Chiang Mai J. Sci. 2016; 43(4) : 825-833
http://epg.science.cmu.ac.th/ejournal/
Contributed Paper

Catalytic Oxidation of Glucose with Hydrogen Peroxide and Colloidal Gold as Pseudo-Homogenous Catalyst: A Combined Experimental and Theoretical Investigation

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Received: 10 July 2013
Accepted: 25 April 2014

ABSTRACT

Gold nanoparticles have been proved to act as oxidation catalyst for glucose oxidation, offering a "chemical" synthetic route to gluconic acid and gluconates - nowadays commercially produced by an enzyme catalyzed oxidation. Our investigations of the gold catalyzed oxidation route showed that gold nanoparticles produced by a modified Turkevich method have a high activity for this pseudo-homogenous catalytic reaction. Under mild reaction conditions, glucose could be oxidized in good yields (~70%) and the resulting gluconate could be isolated by column chromatography and precipitation as calcium salt. The catalytic oxidation reaction was found to follow the first-order kinetic with a rate constant of 4.95 h^{-1}, in good agreement with previous finding. The underlying reaction mechanism is discussed, assuming that the formation of a gold-glucose cluster intermediate is a key catalytic step. Several structures of the gold-glucose intermediates were examined using density functional theory methods. The molecular behavior of glucose adsorption in gold colloid solution is present.

Keywords: colloidal gold catalyst, glucose oxidation, gold nanoparticle, gluconic acid, DFT

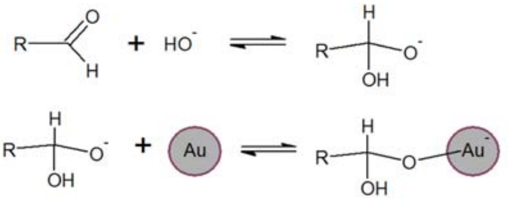
1. INTRODUCTION

Gold nanoparticles (Au NPs) as highly effective green catalysts for oxidative processes have become a research topic of wide-spread interest in recent years [1-5], representing a bridge between homogeneous and heterogeneous catalysis. Au NPs are among the most popular metal nanoparticles due to their stability and fascinating properties. They have applications in very important fields such as catalysis and medicine [5,3,6].

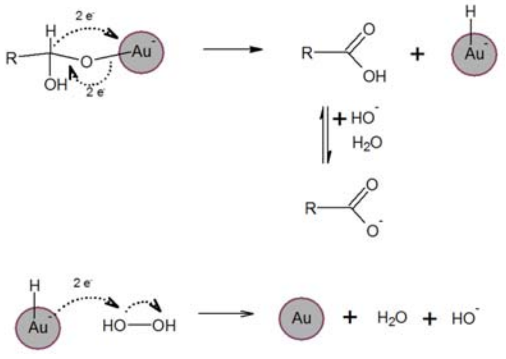
Catalysis by Au NPs has been emerged by the discovery of gold nanoparticles as highly active supported catalysts for oxidation of CO into CO_2 by atmospheric air [7]. Since then, much effort has been tried to understand the catalytic activity of Au NPs [8-10]. With high potency of Au NPs, they have attracted many industries utilizing metal-catalyzed chemical processes. Among those reactions, the gold-catalyzed oxidation of glucose to gluconic acid by Au NPs has received much attention in recent years [11-14,10,15]. In addition, the glucose-gluconic acid oxidation reaction have shown to be a promising “chemical” synthetic route to sodium gluconate [14], which is commercially produced by a fermentation process [16], making a catalytic chemical reaction of high industrial interest. The product gluconic acid is an important compound with cation complexing abilities and is used as additive with many applications in the pharmaceutical, food and detergent industry as mild, non-toxic acid [16].

