minimal protein structural rearrangement. Moreover, the activation parameters for the cross-reactions between ferrocene and ferricenium ion derivatives[32] are close to the values reported here and to the activation parameters for the ferrocene–ferricenium ion self-exchange reactions[32] suggesting that the ferricenium ion–protein cross-reaction activation processes are modeled well by the ferricenium ion–ferrocene reactions. While this agreement could result from fortuitous cancellations of various factors in the activation process it is worth noting that these cancellations would have to occur across the range of derivatives studied. It is interesting to note that $\Delta H^{\ddagger}$ apparently does not decrease with increasing $\Delta E^{\circ\prime}$ for these four reactions as might be expected from Marcus theory. This may simply reflect the small range of driving force for these four reactions, and it may require determining $\Delta H^{\ddagger}$ for a larger range of driving force than was possible in this study for such a relationship to become evident.

Finally, the ferricenium ion derivatives have proven to be a predictable class of cytochrome *c* titrants. They have low charges, are substitution inert, and are facile outer-sphere reagents with a wide range of reduction potentials. Studies[33] with copper proteins and iron–sulfur proteins indicate that these derivatives also react predictably with these metalloproteins.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research and to Dr. Paul Kelter, Ms. Barbara Kelter, and Dr. Robert Badger for assistance with interfacing the Apple II computer and Nicolet digital oscilloscope.

Registry No. Cytochrome *c*, 9007-43-6; 1,1′-dimethylferricenium, 12276-63-0; *n*-butylferricenium, 32914-29-7; ferricenium, 12125-80-3; chloromercuriferricenium, 34742-71-7; hydroxymethylferricenium, 34742-72-8; phenylferricenium, 32839-60-4; decamethylferrocene, 12126-50-0.

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[32] The activation parameters from ref 19 for the cross-reactions of 1,1′-dimethylferrocene with ferricenium ion and of ferrocene with phenylferricenium ion are $\Delta H^{\ddagger}$ 3.0 ± kcal/mol and $\Delta S^{\ddagger}$ −15 ± 3 cal/(mol K) and $\Delta H^{\ddagger}$ 3.0 ± 0.64 kcal/mol and $\Delta S^{\ddagger}$ −14.4 ± 2.1 kcal/(mol K), respectively. The activation parameters for the self-exchange reactions recalculated from data in ref 18 are $\Delta H^{\ddagger}$ 5.5 ± 0.2 kcal/mol and $\Delta S^{\ddagger}$ −8.2 ± 0.7 cal/(mol K) for 1,1′-dimethylferrocene self-exchange and $\Delta H^{\ddagger}$ 5.6 ± 0.6 kcal/mol and $\Delta S^{\ddagger}$ −8.9 cal/(mol K) for the ferrocene self-exchange in acetonitrile.

[33] Rodeberg, D. A.; Likar, M. D.; Carney, M. J.; Pladziewicz, J. R., unpublished results.

Polymer-Bound Substrates: A Method To Distinguish between Homogeneous and Heterogeneous Catalysis

J. P. Collman,* K. M. Kosydar, M. Bressan, W. Lamanna, and T. Garrett

Contribution from the Department of Chemistry, Stanford University, Stanford, California 94305. *Received August 8, 1983*

Abstract: Soluble and cross-linked polymers have been prepared and examined as substrates for hydrogenation reactions in the presence of homogeneous precatalysts, metal sols, and heterogeneous catalysts. These polymeric substrates are hydrogenated in the presence of soluble catalysts, whereas heterogeneous catalysts are ineffective. This phenomenon is proposed as a method to distinguish truly homogeneous from particulate catalysts. Using this test, we have found Crabtree's precatalyst, $[Ir(COD)L_2]PF_6$, to behave as a homogeneous olefin hydrogenation catalyst. The Maitlis precatalyst, $[Rh(C_5Me_5)Cl_2]_2$, acts as a homogeneous catalyst in the hydrogenation of olefins, but behaves like a heterogeneous catalyst in the hydrogenation of polymer-bound benzene derivatives.

The identification of the active metal species in homogeneous catalytic reactions continues to be a difficult and challenging problem. Halpern's elegant study of homogeneous asymmetric hydrogenation[1] illustrates the important point that the catalytically active forms of the metal may be very minor components in the reaction mixture. Other work[2,3] suggests that heterogeneous metal particles may be the true catalysts in some supposedly homogeneous reactions.

Few methods currently exist for distinguishing between homogeneous and heterogeneous catalysts. Physical methods such as light scattering[4] and filtration[3-5] may detect the presence of insoluble material, but they provide no information on the catalytic activity of this material. Differences between the general reactivity patterns of homogeneous and heterogeneous catalysts may serve as useful guidelines.[6,7] However, identification of catalysts based on these patterns is often inconclusive because of the wide differences in reactivity observed within each class of catalysts.

The information available on the chemical reactions of polymers[8-11] suggests that polymers may be useful in distinguishing soluble from particulate catalysts. With appropriate caution,[9] the reactivity of polymers may be compared with that of their low molecular weight analogues. In general, simple homogeneous reactions involving soluble and cross-linked polymers are reported to occur at rates similar to those observed for low molecular weight compounds.[12,13] Rate differences of 5–10-fold are common.[13] However, many heterogeneous reactions of soluble polymers, such as catalytic hydrogenation, are known to be *orders of magnitude* slower than the corresponding reactions of monomers.[9] In fact, higher temperatures and pressures, higher catalyst concentrations, and longer reaction times are typically required to achieve significant reaction of polymeric substrates.[14-16] Although no de-

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[1] Chan, A. S. C.; Pluth, J. J.; Halpern, J. *J. Am. Chem. Soc.* **1980**, *102*, 5952.

[2] Bradley, J. S. *J. Am. Chem. Soc.* **1979**, *101*, 7419.

[3] Hamlin, J. E.; Hirai, K.; Millan, A.; Maitlis, P. M. *J. Mol. Catal.* **1980**, *7*, 543.

[4] Crabtree, R. H.; Mellea, M. F.; Mihelcic, J. M.; Quirk, J. M. *J. Am. Chem. Soc.* **1981**, *104*, 107.

[5] Laine, R. M.; Rinker, R. G.; Ford, P. C. *J. Am. Chem. Soc.* **1977**, *99*, 252.

[6] Martino, G. "Catalysis: Heterogeneous and Homogeneous"; Delman, B., Jannes, G., Eds.; Elsevier: Amsterdam, 1975; p 439.

[7] Laine, R. M. *J. Mol. Catal.* **1982**, *14*, 137.

[8] Kosydar, K. M., Ph.D. Thesis, Stanford University, 1982.

[9] "Chemical Reactions of Polymers"; Fettes, E. M., Ed.; Interscience: New York, 1964.

[10] "Reactions of Polymers"; Moore, J. A., Ed.; Reidel: Dordrecht, Holland, 1973.

[11] "Modification of Polymers"; Carraher, C. E.; Tsuda, M., Eds.; American Chemical Society: Washington, DC, 1980.

[12] Flory, P. J. "Principles of Polymer Chemistry"; Cornell University Press: Ithaca, NY, 1953; Chapter 3.

[13] Letsinger, R. L.; Jerina, D. M. *J. Polym. Sci., Part A-1* **1967**, *5*, 1977.

[14] Lapporte, S. J. *Ann. N.Y. Acad. Sci.* **1969**, *158*, 510.

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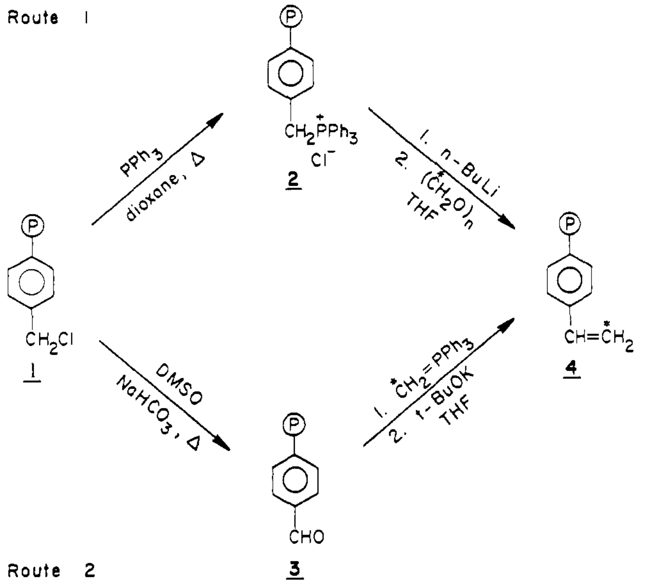
Scheme I. Synthesis of Polymer-Bound Styrene Units



tailed study of this behavior has been reported, this phenomenon may be attributed to a lack of mobility of the heterogeneous catalyst in the region occupied by the polymer. This may include adsorption of the polymer onto the catalyst surface.[14]

On the basis of this information, we propose that one may be able to differentiate homogeneous from heterogeneous catalysts based on their reactivity with substrates that are bound to polymers. It is expected that the discrimination reported for soluble polymers can be enhanced by cross-linking the polymer to further restrict mobility. Then, only a truly soluble, molecular catalyst is expected to diffuse readily into the polymer network and react with attached functional groups. The rates observed for reactions of these polymer-bound substrates with homogeneous catalysts should be similar to rates observed for reactions of an analogous monomer. It is expected that heterogeneous reactions involving soluble polymers will be sluggish, and such reactions with crosslinked polymers will be exceedingly slow if they occur at all.

In order to test this hypothesis, we have prepared a series of soluble and cross-linked polymers that contain functional groups which may serve as substrates or poisons for catalytic reactions. This report will describe their synthesis and reactions with both homogeneous and heterogeneous catalysts.

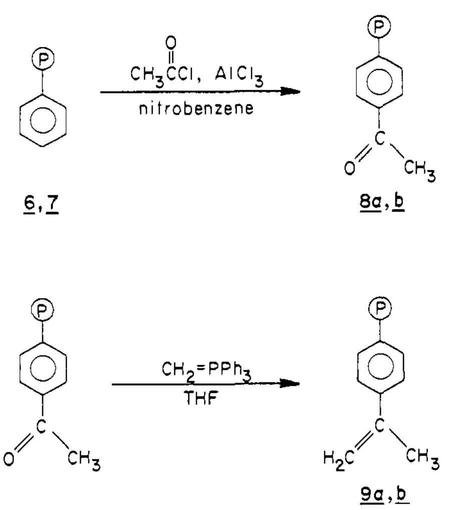
Results

Synthesis of Polymer-Bound Substrates. In order to study the hydrogenation of unsaturated groups, special polymers containing olefinic and aryl substituents were prepared from styrene polymers and copolymers.

Our choice of synthetic pathways was influenced by several important criteria. First, the polymers had to be fully swollen or dissolved in the reaction medium at all times. Second, the organic transformation could not provide a pathway for crosslinking of the polymer. Finally, the organic reaction had to proceed in essentially quantitative yield with respect to the polymer-bound functional group. This is necessary to reduce the introduction of impurities which may act as catalyst poisons in subsequent reactions.

