Dendrimer–Palladium Complex Catalyzed Oxidation of Terminal Alkenes to Methyl Ketones

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Dedicated to Dr. Joe P. Richmond on the occasion of his 60th birthday.

Abstract: Silica-supported polyamidoamine (PAMAM) dendrimers with different spacer lengths were prepared. After the introduction of diphenylphosphino groups, complexation to dibenzylidenepalladium(0) gave the desired silica-supported dendrimer–palladium catalyst complexes G0 to G4-C2-Pd. These catalysts showed activity towards the oxidation of terminal alkenes to methyl ketones. A dependence of catalytic activity on the spacer length of the diamine in PAMAM was observed.

Keywords: alkenes; ketones; oxidation; palladium; silica-supported PAMAM dendrimers

Introduction

In light of the changing awareness and responsibility to the environment, as well as stricter environmental laws, the focus on research has shifted towards cleaner technologies. The field of catalysis is viewed as one such technology. Of the two classes of catalysis, heterogeneous catalysis is preferred industrially due to the fact that separation of reactants from products is much easier and generates less waste than homogeneous catalysis. There have been many attempts at heterogenizing homogeneous catalysts by immobilizing them on supports; however, problems like lower catalyst activity, the leaching of the metal from the support, deactivation and decomposition of active species have been encountered.

Dendrimers[1–7] discovered more than two decades ago have added a new strategy towards catalysis.[8–13] Dendrimers are highly branched macromolecules thought to be globular in shape. Their characteristics such as shape, structure, size and solubility can be tailored accordingly. This can be achieved by locating catalytically active sites either at the core, periphery or interior of the dendritic structure. Because of their size, dendrimers can be easily separated from the reaction mixture by simple techniques such as precipitation or simple filtration, while their multiple functionality can ensure high specificity and activity. Hence, dendrimers are considered as having the potential of combining the advantages of both heterogeneous and homogeneous catalysis.[14,15]

In their first publication on the application of dendrimers to catalysis, van Koten and co-workers used polycarbosilane dendrimer-Ni(II) complexes to catalyze the Kharasch reaction.[14] In the same year, Dubois[16] reported that palladium complexes of small organophosphine dendrimers catalyzed the electrochemical reduction of CO_2, while Brunner[17] showed that core-functionalized Cu complexes catalyzed the cyclopropation of styrene. Nowadays a plethora of examples on transition metal-bound dendrimer catalysts exists.[8–13]

Our group has been involved with the synthesis of silica- and resin-supported poly(amidoamine) dendrimer metal complexes. The Rh complexes display excellent activity and recyclability towards the hydroformylation of styrenes, vinyl acetates and other olefins.[18–20] Palladium complexes have been used to catalyze the Heck coupling reaction of aryl bromides[21], carbonylation of haloarenes[22], and, recently, the hydroesterification of alkenes.[23] We now report the use of dendrimer-Pd complexes for the oxidation of terminal alkenes, a very different type of reaction.

There has been great interest in olefin oxidation since the successful application of the Wacker process for the industrial production of acetaldehyde.[24] This catalytic system consists of an aqueous acidic solution of a palladium salt as catalyst with a copper(I) salt as the cocatalyst, and oxygen or air as oxidant. Substantial research has focused on modification of the cocatalyst, e.g., heteropoly acids[25] and benzoquinone[26] amongst others.

The application of the Wacker process to longer chain alkenes has been a challenge due to their low solubility

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in aqueous medium. This has led to research in biphasic systems using tetraalkylammonium salts,[27] polyethylene glycols,[28] and cyclodextrins.[29,30]

Uemera and co-workers have reported on the use of a $Pd(OAc)_2$/pyridine/O_2 catalytic system using alcohol as the reductant.[31] In this system the formation of a Pd(II)-OOH species is proposed. This is in line with earlier publications by Mimoun,[32,33] who reported the synthesis and structure of palladium peroxo complexes of general formula $[RCO_2PdCO\text{-}t\text{-}Bu]_4$. These complexes could transform terminal alkenes to methyl ketones, and varying the steric bulk of the alkyl substituents could effect different selectivities.

