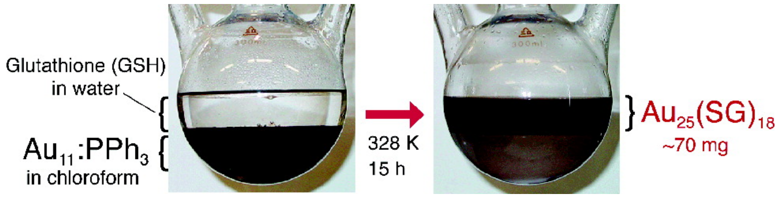
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Communication

Large-Scale Synthesis of Thiolated Au Clusters via Ligand Exchange Reactions of Phosphine-Stabilized Au Clusters

Yukatsu Shichibu, Yuichi Negishi, Tatsuya Tsukuda, and Toshiharu Teranishi

J. Am. Chem. Soc., **2005**, 127 (39), 13464-13465• DOI: 10.1021/ja053915s • Publication Date (Web): 08 September 2005



Journal of the American Chemical Society is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036

J|A|C|S
COMMUNICATIONS

Large-Scale Synthesis of Thiolated Au_{25} Clusters via Ligand Exchange Reactions of Phosphine-Stabilized Au_{11} Clusters

Yukatsu Shichibu,[†] Yuichi Negishi,[‡] Tatsuya Tsukuda,*[,‡] and Toshiharu Teranishi*[,§]

School of Materials Science, Japan Advanced Institute of Science and Technology, 1-1 Asahidai, Nomi, Ishikawa 923-1292, Japan, Research Center for Molecular-Scale Nanoscience, Institute for Molecular Science, Myodaiji, Okazaki 444-8585, Japan, and Graduate School of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan

Received June 14, 2005; E-mail: tsukuda@ims.ac.jp; teranisi@chem.tsukuba.ac.jp

Subnanometer-sized gold clusters protected by thiolates, which we refer to as *thiolated gold clusters*,[1] exhibit unique physicochemical properties arising from a small core size and heavy ligation by the thiolates.[1−7] Synthesis of thiolated gold clusters with well-defined chemical composition is crucial for fundamental studies and applications. Recently, we demonstrated that a series of thiolated gold clusters with well-defined compositions could be synthesized by utilizing polyacrylamide gel electrophoresis (PAGE) and electrospray ionization (ESI) mass spectrometry.[1] The clusters we isolated included $Au_{10}(SG)_{10}$, $Au_{15}(SG)_{13}$, $Au_{18}(SG)_{14}$, $Au_{22}(SG)_{16}$, $Au_{22}(SG)_{17}$, $Au_{25}(SG)_{18}$, $Au_{29}(SG)_{20}$, $Au_{33}(SG)_{22}$, and $Au_{39}(SG)_{24}$, where GSH represents glutathione (γ-Glu-Cys-Gly).[1] Although this approach provides a versatile method of synthesizing thiolated gold clusters, a major drawback is the small yields obtained; typically, only a few milligrams of the purified clusters are obtained after elaborate and time-consuming workup procedures. An alternative synthetic method is to utilize the ligand exchange reactions developed by Hutchison, where the phosphine ligands of undecagold Au_{11} clusters are replaced by thiolates without change in the core size.[4,5] In the present study, we show that the cluster size increases during the ligand exchange reaction of $Au_{11}(PPh_3)_8Cl_3$ by GSH and that thermodynamically stable $Au_{25}(SG)_{18}$ can be selectively obtained on the sub-100 mg scale under controlled conditions.

Phosphine-stabilized gold clusters (**1**) were prepared by reduction of $AuCl(PPh_3)$ in ethanol by $NaBH_4$ under N_2 atmosphere.[4,8] The subnanometer gold clusters are barely discernible in the TEM image of **1**.[9] The optical absorption spectrum of **1** is similar to those of undecagold purchased from Nanoprobe Inc. (Figure 1) and $Au_{11}(PPh_3)_8Cl_3$ reported in the literature,[4] indicating that the Au_{11} clusters are the main ingredients of sample **1**. Indeed, the ESI mass spectrum of **1** exhibited peaks of $[Au_{11}(PPh_3)_8Cl_2]^+$ and $[Au_{11}(PPh_3)_8Cl]^{2+}$.[9] The mass peaks of Au_9- and Au_{10}-based clusters were concomitantly observed in the mass spectrum, suggesting the smaller clusters are contained as an impurity of **1**. We found that $Au_{11}(PPh_3)_8Cl_3$ isolated from **1** yielded the same ligand exchange products as sample **1**. Thus, as-prepared clusters **1** were used as the precursors in the present work.

