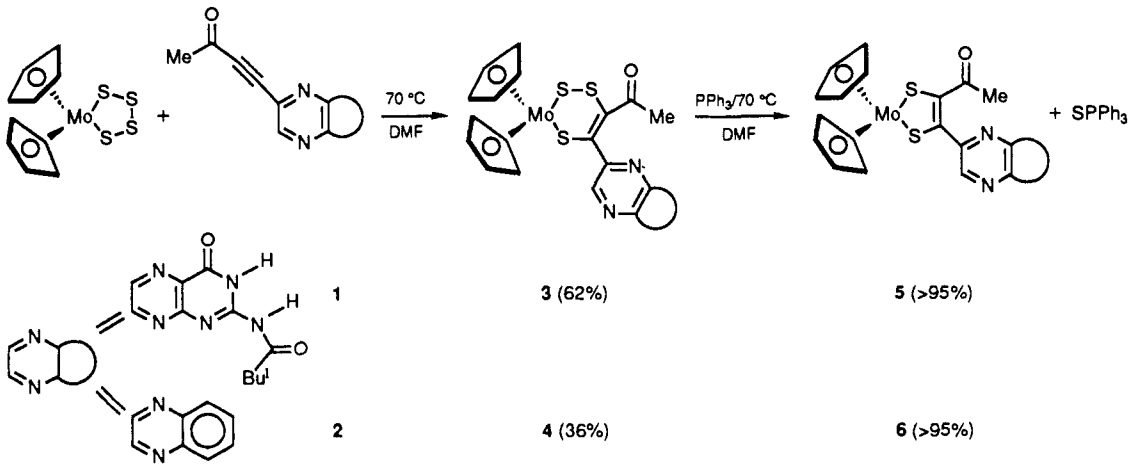
Scheme I



with a deviation from planarity of only 0.01 Å. This plane bisects the dihedral angles defined by the cyclopentadienyl rings. The bond lengths and angles in complex **6** are similar to other crystallographically characterized 1,2-enedithiolate complexes of molybdenum.[4c,d,9] The plane of the quinoxaline ring forms a 94.0° angle with the S(1), C(19), C(20), S(3) plane in complex **8** and a 19.5° angle with the S(1), C(13), C(14), S(2) plane of complex **6**.

The preparation of complexes **3** and **4** and the conversion of these complexes to **5** and **6**, respectively, are important to the mechanistic understanding of 1,2-enedithiolate synthesis from the reaction of metal polysulfides and alkynes. In many instances vinyl disulfides are the initial products from the reaction of a metal polysulfide complex and an alkyne. The vinyl disulfides are isomerized to the 1,2-enedithiolate complexes by exogenous sulfur,[4c-g] and the trithiolate complex is a likely intermediate.[4d] Here we provide the first definitive examples of such complexes and demonstrate that they are indeed readily converted to 1,2-enedithiolates.

Complex **5** was ≥90% enriched in ^{34}S and the natural abundance and ^{34}S-enriched samples have been studied by resonance Raman spectroscopy. The Mo–S stretch in complex **5** is identified as a band at 349 cm^{-1} which upon ^{34}S enrichment shifts to 341 cm^{-1}.[12] The Moco enzyme DMSO reductase (oxidized) from *Rhodobacter sphaeroides* has a band at 350 cm^{-1}, which upon ^{34}S enrichment shifts to 341 cm^{-1}.[13]

An interesting feature of complexes **3** and **5** is the weak fluorescence of the oxidized pterin. This stands in contrast to the very strong fluorescence of **1**, which emits at 496 nm with excitation maxima at 362 nm or 420 nm. At the same concentration as compound **1**, complexes **3** and **5** show greater than 95% quenching of the fluorescence. Since the observed fluorescence has the identical excitation profile as compound **1**, it is likely that complexes **3** and **5** are not fluorescent and that a small impurity of compound **1** causes the observed fluorescence. In any case, it is clear that metallodithiolates on the C(6) side chain of an oxidized pterin quench the fluorescence of the pterin.

The results presented here show that the reaction of a molybdenum polysulfide and an alkyne could be an important component of the total synthesis of active molybdenum cofactor. Moreover, the pterin–dithiolene complexes that have now been produced are the closest structural analogues of the molybdenum–dithiolene–pterin portion of the Moco active site and as such are useful spectroscopic and reactivity models for the native center. Work on synthetic, spectroscopic, and reactivity aspects of these complexes is continuing.

Acknowledgment. We thank Exxon Research and Engineering, Co. and the National Institutes of Health (DK35642 to Princeton University) for supporting this research.

