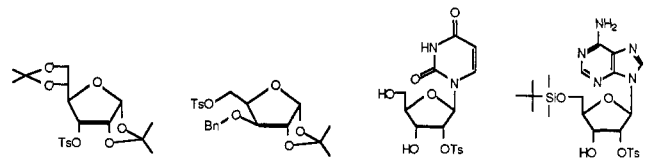
**Table I. Photosensitized Cleavage of Tosyl Esters**




[A] [B] [C] [D]

| run | substrate (mM) | solvent | donor[a] (mM) | reductant (mM) | time (h) | yield (%) |
|---|---|---|---|---|---|---|
| 1 | *O*-tosylcyclohexanol (10) | 70% EtOH | DMNP (10) | $NaBH_4$ (1 M) | 7.0 | 85[b,c] |
| 2 | *O*-tosylphenethyl alcohol (10) | 70% EtOH | DMNP (10) | $NaBH_4$ (0.5 M) | 7.0 | 90[b,c] |
| 3 | *O*-tosylcholesterol (2.0) | $H_2O$–$Et_2O$–DMF (1:2.1:6.9) | DMNP (2) | $NaBH_4$ (12) | 6.0 | 86[b] |
| 4 | *O*-tosylcholestanol (4.6) | $CH_3CN$ | DMN (4.6) | $NaBH_4$ (46) | 5.4 | 97[b] |
| 5 | *O*-tosylcholestanol (1.4) | 97% $CH_3CN$ | DMNP (1.7) | $H_2NNH_2$ (44) | 1.5 | 93[d] |
| 6 | A (2.0) | 90% $CH_3CN$ | DMNP (2.4) | $H_2NNH_2$ (62) | 2.0 | 65[d] |
| 7 | B (1.8) | 90% $CH_3CN$ | DMN (2.7) | $H_2NNH_2$ (50) | 2.6 | 68[d] |
| 8 | B (3.0) | MeOH | DABCO (6.6) | none | 1.8 | 59[e] |
| 9 | C (2.3) | 90% $CH_3CN$ | DMNP (2.7) | $H_2NNH_2$ (90) | 1.6 | 76[d] |
| 10 | C (3.9) | MeOH | DABCO (6.6) | none | 2.0 | *e,f* |
| 11 | D (1.1) | 90% $CH_3CN$ | DMNP (2.2) | $H_2NNH_2$ (43) | 2.0 | 84[d] |
| 12 | D (2.4) | MeOH | DABCO (4.1) | none | 4.0 | *e,g* |

[a] DMNP = (4,8-dimethoxynaphthyl)propionic acid, DMN = 1,5-dimethoxynaphthalene. [b] 300-W high pressure mercury lamp, Pyrex filter. [c] Determined by GLC. [d] 500-W lamp, Pyrex filter. [e] 60-W low pressure mercury lamp (254 nm).[4] [f] Complex mixture was obtained. [g] No desired product was detected and 37% of the starting material was recovered.

superior to sodium borohydride or amine borane, which were employed for the tosylamide reaction, because of less reactivity with carbonyl compounds and of the lack of formation of precipitates.

Under these conditions, primary and secondary tosylates of sugar derivatives, even a sterically hindered tosylate (run 6), afforded the corresponding alcohols in satisfactory yields. Deprotection of the tosylates of nucleosides also proceeded without any difficulties. There was no evidence for the reduction of the pyrimidine ring in the reaction of 2′-*O*-tosyluridine (run 9).[11,12] On the other hand, irradiation of the nucleosides using 254-nm light in the presence of 1,4-diazabicyclo[2.2.2.]octane (DABCO)[4] afforded complex mixtures of the products (run 10 and 12).

In summary, we have shown that tosyl esters can be hydrolyzed via a photosensitized electron-transfer process and that this new reaction is applicable to the deprotection of the tosylates of sugar and nucleoside derivatives.

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(11) (a) Photohydration and photodimerization are the typical reaction observed on irradiation of pyrimidine nucleosides: Fisher, G. J.; Johns, H. E. *Photochemistry and Photobiology of Nucleic Acids*; Wang, S. Y.; Ed.; Academic Press: New York, 1976; pp 169–294. (b) The reduction of uridine by UV irradiation in the presence of sodium borohydride has been reported: Cerutti, P.; Ikeda, K.; Witkop, B. *J. Am. Chem. Soc.* **1965**, *87*, 2505. Cerutti, P.; Kondo, Y.; Landis, W. R.; Witkop, B. *J. Am. Chem. Soc.* **1968**, *90*, 771.