The glucose oxidation can be efficiently catalyzed by using supported and unsupported Au NPs. The carbon-supported gold catalysts have been widely used for the liquid-phase oxidation of glucose due to their high activity compared to conventional catalysts. Biella et al. [15] firstly used the carbon-supported Au NPs as catalysts for aerobic oxidation of D-glucose, exhibiting a much higher activity than the conventional platinum and paladium based catalysts. Further work by Önal et al. [14] found that D-glucose oxidation to D-gluconic acid over Au/C catalysts is structure sensitive. The kinetics of glucose oxidation to gluconic acid with Au/Al_2O_3 catalyst has also been reported by Prüβe and co-workers [11] with a modified oxidative dehydrogenated mechanism proposed. Despite the rare use of unsupported colloidal gold catalyst compared to those supported catalysts, it was found that catalysis by colloidal gold showed a surprisingly high activity in the aerobic oxidation of glucose, comparable with the supported Au/C catalyst and an enzymatic system [10,13]. Presently, unsupported Au NPs as catalyst for glucose oxidation with hydrogen peroxide have been examined yet only by Comotti et al. [12], showing good results in terms of reaction time and yield.

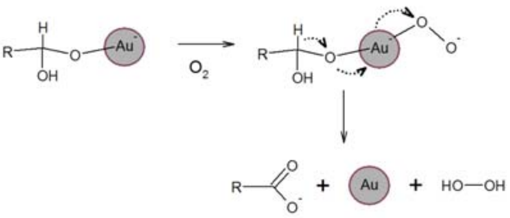
The reaction mechanism for the glucose oxidation with Au NPs catalysts has been proposed recently [11]. The first reaction step is the formation of the Au-glucose intermediate, which is initiated by the nucleophilic attack of a hydroxide ion on glucose followed by adsorption of the resulting alkoxy group to a gold particle. As a result, the relative high electro-negativity of gold is generated (Scheme 1). The oxidation step could occur via either gold hydride anion [11] or peroxygen [12] depending on the present of oxygen. In hydride anion pathway, the oxidation proceeds by transferring the carbon-bound hydrogen together with two electrons to the gold particle, releasing the gluconate anion. Subsequently, the transferred hydrogen could be transferred to hydrogen peroxide as hydride anion, reducing it to water and hydroxyl (Scheme 2). In peroxygen pathway, the addition of oxygen (from the decomposition of hydrogen peroxide) to the Au-glucose adduct was proposed (Scheme 3). It is interesting to note that both pathways share common specie of Au-glucose intermediate, which is thought to be critical during catalysis [11,12]. At present, no structural information of the key intermediate has been reported and, thus, the complete understanding for the glucose oxidation mechanism is limited.



Scheme 1. The formation of the Au-glucose intermediate



Scheme 2. The decomposition of the Au-glucose intermediate via hydride anion if the oxygen is absent



Scheme 3. The decomposition of the Au-glucose intermediate via peroxygen if the oxygen is present

In this study, the conditions for a high-yield oxidation of glucose by hydrogen peroxide using unsupported Au NPs were examined, together with a theoretical model to explain the structure of the key Au-glucose intermediate as well as its molecular behavior of glucose adsorption in gold colloid solution. Our study indicates that, even in very low concentration (about 30 ppm), gold colloid is an effective catalyst for the oxidation of glucose to gluconate salts with hydrogen peroxide under mild, alkaline conditions. The underlying mechanism for the glucose absorption on gold nanoparticle is also discussed.

2. MATERIALS AND METHODS

2.1 Chemicals and Equipment

D(+)-glucose monohydrate (for biochemical use), sodium hydroxide p.a. grade (Aldrich), hydrochloric acid conc. (Aldrich), silica gel for chromatography (Aldrich) and hydrogen peroxide solution 50% (commercial grade) was used. As gold precursor, gold leaves of 96.5% purity ("Thai gold") were used. For the recording of the VIS spectra, a Jasco V-530 UV/VIS spectrometer was used.

