a strong influence from steric interactions.

III. Thermochemical Comparisons of Three Coal Samples: As Acids. Table VI presents heats of immersion, ΔH_{imm}, of three 45/60 mesh coal samples (Wyoming Rawhide, Texas Big-Brown, and Illinois No. 6) measured at 80 °C in 12 basic liquids selected from a list of 31 liquids used for ΔH_{imm} measurements for Rahwide coal as given in Table V.

A good linear correlation (r = 0.998) with almost zero intercept shown in Figure 6 (and only a few points removed from the correlation line) is found between the $\Delta H_{imm}{}^{80}$ values of Rawhide subbituminous and Texas Big-Brown for eight liquids. These two coals have quite similar analyses (Table I), and it is interesting to see that their acid–base behavior is also similar although the slope of the line (1.16) suggests that the interactions of Rawhide coal with these eight liquids are slightly more exothermic than those of Texas Big-Brown.

Figure 7 compares the ΔH_{imm} values of Rawhide coal with those of Illinois No. 6 coal. The scatter diagram suggests that interaction of bases with acidic sites in Illinois No. 6 coal is different from that for Wyoming Rawhide and Texas lignite coals. Table I shows that the Illinois coal differs considerably from the other coals in several features of its analysis, the most important being mineral content. It is reasonable to suppose that different Lewis acid interactions with coal minerals as well as hydrogen bonding, proton transfer, and various other types of adsorption contribute to heats of immersion in basic solvents. We hope to clarify the role of these interactions in future work.

Acknowledgment. We are glad to acknowledge support for this work by Department of Energy Grant DE-FG22-82PC50807 and a grant from the Exxon Education Foundation. Also we appreciate the contribution of coal samples and advice by Dr. Ronald Liotta and help with instrumentation by Mr. Eric Johnson.

Registry No. 1,3-Diaminopropane, 109-76-2; ethylenediamine, 107-15-3; *n*-hexylamine, 111-26-2; *n*-octylamine, 111-86-4; dimethylformamide, 68-12-2; dimethyl sulfoxide, 67-68-5; methylformamide, 123-39-7; 4-methylpyridine, 108-89-4; pyridine, 110-86-1; 2-methylpyridine, 109-06-8; 3,5-dimethylpyridine, 591-22-0; 2,6-dimethylpyridine, 108-48-5; 2,6-diethylpyridine, 935-28-4; 2,4,6-trimethylpyridine, 108-75-8; quinoline, 91-22-5; isoquinoline, 119-65-3; piperidine, 110-89-4; aniline, 62-53-3; *N,N*-dimethylaniline, 121-69-7; Triethylamine, 121-44-8; *tert*-octylamine, 107-45-9; *p*-dioxane, 123-91-1; acetophenone, 98-86-2; acetonitrile, 75-05-8; cyclohexanone, 108-94-1; propylene carbonate, 108-32-7; decalin, 91-17-8; naphthalene, 91-20-3; tetrabutylammonium hydroxide, 2052-49-5; sodium hydroxide, 1310-73-2; water, 7732-18-5.

$(\eta^5\text{-}C_5H_5)Fe(CO)_2(\eta^1\text{-}C_5H_5)$. A Useful Synthetic Equivalent of Methyl 1,3-Cyclopentadiene-5-carboxylate in Cycloaddition Reactions

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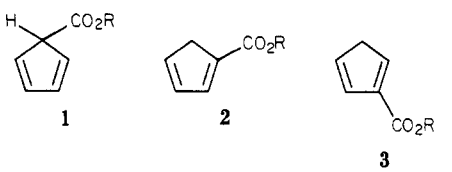
A variety of activated unsaturated compounds, including acrylonitrile, react with $Fp(\eta^1\text{-}C_5H_5)$, where Fp = $(\eta^5\text{-}C_5H_5)Fe(CO)_2$, to give cycloadducts in good yield. Diethylchloroalane facilitates these cycloadditions and even methyl acrylate cycloadds in good yield in the presence of this Lewis acid. These reactions all occur regio- and stereoselectively to afford syn-7-Fp cycloadducts exclusively. The stereochemistry at C(2) and C(3) is selective in some cases but not in others. Stereospecific replacement of the Fp moiety in these cycloadducts by a CO_2Me group with retention of configuration occurs in good yield by oxidation with ammonium cerium(IV) nitrate in carbon monoxide saturated methanol. This two-step sequence, cycloaddition followed by oxidation, renders $Fp(\eta^1\text{-}C_5H_5)$ a synthetic equivalent of methyl 1,3-cyclopentadiene-5-carboxylate in cycloaddition reactions.

Diels–Alder reactions of cyclopentadiene are widely used in organic synthesis.[2] However, the value of such reactions with substituted cyclopentadienes is limited by their facile isomerization.[3] Thus, no Diels–Alder reactions of esters of 1,3-cyclopentadiene-5-carboxylate **1** have been reported, undoubtedly, due to their isomerization to the thermodynamically more stable 1- and 2-isomers, **2** and **3**, respectively.[4] Diels–Alder reactions of these latter isomers are known.[4,5]



1 **2** **3**

The Diels–Alder adducts **6** and **7b**, derived in principle but not practice from methyl 1,3-cyclopentadiene-5-

(1) Presently located at Research Laboratories, Tennessee Eastman, Co., Kingsport, TN 37662.

(2) An especially elegant and important example is the stereocontrolled total synthesis of all of the primary prostaglandins from a single resolved precusor reported by Corey and co-workers: Corey, E. J.; Weinshenker, N. M.; Schaaf, T. K.; Huber, W. *J. Am. Chem. Soc.* **1969**, *91*, 5675. Corey, E. J.; Schaaf, T. K.; Huber, W.; Koelliker, U.; Weinshenker, N. M. *Ibid.* **1970**, *92*, 397. Corey, E. J.; Noyori, R.; Schaaf, T. K. *Ibid.* **1970**, *92*, 2586. Corey, E. J.; Shirahama, H.; Yamamoto, H.; Terashima, S.; Venkateswarlu, A.; Schaaf, T. K. *Ibid.* **1971**, *93*, 1490. Corey, E. J.; Varma, R. K. *Ibid.* **1971**, *93*, 7319. Corey, E. J. *Ann. N.Y. Acad. Sci.* **1971**, *180*, 24. Corey, E. J.; Becker, K. B.; Varma, R. K. *J. Am. Chem. Soc.* **1972**, *94*, 8616. Corey, E. J.; Schaaf, T. K. *J. Org. Chem.* **1972**, *37*, 2921. In this synthesis a 5-substituted-1,3-cyclopentadiene is selectively prepared and trapped in a Diels–Alder reaction before isomerization (see ref 3).

