Water-Soluble Complexes of Tertiary Phosphines and Rhodium(I) as Homogeneous Catalysts[1]

Sir:

The low solubility of common phosphine–transition metal complexes in water has inhibited their application to catalytic transformations in aqueous solutions. Recent experiments have established that complexes derived from $Ph_2P(m\text{-}C_6H_4\text{-}SO_3Na)$[2] are catalytically active in homogeneous olefin hydrogenation and hydroformylation reactions in water.[3-5] Complexes derived from bidentate ligands can have useful differences in chemical stability and catalytic activity from analogous complexes containing only monodentate ligands.[6] Here we report the development of coupling reactions which permit the facile conversion of (bis(2-diphenylphosphinoethyl)amine (**1**)[7,8] to a wide variety of water-soluble diphosphines

Table I. Homogeneous Hydrogenation Reactions in Water (TN = Turnover Number, h^{-1})^a

substrate	product^b	catalyst	TN initial, h^{-1} ^{c}	TN total^d
CH_2=C(NHAc)CO$_2$H		3-Rh(I)	>200	4070 (20)^e
(Z)-PhCH=C(NHAc)CO$_2$H			>30	600 (20)^e
CH_2=CHCONH$_2$			>12	1000 (86)^e
(E)-CH$_3$CH=CHCO$_2$H			13	560 (110)
(E)-4(OH)C$_6$H$_4$CH=CHCO$_2$H			13	540 (88)
(E)-HO$_2$CCH=CHCO$_2$H			48	970 (20)
			144^f	259 (18)
			130^g	570 (4.5)
[CH$_2$=CHCH$_2$NCOCHOH$\cdot$]$_2$			6.2	300 (66)
$\underline{CH_2}$=CHCH$_2$NHCONH$_2$	(CH$_3$CH=CHNHCONH$_2$)		7.0	410 (90)
$\underline{CH}$=CH(CH$_2$)$_3$CH$_2$			1.6	32 (20)
FMN^h	FMNH$_2$^{h}		5.0	300 (70)
CH$_3$COCO$_2$H	CH$_3$CHOHCO$_2$H		14	600 (85)^c
CH_2=CHCH$_2$OH	(CH$_3$CH$_2$CHO)		19	330 (18)
		5-Rh(I)	4.4	84 (19)
		8-Rh(I)	2.0	40 (20)
		10-Rh(I)	1.5	27 (18)
		11-Rh(I)^i	23	140 (6)
		(PhP)$_3$RhCl^j	130	800 (6)
		4(H$^+$)$_2$-Rh(I)^j	25	445 (18)
oxidized lipoic acid		3-Rh(I)	no reaction	
(HOCH$_2$CH$_2$S)$_2$			no reaction	
CH_2=CHCH$_2$NHCSNH$_2$			no reaction	
bicyclo[2.2.1]hept-2-ene-5,6-dicarboxylic acid			no reaction	
iron(III)			no reaction	

^{a} Unless otherwise indicated, hydrogenations were carried out in 0.1 M phosphate buffer, pH 7.0, T = 25 °C, P(H$_2$) = 32 psi. ^{b} The product is that derived by reduction of the C=C group unless indicated otherwise. Products derived from isomerization of the olefinic linkage are indicated in parentheses. ^{c} The initial turnover number ((moles of substrate transformed) (mol of Rh)$^{-1}$ h^{-1}) was calculated from data obtained over the first 20 h of reaction. ^{d} The total turnover is the number of moles of substrate transformed per mole of Rh in the indicated time. ^{e} These values represent minimum rates; the samples used were completely hydrogenated in the interval indicated. ^{f} T = 60 °C, P(H$_2$) = 32 psi. ^{g} T = 25 °C, P(H$_2$) = 120 psi. ^{h} FMN = flavin mononucleotide; FMNH$_2$ = dihydroflavin mononucleotide. ^{i} 11-Rh is [CH$_3$O-(CH$_2$CH$_2$O)$_{\sim 15}$–CH$_2$CH$_2$PPh$_2$]$_2$Rh. This ligand was prepared by treating CH$_3$O(CH$_2$CH$_2$O)$_{\sim 16}$–H with thionyl chloride, followed by reaction of the resulting chloride with potassium diphenylphosphine; cf. D. Feitler, Ph.D. Thesis, MIT, 1977. ^{j} In acetone solution.