2.2 Preparation of the Nano Gold Catalyst

A small gold leave (weight 3 mg) was dissolved in ca. 0.5 ml conc. HCl and 0.5 ml hydrogen peroxide (50%) by gentle heating in a test tube. The resulting clear yellow solution was evaporated to dryness in a water bath to eliminate all traces of HCl. The residue was dissolved in 5 ml of distilled water. In an Erlenmeyer, 100 ml distilled water with 5 ml 1% trisodium citrate solution was heated to boiling under magnetic stirring. Compared to the classical Turkevich method [18,19], a higher water volume showed to produce smaller nanoparticles with better reproducibility. The above solution of chloroauric acid was added quickly under vigorous stirring. After 10 minutes of boiling and stirring, the solution was allowed to cool to room temperature and a VIS-spectrum was taken to confirm the particle size of the gold nanoparticles. The reaction mixture was used as catalyst without further treatment.

2.3 Oxidation of Glucose

1.8g (10 mmol) of glucose and 2 ml (26 mmol) of hydrogen peroxide (50%) was added to the nano gold suspension and the mixture was heated under stirring to 50°C. With the use of a pH meter, the pH was continually adjusted to 9 by drop wise addition of 0.2M NaOH. The progress of the reaction:

$$\text{R-C(=O)H} + H_2O_2 + OH^- \rightarrow \text{R-C(=O)}O^- + 2\,H_2O$$

could be estimated by the amount of sodium hydroxide - to obtain 100 % yield, a total of 50 ml is required (10 mmol hydroxide).

2.4 Isolation of the Product

In order to separate the product (sodium gluconate) from remaining glucose and catalyst, the reaction mixture was concentrated to about 20 ml by rotation evaporation. A column with diameter of 3-4 cm was filled with slurry of silica gel in iso-propanol (about 50 ml). The reaction mixture was passed slowly through the column using iso-propanol as solvent. The out-coming fractions were tested for product by TLC (using iso-propanol/water 4:1). The product containing fractions showed an oily layer which is supposed to be sodium gluconate dissolved in iso-propanol. This gel-like product could not be crystallized, so it was transferred to the calcium salt: the product fractions were evaporated to dryness resulting in a light brown gel, which was dissolved in about 10 ml distilled water. About 1 g of calcium chloride was added forming a clear solution. Slow addition of iso-propanol resulted in a white precipitate, which could be filtrated to give 1.6 g of calcium-gluconate (3.65 mmol), corresponding to 73% yield.

3. THEORETICAL

Previous studies [20-24] have shown that the DFT calculations are quite useful for understanding the adsorption orientation of a molecule on a metal nanoparticle at molecular level. Here, two models of glucose (Glc) and glucose substituted with hydroxide from metal alkaline (GlcOH) absorbed on the gold atom were chosen to represent the formation of key gold-glucose intermediate. Two orientations of the glucose were considered in which an aldehyde or a C6-OH end-group of glucose is preferred to adsorb with the gold atom. A total of four models were thus modeled in this study. The D-glucose isomer was considered in the models. A single Au atom was used as a representative surface of gold nanoparticle. Despite the gold model used is very simple, it has also been applied in several literatures [21-23], which is enough for the purpose of the present study. All system structures were fully optimized using the Density Functional Theory (DFT) method with the Becke three parameter hybrids functional with Lee-Yan-Parr correlation function (B3LYP) level of theory. An effective core potential basis set LANL2DZ (Los Alamos set of double-zeta) [25] was used for a description of Au atom. The energetic of the adsorption process were calculated at the same level as geometry optimization using following equation:

$$E_{ads} = E_{complex} - E_{glucose} - E_{Au}$$

where $E_{complex}$, $E_{glucose}$ and E_{Au} are the total ground state (electronic) energies of the Au–glucose complex, the isolated glucose (Glc or GlcOH) and the isolated Au, respectively. The more negative the adsorption energy, the stronger the adsorption. All calculations were performed using Gaussian09 program [26].