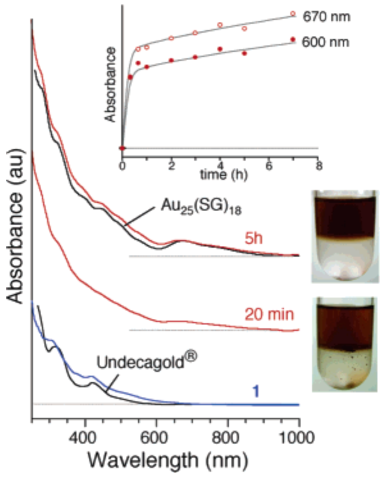


Figure 1. Optical absorption spectra of **1** in chloroform (blue) and the clusters transferred into the aqueous phase (red) at 328 K and $[GSH]/[\mathbf{1}] = 400$. The spectra of undecagold and $Au_{25}(SG)_{18}$ (taken from ref 1) are shown in black for comparison. Inset shows the time course of the ODs at 600 and 670 nm of the aqueous phase.

The ligand exchange reaction was conducted as follows. To the top of a chloroform solution (7 mL) containing 4.7 mg of **1** was added an aqueous solution (7 mL) of GSH under vigorous stirring. Both solutions were deaerated by freeze−pump−thaw cycles prior to mixing. The reaction was performed under a N_2 atmosphere to avoid the possibility of GSH oxidation into the corresponding sulfonate or disulfide. The aqueous phase was monitored as a function of reaction time by optical spectroscopy, which is a sensitive and convenient probe for estimating the quantity and composition of the Au:SG clusters produced.[1] The red curves in Figure 1 represent the spectra of the aqueous phase at 328 K and for $[GSH]/[\mathbf{1}] = 400$. Under these conditions, the brownish color of the organic phase was almost completely transferred to the aqueous phase within 20 min, with concurrent formation of dark-brown floccules at the biphasic interface (Figure 1). From this point, the optical density (OD) of the aqueous phase continued to increase gradually without any noticeable change in the profile. In parallel with this, the floccules decreased in quantity and were scarcely visible after 5 h. The optical spectrum of the resulting Au:SG clusters exhibits some notable features: the absorption onset is red-shifted significantly as compared with that of **1** and a hump appears at 670 nm. These features are characteristic of the spectrum of $Au_{25}(SG)_{18}$, which has been identified as one of the major products in the chemical reduction of Au(I):SG species.[1] However, close comparison reveals that the OD of the Au:SG clusters is larger than that of the $Au_{25}(SG)_{18}$ clusters in the region of <600 nm (Figure 1). This difference implies that, as well as the Au_{25}:SG clusters, smaller Au_n:SG clusters are formed during the phase transfer. Similar spectra were always observed under the experimental conditions we employed (308−328 K, $[GSH]/[\mathbf{1}] = 60-400$).[9] On the basis of these optical measurements, we conclude that phosphine-stabilized undecagold (**1**) undergoes aggregation during the reaction with GSH. This conclusion is further confirmed by product analysis using ESI-MS and PAGE as described below.

[†] Japan Advanced Institute of Science and Technology.
[‡] Institute for Molecular Science.
[§] University of Tsukuba.

10.1021/ja053915s CCC: $30.25

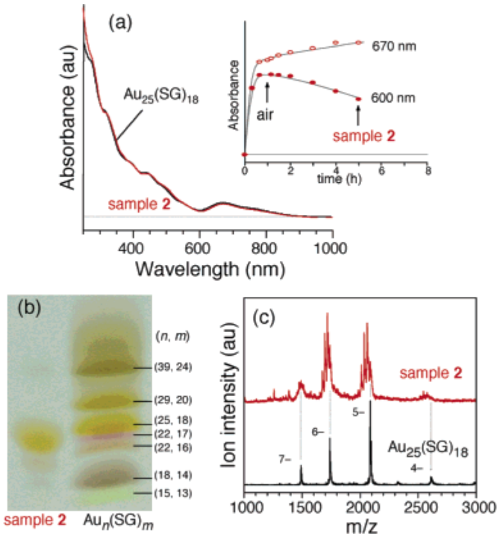


Figure 2. (a) Optical absorption spectra of **2** (red) and $\mathrm{Au_{25}(SG)_{18}}$ (black). Inset shows the time evolution of the ODs at 600 and 670 nm under aerobic condition. (b) PAGE result and (c) ESI mass spectra of **2** and $\mathrm{Au_{25}(SG)_{18}}$. The progression of the mass peaks in the spectrum of sample **2** is due to the partial hydrolysis of the GS ligands.[9]