Synthesis of Olefin-Containing Polymers. The synthesis of a cross-linked polymer containing styrene moieties is illustrated in Scheme I. Two routes were employed starting from polymer **1**, a commercially available 1% divinylbenzene/styrene copolymer in which 15% of the aromatic rings have been chloromethylated. In route 1, this polymer was treated with triphenylphosphine to

Scheme II. Synthesis of Polymer-Bound α-Methylstyrene Units



give the polymer-bound phosphonium salt **2**, which has been described by Frechet.[17] Formation of the ylide by treatment with *n*-butyllithium, followed by coupling with formaldehyde, yielded the desired olefin-containing polymer **4**. Alternatively, an aldehyde-containing polymer, **3**, was prepared from polymer **1** by a Moffat oxidation with dimethyl sulfoxide (Me_2SO) and base.[17] The aldehyde was treated with the ylide, which was generated from methyltriphenylphosphonium iodide (**5**) and phenyllithium, to give the styrene moiety. This Wittig reaction proceeded very slowly, presumably via the formation of a relatively stable lithium–betaine intermediate. The reaction of this intermediate could be accelerated by exchanging the lithium cation for potassium, through addition of an excess of potassium *tert*-butoxide.[18]

The progress of these reactions could be easily monitored through the use of Fourier transform infrared (FTIR) spectroscopy. The aldehyde-containing polymer **3** exhibits a strong carbonyl absorption at 1690 cm^{-1}. The styrene group can be detected by the presence of a moderate absorption at 1630 cm^{-1}. Other bands expected for the styrene unit at 1410, 990, and 900 cm^{-1} are partially obscured by the absorbances that are characteristic of the polystyrene backbone.

The ^1H and ^{13}C NMR spectra of solvent-swollen samples of the product polymer exhibited only broad, poorly resolved resonances. However, both synthetic routes allow the incorporation of a ^{13}C label in the terminal position of the olefin. Route 2 was used to prepare a labeled polymer starting from $^{13}CH_3I$ of 90% isotopic purity. The ^{13}C NMR spectrum obtained for this polymer, swollen in $CDCl_3$, shows the resonance of the olefinic carbon at 113 ppm downfield from Me_4Si. Further studies of this polymer after hydrogenation showed this band is absent and a new aliphatic carbon resonance at 16 ppm is visible.

Quantitative analysis, to determine the extent of ring substitution, was carried out through elemental analysis of the polymers and/or suitable derivatives. The oxime and dibromo derivatives were used to characterize the aldehyde- and olefin-containing polymers, respectively. Although completely accurate elemental analyses of polymer samples are often difficult to obtain,[19] a minimum degree of functionality can be established from the analysis for the heteroatom(s) present. Such analyses indicated 65–75% functional yield for the syntheses of polymer **4** from **1**. The elemental analysis also showed trace amounts of phosphorus, chlorine, and sometimes sulfur in the product. In general, route 2 produced higher yields and cleaner products. Therefore, this route was used more often.

Attempts to prepare a soluble analogue of polymer **4**, via route 2, were unsuccessful. Moffat oxidation of soluble poly(vinylbenzyl

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(15) Pendleton, J. F.; Hoag, D. F.; Goldberg, E. P. "Polymerization Reactions and New Polymers"; Platzer, N. A. J., Ed.; American Chemical Society: Washington, DC, 1973; Adv. Chem. Ser. No. 129, 1973.

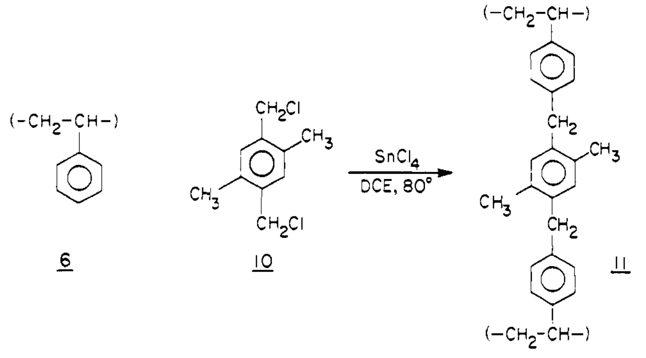
(16) Wicklatz, J. "Chemical Reactions of Polymers"; Fettes, G. M., Ed., Interscience: New York, 1964; p 173.

(17) Frechet, J. M.; Schuerch, C. *J. Am. Chem. Soc.* **1971**, *93*, 492.

(18) Schlosser, M.; Christmann, K. F. *Angew. Chem., Int. Ed. Engl.* **1964**, *3*, 636.

(19) Frommer, J. F.; Bergman, R. G. *J. Am. Chem. Soc.* **1980**, *102*, 5227.

Scheme III. Synthesis of Macronet Isoporous Polymer



chloride) produced an insoluble gel.[20] Partially chloromethylated soluble polymers, similar to **1**, were not readily available. Although several other routes were investigated, none yielded the desired polymer.

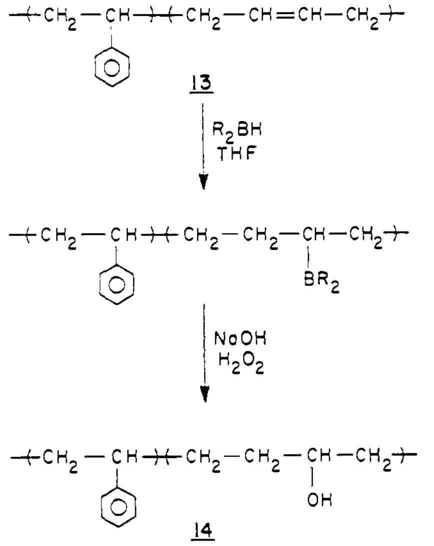
Soluble and cross-linked polymers containing α-methylstyrene units were prepared as shown in Scheme II. Purified polystyrene (**6**) (M_w 321 000) and 1% divinylbenzene/styrene beads (**7**) were separately acetylated[13] with acetyl chloride and aluminum trichloride in nitrobenzene to give ketone-containing polymers **8a**,**b**. Analysis of the oxime derivative indicated 18–20% ring substitution had been achieved. Reaction of these polymers with methylenetriphenylphosphine ylide produced the olefin-containing polymers **9a**,**b** in nearly quantitative yields based on FTIR and elemental analysis of the dibromo derivatives. Elemental analysis also shows these polymers to be free from detectable levels of phosphorus and chlorine impurities. The infrared spectrum shows a characteristic olefin absorbance at 1625 cm^{-1}. The ^{1}H NMR spectrum of the soluble polymer **9a** in $CDCl_3$ contains two broad signals in the vinyl region (5.3 and 5.0 ppm) as well as broad aromatic and aliphatic resonances.

Gel permeation chromatography (GPC)[21] was used to analyze the molecular weight distribution of the soluble polymer series **6**, **8a**, and **9a**. A comparison of the distributions should reveal any significant changes in polymer chain length caused by these reactions. The measured value for the average molecular weight of polystyrene **6** was 160 000 daltons, based on a calibration with polystyrene standards. The GPC analysis showed no major change in the molecular weight distribution of the polymer after acetylation. However, the distribution of the olefin product showed a slight shift toward lower molecular weight. These results imply that the synthesis of the olefin-containing polymer does not lead to significant degradation of the polymer backbone.

Macronet Isoporous Polymers. It is known that suspension-polymerized styrene/divinylbenzene beads have a significantly nonuniform distribution of cross-links.[22,23] Under typical free-radical polymerization conditions, the divinylbenzene polymerizes faster and thereby produces a higher cross-link density at the initiation sites.[23] This implies that areas of highly different permeability may exist within the same bead. For this study, a comparison of polystyrene beads with a more uniformly cross-linked system was desired.

A number of workers[24-26] have described the cross-linking of soluble polystyrene in a Friedel–Crafts reaction employing a difunctional benzyl chloride. Since all components are in solution before the temperature is raised to initiate the reaction, a statistical distribution of cross-links is claimed to be present in the "macronet isoporous" gels that form. Such polymers with high cross-link densities, 10–50%, swell slightly in all solvents and have been used in ion exchange resins.

Scheme IV. Hydration of Styrene/Butadiene Copolymer



The synthesis of a macronet isoporous polymer that we employed is shown in Scheme III. A sterically hindered compound, 1,4-dimethyl-2,5-bis(chloromethyl)benzene (**10**), was preferred as the cross-linking agent, because it shows a limited tendency toward self-condensation.[26] An insoluble polymer containing 1% cross-linking was prepared by using tin tetrachloride as a catalyst in dichloroethane (DCE) solution. The resulting white to colorless gel exhibited swelling properties similar to the 1% cross-linked beads.

Attempts to functionalize the macronet isoporous polystyrene by acetylation led to degradation of the polymer network, presumably because of the reversibility of the Friedel–Crafts alkylation. Therefore, the order of the two reactions was reversed. Cross-linking of an 18% acetylated soluble polystyrene with **10** and tin tetrachloride was readily accomplished. The olefinic group was then synthesized via a Wittig reaction as described for the other polymers. Elemental analysis indicated a functional yield of 94% from the soluble polymer. The spectroscopic properties of the olefin-containing polymer **12** are similar to those previously described for the polystyrene beads.

Hydration of a Styrene/Butadiene Copolymer. Although polystyrene is soluble in many solvents, from benzene to chloroform and *N*,*N*-dimethylformamide (DMF), the polymer is incompatable with protic media such as alcohols. Since 2-propanol is a common solvent for arene hydrogenation,[47,50,51] a special polymer containing

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(20) Gibson, H. W.; Bailey, F. C. *J. Polym. Sci., Polym. Chem. Ed.* **1975**, *13*, 1951.

(21) Collins, E. A.; Bares, J.; Billmeyer, F. W. "Experiments in Polymer Science"; Wiley-Interscience: New York, 1973; p 399.

(22) Guyot, A.; Bartholin, M. *Prog. Polym. Sci.* **1982**, *8*, 277.

(23) Patterson, J. A. "Biochemical Aspects of Reactions on Solid Supports"; Stark, G. R., Ed.; Academic Press: New York, 1971; p 189.

(24) Davankov, V. A.; Rogoshin, S. V.; Tsyurupa, M. P. *J. Polym. Sci., Polym. Symp.* **1974**, *47*, 95.

(25) Grassie, N.; Gilks, J. *J. Polym. Sci., Polym. Chem. Ed.* **1973**, *11*, 1531.

(26) Peppas, N. A.; Bussing, W. R.; Slight, K. A. *Polym. Bull.* **1981**, *4*, 193.

(27) Minoura, Y.; Ikeda, H. *J. Appl. Polym. Sci.* **1971**, *15*, 2219.

(28) Pinazzi, C.; Vassort, J.; Reyx, D. *Bull. Soc. Chim. Fr.* **1973**, 1656.

(29) Masuda, T.; Ohtori, T.; Higashimura, T. *Polym. J. (Tokyo)* **1979**, *11*, 849.

(30) Knights, E. F.; Brown, H. C. *J. Am. Chem. Soc.* **1968**, *90*, 5281.

(31) Rylander, P. "Catalytic Hydrogenation in Organic Syntheses"; Academic Press: New York, 1976; p 271.

