 (0.054 mmol) were added into the solution. After stirring the reaction mixture at 90℃ in the darkness for the given hours on the Table 2, they were treated in the same manner as above mentioned procedure for the condition I.

p-Nitrophenyl 2,3,4,6-tetra-O-benzoyl-β-D-glucopyranoside (1). **1** (69 mg, 80%) was obtained from α-chloride

1b (75 mg, 0.1228 mmol) under the condition I; R_f 0.55 for **1b** and 0.37 for **1** (hexane : ethyl acetate, 5 : 2); crystallization from methanol, mp. 145-147℃; ^{13}C-NMR ($CDCl_3$): 98.34 (C-1)/ 72.96, 72.49, 71.48, and 69.36 (C-2, 3, 4, and 5)/ 62.91 (C-6)/ 160.96, 143.09, 125.56, 116.72 (p-$NO_2C_6H_4O$-); ^{1}H-NMR ($CDCl_3$) δ 8.10-7.07 (m, 24H, aromatic H, p-$NO_2C_6H_4O$-), 6.12-5.76 (m, 3H, H-2, 3, 4), 5.59 (d, 1H, $J_{1,2}$=7.6 Hz, H-1), 4.70-4.53 (m, 3H, H-5, 6_a, 6_b)

p-Nitrophenyl 2,3,4,6-tetra-O-benzoyl-β-D-galactopyranoside (2). **2** (238 mg, 89%) was obtained from **2b** (233 mg, 0.382 mmole) under the condition I; R_f 0.59 for **2b** and 0.41 for **2** (hexane : ethylacetate, 5 : 2); crystallization from methanol, mp. 178-179℃; ^{13}C-NMR ($CDCl_3$): 98.92 (C-1)/ 72.35, 71.49, 69.31, and 67.91 (C-2, 3, 4, and 5)/ 62.32 (C-6)/ 161.17, 143.18, 125.62, 116.84 (p-$NO_2C_6H_4O$-); ^{1}H-NMR ($CDCl_3$): δ 8.2-7.09 (m, 24H, aromatic H, p-$NO_2C_6H_4O$-), 6.21-6.12 (m, 2H, H-2.4), 5.83 (dd, 1H, $J_{2,3}$=10 Hz, $J_{3,4}$=3.4 Hz, H-3), 5.61 (d, 1H, $J_{1,2}$=8 Hz, H-1), 4.69 (m, 3H, H-5, 6_a, 6_b).

p-Nitrophenyl 2,3,4,6-tetra-O-benzoyl-α-D-mannopyranoside (3α) and 1,2,3,4,6-penta-O-benzoyl-α-D-mannopyranose (3'). α-Chloride **3b** (400 mg, 0.655 mmole) gave a mixture of p-nitrophenyl α-D-mannnopyranoside **3α** and α-manopyranosyl pentabenzoate **3'** (400 mg, 89%). ^{13}C-NMR spectroscopy showed the existence of **3α** and **3'** in a ratio of 3 : 2. In case of α-bromide **3a** α-mannoside **3α** and α-mannopyranosyl pentabenzoate **3'** were obtained in 3 : 1 ratio(pale yellow syrup, 75%) under the same reaction condition.; ^{13}C-NMR ($CDCl_3$) for **3α**: 95.73 (C-1)/ 70.23, 69.92, 69.66, and 66.62 (C-2,3,4, and 5)/ 62.65 (C-6)/ 160.1, 143.1, 125.8, 116.6 (p-$NO_2C_6H_4O$-); ^{1}H-NMR ($CDCl_3$): δ 8.26-7.21 (m, 24H, aomatic H, p-$NO_2C_6H_4O$-), 6.220-6.16 (m, 2H, H-1, 4), 5.96 (s, 2H, H-2, 3), 4.72-4.51(m, 3H, H-5, 6_a, 6_b); ^{13}C-NMR ($CDCl_3$) for **3'**: 91.34 (C-1)/ 71.16, 69.97, 69.40, and 66.13 (C-2, 3, 4, and 5)/ 62.30 (C-6).