(3) This is particularly true of 5-alkyl-1,3-cyclopentadienes. 5-Methyl-1,3-cyclopentadiene readily isomerizes to the thermodynamically more stable 1- and 2-isomers: Mironov, V. A.; Sobolev, E. V.; Elizarova, A. N. *Tetrahedron* **1963**, *19*, 1939. McLean, S.; Haynes, P. *Tetrahedron Lett.* **1964**, 2385. McLean, S.; Haynes, P. *Tetrahedron* **1965**, *21*, 2329. McLean, S.; Webster, C. J.; Rutherford, R. J. D. *Can. J. Chem.* **1969**, *47*, 1555.

(4) Alder, K.; Flock, F. H.; Hausweiler, A.; Reeber, R. *Chem. Ber.* **1954**, *87*, 1752. Peters, D. *J. Chem. Soc.* **1959**, 1761. Franklin, W. E.; Mack, C. H.; Rowland, S. R. *J. Org. Chem.* **1968**, *33*, 626.

(5) Kresze, G.; Schulz, G.; Walz, H. *Liebigs Ann. Chem.* **1963**, *666*, 45. Wiesner, K.; Philipp, A. *Tetrahedron Lett.* **1966**, 1467. Stedman, R. J.; Miller, L. S. *J. Org. Chem.* **1967**, *32*, 3544. Mamer, O. A.; Rutherford, K. G.; Siedewand, R. J. *Can. J. Chem.* **1974**, *52*, 1983. Kyba, E. P.; Hudson, C. W. *J. Org. Chem.* **1977**, *42*, 1935. Irie, T.; Tanida, H. *Ibid.* **1978**, *43*, 3274. Nallet, J. P.; Arnaud, C.; Huet, J. *Tetrahedron Lett.* **1979**, 2583. Yates, P.; Gupta, I. *J. Chem. Soc., Chem. Commun.* **1981**, 449.

0022-3263/84/1949-3059$01.50/0

Table I. Cycloaddition Products from Fp(η^1-C_5H_5) (4) with Unsaturated Compounds and Their Oxidation

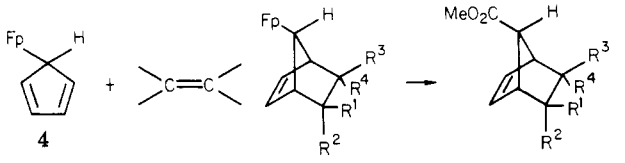
unsaturated compound	cycloaddition product (yield, %)[a]	oxidation product (yield, %)[b]
maleic anhydride	**5a** (73)	
dimethyl fumarate	**5b** (90)	**6b** (75)
2-chloroacrylonitrile	**5c** (87)[c]	**6c** (60)
acrylonitrile	**5d** (74)[d]	*exo*-**6d** (82)[f]
	(82)[e]	*endo*-**6d** (63)[f]
dimethyl acetylenedicarboxylate	**7a** (85)	**7b** (60)
methyl acrylate	**5e** (85)[g]	*exo*-**6e** (80)[f]
		endo-**6e** (92)[f]
dimethyl maleate	**5b** (73)[h]	

[a] Reported yields are for isolated, purified adducts. The limiting reagent is Fp(η^1-C_5H_5), **4**, and excess unsaturated compound is used except for maleic anhydride. [b] These are isolated yields of pure products. [c] A mixture of isomers epimeric at C(2) are obtained in a 4:1 ratio in the yield shown. [d] A 1:1 mixture of exo:endo isomers is obtained in the yield shown. [e] This is the yield of a 1:1 mixture of exo:endo isomers obtained in the presence of diethylchloroalane. [f] Each pure isomeric cycloadduct is oxidized separately and isomerically pure products **6** are obtained in the yields shown. [g] This is the yield of a 1:1 mixture of exo:endo isomers obtained in the presence of diethylchloroalane. [h] This is the yield of pure adduct obtained in the presence of diethylchloroalane.

carboxylate 1, R = Me, were prepared efficiently by a two-step sequence.[6] Reaction of Fp(η^1-C_5H_5) (**4**), where Fp = (η^5-C_5H_5)Fe(CO)$_2$, with activated unsaturated compounds gave cycloadducts **5**[7,8] regio- and stereoselectively.[6,9] Oxidation of these cycloadducts with ammonium cerium(IV) nitrate in methanol saturated with carbon monoxide resulted in the stereospecific[6,10] replacement of the Fp moiety with a CO_2Me group. Thus, Fp(η^1-C_5H_5) is a synthetic equivalent of methyl 1,3-cyclopentadiene-5-carboxylate in cycloaddition reactions. Full details of the synthetic utility of Fp(η^1-C_5H_5) in cycloadditions is presented. In addition, catalysis of the cycloaddition of this organometallic reagent effected by diethylchloroalane,[11] which significantly expands the scope of this reaction, is presented in this paper.

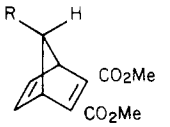
Results and Discussion

Cycloaddition of Fp(η^1-C_5H_5) (**4**) to give cycloadducts **5** occurred readily and in good yield with maleic anhydride, dimethyl fumarate, 2-chloroacrylonitrile, and acrylonitrile but not with dimethyl maleate or methyl acrylate, as shown in Table I. In addition, Fp(η^1-C_5H_5) and dimethyl acetylenedicarboxylate afforded adduct **7a** in good yield. We were surprised by these facile cycloadditions, with even monoactivated alkenes such as acrylonitrile, because Fp(η^1-C_5H_5)[9] and other Fp(η^1-allyl) systems[12] were reported to react only with more highly activated alkenes.