(32) Jardine, F. H. "Progress in Inorganic Chemistry"; Lippard, S. J., Ed.; Interscience: New York, 1981; Vol. 28, p 63.

(33) Osborn, J. A.; Jardine, F. H.; Young, J. F.; Wilkinson, G. *J. Chem. Soc. A* **1966**, 1711.

(34) Schrock, R. R.; Osborn, J. A. *J. Am. Chem. Soc.* **1971**, *93*, 2397.

(35) Weiser, H. B. "Inorganic Colloid Chemistry"; Wiley: New York, 1933; Vol. 1.

(36) Brunet, J.; Gallois, P.; Caubere, P. *J. Org. Chem.* **1980**, *45*, 1937.

(37) Falk, J. C. "Catalysts in Organic Syntheses"; Rylander, P. N., Greenfield, H., Eds.; Academic Press: New York, 1976; p 305.

(38) Brown, C. A.; Ahuja, V. K. *J. Org. Chem.* **1973**, *12*, 2226.

(39) Farrel, M. J.; Frechet, J. M. J. *J. Org. Chem.* **1976**, *41*, 3877.

(40) Birch, A. J.; Walker, K. A. M. *Tetrahedron Lett.* **1967**, 1935.

(41) Demitras, G. C.; Muetterties, E. L. *J. Am. Chem. Soc.* **1979**, *99*, 2796.

(42) Abley, P.; Jardine, I.; McQuillin, F. J. *J. Chem. Soc. C* **1971**, 840.

(43) Muetterties, E. L.; Bleeke, J. R. *Acc. Chem. Res.* **1979**, *12*, 324.

Table I. Reactions with Supported Palladium Catalysts

substrate	catalyst	cat:sub ratio	time, h	yield
Ph-CH_2Cl	5% Pd/$CaCO_3$[a]	1:100	0.5	100%
(SOL)-Ph-CH_2Cl[b]	5% Pd/$CaCO_3$	1:60	18	30%
Ⓟ-Ph-CH_2Cl[c]	5% Pd/$CaCO_3$	1:8	18	0%
Ph-NO_2	5% Pd/C[d]	1:1000	0.5	100%
Ⓟ-Ph-NO_2[e]	5% Pd/C	1:160	72	0%

[a] Room temperature, 1 atm hydrogen pressure, benzene solvent (8 mL). [b] Soluble poly(vinylbenzyl chloride). [c] 1% cross-linked polystyrene beads, 1.34 mequiv/g. [d] Room temperature, 20 psig of hydrogen pressure, DMF solvent (5 mL). [e] 1% cross-linked polystyrene beads, 3.62 mequiv/g.

hydrophilic hydroxyl groups as well as hydrophobic aryl groups was prepared.

Scheme IV illustrates the hydration of a styrene/butadiene copolymer via hydroboration.[27] Similar reactions have been reported for polybutadiene[28] and poly(phenylacetylene).[29] The NMR spectrum of the starting copolymer **12** indicates a composition of 21% styrene, 68% butadiene polymerized in the 1,4 mode and 11% butadiene polymerized in a 1,2 manner.

Reaction of **13** with 0.34–1.0 equiv of borane–tetrahydrofuran (THF) complex per olefin yielded an insoluble gel. This gel remained intractable even after treatment with hydrogen peroxide and base. The presence of organoboron cross-links was considered likely. However, the hydroboration was successfully accomplished by the use of 9-borabicyclo[3.3.1]nonane (9-BBN),[30] a boron monohydride, as the hydroborating agent. Oxidative workup yields a white elastomeric polymer that is soluble in 10–20% H_2O/THF, 2-propanol, and DMF, but insoluble in methanol, pure THF, and pure H_2O. This is consistent with solubility parameter calculations based on the composition of the expected polymer. The FTIR and ^1H NMR spectra confirm the presence of hydroxyl and aryl groups.

In addition to the specially synthesized polymers described above, polystyrene, nitrated polystyrene,[23] poly(*cis*-butadiene), and poly(vinylbenzyl chloride) were employed as polymeric substrates.

Reactions of Standard Catalysts with Polymeric Substrates. The ability of polymers to discriminate between homogeneous and heterogeneous catalysts was tested by examining the reactivity of polymer-bound substrates with several catalysts of known composition. A variety of catalyst forms were employed, including soluble, discrete transition-metal complexes as well as supported, suspended, or "solubilized" metal particles. Since each catalyst system is unique, conditions such as temperature, pressure, solvent, etc. were first experimentally established for reaction with a suitable monomer. The reaction of the polymeric analogue was then attempted under these conditions.

Reactions of Supported Heterogeneous Catalysts. Hydrogenolysis of benzyl derivatives (eq 1) is commonly catalyzed by

$$\text{Ph-CH}_2\text{Cl} \xrightarrow[\text{catalyst}]{H_2} \text{Ph-CH}_3 \qquad (1)$$

supported transition metals such as palladium.[31] The results of such reactions with monomeric and polymeric benzyl chlorides are given in Table I. Under similar reaction conditions, large differences in substrate reactivity were observed. Complete conversion of the monomer was achieved in less than 30 min. The reaction of soluble poly(vinylbenzyl chloride) was less facile. After 18 h, 30% conversion was indicated by the ^1H NMR spectrum of the reaction mixture. (The resonances observed for the methyl and chloromethyl groups were 2.3 and 4.4 ppm, respectively.) In contrast, no reaction of the cross-linked polymer was detected by examination of the ^1H NMR and IR spectra of the reaction mixture.

A similar reactivity pattern was observed (Table I) for the reduction of aromatic nitro groups (eq 2) with palladium catalysts.

$$\text{Ph-NO}_2 \xrightarrow[\text{catalyst}]{H_2} \text{Ph-NH}_2 \qquad (2)$$

Although the monomer reacts rapidly, no evidence of polymer reduction was observed even after prolonged periods of time. Examination of the infrared spectrum of the polymer showed no change in the nitro group absorbances at 1535, 1350, and 860 cm^{-1}.

Olefin Hydrogenation. Most of the work described in this study was centered on the catalytic hydrogenation of olefins. This reaction is important here because it is catalyzed by a variety of transition metals in many, well-characterized homogeneous and heterogeneous forms. In fact, olefin hydrogenations by soluble rhodium complexes[1,32,34] are perhaps the best documented examples of catalysis by discrete molecular species. Thus, this area provides an excellent opportunity to compare the reactivity of different types of catalysts with the same set of substrates.

Table II summarizes the results obtained for hydrogenation reactions of monomeric and polymeric substrates with several homogeneous and heterogeneous catalysts. The reactions were carried out as closed, batch reactions for 24 h. The extent of hydrogenation was determined by gas chromatography (GC) for monomeric substrates and by quantitative FTIR or NMR spectroscopy for polymeric systems. The accuracy of polymer analyses was ±5%. In some cases, deuterium was employed. Qualitative analysis of the resulting deuterated products was based on two weak infrared C–D absorption bands at 2180 and 2220 cm^{-1}.

Table II clearly shows the different reactivity patterns observed for the different classes of catalysts. The homogeneous precatalyst compounds (entries 1, 2, and 3) catalyzed the hydrogenation of all forms of olefin substrates. The ability to react with cross-linked polymers was not dependent upon the formal charge possessed by the catalyst species. It was also independent of the method used to prepare the chemical cross links.

The reactions of Wilkinson's catalyst, $RhCl(PPh_3)_3$,[32,33] were studied in greater detail with a constant pressure apparatus. The consumption of the H_2 was monitored by measuring the volume change of the system. Toluene, instead of benzene, was preferred as the solvent. The lower vapor pressure of toluene allows more reproducible measurements of the gas consumption. The rates observed in the two solvents were otherwise similar. The commonly employed solvent mixtures of benzene/ethanol[33] were not suitable for this study. The polystyrene beads are not fully swollen under these conditions, and thus the beads are inaccessible to reactants.

The rates observed for olefin hydrogenation with $RhCl(PPh_3)_3$ are shown in Table III. In general, the hydrogenations of styrene units proceeded faster than reactions of analogous α-methylstyrene units because of steric effects. The differences in reactivity, however, were minimal since both substrates are terminal olefins. In both series, the polymers are found to react 3–5 times slower than the corresponding monomers. This agrees closely with results obtained for comparisons of monomer and polymer reactivity in noncatalytic reactions such as the aminolysis of esters.[13]

In contrast, olefin hydrogenation with supported heterogeneous catalysts (Table II, entries 4 and 5) showed reactivity patterns similar to those described in the previous section for reactions of chloromethyl and nitro groups. The reactions involving monomers were very rapid. Turnover numbers typically ranged from 400 to 1000 per hour under the standard reaction conditions. However,

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(44) Jardine, I.; McQillin, F. J. *J. Chem. Soc., Chem. Commun.* **1969**, 502.

(45) Crabtree, R. H.; Felkin, H.; Morris, G. E. *J. Organomet. Chem.* **1977**, *141*, 205.

(46) Crabtree, R. H.; Demou, P. C.; Eden, D.; Mihelcic, J. M.; Parnell, C. A.; Quirk, J. M.; Morris, G. E., to be published.

(47) Maitlis, P. M. *Acc. Chem. Res.* **1978**, *11*, 301.

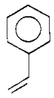
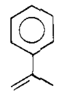
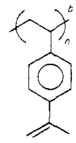
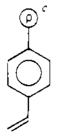
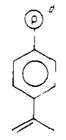
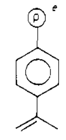
(48) Smith, H. A. "Catalysis"; Emmet, P. H., Ed.; Reinhold: New York, 1957; p 175.

(49) Stuhl, L. S.; DuBois, M. R.; Hirsekorn, F. J.; Blecke, J. R.; Stevens, A. E.; Muetterties, E. L. *J. Am. Chem. Soc.* **1978**, *100*, 2405.

(50) Bennet, M. A.; Huang, T.; Smith, A. K.; Turndy, T. W. *J. Chem. Soc., Chem. Commun.* **1978**, 582.

(51) Bennet, M. A.; Huang, T.; Turney, T. W. *J. Chem. Soc., Chem. Commun.* **1979**, 312.

Table II. Olefin Hydrogenation[a]

run	catalyst	monomers		soluble polymers		cross-linked polymers			ref
					 [b]	 [c]	 [d]	 [e]	
1	$RhCl(PPh_3)_3$	100	100	30[f]	100	100	100	100	33
2	$[Rh(NBD)(PPh_3)_2][ClO_4]$	100	100				90		34
3	$[Rh(NBD)(PPh_3)_2][ClO_4] + NEt_3$		100				65		34
4	5% Pd/C	100	100	[5][i]	[5]	[0]	[0]	[0]	31
5	5% Rh/Al_2O_3		100			[0]	[3]		31
6	$Ni(acetate)_2$[g] + NaH + ROH	100	100		3–22		[5]	[0]	36
7	$Ni(2\text{-ethylhexanoate})_n + NaBH_4$	100	100	30		[0]	[4]		
8	$Co(2\text{-ethylhexanoate})_n$[h] + n-BuLi		100				20		37

[a] Values given in the table are the percent olefin hydrogenated under the following conditions: 3.0 μmol of catalyst, 300 μmol of olefin, 5 mL of solvent, room temperature, 1–2 atm of hydrogen, 24 h unless otherwise indicated. [b] 1.44 mequiv/g. [c] 1% cross-linked beads, 0.99 mequiv/g. [d] 1% cross-linked polystyrene beads, 1.74 mequiv/g. [e] Macronet isoporous resin, 1.56 mequiv/g. [f] 0.5 h. [g] 30 μmol of catalyst, 600 μmol of olefin. [h] 50 μmol of catalyst, 5 mmol of olefin monomer, 300 μmol of olefin polymer, 50 °C, 50 psig hydrogen, 8 h. [i] Values in brackets are equal to zero within the limited accuracy of the measurement (±5%).

