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## A R T I C L E S

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### Encapsulation and Stabilization of Gold Nanoparticles with “Click” Polyethyleneglycol Dendrimers

Elodie Boisselier,<sup>†</sup> Abdou K. Diallo,<sup>†</sup> Lionel Salmon,<sup>‡</sup> Cátia Ornelas,<sup>†</sup> Jaime Ruiz,<sup>†</sup>  
and Didier Astruc<sup>\*†</sup>

*Institut des Sciences Moléculaires, UMR CNRS No 5255, Université Bordeaux I, 33405 Talence  
Cedex, France, and Laboratoire de Chimie de Coordination, UPR CNRS No 8241,  
205 Route de Narbonne, 31077 Toulouse Cedex 04, France*

Received October 27, 2009; E-mail: d.astruc@ism.u-bordeaux1.fr

**Abstract:** Water-soluble arene-cored “clicked” and non-“clicked” dendrimers terminated by 27, 81, and 243 triethyleneglycol (TEG) tethers (respectively generations G0, G1, and G2) have been synthesized and shown to form dendrimer-encapsulated gold nanoparticles (DEAuNPs) and dendrimer-stabilized gold nanoparticles (DSAuNPs). The dendrimers have been characterized by IR, <sup>1</sup>H NMR, <sup>13</sup>C NMR, size-exclusion chromatography, elemental analysis, MALDI-TOF mass spectroscopy, DOSY NMR, and dynamic light scattering. The AuNPs have been generated and stabilized by these PEGylated dendrimers using a variety of reduction modes, including NaBH<sub>4</sub> in methanol, various single-electron metallocene-type reductants, and even in the absence of additional reductants. The active role of the “clicked” triazole rings, dendrimer generation, stoichiometry of Au precursor, and nature of the reductant and of the solvent are delineated, leading to DSAuNPs with the G0 dendrimer and smaller DEAuNPs with the G1 and G2 dendrimers. Altogether, AuNPs in the size range from 1.8 to 42 nm were formed and characterized by transmission electron microscopy (TEM), high resolution TEM (HRTEM) and UV–vis spectroscopy. Both 1,2,3-triazole and PEGylated Percec-type dendrons are required in the dendrimer structure for the stabilization of AuNPs upon NaBH<sub>4</sub> reduction of HAuCl<sub>4</sub> in methanol. On the other hand, in the absence of other reductant in water, only PEGylated Percec-type dendrons in dendrimers were found to be indispensable, because of their semicavitand shape, for the spontaneous reduction of HAuCl<sub>4</sub> and stabilization of DSAuNPs.

### Introduction

Substrate encapsulation by dendrimers<sup>1</sup> is a major property of dendrimer chemistry that has potential applications in catalysis,<sup>2</sup> photophysics,<sup>3</sup> materials science<sup>4</sup> and nanomedicine.<sup>5</sup> One of the most remarkable examples of dendritic encapsulation is that of transition-metal nanoparticles (NPs) that was disclosed more than a decade ago using polyamidoamine (PAMAM) dendrimers,<sup>6</sup> then polypropyleneimine (PPI) dendrimers.<sup>7</sup> Crooks and his group,<sup>8</sup> among others,<sup>7–9</sup> have demonstrated the enormous potential of this concept in catalysis under various

“green” conditions and have shown that the dendrimer plays the role of a nanoreactor and nanofilter.<sup>8</sup> In particular, NP encapsulation has been applied to many transition metals including the use of a redox reaction between a NP and other metal cations.<sup>2</sup> However, the studies of dendrimer-encapsulated NPs (DENs) have essentially concerned the PAMAM and PPI dendrimer families that are commercial, with the main exception

<sup>†</sup> Institut des Sciences Moléculaires.

<sup>‡</sup> Laboratoire de Chimie de Coordination.

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of Yamamoto's phenylazomethine dendrimers whose rigidity brings about new specific features for properties of phenylazomethine-DENs in materials science.<sup>9</sup>

It has recently been shown that dendrimers assembled by click chemistry<sup>10</sup> can coordinate and electrochemically recognize various transition-metal cations,<sup>11</sup> and that such palladodendritic complexes can be reduced to DEPdNPs that have remarkable catalytic properties.<sup>12</sup> Such a strategy does not work in the same way for an approach to arene-cored DEAuNPs,<sup>13</sup> and the investigation toward a rationalization of the syntheses toward this goal is presented and generalized here. Besides encapsulation, exodendrimer stabilization is also well-known,<sup>14</sup> and this alternative has also been searched with arene-cored dendrimers<sup>15</sup> constructed using a Newkome-type 1 → 3 connectivity.<sup>16</sup> Moreover, our goal was to stabilize and *inter alia* encapsulate

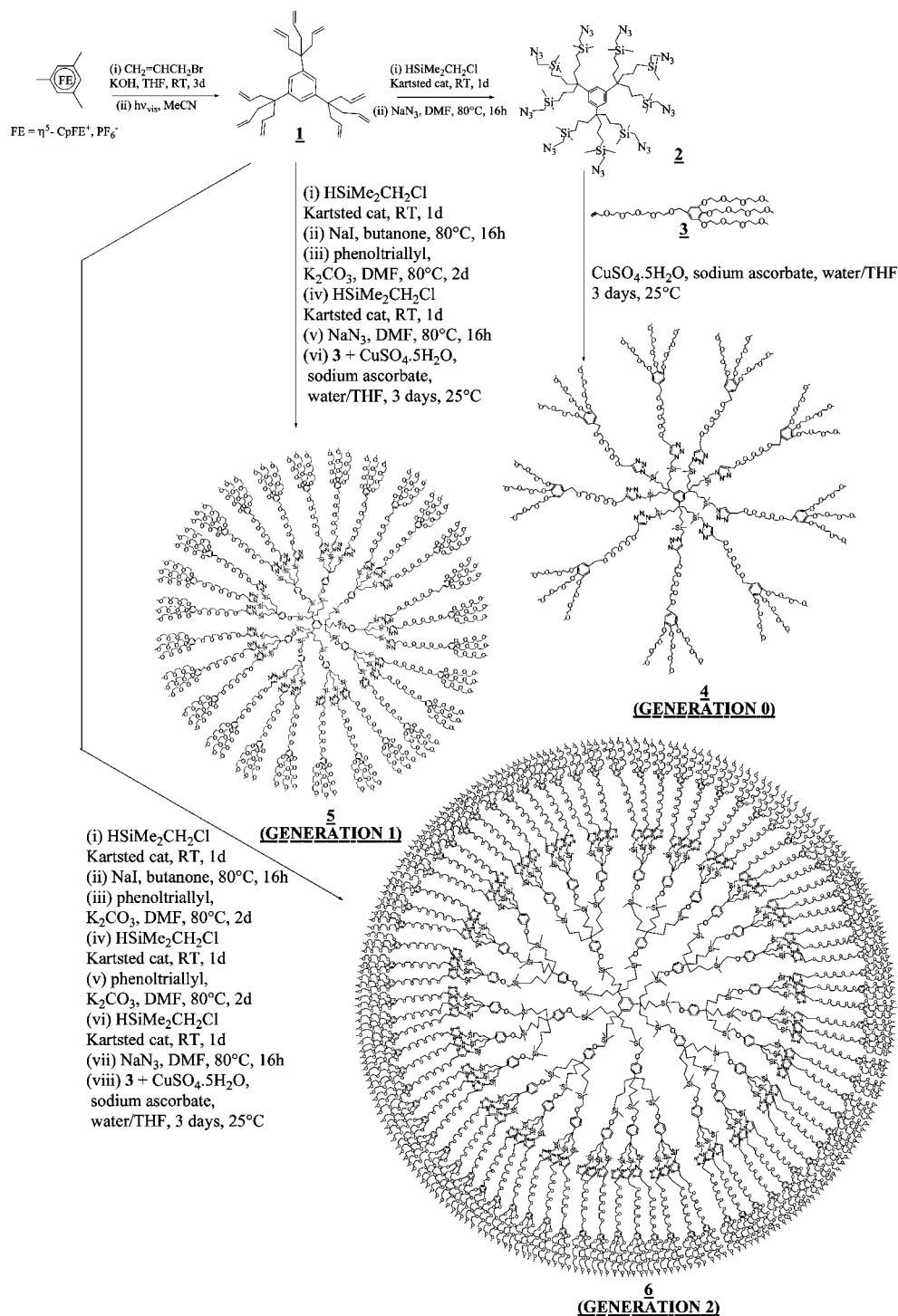
AuNPs using polyethyleneglycol-terminated dendrimers,<sup>17</sup> because of their biocompatibility<sup>17</sup> and the applications of AuNPs in nanomedicine.<sup>18</sup>

A major finding in this work is that Percec-type triethyleneglycol (TEG) tethers<sup>19</sup> are not only tolerated for the synthesis of DEAuNPs and DSAuNPs but they are even required for this purpose in this new arene-cored dendrimer series, and under certain circumstances they allow the AuNP formation. The key additional role of the intradendritic 1,2,3-triazole rings, formed by "click" reaction, on the AuNP formation and stabilization is also shown.

## Results

The synthesis of two series of arene-cored, PEG terminated dendrimers of three generations has been carried out. For both series, the dendrimer syntheses start by CpFe<sup>+</sup>-induced non-allylation of mesitylene<sup>15</sup> followed by photolytic decomplexation<sup>20</sup> and Newkome-type 1 → 3 connectivity.<sup>16</sup> The first series of dendrimers was synthesized using "click" chemistry (dendrimers **4**, **5** and **6**, Scheme 1), and the other one using the Williamson reaction (dendrimers **9**, **10** and **11**, Scheme 2) in order to graft PEG dendrons at the periphery of the dendrimers. The AuNPs are stabilized by these PEGylated dendrimers, synthesized by "click" chemistry (**4**, **5** and **6**), in methanol using NaBH<sub>4</sub> as the reductant. The PEG-terminated (dendronized) dendrimers (**4–6** and **9–11**) also allowed the reduction of Au<sup>III</sup> to Au<sup>0</sup> in water without the presence of an additional reductant. The shape and the size of the AuNPs have been studied by UV-vis spectroscopy and transmission electron microscopy (TEM) and the kinetics of formation and size variations of the

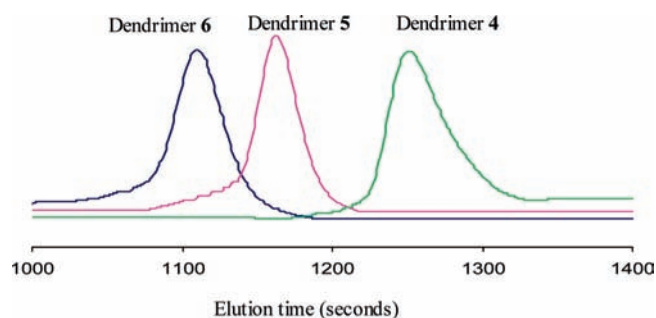
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Scheme 1. Synthesis of the Three Generations of "Click" Dendrimers **4**, **5** and **6**

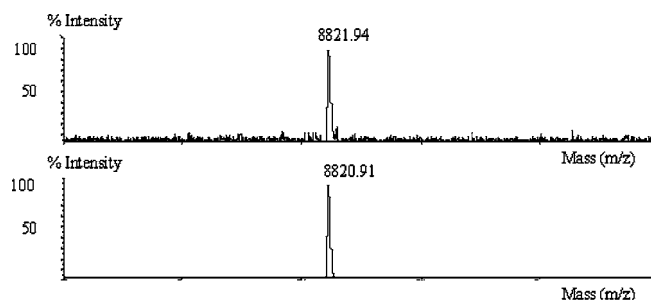
88 AuNPs have been examined when the number of equivalents  
 89 of  $\text{HAuCl}_4$  added per dendrimer was increased. The influence  
 90 of the nature of the reductant used in methanol, that is,  $\text{NaBH}_4$   
 91 or an electron-reservoir organometallic sandwich complex, was  
 92 also studied, and the role of the standard redox potential of the  
 93 reductant on the AuNP formation was finally scrutinized.  
 94 Overall, the synthesis of AuNPs stabilized or encapsulated by  
 95 PEGylated dendrimers is detailed.