This finding is in sharp contrast to previous reports,[4,5] in which the undecagold core was thought to be preserved during the reaction on the basis of the TEM measurements. In support of our result, Murray et al. have recently demonstrated by mass spectrometry that reaction of $\mathrm{Au_{55}(PPh_3)_{12}Cl_6}$ with hexanethiol yields $\mathrm{Au_{75}}$ clusters.[11]

Hutchison et al. have studied a mechanism for the ligand exchange reactions of 1.5 nm Au:$\mathrm{PPh_3}$ nanoparticles with RSH.[10] The mechanism they proposed includes (i) "rapid" replacement of the Au(I)Cl($\mathrm{PPh_3}$) moieties by RS ligands, (ii) subsequent "slow" removal of the remaining $\mathrm{PPh_3}$ ligands, and finally (iii) completion of the RS shells. This mechanism is probably oversimplified as the authors have noted, but explains well the formation of floccules at the initial stage of reaction: the rapid replacement of Au(I)Cl($\mathrm{PPh_3}$) of **1** by GS results in the formation of gold clusters with mixed ligand shells, which are soluble neither in water nor in chloroform. To understand how the core size increases during the reaction, the clusters in the floccules were examined by TEM.[9] Surprisingly, the average core size was 1.5 nm, which was further supported by the diffuse reflectance spectrum.[9] Within the framework of the model by Hutchison, these results imply that the core size increases in step (i) and decreases in the subsequent steps. Thus, the memory of the core size of precursor **1** is lost during the exchange process, and Au:SG clusters with large kinetic and/or thermodynamic stabilities are obtained.

The spectral profile in the aqueous phase did not change appreciably during the reaction at 328 K under $\mathrm{N_2}$ (see the inset of Figure 1). This indicates that the size distribution of the Au:SG clusters remains the same, which is in contrast with the size reduction that occurs in the heat treatment of Au:$\mathrm{SC_{12}H_{25}}$ clusters (~6 nm) in octyl ether at 300 °C[7] and Au:$\mathrm{SC_6H_{13}}$ clusters in neat dodecanethiol at 70 °C.[12] However, we found that aeration of the biphasic system induces a change in the spectral profile. The inset of Figure 2a shows the time course of OD at 600 and 670 nm for the aqueous phase after aeration. As can be seen, the OD at 600 nm starts to decrease, and eventually, the optical spectrum of the aqueous phase after 4 h aeration (sample **2**) coincides almost completely with that of $\mathrm{Au_{25}(SG)_{18}}$. This result suggests that populations of Au:SG clusters smaller than $\mathrm{Au_{25}}$ are preferentially decreased in aerobic conditions. Although the mechanism is not clear at present, we speculate that removal of the Au species (probably in the form of Au(I)−thiolate)[13] preferentially from the smaller clusters plays a role in the cluster distribution narrowing to give mainly $\mathrm{Au_{25}(SG)_{18}}$. Selective formation of $\mathrm{Au_{25}(SG)_{18}}$ clusters in sample **2** was further confirmed by PAGE and ESI-MS (Figure 2b,c).[14] Preliminary optical measurements suggest that the $\mathrm{Au_{25}}$ clusters are also formed in the reactions of **1** with other thiols, such as (*N*,*N*-dimethylamino)ethanethiol hydrochloride, 3-mercaptobenzoic acid, sodium 3-mercapto-1-propanesulfonate, and 16-mercaptohexadecanoic acid.[9,15]

Finally, the scale of the reaction was enlarged by a factor of ~14 in order to confirm that the protocol reported here is practical for the large-scale synthesis of thiolated $\mathrm{Au_{25}}$ clusters. After removal of the free GSH and byproducts, we obtained ~70 mg of $\mathrm{Au_{25}(SG)_{18}}$ in a pure form. This yield is about 50 times larger than that typically obtained by PAGE fractionation of the as-prepared Au:SG clusters using a single gel (3t × 160 × 160 mm).[1]

To summarize, we have demonstrated that phosphine-stabilized $\mathrm{Au_{11}}$ clusters undergo aggregation and dissociation in reaction with a water-soluble thiol, GSH. Under optimized conditions, $\mathrm{Au_{25}(SG)_{18}}$ clusters are selectively formed, reflecting their extraordinarily high stability. The large-scale synthesis of thiolated $\mathrm{Au_{25}}$ clusters by the ligand exchange strategy will enable us to promote a deep understanding of their basic properties via multiple experimental approaches and open up possibilities for various applications.