p-Nitrophenyl 3,4,6-tri-O-acetyl-2-azido-2-deoxy-β-D-altropyranoside (4). **4** (158 mg, 95%) was obtained from **4b** (124 mg, 0.3533 mmole); R_f 0.66 for **4b** and 0.47 for **4** (toluene : ethylacetate, 5 : 3); syrup; ^{13}C-NMR ($CDCl_3$): 96.92 (C-1)/ 72.89, 67.03, 65.78, and 58.92 (C-2, 3, 4, and 5)/ 62.81 (C-6)/ 160.88, 143.1, 125.75, 116.44 (p-$NO_2C_6H_4O$-); ^{1}H-NMR ($CDCl_3$): δ8.21 and 7.18 (both d, 2H each, $J_{H,H}$=9.2 Hz, p-$NO_2C_6H_4O$-), 5.75 (d, 1H, $J_{1,2}$=2.2 Hz, H-1), 5.58 (dd, 1H, $J_{4,5}$=7.1 Hz, $J_{3,4}$=3.0 Hz, H-4), 5.29 (dd, 1H, $J_{2,3}$=6.9 Hz, $J_{3,4}$= 3.0 Hz, H-3), 4.31-4.2 (m, 3H, H-5, 6_a, 6_b), 4.06 (dd, 1H, $J_{2,3}$= 6.9 Hz, H-2), 2.16, 2.1, 2.0 (s, 3H each, CH_3CO_2-). Compound **4b** was prepared by acetolysis of methyl 2-azido-4,6-benzylidene-2-deoxy-α-D-altropyranoside[22], and subsequent chlorination with $TiCl_4$ at r.t. in dry $CHCl_3$-CH_3NO_2.

p-Nitrophenyl 2,3,4,6-tetra-O-benzyl-α (and β)-D-mannopyranoside (6α and 6β). **6α** and **6β** were obtained from 2,3,4,6-tetra-O-benzyl-1-chloro-1-deoxy-α-D-mannopyranose (**6b**) in 3 : 1 ratio on the basis of ^{13}C-NMR. **6b** was synthesized from the corresponding α-1-O-acetyl derivative by treatment with $TiCl_4$ in $CHCl_3$-CH_3NO_2 at 0℃ for 1h. The overall yield from the 1-O-acetyl compound to **6α** and **6β** was 50%.; ^{13}C-NMR ($CDCl_3$) for **6α**: 96.61 (C-1)/ 79.49, 75.08, 74.38, 74.29, 73.41, 73.24, 73.06, and 72.94 (C-2, 3, 4, 5, and -CH_2Ph)/66.71 (C-6)/ 160.93, 142.55, 125.72, and 116.37 (p-$NO_2C_6H_4O$-); ^{1}H-NMR ($CDCl_3$): δ 5.605 (d, 1H, $J_{1,2}$=1.9 Hz, H-1); ^{13}C-NMR ($CDCl_3$) for **6β**: 98.5 (C-1)/ 81.9, 76.2, 74.5, 74.2, 73.6, 73.4, and 72.6 (C-2, 3, 4, 5, and -CH_2Ph)/ 69.1 (C-6).

p-Nitrophenyl 2,3,4,6-tetra-O-acetyl-β-D-glucopyranoside (5). **5** (106 mg, 82%) was obtained from **5b** (100 mg). R_f 0.47 for **5** compared with R_f 0.59 for **5b** (hexane : ethyl acetate, 5 : 3); crystallization from toluene-petroleum ether, mp. 174-175℃ (Lit[23] 174-175℃); ^{13}C-NMR ($CDCl_3$): 97.98 (C-1)/ 72.35, 72.35, 70.88, and 67.79 (C-2, 3, 4, and 5)/ 61.76 (C-6)/ 161.08, 143.18, 125.68, 116.56 (p-$NO_2C_6H_4O$-); ^{1}H-NMR ($CDCl_3$): δ8.22 and 7.09 (both d, 2H each, $J_{H,H}$=9.2 Hz, p-$NO_2C_6H_4O$-), 5.36-5.13 (m, 4H, H-1, 2, 3, and 4), 4.35-4.26 (dd, 1H, H-6a), 4.22-4.15 (dd, 1H, H-6b), 4.0-3.93 (m, 1H, H-5), 2.08, 2.07, 2.06, 2.05 (s, 3H each, CH_3CO_2-).