96 **1. Synthesis and Characterizations of Dendrimers **4**, **5****  
 97 **and **6** Synthesized by "Click" Chemistry.** The synthesis of three  
 98 generations of arene-cored dendrimers with 1  $\rightarrow$  3 connectivity  
 99 (**4**, **5** and **6**) terminated with 27, 81 and 243 PEG tethers ( $G_0$  to

$G_2$ ) is shown in Scheme 1. The dendritic precursors with 9  
 100 chloromethyl and azido groups were reported earlier.<sup>15</sup> The  
 101 Newkome-type 1  $\rightarrow$  3 connectivity<sup>16</sup> was continued by the  
 102 Williamson reaction between the nonachloromethyl core and a  
 103 Percec-type dendron.<sup>19</sup> This dendron was synthesized from a  
 104 modified gallic acid core functionalized at the focal point by a  
 105 tetraethyleneglycol (TAEG) linker, then by a propargyl group,  
 106 and on the peripheral tethers by triethylene glycol (TEG) termini  
 107 (**3**). Finally, the dendrons were linked to the core using the  $\text{Cu}^I$ -  
 108 catalyzed "click" reaction between the terminal alkyne tail and  
 109 the azido-terminated dendritic core.<sup>11</sup> A stoichiometric amount  
 110 of  $\text{Cu}^I$ , generated using  $\text{CuSO}_4$  and sodium ascorbate, has been  
 111



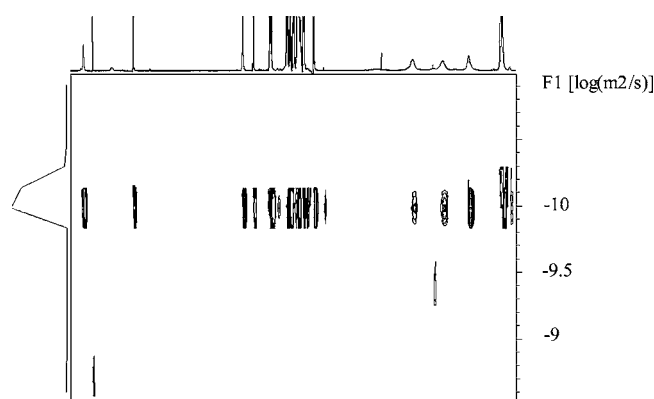
**Figure 1.** Size Exclusion Chromatography of the three generations of the “click” dendrimers 4–6 containing polyethyleneglycol tethers (PDI = 1.02 ± 0.01).



**Figure 2.** MALDI-TOF mass spectrum of the dendrimer 4. Calcd for  $C_{414}H_{741}O_{153}N_{27}Si_9$ : 8798; found: 8821.25 (MNa).

used, because dendritic metal encapsulation considerably slows down the click reaction or inhibits it,<sup>11,21</sup> especially with large dendrimers. The dendrimers of generation 0 (**4**, 27 TEG termini) to 2 (**6**, 243 TEG termini) were synthesized in this way in nearly quantitative yields (92–95%), and characterized by IR, <sup>1</sup>H and <sup>13</sup>C NMR, size exclusion chromatography (**4**, **5** and **6**, Figure 1), correct elemental analysis (**4**), and MALDI TOF (**4**, major peak at MNa<sup>+</sup>: calcd 8820.91; found: 8821.24, Figure 2). DOSY NMR and dynamic light scattering give consistent data for dendrimers **4** and **5**, both methods giving a diameter values of 9 ± 1 nm for **4** and 18 ± 2 nm for **5**. For the dendrimer **6**, light scattering provides a diameter value of 20 ± 2 nm (Figure 3, see also the Supporting Information, ESI).

**2. Synthesis and Characterizations of Dendrimers 9, 10 and 11 by the Williamson Reaction.** The syntheses of three generations of the arene-cored, TEG-terminated dendrimers **9**, **10** and **11** with 27, 81 and 243 TEG dendrimers (G<sub>0</sub> to G<sub>2</sub>) are shown in Scheme 2. They start with the same steps as for the syntheses of dendrimers **4**, **5** and **6** (see Scheme 1) until the hydrosilylation step. Then, reaction of the dendrimer core terminated by chloromethylsilyl groups with NaI yields the nonaiodomethylsilyl core (**7**). The Percec-type dendron is functionalized at the focal point by a hydroquinone linker in order to introduce a phenol terminus (**8**). Finally, the dendrons are linked to the core using a Williamson reaction between the terminal phenol tail and the iodomethylsilyl-terminated dendritic core. The dendrimers **9**, **10** and **11** of generation 0 (**9**, 27 TEG termini) to 2 (**11**, 243 TEG termini) were synthesized in this way and characterized by IR, <sup>1</sup>H and <sup>13</sup>C NMR, size exclusion chromatography (**9**, **10** and **11**), MALDI TOF (**9**, major peak



**Figure 3.** DOSY NMR spectrum of the dendrimer **4**.  $D = 1.16 (\pm 0.1) \times 10^{-10} \text{ m}^2/\text{s}$ ,  $R_h = 4.9 (\pm 0.1) \text{ nm}$ .  $D$ , diffusion coefficient;  $R_h$ , hydrodynamic radius.

at M<sup>+</sup>: calcd 7311.54; found: 7334.47 (MNa<sup>+</sup>). DOSY NMR and dynamic light scattering provide consistent data for the dendrimers **10** and **11**, both methods giving a diameter values of 13 ± 1.2 nm for **10** and 15 ± 1.5 nm for **11**. For the dendrimer **9**, DOSY NMR yielded a diameter value of 8 ± 0.6 nm (ESI).

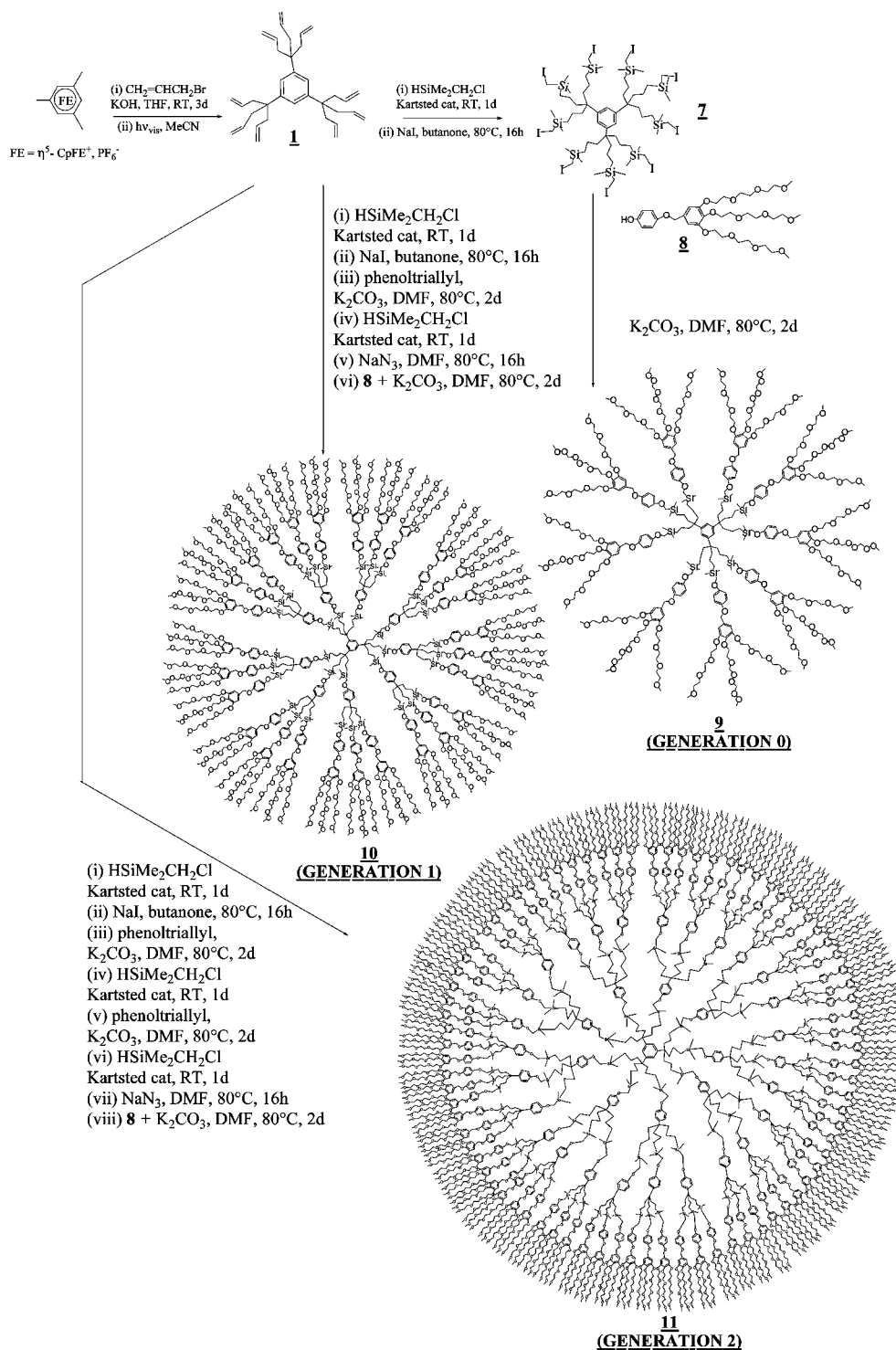
**3. AuNPs Synthesized using NaBH<sub>4</sub> and Stabilization in Methanol by the “Click” Dendrimers 4, 5 and 6.** The AuNPs were synthesized by reaction between the “click” dendrimers **4**, **5** and **6**, and a stoichiometric amount of HAuCl<sub>4</sub> vs. the dendrimer triazole groups, followed by NaBH<sub>4</sub> reduction in methanol. This stoichiometry was selected, because we believed that the AuNPs formed would contain a number of atoms equal to the number of triazole rings in the dendrimer, as with PdNPs. It also allows comparisons between the various procedures used throughout this study. Later, the amount of HAuCl<sub>4</sub> was also increased, in order to examine its influence on the AuNP size. The UV–vis spectrum shows a plasmon band at 540 nm for the dendrimer **4**-stabilized AuNPs, but this band is absent in the spectrum of the AuNPs stabilized by the higher-generation dendrimers **5** and **6** (Figure 4). The transmission electron microscopy (TEM) data confirm this trend (Figure 5) showing that the dendrimer **4**-stabilized AuNPs are larger than the dendrimer (4.1 ± 0.5 nm) and cannot be encapsulated in such a small dendrimer that contains only 27 tethers. Thus, several dendrimers **4** are surrounding each AuNP (Figure 6). On the other hand, the larger dendrimers **5** and **6** containing respectively 81 and 243 TEG tethers encapsulate AuNPs of small size (1.9 ± 0.4 nm). Dendrimer **4** has an open structure, and any AuNPs formed therein will start to come out and aggregate into larger AuNPs, while dendrimers **5** and **6** will engulf any forming AuNPs.

**4. Attempts to Stabilize AuNPs in Methanol by Other Dendrimers.** The syntheses and stabilization of AuNPs using a stoichiometric amount of HAuCl<sub>4</sub> per triazole or Percec-type dendron and NaBH<sub>4</sub> reduction in methanol was attempted using six others dendrimers. Three of them, that were reported earlier,<sup>12a</sup> only contain triazole groups and do not contain any PEG (**12**, **13** and **14**), and the three others only contain PEG but no triazole groups (**9**, **10** and **11**).<sup>15b</sup> “Click” dendrimers with 27 and 81 allyl tethers (**13** and **14**) and a “click” dendrimer with 27 phenyl tethers (**12**) were used (Chart 1).

The procedure used for the addition and reduction of HAuCl<sub>4</sub> in these dendrimers was the same one as that previously described using a stoichiometric amount of HAuCl<sub>4</sub> vs the dendrimer triazole groups. When NaBH<sub>4</sub> in methanol was added,

(21) Candelon, N.; Lastécouères, D.; Diallo, A. K.; Ruiz, J.; Astruc, D.; Vincent, J.-M. *Chem. Commun.* **2008**, 741–743.