Table III. Hydrogenation[a] of Olefins with $RhCl(PPh_3)_3$

substrate	initial rate[b]
α-methylstyrene	
monomer	54
soluble polymer	13
cross-linked polymer beads[c]	8
macronet isoporous polymer[c]	12
styrene	
monomer	126
cross-linked polymer beads[c]	44

[a] 3.0 μmol of $RhCl(PPh_3)_3$, 300 μmol of olefin, 5 mL of toluene, room temperature, 1 atm of H_2. [b] Rate = turnover number = mol of product/[(mol of catalyst)(h)]. [c] 1% cross-linked polymer.

polymeric systems appeared to be quite unreactive. No change was observed in the infrared absorbance characteristic of the olefin at 1625 or 1630 cm^{-1} after 24 h of reaction. This lack of reactivity was confirmed by the ^{13}C NMR spectrum of solvent-swollen ^{13}C-enriched polymer samples which also showed no detectable change.

Our results with supported metal catalysts prompted the examination of smaller heterogeneous particles. This work with colloidal or suspended metal species was plagued with several problems. First, these particles are typically unstable. Particle aggregation over time can change activity as well as particle size. Few of these systems are well-characterized. Second, the colloidal metals must be prepared in solvents that are known to swell polystyrene beads. This greatly restricts the number of suitable metal species, because many metal sols require aqueous or alcoholic media for their formation and stabilization.[35]

Three dispersed metal systems, described in the literature, were found to be suitable for this study. Their preparations are shown in eq 3, 4, and 5.

$$\text{Ni(acetate)}_2 + \text{NaH} + \text{ROH} \xrightarrow[45^\circ\text{C}]{\text{THF}} \text{NIC} \qquad (3)$$

$$\text{Co(2-ethylhexanoate)}_n + \text{BuLi} \xrightarrow[\text{or benzene}]{\text{cyclohexane}} \text{complex cobalt catalyst} \qquad (4)$$

$$\text{Li/Co} = 3.0\text{–}4.0$$

$$\text{Ni(2-ethylhexanoate)}_n + \text{NaBH}_4 \xrightarrow[\text{dioxane/ethanol}]{\text{THF/ethanol or}} \text{Ni}_x\text{B} \qquad (5)$$

$$\text{Ni/B} = 1.0$$

The synthesis (eq 3) and properties of NIC have been described by Caubere.[36] NIC was reported to contain nickel alkoxide particles which are 80–90 Å in size as determined by X-ray and electron microscopy. These particles are active for the hydrogenation of olefins in a variety of solvents. This catalyst was reproducibly prepared by Caubere. In addition, NIC retained its catalytic activity after months of storage under argon.

A dispersed cobalt catalyst (eq 4) was one of the most active "complex catalysts" for olefin hydrogenation reported by Falk.[37] This species was found by Falk to catalyze the hydrogenation of soluble polybutadiene and polyisoprene as well as low molecular weight olefins. Light-scattering studies identified the presence of colloidal materials in the 3500–3900-Å range. However, no claim was made about the catalytic activity of these particles.

A third dispersed catalyst (eq 5) was prepared for our study by modifying Brown's synthesis of P-2 nickel[38] (eq 6) to facilitate

$$\text{Ni(acetate)}_2 + \text{NaBH}_4 \xrightarrow{\text{ethanol}} \text{“P-2 nickel”} \qquad (6)$$

$$\text{Ni/B} = 0.5\text{–}2.0$$

the preparation in less polar solvents. In THF or dioxane solution, reduction of nickel 2-ethylhexanoate yields a black-brown suspension in which no particulate matter was visible to the naked eye.

The dispersed metal catalysts prepared for our study are all dark, air-sensitive suspensions that require careful handling to achieve reproducible results. As a precaution, two types of control experiments were used during the hydrogenation reactions with these catalysts. In one approach, monomeric and polymeric substrates in different reaction vessels were each treated with aliquots of the same catalyst preparation. Failure of the monomer reaction signaled a problem with the catalyst. Alternatively, hydrogenation of a monomeric and polymeric substrate was carried out in the same reaction vessel. This method allows one to verify the activity of a catalyst in the presence of a polymer.

The results for some hydrogenation reactions of these catalysts are shown in Table II (entries 6, 7, and 8). The reactivities of the nickel species were similar to those observed for supported catalysts. Control reactions showed that α-methylstyrene monomer could be hydrogenated in a vessel containing its cross-linked polymer analogue. The observed rates are comparable to those obtained for the monomer reaction alone. In such control reactions, the monomer hydrogenation was complete in 10–20 min, while no reaction of the polymer was detected even after 24 h.

For the complex cobalt catalyst, partial hydrogenation of the cross-linked polymer was observed. This result implies the presence of a homogeneous component in this reaction mixture.

Poisoning Experiments. The experiments with polymer-bound substrates suggested that soluble molecular catalysts can diffuse into swollen, cross-linked polymer networks and interact with attached functional groups, whereas insoluble catalysts cannot. Likewise, homogeneous catalysts should be susceptible to inhibition of their catalytic reactions by polymer-bound poisons.

The benzenethiol group was chosen to test this hypothesis. The incorporation of a thiol functionality in cross-linked polystyrene

Table IV. Hydrogenation of Styrene in the Presence of Sulfur-Containing Molecules

catalyst	poison	cat:sub:poison	*t*, h	max rate	yield, %
$RhCl(PPh_3)_3$	none	1:100:0	18	125	100
$RhCl(PPh_3)_3$	Ph-SH	1:100:100	18	*a*	31
$RhCl(PPh_3)_3$	Ⓟ-Ph-SH	1:100:100	18	*a*	20
Pd/C	none	1:100:0	1	980	100
Pd/C	Ph-SH	1:100:100	18	*a*	0
Pd/C	Ⓟ-Ph-SH	1:100:100	1	1960	100
NIC	none	1:20:0	2	*b*	100
NIC	Ph-SH	1:20:10	11	*a*	0
NIC	Ⓟ-Ph-SH	1:20:10	2	19	100

[a] Rate is too slow to measure. [b] Rates vary from 10 to 100 per hour depending on catalyst preparation and concentration. [c] 1% cross-linked polystyrene beads, 2.1 mequiv/g.

Table V. Hydrogenation with $RhCl_3py_3 + NaBH_4$[a]

substrate	time, h	conversion, %
$Ph\text{-}NO_2$	1	>90
Ⓟ-$Ph\text{-}NO_2$[b]	6	>90

[a] Room temperature, 2 atm of H_2. [b] 1% cross-linked polystyrene beads, 0.13 and 3.62 mequiv/g.

beads has been described by Frechet.[39]

The results obtained for the hydrogenation of styrene with homogeneous and heterogeneous catalysts in the presence of sulfur-containing compounds are shown in Table IV. The reaction of homogeneous $RhCl(PPh_3)_3$ is inhibited by the presence of the cross-linked polymeric thiol as well as by monomeric thiol.[40] For the two types of heterogeneous catalysts, Pd/C and NIC, benzenethiol acts as a severe poison, preventing all hydrogenation activity. In contrast, styrene hydrogenation with heterogeneous catalysts occurs at high rates in the presence of the sulfur-containing polymer. The accelerated rate of reaction with Pd/C in the presence of the cross-linked polymer is not understood.

Reactions of Some Unusual Catalysts. The field of homogeneous catalysis continues to expand, stimulated by the constant introduction of new catalysts and new synthetic applications. Recently the domain of homogeneous catalysts has been extended to include several reactions that were previously known to be catalyzed exclusively by heterogeneous species. These reactions include the hydrogenation of carbon monoxide,[41] nitro groups,[45] and arenes.[43] The reactivity of several of these catalysts has been examined by using the polymer-bound substrates.

Hydrogenation of Nitro Groups. McQuillin and co-workers have reported the use of a novel hydrogenation catalyst,[42] prepared by the reaction of sodium borohydride with the tris(pyridine) adduct of rhodium trichloride in DMF (eq 7). Although the complex

$$RhCl_3py_3 + NaBH_4 \xrightarrow{DMF} [Rh(BH_4)Cl_2(DMF)py_2] \tag{7}$$

can be isolated as a brown solid and characterized, it is usually generated in situ. This method of preparation is similar to reactions used to produce metal particles.[37] In fact, reduction to metallic rhodium was observed by McQuillin when alcohol solvents were employed.

This catalyst exhibits several unusual properties. It is effective in the hydrogenation of $-N{=}N-$, $-CH{=}N-$, $-NO_2$, and pyridine units as well as olefins. In addition, the rates observed for olfin hydrogenation showed zero-order dependence on olefin concentration. Both of these traits are typically associated with heterogeneous catalysts.[44]

The reduction of nitro groups to amines by the catalyst was examined by using polymeric and monomeric substrates. As shown in Table V, extensive reaction with both types of substrates was indicated by the infrared spectra of the products. This strongly suggests the presence of a homogeneous catalyst.

Hydrogenation of Olefins. An interesting family of iridium complexes having the form $[Ir(COD)L_2]PF_6$ has been reported by Crabtree.[45] These compounds are extremely active catalysts for olefin hydrogenation and possess some properties that are not commonly associated with homogeneous catalysts. Olefin hydrogenation occurs readily only in noncoordinating solvents such as methylene chloride. The reactions are insensitive to the presence of oxidizing agents and molecular oxygen. The catalysts are known to deactivate under hydrogen in the absence of an easily coordinating olefin. In addition, these catalysts exhibit a low degree of steric selectivity. Highly substituted olefins are hydrogenated at rates comparable to those observed for terminal olefins.[45] However, higher selectivity has been observed in direct competition experiments.[46]

Table VI. Hydrogenation of α-Methylstyrene Units with $[Ir(COD)P(i\text{-}Pr)_3py]PF_6$[a]

rxn	substrate	sub:cat ratio	conversion, %
1	monomer	1000:1	100
		100:1	100
2	cross-linked polymer[b]	100:1	0
3	monomer + cross-linked polymer[b]	1000:1	11
		100:1	3
4	monomer + cross-linked polymer[b]	130:1	100
		13:1	77
5	monomer + soluble polymer[c]	130:1	100
		13:1	100

[a] Reactions were carried out with catalyst concentrations 0.6-4.5 mM in CH_2Cl_2 at 0 °C for 1 h. [b] 1% cross-linked polystyrene beads, 1.74 mequiv/g. [c] Soluble polystyrene, 1.44 mequiv/g.

