

Asymmetric Hydrogenation of α -Ketoesters over Finely Dispersed Polymer-stabilized Platinum Clusters

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Abstract: Finely dispersed polyvinylpyrrolidone-stabilized platinum clusters (PVP-Pt) modified with cinchonidine catalyze the asymmetric hydrogenation of α -ketoesters, giving enantiomeric excesses in favour of R-(+)-methyl lactate up to 97.6%. The reaction is demonstrated to be structure insensitive and runs best over a tiny cluster with a mean size of 1.4 nm, which is quite different from conventional supported catalysts. © 1998 Elsevier Science Ltd. All rights reserved.

Among the asymmetric heterogeneous catalysts, there are only two systems in which prochiral substances can be converted with substantial yield into optically pure products at solid surfaces: the hydrogenation of β -ketoesters with Raney nickel modified by tartaric acid¹ and the hydrogenation of α -ketoesters on platinum using cinchona alkaloids (and also some newly developed chiral substances) as chiral modifiers². The latter was first reported by Orito et al. in 1978³ and has been extensively studied ever since². Over supported Pt catalyst the hydrogenation of ethyl pyruvate was commonly selected as the model reaction. It was found that the reaction was very sensitive to the Pt particle size⁴. Catalysts with large particle sizes (corresponding to low dispersion) showed better performance than those with smaller ones, both the activity and enantioselectivity decreased significantly when the particle diameter is below 3.0 nm. With acetic acid as solvent, the enantioselectivity of ethyl lactate could be achieved as high as 95%⁵, the highest value ever reported for an asymmetric heterogeneous catalyst.

Nanosopic metal clusters or colloids, because of their unique chemical and physical properties as compared to either bulk metal or single metal atoms, have been attracting great attention in academia and industries, especially in the field of catalysis⁶. A variety of catalytic reactions such as hydrogenation of various alkenes⁷, selective hydrogenation of cinnamaldehyde⁸ and o-chloronitrobenzene⁹, hydration of acrylonitrile¹⁰ and photochemical evolution of hydrogen¹¹ have been carried out successfully with noble metal clusters. However, to the best of our knowledge, their application in asymmetric hydrogenation is rather scarce. During the meantime of our preparing for this report, we noticed Bönnemann's outstanding work¹², in which the protonated dihydrocinchonidine modifier also functioned as the stabilizer of the Pt colloid. With excessive dihydrocinchonidine added into the reaction mixture to prevent agglomeration of the colloid, the hydrogenation of ethyl pyruvate was conducted at atmospheric pressure, yielding products with the enantioselectivity of nearly 80%.

In this communication, we report the performance of polymer-stabilized colloidal Pt clusters on the enantioselective hydrogenation of α -ketoesters. PVP was chosen as the stabilizer because of its excellent stabilizing effect on Pt colloid, with which Pt clusters in small size with narrow distribution can be obtained.

Preparation of PVP-Pt cluster was similar to that of the reported method¹³. By changing the preparative conditions such as the kind and concentration of alcohol and PVP/Pt molar ratio, a series of catalysts with different Pt diameters were synthesized by the alcoholic reduction and characterized by transmission electron microscopy (TEM). The as-synthesized PVP-Pt clusters were evaporated to dryness with rotated evaporator under reduced pressure at $\sim 30^\circ\text{C}$. The solid residues so obtained were redispersed in a proper solvent with a definite concentration, giving a thoroughly homogeneous dispersion prior to the reaction.

Hydrogenation of ethyl pyruvate and methyl pyruvate was carried out in a 150 mL stainless steel autoclave. Typically, 1.0 mL substrate, 1.0 mL 1-butanol (as an internal standard for GC), 2.0 mg cinchonidine, 6.0 mL PVP-Pt dispersion (containing 1.25 mg Pt, 6.0 mL ethanol or acetic acid, which was also served as the reaction solvent) were used. The reaction mixture was stirred vigorously in 4.0 MPa hydrogen at 25°C . Conversion and enantioselectivity, expressed as the enantiomeric excess, e.e. (%) = $100 \times ([R] - [S]) / ([R] + [S])$ were determined by GC on a modified β -cyclodextrin capillary column.

