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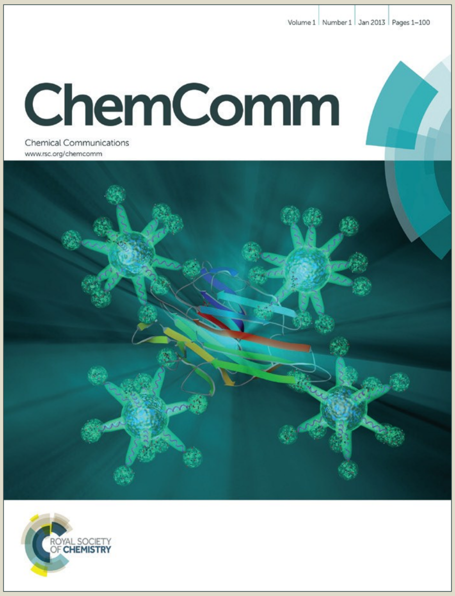

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Being Two is Better than One — Catalytic Reductions with Dendrimer Encapsulated Copper- and Copper-Cobalt - Subnanoparticles

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Copper and Copper-Cobalt subnanoparticles have been synthesized using 4-carbomethoxypyrrolidone terminated PAMAM-dendrimers as templates. The metal particles were applied in catalytic reduction reactions. While Cu subnanoparticles were only capable of reducing conjugated double bonds, enhancing the Cu particles with Co, lead to a surprising increase in catalytic activity, reducing also isolated carbon double and triple bonds.

Copper has a long history in organic chemistry from Ullman-[1,2] and Sandmeyer-reactions[3], Copper-Chromite reductions[4] at high pressure to Cu(I)-catalyzed reactions such as aromatic nucleophilic substitutions[1,2,5], 1,3-dipolar cycloadditions[6] and C-H activation[7], but what about copper subnanoparticles? Size matters and nanoparticles with less than 50 atoms (subnanoparticles) can have quite different properties than larger particles. The aluminium cluster Al_{13} have an electron affinity similar to chlorine[8] and behaves essentially like a nanoelement-analog to the halogens[9,10] and other examples could be the metaloxides and Pt-subnanoparticles reported by Yamamoto and coworkers[11,12]. Synthesizing nanoparticles of this size either needs to take place in the gas-phase or by using a “chaperone” molecule that can serve as protective coating as well as being the mold in which the subnanoparticles are cast. Such protective coatings can be porous solids (i.e. as in solid supported catalysts), surfactants, peptides, thiols or dendrimers depending on the chemical nature of the nanoparticles[13-16].

Dendrimer-encapsulated metal nanoparticles (DENs) have mainly been reported with noble metals such as Pd, Pt, Rh, Ag and Au[14], with Cu[17,18] and Ni[16] as exceptions. Small Pd-[19] and Pt-DENs[20] have high reactivity in Heck- and Suzuki-Miyura-reactions[19,20] and hydrogenations[21].

Herein, we report on dendrimer-encapsulated nanoparticles synthesized by complexation of Cu(II) to the tertiary amines in the interior of PAMAM-Pyr dendrimers (monitored by the absorption around 650 nm), followed by reduction to Cu(0) with $NaBH_4$ as shown in Figure 1.

4-Carbomethoxypyrrolidone terminated PAMAM-dendrimers (PAMAM-Pyr) have excellent solubility in different solvents in contrast to the commonly used hydroxy-terminated PAMAM-dendrimers[14,15] and the complexation of Cu(II) to the interior of these dendrimers had been studied previously by EPR[22].

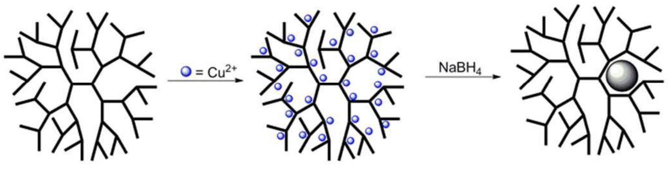


Fig. 1 Complexation of Cu(II) ions to the dendrimer followed by a $NaBH_4$ reduction to the encapsulated nanoparticle.