Registry No. **1**, 131863-93-9; **2**, 136863-52-0; **3**, 136863-53-1; **4**, 136863-54-2; **5**, 136863-55-3; **6**, 136863-56-4; Moco, 73508-07-3; Cp_2MoS_4, 54955-47-4.

Supplementary Material Available: Tables of crystallographic data, atomic coordinates, bond distances and angles, and anisotropic thermal parameters, spectroscopic data for complexes **3–6** and the preparation of $Cp_2Mo^{34}S_4$ (11 pages); structure factor tables for **4** and **6** (17 pages). Ordering information is given on any current masthead page.

(12) The spectra of **5** (natural abundance and ^{34}S labeled) were obtained with a backscattering geometry from a KCl pellet mounted on a cold finger cooled to 77 K. The spectra were collected with 568.1-nm laser excitation from a coherent Kr^+ ion laser. Conditions: 80 mw laser output and 4-cm^{-1} resolution. The light was dispersed through a Spex 1401 double monochromator equipped with photon-counting electronics.

(13) Gruber, S.; Kilpatrick, L. T.; Bastian, N. R.; Rajagopalan, K. V.; Spiro, T. G. *J. Am. Chem. Soc.* **1990**, *112*, 8179.

Isolation and Characterization of Stereoisomers of Pentacoordinated Phosphorus. Hydrolysis of Unsymmetrically Substituted Chiral Monocyclic Oxyphosphoranes

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Pentacoordinated phosphorus compounds (phosphoranes) have attracted attention as models for the intermediate or transition state in nonenzymatic and enzymatic phosphoryl transfer reactions.[1] The stereochemical course and product distribution of

(1) (a) Westheimer, F. H. *Acc. Chem. Res.* **1968**, *1*, 70–78. (b) Buchwald, S. L.; Pliura, D. H.; Knowles, J. R. *J. Am. Chem. Soc.* **1984**, *106*, 4916–4922. (c) Knowles, J. R. *Ann. Rev. Biochem.* **1980**, *49*, 877–919. (d) van Ool, P. J. J. M.; Buck, H. M. *Recl. Trav. Chim. Pays-Bas* **1984**, *103*, 119–122. (e) Holmes, R. R. *Pentacoordinated Phosphorus*; American Chemical Society: Washington, DC, 1980; Vol. II, p 87 and references cited therein.

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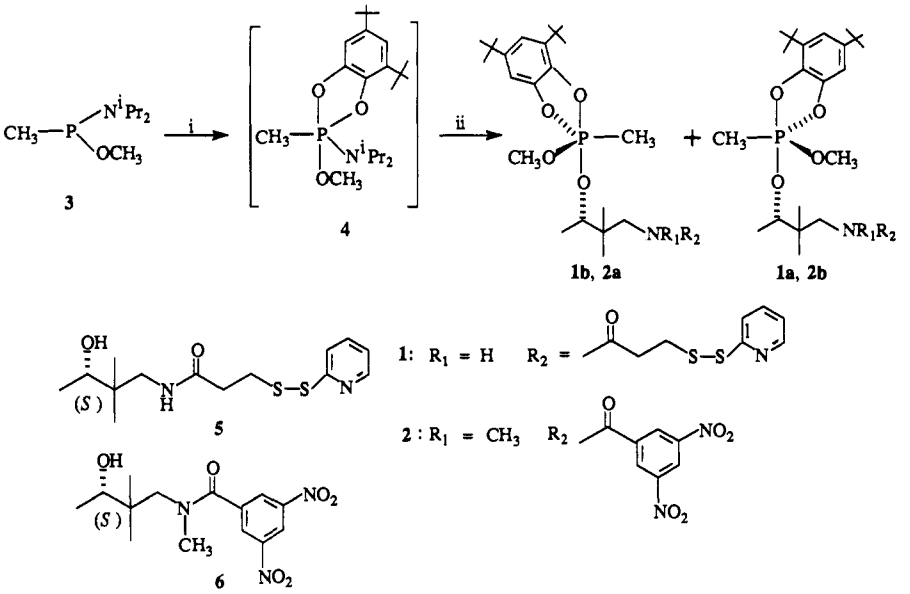
Scheme I[a]



[a] Reagents and conditions: (i) 3,5-di-*tert*-butyl-1,2-benzoquinone (1 equiv), dry CH_2Cl_2, 0–25 °C, 2 h; (ii) alcohols **5** or **6** (1 equiv), 1*H*-tetrazole (10 mol %), dry CH_2Cl_2, 0–25 °C, 1 h.