4 **5** **6**

a, $R^1 = R^3 = H$; $R^2 = R^4$ = -C(O)OC(O)-
b, $R^1 = R^4 = CO_2Me$; $R^2 = R^3 = H$
c, R^1 or R^2 = Cl or CN; $R^3 = R^4 = H$
d, R^1 or R^2 = CN or H; $R^3 = R^4 = H$
e, R^1 or $R^2 = CO_2Me$ or H; $R^3 = R^4 = H$



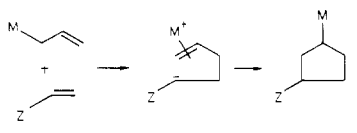
7a, R = Fp
b, R = CO_2Me

Although Fp(η^1-C_5H_5) did not form cycloadducts with dimethyl maleate or methyl acrylate thermally, rapid cycloaddition with both substituted alkenes occurred in good yield in the presence of diethylchloroalane. The sole product formed with dimethyl maleate was the same as that obtained with dimethyl fumarate. Methyl acrylate produced cycloadduct **5e**. Similar Lewis acid catalysis of the cycloaddition of Fp(η^1-allyl) systems with 2-cyclohexenone was reported.[12a] However, only a modest yield (45%) at best of cycloadduct was formed with the most effective Lewis acid studied (freshly sublimed aluminum bromide).

Only one isomeric cycloadduct was obtained in each of the reactions of Fp(η^1-C_5H_5) with maleic anhydride, dimethyl fumarate, and dimethyl maleate. However, two isomeric cycloadducts were produced in each of the reactions of Fp(η^1-C_5H_5) with 2-chloroacrylonitrile, acrylonitrile, and methyl acrylate. Each of the pairs of cycloadducts obtained with acrylonitrile and methyl acrylate but not 2-chloroacrylonitrile could easily be separated by medium-pressure chromatography on activity grade III alumina.

The structure of the cycloadduct obtained from Fp(η^1-C_5H_5) and maleic anhydride was unequivocally shown to be **5a** by single-crystal X-ray analysis.[6] The structures of the other cycloadducts were assigned on the basis of their NMR spectra.[13] Of special importance is that in all of the cycloadducts formed from substituted alkenes the Fp group is at C(7) and syn to the double bond. The stereochemistry at C(7) was deduced from the lack of coupling between H(7) and H(3-endo) (and H(2-endo) in those cases with such a proton). The coupling constant for H(7-anti) and H(2-endo) in norbornenes is known to

(6) Wright, M. E. *Organometallics* **1983**, *2*, 558.
(7) Metal η^1-allyl complexes cycloadd to activated alkenes by a stepwise [3 + 2] mechanism:[8]



Cycloaddition of Fp(η^1-C_5H_5)[9] may proceed by an analogous mechanism or a Diels–Alder, i.e., concerted [4 + 2], mechanism.
(8) (a) Giering, W. P.; Rosenblum, M. *J. Am. Chem. Soc.* **1971**, *93*, 5299. (b) Su, S. R.; Wojcicki, A. *Inorg. Chim. Acta* **1974**, *8*, 55.
(9) (a) Cutler, A.; Ehntholt, D.; Gierinin, W. P.; Lennon, P.; Raghu, S.; Rosan, A.; Rosenblum, M.; Tancrede, J.; Wells, D. *J. Am. Chem. Soc.* **1976**, *98*, 3495. (b) Williams, J. P.; Wojcicki, A. *Inorg. Chem.* **1977**, *16*, 3116.
(10) Whitesides, G. M.; Buck, P. L.; Boschetto, D. J.; Rasmussen, J. R.; Deners, J. P. *J. Am. Chem. Soc.* **1974**, *96*, 2814.
(11) Snider, B. B.; Rodini, D. J.; Karras, M.; Kirk, T. C.; Deutsch, E. A.; Cordova, R.; Price, R. T. *Tetrahedron* **1981**, *37*, 3927.
(12) (a) Bucheister, A.; Klemarczyk, P.; Rosenblum, M. *Organometallics* **1982**, *1*, 1679. (b) Abram, T. S.; Baker, R.; Exon, C. M.; Rao, V. B. *J. Chem. Soc., Perkin Trans. 1*, **1982**, 285. (c) Baker, R.; Exon, C. M.; Rao, V. B.; Turner, R. W. *Ibid.* **1982**, 295, 301.
(13) Davis, J. C.; Van Auken, T. V. *J. Am. Chem. Soc.* **1965**, *87*, 3900.

be small, but that between H(7-syn) and H(2-endo), which are in a W arrangement, is 2–4 Hz.[13,14] The isomers formed from 2-chloroacrylonitrile and $Fp(\eta^1\text{-}C_5H_5)$ were epimeric at C(2) as deduced from their ^1H and ^{13}C NMR spectra. The stereochemistry of the cycloadduct obtained from dimethyl fumarate and dimethyl maleate was established as **5b** by analysis of its NMR spectra. The pairs of isomers produced in the reactions of $Fp(\eta^1\text{-}C_5H_5)$ with acrylonitrile and methyl acrylate were C(2) epimers. The absorption of H(2-endo) in the exo cycloadduct **5d** (R^1 = CN, $R^2 = R^3 = R^4$ = H) occurred at higher field (δ 2.22 vs. 2.74) than that of the 2-exo hydrogen in endo cycloadduct **5d** (R^2 = CN, $R^1 = R^3 = R^4$ = H). Also the coupling constant between H(2-endo) and bridgehead hydrogen H(1) in the exo adduct was smaller than the corresponding coupling constant with H(2-exo) in the endo adduct (0 vs. 4 Hz). Similar analysis permitted assignment of the structures of the methyl acrylate cycloadducts.