The hydrodynamic size of the dendrimers with encapsulated copper nanoparticle was measured in water with dynamic light scattering (DLS), exhibiting increasing size with increasing dendrimer generation (G3 5.57±1.27 nm, G4 7.09±1.77 nm and G5 7.51±2.05 nm). The particles encapsulated by PAMAM -Pyr dendrimers were also investigated by scanning transmission electron microscopy (STEM) revealing for the G3 and G4 dendrimers sub nanometer particles with diameters less than 1 nm. For the G5 dendrimers, the particle diameters measured in the STEM images are between 2 and 4 nm with a majority having a diameter of 3 nm. Figure 2 shows a TEM image of Cu_{32}@PAMAM-G5-Pyr nanoparticles.

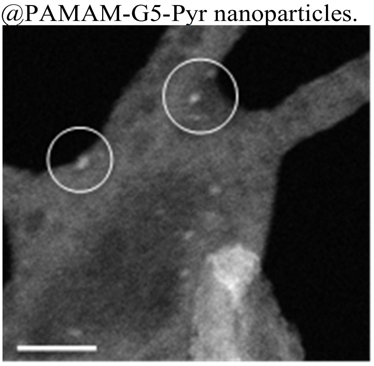
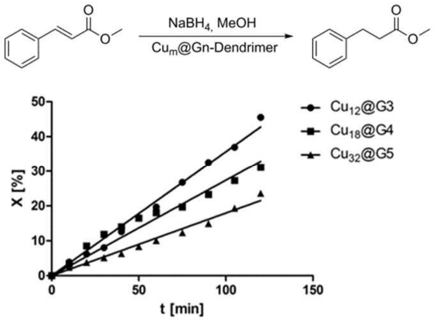


Fig. 2 TEM image of Cu_{32}@PAMAM-G5-Pyr. The white circles highlight individual particles. Scale bar corresponds to 20 nm.

The reduction of methyl cinnamate to methyl 3-phenylpropionate with $NaBH_4$ catalyzed by Cu-DENs (Scheme 1) was used to study the relationship between particle size and reactivity. Sodium borohydride was applied as an easily employable hydrogen source with no need for high pressure equipment; all reactions were performed at atmospheric pressure and ambient temperature. The reaction follows first order kinetics and the highest reaction rate was found for the smallest copper nanoparticles, showing decreasing efficiency as the particle size increased (Fig. 3). The turnover frequencies are shown in Table 1.

Scheme 1. Reduction of methyl cinnamate with 0.4 mol% Cu_n@PAMAM-G3-5-Pyr.[a]



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[a] (1.5 mmol of methyl cinnamate with 0.4 mol% catalyst in 15 mL methanol, addition of 0.45 eq. $NaBH_4$ every 5 min., at room temperature. Monitored by GC-MS and ^{1}H-NMR.)

Table 1. Turnover frequencies (TOF) for the hydrogenation of methyl cinnamate with different sized dendrimer encapsulated copper nanoparticles.

Catalyst	TOF [h-1] (per dendrimer)	TOF [h-1] (per Cu)
Cu_{12}@PAMAM-G3-Pyr	53.4	4.5
Cu_{18}@PAMAM-G4-Pyr	41.0	2.3
Cu_{32}@PAMAM-G5-Pyr	26.9	0.8

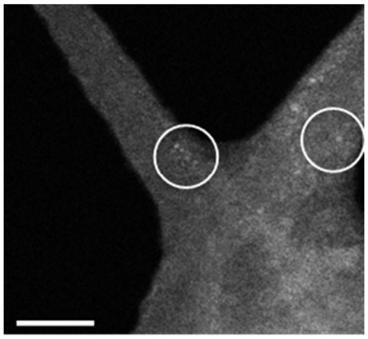


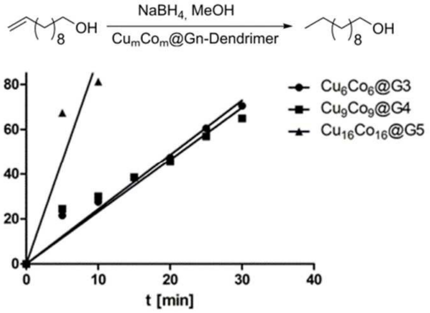
Fig. 3 TEM image of $Cu_{16}Co_{16}$@PAMAM-G5-Pyr. White circles highlight individual particles. Scale bar corresponds to 20 nm.