As the backbone of PAMAM dendrimers can be considered as more bulky than the ligands studied by Mimoum, we reasoned that our catalysts could exhibit greater selectivity. This led us to examine the catalytic activity of these dendrimer-Pd complexes towards the oxidation of terminal alkenes to methyl ketones using *tert*-butyl hydroperoxide as oxidant. To our knowledge this is the first study of such a transformation using recyclable dendrimer-Pd complexes.

Results and Discussion

Catalyst Synthesis and Characterization

The preparation of silica-supported polyamidoamine (PAMAM) dendrimers is readily achieved by Michael addition of the amine group of the aminopropyl-silica on methyl acrylate followed by amidation of the methyl ester with a diamine. Diamines of different chain lengths such as ethylenediamine (C2), 1,6-diaminohexane (C6), and 1,12-diaminododecane (C12) were used following published methods.[2,34] Higher generations were obtained by repetition of these two steps. The introduction of diphenylphosphino groups was achieved by use of diphenylphosphine and paraformaldehyde.[35,36] The occurrence of the phosphomethylation step was confirmed by the solid state ^{31}P NMR spectrum, which showed a signal at -27 ppm. Complexation with the chloroform adduct of $Pd_2(dba)_3$ resulted in a downfield shift to 25–28 ppm.

The extent of dendrimer growth for the C2 series was assessed by performing a back titration with NaOH to determine the amine content as reported by Tsubokawa and co-workers.[37] The amine content obtained for the first generation is comparable to the theoretical value (Table 1, entry 2). The second-generation dendrimer gave quantitative amine content, while the third-generation dendrimer displayed a relatively low amine content (Table 1, entries 3 and 4).

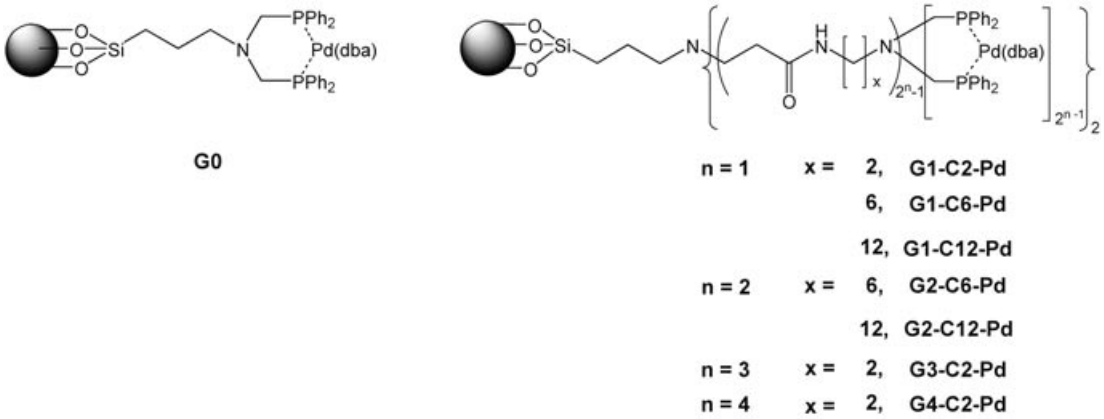
Further information was gained from thermal gravimetric analysis and determination of the surface area. Complete growth was observed for the synthesis of the first-generation dendrimer with an ethylenediamine backbone (Table 2, entry 1). The synthesis of higher generation dendrimers was less efficient as was displayed by the lower percentage of grafted material (Table 2, entries 2–4). Also, the amidation step became less efficient as the chain length of the diamine increased.

It was expected that the surface area and pore volume should decrease as more dendrimer was grafted on silica; however, there is no means of predicting the magnitude of these values. Quantification is possible through

Table 1. Amine contents for the C2* series as determined by titration.

Entry	Generation	Theoretical (mmol NH_2/g)	Actual (mmol NH_2/g)
1	0	0.9	0.8
2	1	1.5	1.4
3	2	2.2	1.8
4	3	3.5	1.4

C2* means that ethylenediamine was used for the amidation step of the dendrimer growth.



Scheme 1. Dendritic catalysts.

Table 2. BET measurements.