(22) (a) Komeda, S.; Lutz, M.; Speck, A. L.; Yamanaka, Y.; Sato, T.; Chikuma, M.; Reedijk, J. *J. Am. Chem. Soc.* **1997**, *119*, 2588. (b) Barz, M.; Herdtweck, E.; Thiel, W. R. *Angew. Chem., Int. Ed.* **1998**, *37*, 2262–2265. (c) Chan, T. R.; Holgraf, R.; Sharpless, K. B.; Fokin, V. V. *Org. Lett.* **2004**, *6*, 2853–2856.

**Scheme 2.** Syntheses of the Three Generations of Dendrimers **9**, **10** and **11** by the Williamson Reactions

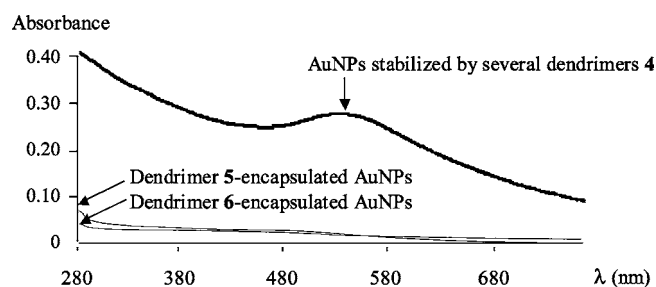
188 the AuNPs were formed, but they precipitated after a few  
189 minutes, and AuNPs could never be stabilized (although PdNP  
190 could be stabilized<sup>19</sup>).

191 The dendrimers **9**, **10** and **11** containing respectively 27, 81  
192 and 243 PEG tethers but no triazole ligand were used for  
193 comparison (Scheme 2). The procedure used for the addition  
194 and reduction of  $\text{HAuCl}_4$  in this dendrimer was the same as  
195 previously described with 27, 81 and 243 equiv of Au per  
196 dendrimer. The result was similar to that obtained with the above  
197 dendrimers containing only triazole groups, that is, AuNPs

immediately precipitated when  $\text{NaBH}_4$  in methanol was added,  
and no AuNP could be obtained.

These six experiments support the fact that the presence of  
both the PEG and triazole groups in the dendrimers **4**, **5** and **6**  
are essential for the stabilization of AuNPs in methanol, when  
 $\text{NaBH}_4$  is used as the reductant.

**5. AuNP Size Variation upon Change of  $\text{HAuCl}_4$   
Stoichiometry in Methanol.** The size variation of the AuNPs  
synthesized using  $\text{NaBH}_4$  in methanol was observed in the case  
of AuNP stabilization with the dendrimer **5** upon change of

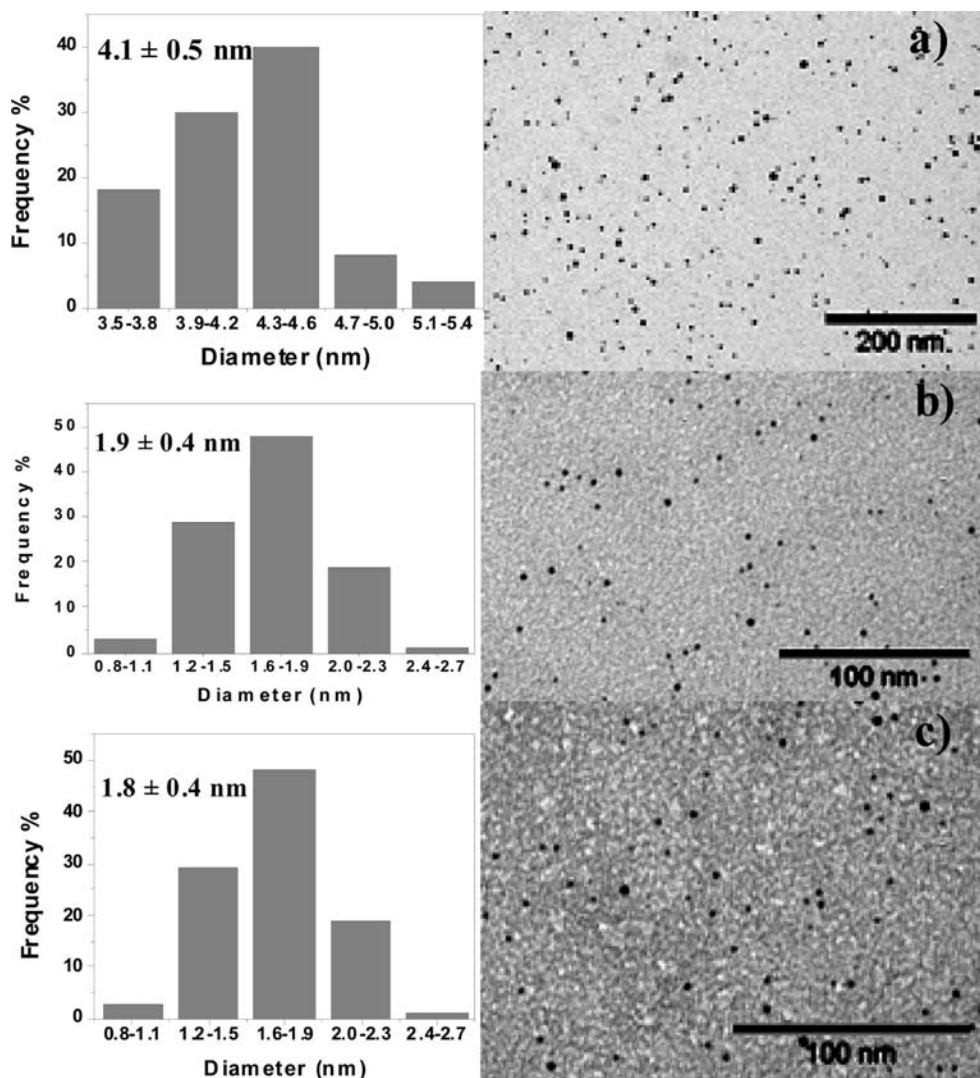


**Figure 4.** UV-Vis spectra of AuNPs stabilized by several dendrimers **4** and encapsulated by dendrimers **5** and **6**.

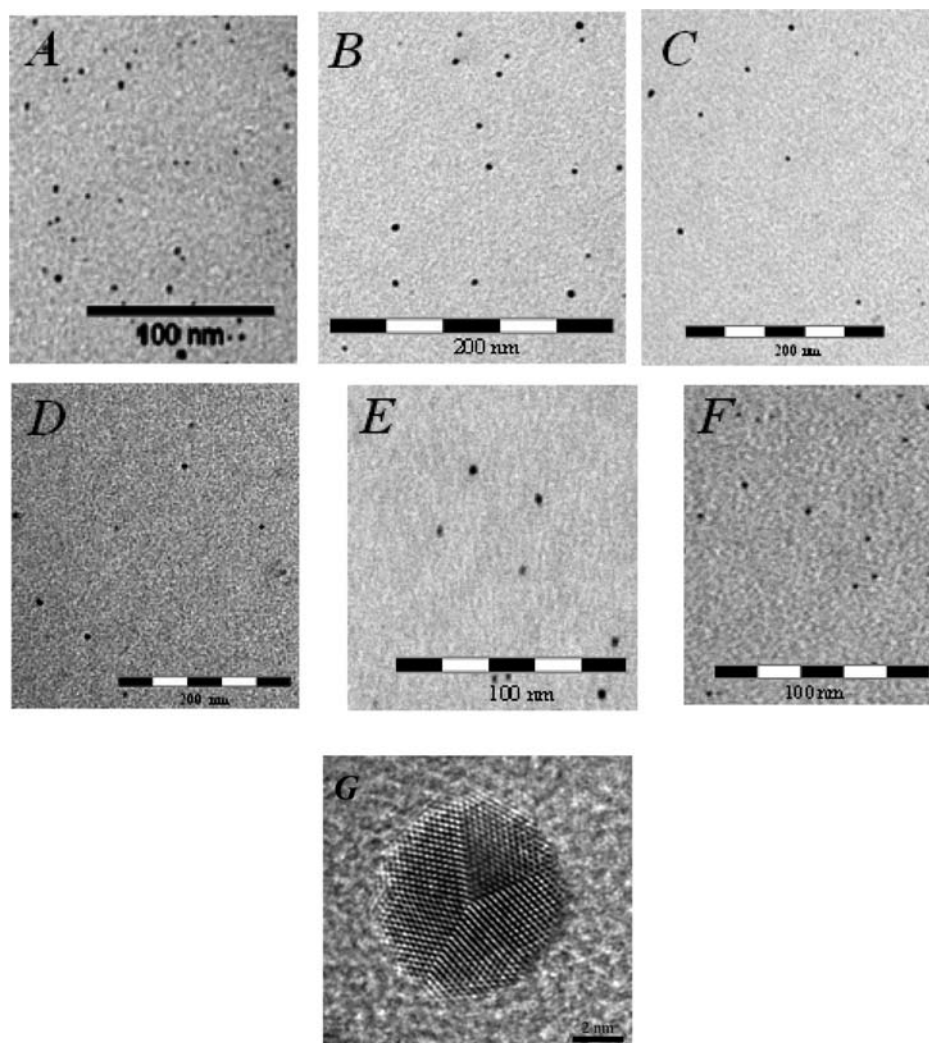
208 stoichiometry of the  $\text{HAuCl}_4$  precursor. TEM images were  
 209 recorded (Figure 6) for an increase of the equiv. number of  
 210 added  $\text{HAuCl}_4$  from 1 to 20  $\text{Au}^{\text{III}}$  per intradendritic triazole  
 211 ligand. All the AuNPs obtained are spherical, and their size is  
 212 very homogeneous. Moreover, a high resolution TEM was  
 213 recorded for 7 equiv of  $\text{Au}^{\text{III}}$  per triazole, in order to observe  
 214 the crystalline structure of the AuNP (Figure 6, G). The increase  
 215 of the number of equiv.  $\text{HAuCl}_4$  per triazole leads to a variation  
 216 of the diameter of the AuNPs from  $1.9 \pm 0.2$  nm (1 equiv of  
 217  $\text{Au}^{\text{III}}$  per triazole) to  $11.3 \pm 1$  nm (20 equiv of  $\text{Au}^{\text{III}}$  per triazole).  
 218 From 1 to 10 equiv of  $\text{Au}^{\text{III}}$  per triazole, the AuNP size varies

219 linearly with the number of  $\text{HAuCl}_4$  equiv added before reaching  
 220 a plateau at approximately 11 nm (Figure 7). This maximum  
 221 size is expected, because the AuNPs are stabilized with the  
 222 dendrimer **5** in an intradendritic way (see section 2), and the  
 223 diameter of this dendrimer is confirmed by both DOSY NMR  
 224 and light scattering ( $18 \pm 2$  nm). When the number of  
 225 equivalents of  $\text{HAuCl}_4$  per triazole is larger than 10, excess  $\text{Au}^0$   
 226 immediately precipitates.

**6. AuNP Synthesis in Water and Stabilization by Dendrimers Terminated by Percec-Type PEG Dendrons in the Absence of External Reductant.** AuNPs were synthesized according to a new protocol, without external reductant and in aqueous dendrimer solution at room temperature. The AuNP were formed by reaction between the TEGylated dendrimers and a stoichiometric amount of  $\text{HAuCl}_4$  per PEG dendron in water in the dark (i.e., 9 equiv of  $\text{HAuCl}_4$  per dendrimers **4** and **9**, 27 per dendrimers **5** and **10** and 81 per dendrimers **6** and **11**). The solution became red after a few minutes of stirring. The synthesis of the AuNPs in the presence of dendrimers **9**, **10** and **11** was faster than for the AuNPs obtained with “click” dendrimers **4**, **5** and **6**. This reduction was followed by the evolution of the AuNP plasmon band in UV-vis spectroscopy. For example, the synthesis of the AuNPs with the dendrimer **9**



**Figure 5.** (a) Dendrimer **4**/AuNPs: TEM image and size distribution. (b) Dendrimer **5**/AuNPs: TEM image and size distribution. (c) Dendrimer **6**/AuNPs: TEM image and size distribution.



