Gold nanoparticles synthesis and stabilization *via* new "clicked" polyethyleneglycol dendrimers†

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Gold nanoparticles (AuNPs) are synthesized and stabilized by new "clicked" dendrimers of generations zero to two (G_0–G_2) containing tri- and tetra-ethyleneglycol tethers; they are either encapsulated by G_1 (81 tethers) and G_2 (243 tethers) or stabilized without encapsulation by G_0 (27 tethers).

The synthesis and stabilization of transition metal nanoparticles (NPs) inside dendrimers have created a timely entry to their application in catalysis and nanosciences.[1–3] In particular, nanometer-sized gold nanoparticles (AuNPs) have been synthesized in this way.[2] Small AuNPs[3,4] are important nanomaterials for catalysis,[5] nanomedicine[6] (*e.g.* cancer cell diagnosis[6a] and treatment[6b]), optics[7] and materials science.[8] So far, however, AuNPs stabilization by dendrimers has only been carried out using PAMAM dendrimers.[9] We recently reported the stabilization of PdNPs by "click" dendrimers and their high catalytic efficiency.[10] We now find that these dendrimers do not stabilize AuNPs, but also that "click" functionalization of the arene-cored polyazido dendrimers with polyethyleneglycol (PEG) tethers provides stabilization of nano-sized AuNPs. Indeed, the "click" reaction[11] has already been largely exploited in dendrimer synthesis.[12]

The synthesis of three generations of dendrimers from G_0 PEG to G_2 PEG dendrimers is shown on Scheme 1. It starts with the known $CpFe^+$-induced nanoallylation of mesitylene under ambient conditions in the presence of KOH and allyl bromide[13a,b] followed by visible-light photolysis in MeCN in the presence of PPh_3 to remove the $CpFe^+$ group and hydrosilylation with $HSiMe_2CH_2Cl$ and Karsted catalyst,[13c,d] then reaction with NaN_3 yields the nona-azide core. The Newkome-type 1 → 3 connectivity[14] is insured by Williamson reaction between the nonachloromethyl core and a Percec-type dendron[15] made of modified gallic acid core functionalized at the focal point by a tetraethylene glycol (TAEG) linker, then by a propargyl group and on the peripheral tethers by triethylene glycol (TEG) termini. Finally, the dendrons are linked to the core using the Cu^I-catalyzed click reaction between the terminal alkyne tail and the azido-terminated dendritic core.[13] We are using stoichiometric amounts of Cu^I, (generated using $CuSO_4$ and ascorbic acid), because dendritic metal encapsulation considerably slows down the reaction or inhibits it,[10b] especially with large dendrimers. The dendrimers of generation 0 (27 TEG termini) to 2 (243 TEG termini) were synthesized in this way and characterized by IR, ^1H and ^{13}C NMR, size exclusion chromatography (G_1, G_2 and G_3), correct elemental analysis (G_0), MALDI TOF (G_0, major peak at M^+: calc. 8820.91; found: 8821.24). DOSY and light scattering gave consistent data for both G_0 and G_1, both methods giving a diameter values of 9 ± 1 nm for G_0 and 18 ± 2 nm for G_1. For G_2, light scattering yielded a diameter value of 20 ± 2 nm (ESI).

The AuNPs were synthesized by reaction between the triazole-containing dendrimers and a stoichiometric amount of $HAuCl_4$ *vs.* the dendrimer triazolyl groups, followed by $NaBH_4$ reduction in methanol. The UV-Vis spectrum shows a plasmon band[4] at 540 nm for the G_0-27-TEG dendrimer-stabilized AuNPs, but this band is absent in the AuNPs stabilized by the higher-generation dendrimers (G_1 and G_2) (Fig. 1). The transmission electron microscopy (TEM) data confirm this trend (Fig. 2) showing that the G_0-dendrimer-stabilized AuNPs are large (4.1 ± 0.5 nm) and cannot be encapsulated in such a small dendrimer that contain only 27 tethers. Thus, several dendrimers are surrounding each AuNP (Fig. 3). On the other hand, the dendrimers of next generations G_1 and G_2 containing, respectively 81 and 243 TEG tethers encapsulate AuNPs of small size (1.9 ± 0.4 nm). The two arguments in favor of dendrimer-encapsulated AuNPs with G_1 and G_2 *vs.* dendrimer-stabilized (but not encapsulated) AuNPs with G_0 are (i) the small size of the AuNPs obtained with G_1 and G_2 *vs.* the their large size with G_0, (ii) the fact that with click-dendrimer-stabilized PdNPs, the same trend was previously shown.[10b] It is noteworthy that the presence of PEG tethers in these dendrimer is required for the formation of AuNPs. Indeed, if either the PEG tethers or the triazole ligands are absent in the dendrimer structure (see ESI†), the AuNPs do not form or are not stable longer than one hour. In conclusion, three generations of "click" dendrimer with PEG tethers has been synthesized and characterized. These dendrimers stabilized AuNPs either by surrounding the AuNP if the dendrimer is small (G_0) or by encapsulating the AuNP if it is large (G_1 and G_2). This stabilization is possible only by the combined action of the 1,2,3-triazolyl and PEG ligands. Other reported non-PEG "click" dendrimers that stabilize PdNPs do not stabilize such AuNPs. Given the optimized biocompatibility of PEG dendrimers and AuNPs,[16] the present PEG dendrimer-stabilized AuNPs might be useful as drug vectors.