4. RESULTS AND DISCUSSION

4.1 Characterizations of Gold Nanoparticle Size, Optimum pH and Temperature for the Reaction and the Gluconate Product

Figure 1 shows the VIS spectrum of the gold NP suspension after preparation with sodium citrate and after the completion of reaction with glucose and hydrogen peroxide at pH 9. It is clearly shown that addition of glucose significantly changes in both color of the gold suspension and the spectrum. The color of the suspension changed during one hour from wine-red to dark-blue (data not shown) and a part of the particles agglomerated giving rise to a second mai peak around 600 nm, as would be expected in an alkaline solution with sodium anions [27]. Haiss et al. [28] have demonstrated that there is a good correlation between the medium particle size of gold NP and the wavelength of the absorption maximum in visible light. According to them, the particle size can be estimated using the formula: $d \sim \ln[(\lambda_{max} - 512)/6.53]/0.0216$ nm. With an absorption maximum at about 520 nm, it can be concluded that the particle sizes are in the magnitude of 10 nm.

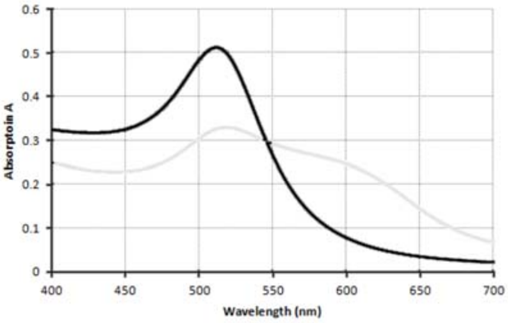


Figure 1. VIS spectrum of gold NP suspension directly after the preparation with sodium citrate (black line) and after one-hour-reaction with glucose and hydrogen peroxide at pH 9 (grey line).

To find the optimum conditions for the oxidation reaction, it has to be ensured that the pH and temperature are well below the critical limits when caramelization of glucose occurs. This phenomenon [17] could be qualitatively followed by observing the color of a solution of 10 mmol glucose in diluted sodium hydroxide at different pH. Several solutions were prepared with different pH values and heated at 60°C, which, according to [11], could be the maximum reaction temperature. It could be detected that glucose starts to decompose into brown-colored by-products at pH >= 10 at T >= 55°C within 1 hour. From this finding, a pH of 9 and 50°C were chosen to avoid this decomposition reaction during the oxidation with hydrogen peroxide.

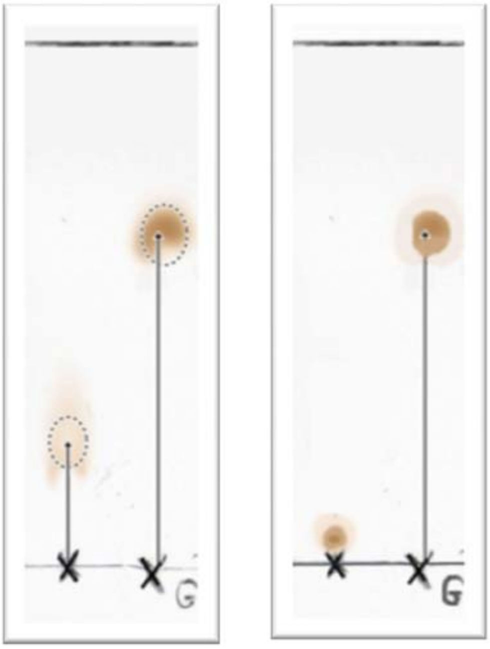


Figure 2. TLC of sodium gluconate (left) and calcium gluconate (right) vs. glucose in i-propanol/water 4:1.

To characterize the products after completed reaction and after re-crystallization as calcium salt, standard TLC plates with silica on aluminum were used. A mixture of i-propanol with water (4:1) is a suitable solvent. To develop the TLC, the plates were heated on a hot plate where the products appear as brown spots. Figure 2 shows a TLC of the sodium gluconate from the reaction mixture, which has a spot at significant lower R_f than glucose (0.24 vs. 0.64). The final product, the calcium salt, does barely move on the plate and has an R_f close to zero, shown in the right part of Figure 2.