(12) Typical reaction procedure: A mixture of 5′-*O*-(*tert*-butyldimethylsilyl)-2′-*O*-tosyladenosine (92 mg, 1.1 mM), DMNP (2.2 mM), and hydrazine hydrate (43 mM) in 140 mL of 90% acetonitrile was irradiated with a 500-W mercury lamp through a Pyrex filter at ambient temperature under an argon atmosphere for 2 h. After the solvent was removed in vacuo, the residue was purified by silica gel column chromatography, eluting with ethyl acetate, yielding 56 mg (84%) of 5′-*O*-(*tert*-butyldimethylsilyl)adenosine.

Extractive workup to remove DMNP and hydrazine is also applicable in a larger scale reaction.

## Catalytic Siloxymethylation of Glycosides by the $HSiR_3/CO/Co_2(CO)_8$ Reaction. A New Entry to *C*-Glycosyl Compounds

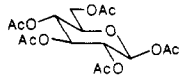
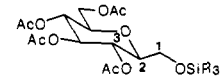
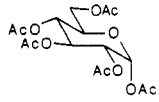
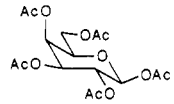
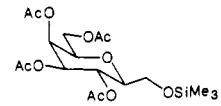
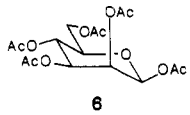
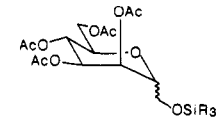
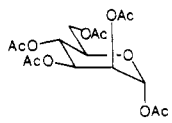
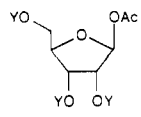
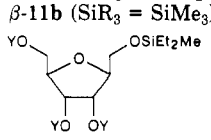
*Summary:* The acetoxy group at the anomeric center of glycosides can be replaced with a siloxymethyl group by $Co_2(CO)_8$-catalyzed reaction with carbon monoxide and a hydrosilane.

*Sir:* Carbon–carbon bond formation at the anomeric sites of saccharides is of great importance for preparation of *C*-glycosyl compounds[1] including *C*-nucleosides[2] as well as

(1) For examples, see: (a) Hanessian, S.; Pernet, A. G. *Adv. Carbohydr. Chem. Biochem.* **1976**, *33*, 111. (b) Goodchild, J. *Topics in Antibiotic Chemistry*; Sammes, P. G., Ed.; Ellis Horword: Chichester, 1982; Vol. 6, p 105. (c) Lichtenthaler, W. In *Natural Products Chemistry*; Atta-Ur-Rahman, Ed.; Springer-Verlag: Berlin, 1986; p 227.

0022-3263/88/1953-3387$01.50/0 

**Table I. $Co_2(CO)_8$-Catalyzed Siloxymethylation of Glycosyl Acetates with $HSiR_3$ and CO[a]**

| glycosyl acetate | $HSiR_3$, solvent temp,[c] time[d] | product | yield (%)[b] |
|---|---|---|---|
|  **3** | $HSiMe_3$, $C_6H_6$, 40 °C, 20 h |  **9a** ($SiR_3$ = $SiMe_3$) | 75 |
| **3** | $HSiEt_2Me$, $CH_2Cl_2$, 25 °C, 2 days | **9b** ($SiR_3$ = $SiEt_2Me$) | 82 |
|  **4** | $HSiMe_3$, $C_6H_6$, 40 °C, 20 h | **9a** | 78 |
|  **5** | $HSiMe_3$, $C_6H_6$, 40 °C, 20 h |  **10** | 63 |
| **5** | $HSiMe_3$, $CH_2Cl_2$, 10 °C, 6 days | **10** | 82 |
|  **6** | $HSiMe_3$, $C_6H_6$, 40 °C, 8 days |  **α-11a** ($SiR_3$ = $SiMe_3$) | 51 |
|  **7** | $HSiMe_3$, $C_6H_6$, 40 °C, 8 days | **α-11a** | 45 |
| **7** | $HSiEt_2Me$, $C_6H_6$, 15 °C, 47 h | **α-11b** ($SiR_3$ = $SiEt_2Me$)<br>**β-11b** ($SiR_3$ = $SiMe_3$) | 19[e]<br>31[e] |
|  **8a** (Y = Ac) | $HSiEt_2Me$, $CH_2Cl_2$, 30 °C, 20 h |  **12a** (Y = Ac) | 70[f] |
| **8b** (Y = COPh) | $HSiEt_2Me$, $CH_2Cl_2$, 25 °C, 40 h | **12b** (Y = COPh) | 75 |