Entry	Generation	BET_{SA} (m^2/g)	PV (cm^3/g)	% grafted
1	G1-C2	229	0.514	92
2	G2-C2	133	0.310	72
3	G3-C2	53	0.146	58
4	G4-C2	36	0.086	52
5	G1-C6	*238*	0.534	61
6	G1-C12	245	0.550	56

Initial amine content of aminopropyl-silica used was 0.9 mmol/g. PV = pore volume. % Grafted determined from thermal gravimetric analysis.

Table 3. Pd content as determined by ICP analysis.

Entry	Generation	Pd (%)
1	0	0.86
2	G1-C2	1.13
3	G2-C2	0.80
4	G3-C2	0.59
5	G1-C6	*1.52*
6	G1-C12	1.72

Complexes prepared with the chloroform adduct of $Pd_2(dba)_3$.
ICP = inductively coupled plasma spectroscopy.

Brunauer–Emmett–Teller (BET) measurements. There is a slight variation in the surface area and pore volume between dendrimers of the same generation with different spacer lengths (Table 2, entries 1, 5 and 6). G1-C12 has the highest surface area while G1-C2 has the lowest – a confirmation that different spacer lengths can bring about different surface properties.

We learned that the phosphomethylation step does not go to completion. At the most about 50% of the amines get phosphonated. It has also been observed that there is always less Pd complexed than there are phosphine groups present in the dendrimer, meaning that there is a limit for complexation. Below this limit, the Pd loading can be varied by controlling the amount of metal complex charged during the complexation step. The maximum amount of Pd content is a function of diamine spacer length and generation number (Table 3). It increases with spacer length and decreases at higher generations.

Of the different palladium compounds that were used for the complexation step, $Pd_2(dba)_3$ was found to be the best Pd precursor. Different dendrimer complexes were obtained with $[Pd(OAc)_2]_2$ as precursor even if the same conditions were used. These complexes had different Pd loadings, meaning that there was no consistency in the complexation step.

Oxidation of Terminal Alkenes to Methyl Ketones

Initially we attempted to oxidize terminal alkenes to methyl ketones under Wacker-type conditions using the catalysts **G0** to **G4-C2-Pd**. For the oxidation of 1-decene we observed that the activity and selectivity were dependent on the solvent used. When THF was used, two things were observed. At low substrate to catalyst ratio, the conversion was low, and the selectivity was good. Increasing the substrate-to-catalyst ratio resulted in an increase in conversion but at the expense of selectivity – more double bond isomerization was observed.

Methylene chloride only promoted the rearrangement of the double bond. The polar solvent, *N,N*-dimethylacetamide gave excellent selectivity but the conversion was quite low. 1-Propanol gave the highest conversion (57%), but the product spectrum was broad – with only 56% as the methyl ketone. Attempts to further optimize the Wacker-type conditions using Pd complexes of silica-supported PAMAM dendrimers, as catalysts were unfruitful.

Table 4. Oxidation of various alkenes using TBHP as oxidant.

Entry	Substrate	Yield[a] (%)
1	Cyclohexene	11
2	1-Octene	42
3	1-Decene	28
4	1-Tetradecene	27

Catalyst G0-Pd(dba), the Pd content in the reaction mixture was 0.5 mol %, substrate (1.50 mmol), TBHP (1.65 mmol), 55 °C, 24 h.
[a] Yield by GC.

Consequently, the oxidant was changed to *tert*-butyl hydroperoxide. As a benchmark, the catalytic performance of **G0** was investigated using different alkenes. The addition of organic solvents inhibited the oxidation reaction, and thus the reactions were carried out under neat conditions. Cyclohexene gave the lowest yield – not surprising because internal alkenes are usually less reactive than terminal alkenes[38] (Table 4, entry 1). 1-Octene gave higher product yields than 1-decene and 1-tetradecene (Table 4, entries 2–4).

The catalytic activity also proved to be a function of the dendrimer backbone. The higher generations were less active when screened using 1-octene. Only the first-generation dendrimer complex gave the methyl ketone in reasonable yield (Table 5, entry 2). The second- and third-generation dendrimer complexes gave poor yields (Table 5, entries 3 and 4).