**Figure 6.** (A) Dendrimer **5** + 1 equiv of  $\text{HAuCl}_4$  per triazole, diameter =  $1.9 (\pm 0.2)$  nm; (B) dendrimer **5** + 3 equiv of  $\text{HAuCl}_4$  per triazole, diameter =  $3.8 (\pm 0.4)$  nm; (C) dendrimer **5** + 5 equiv of  $\text{HAuCl}_4$  per triazole, diameter =  $5.3 (\pm 0.5)$  nm; (D) dendrimer **5** + 7 equiv of  $\text{HAuCl}_4$  per triazole, diameter =  $6.8 (\pm 0.7)$  nm; (E) dendrimer **5** + 10 equiv of  $\text{HAuCl}_4$  per triazole, diameter =  $11.0 (\pm 1)$  nm; (F) dendrimer **2** + 20 equiv of  $\text{HAuCl}_4$  per triazole, diameter =  $11.3 (\pm 1)$  nm; (G) HRTEM of dendrimer **5** + 7 equiv of  $\text{HAuCl}_4$  per triazole.

242 was completed in 3.5 h, whereas that with the dendrimer **5** was  
 243 completed in one day in order to achieve complete reduction  
 F8 244 (Figure 8).

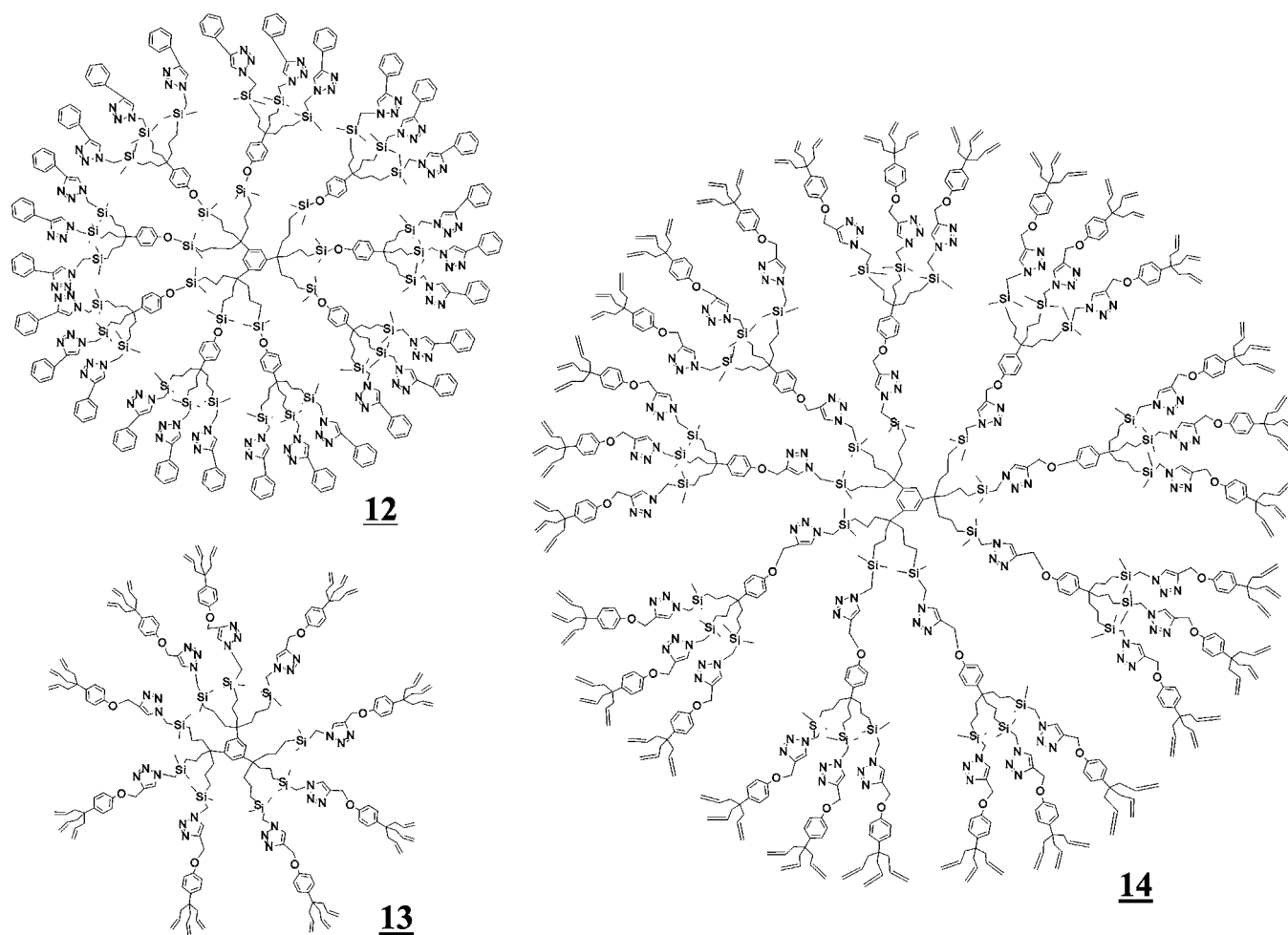
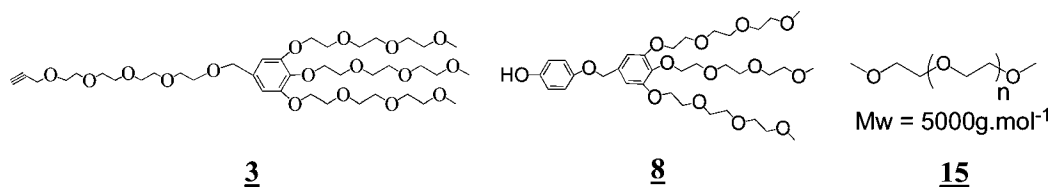
245 For all the experiments, the UV–vis spectrum shows a  
 246 plasmon band between 530 and 570 nm depending on the cases  
 247 (see the examples with the dendrimers **9**, **10** and **11** in Figure  
 F9 248 9). This means that all the observed AuNPs have a diameter  
 249 larger than 3 nm. The transmission electron microscopy (TEM)  
 250 data confirm this trend (see ESI), showing that the dendrimer  
 251 **9**-stabilized AuNPs have a diameter of  $23 \pm 0.5$  nm, the  
 252 dendrimer **10**-stabilized AuNPs have a diameter of  $34 \pm 1$  nm  
 253 and the dendrimer **11**-stabilized AuNPs have a diameter of  $36$   
 254  $\pm 0.5$  nm.

255 The various generations of “click” dendrimers **4**, **5** and **6** give  
 256 the same AuNP diameters as dendrimers **9**, **10** and **11**. Indeed,  
 257 the dendrimer **4**-stabilized AuNPs have a diameter of  $22 \pm 0.5$   
 258 nm, the dendrimer **5**-stabilized AuNPs have a diameter of  $33$   
 259  $\pm 0.5$  nm, and the dendrimer **3**-stabilized AuNPs have a  
 260 diameter of  $36 \pm 1$  nm (see ESI). This leads to a characteristic  
 261 size for each generation of dendrimers containing or not triazole  
 262 groups, and in these syntheses only the reaction time changes.

The sizes of these AuNPs are much larger than those observed  
 263 with the first protocol with  $\text{NaBH}_4$  in methanol. The presence  
 264 of Percec-type PEG tethers in these dendrimers is required for  
 265 the reduction and the stabilization of AuNPs in water.  
 266

267 Several tests were performed with the two PEGylated Percec-  
 268 type dendrons **3** and **8** (used to synthesize the PEGylated  
 269 dendrimers), and the PEG polymer **15** (mass molar:  $5000 \text{ g}$   
 270  $\text{mol}^{-1}$ ) (Chart 2). Mixing **3**, **8** or **15** with  $\text{HAuCl}_4$  in water did  
 C2 271 not result in any color change of the yellow aqueous solution  
 272 after several days nor any change in the UV–vis spectrum.  
 273 Thus, reduction of AuNPs did not proceed in these cases, in  
 274 sharp contrast to what was observed with the PEGylated  
 275 dendrimers under the same conditions. This shows that a  
 276 PEGylated dendron or PEG polymer is not sufficient to reduce  
 277  $\text{HAuCl}_4$  in water, but that the PEGylated dendron must be  
 278 embedded within the dendritic structure to become efficient for  
 279 this process.

280 To further examine the frontier of the feasibility of  $\text{HAuCl}_4$   
 281 reduction and AuNP stabilization in water in the absence of  
 282 external reductant, we synthesized the dendrimer **16** by “click”  
 283 reaction between the 27-azido dendrimer precursor of **5** and

**Chart 1.** Structure of the Known Dendrimers **12–14** that Do Not Contain PEG Termini and Stabilize PdNPs<sup>12a</sup> but Not AuNPs.**Chart 2.** PEG Dendrons and Polymer that Do Not Undergo AuNP Formation from HAuCl<sub>4</sub> in Water in the Absence of External Reductant, Unlike the PEGylated Dendrimers **4–6** and **9–11**

284 propargyltetraethylene glycol (instead of the dendron **3** used  
 285 for the synthesis of **6**; compare Chart 3 with Scheme 2). The  
 286 structure of **16** is thus intermediate between those of the  
 287 PEGylated dendrimers **4** and **5**, but with 27 linear (nonden-  
 288 dronic) tetraethyleneglycol tethers instead of PEGylated Percec-  
 289 type dendrons (Chart 3). In **16**, the branching point of the 1 →  
 290 3 connectivity is remote from the tetraethyleneglycol groups,  
 291 unlike in **4** and **5**.

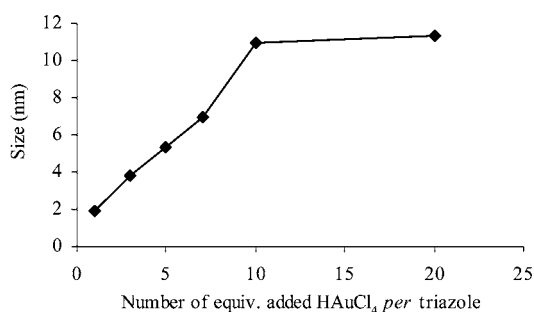
292 Mixing this white crystalline dendrimer **16** with the yellow  
 293 aqueous solution of HAuCl<sub>4</sub> resulted in a clear yellow solution  
 294 from which a pale yellow precipitate formed after 15 min,  
 295 whereas the solution became colorless. Addition of dichlo-  
 296 romethane and shaking the two phases recovered the clear  
 297 yellow aqueous solution of Au<sup>III</sup> and the colorless organic phase  
 298 from which the dendrimer **16** was recovered quantitatively and  
 299 identified by <sup>1</sup>H NMR. Extraction with dichloromethane ap-  
 300 parently breaks the weak triazole–Au<sup>III</sup> bond, but no AuNPs  
 301 were formed in this process. This experiment is in sharp contrast

302 with the similar experiments carried with all the dendrimers  
 303 terminated by Percec-type PEG dendrons that produced red  
 304 AuNPs (Scheme 3).

305 Many transition-metal-1,2,3-triazole complexes are known  
 306 with a variety of coordination modes.<sup>11d,21</sup> With ferrocenyl  
 307 “click” dendrons and ferrocenyl-terminated “click” dendrimers  
 308 related to **12–14**, such intradendritic triazole complexation by  
 309 late transition-metal cations has also been shown by  
 310 electrochemistry<sup>11a</sup> and X-ray crystal structures.<sup>11d</sup> In the present  
 311 case, complexation of the triazole group of the dendrimer **4** has  
 312 been monitored by UV–vis spectroscopy before NaBH<sub>4</sub> reduc-  
 313 tion to AuNPs (ESI), although the complexation mode is still  
 314 unknown, the possibilities being multifold in the literature.<sup>11d,21</sup>

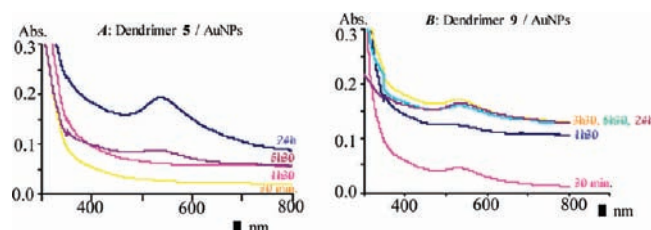
315 It can be concluded that the driving force provided by the  
 316 linear TEG termini in **16** or by the open PEG structures **3**, **8**  
 317 and **15** of Chart 1 is insufficient to reduce Au<sup>III</sup>. This shows  
 318 that it is the semicavitand-shaped Percec-type PEG, when it is  
 319 sterically constrained within the dendrimer frame, that is





equiv. number of H[Au <sup>III</sup> Cl <sub>4</sub> ] per triazole	AuNP diameter (nm)
1	1.9 (± 0.2)
3	3.8 (± 0.4)
5	5.3 (± 0.5)
7	6.8 (± 0.7)
10	11.0 (± 1)
20	11.3 (± 1)

**Figure 7.** Size variation of AuNPs stabilized by the "click" dendrimer 6 G1-81-PEG in methanol upon reduction using NaBH<sub>4</sub> in methanol.



