110 (9.9), 95 (30.4), 82 (22.9); found M^+ = 180.0764, $C_{10}H_{12}O_3$ requires M^+ = 180.0786.

Sodium Borohydride Reduction of the Enone 24 to the Hydroxy Lactone 21a. The enone **24** (36 mg, 0.2 mmol) was dissolved in methanolic $CeCl_3,6H_2O$ (0.07 g in 2.5 mL MeOH), and $NaBH_4$ (0.2 mmol) was slowly added with stirring at 0 °C. The mixture was allowed to react for 10 min and was then treated with water and extracted with ether. The ether layer was dried and evaporated. The residue was purified by chromatography and found to be identical in all respects (IR, ^{1}H NMR, and mass) with the hydroxy lactone **21a**.

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Registry No. 1, 12212-05-4; **2a**, 85994-17-8; **2b**, 91550-49-1; **2c**, 91550-50-4; **2d** (isomer 1), 91684-26-3; **2d** (isomer 2), 91550-51-5; **5**, 91604-69-2; **6**, 85956-43-0; **7** (L = Co), 40674-86-0; **7a**, 12213-31-9; **7b**, 67663-92-7; **8a**, 55744-14-4; **8b**, 85956-40-7; **9a**, 55938-82-4; **9b**, 91550-52-6; **9e**, 85956-45-2; **9f**, 85956-46-3; **9g**, 91550-53-7; **9h**, 91550-54-8; **9i**, 91550-55-9; **9j**, 91550-56-0; **9k**, 91550-57-1; **9l**, 91550-58-2; **9m**, 91550-59-3; **9n**, 91550-60-6; **9o**, 91550-61-7; **9p**, 91550-62-8; **10b**, 91550-63-9; **10c**, 91550-64-0; **10d**, 91550-65-1; **10e**, 85994-18-9; **10f**, 85956-47-4; **10g**, 91550-66-2; **10h**, 91550-67-3; **10i**, 91550-68-4; **10j**, 91550-69-5; **10k**, 91550-70-8; **10l**, 91550-71-9; **10m**, 91550-72-0; **10n**, 91550-73-1; **10o**, 91550-74-2; **10p**, 91550-75-3; **10q**, 85956-48-5; **10r**, 85939-52-2; **10s** (isomer 1), 91604-70-5; **10s** (isomer 2), 91604-71-6; **10t** (isomer 1), 91604-72-7; **10t** (isomer 2), 91604-73-8; **10u** (isomer 1), 91604-74-9; **10u** (isomer 2), 91604-75-0; **10v** (isomer 1), 91604-76-1; **10v** (isomer 2), 91604-77-2; **10w** (isomer 1), 91550-76-4; **10w** (isomer 2), 91604-78-3; **10x** (isomer 1), 91550-77-5; **10x** (isomer 2), 91604-79-4; **11a**, 85939-58-8; **11b**, 85939-60-2; °11°c, 91550-79-7; **12a**, 85939-61-3; **12b**, 85939-62-4; **12c**, 91550-80-0; **12d**, 91550-81-1; **12e**, 85939-63-5; **12f**, 85939-64-6; **12g** (isomer 1), 91550-82-2; **12g** (isomer 2), 91604-80-7; **12h** (isomer 1), 91604-81-8; **12h** (isomer 2), 91604-82-9; **12i** (isomer 1), 91604-83-0; **12l** (isomer 2), 91604-84-1; **12j**, 91550-83-3; **12k**, 91550-84-4; **13c**, 91550-85-5; **13k**, 91550-86-6; **16a**, 91550-40-2; **16b**, 85939-65-7; **16d**, 89860-90-2; **16e**, 91550-41-3; **16f**, 91550-42-4; **16g**, 91550-43-5; **16h**, 91550-44-6; **17g**, 91604-63-6; **17b**, 91604-64-7; **18a**, 91604-65-8; **18b**, 91604-66-9; **19**, 91604-67-0; **21a**, 91550-45-7; **21b**, 91604-68-1; **22a**, 91550-46-8; **23**, 91550-47-9; **24**, 91550-48-0; NaSPh, 930-69-8; $NaSC_6H_4$-*p*-NO_2, 13113-79-6; CC≡CCMgCl, 6088-88-6; $(CC{\equiv}CC)_2CuMgCl$, 91550-87-7; C≡CCMgCl, 2622-05-1; $(C{\equiv}CC)_2CuMgCl$, 91550-88-8; $NaCH(CO_2CH_3)_2$, 18424-76-5; $NaCH(CO_2CH_3)(COCH_3)$, 34284-28-1; $NaCH(SO_2Ph)(CO_2CH_3)$, 60729-65-9; $NaCH(CN)(CO_2CH_3)$, 24163-38-0; $Ph_3C^+PF_6^-$, 437-17-2; PhSeBr, 34837-55-3; cycloheptadiene, 4054-38-0.