4.2 Reaction Rate

Following the addition of sodium hydroxide to the reaction mixture of glucose and hydrogen peroxide in gold NP suspension, a theoretical yield of nearly 90% could be detected after 30 minutes. The amount of added sodium hydroxide to maintain pH 9 declines during the reaction, indicating a first order kinetics with respect to glucose. The remaining glucose concentration in mol/L can be calculated from the consumption of NaOH: 1 ml of 0.2M NaOH corresponds to the loss of 0.2 mmol of glucose, corresponding to 2 mmol/L. For a first order kinetics, the natural logarithm of the glucose concentration over time should give a straight line with the slope representing the reaction constant. The result is shown in Figure 3. A rate constant for the first-order reaction was found to be 4.95 h^{-1}, in good agreement with the kinetic observation of Comotti et al. [12], who estimated a rate constant of 4 h^{-1} for the product formation.

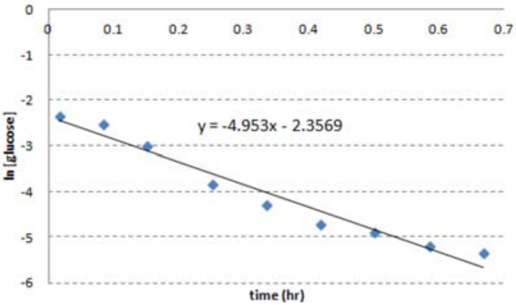


Figure 3. Plot of the logarithm of the remaining glucose concentration during the oxidation reaction in alkaline H_2O_2 over the reaction time.

4.3 Proposed Glucose Adsorption on Gold Nanoparticle

In order to understand the molecular behavior of glucose adsorption in gold colloid solution such as adsorption orientation and interaction, four models of glucose absorbed on gold nanoparticles were calculated using the DFT calculations with LANL2DZ basis set. The optimized structures (**Model I-IV**) of the Au-Glc and Au-GlcOH complexes with one Au atom absorbed on the oxygen atoms of the aldehyde and C6-hydroxyl end-group of glucose are illustrated in Figure 4. The calculated adsorption energies for the four models are listed in Table 1. For the Au-Glc complexes, the Au atom is preferred to adsorb with the C6-hydroxyl oxygen of glucose end-group (see **Model II**; Figure 4b, right), as suggested by the energetically favorable structure and a shorter Au-O distance of 2.54 Å compared to those from **Model I** (Figure 4a, left). For the Au-GlcOH complexes, the GlcOH molecule is most likely to adsorb on the Au atom through the carbonyl oxygen of the aldehyde end-group of glucose, shown in **Model III** (Figure 4b, left), with the lowest energy structure found among the four models (Table 1) and a short Au-O distance of 2.25 Å. This orientation was found to give the most favorable absorption with the lowest adsorption energy of -22.56 kcal/mol, indicating that the glucose adsorption is an exothermic process. Based on the obtained calculations, the glucose may weakly interact with the gold nanoparticles through the CH_2OH end-group then it may react with the NaOH prior to adsorb with the gold nanoparticles as shown in Figure 5. However, it is also possible that the glucose may react with NaOH to generate the glucose anion and then adsorb on the gold nanoparticles.

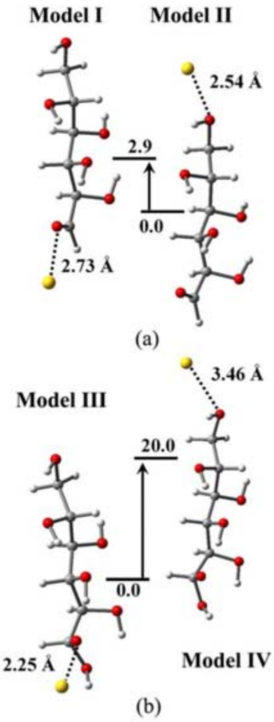


Figure 4. Optimized structures of four models (**I-IV**) representing the Au-Glc (a) and Au-GlcOH (b) complexes with Au absorbed on the oxygen atoms from the aldehyde (left) and C6-OH (right) end-group of glucose. The unit of energy is in kcal/mol**.**

Table 1. The adsorption energies for the four models (**I-IV**) from Figure 4.