Oxidation of cycloadducts **5b–e** and **7a** with ammonium cerium(IV) nitrate in methanol saturated with carbon monoxide stereospecifically converted the Fp moiety into a CO_2Me group in good yield as shown in Table I. The other functional groups in these molecules were unaffected under these mild reaction conditions. In addition, separate oxidation of each of the isolated exo and endo adducts of acrylonitrile (**5d**) and methyl acrylate (**5e**) resulted in the formation of the corresponding products **6** without epimerization at C(2). The stereochemistry at C(2) for the oxidized products **6** was assigned by analyses of their ^1H NMR spectra as done before for cycloadducts **5**. Thus, the absorption of endo-H(2) in exo product **6** (R^1 = CN, $R^2 = R^3 = R^4$ = H) occurred at higher field than that of exo-H(2) in the endo product **6** (R^2 = CN, $R^1 = R^3 = R^4$ = H), 2.26 and 2.97 ppm, respectively. Also $J_{1,2\text{-endo}}$ was smaller than $J_{1,2\text{-exo}}$, 0 and 3.9 Hz, respectively. Similarly, H(2-endo) in exo product **6** ($R^1 = CO_2Me$, $R^2 = R^3 = R^4$ = H) resonated at higher field than exo-H(2) in the corresponding endo compound, and $J_{1,2\text{-endo}}$ was smaller $J_{1,2\text{-exo}}$ (0 vs. 3.7 Hz). In all of the oxidized products **6**, no significant coupling was observed between H(7-anti) and H(2-endo) or H(3-endo) in those cases where there is either or both such endo hydrogen atoms. Therefore, there was retention of stereochemistry at C(7) on oxidation as expected.[10] Stereoselective formation of triester **7b** as outlined above complements the reported preparation of its C(7) epimer by using organonickel intermediates.[15]

Experimental Section

All manipulation of complexes and solvents were carried out by using standard Schlenk techniques under an atmosphere of purified argon or nitrogen. Solvents were degassed and purified by distillation under nitrogen from standard drying agents. Spectroscopic measurements utilize the following instrumentation: ^1H NMR, ^{13}C NMR, Bruker WM 250 FT; IR Perkin-Elmer 983; NMR chemical shifts were reported in δ units downfield from internal tetramethylsilane. The $(\eta^5\text{-}C_5H_5)Fe(CO)_2(\eta^1\text{-}C_5H_5)$ (**4**) was prepared by the method of Wilkinson and Piper.[16] It was contaminated by ferrocene (ca. 20%) after column chromatography (alumina III, hexane/benzene, 3:2, v/v) and used in this form. The weight of **4** given in the experimental section was corrected for ferrocene contamination. The alumina (Woelm N32-63) for the medium-pressure chromatography was purchased from Universal Scientific Company and deactivated to grade III. The alumina (60 mesh) used for column chromatography was bought from Alfa Products, Ventron Corp., and deactivated to grade III. Medium-pressure chromatography utilized a column of 15 × 500 mm unless otherwise specified. NMR solvents were routinely degassed by three consecutive freeze–pump–thaw cycles and stored under nitrogen. Elemental analyses were performed at Atlantic Microlab, Inc., Atlanta, GA.

Preparation of 5a. Maleic anhydride (0.40 g, 4.1 mmol) was added to a dichloromethane (CH_2Cl_2)/(25 mL) solution containing **4** (1.01 g, 4.1 mmol) at 0 °C. The solution was stirred for 30 min and the solvent was evaporated under reduced pressure. The solid was recrystallized from ether (ca. 5 mL) at −25 °C to yield pure **5a** (1.10 g, 73%): ^1H NMR ($CDCl_3$, 250 MHz) δ 6.20 (m, 2, CH=), 4.73 (s, 5, C_5H_5), 3.54 (m, 2, H-2, H-3), 334 (m, 2, H-1, H-4), 2.59 (t, 1, J = 0.8 Hz, H-7); ^{13}C NMR ($CDCl_3$, 62.9 MHz) δ 216.51 (CO), 170.97 (CO), 135.47 (C-5, C-6), 85.59 (C_5H_5), 56.83 (C-1, C-4), 50.77 (C-7), 48.25 (C-2, C-3); IR (CH_2Cl_2) ν (CO) 2011, 1955, 1776 cm^{-1}. Anal. Calcd for $C_{16}H_{12}FeO_5$: C, 56.50; H, 3.56. Found: C, 56.45; H, 3.74.

Preparation of 5b. Dimethyl fumarate (1.18 g, 8.2 mmol) was added to a CH_2Cl_2 (25 mL) solution containing **4** (1.10 g, 4.6 mmol) at 25 °C. The mixture was stirred for an additional 4 h. The solvent was removed under reduced pressure and the residue was medium-pressure chromatographed on alumina III, eluting first with hexane/benzene (4:1, v/v) to remove the ferrocene. Final elution with hexane/ethyl acetate (3:2, v/v) produced **5a** (1.60 g, 90%): ^1H NMR ($CDCl_3$) δ 6.18 (m, 1 HC=), 5.86 (m, 1, HC=), 4.71 (s, 5, C_5H_5), 3.71 (s, 3, CH_3), 3.62 (s, 3, CH_3), 3.26, 3.12, 3.01, 2.78 (m's, 4, CH), 2.74 (s, 1, CH); ^{13}C NMR ($CDCl_3$) δ 217.20, 217.05 (CO), 175.40, 173.22 (CO), 137.47, 134.80 (CH=), 85.61 (C_5H_5), 57.98, 55.96 (CH), 51.69, 51.46 (CH_3), 48.78, 47.81, 45.21 (CH); IR (CH_2Cl_2) ν (CO) 2005, 1949, 1728 cm^{-1}. Anal. Calcd for $C_{18}H_{18}FeO_6$: C, 55.98; H, 4.70. Found: C, 56.02; H, 4.75.