In our hands, the complex $[Ir(COD)P(iPr)_3py]PF_6$ rapidly hydrogenates olefins at 0 °C under 1 atm of hydrogen. Rates of 990 and 1140 turnovers per hour, for styrene and α-methylstyrene, respectively, were observed for reactions employing a 0.6 mM solution of catalyst. These rates are somewhat slower than those that have been reported for nonaromatic substrates,[45] possibly due to differences in handling or purifying of reactants. However, the rates may also signal some inhibition by π-coordination of the arene to the active catalyst. The results do indicate that the catalyst is not sensitive to minor steric hindrance.

Some results with α-methylstyrene monomers and polymers are shown in Table VI. Reaction of the cross-linked polymer alone showed no detectable hydrogenation, perhaps because of rapid deactivation of the catalyst before it is able to diffuse into the polymer network. To extend the lifetime of the catalytic species, the reaction was repeated in the presence of excess olefin monomer (Table VI, reaction 3). The results showed an unexpectedly low conversion of the monomer, raising the suspicion that the polymer was acting as a catalyst poison. Many molecules containing oxygen functional groups are known to deactivate this catalyst, presumably by coordination with an unsaturated iridium species. The polymer may contain some ketone groups, which were not converted into olefins during the Wittig reaction used in the polymer synthesis.

If deactivation were occurring by simple coordination, the problem could be overcome by increasing the catalyst-to-substrate ratio. Several experiments with increasing amounts of catalyst showed increasing conversion of both monomer and polymer substrates. Under the conditions of reaction 4, monomer hydrogenation was complete, and the cross-linked polymer showed a significant degree of conversion. Under these same conditions, the reaction of a mixture of soluble polymer with monomer was complete for both substrates.

Overall, our experiments with this catalyst point to the presence of an active homogeneous species. Since our work began, Crabtree has conducted additional tests to determine the homogeneity of his catalysts.[46] In these studies, no heterogenous material was detected by light-scattering or filtration techniques. In several reactions, these iridium complexes exhibited reactivity patterns different from metallic iridium.

Arene Hydrogenation. Hydrogenation of an unactivated benzene moiety was once taken as an indication of the presence of metal particles.[48] Since 1976, several reports of arene hy-

Table VII. Reported Homogeneous Catalysts for Benzene Hydrogenation, Part I

catalyst	solvent	conditions: *P*, atm	*T*, °C	time, h	yield, % (turnovers^d)	ref
$[Rh(C_5Me_5)Cl_2]_2 + NEt_3$	2-propanol^a	50	50	36	100 (450)	47
Ni(2-ethylhexanoate)$_2$ + 3AlEt$_3$	benzene	70	150–210	1	100 (330)	14
$(\eta^3\text{-}C_3H_5)Co[P(OR)_3]_3$						
R = Me	benzene	1	20	24^b	16 (16)	49
R = *i*-Pr	benzene	1	20	5^b	*c*	49

^{a} Catalyst is also reported to be active in neat benzene. ^{b} Approximate catalyst lifetime. ^{c} No value given. Compound is reported to be more active, but shorter lived than methyl analogue. ^{d} Mol of product/mol of catalyst produced in the time given in the table.

Table VIII. Reported Homogeneous Catalysts for Benzene Hydrogenation, Part II

	conditions				
catalyst	solvent	*P*, atm	*T*, °C	turnover rate	ref
$(\eta^6\text{-}C_6Me_6)Ru(\eta^4\text{-}C_6Me_6)$	benzene	2–3	90	0.08/min	52
$RuHCl(\eta^6\text{-}C_6Me_6)PPh_3$	benzene	50	50	0.8/min	50
$[(\eta^6\text{-}C_6Me_6)Ru(\mu\text{-}H)_2(\mu\text{-}Cl)\text{-}Ru(\eta^6\text{-}C_6Me_6)]Cl$	benzene^a	50	50	4.1/min	51
$(HRh[P(O\text{-}i\text{-}Pr)_3]_2)_2$	benzene	1	20	1.0/day^{-1}	53

^{a} Catalyst is also reported to be active in 2-propanol solvent.

Table IX. Hydrogenation Activity of $[Rh(C_5Me_5)Cl_2]_2$

$$\text{substrate} + NEt_3 + [Rh(C_5Me_5)Cl_2]_2 \xrightarrow[i\text{-PrOH or } CH_2Cl_2]{H_2} \text{product}$$

substrate	*T*, °C	*P*, atm	*t*, h	product (%)	ref
cyclohexene^a	20	1	(9.8 mL/min)	cyclohexane (100)	41
cyclohexene^b	20	1	(2.3 mL/min)	cyclohexane (100)	41
styrene^c	50	50	36	ethylbenzene (97) ethylcyclohexane (3)	42
benzene^c	50	50	36	cyclohexane (100)	43
ethylbenzene^c	50	50	36	ethylcyclohexane (60)	43

^{a} Conditions: 0.04 mmol of catalyst, 11.8 mmol of cyclohexene, excess NEt$_3$, 20 mL of 2-propanol solution. ^{b} Conditions: same as above with CH$_2$Cl$_2$ solvent. ^{c} Conditions: 0.05 mmol of catalyst, 1.5 mmol of NEt$_3$, 22.5 mmol of arene, 20 mL of 2-propanol solution.

drogenation by discrete transition-metal complexes have appeared. These precatalysts and their operating conditions are summarized in Tables VII and VIII. The determination of the active catalyst in these reactions is difficult. Thus, this area could benefit from examination using our polymer-bound substrate concept.

Some catalysts are not suitable, however, for testing by reaction with polymer-bound substrates. It is known from our reactions with well-characterized homogeneous catalysts that the reactivity of the polymer is three to five times lower than that of the corresponding monomer. Therefore, the catalyst must be moderately reactive so that the reaction of the polymer can be detected in a reasonable amount of time. Also, the catalyst must be active in a nonparticipating solvent. Although polymeric poisons can provide some information, reactions reported to occur only when the substrate (benzene) is employed as the solvent cannot be easily studied.

One robust catalyst is $[Rh(C_5Me_5)Cl_2]_2$, which has been described by Maitlis and co-workers.[47,54,55] Table IX summarizes some results reported for hydrogenation with this catalyst. Simple olefins reacted readily under mild conditions in 2-propanol or methylene chloride solvent, while increased temperature and pressure were necessary to produce arene hydrogenation. The question this raises is whether or not the harsher conditions are required to produce a different kind of active catalyst.

To attempt to answer this question, the catalyst system was studied under both conditions with suitable monomeric and polymeric substrates. For olefin hydrogenation, methylene chloride was chosen as solvent because it allows the swelling of the polystyrene beads. As seen in Table IX, the hydrogenation of styrene was reported to require the harsher conditions typically employed for arene hydrogenation. In our studies, it was found that the reaction with styrene could be accomplished at 50 psig (4–5 atm) hydrogen pressure and 50 °C, in methylene chloride using long reaction times. Our results, as illustrated in Table X, show that under similar conditions, the hydrogenation of the olefinic group in both the monomer and the cross-linked polymer occurs at comparable rates. The polymer reaction was confirmed by FTIR analysis and also by bromination of the product polymer followed by elemental analysis. These results indicate that under mild conditions a homogeneous catalyst is active for the reduction of olefinic groups.

Arene hydrogenation of monomeric and soluble polymeric substrates was examined employing both methylene chloride and 2-propanol as solvent. Under low-pressure conditions (50 psig of H$_2$) only trace hydrogenation of benzene was observed in the dark reaction mixtures. Reactions at high pressure (50 atm of H$_2$) were carried out in a stainless steel autoclave, equipped with a tube to provide samples for periodic analysis. The reaction conditions were similar to those reported by Maitlis for arene hydrogenation in 2-propanol.[55] The results are summarized in Table XI.

Initial experiments in methylene chloride showed that benzene hydrogenation was sluggish, proceeding to only 63% conversion in 29 h. It was found that the reaction rate could be greatly increased by increasing the triethylamine concentration 2-fold. Under these conditions, the reaction rates in methylene chloride solvent are still slower than those obtained in 2-propanol (Table XI). The triethylamine has been proposed to function as a scavenger of HCl generated in the heterolytic cleavage of molecular hydrogen by the precatalyst.[55] In methylene chloride at high pressure, it seems likely that solvent hydrogenolysis is a competing reaction and a secondary source of HCl.

The results of hydrogenation of low molecular weight arenes are instructive. First, a 1–2-h induction period is routinely observed in both solvents. Second, the turnover numbers calculated for a series of arenes indicate that the reaction rate is sensitive to steric bulk of the ring substituents. In addition, after hydrogenations with Maitlis' catalyst, control reactions using soluble arene, triethylamine, and no precatalyst were found to exhibit up to 16% of the catalytic activity of the original reaction mixture over 12 h. This activity for arene hydrogenation cannot be attributed to any of the components of the stainless steel of the autoclave. This contaminant could be removed only by physically repolishing the metal surfaces of the stir rod and sampling tubes that come in contact with the reaction mixture. (The reaction vessel itself is a glass liner that can be easily freed from metal by treatment with acid.) It is possible that this apparent deposition of rhodium metal occurs upon exposing the reaction mixture to air at the termination of an experiment. However, the consistent observation of a substantial induction period in all the reactions of this catalyst

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(52) Johnson, W.; Muetterties, E. L. *J. Am. Chem. Soc.* **1977**, *99*, 7395.

(53) Sivak, A. J.; Muetterties, E. L. *J. Am. Chem. Soc.* **1979**, *101*, 4878.

(54) Gill, D. S.; White, C.; Maitlis, P. M. *J. Chem. Soc., Dalton Trans.* **1978**, 617.

(55) Russel, M. J.; White, C.; Maitlis, P. M. *J. Chem. Soc., Chem. Commun.* **1977**, 427.

suggests that this metal may be formed under reaction conditions.

The hydrogenation of soluble polystyrene in methylene chloride was attempted under conditions similar to those used for the monomeric substrates. The active catalyst was first performed in the absence of polymer by initiating the hydrogenation reaction with benzene substrate. After benzene hydrogenation was allowed to proceed to 50% (ca. 2 h) a solution of polystyrene in methylene chloride was added and the reaction was resumed. Benzene hydrogenation continued at an appreciable rate and was virtually complete in 30 h, indicating that polystyrene was not acting as a catalyst poison. After a reaction time of 123 h, half of the reaction mixture was removed for polymer analysis. Hydrogenation of benzene, added to the remaining reaction mixture, proceeded at a rate that was comparable to the initial rate of benzene hydrogenation (considering dilution effects), indicating that the catalyst remains active long after all the original benzene has been depleted.

The extent of polystyrene hydrogenation was determined by FTIR analysis of polymer films. Comparison of the areas of the aromatic and aliphatic C–H stretching bands before and after exposure of polystyrene to the hydrogenation conditions indicates less than 0.5% (±2%) arene hydrogenation after ca. 5 days. The hydrogenation of cumene performed in the presence of polystyrene under identical conditions proceeds to 32% conversion in the same time period. Assuming that cumene is a reasonable model for the electronic and steric properties of the arene unit in the polymer, the difference in the rates is large enough to suggest that a heterogeneous catalyst may be involved.