Model	total energies/ relative energies (kcal/mol)	adsorption energy (kcal/mol)
I	-516168 / 0.0	4.3
II	-516171 / 2.9	1.4
III	-563801 / 0.0	-22.6
IV	-563781 / 20.0	-2.5

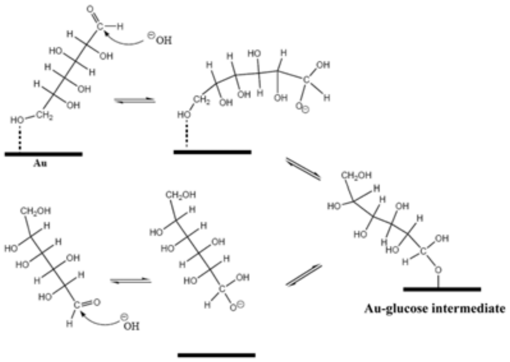


Figure 5. Possible glucose adsorption on gold nanoparticles during the formation of key Au-glucose intermediate as suggested by the present calculations.

5. CONCLUSIONS

Our investigations of the gold catalyzed oxidation route showed that the gold nanoparticles produced by a modified Turkevich method have a high activity for this reaction, which then becomes a pseudo-homogenous catalysis. It was found that nanoparticles in the magnitude of around 10 nm could be produced in higher dilution and citrate concentrations as by the classic method. Under mild reaction conditions, glucose could be oxidized in good yields (72%) and the resulting sodium gluconate could be isolated by column chromatography with iso-propanol on silica gel. Since the underlying reaction mechanism for the glucose oxidation is most likely based on the formation of Au-glucose intermediates, four possible reaction intermediates of Au-glucose complexes were examined based on DFT methods and the calculations showed that the GlcOH molecule gives a stronger adsorption to the gold atom compared to the Glc molecule, emphasizing the requirement of alkaline conditions in the glucose oxidation. Based on the present calculations, the glucose adsorption on gold nanoparticles during the formation of Au-glucose intermediate was explained for the first time, demonstrating that the aggregation of the alkoxy-group to a gold-cluster is indeed thermodynamically favored.

ACKNOWLEDGMENTS

The authors would like thank Ms. Benjawan Auanwijit and Ms. Chitchanok Manian for their help with the experiments. We thank the National e-Science Infrastructure Consortium for providing computing resources that have contributed to the research results reported within this paper (URL: http://www.e-science.in.th). J.J. is a Thailand Research Fund–Commission on Higher Education (TRF-CHE) Young Research Scholar (MRG5680143), and thanks the University of Phayao for financial support (R020056216016).

REFERENCES

[1] Astruc D., Lu F. and Aranzaes J.R., *Angew. Chem. Int. Ed.*, 2005; **44**: 7852-7872. DOI 10.1002/anie.200500766.

[2] Haruta M. and Masakazu D., *Appl. Catal. A*, 2001; **222**: 427-437. DOI 10.1016/S0926-860X(01)00847-X.

[3] Haruta M., *Gold Bulletin*, 2004; **37**: 27-36. DOI 10.1007/BF032 15514.

[4] Hutchings G.J., *Catal. Today*, 2005; **100**: 55-61. DOI 10.1007/BF03214746.

[5] Thompson D.T., *Nano Today*, 2007; **2**: 40-43. DOI 10.1016/S1748-0132(07)70116-0.

[6] Liu A. and Ye B., *Clin. Lab*, 2013; **59**: 23-36. DOI 10.7754/Clin.Lab.2012.120614.