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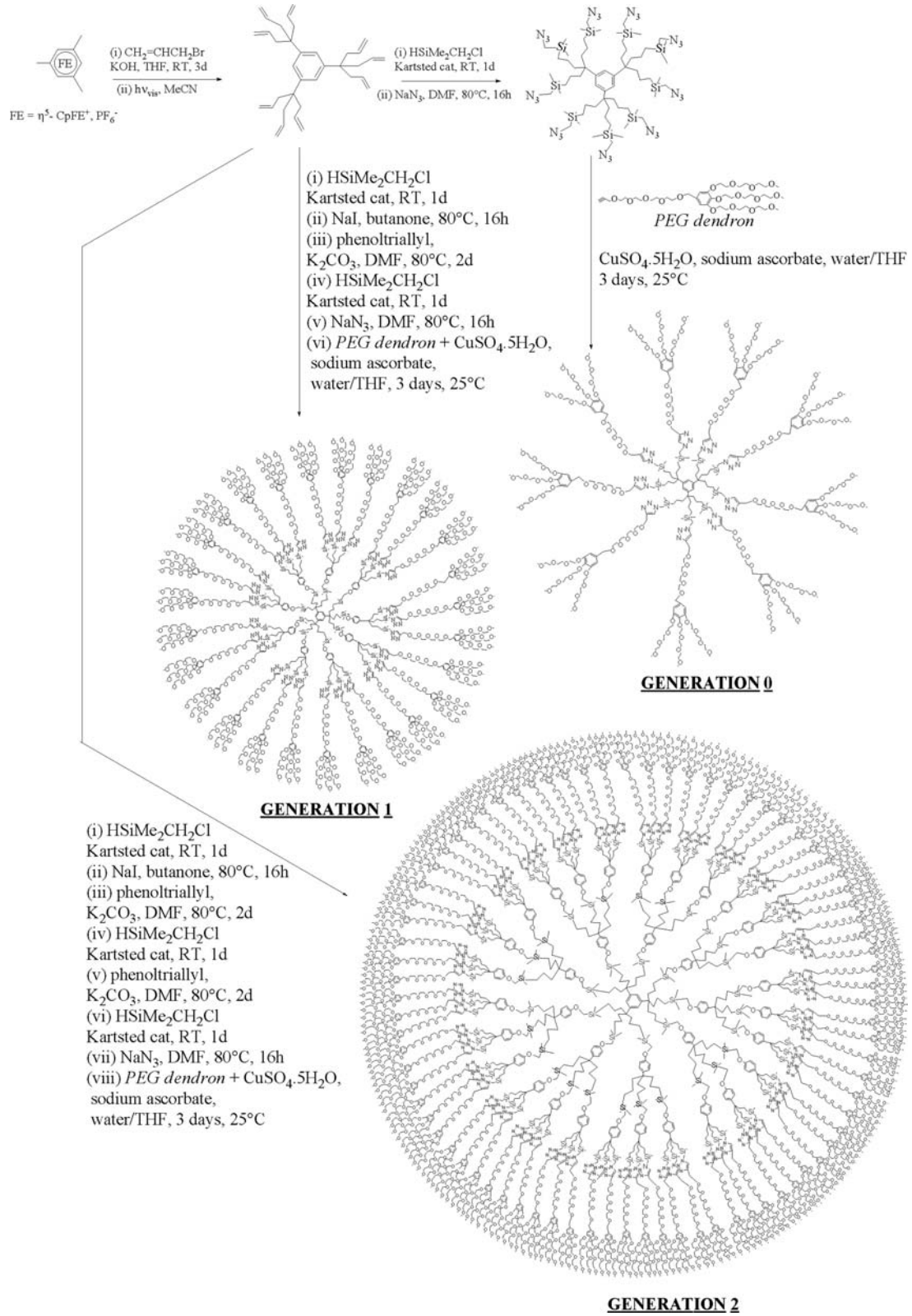

Scheme 1 Synthesis of the three generations of dendrimers from G_0-27-TEG to G_2-243-TEG.