Reaction of the hydrated styrene/butadiene copolymer (**14**) in 2-propanol was also attempted since arene hydrogenation in this solvent was preferred by Maitlis. Initial attempts to hydrogenate benzene in the presence of this polymer indicated that **14** somehow inhibits the formation of the active catalytic species and thereby prevents catalytic arene hydrogenation. This problem could be overcome by preforming the active catalyst prior to polymer addition as described for polystyrene hydrogenation. Periodic GC analysis of reaction aliquots following polymer addition indicated that the active catalytic species for arene hydrogenation, once formed, remains active in the presence of the copolymer. Benzene hydrogenation was complete after 75 h. After 200 h, hydrogenation was terminated and the polymer analyzed by FTIR and ^{1}H NMR spectroscopy. The disappearance of the IR band at 967 cm^{-1} (alkene C–H def) and the ^{1}H NMR resonances at 5.4 (vinyl) and 2.0 (allylic) ppm in the product indicates nearly quantitative hydrogenation of the residual alkene units in the copolymer. This is consistent with our earlier findings that the active olefin hydrogenation catalyst is homogeneous. No evidence of arene hydrogenation on the polymer was apparent from the spectroscopic data, suggesting that the active arene hydrogenation catalyst may be heterogeneous. However, due to the low concentration of arene units in the copolymer and the poor spectral resolution, the sensitivity of this test may be poorer than that employing polystyrene.

Although no undisputed homogeneous arene hydrogenation catalyst is available for comparison, our results with $[Rh(C_5Me_5)Cl_2]_2$ may be compared with the reactivity of truly heterogeneous rhodium on alumina. Hydrogenation of cumene with this catalyst occurs even at room temperature and atmospheric pressure. In 2-propanol solvent at 50 °C and 50 atm of hydrogen pressure, cumene hydrogenation occurs at rates exceeding 170 turnovers per metal atom per hour. Two soluble polymers were examined under these conditions, hydrated styrene/butadiene copolymer in 2-propanol solution and polystyrene in THF solution. However, no hydrogenation of arene units in either of these soluble polymers was detected under these conditions.

Although these experiments do not definitively establish the presence of a heterogeneous metal catalyst, the overall reactivity patterns suggest that Maitlis's catalyst has some properties in common with heterogeneous catalysts. The mechanism of arene hydrogenation by this catalyst should be examined more carefully before concluding that this catalyst is truly homogeneous. The results with Maitlis' catalyst also suggest that other homogeneous precatalysts for monocyclic arene hydrogenation might benefit from this type of study.

Discussion

This study has demonstrated that polymers can be effective in distinguishing homogeneous catalysts from heterogeneous metal particles that are greater than 80 Å in size. Only the soluble molecular catalysts have been found to interact with functional groups attached to lightly cross-linked polymer networks. This discrimination was exhibited to a lesser extent by soluble polymers. This phenomenon appears to be general. It did not depend on the type of polymer employed or the specific catalytic reaction being studied.

The differences in apparent reactivity observed for the two types of catalysts reflect a lack of mobility of the heterogeneous catalyst in and around the polymer matrix. This decreased mobility may be caused by adsorption of some portion of the polymer onto the catalyst surface or by the simple exclusion of large particles from the pores set up in the cross-linked polymer network. Alternatively, the diffusion of the heterogeneous catalyst into the polymer network may be prohibitively slow.

Exclusion by size alone is not likely to be solely responsible for the discrimination between the catalyst types. Other workers[22,56] have shown that the network structure in 1–2% cross-linked polystyrene beads and gels is open and accessible to many large, homogeneous reagents such as porphyrins[57] and transition-metal complexes.[58,59] The low reactivity of soluble polymers with heterogeneous catalysts suggests that a rigid network, with well-defined pores, is not necessary to differentiate between soluble and insoluble catalysts.

The adsorption or attachment of the polymer to the heterogeneous catalyst is probably an important factor. Soluble and cross-linked polymers recovered from our reactions with insoluble catalysts were often gray, indicating the presence of metal. In addition, polymers such as poly(vinyl alcohol) have been routinely used to stabilize preparations of colloidal metals.[35]

The role of diffusion may also be important. The mobility of a poorly solvated heterogeneous particle may be severely limited in the region occupied by the polymer.

The above reasoning supports the theory that the selectivity of the polymer is related more to the physical state of the catalyst than the size of the catalyst.

The absolute sensitivity of this method is not yet known. This is due primarily to a lack of well-characterized catalyst systems, containing from two to several hundred metal atoms, which can be used as standards. The study of molecular clusters can potentially provide information to fill this gap. However, few if any proven examples of catalysis by intact clusters have been recognized to date.[7]

Because the limits of detection using our technique are not known at this point, a conclusive answer to the question of catalyst phase cannot be given. In spite of this drawback, the method possesses several advantages over other attempts to distinguish between homogeneous and heterogeneous catalysis. First, the test is based on a fundamental property common to all catalysts, i.e., the solubility or physical phase of the reacting species. Second, the evaluation of the catalyst's phase is based on the reactivity pattern exhibited by the *active catalytic species* and is not influenced by *inactive components* (homogeneous or heterogeneous) which may be present in the reaction mixture. Finally, although the present study has concentrated on hydrogenation reactions, this method could, in principle, be applied to any type of catalytic reaction in which a reactant or catalyst inhibitor may be attached

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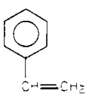
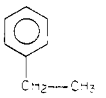
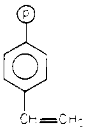
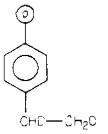
(56) Frechet, J. M. J.; Farrall, M. J. "Chemistry and Properties of Crosslinked Polymers"; Labana, S. S., Ed.; Academic Press: New York, 1977; p 59.

(57) Collman, J. P.; Reed, C. A. *J. Am. Chem. Soc.* **1973**, *95*, 2048.

(58) Collman, J. P.; Hegedus, L. S.; Cooke, M. P.; Norton, J. R.; Dolcetti, G.; Marquardt, D. N. *J. Am. Chem. Soc.* **1972**, *94*, 1789.

(59) Rafalko, J. J.; Lieto, J.; Gates, B. C.; Schrader, G. L. *J. Chem. Soc., Chem. Commun.* **1978**, 540.

Table X. Olefin Hydrogenation with $[Rh(C_5Me_5)Cl_2]_2$[a]

substrate	*P*, atm	*t*, h	sub:cat	results	
	4–5(H_2)	70	300:1		>90%
	4–5(D_2)	96	20:1		>95%

[a] Reactions were carried out with NEt_3 (180 equiv) in CH_2Cl_2 (5 mL) at 50 °C. [b] 1% cross-linked polystyrene beads, 0.87 mequiv/g.

Table XI. Hydrogenation of Arenes with $[Rh(C_5Me_5)Cl_2]_2$

substrate	initial rate,[a] turnovers/h	initial rate,[b] turnovers/h
benzene	111	49
toluene		48
cumene	32	15
polystyrene[c]	none detected	
hydrated styrene/ butadiene copolymer (14)		none detected

[a] Conditions: 0.05 mmol of catalyst, 1.5 mmol of NEt_3, 22.5 mmol of arene, 20 mL of CH_2Cl_2. [b] Conditions: 0.05 mmol of catalyst, 3.0 mmol of NEt_3, 22.5 mmol of arene, 20 mL of 2-propanol. [c] Soluble polymer, M_w = ca. 320 000.

to a suitable polymeric support.

Experimental Section

All reactions were conducted under a nitrogen atmosphere in Schlenk-type glassware[60] or in an inert atmosphere glovebox (Vacuum Atmospheres Co.).

Materials. Insoluble, 1% divinylbenzene/styrene copolymer beads (**7**) (SX-1 Bio-beads) were purchased from Bio-Rad Laboratories. Before use, these beads were washed with aqueous acid, aqueous base, and organic solvents as described by Relles.[61] Chloromethylated SX-1 Bio-Beads (**1**) (Bio-Rad Laboratories) having a capacity of 1.34 mequiv Cl/g were washed sequentially with methylene chloride, THF, acetone, and methanol before use. Soluble polystyrene (**6**) (Aldrich, secondary standard, M_w = 321 000) and 23% styrene/butadiene copolymer (Aldrich) were purified by precipitation from THF solution into methanol.

Monomers for catalytic reactions were purified by standard procedures.[62] Styrene (Aldrich) and α-methylstyrene (Matheson, Coleman and Bell) were extracted with aqueous 5% NaOH followed by water to remove free-radical inhibitors. After drying over anhydrous $MgSO_4$, each olefin was passed down a column of activated alumina (Matheson, Coleman and Bell) to remove peroxides. Distillation was then carried out at reduced pressures (30 °C/10 mm and 43 °C/7 mm, respectively). Cumene (Aldrich) was passed down a column of activated alumina and then distilled under nitrogen (152 °C/760 mm). Thiophene-free benzene (Aldrich) was distilled from sodium metal under nitrogen. The purified substrates were degassed by three freeze–thaw cycles under vacuum and then stored under nitrogen at -20 °C.

Solvents were distilled under a nitrogen atmosphere from appropriate drying agents.

Physical and Spectroscopic Methods. Infrared spectra were recorded on either a Beckman Acculab 3 spectrometer or a Nicolet Technologies 7000 Fourier transform infrared (FTIR) spectrometer. Nuclear magnetic resonance spectra were measured with either a Varian T-60 instrument or a Nicolet Technologies 300 Fourier transform nuclear magnetic resonance spectrometer. Chemical shifts are reported in ppm (δ) relative to tetramethylsilane (Me_4Si).

Elemental analyses were performed at the Microanalytical Laboratories of Stanford University and the University of California at Berkeley.

Analysis of hydrogenation reactions involving monomeric substrates was carried out on a Hewlett-Packard 5880 gas chromatograph equipped with a flame ionization detector and a 6 ft × $^1/_8$ in. column of 20% β,β′-oxydipropionitrile on Chromosorb W (Supelco). Cyclohexane and *n*-decane were used as internal standards as needed.

Hydrogenation of olefin-containing polymers was monitored with FTIR spectroscopy. Samples of soluble polymers were prepared by casting films from THF solution. Insoluble polymers were swollen in dry THF and pressed between sodium chloride plates. The extent of hydrogenation could be determined by comparing the intensity of the absorbance at 1625–1630 cm^{-1} (C=C) with that of the absorbance at 1600 cm^{-1} (aromatic ring) and referring to an appropriate calibration chart.