[a] Reactions were carried out with a glycosyl-OAc (2.5 mmol), $HSiMe_3$ (25 mmol) (or $HSiEt_2Me$ (7.5 mmol)), $Co_2(CO)_8$ (0.1 mmol), a solvent (5 mL), and under 1 atm of CO. [b] Selectivities to α (or β) were >95%, unless otherwise noted. GC yields (OV-1, 6 m, 250 °C). [c] Reaction bath temperatures. [d] In hours (h) or days. [e] Obtained as a mixture of α- and β-isomers. [f] In addition, the α-isomer was obtained in 5% yield.

for synthesis of useful building blocks.[2] Increasing interest in this area has resulted in development of various synthetic methods.[1,3] Among these, reactions using silylated C-nucleophiles such as allylsilanes and enol silyl ethers have been thoroughly studied.[3] Organotransition-metal chemistry[4] has also been applied to this field, but not extensively and only with limited success. *C*-Glycosyl compounds have been obtained by cobalt,[5] palladium,[6] rhodium,[7] and manganese[8] mediated reactions. As part of an ongoing study of $Co_2(CO)_8$-catalyzed reactions with hydrosilanes and carbon monoxide,[9] we report a novel entry to *C*-glycosyl compounds. As shown in eq 1, the new

$$\underset{\mathbf{1}}{\text{glycosyl-OAc}} \xrightarrow[\text{cat. } Co_2(CO)_8,\ 1\text{ atm},\ 10\text{–}40\ ^\circ C]{HSiR_3,\ CO} \underset{\mathbf{2}}{\text{glycosyl-CH}_2\text{OSiR}_3} \qquad (1)$$

(2) Hanessian, S. *Total Synthesis of Natural Products: The "Chiron" Approach*; Pergamon Press: New York, 1983; p 1.

(3) For examples, see: (a) Ogawa, T.; Pernet, A. G.; Hannessian, S. *Tetrahedron Lett.* **1973**, 3543. (b) de las Heras, F. G.; Fernandez-Resa, P. *J. Chem. Soc., Perkin Trans. 1* **1982**, 903. (c) Kozikowski, A. P.; Sorgi, K. L. *Tetrahedron Lett.* **1982**, *23*, 2281. (d) Cupps, T. L.; Wise, O. S.; Townsend, L. B. *J. Org. Chem.* **1982**, *47*, 5115. (e) Lewis, M. D.; Cha, J. K.; Kishi, Y. *J. Am. Chem. Soc.* **1982**, *104*, 4976. (f) Schmidt, R. R.; Hoffmann, M. *Angew. Chem., Int. Ed. Engl.* **1983**, 22, 406. (g) Utimoto, K.; Wakabayashi, Y.; Horiie, T.; Inoue, M.; Shishiyama, Y.; Obayashi, M.; Nozaki, H. *Tetrahedron* **1983**, *39*, 967. (h) Kozikowski, A. P.; Sorgi, K. L. *Tetrahedron Lett.* **1983**, *24*, 1563. (i) Hosomi, A.; Sakata, Y.; Sakurai, H. *Tetrahedron Lett.* **1984**, *25*, 2383. (j) Nicolau, K. C.; Dolle, R. E.; Chucholowski, A.; Randall, J. L. *J. Chem. Soc., Chem. Commun.* **1984**, 1153. (k) Araki, Y.; Watanabe, K.; Kuran, F.-H.; Itoh, K.; Kobayashi, N.; Ishido, Y. *Carbohydr. Res.* **1984**, *127*, C5. (l) Stewart, A. O.; Williams, R. M. *J. Am. Chem. Soc.* **1985**, *107*, 4289. (m) Allevi, F.; Anastasia, M.; Ciuffreda, P.; Fiecchi, A.; Scala, A. *J. Chem. Soc., Chem. Commun.* **1987**, 1245. (n) Dunkerton, L. V.; Adair, N. K.; Euske, J. M.; Brady, K. T.; Robinson, P. D. *J. Org. Chem.* **1988**, *53*, 845.

(4) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; Univ. Sci. Books: Mill Valley, CA, 1987.

(5) (a) Rosenthal, A. *Adv. Carbohydr. Chem.* **1968**, *23*, 59. (b) Rosenthal, A.; Koch, H. J. *Tetrahedron Lett.* **1967**, 871.