Preparation of 5c. 2-Chloroacrylonitrile (0.65 mL, 0.72 g, 8.2 mmol) was added to a CH_2Cl_2 (25 mL) solution containing **4** (0.70 g, 2.9 mmol) which was then allowed to stir at 25 °C for 4 h. The solvent was removed under reduced pressure and the residue medium-pressure chromatographed as above. This produced a single yellow band. Removal of the solvent from the band afforded **5c** as a yellow oil (0.83 g, 87%) containing a mixture of epimers at the C(2) position. **5c** (major isomer): ^1H NMR ($CDCl_3$) δ 6.29 (m, 1, HC=), 6.01 (m, 1, HC=), 4.74 (s, 5, C_5H_5), 3.28 (m, 1, CH), 2.88 (m, 1, CH), 2.83 (s, 1, CH), 2.68 (dd, 1, J = 3.7, 12.8 Hz, CH_2), 1.74 (d, 1, J = 12.8 Hz, CH_2); ^{13}C NMR ($CDCl_3$) δ 216.66, 216.51 (CO), 139.44, 131.96 (CH=), 123.90 (CN), 85.69 (C_5H_5), 65.75 (CH), 55.11 (*C*(Cl)CN), 53.07 (CH), 47.23 (CH_2), 44.56 (CH). **5c** (minor isomer): ^1H NMR ($CDCl_3$) δ 6.31 (m, 1, CH=), 6.11 (m, 1, CH=), 4.74 (s, 5, C_5H_5), 3.12 (m, 1, CH), 3.05 (s, 1, CH), 2.88 (s, 1, CH), 2.29 (d, 2, J = 2.6 Hz); ^{13}C NMR ($CDCl_3$) δ 216.66, 216.51 (CO), 142.20, 132.78 (CH=), 121.22 (CN), 85.69 (C_5H_5), 66.48 (CH), 55.11 (*C*(Cl)CN), 53.07 (CH), 47.97 (CH_2), 42.37 (CH); IR (both isomers) ν (C≡O) 2009, 1960 cm^{-1}. Anal. Calcd for $C_{15}H_{12}ClFeNO_2$: C, 54.67; H, 3.67. Found: C, 54.56; H, 3.70.

Preparation of 5d. A CH_2Cl_2 (35 mL) solution containing acrylonitrile (0.57 mL, 8.6 mmol) and **4** (0.36 g, 1.5 mmol) was stirred at 25 °C for 72 h. The solvent was removed under reduced pressure and the residue was medium-pressure chromatographed on alumina III, eluting with benzene. The second yellow band afforded 0.20 g (36% yield) of *exo*-**5d**. The third band gave 0.21 g (38% yield) of *endo*-**5d**. ***exo*-5d**: ^1H NMR ($CDCl_3$) δ 6.05 (dd, 1, J = 5.5, 3.1 Hz, HC=), 5.92 (dd, 1, J = 5.5, 3.0 Hz, HC=), 4.73 (s, 5, C_5H_5), 3.05 (s, 1, H-1), 2.88 (s, 1, H-4), 2.70 (s, 1 H, H-7), 2.23 (dd, 1, J = 9.2, 4.1 Hz, H-2, endo), 1.90 (dd, 1 H, J = 11.3, 3.8 Hz, H-3, exo), 1.59 (t, 1 H, J = 11.3 Hz, H-3, endo). Anal. Calcd for $C_{15}H_{13}FeNO_2$: C, 61.01; H, 4.50. Found: C, 61.06; H, 4.59. ***endo*-5d**: ^1H NMR ($CDCl_3$) δ 6.21 (dd, 1, J = 5.5, 2.3 Hz, HC=), 6.07 (dd, 1, J = 5.4, 2.8 Hz, HC=) 4.67 (s, 5, C_5H_5), 3.06 (s, 1, H-1), 2.84 (s, 1, H-4), 2.74 (ddd, 1, J = 9.2, 5.3, 3.9 Hz, H-2, exo), 2.25 (s, 1, H-7), 2.03 (m, 1, H-3, exo), 1.38 (dd, 1, J = 11.4, 4.0 Hz, H-3, endo); IR (CH_2Cl_2) ν (C≡O) 2005, 1949, and ν (C≡N) 2230 cm^{-1}. Anal. Calcd for $C_{15}H_{13}FeNO_2$: C, 61.01; H, 4.50. Found: C, 60.91; H, 4.51.

Preparation of 5d Using Diethylchloroalane. Diethylchloroalane (25% solution in toluene, 2.80 mL, 5.3 mmol) was syringed into a CH_2Cl_2 (50 mL) solution at 0 °C containing acrylonitrile (1.05 mL, 16.1 mmol). A CH_2Cl_2 (10 mL) solution containing **4** (1.3 g, 5.3 mmol) was added dropwise over 20 min

(14) Wiberg, K. B.; Lowry, B. R.; Nist, D. J. *J. Am. Chem. Soc.* **1962**, *84*, 1594. Meinwald, J.; Meinwald, Y. C. *Ibid.* **1963**, *85*, 2514. Laszlo, P.; Schleyer, P. R. *Ibid.* **1964**, *86*, 1171.
(15) Luh, T.-Y.; Lung, C. L. *J. Chem. Soc., Chem. Commun.* **1982**, 57.
(16) Wilkinson, G.; Piper, T. S. *J. Inorg. Nucl. Chem.* **1956**, *2*, 32.

to the acrylonitrile/diethylchloroalane mixture at 0 °C and then allowed to warm to 25 °C with stirring over a period of 30 min. The reaction was quenched with water (10 mL) and the aqueous layer was extracted with CH_2Cl_2 (2 × 25 mL). The organic fractions were combined, dried over anhydrous magnesium sulfate, and filtered, and the solvent was removed under reduced pressure. Medium-pressure column chromatography (alumina III, benzene) of the crude product gave ferrocene, exo nitrile, and endo nitrile as three yellow bands, in that order. Removal of solvent from the second and third bands afforded 0.65 g (42%) of *exo*-**5d** and 0.63 g (40%) of *endo*-**5d**, respectively.