Scheme I. Synthesis of Water-Soluble Diphosphines
(Tau = Sodium Taurinate, NH$_2$CH$_2$CH$_2$SO$_3^-$Na$^+$)^{10}
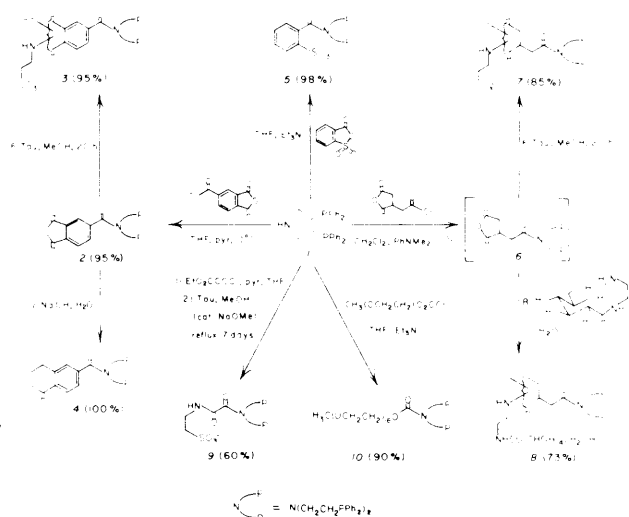
(Scheme I), and a survey of the catalytic activity of rhodium complexes of several of these new ligands.

Trimellitic anhydride acid chloride, *o*-sulfobenzoic anhydride, and ethyl oxalyl chloride are commercially available; tricarballylic α,β-anhydride acid chloride was prepared by standard procedures.[9] The conditions used for the coupling reactions were unexceptional. Although the product diphosphines were difficult to purify to homogeneity, ^{1}H and ^{31}P NMR spectroscopy, IR spectroscopy, and solubility provided good evidence for the assigned structures. The corresponding rhodium complexes X-Rh(I)NBD$^+$Tf$^-$ (NBD = norbornadiene, Tf$^-$ = triflate) were prepared in situ and used without
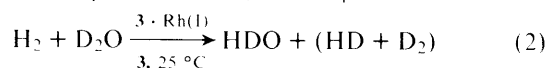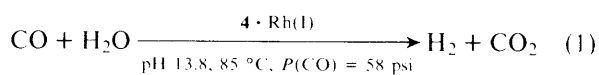
characterization.[10,11] Both the phosphines and the derived rhodium complexes appeared to form homogeneous solutions in water, although certain of these solutions may contain micelles, especially at high concentrations. Complex 7 appeared to be the most soluble, with a concentration in saturated aqueous solution of ~0.3 M (pH 7.0, 25 °C).

A representative hydrogenation was conducted as follows. Into a 5-mL round-bottomed flask equipped with a Teflon-coated stirring bar was weighed 3.6 mg (8.0 μmol) of [Rh(NBD)Cl]$_2$ and 4.0 mg (16 μmol) of AgTf. The flask was capped with a rubber septum and flushed thoroughly with argon. Dioxane (0.5 mL, distilled from NaBH$_4$ under argon) was added by syringe. The mixture was stirred for 5 min and the resulting yellow-orange solution decanted from the AgCl precipitate by cannula into a solution of 13.8 mg (17.5 μmol) of 3 in 1.0 mL of aqueous dioxane (1:1). The solution was stirred for an additional 15 min and transferred by cannula into an argon-flushed pressure reaction bottle (Lab Glass) containing 8.40 g (65.1 mmol) of α-acetamidoacrylic acid suspended in 200 mL of 0.1 M aqueous phosphate buffer (initial pH 7.60 before the addition of the substrate).[13] The system was purged with hydrogen for 5 min, the hydrogen pressure adjusted to 32 psi, and the reaction mixture stirred at ambient temperature. Aliquots removed from the reaction bottle by cannula under a positive hydrogen pressure were analyzed by a combination of GLC and NMR spectroscopy.