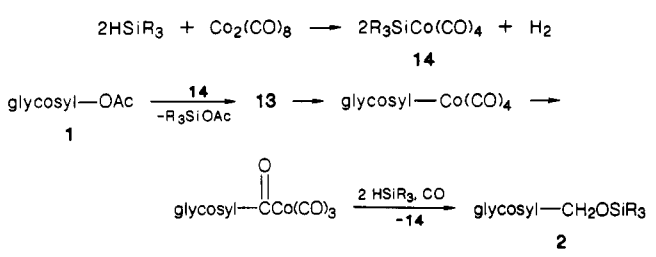
(6) Arai, I.; Daves, G. D., Jr. *J. Am. Chem. Soc.* **1978**, *100*, 287. Dunkerton, L. V.; Serino, A. J. *J. Org. Chem.* **1982**, *47*, 2812. Arai, I.; Lee, T. D.; Hanna, R.; Daves, G. D., Jr. *Organometallics* **1982**, *1*, 742. Yougai, S.; Miwa, T. *J. Chem. Soc., Chem. Commun.* **1983**, 68. Hacksell, U.; Daves, G. D., Jr. *J. Org. Chem.* **1983**, *48*, 2870. RajanBabu, T. V. *J. Org. Chem.* **1985**, *50*, 3642. Cheng, J. C.-Y.; Daves, G. D., Jr. *Organometallics* **1986**, *5*, 1753. Cheng, J. C.-Y.; Daves, G. D., Jr. *J. Org. Chem.* **1987**, *52*, 3083. Outten, R. A.; Daves, G. D., Jr. *J. Org. Chem.* **1987**, *52*, 5064. Brakta, M.; Le Borgne, F.; Sinou, D. *J. Carbohydr. Chem.* **1987**, *6*, 307.

(7) Kametani, T.; Kawamura, K.; Honda, T. *J. Am. Chem. Soc.* **1987**, *109*, 3010.

(8) Deshong, P.; Slough, G. A.; Elango, V.; Trainor, G. L. *J. Am. Chem. Soc.* **1985**, *107*, 7788.

(9) For previous papers of this series, see: Chatani, N.; Fujii, S.; Yamasaki, Y.; Murai, S.; Sonoda, N. *J. Am. Chem. Soc.* **1986**, *108*, 7361. Murai, T.; Furuta, K.; Kato, S.; Murai, S.; Sonoda, N. *J. Organomet. Chem.* **1986**, *302*, 249.

**Scheme I**

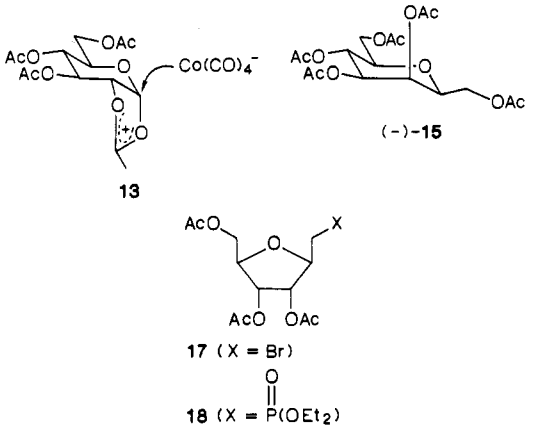



reaction of glycosyl acetates proceeds under mild reaction conditions *catalytically* and stereoselectively. This unprecedented type of transformation leads to products that are valuable not only as multipurpose building blocks but also as intermediates for methylenephosphonate sugars[10] and homo-*C*-nucleosides.[11]

The $Co_2(CO)_8$-catalyzed reaction of glucopyranosyl acetate **3** (see Table I) with $HSiMe_3$ and CO serves as an example.[12] In a 10-mL flask fitted with an efficient condenser (dry ice–MeOH) was placed $Co_2(CO)_8$ (0.1 mmol, 34 mg), and the flask was flushed with CO (1 atm). $HSiMe_3$[13] (25 mmol, 3 mL) was then added to the flask. After 5 min, benzene (5 mL) and **3** (2.5 mmol, 0.975 g) were added. The solution was stirred at 40 °C (bath temperature, under reflux of $HSiMe_3$) for 20 h under CO (1 atm). GC analysis showed that *C*-glucosyl compound **9a** was formed in 75% yield. A few drops of pyridine were added and air was bubbled in (10 min) to precipitate the Co catalyst, which was filtered off through a short column ($SiO_2$, $CHCl_3$). Pure **9a** was obtained by flash chromatography ($SiO_2$, hexane/EtOAc = 3/1) as a colorless syrup.