The extent of hydrogenation of the aromatic and residual olefinic units in the hydrated styrene/butadiene copolymer was determined by FTIR and ^1H NMR spectroscopy. Polymer films for IR analysis were cast from 2-propanol solution and dried at 60 °C in vacuo (ca. 0.1 torr). The peak absorbance intensity at 967 cm^{-1} (trans, disubstituted alkene C–H def) was used as a measure of percent olefin hydrogenation. Similarly, arene hydrogenation was estimated from absorbance intensities at 699 (arene C–H def), 759 (arene C–H def), 1451 (arene C=C str), and 1600 cm^{-1} (arene *i*-*p* vib). The peak absorbance of the band corresponding to the O–H stretch (3323 cm^{-1}) was used as an internal standard in both cases. Polymer samples were prepared for ^1H NMR analysis by drying under high vacuum (0.001 torr) for at least 24 h at room temperature and dissolving in dry 2-propanol-d_8. Polymer solutions were transferred to 5-mm NMR tubes and sealed in vacuo (0.001 torr). ^1H NMR spectra were recorded at 300 MHz and the degree of olefin and arene hydrogenation was estimated from the appropriate ^1H integrals. Due to the low density of arene units in the copolymer and the poor IR and NMR spectral resolution, the estimated error in the calculated percent conversion values for this system is ±15%.

Percent arene hydrogenation in soluble polystyrene samples was determined exclusively by FTIR spectroscopy of polymer films cast from methylene chloride solution. Films were thoroughly dried at 55 °C in vacuo (0.1 torr) for at least 24 h prior to analysis. The extent of arene hydrogenation was estimated from the relative areas of the two strong, well-resolved aromatic and aliphatic C–H stretching bands centered at ca. 3025 and 2922 cm^{-1}, respectively. Areas were measured with a Nicolet digital integration routine. On the basis of calculated response factors for the aromatic and aliphatic C–H bands in unreacted polystyrene, the percentage of arene units hydrogenated can be related directly to the ratio of these peak areas. The error in the measurement of this ratio is estimated at ±5%. Thus, the error in the calculated percent conversion values using this technique is less than ±2%.

Preparation of Ⓟ—PhCH=CH$_2$ (4). Method 1. The polymer, Ⓟ—$PhCH_2P(Ph)_3{}^+Cl^-$ (**2**), was prepared according to the literature[17] from chloromethylated polystyrene beads **1** and triphenylphosphine. To a suspension of **2** (1 g, ca. 1.0 mequiv/g) in THF (30 mL) was added a solution of *n*-butyllithium in hexane (0.65 mL, 1.6 M). After the mixture was stirred for 1 h, an excess of paraformaldehyde (90 mg, 3.0 mmol) was added and the mixture stirred for 18 h. The colorless polymer was isolated by filtration, washed sequentially with THF, water, methanol, dichloromethane, and methanol, and then dried under vacuum at 50 °C. Anal. Found: Cl, 0.14; P, 0.06.

The dibromo derivative was prepared by stirring a suspension of the olefin-containing polymer **4** with excess bromine in carbon tetrachloride in the absence of light for 30 min. Anal. Found: Br, 12.28. This corresponds to a loading level of 0.88 mequiv of olefin/g (9.5% ring substitution) and indicates a 65% functional yield from the chloromethylated polymer.

Route 2. The aldehyde-containing polymer Ⓟ-Ph-CHO (**3**) (1.13 mequiv of aldehyde/g) was prepared from chloromethylated Bio-Beads as reported by Frechet.[17] To a suspension of finely powdered methyltriphenylphosphonium iodide (0.425 g, 1.05 mmol) in THF (20 mL) was added a solution of phenyllithium in benzene (0.50 mL, 2.09 M). The clear yellow solution that formed was stirred for 1 h. After a negative Gilman test,[63] the solution was added to a suspension of aldehyde resin **3** (0.50 g, 1.13 mequiv/g) in THF (20 mL) over 30 min. The yellow suspension was stirred at reflux temperature for 6 h. An excess of potassium *tert*-butoxide (1.1 g, 10 mmol) was added[18] and the mixture again heated for 12 h. After addition of 1 mL of water, the resin was isolated and washed with THF, water, methanol, methylene chloride, and methanol. The resin was dried under vacuum at 50 °C. IR (KBr): 1630 cm^{-1} (m, C=C). The carbonyl absorbance at 1690 cm^{-1} was absent. Anal. Found: Cl, <0.019; P, 0.00.

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(60) Shriver, D. F. "The Manipulation of Air-Sensitive Compounds"; McGraw-Hill: New York, 1969.

(61) Relles, H. M.; Schluenz, R. W. *J. Am. Chem. Soc.* **1974**, *96*, 6469.

(62) Perrin, D. D.; Armarego, W. L. S.; Perrin, D. R. "Purification of Laboratory Chemicals"; Pergamon Press: New York, 1966.

(63) "Vogel's Textbook of Practical Organic Chemistry", 4th ed.; Furniss, B. S.; Hannaford, A. J.; Rogers, V.; Smith, P. W.; Tatchell, A. R., Eds.; Longman: 1978; p 340.

The dibromo derivative was also prepared. Anal. Found: Br, 13.7. This corresponds to an olefin capacity of 0.99 equiv/g (11% ring substitution). This indicates a functional yield of 92% from the aldehyde polymer **3**.

Preparation of Ⓟ—PhC(CH_3)=CH_2 (9). Soluble polystyrene (**6**) and SX-1 Bio-Beads (**7**) were acetylated by using a reported procedure.[13] The resulting polymers were treated with methylenetriphenylphosphorane ylide as described in route 2, above. Longer reaction times (48–72 h) were necessary to obtain high yields of olefin products. The extent of the reactions was monitored by IR spectroscopy of small aliquots. IR (film or suspension): 1625 cm^{-1} (m, C=C). ^1H NMR ($CDCl_3$): δ 7.03 and 6.56 (each br, aromatic protons); 5.31 and 5.01 (each br, vinyl protons); 2.27 (br, CH_3); 1.43 (br, aliphatic protons). The cross-linked polymer was characterized in its dibromo derivative. Anal. Calcd for 19.4% ring substitution: C, 72.12; H, 6.15; Br, 21.74. Found: C, 72.01; H, 6.11; Br 21.72. This corresponds to 1.74 mequiv of olefin/g polymer.

Preparation of Macronet Isoporous Polystyrene (12). The cross-linking reaction was modeled on the work of Peppas[26] and Davankov.[24] The cross-linking agent, 1,4-dimethyl-2,5-bis(chloromethyl)benzene (**10**), was prepared by the chloromethylation of *p*-xylene according to the procedure of Peppas and Valkanas.[64] To a solution of polystyrene (**6**) (5.2 g, 50 mmol) and cross-linking agent (**10**) (0.101 g, 0.50 mmol) in 1,2-dichloroethane (DCE) (50 mL) was added a solution of tin tetrachloride (0.12 mL, 1.0 mmol) in DCE (1.0 mL). The colorless solution was heated to 70 °C with vigorous stirring. After 30 min, gel formation was observed. The reaction was maintained at 65–70 °C for 18 h. The gel was broken into small pieces, washed with acetone, THF, acetone, and methanol, and dried under vacuum at 65 °C for 24 h. Anal. Found: C, 91.1; H, 7.7; Cl, <0.1.

Preparation of Hydrated Styrene/Butadiene Copolymer (14). The procedure for this reaction was based on the work of Brown[30] and Pinazzi.[28] To a solution of 23% styrene/butadiene copolymer **13** (3.4 g, ca. 40 mmol of olefin) in THF (600 mL) was added 9-BBN (5.4 g, 44 mmol). The solution was stirred for 5 h at reflux temperature, and then for 20 h at room temperature. The reaction mixture was cooled to 0 °C and NaOH (45 mL, 3 N solution) and H_2O_2 (22 mL of 30% solution) were added rapidly. After stirring for 23 h at room temperature, two layers were clearly visible. The top (THF) layer was removed and filtered through a medium glass-fritted funnel. The volume of the clear colorless solution was reduced under vacuum, causing the polymer to precipitate as a gel. This gel was immediately redissolved in THF. The polymer was isolated by adding 2-propanol (an amount equal to two times the volume of the THF solution) to the THF solution and then removing all solvent under vacuum. The resulting polymer was soluble in 2-propanol and THF/water mixtures but not in pure THF. The polymer was purified by precipitation of an 2-propanol solution of the polymer in water. The polymer was dried at room temperature for 24 h. Attempts to isolate this polymer by other methods such as precipitation of the THF solution, or attempts to dry this polymer at elevated temperatures, led to insoluble gels. Anal. Calcd for 100% hydration: C, 74.4; H, 10.10; Found: C, 71.45; H, 9.90. IR (film): 3323 (br, OH), 2856 (s, aliphatic C–H str), 1600 and 1451 (w, aromatic C=C vib), 1055 (m, C–O str), 967 (w, alkene C–H def), and 699 and 759 cm^{-1} (m, aromatic C–H def). ^1H NMR (2-propanol-d_8): δ 7.2 and 7.1 (br, aromatic), 5.3 (br, vinyl), 3.5 (br, H–C–OD), 2.0 (br, allylic), 1.2–1.6 (br, aliphatic). The NMR spectrum also indicates the presence of traces of THF and 2-propanol. Because of these impurities, accurate integrations could not be obtained.

Catalytic Reactions. Catalysts. Supported heterogeneous catalysts, 5% rhodium on alumina and 5% palladium on charcoal, were purchased from Englehard Industries and used as received. Organometallic compounds used as catalyst precursors were synthesized according to literature methods.[65] Dispersed nickel (NIC) and cobalt catalysts were prepared following procedures reported by Caubere[36] and Falk,[37] respectively. The nickel boride catalyst was prepared in bulk and in situ as follows.

A standard solution (0.06 M in Ni) was prepared by dissolving nickel 2-ethylhexanoate (0.21 g, 0.60 mmol) in THF or dioxane (10 mL) under nitrogen. A mixture (10 mL) of ethanol/aqueous 2 N sodium hydroxide (95/5) was added to sodium borohydride (0.223 g, 3.0 mmol) to yield a 0.3 M solution. Both solutions were degassed by using three freeze–pump–thaw cycles and stored under nitrogen at −20 °C. The catalyst was generated immediately before use in a Schlenk tube under nitrogen or in a reaction vessel under hydrogen by addition of equimolar amounts of the two standard solutions. During the addition, the green color of the nickel complex immediately disappeared and the solution changed to a brown-black color. No precipitation of particles was observed.

Low-Pressure Hydrogenations. Reactions rapid enough to monitor at low hydrogen pressures were carried out by using one of two types of reactors. Kinetic measurements were made with a constant-pressure (1 atm) apparatus, previously described by Marquardt.[66] Reactions could be monitored by gas uptake as well as by removing aliquots for GC analysis. Unsampled batch reactions, which required pressures from 1 to 5 atm, were carried out in Fischer–Porter bottles. The reactor consists of a heavy-walled glass pressure vessel attached to a brass head containing gas and sample inlets, a pressure gauge, and a safety relief valve.

Procedure. The following illustrates a typical procedure for the hydrogenation of olefins with $RhCl(PPh_3)_3$ using the constant pressure apparatus. The reaction vessel consisted of a 25-mL, 2-neck, heart-shaped flask equipped with a stirring bar, a needle inlet, and an adapter for connection to the hydrogenation line. When a conventional nitrogen/vacuum manifold was used, a solution (or suspension) of olefin substrate in toluene was prepared under nitrogen in the reaction flask. The mixture was degassed by using three freeze–pump–thaw cycles. The reaction vessel, still under vacuum, was then attached to the hydrogenation line and the connection evacuated for 15–20 min. The substrate mixture was allowed to come to room temperature. After the hydrogen line was evacuated and filled with hydrogen three times, the final hydrogen atmosphere was admitted to the reaction flask. A freshly prepared solution of $RhCl(PPh_3)_3$ in toluene was then added by syringe. The hydrogen pressure was quickly set by adjusting the heights of two columns of mercury. The initial hydrogen volume was measured, and then stirring was started to begin the reaction. Hydrogen uptake was typically observed within 4–6 min. Maximum rate was established shortly thereafter.