**Figure 8.** UV-Vis spectra of AuNPs formed and stabilized by the dendrimers 5 and 9 at different times.

responsible for reduction of H[AuCl<sub>4</sub>] and stabilization of AuNPs. The experiment with the nonclick PEGylated dendrimers 9-11 that also reduce H[AuCl<sub>4</sub>] shows that the triazole ring is not involved in the reduction, as also confirmed by the negative result obtained with the dendrimer 16. When both the triazole and dendronic Percec-type PEG are present in the dendrimer structure, reduction of H[AuCl<sub>4</sub>] still occurs, but more slowly than in the absence of triazole, because of triazole complexation. Some PEGs are known to complex and reduce Au<sup>III</sup> to AuNPs,<sup>23</sup> the mechanism involving oxidative cleavage of ether C-O bonds by the strong oxidant Au<sup>III</sup>.<sup>23f</sup> It appears here that the dendronic nature of the Percec-type TEGs strongly favors this process compared to linear tetraethylene glycol termini. Chelating or encapsulating oxygen atoms of crown ethers are much more easily protonated than linear PEG,<sup>23c</sup> and ion pair formation den-PEGH<sup>+</sup>, AuCl<sub>4</sub><sup>-</sup> or den-PEGH<sup>+</sup>, [AuCl<sub>3</sub>(OH)]<sup>-</sup> becomes possible,<sup>23c</sup> which accounts for intradendritic extraction of H[AuCl<sub>4</sub>] by the dendritic Percec-type PEG from the peripheral aqueous medium. Finally, coordination/chelation of Au<sup>III</sup> by PEG oxygen atoms of the Percec-type dendron constrained in

the dendrimers presumably occurs, before oxidative C-O cleavage concomitant with Au<sup>III</sup> reduction.

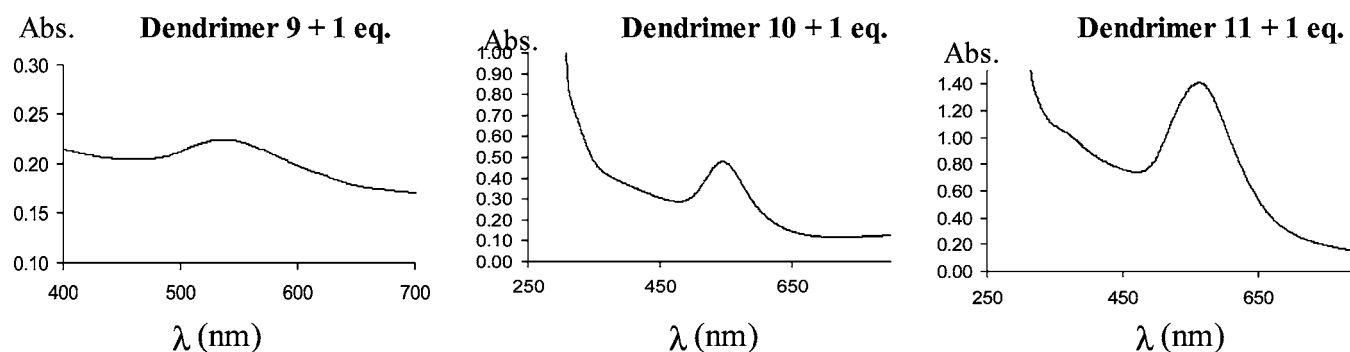
**7. AuNPs Size Variation in Water upon Change of the AuCl<sub>4</sub> Stoichiometry.** The AuNP size variation when H[AuCl<sub>4</sub>] is reduced and the AuNPs stabilized by dendrimers 9, 10 and 11 in water is observed when the number of equivalents of added H[AuCl<sub>4</sub>] is multiplied by two and by five (i.e., 18 and 45 equiv of Au for 9, 54 and 135 equiv of Au for 10, and 162 and 405 equiv of Au for 11). The TEM images were recorded (see ESI), and the diameters of the AuNPs obtained were estimated (Table 1). The diameter of dendrimer 9-stabilized AuNPs varies from 23 ± 0.5 nm to 32 ± 1 nm, from 34 ± 1 nm to 38 ± 1 nm for dendrimer 10-stabilized AuNPs and from 36 ± 0.5 nm to 42 ± 1 nm for dendrimer 11-stabilized AuNPs.

**8. AuNP Formation in Methanol upon H[AuCl<sub>4</sub>] Reduction by Organometallic "Electron-Reservoir" Complexes.** The AuNP precursor H[AuCl<sub>4</sub>] was also reduced in methanol to AuNPs by the organometallic electron-reservoir sandwich complexes, [Fe<sup>I</sup>Cp(η<sup>6</sup>-C<sub>6</sub>Me<sub>6</sub>)],<sup>24</sup> ferrocene, ethynylferrocene and decamethylferrocene that are single-electron reductants with various redox potentials. In these cases, the AuNPs were synthesized by reaction between the "click" dendrimer 5 and a stoichiometric amount of H[AuCl<sub>4</sub>] per dendrimer triazole group, followed by reduction in methanol using the organometallic compound. The TEM data (see ESI) show that the dendrimer 5-stabilized AuNPs obtained using the organometallic compounds are much larger than the AuNPs obtained by reduction using NaBH<sub>4</sub> (1.9 ± 0.4 nm). Indeed, the AuNP diameter synthesized using ferrocene is 38 ± 3 nm, with ethynylferrocene it is 30 ± 3 nm, with decamethylferrocene it is 23 ± 2 nm, and with [Fe<sup>I</sup>Cp(η<sup>6</sup>-C<sub>6</sub>Me<sub>6</sub>)] it is 7 ± 1 nm. The high resolution TEM (Figure 10B) shows the cubic crystalline structure of the AuNPs obtained AuNP under these conditions using [Fe<sup>I</sup>Cp(η<sup>6</sup>-C<sub>6</sub>Me<sub>6</sub>)] as the reductant.

## Discussion

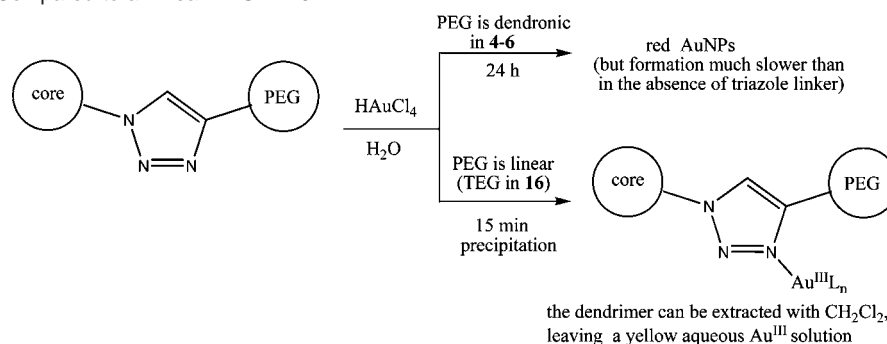
Dendrimers that contain both triazole rings and TEGylated Percec-type dendrons are able to stabilize AuNPs in methanol, but related dendrimers lacking one of these structural features cannot stabilize AuNPs upon NaBH<sub>4</sub> reduction of H[AuCl<sub>4</sub>] in this solvent. We already know from previous electrochemical<sup>11a</sup> and X-ray structural studies<sup>11d</sup> that various late transition-metal ions are coordinated by the intradendritic triazole ligands of "click" dendrimers. Thus, in the present case, the triazole ligands analogously serve to trap the Au<sup>III</sup> ions inside the "click" dendrimers, then stabilization of the reduced Au atoms in AuNPs is provided by the nearby semicavitand formed by the TEGy-

- (23) (a) Liu, K. J. *Macromolecules* **1968**, *1*, 308-311. (b) Yanagida, S.; Takahashi, K.; Okahara, M. *Bull. Chem. Soc. Jpn.* **1977**, *50*, 1386-1390. (c) Warshawsky, A.; Kalir, R.; Deshe, A.; Berkovitz, H.; Patchornik, A. *J. Am. Chem. Soc.* **1979**, *101*, 4249-4256. (d) Yokota, K.; Matsumura, M.; Yamaguchi, K.; Takada, Y. *Makromol. Chem. Rapid Commun.* **1983**, *4*, 721-724. (e) Adams, M. D.; Wade, P. W.; Hancock, R. D. *Talanta* **1990**, *37*, 875-883. (f) Longenberger, L.; Mills, G. J. *Phys. Chem.* **1995**, *99*, 475-478. Mathur, A. M.; Scranton, A. B. *Sep. Sci. Technol.* **1995**, *30*, 1071-1086. (g) Sanai, Y.; Ono, K.; Hidaka, T.; Takagi, M.; Cattrall, R. W. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 1165-1169. (h) Elliott, B. J.; Scranton, A. B.; Cameron, J. H.; Bowman, C. N. *Chem. Mater.* **2000**, *12*, 633-642. (i) Sakai, T.; Alexandridis, P. *J. Phys. Chem. B* **2005**, *109*, 7766-7777.
- (24) (a) Hamon, J.-R.; Astruc, D.; Michaud, P. *J. Am. Chem. Soc.* **1981**, *103*, 758-766. (b) Green, J. C.; Kelly, M. R.; Payne, M. P.; Seddon, E. A.; Astruc, D.; Hamon, J.-R.; Michaud, P. *Organometallics* **1983**, *2*, 211-218. (c) Desbois, M.-H.; Astruc, D.; Guillin, J.; Varret, F.; Trautwein, A. X.; Villeneuve, G. *J. Am. Chem. Soc.* **1989**, *111*, 5800-5809.



**Figure 9.** UV-Vis spectra of AuNPs formed and stabilized by the dendrimers **9**, **10** and **11**.

**Scheme 3.** Dramatic Influence of the Dendronic Percec-type PEG in **4–6** on Au<sup>III</sup> Reduction and AuNP Formation in Water without Additional Reductant, Compared to a Linear TEG in **16**



386 lated Percec-type dendrons. “Click” TEG-terminated dendrimer  
387 stabilized AuNPs formed upon NaBH<sub>4</sub> reduction in methanol,  
388 but the generation dependence influenced the AuNP size and  
389 mode of stabilization. DSAuNPs are formed with G<sub>0</sub>-27TEG,  
390 and they are larger (4.1 nm) than the dendrimer and thus  
391 surrounded by several dendrimers (Figure 11). On the other  
392 hand, DEAuNPs are formed from the large G<sub>1</sub>-81TEG and G<sub>2</sub>-  
393 243 TEG dendrimers. These findings were obtained using a 1:1  
394 HAuCl<sub>4</sub>/triazole stoichiometry, but the AuNP size was steadily  
395 increased when this stoichiometry was increased until a plateau  
396 was reached at a 10:1 stoichiometry with G<sub>1</sub>-81TEG, indicating  
397 that the AuNPs have become so large that they could no longer  
398 be encapsulated. This shows the progressive transition between  
399 DEAuNPs and DSAuNPs as well as the maximum size of  
400 AuNPs that can be reached by this method.