Notes and references

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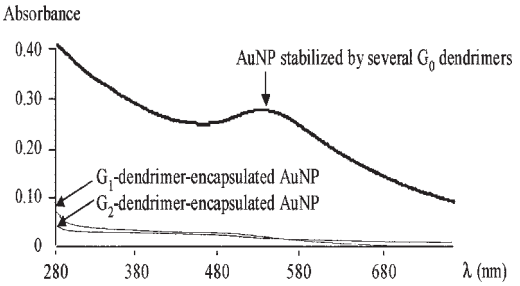

Fig. 1 UV-Vis spectra of AuNP stabilized by several G_0 dendrimers and encapsulated by G_1- and G_2 dendrimers.

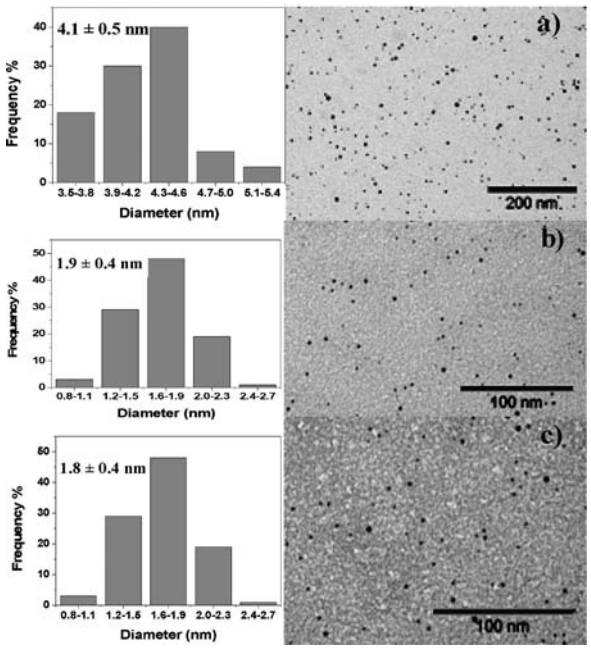

Fig. 2 (a) Dendrimer G_0-27-TEG/AuNPs: TEM image and size distribution; (b) dendrimer G_1-81-TEG/AuNPs: TEM image and size distribution; (c) dendrimer G_2-243-TEG/AuNPs: TEM image and size distribution.

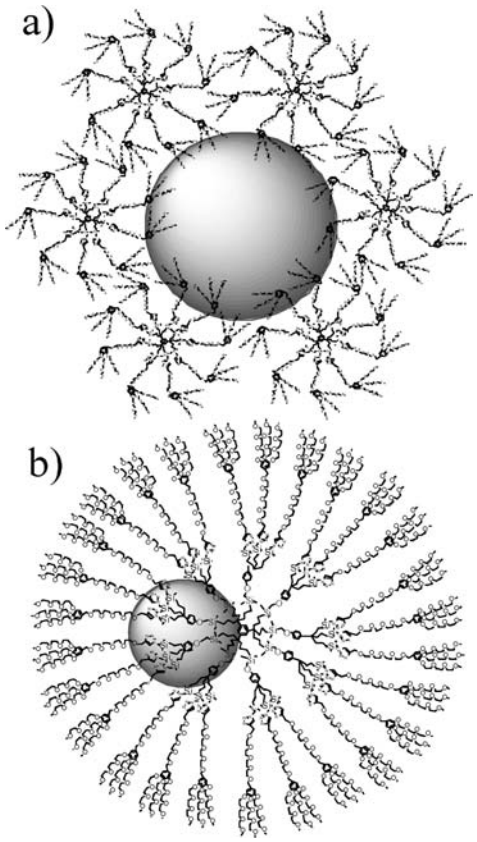

Fig. 3 (a) AuNPs stabilized by several G_0 dendrimers; (b) G_1 dendrimer-encapsulated AuNPs.

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