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Enantioselective Hydrogenation of Prochiral C=C Bonds Over Noble Metal Catalysts Supported by β-Cyclodextrin Polymer

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ABSTRACT

Platinum, palladium, rhodium, and ruthenium were deposited onto a β-cyclodextrin/epichlorohydrin copolymer (β-CDP) to produce enantioselective heterogeneous catalysts. These catalysts were prepared by refluxing a suspension of the corresponding metal salt and β-cyclodextrin polymer in either mixed methanol-water or methanol-NaOH. The ability of these catalysts to catalyze the enantioselective hydrogenation of carbon-carbon double bonds was tested with dimethyl itaconate (DMI) and *trans*-2-methyl-pentenoic acid (TMPA).

INTRODUCTION

Enantioselective hydrogenation of carbon-carbon double bonds is highly successful [1]. Many functionalized olefins are hydrogenated with high enantiomeric excess (ee) (>90%) using soluble or immobilized Rh and Ru diphosphine complexes. However, obtaining any ee from heterogeneous hydrogenation of prochiral carbon-carbon double bonds is rare . Hydrogenation of oxazolinone derivative gives 66% ee over Pd/silk fibroin, but such yields are not reproducible [2]. Raney nickel modified with tartaric acid and sodium bromide catalyzes high ee's from prochiral ketones [3-5], but is practically ineffective for hydrogenation of prochiral C=C double bonds [6-9].

Cyclodextrins provide chiral binding sites [10] capable of including guest molecules and are known to induce both asymmetric reductions of prochiral ketones [11-14] as well as asymmetric additions across prochiral carbon-carbon double bonds [15,16]. For example, reduction of acetophenone with a pyridine-borane-β-cyclodextrin complex yields 91% ee [13], and chlorination of α- and β-cyclodextrin complexed methacrylic acid yields 100% and 88% ee's respectively. Since cyclodextrins show considerable promise as an asymmetric environment for chemical reactions, we deposited metals onto β-cyclodextrin copolymers to create a new enantioselective heterogeneous catalyst for hydrogenation of prochiral carbon-carbon double bonds.

EXPERIMENTAL

Materials: The chemicals purchased from Aldrich are palladium(II) chloride (99%), ruthenium(III) chloride hydrate, *trans*-2-methyl-2-pentenoic acid (TMPA, 99%), (±)-2-methylvaleric acid, and β-cyclodextrin/epichloro-hydrin copolymer (β-CDP, 60-67% of β-cyclodextrin). The other chemicals are rhodium trichloride hydrate from K&K Laboratories, platinum(IV) chloride (99.9%) from Johnson Matthey Electronics, and dimethyl itaconate (DMI, 97%) from Fluka. All of the chemicals were used without further purification.

Hydrogenation Apparatus: The hydrogenation reactions were conducted on an apparatus previously described [17]. Briefly, it consisted of a reaction vessel, which can be shaken in a vortex manner at 2000-2800 revolutions per minute, attached to a hydrogen reservoir made of metal tubing. The rate of hydrogen consumption is electronically monitored and a trace of the rate is furnished on a strip chart recorder (Cole Parmer, Model 8372-00). This is achieved by transforming the pressure changes in the hydrogen reservoir into electrical signals which are amplified and recorded.

Procedures: The reactor was charged with a known amount of catalyst (0.05-0.2 g) and purged with H_2, then 2 mL of a 0.8- 2.4 M solution of prochiral acids in methanol was introduced. The hydrogenation was carried out at either 0°C or 25°C under 16.7 psig of hydrogen. After the reaction mixture was filtered, the products were analyzed by gas chromatography (GC) and/or a polarimeter.

Product Analysis: The optical rotations of dimethyl methylsuccinate, the hydrogenation product of dimethyl itaconate, were determined on a polarimeter (Autopol III) and the enantiomeric excess (ee) was calculated based on a literature value of $[\alpha]_D^{25} = 4.8°$. The enantiomers of 2-methylvaleric acid, the hydrogenation product of *trans*-2-methyl-2-pentenoic acid, were separated on a GC (Shimadzu, GC-9A) equipped with a capillary β-cyclodextrin column (BETA-DEX 120, 30m×0.25mm) from Supelco Company. The column temperature was increased from 40°C to 150°C at a rate of 2°C per minute with a 1:100 carrier gas split.

Catalyst Preparation: Noble metals were dispersed on polymers and reduced with methanol (as shown by following equation), such as the formation of

$$2RhCl_3 \cdot 3H_2O + 3CH_3OH = 2Rh + 3HCHO + 6HCl + 6H_2O$$

poly(vinyl alcohol)-Rh metal colloid. The average diameters of metal particles vary depending upon reduction systems [18,19]. The particle size of metallic

rhodium was in a range of 30-70 Å in the CH_3OH/H_2O system and as low as 8 Å in the $CH_3OH/NaOH$ system [20]. We used similar procedures to deposit several noble metals including platinum, palladium, rhodium, and ruthenium onto the β-cyclo-dextrin/epichlorohydrin copolymer (β-CDP).