Acknowledgement. This research was supported by Research Center for New Bio-Materials in Agriculture, Seoul National University-KOSEF.

References

1. Paulsen, H. *Selectivity- a Goal for Synthetic Efficiency*; Barrtmann W. Trost, Barry M., Ed.; Verlag Chemie; Germany, 1984; p 169.
2. Abbas, S. A.; Barlow, J. J.; Matta, K. L. *Carbohydr. Res.* **1981**, *89*, 37.
3. Ekborg, G.; Galudemans, C. P. J. *Carbohydr. Res.* **1984**, *129*, 287.
4. Ekborg, G.; Glaudemans, C. P. J. *Carbohydr. Res.* **1984**, *134*, 83.
5. Eschenfelder, V.; Brossmer, R. *Carbohydr. Res.* **1987**, *162*, 294.
6. Jain, R. K.; Abbas, S. A.; Matta, K. L. *Carbohydr. Res.* **1988**, *173*, 297.
7. Satomura, S.; Iwata, T.; Sakata, Y. *Carbohydr. Res.* **1988**, *176*, 107.
8. Trevelyan, W. E. *Carbohydr. Res.* **1966**, *2*, 418.
9. Apparu, M.; Blanc-Muesser, M.; Defaye, J.; Driguez, H. *Can. J. Chem.* **1981**, *59*, 314.
10. Dick, W. E. Jr. *Carbohydr. Res.* **1979**, *70*, 313.
11. Kohata, K.; Abbas, S. A.; Matta, K. L. *Carbohydr. Res.* **1984**, *132*, 345.
12. Ekborg, G.; Vranesic, B.; Bhattacharjee, A. K.; Kovac, P.; Glaudemans, C. P. J. Carbohydr. Res. **1985**, *142*, 203.
13. Tietze, Lutz-F.; Fischer, R.; Guder, Hans-J. *Tetrahedron Lett.* **1982**, *23*, 4661.
14. Garegg, P. J.; Henrichson, C.; Norberg, T. *Carbohydr. Res.* **1983**, *116*, 162.
15. Shin, Y. S.; Nam Shin, J. E. *Bull. Korean Chem. Soc.* **1993**, *14*, 188.
16. D'Accorso, N. B.; Thiel, I. M. E.; Schuuler, M. *Carbohydr. Res.* **1983**, *124*, 177.
17. Loganathan, D.; Trivedi, G. K. *Carbohydr. Res.* **1987**, *162*, 117.
18. Rena, S. S.; Barlow, J. P.; Matta, K. L. *Carbohydr. Res.* **1981**, *88*, C20.
19. Aspinall, G. O.; McDonald, A. G.; Pang, H. *Carbohydr. Res.* **1992**, *231*, 13.
20. Lemieux, R. U. *Methods in Carbohydrate Chem.*; Whistler, R. L.: Wolform, M. L. Ed.; Academic Press: New York, U. S. A., 1963; Vol. 2, p 223.
21. Fletcher, M. G. Jr., *Methods in Carbohydrate Chem.*; Whi-

stler, R. L.; Wolform, M. L. Ed.; Academic Press: New York, U. S. A., 1963: Vol. 2, p 228.
22. Faghih, R.; Escribano, F. C.; Castillon, S.; Garcia, J.; Lucas, G.; Olesker, A.; Thang, T. T. *J. Org. Chem.* **1986**, *51*, 4558.
23. Iversen, T.; Johansson, R. *Synthesis* **1979**, 823.