This poor activity was attributed to steric congestion of the dendrimer. This leads to the threshold for dendrimer growth being reached.[19] Extending the chain length of the diamine used during dendrimer synthesis can bring relief to steric crowding. A comparison of the activity of the various catalysts prepared with different spacer lengths can be seen in Figure 1.

Table 5. The effect of dendrimer generation.

Entry	Generation	Yield[a] (%)
1	0	42
2	1	33
3	2	traces
4	3	No reaction

Catalyst Gn-Pd(dba), the Pd content in the reaction mixture was 0.5 mol %, 1-octene (1.50 mmol), TBHP (1.65 mmol), 55 °C, 24 h.
[a] Yield by GC.

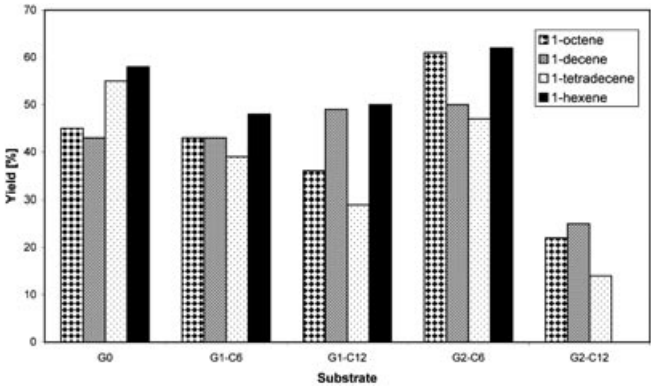


Figure 1. Effect of spacer length on catalytic activity.

The various silica-supported PAMAM-Pd catalysts displayed comparable activity towards the oxidation of 1-hexene. Extending the olefin length by two methylene groups starting from 1-hexene to 1-tetradecene gave different results. The different catalysts started to show different activities. The monomeric catalyst and 1st generation C6 and C12 catalysts once again gave comparable results. G2-C6 gave the highest conversion of 1-octene while G2-C12 gave the lowest. A similar trend was observed for 1-decene. In the oxidation of 1-tetradecene, the G0 and G2-C6 catalysts gave good yields while G2-C12 gave lower yields.

A direct comparison of the above results with literature values is difficult because different catalytic systems and reaction conditions have been used. We can only draw up a comparison by considering the amount of palladium used for the reaction and the yield of ketone obtained. Under phase-transfer catalysis, using 2 mol % Pd, the yields of 2-decanone obtained ranged from 9–73% depending on the phase transfer agent that was used.[29] Our catalytic system faired well by giving 50% of 2-decanone with only 0.5 mol % Pd. An added advantage is that these catalysts can be recycled as shown below.

Figure 2 shows the recycle reactions of G0 and 1st and 2nd generation C6 catalysts for the oxidation of 1-octene. The G0 catalyst can be reused up to eight times giving good yields of 2-octanone. Meanwhile, G1 and G2 complexes can be reused four times.

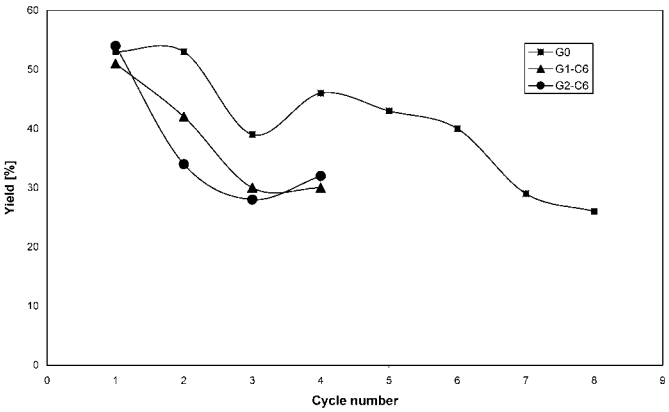


Figure 2. Recycle reactions for 1-octene.

Table 6. Scope of the reaction.