Acknowledgment. The present work was financially supported by Grants-in-Aid for Scientific Research (Nos. 16510079 and 15681009) and the "Nanotechnology Support Project" of MEXT, Japan, and also by the Industrial Technology Research Grant Program in 2004 from NEDO of Japan. We thank Prof. Nishi for measurement of the diffuse reflectance spectrum of the floccules.

Supporting Information Available: Details of experimental procedures and characterizations (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Negishi, Y.; Nobusada, K.; Tsukuda, T. *J. Am. Chem. Soc.* **2005**, *127*, 5261.
(2) (a) Schaaff, T. G.; Knight, G.; Shafigullin, M. N.; Borkman, R. F.; Whetten, R. L. *J. Phys. Chem. B* **1998**, *102*, 10643. (b) Schaaff, T. G.; Whetten, R. L. *J. Phys. Chem. B* **2000**, *104*, 2630. (c) Link, S.; Beeby, A.; Fitzgerald, S.; El-Sayed, M. A.; Schaaff, T. G.; Whetten, R. L. *J. Phys. Chem. B* **2002**, *106*, 3410. (d) Link, S.; El-Sayed, M. A.; Schaaff, T. G.; Whetten, R. L. *Chem. Phys. Lett.* **2002**, *356*, 240.
(3) (a) Donkers, R. L.; Lee, D.; Murray, R. W. *Langmuir* **2004**, *20*, 1945. (b) Jimenez, V. L.; Georganopoulou, D. G.; White, R. J.; Harper, A. S.; Mills, A. J.; Lee, D.; Murray, R. W. *Langmuir* **2004**, *20*, 6864. (c) Lee, D.; Donkers, R. L.; Wang, G.; Harper, A. S.; Murray, R. W. *J. Am. Chem. Soc.* **2004**, *126*, 6193.
(4) Woehrle, G. H.; Warner, M. G.; Hutchison, J. E. *J. Phys. Chem. B* **2002**, *106*, 9979.
(5) (a) Yang, Y.; Chen, S. *Nano Lett.* **2003**, *3*, 75. (b) Grant, C. D.; Schwartzberg, A. M.; Yang, Y.; Chen, S.; Zhang, J. Z. *Chem. Phys. Lett.* **2004**, *383*, 31.
(6) (a) Negishi, Y.; Tsukuda, T. *J. Am. Chem. Soc.* **2003**, *125*, 4063. (b) Negishi, Y.; Tsukuda, T. *Chem. Phys. Lett.* **2004**, *383*, 161. (c) Negishi, Y.; Takasugi, Y.; Sato, S.; Yao, H.; Kimura, K.; Tsukuda, T. *J. Am. Chem. Soc.* **2004**, *126*, 6518.
(7) Jin, R.; Egusa, S.; Scherer, N. F. *J. Am. Chem. Soc.* **2004**, *126*, 9900.
(8) Bartlett, P. A.; Bauer, B.; Singer, S. J. *J. Am. Chem. Soc.* **1978**, *100*, 5085.
(9) See Supporting Information.
(10) Woehrle, G. H.; Brown, L. O.; Hutchison, J. E. *J. Am. Chem. Soc.* **2005**, *127*, 2172.
(11) Balasubramanian, R.; Guo, R.; Mills, A. J.; Murray, R. W. *J. Am. Chem. Soc.* **2005**, *127*, 8126.
(12) Schaaff, T. G.; Whetten, R. L. *J. Phys. Chem. B* **1999**, *103*, 9394.
(13) Song, Y.; Huang, T.; Murray, R. W. *J. Am. Chem. Soc.* **2003**, *125*, 11694.
(14) The content of the $\mathrm{Au_{25}(SG)_{18}}$ clusters in sample **2** is estimated to be ~85 mol % on the basis the ODs (ref 1).
(15) Some of the optical spectra assigned to thiolated $\mathrm{Au_{11}}$ clusters (ref 5) and $\mathrm{Au_{38}}$ clusters (ref 3c) exhibit features similar to that of $\mathrm{Au_{25}(SG)_{18}}$ (ref 1).

JA053915S