Figure 1 shows the influence of Pt particle size on the activity (expressed as turnover frequencies, TOF) and enantioselectivity of the asymmetric hydrogenation of ethyl pyruvate. With the constant molar ratio of PVP to Pt (10:1), TOF changes little with Pt diameter. When the ratio is lower (1:1), TOF increases somewhat, indicating that PVP has some inhibiting effect on the reaction. However, the effect is not so evident with the

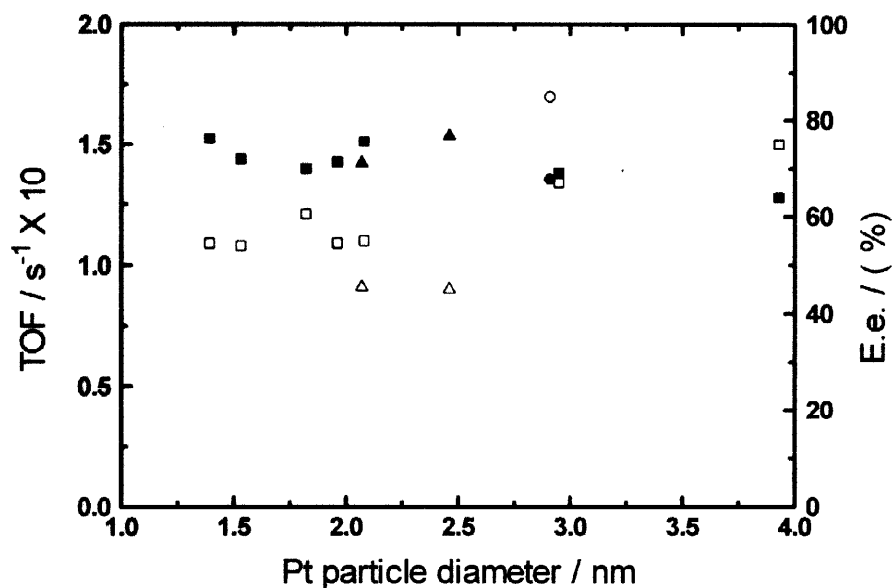


Figure 1. Influence of Pt Particle size on the TOF and E.e. of the Enantioselective Hydrogenation of Ethyl Pyruvate (solvent= ethanol, $t=4.5$ hr). TOF is calculated on the basis of average rate and in terms of the fraction of the surface atoms determined according to the $10n^2+2$ packing rule for cubic close-packed arrangements of metal atoms with respective particle diameter.

TOF open signals: \square with [PVP]:[Pt]=10:1, \circ [PVP]:[Pt]=1:1, \triangle [PVP]:[Pt]=50:1
 E.e. solid signals: \blacksquare with [PVP]:[Pt]=10:1, \bullet [PVP]:[Pt]=1:1, \blacktriangle [PVP]:[Pt]=50:1

ratio increased from 1 to 50. Just like TOF, e.e. is almost independent of the particle size except for the larger clusters ($d=3.9$ nm, $\sigma=0.42$ nm) showing slightly less enantioselectivity. Accordingly, the reaction is obviously associated with structure insensitivity in our quasi-homogeneous system, in contrast to what has been exhibited by heterogeneous catalysts⁴. The same conclusion was deduced in Bönemann's report¹², however, the dihydrocinchonidine-stabilized Pt colloids they synthesized were broadly distributed in size, e.g. a $d=3.9$ nm colloidal sample seems like a mixture widely dispersed from 0.8-6.2 nm without a predominant particle component in definite diameter. With such a set of data, it is hard to make an unambiguous conclusion about the size effect on this reaction.