Table I summarizes the activity of these complexes in the hydrogenation of representative substrates: Most data were obtained using 3-Rh(I)NBD$^+$Tf$^-$, since it was easy to prepare and manipulate. The order of reactivity of olefinic substrate in hydrogenation is similar to that observed in organic solvents. The catalysts are poisoned by sulfur-containing compounds. Comparison of the activity toward allyl alcohol of 3-Rh(I) in

water with that of the structurally similar $4(H^+)_2 \cdot Rh(I)$[14] in acetone suggests little or no rate supression due to water.[15] Catalyst $4(H^+)_2 \cdot Rh(I)$ is less active than Wilkinson's catalyst by approximately a factor of 5–10 in acetone solution.

Water-soluble diphosphine–rhodium complexes show catalytic activity in potentially useful types of reactions other than homogeneous hydrogenation. For example, $4 \cdot Rh(CO)Cl$[16] in the presence of fourfold excess of 4 catalyzes the shift reaction (eq 1; TN = 32 h^{-1}),[17] while $3 \cdot Rh(I)NBD^+Tf^-$ in the presence of 1 equiv of added 3 catalyzes exchange between water and dihydrogen (eq 2, TN = 8 h^{-1} (0.1 M NaOAc); TN = 10 h^{-1} (0.1 M HOAc)). A similar catalysis of eq 2 was found using $7 \cdot Rh(I)$ in the presence of a twofold excess of 7 (TN = 5 h^{-1}).

$$CO + H_2O \xrightarrow[\text{pH 13.8, 85 °C, } P(CO) = 58 \text{ psi}]{4 \cdot Rh(I)} H_2 + CO_2 \quad (1)$$

$$H_2 + D_2O \xrightarrow[\text{3, 25 °C}]{3 \cdot Rh(I)} HDO + (HD + D_2) \quad (2)$$

These results establish a practical strategy for the synthesis of water-soluble chelating diphosphine complexes of transition metals, and illustrate that the catalytic activity of these complexes in water need not be intrinsically small, nor their stability inherently low. Using these catalysts, it may be possible to effect types of transformations which cannot be easily accomplished using conventional catalysts: the homogeneous reduction of biological substrates by dihydrogen represented by FMN → FMNH$_2$ represents one such example. We will describe further applications of water-soluble phosphine–metal complexes in catalysis in subsequent publications.

References and Notes

(1) Supported by the National Institutes of Health (5 T32 CA 09112CT) and the National Science Foundation (7711282 CHE).
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(11) The ^{31}P NMR spectrum of the model complex of $CH_3CON(CH_2CH_2PPh_2)_2$ with $PtCl_2$ at ambient temperature shows a complex spectral pattern with the coupling constant expected for a cis-P–Pt–P coordination (J_{Pt-P} = 3600 Hz; see Kennedy, J. D.; McFarlane, W.; Puddephatt, R. J.; Thompson, P. J. *J. Chem. Soc. Dalton Trans.* **1976**, 874–879). The solution chemistry of related rhodium–phosphine complexes is influenced by the presence of other groups in the ligand capable of coordination.[5] Bidentate complexes of analogous ligands with nickel(II) are well established.[7]
(12) The amine used in making 8 was prepared by reaction of D-glucono-δ-lactone with tenfold excess of ethylenediamine for 20 h at ambient temperature.
(13) The use of a phosphate buffer is not essential. The buffer employed here served only to increase the initial solubility of the substrate.
(14) $4(H^+)_2 \cdot Rh(I)$ is the rhodium complex derived from 4 having both carboxylate groups protonated.
(15) $3 \cdot Rh(I)$ is itself insoluble in acetone; an indirect comparison is required.
(16) Preparation from $(Ph_3P)_2Rh(CO)Cl$ by exchange of 4 for Ph$_3$P in H$_2$O (pH 9.1).
(17) Although direct comparisons are not possible because of differences in reaction conditions, this rate is comparable with that reported in other homogeneous shift systems. Cheng, C.; Hendriksen, D. E.; Eisenberg, R. *J. Am. Chem. Soc.* **1977**, *99*, 2791–2792. King, R. B.; Hanes, R. M.; King, A. D., Jr. *ibid.* **1978**, *100*, 2925–2927. Ford, P. C.; Rinker, R. G.; Ungermann, C.; Laine, R. M.; Landis, V.; Moya, S. A. *ibid.* **1978**, *100*, 4595–4597. Kang, H. C.; Mauldin, C. H.; Cole, T.; Slegeir, W.; Cann, K.; Pettit, R. *ibid.* **1977**, *99*, 8323–8325.

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