Preparation of 5e. Diethylchloroalane (25% solution in toluene, 0.88 mL, 1.5 mmol) was syringed into a CH_2Cl_2 (50 mL) solution at 0 °C containing methyl acrylate (1.4 mL, 15 mmol). A CH_2Cl_2 (10 mL) solution containing **4** (0.36 g, 1.5 mmol) was added dropwise over 20 min to the methyl acrylate/diethylchloroalane mixture at 0 °C. The reaction mixture was allowed to warm to 25 °C and stirred for an additional 30 min. The reaction was then quenched with water (10 mL), and the aqueous layer was extracted with CH_2Cl_2 (2 × 25 mL). The organic fractions were combined, dried ($MgSO_4$), and filtered, and the solvent was removed under reduced pressure. Medium-pressure column chromatography (alumina III, benzene) of the crude product yielded ferrocene, *exo*-**5e**, and *endo*-**5e** as three yellow bands, in that order. Removal of solvent from the latter two bands afforded 0.19 g (43%) of *exo*-**5e** and 0.18 g (42%) of *endo*-**5e**. ***endo*-5e**: ^{1}H NMR ($CDCl_3$) δ 6.10 (dd, 1, J = 3.1, 5.6 Hz, HC=), 5.79 (dd, 1, J = 2.8, 5.6 Hz, HC=), 4.68 (s, 5, C_5H_5), 3.61 (s, 3, CO_2CH_3), 3.06 (m, 1, CH), 2.90 (ddd, 1, J = 4.0, 3.9, 8.8 Hz, CH), 2.77 (s, 1, CH), 2.51 (s, 1, CH), 1.87 (ddd, 1, J = 3.7, 8.8, 11.5 Hz, CH) 1.50 (dd, 1, J = 4.1, 11.5). ***exo*-5e**: ^{1}H NMR ($CDCl_3$) δ 6.03 (m, 1, HC=), 5.99 (m, 1, HC=), 4.71 (s, 5, C_5H_5), 3.69 (s, 3, CO_2CH_3), 2.91 (s, 1, CH), 2.77 (s, 1, CH), 2.72 (s, 1, CH), 2.29 (dd, 1, J = 4.4, 10.0 Hz, CH) 1.83 (ddd, 1, J = 4.0, 3.8, 11 Hz, CH), 1.48 (dd, 1, J = 10.1, 11.0 Hz, CH); IR (CH_2Cl_2) 2003, 1944 cm^{-1}. Anal. Calcd for $C_{16}H_{16}FeO_4$: C, 58.55; H, 4.9. Found: C, 58.52; H, 5.11.

Preparation of 6b. Carbon monoxide was bubbled through a methanol (25 mL) solution containing **5b** (0.94 g, 2.4 mmol) for 15 min. Ammonium cerium(IV) nitrate (6.70 g, 12.1 mmol) was added to the methanol solution in one portion. The resulting clear orange solution was stirred with CO bubbling for an additional 1 h at ca. 20 °C. Water (50 mL) was added to the reaction mixture, and then it was extracted with benzene/ether (1:1, v/v, 2 × 50 mL). The organic fractions were combined, dried over anhydrous magnesium sulfate, and filtered, and the solvent was removed under reduced pressure. The resulting yellow oil was column chromatographed (2 × 10 cm) on alumina III with CH_2Cl_2 to afford pure **6b** (0.48 g, 75%): ^{1}H NMR ($CDCl_3$) δ 6.14 (dd, 2, J = 5.7, 3.1 Hz, HC=), 3.70 (s, 3, CH_3), 3.62 (s, 3, CH_3), 3.57 (s, 3, CH_3), 3.42, 3.38, 2.91 (m's, 3, CH's), 2.70 (d, 1, J = 4.6 Hz, CH); ^{13}C NMR ($CDCl_3$) δ 174.21, 172.57, 171.18 (C=O), 135.58, 133.46 (HC=), 61.08 (CH), 52.26, 51.93, 51.62 (CH_3), 49.27, 47.51, 47.13, 46.91 (CH); IR (CH_2Cl_2) ν (CO) 1731 cm^{-1}. Anal. Calcd for $C_{13}H_{16}O_6$: C, 58.21; H, 6.01. Found: C, 58.54, H, 6.07.

Preparation of 6c. In a similar manner as above **5c** (0.20 g, 0.61 mmol) was oxidized to give **6c** (0.076 g, 60%). **6c** (major isomer): ^{13}C NMR ($CDCl_3$) δ 169.33 (C=O), 137.46, 130.01 (CH=), 120.41 (CN), 62.05, 56.59 (CH), 55.12 (*C*(Cl)CN), 51.92 (CH_3), 45.36 (CH_2), 44.81 (CH). **6c** (minor isomer): ^{13}C NMR ($CDCl_3$) δ 169.85 (C=O), 140.11, 130.55 (HC=), 119.10 (CN), 61.15, 57.50 (CH), 55.12 (*C*(Cl)CN), 51.92 (CH_3), 46.45, 44.43; ^{1}H NMR ($CDCl_3$, both isomers) δ 6.40, 6.36, 6.15, 6.05 (m's, 2, HC=), 3.75 (CH), 3.56 (s, 3, CH_3), 3.34 (br s, CH), 3.13 (m, CH), 2.93 (s, 1, CH), 2.76 (dd, J = 3.6, 13.6 Hz, CH_2), 1.71 (d, J = 13.6 Hz, CH_2); IR (CH_2Cl_2) ν (C=O) 1737 cm^{-1}. Anal. Calcd for $C_{10}H_{10}ClNO_2$: C, 56.75; H, 4.76. Found: C, 56.66; H, 4.80.

Preparation of *exo*-6d. A dry 100-mL, round-bottomed flask was charged with *exo*-**5d** (0.13 g, 0.44 mmol), methanol (40 mL), a stirring bar, and ammonium cerium(IV) nitrate (1.44 g, 2.64 mmol) and placed under a CO atmosphere. The reaction was stirred at room temperature for 4 h. At the end of the 4 h the reaction was poured into water in a 125-mL separatory funnel. The solution was saturated with NaCl and extracted with 50:50 benzene:diethyl ether (3 × 50 mL). The organic layers were combined and dried over anhydrous magnesium sulfate and filtered, and the solvent was then removed under reduced pressure. The remaining yellow residue was drawn up in a minimum of benzene and placed upon a column (alumina III, 0.5 cm in diameter, 5-cm in length). The column was eluted with 100 mL of methylene chloride. The solvent was removed under reduced pressure and the residue placed on an oil pump overnight. This gave 0.53 g (82%) of *exo*-**6d**: IR (CH_2Cl_2) 1736 (CO), 2239 (CN) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.11 (m, 1, HC=), 5.99 (m, 1, HC=), 3.55 (s, 3 CO_2CH_3), 3.45 (s, 1, H-7), 3.29 (s, 1, H-1), 2.77 (s, 1, H-4), 2.19 (dd, 1, J = 4.2, 9.2 Hz, H-2, endo), 2.02 (ddd, 1, J = 3.9, 3.9, 12.3, H-3, exo), 1.56 (dd, 1, J = 9.2, 12.3 Hz, H-3, endo).