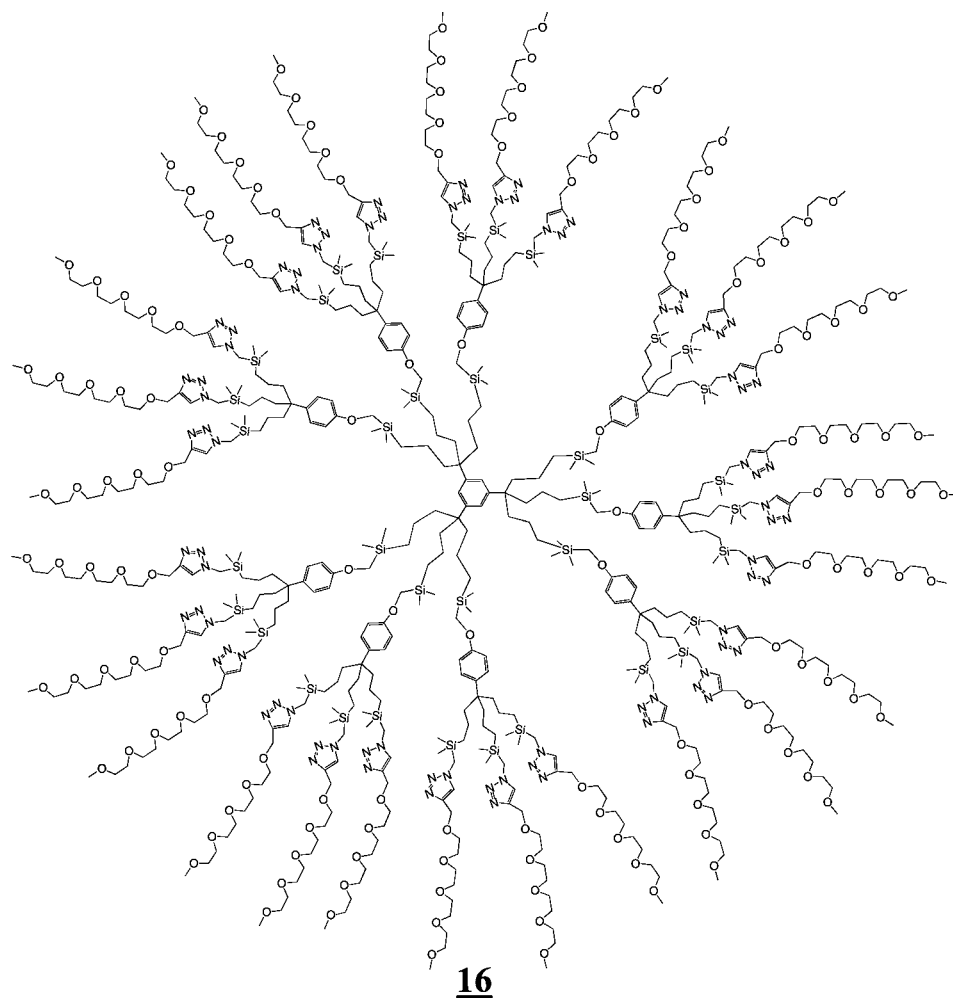
401 Whereas AuNPs were easily formed from PAMAM and PIP  
402 dendrimers by the pioneers in the area,<sup>6</sup> it is surprising that  
403 AuNPs could not be formed here by NaBH<sub>4</sub> reduction in  
404 methanol of Au<sup>III</sup> complexes of arene-cored “clicked” dendrimers  
405 in the absence of TEG termini. This is all the more striking  
406 as our previous studies had shown that, using these same  
407 dendrimers, PdNPs were formed and were shown to be very  
408 active in the catalysis of alkene hydrogenation and C–C forming  
409 reactions. This contrast might be due to the difference of  
410 aggregation mechanism and rate between these two metals.

411 Also remarkable is the success to form these AuNPs when  
412 the TEG termini were introduced as structural complement for  
413 all the dendrimers studied here. It is thus likely that this  
414 outstanding property of Percec-type TEG termini could be  
415 extended to many other dendrimers. Another interesting distinc-  
416 tion is the impossibility to form the dendrimer-stabilized AuNPs  
417 by NaBH<sub>4</sub> reduction of HAuCl<sub>4</sub> in methanol when the arene-  
418 cored TEG-terminated dendrimers do not contain the 1,2,3-

419 triazole ring whatever the generation (nonclick dendrimer series  
420 **9**, **10** and **11**). NaBH<sub>4</sub> is currently believed to be a convenient  
421 reductant of Au<sup>III</sup> to form AuNPs (despite the undesired  
422 formation of borides at the AuNP surface),<sup>24b</sup> but this study  
423 demonstrates that it does not always work, probably because  
424 in this precise case the reduction is too fast to be compatible  
425 with stabilization of the AuNPs.

426 Even if NaBH<sub>4</sub> fails to lead to the formation of AuNPs with  
427 TEG-terminated dendrimers that do not contain a triazole ring,  
428 however, the presence of Percec-type TEG termini is sufficient  
429 to allow the formation of the AuNPs in water in this case in  
430 the absence of reductant. The dendritic effect is required for  
431 this property, as it is shown that nondendritic linear PEGs,  
432 tripodal dendronic PEGs that are not incorporated in dendrimers,  
433 and even a “click” dendrimer terminated by 27 linear (non  
434 dendronic) TEG tethers does not have this property. Au<sup>III</sup> is a  
435 rather strong oxidant,<sup>25</sup> but oxidation of nondendritic PEG is  
436 endergonic and not sufficiently entropy-driven. On the other  
437 hand, Au<sup>III</sup> encapsulation achieved upon multiple proton coordi-  
438 nation by the oxygen atoms of the TEG semicavitands is  
439 facilitated by the dendritic constraint, which brings about ion  
440 pairing to trap Au<sup>III</sup> with favorable entropy conditions for Au<sup>III</sup>  
441 reduction. Yet, the AuNP formation is slow in “click” den-  
442 drimers terminated by Percec-type PEG dendrons, due to the  
443 Au<sup>III</sup>-triazole coordination that is distal from the dendronic PEG  
444 reduction site. Either the requirement of a distal electron transfer  
445 slows it down or the reversible Au<sup>III</sup>-triazole coordination  
446 renders Au<sup>III</sup> less available at the dendronic PEG reduction site.

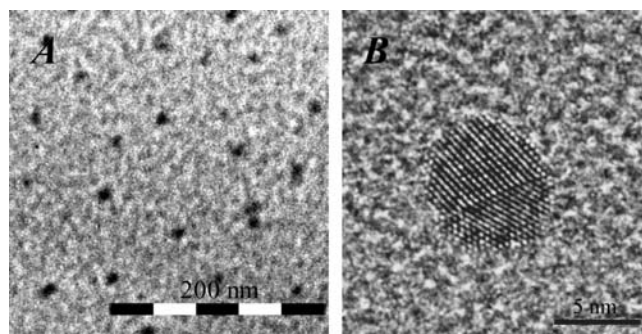
(25) Cotton, F. A.; Wilkinson, G.; Murillo, C. A.; Bochmann, M. *Advanced Inorganic Chemistry*, 6th ed.; John Wiley: New York, pp 1084–1086.

**Chart 3.** Structure of the Dendrimer **16** that Contain Linear (non-Percec-type) TEG Termini and Does Not Undergo AuNP Formation from HAuCl<sub>4</sub> in Water in the Absence of External Reductant**Table 1.** Size Evolution of AuNPs Stabilized by Dendrimers **9**, **10** or **11** in Water

dendrimer + number of equiv of Au per dendron	AuNP diameter (nm)
Dendrimer <b>9</b> + 1 equiv	23 ± 0.5
Dendrimer <b>9</b> + 2 equiv	26 ± 1.0
Dendrimer <b>9</b> + 5 equiv	32 ± 1.0
Dendrimer <b>10</b> + 1 equiv	34 ± 1.0
Dendrimer <b>10</b> + 2 equiv	36 ± 0.5
Dendrimer <b>10</b> + 5 equiv	38 ± 1.0
Dendrimer <b>11</b> + 1 equiv	36 ± 0.5
Dendrimer <b>11</b> + 2 equiv	38 ± 1.0
Dendrimer <b>11</b> + 5 equiv	42 ± 1.0

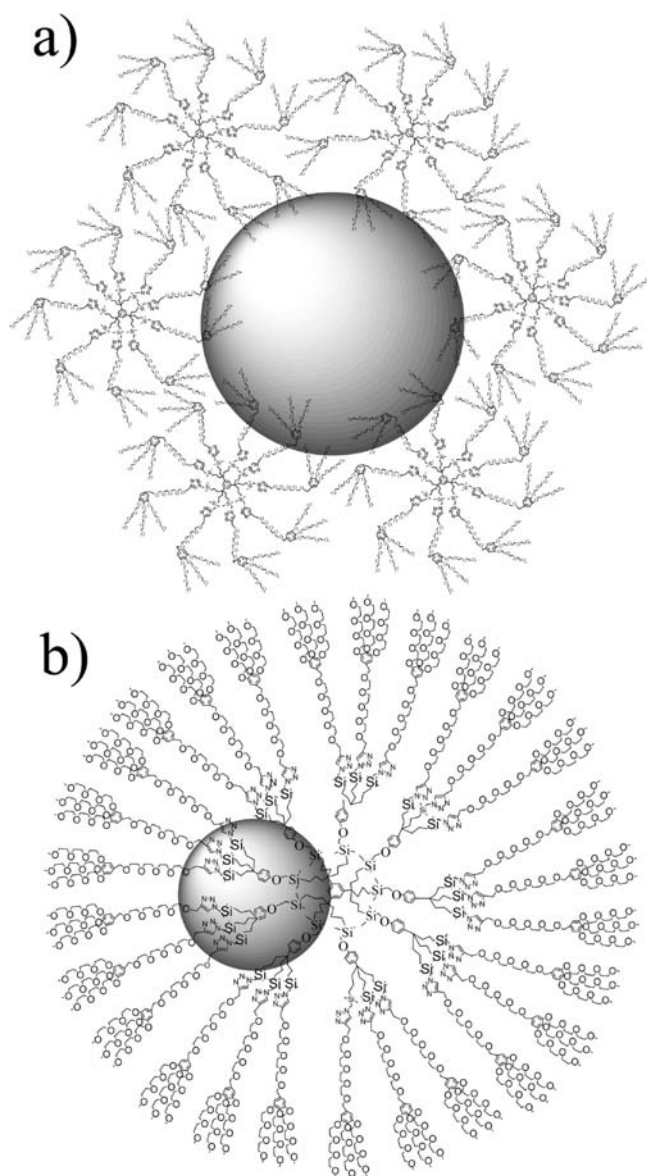
447 The large size of the AuNPs formed by this process is due to  
 448 this very slow kinetics. This means that the AuNPs start growing  
 449 inside the dendrimers, and that these germs continue growing  
 450 outside the dendrimers owing to their large size by trapping  
 451 the Au atoms formed in the TEG semicavities near the  
 452 dendrimer periphery. It is likely that, once the large AuNPs  
 453 grow, the native Au atoms do not form small stable DEAuNPs  
 454 inside the dendrimer, because the latter are not observed by  
 455 TEM.

456 Note that the AuNPs obtained by this method have the same  
 457 size whether or not they contain triazole ligands, confirming  
 458 that it is the TEG oxygen pseudocavities that play the main  
 459 role in the AuNP formation in this case rather than the triazole  
 460 ring. The DSAuNPs formed in this way are much larger than

**Figure 10.** (A) TEM of the dendrimer **5** + 1 equiv of HAuCl<sub>4</sub> reduced by [Fe<sup>1</sup>Cp(η<sup>6</sup>-C<sub>6</sub>Me<sub>6</sub>)]. (B) HRTEM of the dendrimer **5** + 1 equiv of HAuCl<sub>4</sub> reduced by [Fe<sup>1</sup>Cp(η<sup>6</sup>-C<sub>6</sub>Me<sub>6</sub>)].

those formed by NaBH<sub>4</sub> reduction, because the driving force is  
 considerably larger with NaBH<sub>4</sub> than with the TEG semicavitand  
 dendrimer termini.