Table I. ^{31}P, ^1H, and ^{13}C NMR Data and Specific Rotations for Phosphoranes **1a,b** and **2a,b**[a]

phosphoranes	$\delta^{31}P$[b] (ppm)	δ^1H (ppm) for CH_3P[c] [coupling const (Hz)]	$\delta^{13}C$ (ppm) for CH_3P[c] [coupling const (Hz)]	$[\alpha]^{25}_D$ (deg)
1a	−20.36	1.85 (d, 17.3)	20.8 (d, 188.2)	+5.56[d]
1b	−20.39	1.81 (d, 17.4)	20.5 (d, 191.0)	+11.9[e]
2a	−20.70	1.88 (d, 17.5)	21.4 (d, 190.8)	+9.40[f]
2b	−20.17	1.85 (d, 17.6)	20.9 (d, 193.0)	+2.94[g]

[a] Phosphoranes **1a**, **1b**, and **2b** were purified by flash column chromatography on silica gel (hexane–AcOEt–NEt_3, 5:2:0.7 and hexane–CH_2Cl_2–NEt_3, 9:1:1, respectively). Phosphorane **2a** was crystallized from hexane–NEt_3, 9:1. [b] Solvent is $CDCl_3$. Chemical shifts downfield of the reference (85% H_3PO_4 as an external standard) are indicated as positive. [c] Methyl group bound to phosphorus. Solvent is $CDCl_3$. [d] *c* 0.9, $CHCl_3$. [e] *c* 1.03, $CHCl_3$. [f] *c* 1.0, CH_2Cl_2. [g] *c* 1.02, CH_2Cl_2.

phosphoryl transfer reactions have been discussed in terms of structure, stereochemistry, and pseudorotational processes of the proposed pentacoordinated intermediate.[2,1e] Such intermediates or transition states often involve a chiral pentacoordinated phosphorus if it is substituted unsymmetrically. Accordingly, the isolation and characterization of stereoisomers at pentacoordinated phosphorus offers a promising approach for the study of the stereochemistry of phosphoryl transfer reactions as well as for the study of stereochemical nonrigid aspects of phosphoranes. The isolation of stereoisomers of chiral phosphoranes is problematic because of the very low activation energies for pseudorotational interconversions.[3]

We now report the isolation and characterization of diastereomerically related stable pseudorotamers of chiral monocyclic oxyphosphoranes **1** and **2** having five different substituents bound to phosphorus (Scheme I). Phosphoranes **1** and **2** were synthesized according to the method reported previously.[4] Substitution of the *N,N*-diisopropylamino group in the key intermediate **4** by the alcohols **5** or **6** proceeded only in the presence of 1*H*-tetrazole as a catalyst,[5] giving the oxyphosphoranes **1** and **2** in 78 and 91% yield, respectively. Each compound gave two spots on TLC, two signals of approximately equal intensity in ^{31}P NMR, and two sets of signals for ^1H and ^{13}C NMR, indicating that **1** and **2** were composed of two diastereomerically related isomers with different configuration around phosphorus **1a**, **1b** and **2a**,

Table II. Phosphorus Bond Lengths (Å) and Angles (deg)

P(1)–O(2)	1.627 (9)	P(1)–O(9)	1.792 (9)
P(1)–O(10)	1.648 (8)	P(1)–O(22)	1.545 (8)
P(1)–C(24)	1.772 (12)		
O(9)–P(1)–C(24)	85.2 (5)	O(2)–P(1)–O(9)	87.2 (4)
O(2)–P(1)–O(10)	89.8 (4)	O(10)–P(1)–C(24)	90.3 (5)
O(9)–P(1)–O(22)	94.1 (4)	O(10)–P(1)–O(22)	94.5 (4)
O(2)–P(1)–O(22)	115.5 (4)	O(22)–P(1)–C(24)	116.2 (5)
O(2)–P(1)–C(24)	128.2 (5)	O(9)–P(1)–O(10)	171.3 (4)

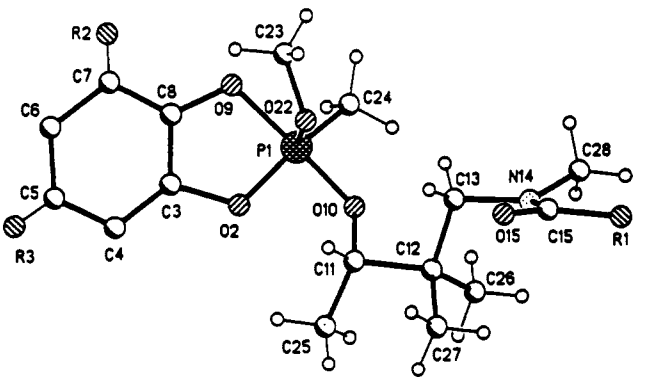


Figure 1. The molecular structure and numbering scheme for the chiral phosphorane **2a**; R1 is the 3,5-dinitrophenyl group, and R2 and R3 are the *tert*-butyl groups.