Selected results are given in Table I. Only the acetoxy group on the anomeric center is replaced with a siloxymethyl group. When reaction conditions are chosen properly, the siloxymethylation takes place stereoselectively from the side opposite to the acetoxy group at C-3 irrespective of the configuration of the leaving acetoxy group at C-2. This may imply that ring opening of an bridged oxonium ion such as **13** by $Co(CO)_4^-$ determines the product stereochemistry. A proposed reaction path in which a silylcobalt carbonyl, $R_3SiCo(CO)_4$ **14**, plays a key role is outlined in Scheme I.[14]

Products **9a**, **9b**, and **10** show large $J_{2-3}$ (9.77, 9.55, and 9.77 Hz, respectively) assignable to axial–axial coupling ($J_{aa}$). Structural assignments based on coupling constants seems to be less reliable for pyranose derivatives with an equatorial hydrogen at C-3 such as **11**. In a different experiment, β-penta-*O*-acetyl-D-mannose (**7**) gives a pair of isomers, β-**11b** and α-**11b** (see Table I).[15] Acetylation (AcCl in $CDCl_3$, 50 °C, ultrasonication for 40 h) of β-**11b** and α-**11b** after chromatographic separation results in replacement of the siloxy group by an acetoxy group and affords pentaacetates (−)-**15** ($[\alpha]^{19}_D$ −11.5° (*c* 0.48, $CHCl_3$)) and (+)-**16** ($[\alpha]^{17}_D$ +4.6° (*c* 0.44, $CHCl_3$), structure not shown), respectively. Similar acetylation of **10** gave penta-*O*-acetyl derivative (+)-**15** which has $^1H$ NMR and IR spectra identical with those of (−)-**15** but has opposite sign of optical rotation, $[\alpha]^{18}_D$ +12.6° (*c* 0.43, $CHCl_3$), and is therefore the enantiomer of (−)-**15**. These transformations establish the structures of **11**. The observed $J_{ee}$ for α-**11b** ($J_{2-3}$ = 3.84 Hz) is larger than $J_{ae}$ for β-**11b** ($J_{2-3}$ = 0 Hz). It has been reported for similar compounds that $J_{ee}$ is smaller than $J_{ae}$.[16]




Products of Table I are amenable to further synthetic elaboration. Preliminary experiments show that **12a** can be converted ($SOBr_2$/pyridine/$CDCl_3$, 40 °C) to bromide **17** (promising as a homo-*C*-nucleoside[11] precursor), from which phosphonate sugar **18** can be prepared ($P(OEt)_3$,[17] no solvent, reflux).

The present reaction is not only unique as an application of a transition-metal-catalyzed carbonylation to relatively complex molecules but also useful as a method for one carbon chain extension[18] at the anomeric center of glycosides.[19]

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**Supplementary Material Available:** Characterization of new compounds (9 pages). Ordering information is given on any current masthead page.

(10) McCland, R. W. *Tetrahedron Lett.* **1983**, *24*, 2631. Engle, R. *Chem. Rev.* **1977**, *77*, 349.
(11) Cupps, T. L.; Wise, D. S., Jr. *J. Org. Chem.* **1986**, *51*, 1058. Renz, H.; Schlimme, E. *Liebigs Ann. Chem.* **1986**, 957.
(12) For characterization of all new compounds, see supplementary material.
(13) The $HSiMe_3$ (bp 7 °C) was handled by a cooled hypodermic syringe or by bulb-to-bulb distillation. In other case when $HSiEt_2Me$ (bp 77 °C) was employed, the amount of $HSiEt_2Me$ used was 5 mmol or 1.5-fold excess.
(14) Murai, T.; Kato, S.; Murai, S.; Toki, T.; Suzuki, S.; Sonoda, N. *J. Am. Chem. Soc.* **1984**, *106*, 6093. See also ref 5b.
(15) The reason for the formation of the β-isomer (β-**11b**) in this case is not clear. It seems that the $S_N1$-like and/or participation mechanism are contaminated with $S_N2$ displacement leading to the β-isomer.
(16) For similar cyanomethyl compounds, $J_{ae}$ = 3.1–5.2 Hz and $J_{ee}$ = 1.7 Hz were reported. See: Giese, J.; Dupuis, J. *Angew. Chem.* **1983**, *95*, 633.
(17) Nicotra, F.; Ronchetti, F.; Russo, G. *J. Org. Chem.* **1982**, *47*, 4459.
(18) For examples of methods for the introduction of one carbon unit at anomeric centers, see: Sakakibara, T.; Takamoto, T.; Matsuzaki, T.; Omi, H.; Maung, V.; Sudeh, R. *Carbohydr. Res.* **1981**, *95*, 291. References 3b, 3f, and 3g.
(19) An elegant application of the present catalytic reaction; see: Tamao, K.; Nakajo, E.; Ito, Y. *Tetrahedron*, in press.

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