Electrocatalytic Reduction of Dioxygen at Glassy Carbon Electrodes with Irreversible Self-assembly of N-hexadecyl-N'-methyl Viologen

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Received March 8, 1994

The electroreduction of dioxygen at glassy carbon electrodes with irreversible self-assembly of N-hexadecyl-N'-methyl viologen ($C_{16}VC_1$) proceeds at potentials more positive than those where the reduction occurs at bare electrodes. The electrocatalyzed reduction takes place at potentials well ahead of those where the catalyst is reduced in the absence of dioxygen and the limiting currents observed at rotating disk electrodes did not deviate from the theoretical Levich line up to 6400 rpm, indicating that the electrocatalysis is extremely rapid. The rate constant for the heterogeneous reaction between $C_{16}V^+C_1$ immobilized on the electrode surface and O_2 in solution was estimated to be *ca.* 10^8 $M^{-1}s^{-1}$. The half-wave potential of dioxygen reduction was independent of solution pH.

Introduction

We describe here the results of electrocatalytic studies of dioxygen reduction at glassy carbon electrodes with irreversible self-assembly of N-hexadecyl-N'-methyl viologen ($C_{16}V^+C_1$). Because of the very high specific rates between viologen radical cations and dioxygen in homogeneous aqueous solutions,[1-3] several different forms of viologens immobilized on carbon electrode surfaces were employed to accelerate the electroreduction of dioxygen.[4-6] Anson used poly(xylylviologen) coatings on basal plane graphite electrodes to catalyze the electroreduction of dioxygen to hydrogen peroxide in order to make the most of the very high concentrations of redox catalyst sites at positions within the polymer where they could be cycled between oxidation states electrochemically.[4] However, the expected advantages inherent with polymeric coatings[7] were not apparent in the study, because the rate of the cross reaction between dioxygen and the viologen radical cations appeared to proceed more slowly within the polyelectrolyte films than in homogeneous solution and therefore only the outermost monolayer was concluded to participate in the electrocatalysis.[4] The intermolecular complexes of poly(xylylviologen)-polystyrene sulfonate and poly (xylylviologen)-Nafion on graphite electrodes were applied to study the effects of the metal-free organic electrocatalyst on dioxygen reduction by Oyama,[5] based on the facts that the polymer complexes were fixed on electrode surfaces more stably and that the polymer functional groups were well solvated[8]. Advantageously for electrocatalysis the coating films of poly(xylylviologen)-poly(sulfonates) had a high permeability of dioxygen but the reaction rates between the viologen radical cations and dioxygen were found to be lower than that with the case of poly(xylylviologen) only.[4,5]

Differently from these previous studies with polymeric forms of viologens, we began to investigate the electroreduction of dioxygen by irreversible self-assembly of viologens at carbon electrodes.[6] Bard was the first to report that $C_{16}VC_1$ formed a monomolecular self-assembly on glassy carbon surfaces in the concentration range of 1-20 μM in the aqueous solution of 50 mM NaCl.[9] We thought that the monomolecular self-assembly of $C_{16}VC_1$ could serve as a better electrocatalytic model system to closely examine the dynamics of the electroreduction of dioxygen by viologen moieties at electrode surfaces, because small variations in electroactive species at monolayer level can be differentiated more effectively through the changes in electrochemical signal than those at polymeric forms and because the electrochemical theory with monolayer catalyst is much simpler to rationalize electrode reactions than the corresponding one with polymer coatings on electrode surfaces.[10] The present results show that the rate of dioxygen reduction by irreversibly adsorbed viologen radical on carbon surfaces is higher than those reported earlier[4-6].

Experimental Section

The $C_{16}V^{2+}C_1$ was prepared by a literature procedure.[9,11,12] Other chemicals were of the best quality available from Aldrich Chemical Company. Solutions were prepared from laboratory deionized water that was passed through a Millipore purification system. Solutions were buffered with hydrochloric acid (pH 1-2), phthalate (pH 3-4), acetate (pH 4-5), phosphate (pH 6-8), carbonate (pH 9-11) and sodium hydroxide (pH 12-14), and contained 0.1 M NaCl. All experiments were performed in the electrochemical cell thermostated at 23(± 2)℃. UV/Vis spectra were obtained by using Shimadzu UV-2100. Cyclic and