It is surprising that, owing to the undesired boride impurities  
 formed at the AuNP surface of AuNPs synthesized using  
 NaBH<sub>4</sub>,<sup>18d</sup> no mono-electronic reductant has been probed to form  
 clean AuNPs. For biomedical applications, the AuNPs are  
 usually synthesized with the Turkevich method,<sup>26</sup> because most  
 (although not all) of the temporary citrate stabilizers can be  
 removed to introduce the biomedical probe or target, and the  
 large AuNPs formed by this method allow monitoring an intense



**Figure 11.** (a) AuNPs stabilized by several dendrimers **4**; (b) dendrimer **5**-encapsulated AuNPs.

472 plasmon absorption. Also, whereas small AuNPs (< 5 nm) are  
 473 of great interest for efficient catalysis,<sup>27</sup> large AuNPs are  
 474 important in nanomedicine, because the plasmon band (AuNP  
 475 > 3 nm) is an indispensable tool in this later area.<sup>18</sup>

476 In the present study, the use of single-electron reductants  
 477 successfully leads to the formation of AuNPs that are much  
 478 larger than those formed using NaBH<sub>4</sub> reduction. This is due  
 479 to the fact that the mechanism of NaBH<sub>4</sub> reduction follows inner-  
 480 sphere electron transfer involving chloride elimination from  
 481 AuCl<sub>4</sub><sup>-</sup>, whereas the mechanism of the single-electron reductants  
 482 involves outer-sphere electron transfer. As shown by the seminal  
 483 work of Henry Taube, inner-sphere mechanisms are consider-  
 484 ably superior to outer-sphere electron-transfer mechanisms in  
 485 terms of reaction kinetics.<sup>28</sup> Again, slow reduction is well-known  
 486 to result in a prolonged aggregation process leading to large  
 487 NPs.<sup>26</sup> Reetz has shown a linear correlation between the driving  
 488 force of carboxylate reductants and the PdNP size, that is, the

PdNPs are all the larger as the driving force is weaker.<sup>29</sup> This  
 is also what is found here with the series of mono-electronic  
 reductants, as the DSAuNPs formed are all the larger as the  
 standard oxidation potential of the reductant is more positive  
 (or less negative). Since the reactions of electron-reservoir  
 complexes are clean because, by definition, both the oxidized  
 and reduced forms are stable,<sup>24</sup> it is possible to define the size  
 of the DSAuNPs between 7 nm (strong Fe<sup>I</sup> mono-electronic  
 reductant) and 38 nm (weakest Fe<sup>II</sup> mono-electronic reductant).  
 The standard potentials of these electron-reservoir complexes  
 are perfectly defined and can be easily tuned even with small  
 variations by change of the nature and number of ring substitu-  
 ents of the transition-metal sandwich complex.<sup>30</sup> This flexibility  
 allows to also finely tune the AuNPs size without inhibiting  
 the AuNP surface upon ligand coordination.

### Concluding Remarks

This study shows the critical structural conditions for the  
 dendrimer-induced formation of DEAuNPs and DSAuNPs of  
 various sizes ranging from 1.8 to 42 nm. A variety of new  
 dendrimers synthesized using 1 → 3 connectivity with Percec-  
 type TEG termini provide ideal conditions for AuNP formations  
 from HAuCl<sub>4</sub> either using NaBH<sub>4</sub> as the reductant or without  
 external reductant. With NaBH<sub>4</sub>, it is also indispensable to use  
 “click” dendrimers terminated by Percec-type TEG dendrons  
 in order to introduce Au<sup>III</sup> inside the dendrimer by coordination  
 to the triazole rings, which adequately modulates the nucleation.  
 On the other hand, in the absence of external reductant, Au<sup>III</sup>-  
 triazole coordination slows down Au<sup>III</sup> reduction, because the  
 distal Percec-type dendron itself is the reductant. The semicav-  
 itand effect is then crucial, as shown by the failure of Au<sup>III</sup>  
 reduction using a “click” dendrimer terminated by a linear  
 tetraethylene glycol instead of a Percec-type TEG dendron.  
 DSAuNPs are formed with all the dendrimers from HAuCl<sub>4</sub> in  
 this way in the absence of additional reductant (23 to 42 nm-  
 size depending on the generation but not on presence of triazole  
 in the dendrimer structure). Finally, choosing the AuCl<sub>4</sub>/  
 dendrimer stoichiometry can orient the size of the AuNPs  
 formed in these processes. Mono-electronic reductants have also  
 been used for the first time for the reduction of HAuCl<sub>4</sub> to  
 AuNPs. Their outer-sphere reduction mechanism implies a much  
 slower reduction than with the inner-sphere reductant NaBH<sub>4</sub>,  
 and the size of the DSAuNP formed (between 7 and 38 nm) is  
 directly related to the standard oxidation potentials of the Fe<sup>I</sup>  
 and Fe<sup>II</sup> reductants. This provides the possibility to finely tune  
 the DSAuNP size.

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534 All these water-soluble dendrimer-stabilized PEGylated AuNPs  
535 are only weakly stabilized and thus should be very useful for  
536 catalytic (small size) and biomedical applications (large size).

## 537 Experimental Section

538 **1. Synthesis and Characterization of the Alkyne Dendron**  
539 **3 (see ESI).** A Percec-type dendron<sup>19</sup> containing a tris-(triethylene  
540 glycol) group (1 g, 1.57 mmol) and tetraethylene glycol (2.95 g,  
541 15.7 mmol) were introduced into a Schlenk flask, and dry THF  
542 (50 mL) was added. NaH (108 mg, 2.7 mmol) was added to the  
543 solution. The mixture was stirred for 12 h at 50 °C. At the end of  
544 the reaction, water was added, and then THF was removed under  
545 vacuum. The product was extracted with CH<sub>2</sub>Cl<sub>2</sub> and purified by  
546 chromatography (MeOH) giving 1 g of yellow oil (83% yield).

547 The tris-(triethylene glycol) tetraethylene glycol dendron (600  
548 mg, 0.65 mmol) and dry THF (50 mL) were introduced into a  
549 Schlenk flask, and NaH (47 mg, 1.95 mmol) was added at 0 °C.  
550 Propargyl bromide (155 mg, 1.3 mmol) was added to the solution,  
551 and the mixture was stirred for 2 h at 0 °C, then 2 h at 25 °C. At  
552 the end of the reaction, water was added, then THF and excess  
553 propargyl bromide were removed under vacuum. The product was  
554 extracted with CH<sub>2</sub>Cl<sub>2</sub>, yielding 600 mg of yellow oil (95% yield).  
555 <sup>1</sup>H NMR (CDCl<sub>3</sub>, 250 MHz): 6.39 (2H, CH-arom. extern), 4.26  
556 (2H, O-CH<sub>2</sub>-arom. extern), 3.98 (4H, CH<sub>2</sub>O-arom. extern and CH<sub>2</sub>-  
557 alkyne), 3.46 (30H, OCH<sub>2</sub>CH<sub>2</sub>O), 3.17 (9H, CH<sub>3</sub>O), 2.36 (1H,  
558 C-CH alkyne); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 62 MHz): 152.41 (Cq-O arom.),  
559 137.50 (Cq-CH<sub>2</sub> arom.), 133.63 (Cq-CH<sub>2</sub>-O), 106.87 (CH arom.),  
560 79.54 (Cq alkyne), 74.75 (CH alkyne), 70.46 (O-CH<sub>2</sub>), 58.74 (O-  
561 CH<sub>3</sub>), 58.13 (CH<sub>2</sub>-alkyne). Infrared  $\nu_{\text{alkyne}}$ : 2100 cm<sup>-1</sup>; MALDI  
562 TOF: Calcd for C<sub>39</sub>H<sub>68</sub>O<sub>17</sub>: 808; found: 831 (MNa<sup>+</sup>)

563 **2. General Procedure for the Synthesis of the "Clicked"**  
564 **PEG Dendrimers 4, 5 and 6.** The azido-terminated dendrimer (2  
565 for the synthesis of the dendrimer **5**, 1 equiv.) and the alkyne  
566 dendron **3** (1.5 equiv. *per* branch) were dissolved in THF. At 0 °C,  
567 CuSO<sub>4</sub> was added (2 equiv *per* branch, 1 M water solution),  
568 followed by the dropwise addition of a freshly prepared solution  
569 of sodium ascorbate (4 equiv *per* branch, 1 M water solution) in  
570 order to set a 1:1 (THF/water) ratio. The solution was allowed to  
571 stir for 12 h at 25 °C under N<sub>2</sub>. After removing THF under vacuum,  
572 CH<sub>2</sub>Cl<sub>2</sub> and an aqueous ammonia solution were added. The mixture  
573 was allowed to stir for 10 min to remove all the Cu<sup>II</sup> trapped inside  
574 the dendrimer as [Cu(NH<sub>3</sub>)<sub>6</sub>]<sup>2+</sup>. The organic phase was washed  
575 twice with water, dried with sodium sulfate, and the solvent was  
576 removed under vacuum. The product was precipitated with MeOH/  
577 ether in order to remove the excess dendron.<sup>19</sup> Yields: 96% (**4**);  
578 95% (**5**) and 92% (**6**). (See details in the ESI.)

579 Characterization of **4**: <sup>1</sup>H NMR (CDCl<sub>3</sub>, 250 MHz): 7.45 (9H,  
580 CH-triazole), 6.93 (36H, CH-arom. intern), 6.56 (18H, CH-arom.  
581 extern), 4.62 (18H, triazole-CH<sub>2</sub>-O), 4.43 (18H, O-CH<sub>2</sub>-arom.  
582 extern), 4.11 (72H, CH<sub>2</sub>O-arom. extern and Si-CH<sub>2</sub>-triazole), 3.64  
583 (414H, OCH<sub>2</sub>CH<sub>2</sub>O), 3.37 (27H, CH<sub>3</sub>O), 1.59 (18H, CH<sub>2</sub>-  
584 CH<sub>2</sub>CH<sub>2</sub>Si), 1.07 (18H, CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 0.60 (18H, CH<sub>2</sub>CH<sub>2</sub>-  
585 CH<sub>2</sub>Si), 0.006 (54H, Si(CH<sub>3</sub>)<sub>2</sub>); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 62 MHz): 151.62  
586 (CH, extern arom.), 144.48 (C<sub>q</sub> of triazole), 136.83 (Cq, arom. core),  
587 132.75 (Cq, arom. extern), 123.52 (CH of triazole and arom. core),  
588 106.23 (Cq-CH<sub>2</sub>O), 69.54 (OCH<sub>2</sub>CH<sub>2</sub>O), 63.53 (triazole-CH<sub>2</sub>-O),  
589 58.00 (CH<sub>3</sub>O), 53.38 (OCH<sub>2</sub>-arom. extern), 43.77 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si),  
590 42.7 (SiCH<sub>2</sub>-triazole), 40.93 (Cq-arom. intern), 17.82  
591 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 14.90 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), -4.84 (Si(CH<sub>3</sub>)<sub>2</sub>); DOSY:  
592  $D = 1.16 (\pm 0.1) \times 10^{-10}$  m<sup>2</sup>/s, Rh = 4.9 ( $\pm 0.1$ ) nm (D: diffusion  
593 coefficient; Rh: hydrodynamic radius); IR: no alkyne and azide  
594 bands; MALDI-TOF mass spectrum: Calcd for C<sub>414</sub>H<sub>741</sub>O<sub>153</sub>N<sub>27</sub>Si<sub>9</sub>:  
595 8798; found: 8824 (MNa<sup>+</sup>). Anal. Calcd for C<sub>414</sub>H<sub>741</sub>O<sub>153</sub>N<sub>27</sub>Si<sub>9</sub>: C  
596 56.52, H 8.49; found: C 56.31, H 8.49; light scattering: diameter  
597 = 9  $\pm$  0.8 nm.