Entry	Substrate	Yield[a] (%)
1	4-methyl-1-pentene	41
2	4-phenyl-1-butene	59
3	1,8-nonadiene	40
4	5-vinyl-2-norbornene	22

Catalyst G1-C6-Pd(dba), the Pd content in the reaction mixture was 0.5 mol %, substrate (1.50 mmol), TBHP (1.65 mmol), 55 °C, 24 h.
[a] Yield by GC.

This catalytic system is not limited to unsubstituted alkenes, but can be applied to other substituted alkenes. 4-Methyl-1-pentene could be oxidized in comparable yield to 1-hexene (Table 6, entry 1). Good yields were obtained for the oxidation of 4-phenyl-1-butene (Table 6, entry 2). Interestingly, the longer chain diene, 1,8-nonadiene, was only oxidized at one double bond (Table 6, entry 3) while 1,5-hexadiene gave a dimerization product in addition to single double bond oxidation. (Table 6, entry 3). For terminal olefins with internal bonds like 5-vinyl-2-norbornene, only the terminal double bond was oxidized (Table 6, entry 4).

Conclusion

We have shown that silica-supported PAMAM-Pd complexes can catalyze the oxidation of terminal alkenes to methyl ketones under mild conditions. Oxidation was selective towards the terminal double bond versus an internal unsaturated bond. Moreover, the catalysts could be reused without significant loss in activity.

Experimental Section

Dendrimer synthesis was initiated on the surface of silica gel functionalized with aminopropyl groups with a loading of

0.9 ± 0.1 mmol NH_2/g and particle size of 35–70 mm (Fluka). Thermal gravimetric analysis (TGA) was done at Sasol Technology R&D, South Africa. Solid state NMR was performed on a Bruker ASX 200 instrument. The Pd content was analyzed by ICP at Galbraith Laboratories, Knoxville. GC analysis was done using an HP5890 with a 5% carbowax packed column.

General Procedure for the Amidation of Ester-Terminated Dendrimers with $H_2N(CH_2)_nNH_2$; n = 6, 12

The diaminoalkane (62.4 mmol NH_2) in methanol (50 ml) was slowly added to silica-supported methyl propylaminopropionate (4 g, 6.24 mmol OCH_3) in methanol (50 mL). The mixture was stirred at room temperature under nitrogen for 7 days. The liquid was decanted. The mixture was then washed with methanol (30 mL) and transferred to a Soxhlet apparatus. Residual diamine was extracted with methanol over 3 days. The resulting first-generation dendrimer was washed with ether and then dried under vacuum (90% yield).

The second-generation dendrimers were prepared in the same manner; however, Soxhlet extraction was extended over 5 days.

General Procedure for the Complexation of Diphenylphosphino-Terminated Dendrimers with $Pd_2(dba)_3 \cdot CHCl_3$

All manipulations were carried out under and inert atmosphere. All solvents were distilled and degassed before use. $Pd_2(dba)_3 \cdot CHCl_3$ (100 mg, 193 μmol Pd) in toluene (15 mL) was added to a phosphomethylated dendrimer (1.0 g) in toluene (10 mL) *via* a cannula. The resultant mixture was stirred at room temperature under N_2 for 18 h. The reaction mixture changes color from deep maroon to orange-red. Excess solvent was decanted and the complex was washed with DMF ($3 \times$ 10 mL) followed by ether (3×5 mL). Residual solvent was removed under vacuum. Pale yellow to brown powders were obtained in 85–95% yield.

General Procedure for the Oxidation of Terminal Alkenes to Methyl Ketones

A mixture of dendrimer-Pd complex (7.5 μmol Pd), substrate (1.5 mmol) and 5.0–6.0 M *tert*-butyl hydroperoxide in nonane (1.65 mmol) was placed in a glass autoclave. The autoclave was immersed in an oil bath set at 55 °C for 24 h. The autoclave was cooled to room temperature, and then pressure that built-up during the reaction period was carefully released. The catalyst was removed from the reaction mixture by filtration and was washed with diethyl ether prior to recycling the reaction. The product was analyzed by FTIR and GC and identified by comparison with authentic samples. In cases where the ketone was isolated, either column chromatography (10:1 hexanes:ethyl acetate) or distillation was used depending on the boiling point. The products were characterized by comparison of spectral data with authentic samples and with GC of authentic samples.

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