Attempts to reduce isolated double bonds with $NaBH_4$ at atmospheric pressure were unsuccessful in contrast to the recent report on Cu-DEN catalyzed hydrogenation with hydrogen under high pressure, where low conversions (≤20 %, in 12 h with Cu_{30}@G6-PAMAM-OH, 10 bar H_2) for the reduction of C=C bonds were reported[23].

By serendipity we discovered that doping the nanoparticles with small amounts of cobalt made the reduction of isolated double bonds possible, applying sodium borohydride as the hydrogen source. The bimetallic CuCo-DENs were synthesized by allowing both Cu^{II} and Co^{II} to complex with the dendrimer. Upon reduction with sodium borohydride the bimetallic nanoparticles were formed. The particles encapsulated by PAMAM-G5-Pyr was also investigated by scanning transmission electron microscopy (STEM) revealing particle sizes between 0.5 and 1.5 nm with a predominance for 1 nm and smaller (Fig 3). The relative ratios between Co and Co was checked by ICP-MS and found to be close to the calculated 1:1.

For the reduction of an isolated double bond 10-undecen-1-ol was chosen. The reaction was tested with three different generations, to study a size dependency on the reaction rate. The reduction of 10-undecen-1-ol was close to first order kinetics (Scheme 2). The reaction rate was observed to be slightly faster in the initial five to ten minutes. After that the reaction expressed a nearly constant rate. It is possible that the slower rates are controlled by the diffusion rate of substrate/product into/out of the dendrimer. Next to the reduction of the terminal double bond a shift of the double bond to inner positions was monitored, even though reduction of the shifted double bond did not occur rapidly. For the $Cu_{16}Co_{16}$@PAMAM-G5-Pyr the reduction was complete within 10 min. giving a mixture of the reduced product (82 %) and internally shifted isomers (18 %).

Scheme 2. Reduction of 10-undecen-1-ol with 0.4 mol% Cu_nCo_m@PAMAM-G3-5-Pyr.[a]

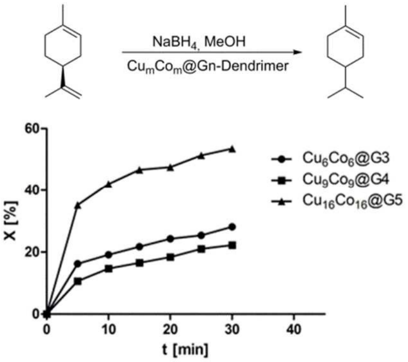


[a] (1.5 mmol of 10-undecen-1-ol with 0.4 mol% catalyst in 15 mL methanol, addition of 0.45 eq. $NaBH_4$ every 5 min., at room temperature. Monitored by GC-MS and ^{1}H-NMR.)

The isolation of some double bond shifted isomers out of the reaction mixture lead to the thought that the hydrogenation might be specific for external double bonds, which are more readily available in a crowded system, like the dendrimer interior. (+)-Limonene was chosen as another test substrate since it contains two different double bonds; an external and a highly shielded internal double bond. Overall the substrate is more rigid then the 10-undecen-1-ol. In Scheme 3 it can be seen that the reduction occurred slower than in the previous case, especially for the generation five dendrimer, this most likely due to the steric hindrance of the double bond and the rigidity of the substrate.

The (+)-limonene has to overcome a barrier to actually reach the nanoparticle catalyst within the dendrimer, and converted substrate needs to diffuse out of the dendrimer. As expected, hydrogenation of the terminal double bond was the major product (up to 50% for $Cu_{16}Co_{16}$@PAMAM-G5-Pyr in 30 minutes), and hydrogenation of the internal double bond was the minor product (<3 %). The reaction rate did not follow first order kinetics and the $Cu_{16}Co_{16}$@PAMAM-G5-Pyr showed very fast reaction rates, converting more than 35% of (+)-limonene to the predicted major product within the first five minutes.

Scheme 3. Reduction of (+)-limonene with 0.4 mol% Cu_nCo_m@PAMAMG3-5-Pyr.[a]



[a] (1.5 mmol of (+)-limonene with 0.4 mol% catalyst in 15 mL methanol, addition of 0.45 eq. $NaBH_4$ every 5 min., at room temperature. Monitored by GC-MS and ^{1}H-NMR.)