Preparation of *endo*-6d. Oxidation of *endo*-**5d** using the same procedure for oxidation of *exo*-**5d** afforded *endo*-**6d** in 63% yield: mp 54–55 °C; IR (KBr) 3056, 2987, 2955, 2238, 1737, 1261, 745 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.34 (dd, 1, J = 5.7, 2.9 Hz, HC=), 6.21 (dd, 1, J = 5.8, 2.9 Hz, HC=), 3.62 (s, 3, H_3CO), 3.53 (m, 1, H-1), 3.34 (s, 1, H-4), 2.97 (dt, 1, J = 9.2, 3.9 Hz, H-2, exo), 2.45 (s, 1, H-7, anti), 2.27 (ddd, 1, J = 12.6, 9.4, 3.6 Hz, H-3, exo), 1.40 (dd, 1, J = 12.2, 3.8 Hz, H-3, endo); MS, m/e calcd for $C_{10}H_{11}NO_2$ 177.0789, found 177.0786.

Preparation of *exo*-6e. Oxidation of *exo*-**5e** (0.61 g, 1.9 mmol) using the same procedure as for oxidation of *exo*-**5d** gave *exo*-**6e** (0.26 g, 80%): IR (CH_2Cl_2) 1731 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.13 (m, 2, HC=CH), 3.72 (s, 3, OCH_3 at C-7), 3.60 (s, 3, OCH_3 at C-2), 3.33 (s, 1, H-7), 3.24 (s, 1, H-1), 2.92 (s, 1, H-4), 2.28 (dd, 1, J = 4.4, 9.1 Hz, H-2, endo), 2.04 (dd, 1, J = 4.3, 12.1 Hz, H-3, exo), 1.43 (dd, 1, J = 9.1, 12.1 Hz, H-3, endo).

Preparation of *endo*-6e. Oxidation of *endo*-**5e** using the same procedure as that for oxidation of *exo*-**5d** gave *endo*-**6e** in 92% yield: IR (CH_2Cl_2) 3056, 2988, 2954, 1732, 1437, 1271, 761 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 6.18 (dd, 1, J = 3.1, 5.9 Hz, HC=), 5.95 (dd, 1, J = 2.8, 5.7 Hz, HC=), 3.65 (s, 3, H_3CO), 3.61 (s, 3, H_3CO), 3.53 (br s, 1, H-1), 3.23 (s, 1, H-4), 3.05 (dt, 1, J = 9.0, 4.0 Hz, H-2, exo), 2.53 (s, 1, H-7), 2.04 (ddd, 1, J = 12.4, 9.4, 3.7 Hz, H-3, exo), 1.50 (dd, 1, J = 12.2, 4.2 Hz, H-3, endo). Anal. (*exo*-, *endo*-**6e**) Calcd for $C_{11}H_{14}O_4$: C, 62.84; H, 6.71. Found: C, 62.70; H, 6.74.

Preparation of 7a. A CH_2Cl_2 solution (25 mL) containing **4** (0.82 g, 3.4 mmol) and dimethyl acetylenedicarboxylate (0.93 g, 0.80 mL, 6.5 mmol) was allowed to stir at 25 °C for 30 min. The solvent was removed under vacuum and the residue medium-pressure chromatographed on alumina III with hexane/ethyl acetate (7:3, v/v). The first yellow band was ferrocene which was not collected. A second yellow band was collected and the solvent removed under vacuum to give pure **7a** (1.10 g, 85%): ^{1}H NMR ($CDCl_3$) δ 6.78 (t, 2, J = 2.0 Hz, CH=), 4.70 (s, 5, C_5H_5), 3.77 (m, 3, CH), 3.76 (s, 6, CH_3); ^{13}C NMR ($CDCl_3$) δ 216.89 (C≡O), 165.96 (C=O), 155.45 (=CCO_2Me), 141.66 (CH=), 85.70 (C_5H_5), 85.17 (CH), 64.62 (CH), 51.78 (CH_3); IR (CH_2Cl_2) ν (CO) 2007, 1951, 1729, 1709 cm^{-1}. Anal. Calcd for $C_{18}H_{16}FeO_6$: C, 56.28; H, 4.20. Found: C, 56.36; H, 4.21.

Preparation of 7b. A carbon monoxide saturated methanol (50 mL) solution containing **7a** (0.62 g, 1.6 mmol) was treated with ammonium cerium(IV) nitrate (5.22 g, 6.4 mmol) at 0 °C. The reaction mixture was handled in a similar fashion as for **6b** above. The crude product was medium-pressure chromatographed on alumina III with CH_2Cl_2/hexanes (4:1, v/v). A UV detector (284 nm) allowed collection of the product **7b** (0.26 g, 60%). This band was preceded by a minor product which has not been identified. ^{1}H NMR ($CDCl_3$) δ 6.87 (t, 2, J = 2.0 Hz, CH=), 4.23 (m, 2, CH), 3.80 (s, 6, CH_3), 3.62 (s, 3, CH_3), 3.36 (t, 1, J = 1.6 Hz, CH); IR (CH_2Cl_2) ν (C=O) 1732, 1712 cm^{-1}. Anal. Calcd for $C_{13}H_{14}O_6$: C, 58.65; H, 5.30. Found: C, 58.67; H, 5.38.

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Registry No. 4, 12247-96-0; **5a**, 84500-50-5; **5b**, 84500-51-6; *exo*-**5c**, 84500-53-8; *endo*-**5c**, 84581-02-2; *endo*-**5d**, 90858-44-9;

exo-5d, 90899-47-1; endo-5e, 90858-45-0; exo-5e, 90899-48-2; 6b, 84500-54-9; exo-6c, 90858-46-1; endo-6c, 90858-47-2; exo-6d, 90858-48-3; endo-6d, 90858-49-4; exo-6e, 90858-50-7; endo-6e, 90858-51-8; 7a, 84500-52-7; 7b, 84500-55-0; maleic anhydride, 108-31-6; dimethyl fumarate, 624-49-7; 2-chloroacrylnitrile, 920-37-6; acrylonitrile, 107-13-1; acetylenedicarboxylate, 44742-97-4; diethylchloroalane, 96-10-6; ammonium cerium(IV) nitrate, 16774-21-3.