Communications to the Editor

Stereospecific Synthesis of P^1,P^2-Bidentate $Co(NH_3)_4$(PPS) and P^1,P^2-Bidentate $Cr(H_2O)_4$(PPS) Enantiomers

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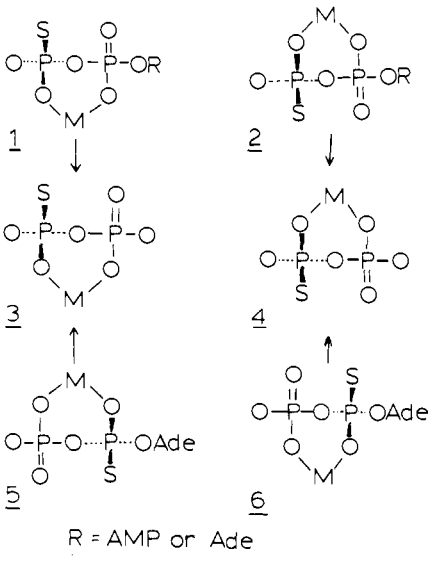
Exchange inert Cr(III) and Co(III) complexes of ATP[1] and ADP have been effectively employed as probes of enzymatic processes that involve Mg(II) complexes of ATP and ADP.[2] Current advances in this area are focussed in part on the development of more versatile enzyme active site probes having Cr(III) or Co(III) complexed to the thiophosphoryl and adjacent phosphoryl centers of the nucleotide analogues, ATPγS and ADPβS. These β,γ-bidentate M^{III}ATPγS and α,β-bidentate M^{III}ADPβS complexes each possess two chiral centers in the phosphate chain and, as a result, will receive unique application in stereochemical studies designed to elucidate the nature of enzyme activation of P–O bond cleavage.

Previous studies have demonstrated that M(III) complexes of ATPγS and ADPβS can be prepared and separated by chromatography on cycloheptaamylose columns and on reverse-phase HPLC columns.[3,4] In addition, the configurations at the chiral phosphoryl centers in these complexes can be correlated with those

Scheme I



of the corresponding bidentate M^{III}ATP and M^{III}ADP complexes through the use of CD techniques.[3,5] The final task in the elaboration of the M^{III}ATPγS and M^{III}ADPβS complexes as stereochemical probes is the assignment of the configurations at the thiophosphoryl centers. We have recently developed an unambiguous technique for accomplishing this task. Our approach, summarized in Scheme I, utilizes the P^1,P^2-bidentate M^{III}PPS enantiomers **3** and **4** as relay species to correlate the unknown configurations at the thiophosphoryl centers in β,γ-bidentate M^{III}ATPγS or α,β-bidentate M^{III}ADPβS (**1** and **2**) with the known configurations at the thiophosphoryl center of the α,β-bidentate M^{III}ADPαS diastereomers **5** and **6**.[6] Importantly,

(1) Abbreviations used: adenosine (Ade), adenosine 5′-monophosphate (AMP), adenosine 5′-triphosphate (ATP), adenosine 5′-diphosphate (ADP), adenosine 5′-(3-thiotriphosphate) (ATPγS), adenosine 5′-(2-thiodiphosphate) (ADPβS), adenosine 5′-(2-thiodiphosphate) (ADPαS), thiopyrophosphate (PPS), pyrophosphate (PP), 2-(morpholino)ethanesulfonate (MES).