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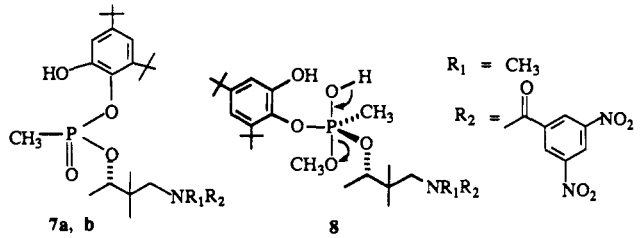
(3) Chiral spirophosphoranes have been synthesized and one of the stereoisomers of them has been isolated by fractional crystallization accompanied by a second-order asymmetric transformation: Klaebe, A.; Carrelhas, A.; Brazier, J.-F.; Houalla, D.; Wolf, R. *Phosphorus and Sulfur* **1977**, *3*, 61–76. Klaebe, A.; Brazier, J. F.; Carrelhas, A. C.; Garrigues, B.; Marre, M. R.; Contreras, R. *Tetrahedron* **1982**, *38*, 2111–2122, and references cited therein.

(4) Moriarty, R. M.; Hiratake, J.; Liu, K. *J. Am. Chem. Soc.* **1990**, *112*, 8575–8577.

(5) Without catalyst, no reaction was observed after 2 h; however, the reaction was completed in 30 min at room temperature in the presence of 0.1 equiv of 1*H*-tetrazole.

2b, respectively. These diastereomers were separated by silica gel column chromatography under basic conditions (**1a**, **1b**, and **2b**) or fractional crystallization (**2a**) (Table I).

The configuration of the crystalline phosphorane **2a** was determined by X-ray diffraction analysis. The distances and angles involving the pentacoordinated phosphorus atom are listed in Table II. The coordination is best described as an almost regular trigonal bipyramid (see Figure 1), with atoms O9 and O10 lying on the trigonal axis, and all angles falling within 10° of the ideal values (90, 120, and 180°). Knowledge of the absolute configuration of C(11) as (*S*)[6] reveals the configuration of the chiral pentacoordinated phosphorus. Another notable feature of these phosphoranes is that the configuration around the phosphorus is interconvertible between the two diastereomeric forms **2a** and **2b** by heating, although the configuration is stable enough to allow the isolation of each form at room temperature. The kinetics of the interconversion was the first order; **2a** was heated at 90 °C to give a 1:1 mixture of **2a** and **2b** with a first-order rate constant of 2.40×10^{-2} [min^{-1}].[7] The Gibbs energy of activation for the formation of **2b** was calculated to be 27.0 [Kcal mol^{-1}] at this temperature. This value is one of the highest energy barriers found for a pseudorotational process of phosphoranes.[8] As a dynamic aspect of chiral phosphoranes, the acid-catalyzed hydrolysis of **1** and **2** was examined.[9] Diastereomer **2a** reacted immediately with 0.1 N HCl to give a 1:1 mixture of two diastereomeric phosphonates **7a** and **7b**, but surprisingly the other diastereomer **2b** under the same conditions gave **7a** and **7b** in unequal amount (27:73).[10] Nucleophilic attack of water was at phosphorus, not



7a, b **8**

at the carbon of the methoxy group of **2b** during the hydrolysis, since ^{18}O was incorporated into the phosphoryl group (P=O) of the phosphonate **7** (*m/z* 610, $[M + 1]^+$) when **2b** was hydrolyzed in $H_2{}^{18}O$.[11] Upon the basis of the relative chemical shifts in phosphonates **7a** ($\delta^{31}P$, +33.85 ppm, $\delta^{13}C$, 10.85 ppm, J = 145.2 Hz) and **7b** ($\delta^{31}P$, +32.41, $\delta^{13}C$, 11.94 (J = 142.7 Hz) we assign the major stereoisomer **7b** as possessing the *R* configuration at phosphorus.[12] We believe the selectivity is based on the relative stabilities of two diastereomeric transition states which yield two diasteromeric hydroxyphosphoranes (**8** → **7a**, **7b**).