Similar induction periods and hydrogenation rates were observed when an alternative procedure was followed. A mixture of olefin substrate, catalyst, and solvent was prepared in the reaction flask under nitrogen. The mixture was degassed by using three freeze–pump–thaw cycles. The reaction flask was attached to the hydrogenation line in the same manner as described above. After the initial hydrogen volume was measured, the reaction was started by stirring.

High-Pressure Hydrogenations. Reactions requiring higher pressures were carried out in a custom-built 50-mL capacity MagneDrive autoclave (Autoclave Engineers). The reactor consists of a stainless steel reaction chamber which may be fitted with a glass liner. The stainless steel reactor lid was equipped with a motor driven MagneDrive stirring mechanism for mechanical stirring, a diptube for the introduction and removal of liquids, and a thermocouple temperature probe for monitoring reaction temperature. An external furnace unit was added to heat the reaction chamber. A typical procedure for the hydrogenation of a monomeric arene using this apparatus is given below.

$[Rh(C_5Me_5)Cl_2]_2$-Catalyzed Hydrogenation of Benzene in 2-Propanol. The glass liner containing the air-stable complex $[Rh(C_5Me_5)Cl_2]_2$ was placed inside the reaction chamber and the autoclave sealed. Nitrogen was admitted to the autoclave via a manifold up to a pressure of 20–30 atm and then vented to 2 atm (4 times). The sample port was fitted with a septum and purged with nitrogen. A solution of benzene substrate in 2-propanol and triethylamine was transferred to the autoclave via a double-pointed needle using the port on the autoclave head as a vent for excess gas. After the transfer, the autoclave was again sealed. Nitrogen (20–30 atm) was introduced and released. This was repeated twice with hydrogen before the autoclave was filled to the desired pressure of 50 atm with hydrogen. At this point, heating and stirring of the autoclave commenced. A stable temperature of 50 °C was reached after 20–30 min.

Samples for analysis were removed from the autoclave at 20–50 °C by terminating the stirring and lowering the pressure to 2 atm using the manifold. Attachment of a small delivery tube to the sample port allowed the collection of a sample in a vial by partially opening the sample valve. Because of the significant dead volume of the sample tube, a "forerun" of approximately 0.4 mL was taken before each sample. After sampling, the pressure was immediately raised to the desired value and the stirring was resumed.

To terminate a reaction, the stirring was stopped and the majority of hydrogen was vented from the autoclave. Nitrogen (20–30 atm) was then introduced into the autoclave and subsequently vented (2 times) to remove remaining hydrogen. The autoclave was then opened and the glass liner removed. The autoclave was cleaned by washing *all* accessible internal parts of the autoclave with organic solvents. In many cases, treatment with aqueous acid or polishing with emery paper was necessary to provide a "clean" autoclave. Test runs with substrate and *no* catalyst were carried out between actual hydrogenation experiments to determine

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(64) Peppas, N. A.; Valkanas, G. N. *Angew. Makromol. Chem.* **1977**, *62*, 163.

(65) References are found in text.

(66) Marquardt, D. N. Ph.D. Thesis, Stanford University, 1974.

J. Am. Chem. Soc. **1984**, *106*, 2579–2583

that the autoclave was free from catalytically active metal impurities.

Acknowledgment.

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Registry No. Polybutadiene, 9003-17-2; poly(vinylbenzyl chloride), 9080-67-5; styrene, 100-42-5; α-methylstyrene, 98-83-9; poly(α-methylstyrene), 25014-31-7; benzene, 71-43-2; toluene, 108-88-3; cumene, 98-82-8; $PhCH_2Cl$, 100-44-7; $PhNO_2$, 98-95-3; Pd, 7440-05-3; Rh, 7440-16-6; Ni, 7440-02-0; Co, 7440-48-4; $RhCl(PPh_3)_3$, 14694-95-2; $[Rh(NBD)(PPh_3)_2][ClO_4]$, 32799-31-8; $[Ir(COD)P(i\text{-}Pr)_3py][PF_6]$, 64536-74-9; $[Rh(C_5Me_5)Cl_2]_2$, 12354-85-7.

Thiocyanate Cleaves the Imidazolate-Bridged Dicopper(II) Center in a Binucleating Macrocycle To Form $[Cu_2(SCN)_4\subset A']$. Model Chemistry for Superoxide Dismutase

Andrea E. Martin[1a] and Stephen J. Lippard*[1a,b]

Contribution from the Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, and Columbia University, New York, New York 10027.
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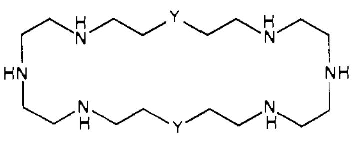
Abstract: When excess potassium thiocyanate is added to an aqueous solution of $[Cu_2(im)\subset A']^{3+}$ (imH = imidazole; A′ = 1,4,7,13,16,19-hexaazacyclotetracosane) the imidazolate bridge cleaves, as judged by frozen solution electron spin resonance (ESR) spectroscopic measurements and structural studies of the isolated reaction product, $[Cu_2(NCS)_4\subset A']$. This chemistry parallels that of the four-copper form of bovine erythrocyte superoxide dismutase, Cu_2Cu_2SOD, which shows similar changes in its ESR spectrum upon addition of thiocyanate ion. X-ray crystallographic study of the product reveals the two copper centers in macrocycle A′ to have distorted square-pyramidal geometry, with three ligand nitrogen atoms and one thiocyanate nitrogen donor in the basal plane (Cu–N distances, 1.93–2.07 Å). The apical site of one copper center is occupied by a thiocyanate nitrogen atom (Cu–N = 2.240 (6) Å) whereas the other copper has a weakly coordinated sulfur atom (Cu–S, 2.733 (2) Å) in the apical position. There is no longer a bridge between the two copper atoms, which are 7.577 (1) Å apart. These results demonstrate the value of $[Cu_2(im)\subset A']^{3+}$ as a model for Cu_2Cu_2SOD and imply that, at least in its reaction with thiocyanate ion, the chemistry of the four-copper form of the protein is controlled by the fundamental coordination chemistry of the bimetallic site rather than by properties unique to a protein environment. The compound $[Cu_2(NCS)_4\subset A']$ crystallizes in the monoclinic system, space group $P2_1/c$, with a = 14.718 (1) Å, b = 14.472 (2) Å, c = 16.569 (1) Å, β = 113.98 (1)°, and Z = 4.

The study of low molecular weight transition-metal complexes is frequently of value in elucidating aspects of the chemistry of metalloproteins.[2] Recently we have prepared and examined imidazolate-bridged dicopper(II) complexes as models[3] for the active site of the 4-Cu form of bovine erythrocyte superoxide dismutase, Cu_2Cu_2SOD.[4,5] The native enzyme, Cu_2Zn_2SOD, is comprised of two identical subunits, each of which contains a histidine (imidazolate)-bridged Cu(II)–Zn(II) active site. These active sites are well separated from one another. In Cu_2Cu_2SOD, the subunits contain fully active imidazolate-bridged bimetallic centers in which Cu(II) has replaced Zn(II). In order to stabilize the imidazolate (imH = imidazole) bridge with respect to hydrolysis in the model compounds,[6] the $[Cu_2(im)]^{3+}$ unit was incorporated into the binucleating macrocyclic ligands A and A′.[7]



macrocycles A (Y = O), A′ (Y = CH_2)

The complex $[Cu_2(im)\subset A']^{3+}$ (**1**) has several features in common with the Cu_2Cu_2SOD subunits and can be regarded as an excellent model for many of the physical properties of the protein active site.[3,7b,8] Although the superoxide dimustase activity of this complex is difficult to test,[9,10] other biologically relevant aspects of its chemistry can be examined.

Previously we used ESR spectroscopy to show that treatment of Cu_2Cu_2SOD with excess thiocyanate disrupted the magnetic coupling between the copper(II) pairs, a result attributed to cleavage of the imidazolate bridge.[5] The thiocyanate adduct was active as a superoxide dismutase, having more than 50% of the enzymatic activity of untreated Cu_2Cu_2SOD by the 6-hydroxydopamine assay.[5] These results implied that the histidine bridge is not essential for enzymatic activity and therefore need not be invoked in the enzyme mechanism. The purpose of the present investigation was to provide support for these interpretations by examining the reaction of thiocyanate ion with the model compound **1**. In particular, we wanted to learn whether or not the $[Cu_2(im)]^{3+}$ unit remained intact in the presence of excess thiocyanate and what the structure of the resulting adduct would be. Here we present the results of ESR spectroscopic and X-ray crystallographic studies demonstrating that excess thiocyanate

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*Address correspondence to this author at M.I.T.

(1) (a) Columbia University. (b) Massachusetts Institute of Technology.

(2) Ibers, J. A.; Holm, R. H. *Science* (*Washington, D.C.*) **1980**, *209*, 223.

(3) Strothkamp, K. G.; Lippard, S. J. *Acc. Chem. Res.* **1982**, *10*, 318.

(4) Fee, J. A.; Briggs, R. G. *Biochim. Biophys. Acta* **1975**, *400*, 439.

(5) Strothkamp, K. G.; Lippard, S. J. *Biochemistry* **1981**, *20*, 7488.

(6) (a) O'Young, C. L.; Dewan, J. C.; Lilienthal, H. R.; Lippard, S. J. *J. Am. Chem. Soc.* **1978**, *100*, 7291. (b) Kolks, G.; Frihart, C. R.; Coughlin, P. K.; Lippard, S. J. *Inorg. Chem.* **1981**, *20*, 2933.

(7) (a) Coughlin, P. K.; Dewan, J. C.; Lippard, S. J.; Watanabe, E-i.; Lehn, J.-M. *J. Am. Chem. Soc.* **1979**, *101*, 265. (b) Coughlin, P. K.; Lippard, S. J.; Martin, A. E.; Bulkowski, J. E. *Ibid.* **1980**, *102*, 7616.

(8) (a) Coughlin, P. K.; Martin, A. E.; Dewan, J. C.; Watanabe, E.-i.; Bulkowski, J. M.; Lehn, J.-M.; Lippard, S. J. *Inorg. Chem.* **1984**, *23*, 1004. (b) Coughlin, P. K.; Lippard, S. J. *Ibid.* **1984**, *23*, in press.

(9) These assays usually require EDTA to suppress the activity of free copper, which is quite an active superoxide dismutase;[10] EDTA extracts copper from $[Cu_2(im)\subset A']^{3+}$.

(10) See, for example: Misra, H. P.; Fridovich, I. *J. Biol. Chem.* **1972**, *247*, 3170.

0002-7863/84/1506-2579$01.50/0