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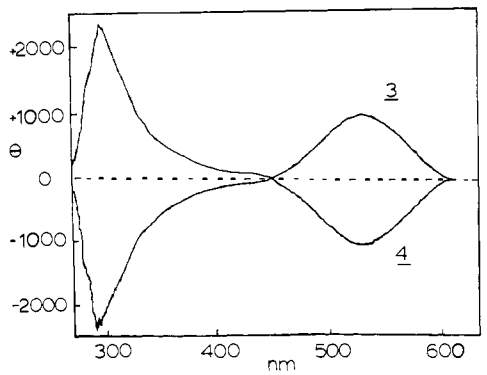

Figure 1. CD spectra of the P^1,P^2-bidentate $Co(NH_3)_4PPS$ enantiomers **3** and **4** generated from the α,β-bidentate $Co(NH_3)_4ADP\alpha S$ α-P epimers.

dissection of the P^1,P^2-bidentate $M^{III}PPS$ units from the nucleotide-bearing metal complexes can be potentially accomplished by enzymatic cleavage or by an oxidation–elimination sequence. In this communication, the feasibility of this approach is demonstrated through the successful synthesis of and stereochemical assignments to the enantiomers of both P^1,P^2-bidentate $Co^{III}PPS$ and P^1,P^2-bidentate $Cr^{III}PPS$.

The α,β-bidentate $Co(NH_3)_4ADP\alpha S$ α-P epimers[6] in a mixture (10 mL, 16.5 mM, pH 5) were separated by chromatography on a cycloheptaamylose column (1.5 × 45 cm) by using 10 mM K^+MES (pH 5.9, 4 °C) as eluant. Solutions containing the individual diastereomers, after concentrating in vacuo to 6 mM and adjusting the pH to 7, were treated with 1 equiv of $NaIO_4$ for 5 min and then with 8 equiv of mercaptoethanol for 5 min to affect oxidative cleavage of the ribose moiety. Liberation of the separate thiopyrophosphate metal complexes by β-elimination was then accomplished by treatment with 0.3 M aniline hydrochloride (pH 5). Product purification was carried out on a Dowex-50 (H^+) column with water as the eluant. The spectroscopic properties of the $Co(NH_3)_4PPS$ enantiomers obtained by use of this sequence in yields of ca. 20% are consistent with those expected λ_{max} 520 nm; ^{31}P NMR (downfield from 0.1 M D_3PO_4) +50.6 (d) and +2.0 ppm (d), J = 24.6 Hz). The CD spectra of these enantiomers, shown in Figure 1, bear a mirror image relationship and differ from those of the precursor $Co(NH_3)_4ADP\alpha S$ diastereomers[6] by a 3-fold reduction in ellipticity at the 525-nm λ_{max} and the appearance of a strong Cotton effect below 350 nm. Finally, solutions of the individual enantiomers stored at pH 4 and 4 °C for several days showed no loss of optical activity.

The applicability of the above-described oxidation–elimination sequence for affecting transformation of the base-labile and paramagnetic α,β-bidentate $Cr(H_2O)_4ADP\alpha S$ to the corresponding P^1,P^2-bidentate $Cr(H_2O)_4PPS$ complexes was first tested by use of the diamagnetic complex α,β-bidentate $Rh(H_2O)_4ADP$.[7,8] The structure and purity of P^1,P^2-bidentate $Rh(H_2O)_4PP$ generated in this way were determined by ^{31}P NMR techniques.[7] Following this successful demonstration, the procedure outlined above, modified only at the oxidative cleavage step,[9] furnished the separate P^1,P^2-bidentate $Cr(H_2O)_4PPS$ enantiomers from pure α,β-bidentate $Cr(H_2O)_4ADP\alpha S$ diastereomers.[6] In this case, the CD spectrum of the enantiomer derived from the Λ diastereomer precursor displays a positive Cotton effect at 610 nm (θ = +100 deg cm^2/dmol) while that coming from the Δ diastereomer shows a negative Cotton effect of the same wavelength and intensity.

The availability of the pure $Co^{III}PPS$ and $Cr^{III}PPS$ enantiomers will in future studies allow us to make configurational assignments at the thiophosphoryl centers of bidentate Cr(III) or Co(III) complexes of ATPγS and ADPβS as well as to probe the stereospecificity of enzymes which in vivo process MgPP.

Acknowledgment. We are grateful to P. Frey for helpful discussions and to the American Hearth Association (83918) and the National Institutes of Health (GM-28688 and ES-00111) for support.

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(8) Like $Cr(H_2O)_4ADP\alpha S$, $Rh(H_2O)_4ADP$ is sensitive to base-catalyzed ligand exchange.
(9) The oxidations of the $Cr(H_2O)_4ADP\alpha S$ and $Rh(H_2O)_4ADP$ were both carried out at pH 6 rather than 7.