598 **3. Synthesis and Characterization of the Phenol Dendron**  
599 **8 (see ESI).** The tris-(triethylene glycol) dendron (300 mg, 0.46  
600 mmol) and hydroquinone (251 mg, 2.28 mmol) were introduced

into a Schlenk flask, and dry DMF (30 mL) was added. K<sub>2</sub>CO<sub>3</sub>  
(315 mg, 2.28 mmol) was added to the solution. The mixture was  
stirred for 18 h at 80 °C under reflux. At the end of the reaction,  
DMF was removed. The product was extracted with CH<sub>2</sub>Cl<sub>2</sub>,  
washed with water, and purified by chromatography (CH<sub>2</sub>Cl<sub>2</sub>/  
MeOH, (97:3), 205 mg of a yellow oil was obtained (65% yield).  
<sup>1</sup>H RMN (CDCl<sub>3</sub>, 250 MHz): 3.35 (CH<sub>3</sub>O); 3.63 (CH<sub>2</sub>O); 4.11  
(CH<sub>2</sub>O arom.); 4.83 (OCH<sub>2</sub>arom.); 6.59 (CH arom.); 6.87 (CH  
arom.-OH); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 62 MHz): 152.82 (Cq-O-CH<sub>2</sub>),  
152.19 ((Cq-OH), 150.56 (Cq extern.-CH<sub>2</sub>-O), 137.87 (Cq middle-  
CH<sub>2</sub>-O), 132.83 (CH<sub>2</sub>-Cq), 116.17 (CH arom.-Cq-O), 107.19 (CH  
arom.-Cq-CH<sub>2</sub>), 71.93 (O-CH<sub>2</sub>-arom), 70.71 (O-CH<sub>2</sub>), 59.06 (O-  
CH<sub>3</sub>). MALDI TOF: Calcd for C<sub>34</sub>H<sub>54</sub>O<sub>14</sub>: 686.35; found: 709.34  
(MNa<sup>+</sup>). Anal. Calcd for C<sub>54</sub>H<sub>54</sub>O<sub>14</sub>: C 59.46, H 7.92; found: C  
59.21, H 8.18.

**4. General Procedure for the Synthesis of the Dendrimers**  
**9, 10, and 11 by the Williamson Reaction.** The iodo-terminated  
dendrimer<sup>20</sup> **7** ( $5.46 \times 10^{-6}$  mol) and the phenol dendron **8** (10  
equiv for G<sub>0</sub>, 30 equiv for G<sub>1</sub> and 90 equiv for G<sub>2</sub>) were introduced  
into a Schlenk flask, and dry DMF (30 mL) was added, then K<sub>2</sub>CO<sub>3</sub>  
(2 equiv *per* dendron) was added to the solution. The mixture was  
stirred for 2 days at 80 °C under reflux. At the end of the reaction,  
DMF was removed. The product was extracted with CH<sub>2</sub>Cl<sub>2</sub> and  
washed with water. G<sub>0</sub> and G<sub>1</sub> were purified by chromatography  
(CH<sub>2</sub>Cl<sub>2</sub>:MeOH, (97:3) to remove the excess dendron and then (90:  
10) to extract the dendrimer). G<sub>2</sub>dHQ was precipitated with MeOH/  
ether in order to remove the excess dendron. The yields were 80%  
for **9** (G<sub>0</sub>), 78% for **10** (G<sub>1</sub>) and 85% for **11** (G<sub>2</sub>).

Characterization of the dendrimer **9**: <sup>1</sup>H NMR (CDCl<sub>3</sub>, 250  
MHz): 6.92 (CH-arom. core), 6.87 (CH-arom. intern), 6.65 (CH-  
arom. extern), 4.85 (O-CH<sub>2</sub>-arom. extern), 4.16 (CH<sub>2</sub>O-arom.  
extern), 3.65 (OCH<sub>2</sub>CH<sub>2</sub>O and Si-CH<sub>2</sub>O), 3.38 (CH<sub>3</sub>O), 1.69  
(CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 1.12 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 0.62 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 0.06  
(Si(CH<sub>3</sub>)<sub>2</sub>); <sup>13</sup>C NMR (CDCl<sub>3</sub>, 62 MHz): 156.09 (O-Cq intern),  
152.61 (Cq intern), 144.71 (Cq arom. Core), 137.97 (Cq-Cq intern),  
130.95 (CH arom. extern), 118.55 (CH arom. core), 115.61 (CH-  
arom intern), 114.79 (CH arom extern), 107.07 (CH arom intern),  
72.3 (OCH<sub>2</sub>CH<sub>2</sub>), 70.80 (OCH<sub>2</sub> arom extern), 68.85 (SiCH<sub>2</sub>O),  
59.05 (CH<sub>3</sub>O), 43.77 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 17.82 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si),  
14.49 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), -4.58 (Si(CH<sub>3</sub>)<sub>2</sub>). MALDI TOF: Calc. for  
C<sub>369</sub>H<sub>606</sub>O<sub>126</sub>Si<sub>9</sub>: 7311.54; found: 7334.47 (MNa<sup>+</sup>); DOSY:  $D =$   
1.47 ( $\pm 0.1$ )  $\times 10^{-10}$  m<sup>2</sup>/s, Rh = 3.9 ( $\pm 0.3$ ) nm (D: diffusion  
coefficient; Rh: hydrodynamic radius); SEC: polydispersity = 1.05.  
Anal. Calcd for C<sub>369</sub>H<sub>606</sub>O<sub>126</sub>Si<sub>9</sub>: C 60.62, H 8.35; found: C 59.64,  
H 8.57.

**5. Synthesis and Characterization of the Dendrimer 16.** The  
27 azido-terminated dendrimer precursor of **5** and **16** (see structure  
in ESI)<sup>11a,12a</sup> (0.2 g, 0.032 mmol) and tetraethylene glycol methyl  
propargyl ether (0.319 g, 1.296 mmol, 1.5 equiv *per* branch) were  
dissolved in 50 mL of THF. At 0 °C, CuSO<sub>4</sub> was added (0.431 g,  
1.728 mmol, 2 equiv *per* branch, 1 M water solution), followed by  
dropwise addition of a freshly prepared solution of sodium ascorbate  
(0.685 g, 3.456 mmol, 4 equiv. *per* branch, 1 M water solution) in  
order to set a 1:1 (THF/water) ratio. The solution was allowed to  
stir for 12 h at 25 °C under N<sub>2</sub>. After removing THF under vacuum,  
CH<sub>2</sub>Cl<sub>2</sub> and an aqueous ammonia solution (28% w/w) were added.  
The mixture was allowed to stir for 10 min in order to remove all  
the Cu<sup>II</sup> trapped inside the dendrimer as [Cu(NH<sub>3</sub>)<sub>6</sub>]<sup>2+</sup>. The organic  
phase was washed twice with water, dried with sodium sulfate,  
and the solvent was removed under vacuum. The product was  
precipitated with MeOH/ether to remove the excess of tetraethylene  
glycol methyl propargyl ether; 0.336 g of **16** was obtained (81%  
yield). <sup>1</sup>H NMR (CDCl<sub>3</sub>, 250 MHz): 7.40 (27H, CH-triazole), 7.08  
(18H, CH-arom. extern.), 7.02 (3H, CH-arom. intern.), 4.61 (54H,  
triazole-CH<sub>2</sub>-O), 3.81 (18H, CH<sub>2</sub>O-arom.), 3.49-3.62 (432H,  
OCH<sub>2</sub>CH<sub>2</sub>O), 3.33 (81H, CH<sub>3</sub>O), 1.55 (72H, CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 1.04  
(72H, CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 0.55 (72H, CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 0.06 (54H,  
O-CH<sub>2</sub>Si(CH<sub>3</sub>)<sub>2</sub>), 0.007 (162H, triazole-CH<sub>2</sub>Si(CH<sub>3</sub>)<sub>2</sub>). <sup>13</sup>C NMR  
(CDCl<sub>3</sub>, 62 MHz): 158.96 (Cq of O-arom.), 144.53 (Cq of triazole),

670 138.61 (Cq, arom. core) 126.94 (CH-arom.) 123.26 (CH of triazole  
671 and arom. core), 113.36 (CH-arom.), 70.33 (OCH<sub>2</sub>CH<sub>2</sub>O), 69.39  
672 (Si-CH<sub>2</sub>-O), 64.51 (triazole-CH<sub>2</sub>-O), 58.87 (CH<sub>3</sub>O), 42.28  
673 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 41.7 (SiCH<sub>2</sub>-triazole), 40.7 (Cq-arom. inter.),  
674 17.26 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), 14.64 (CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>Si), -4.09 (Si(CH<sub>3</sub>)<sub>2</sub>).  
675 IR: no alkyne and azide bands. MALDI TOF: Calcd for C<sub>612</sub>H<sub>1187</sub>  
676 O<sub>144</sub>N<sub>81</sub>Si<sub>36</sub>: 12946.297; found: 12971, major peak (calcd: 12969:  
677 MNa<sup>+</sup>). Anal. Calcd for C<sub>612</sub>H<sub>1187</sub> O<sub>144</sub>N<sub>81</sub>Si<sub>36</sub>: C 56.78, H 8.85;  
678 found: C 55.68, H 8.46.

679 **6. General Procedure for AuNPs Reduction in Methanol**  
680 **with Dendrimers 4, 5 and 6.** The following procedure is described  
681 using the preparation of the dendrimer **4**: 1 mL of a  $1.14 \times 10^{-4}$   
682 M solution of dendrimer (1 mg,  $1.14 \times 10^{-4}$  mmol) in MeOH was  
683 introduced into a Schlenk flask under nitrogen, then 0.349 mL of  
684 a  $2.94 \times 10^{-3}$  M solution of HAuCl<sub>4</sub> (0.349 mg,  $1.03 \times 10^{-3}$  mmol,  
685 1 equiv per triazole) and 4.65 mL of MeOH was added in order to  
686 obtain a solution  $2.21 \times 10^{-4}$  M (in Au). The solution was stirred  
687 for 1 h, the reductant NaBH<sub>4</sub> (0.39 mg), [Fe<sup>4</sup>Cp( $\eta^6$ -C<sub>6</sub>Me<sub>6</sub>)] (4.4  
688 mg), ferrocene (1.92 mg), ethynylferrocene (2.16 mg) or decam-  
689 ethylferrocene (3.36 mg)] was added ( $1.03 \times 10^{-2}$  mmol, 10 equiv  
690 per Au), and the yellow solution turned to golden brown indicating  
691 the formation of the AuNPs.

692 **7. General Procedure for the Preparation of AuNPs in**  
693 **Water without Reductant.** The following procedure is described  
694 using the preparation of the dendrimer **9**: 1 mL of a  $1.37 \times 10^{-4}$  M  
695 solution of dendrimer (1 mg,  $1.37 \times 10^{-4}$  mmol) in H<sub>2</sub>O was placed  
696 into a Schlenk flask under ambient condition, then 0.416 mL of a  
697  $1.23 \times 10^{-3}$  M solution of HAuCl<sub>4</sub> (0.416 mg,  $1.23 \times 10^{-3}$  mmol,  
698 1 equiv per tether). 1.584 mL of H<sub>2</sub>O was added in order to obtain  
699 a final volume of 3 mL. The solution was stirred, and the yellow  
700 solution turned to pink then red, indicating the formation of the  
701 AuNPs.

**8. Transmission Electron Microscopy (TEM and HRTEM).** The  
702 samples were prepared by placing a drop of  $1.6 \times 10^{-4}$  M solution  
703 of AuNPs (concentration in mol Au) on a holey-carbon-coated Cu  
704 TEM grid and they were then analyzed with a JEOL JEM 1011  
705 machine.  
706

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714

**Note Added after ASAP Publication.** The version published  
715 ASAP on February 4, 2010, had incorrect labeling of Figures 10  
716 and 11. The corrected version will publish with the issue on March  
717 3, 2010.  
718

**Supporting Information Available:** Details of the syntheses,  
719 characterizations, <sup>1</sup>H and <sup>13</sup>C spectra for all the new dendrons  
720 and dendrimers, size-exclusion chromatograms of the dendrimers  
721 **9–11**, determination of the diffusion coefficient of the den-  
722 drimers by DOSY NMR, transmission electron microscopy of  
723 the DEAuNPs and DSAuNPs, and UV–vis spectra of HAuCl<sub>4</sub>,  
724 complexation by dendrimer **4**, and reduction to AuNPs by  
725 NaBH<sub>4</sub>. This material is available free of charge via the Internet  
726 at <http://pubs.acs.org>.  
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