Group A catalyst: A typical procedure went as follows: β-CDP (5g) was suspended in 60mL distilled water and stirred overnight, then a solution of 0.2 g $RhCl_3 \cdot 3H_2O$ in 5 mL water was added dropwise to the suspension in an hour and stirred for an extra hour. After that, methanol (65mL) was added dropwise to the mixture and refluxed for two hours. The color of the suspension changed from white to dark brown indicating reduction of the metal salt to metal. After refluxing, water and methanol were removed through suction filtration and the catalyst was washed twice with 100mL distilled water and dried in an oven at 80°C. The metal loading was 2% based on the metal salt added initially, assuming all the metal salt was completely reduced to metal.

Group B catalyst: The catalysts labeled with (B) were prepared as follows: β-CDP (5g) was suspended in 50mL methanol and stirred overnight, then a solution of 0.2g $RhCl_3 \cdot 3H_2O$ in 5mL methanol was added dropwise. When the suspension was about to reflux, 10 mL 0.1 M NaOH solution in methanol was added dropwise and further refluxing was continued for 5-10 minutes. The methanol and NaOH were removed through suction filtration and the catalyst was washed with 20mL methanol twice and dried in an oven at 85°C.

RESULTS AND DISCUSSION

The ability of these catalysts to catalyze asymmetric hydrogenations of carbon-carbon double bonds was tested with dimethyl itaconate (DMI) and *trans*-2-methyl-pentenoic acid (TMPA). The results are listed in Tables 1 and 2.

As shown in Table 1, these metals deposited on β-CDP effectively catalyze hydrogenation of TMPA and DMI at 25°C under an atmosphere of hydrogen. GC analyses show that there are no by-products formed during the hydrogenation. The enantioselectivities of these catalysts, however, vary depending on substrate structure, metal type, metal loading, method of catalyst preparation, percent conversion of the olefins, and reaction temperature. The best results are produced by the Rh catalysts. The 2% Ru catalyst produces ee's ranging from 6.5 to 7.9 for TMPA (exp. 10 and 12 in Table 1) and 4.8 to 5.8 for DMI (exp. 13, 14 and 17). However, increasing the metal loading from 2% to 4% resulted in a dramatic decrease in ee in the case of TMPA (exp. 16). This probably resulted from an increase in metal particle sizes by increasing the metal loading. On the other hand, increasing metal loading has little effect on the ee in the case of DMI (exp.17) because these catalysts were prepared in the

presence of NaOH which is known to reduce the degree of metal aggregations during the preparation of metal colloidal catalysts [18,21]. In one run the Pd catalyst produced the highest ee (9.3), but this result was not reproducible (exp. 18) even though the Ru catalyst gave very reproducible results (exp.10).

At 0°C slightly higher ee's were obtained over Pt catalyst, but the other catalysts produced small ee's from TMPA, as shown in Table 2. When the used catalysts were extracted with 0.02 M cyclohexanol in methanol, no substrate was found, but some products were extracted (presumably from the cavities), which showed ee's as high as 16. This suggests that either the β-cyclodextrin polymer is selectively resolving the product enantiomers or hydrogenation in the cavities of the catalytic support is more selective than on the surface.

Table 1. Hydrogenation of TMPA and DMI at 25°C

Exp.	Catalysts	Substrates	% Conversion	$[\alpha]_D^{25}$	ee
1	2% Pt/β-CDP(B)	TMPA	35		3.3
2		TMPA	70		0.3
3		DMI	40	0.15	3.0
5	2% Pt/β-CDP(A)	TMPA	40		2.5
6		TMPA	65		1.7
7		DMI	49	0.23	4.8
8		DMI	60	0.20	4.2
9	4% Pt/β-CDP(B)	TMPA	45		1.0
10	2% Ru/β-CDP(A)	TMPA	43		7.9
		TMPA	30		7.6
13		DMI	35	0.28	5.8
14		DMI	45	0.23	4.8
12	2% Ru/β-CDP(B)	TMPA	35		6.5
16	4% Ru/β-CDP(B)	TMPA	54		1.4
17	4% Ru/β-CDP(A)	DMI	50	0.25	5.2
18	2% Pd/β-CDP(B)	TMPA	70		9.3
		TMPA	70		2.3
19	2% Rh/β-CDP(B)	TMPA	45		1.0
20	2% Rh/β-CDP(A)	TMPA	35		2.1
		DMI	45	-0.23	4.8

Table 2. Hydrogenation of TMPA at 0°C

Exp.	Catalyst	% Conversion	ee	ee[a]	ee[b]
21	2% Pt/β-CDP(B)	52	4.6	7.4	7.9
22	2% Pt/β-CDP(B)	65	3.3	15.7	
23	2% Ru/β-CDP(B)	72	0.2	1.6	3.4
24	2% Pd/β-CDP(B)	70	0.4	2.5	
25	2% Rh/β-CDP(B)	87	0.2	2.2	

[a] used catalyst was washed twice with acetone and extracted with 2 mL of 0.02 M cyclohexanol in methanol. [b] Second extraction

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