Indirect Electrooxidation of Amines to Nitriles Using Halogen Ions as Mediators[1]

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Indirect electrooxidation using mediators makes it possible to achieve the oxidation of organic compounds with a catalytic amount of chemical oxidizing agent (mediator).[2] Electrooxidation of amines to nitriles has been developed using direct oxidation[3a-d] as well as using nitroxyl radical[3e] as the mediator. This report describes oxidation of amines **1** to nitriles **2** by electrooxidation using halogen ions as mediators (Scheme I).

In a typical procedure, a solution of octylamine (517 mg, 4 mmol) in methanol (30 mL) containing NaBr (618 mg, 6 mmol) was placed in a cell equipped with a carbon rod cathode (8 mm ϕ) and a platinum anode (2 × 2 cm). The distance between two electrodes was 3 mm and no diaphragm was used. A constant current (0.3 A, 75 mA/cm^2, terminal voltage 5–7 V) was passed through the cell at about 10 °C with external cooling. After 8.6 F/mol of electricity was passed, the yield (95%) of heptyl cyanide was determined by GLC method. Then, solvent was evaporated in vacuo at room temperature, and the residue was poured into water. The product, heptyl cyanide, was extracted with CH_2Cl_2 and isolated by bulb-to-bulb distillation (400 mg, 3.20 mmol, 80%).[4] The reaction conditions and the yields of nitriles are summarized in Table I.

The yields of heptyl cyanide from octylamine were satisfactory when bromides were used as the supporting electrolyte (KBr, 76%; $LiBr\cdot H_2O$, 73%; Et_4NBr, 95%), whereas the use of KI or NaCl gave poor results (KI, 28%; NaCl, 26%),[5] and using Et_4NOTs did not afford the corresponding nitrile.[5]

The reaction pathway for the formation of nitriles from amines could be described as Scheme II. The reaction of oxidized active species "Br^+" (**3**)[6] with **1** in the presence of bases[7] formed by cathodic reaction will yield bromoamines **4** as the first intermediates, which are then converted to imines **5** through dehydrobromination. The intermediates **5** will again react with **3** to yield nitriles **2**.

The formation of adiponitrile from 1,2-diaminocyclohexane (Table I, entry 8) requires carbon–carbon bond fission between two carbon atoms bearing the amino groups. Several mechanisms

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(2) For example, see: Shono, T. *Tetrahedron* **1984**, *40*, 811.
(3) (a) Barnes, K. K.; Mann, C. K. *J. Org. Chem.* **1967**, *32*, 1474. (b) Hampson, N. A.; Lee, J. B.; MacDonald, K. I. *Electrochim. Acta* **1972**, *17*, 921. (c) Blackham, A. U.; Kurak, S.; Palmer, J. L. *J. Electrochem. Soc.* **1975**, *122*, 1081. (d) Feldhues, U.; Schäfer, H. J. *Synthesis* **1982**, 145. (e) Semmelhack, M. F.; Schmid, C. R. *J. Am. Chem. Soc.* **1983**, *105*, 6732.
(4) IR (neat) 2250 cm^{-1}; NMR (CCl_4) δ 0.90 (t, 3 H, J = 4 Hz), 1.00–1.93 (m, 10 H), 2.27 (t, 2 H, J = 6 Hz). The purity of the distillate was more than 97% based on its NMR and GLC analyses.
(5) The amine was almost consumed, and formation of a variety of unidentified high-boiling products was observed by GLC.
(6) "Br^+" denotes the positive bromine species anodically generated from bromide anion.
(7) For examples of electrogenerated base, see: (a) Baizer, M. M.; Chruma, J. L.; White, D. A. *Tetrahedron Lett.* **1973**, 5209. (b) Allen, P. M.; Hess, U.; Foote, C. S. *Synth. Commun.* **1982**, *12*, 123. (c) Iversen, P. E.; Lund, H. *Tetrahedron Lett.* **1969**, 3523. (d) Shono, T.; Kashimura, S.; Ishizaki, K.; Ishige, O. *Chem. Lett.* **1983**, *1311*. (e) Shono, T.; Kashimura, S.; Nogusa, H. *J. Org. Chem.* **1984**, *49*, 2043.

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