Preparation of α- and β-Linked Disaccharides of 2,6-Dideoxy-D-*arabino*-hexose. Synthesis of Bamflalactone

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1,4-α-Linked disaccharides of 2,6-dideoxy-D-*arabino*-hexose are prepared from the selectively protected 2,6-dideoxy sugars **3** or **4** and the 1,5-anhydrohex-1-enitol (**9**) by using the *N*-iodosuccinimide (NIS) method or from the deoxy sugar **6** and the acetylated 2,6-dibromo-2,6-dideoxy-α-D-mannopyranosyl bromide (**13**) in a glycosylation reaction. Dehalogenation leads to the tetradeoxy disaccharides **14**, **15**, and **17**. Deprotection of **17** gives the free α-linked disaccharide **19**. The β-linked disaccharide **27** is obtained by a glycosylation reaction involving **6** and the acetylated 2,6-dibromo-2,6-dideoxy-α-D-glucopyranosyl bromide (**26**). Dehalogenation affords the tetradeoxy disaccharide **29**, from which the free β-linked disaccharide (**31**) is obtained. Catalytic hydrogenolysis of **29** yields **30**, which is converted further into bamflalactone acetate (**28**).

Introduction

2-Deoxy saccharides are found as building units in many natural products having biological activities, for example, in antibiotics such as the orthosomycin group,[1] in anthracyclines,[2] and in cardiac glycosides.[3] Therefore, efforts have been made to develop methods for the synthesis of anomerically homogeneous glycosides of these sugars. In the case of 2-deoxy-α-glycopyranosides, efficient methods have been developed with glycals (1,5-anhydrohex-1-enitols) serving as starting materials. Alkoxyselenation[4] or reaction with alcohols in the presence of *N*-iodosuccinimide (NIS)[5] gave, as a result of anti addition to the double bond, α-glycosides with an axial substituent at C2 (SePh or I), subsequently removable to give α-glycosides of 2-deoxy sugars. Thus, this NIS method has been used extensively to assemble the α-linked sugar sequences in cardiac glycosides.[6] In these reactions, the high stereoselectivity is probably a result of a directing effect from the substituent at C2. That such an effect is operative, also in the case of a bromine atom positioned at C2, follows from our recent studies[7] of the glycosylation reaction between the two readily available[8] C2 epimeric 2,6-dibromo-2,6-dideoxy-D-manno- (**13**) and -D-glucopyranosyl bromides (**26**) and simple alcohols. From the manno isomer (**13**) only α-glycosides were obtained, while the gluco isomer (**26**) and other 2-bromo-2-deoxy sugars with a gluco configuration[7] gave the β-anomers as the main products. In other words 1,2-*trans*-glycosides were obtained in both cases. On hydrogenolysis these products were converted into simple α- or β-2-deoxyglycosides.[7]

In the present paper we describe the usefulness of the method for preparing 2'-deoxy-β-disaccharides including a 1,4-β-linked disaccharide of 2,6-dideoxy-D-*arabino*-hexose (**31**), which was further converted into the acetylated bamflalactone[9] (**28**), thus supporting the structure[8,10,11] of the terminal disaccharide unit in flambamycin.[1,9] We also prepared the corresponding α-anomer (**19**) both by a glycosylation reaction and by applying the NIS method.

Results and Discussion

When 3,4-di-*O*-acetyl-1,5-anhydro-2,6-dideoxy-6-iodo-D-*arabino*-hex-1-enitol (**9**)[12] was allowed to react with methyl 3-*O*-benzyl-2,6-dideoxy-α-D-*arabino*-hexopyranoside (**3**) following the NIS procedure,[5] a high yield of the 1,4-α-linked disaccharide (**10**) was obtained. When the 3-*O*-*p*-nitrobenzoate (**4**) was employed, the disaccharide (**11**) was similarly formed. Alternatively, reaction of 3,4-di-*O*-acetyl-2,6-dibromo-2,6-dideoxy-α-D-mannopyranosyl bromide (**13**)[8] with benzyl 3-*O*-benzyl-2,6-dideoxy-α-D-*arabino*-hexopyranoside (**6**) yielded the 1,4-α-linked disaccharide (**12**). Since the equatorial hydroxy group at C-4

(1) Wright, D. E. *Tetrahedron* **1979**, *35*, 1207.
(2) Kelly, T. R. *Annu. Rep. Med. Chem.* **1979**, *14*, 288.
(3) Reichstein, T.; Weiss, E. *Adv. Carbohydr. Chem.* **1962**, *17*, 65.
(4) Jaurand, G.; Beau, J.-M.; Sinaÿ, P. *J. Chem. Soc., Chem. Commun.* **1981**, *572*.
(5) Thiem, J.; Karl, H.; Schwentner, J. *Synthesis* **1978**, 696.
(6) Thiem, J.; Ossowski, P. *Chem. Ber.* **1981**, *114*, 733.
(7) Bock, K.; Lundt, I.; Pedersen, C. *Carbohydr. Res.*, in press.
(8) Bock, K.; Lundt, I.; Pedersen, C. *Carbohydr. Res.* **1981**, *90*, 7.
(9) Ollis, W. D.; Smith, C.; Wright, D. E. *Tetrahedron* **1979**, *35*, 105.
(10) Thiem, J.; Ossowski, P.; Ellermann, U. *Liebigs Ann. Chem.* **1981**, 2228.
(11) Brimacombe, J. S.; Hanna, R.; Saeed, M. S.; Tucker, L. C. N. *J. Chem. Soc., Perkin Trans. 1* **1982**, 2583.
(12) Descotes, G.; Martin, J.-C.; Tachi-Dung, *Carbohydr. Res.* **1978**, *62*, 61.

0022-3263/84/1949-3063$01.50/0