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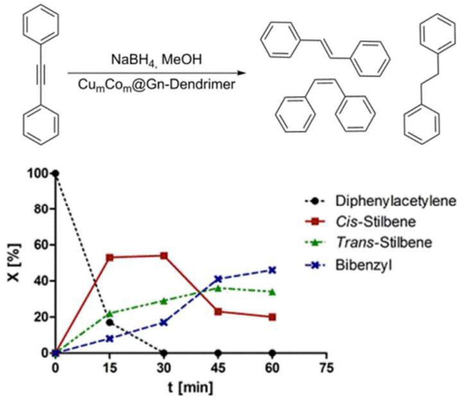
Table 2. Turnover frequencies (TOF) for the hydrogenation of 10-undecen-1-ol and (+)-limonene with dendrimer encapsulated copper nanoparticles.

Substrate	Catalyst	TOF [h-1] (per [Cu+Co])
10-undecen-1-ol	Cu_6Co_6@G3-Pyr	30
10-undecen-1-ol	Cu_9Co_9@G4-Pyr	19
10-undecen-1-ol	$Cu_{16}Co_{16}$@G5-Pyr	43
(+)-limonene	Cu_6Co_6@G3-Pyr	28
(+)-limonene	Cu_9Co_9@G4-Pyr	18
(+)-limonene	$Cu_{16}Co_{16}$@G5-Pyr	13

For (+)-Limonene a dependence on dendrimer size on the reaction rate was found. The bigger generations had lower TOF's per metal atom compared to the smaller dendrimers, indicating that larger dendrimer possess a barrier to reach the nanoparticle within the dendrimer. (+)-Limonene, as a very rigid molecule, was more affected by this diffusion barrier then 10-undecen-1-ol, which can also explain the difference in reaction rate between the two substrates.

To elucidate the possible mechanism for the transfer of hydrogen to the double-bond the model compound diphenylacetylene was chosen. A one step *syn*-addition of hydrogen to the triple bond would give *cis*-stilbene whereas a two-step process would give the thermodynamically more stable *trans*-stilbene. The results are shown in Scheme 4.

Scheme 4. Reduction of diphenylacetylene with 0.5 mol% Cu_6Co_6@PAMAMG3-Pyr.[a]



[a] (1.5 mmol of diphenylacetylene with 0.5 mol% catalyst in 15 mL methanol, addition of 0.45 eq. $NaBH_4$ every 5 min., at room temperature. Monitored by GC-MS and ^{1}H-NMR.)

The triple-bond is readily reduced (complete removal after 30 min), forming mainly the *cis*-isomer. A small build-up of the *trans*-isomer is also observed though (*cis*:*trans* 3:1), which could be due to isomerization into the more stable *trans*-stilbene. The *cis*-stilbene is again readily reduced to the bibenzyl product, while the *trans*-product remains nearly unaffected to further reduction. This is further support of a mechanism involving *syn*-addition of hydrogen to the double-bond.

In conclusion, we have demonstrated that dendrimer encapsulated Cu- and Cu-Co subnanoparticles catalyze the reduction of carbon-carbon double or triple bonds under mild conditions. While Cu particles alone were only capable of reducing conjugated double bonds, Co doting improved the catalytic activity significantly. CuCo subnanoparticles were found to reduce isolated carbon-carbon double bonds with selectivity for terminal double bonds. A correlation between size and reactivity was found for the Cu-subnanoparticles, where the highest catalytic activity was found for Cu_{12}@PAMAMG3-Pyr. For the rigid test substrate (+)-limonene a size dependence of the reaction rate on the dendrimer generation was found. The G5 dendrimer with the densest interior branching showed the lowest TOF per metal atom and the G3 dendrimer the fastest. The mechanism of the reaction was found to involve a *syn*-addition of hydrogen. The two nanoparticlar systems have great potential as catalysts for hydrogenation reactions, while using sodium borohydride as convenient and easy employable solid hydrogen and mild reaction condition as ambient temperature and atmospheric pressure.

Notes and references

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Electronic Supplementary Information (ESI) available: General experimental details, preparation of the dendrimers, and nanoparticles, further characterization and procedures for the catalytic reduction reactions are included in the supporting information. See DOI: 10.1039/c000000x/

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