Similar to what has been reported for the heterogeneous catalysts⁵, there is a considerable enhancement of activity as well as enantioselectivity when acetic acid substitutes ethanol as solvent (Table 1). For the hydrogenation of ethyl pyruvate, e.e. is increased to 92.2% at 100% conversion, while for that of methyl pyruvate, it reaches 97.6%, the best enantioselectivity that has been achieved so far in the hydrogenation of α -ketoesters. It is noteworthy that the 92-95% e.e. of ethyl lactate over supported Pt was afforded at a much higher pressure of 100 bar⁵ and dropped to 87% at 75 bar¹⁴, indicating that the PVP-Pt cluster is superior to those supported catalysts at a relatively mild condition. According to the mechanism proposed by Baiker et al. on the basis of computer modeling and quantum chemical calculations¹⁵, the better performance in acetic acid is likely due to the favorable interaction between the protonated N-base alkaloid modifier and the activated carbonyl compound reactant. Moreover, the rate increase is also attributed to the acid catalysis of carbonyl reduction¹⁶. Taking the two factors into account, we feel, however, that another one should not be neglected for PVP-Pt system either. As mentioned above, PVP has a detrimental effect on the reaction by coordinating with Pt through the carbonyl groups on its polymer chain¹⁷, thus obscuring the efficient adsorption of modifiers on the catalyst. In comparison with PVP, acetic acid can also coordinate with Pt, the interaction of which is much weaker as concerned with one carbonyl group per a molecule. In spite of this, the coordination effect of PVP on Pt may be shielded effectively by acetic acid since it extremely outnumbered PVP under the reaction conditions. Consequently, the modifiers are able to be more accessible to Pt surface and induce the hydrogenation with higher enantioselectivity and reaction rate.

Table 1. Comparison of Ethanol and Acetic Acid as Solvent for the Enantioselective Hydrogenation of α -Ketoesters

Catalyst ^a	Solvent	Substrate ^b	Reaction Time(h)	Conversion (%)	TOF(s ⁻¹)	E.e.(%)
1	EtOH	EP	4.5	97.0	0.11	76.2
1	HAc	EP	4.5	100	>0.11	92.2
1	EtOH	MP	0.5	61.3	0.76	84.7
1	HAc	MP	0.5	100	>1.21	97.6
2	EtOH	MP	0.5	60.2	0.75	78.3
2	HAc	MP	0.5	100	>1.24	93.6
3	EtOH	MP	0.5	82.4	1.16	81.4
3	HAc	MP	0.5	100	>1.45	95.9

a) Catalyst 1, 2, 3 with particle diameter of 1.4 nm ($\sigma=0.35$ nm), 1.5 nm ($\sigma=0.38$ nm) and 1.8 nm ($\sigma=0.32$ nm) respectively, as shown in Figure 1. b) EP=ethyl pyruvate MP=methyl pyruvate

In conclusion, the monodispersed PVP-Pt clusters have been demonstrated to be very effective in the enantioselective hydrogenation of α -ketoesters. Simultaneously, they are very stable in the course of the

hydrogenation and no change in size and agglomeration takes place after the reaction as verified by TEM observation. Furthermore, we immobilized the PVP-Pt cluster (with a mean particle diameter of 1.1 nm, $\sigma=0.3$ nm) onto alumina and a cross-linked polystyrene (designated as GDX) support, then extensively rinsed the all PVP out as described in literature¹⁸. The supported Pt clusters as-prepared could also induce a high e.e. (91.3% and 88.9% for Al₂O₃-Pt and GDX-Pt respectively, with TOF>1.15 s⁻¹ for both) for the hydrogenation of methyl pyruvate. That the small cluster showing the excellent catalytic performance is a new experimental fact which may afford us a deeper insight into the adsorption mode of the cinchonidine modifier-substrate activated species on the platinum surface, since such a tiny cluster has no flat surface large enough to accommodate it. A further investigation including the refinement of the model of the modified cluster surface by use of molecular simulation is now being undertaken in our laboratory.

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