Acknowledgment. We thank the U.S. Army Medical Research and Development Command for support of the work under Contract No. DAMD 17-88-C-8021 and Dr. David Lenz, Biochemical Pharmacology Branch of the USAMRICD, for valuable discussions. The research of R.G. was supported in part by the Office of Naval Research.

Supplementary Material Available: Experimental details, molecular structure of **2a**, and tables of phosphorane epimerization, atomic coordinates, and bond lengths and angles (18 pages). Ordering information is given on any current masthead page.

(6) The alcohol **5** and **6** were synthesized from (*S*)-3-hydroxy-2,2-dimethylbutanenitrile prepared by yeast reduction of 2,2-dimethyl-3-oxobutanenitrile. The stereochemistry of the yeast reduction of unsymmetric ketones is well established: Prelog, V. *Pure Appl. Chem.* **1964**, *9*, 119. Zhou, B.-N.; Gopalan, A. S.; VanMiddlesworth, F.; Shieh, W.-R.; Sih, C. J. *J. Am. Chem. Soc.* **1983**, *105*, 5925.

(7) A solution of **2a** (15 mg) in $CDCl_3$ (600 μL) was placed in a sealed tube and heated at 90 °C for certain periods of time; the course of the reaction was determined with ^{31}P NMR.

(8) (a) Holmes, R. R. Pentacoordinated Structures. In *Progress in Inorganic Chemistry*; Lippard, S. J., Ed.; John Wiley & Sons: New York, 1984; Vol. 32, p 119. (b) Holmes, R. R. *Pentacoordinated Phosphorus*; American Chemical Society: Washington, DC, 1980; Vol. I, pp 101-233.

(9) The phosphoranes **1** and **2** are extremely labile to aqueous acids but hydrolytically stable in neutral and basic conditions; they remained unchanged for at least 3 days in the presence of water or 0.1 N NaOH at room temperature. Also see ref 4.

(10) Similar results were obtained for the acid hydrolysis of **1**: the diastereomer **1a** gave a 63:36 mixture of the corresponding diasteromeric phosphonates, whereas **1b** afforded a 1:1 mixture. These phosphonates are configurationally stable, and no epimerization around phosphorus was observed in acidic conditions used for the hydrolysis.

(11) No oxygen of phosphonate **7b** was exchanged in the same reaction conditions as used for the hydrolysis (0.2 N HCl in $H_2{}^{18}O$, 25 °C, 20 min).

(12) For the four stereoisomers of a series of compounds $CH_3PO(OCH_3)[OCH(CH_3)C(CH_3)_2X]$ the P_R series has for $\delta^{31}P$, $\delta^{13}C$ (ppm) X = CN, 32.57, 10.87; NH_2, 32.26, 10.72; $NHCO(CH_2)_2CO_2H$, 34.98, 10.36; while in the P_S series X = CN, 31.64, 11.76; NH_2, 31.51, 12.97; $NHCO(CH_2)_2CO_2H$, 33.83, 11.44. The P_S chemical shift is invariably higher field, while the ^{13}C chemical shift is invariably lower field. The configuration of **7b** is therefore corresponding to P_S series but is designated *R* because of the sequence rule.

Synthesis of β-Mannopyranosides by Intramolecular Aglycon Delivery

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As the biological significance of glycosylation becomes increasingly evident,[1] the generation of reliable methods for the synthesis of complex oligosaccharides becomes even more important. Despite the great ingenuity applied in recent years to the development of new synthetic methods for stereospecific glycoside formation,[2] the construction of the 1,2-*cis*-β-D-mannopyranosidic linkage remains a particular problem.[3] We present here a new strategy for the construction of 1,2-*cis*-glycosidic linkages and the results obtained on its application to β-mannosides. This strategy (Scheme I) involves first the covalent attachment of the aglyconic alcohol (**1**) to a group on O-2 of a latent glycosyl donor (**2**) in a coupling reaction where stereospecificity is not a concern. Adduct **3** could conceivably be prepared in two ways as shown. Next, the aglycon is delivered *intra*molecularly in a concerted reaction to produce the intermediate **4**, which, on quenching with water, would give β-mannoside **5**. Quenching with other nucleophiles might yield β-mannosides protected at O-2. There are many possibilities for groups X, Y, and Z, and their selection will be critical to the success of this approach. We report here the results of initial experiments with one such set of groups.

Treatment of vinyl ether **6** (obtained in 83% yield by reaction of the 2-*O*-acetate with Tebbe's reagent[4]) with an equimolar

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