[7] Haruta M., Yamada N., Kobayashi T. and Iijima S., *J. Catal.*, 1989; **115**: 301-309. DOI 10.1016/0021-9517(89)90034-1.

[8] Hvolbæk B., Janssens T.V.W., Clausen B.S., Falsig H., Christensen C.H. and Nørskov J.K., *Nano Today*, 2007; **2**: 14-18. DOI 10.1016/S1748-0132(07)70113-5.

[9] Mikami Y., Dhakshinamoorthy A., Alvaro M. and Garcia H., *Catal. Sci. Technol.*, 2013; **3**: 58-69. DOI 10.1039/C2CY20068F.

[10] Comotti M., Della Pina C., Matarrese R. and Rossi M., *Angew. Chem. Int. Ed.*, 2004; **43**: 5812-5815. DOI 10.1002/anie.200460446.

[11] Prüβe U., Heidinger S. and Baatz C., *Agric. Forestry Res.*, 2011; **3**: 261-272.

[12] Comotti M., Della Pina C., Falletta E. and Rossi M., *Adv. Synth. Catal.*, 2006; **348**: 313-316. DOI 10.1002/adsc.200505389.

[13] Beltrame P., Comotti M., Della Pina C. and Rossi M., *Appl. Catal. A*, 2006; **297**: 1-7. DOI 10.1016/j.apcata.2005.08.029.

[14] Önal Y., Schimpf S. and Claus P., *J. Catal.*, 2004; **223**: 122-133. DOI 10.1016/j.jcat.2004.01.010.

[15] Biella S., Prati L. and Rossi M., *J. Catal.*, 2002; **206**: 242-247. DOI 10.1006/jcat.2001.3497.

[16] Ramachandran S., Fontanille P., Pandey A. and Larroche C., *Food Technol. Biotechnol.*, 2006; **44**: 185-195.

[17] Ajandouz E.H., Tchiakpe L.S., Ore F.D., Benajiba A. and Puigserver A., *J. Food Sci.*, 2001; **66**: 926-931. DOI 10.1111/j.1365-2621.2001.tb 08213.x.

[18] Kimling J., Maier M., Okenve B., Kotaidis V., Ballot H. and Plech A., *J. Phys. Chem. B*, 2006; **110**: 15700-15707. DOI 10.1021/jp 061667w.

[19] Turkevich J., Stevenson P.C. and Hillier J., *Discuss Faraday Soc.*, 1951; **11**: 55-75. DOI 10.1039/DF9511100055.

[20] Sajan D., Bena Jothy V., Kuruvilla T. and Hubert Joe I., *J. Chem. Sci.*, 2010; **122**: 511-519. DOI 10.1007/s12039-010-0085-9.

[21] Maniu D., Chis V., Baia M., Toderas F. and Astilean S., *J. Optoelectron. Adv. Mater.*, 2007; **9**: 733-736.

[22] Ma W. and Fang Y., *J. Colloid Interf. Sci.*, 2006; **303**: 1-8. DOI 10.1016/j.jcis.2006.05.001.

[23] Ma W. and Fang Y., *J. Nanopart. Res.*, 2006; **8**: 761-767. DOI 10. 1007/s11051-005-9059-0.

[24] Pérez L.A., López-Lozano X. and Garzóna I.L., *Eur. Phys. J. D*, 2009; **52**: 123-126. DOI 10.1140/epjd/e2008-00289-5.

[25] Hay P.J. and Wadt W.R., *J. Chem. Phys.*, 1985; **82**: 270-283. DOI 10.1063/1.448799.

[26] Gaussian 09, Revision B.01, Gaussian Inc., Wallingford CT, USA, 2010.

[27] McFarland A.D., Haynes C.L., Mirkin C.A., Van Duyne R.P. and Godwin H.A., *J. Chem. Educ.*, 2004; **81**: 544a.

[28] Haiss W., Thanh N.T.K, Aveyard J. and Fernig D.G., *Anal. Chem.*, 2007; **79**: 4215-4221. DOI 10.1021/ac0702084.