**From Redox Reactions to Nanomaterials: Visual Lab Activity for Exploring the Stabilization and Aggregation of Silver Nanoparticles**

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Abstract

This study proposes a lab experiments consisting of three consecutive steps designed to expose undergraduate students to the fundamental aspects of nanoscience. Two different procedures for the reduction of silver ions were provided, the first resulted in a precipitate, whereas in the second reaction a colored solution of silver nanoparticles was obtained. Next the students explore the aggregation process of silver nanoparticles by converting one solution to the other, which produced interesting color changes. The discussion centers on the role of this lab activity as a visual affordance to introduce students to basic concepts related to nanomaterials: metal nanoparticles, colloidal suspension, colloid stability, surface plasmon resonance of metal nanoparticles, zeta potential, electric double layer, and aggregation process. The experiments were carried out by a group of second-year college students majoring in chemistry.

תמונה שמכילה גביע, שולחן, מקורה, שתייה

התיאור נוצר באופן אוטומטי

Keywords

Second-Year Undergraduate, Laboratory Instruction, Interdisciplinary/Multidisciplinary, Hands-On Learning/Manipulatives, Aqueous Solution Chemistry, Colloids, Electrochemistry, Nanotechnology, Oxidation/Reduction, Solid State Chemistry, UV-Vis Spectroscopy.

Introduction

Nanoscience and nanotechnology are at the forefront of 21st century science. It deals with creation of materials, systems, and devices having fundamentally new properties and functions.1 The new properties are utilized for developing new applications that affect our lives and daily needs in different domains. 2,3 In fact, the only criterion for 'entering' the world of nanotechnology is size. By definition, a nanometer is a billionth of a meter (1nanometer = 1x10-9m), and a nanomaterial is a material whose at least one-dimension ranges from 1 to 100 nanometers. To imagine structures at the nanoscale, the diameter of a living cell is several hundred nanometers, whereas Corona virus is composed of spherical particles of about 100 nanometers in diameter. On the other hand, the smallest things that can be seen with the human eye are 10,000 nanometers in size. The importance and uniqueness of nanoscience stems from the fact that properties of materials at the nanoscale are different from its familiar physical and chemical properties when it is at the macroscale.4

In recent years, there has been a growing demand to introduce nanoscience teaching in high schools and undergraduate courses. Roco described the importance of education for the development of this field (ref *5*, p 1247):

One of the grand challenges for nanotechnology is education, which is looming as a bottleneck for the development of the field.

Several publications in the last two decades have described attempts to introduce nanoscience and nanotechnology to K-12 and undergraduate students. 6-11 They have all suggested lab experiments and activities for teaching the basic concepts of nanoscience, including the preparation of different nanomaterials, which is defined as a separate field of science. In addition, several educational programs for different grades have been developed for teaching nanoscience and nanotechnology. 12-16 Although nanoscience is considered a motivating interdisciplinary scientific field, it is not easy to integrate it into teaching curricula. 17

Colloidal suspension is defined as composed of two phases, dispersion phase and dispersed phase. In the case of metallic nanoparticles, water or organic solvent is defined as the dispersion phase in which metal nanoparticles are dispersed. The key feature in applications of metal nanoparticles is the stability of the colloid solutions. Due to the large surface area of materials at the nanoscale, attractive forces between the nanoparticles are very significant and could lead to the process of aggregation, that is, the nanoparticles are clustering together to macroscale particles and precipitate. To prevent that and keep the nanoparticles from adhering to each other, three stabilization mechanisms are proposed, electrostatic stabilization, in which the nanoparticles acquire electrostatic charge, steric stabilization occurs by physical or chemical adsorption of polymers or surfactant molecules having long hydrocarbon chains onto the surface of nanoparticles, and depletion stabilization which occurs in the presence of free long-chain polymers, the large dimensions of these chains can compete with possible attractive forces among the nanoparticles. 18

The most effective way to stabilize metal nanoparticles in solution is based on electrostatic stabilization mechanism, the electric charge on the nanoparticle surface provides electrostatic repulsion between them and prevent aggregation. The distribution of different co-ions (ions of similar charge of nanoparticle surface), and counter ions (ions of opposite charge of nanoparticle surface) onto the colloidal suspension produces a so called Electric Double Layer around each nanoparticle. Counter ions are ions with opposite charges stay close to the nanoparticle surface due to the electrostatic attraction between them, forming a Stern layer, as we continue outwards, a diffuse layer is formed, it extends to some distance around the nanoparticle surface. The majority ions in this layer are co ions, counter ions are in lesser number. The potential, caused by the surface charges, at the edge of the Stern layer is called Stern potential, while the potential at the edge of the diffuse layer (Slipping plane) is called zeta potential (ζ). Zeta potential is an important concept, since it gives a relatively good indication of the nanoparticle surface charge. Experimentally, it can be measured in an adapted dynamic light scattering experiment where the electrophoretic mobility of the nanoparticles is translated into a zeta potential value.

In principle, its numerical value is an indication of the stability of a colloidal suspension, lower zeta potential values specify that the electrical charge is not sufficient to prevent attraction between nanoparticles. Higher zeta potential values indicate that the electrostatic repulsion forces between the nanoparticles in colloid solution could exceed the attractive forces, as a result the colloid solution is stable. Basically, if the measured value of zeta potential more positive than (+25) mV, or more negative than

(-25) mV, the nanoparticles are said to be colloidally stable with time. Figure 1 presents schematic illustration of electric double layer of negatively charged nanoparticle, and a curve that represents the electrical potential as a function of distance from nanoparticle surface. 19-20

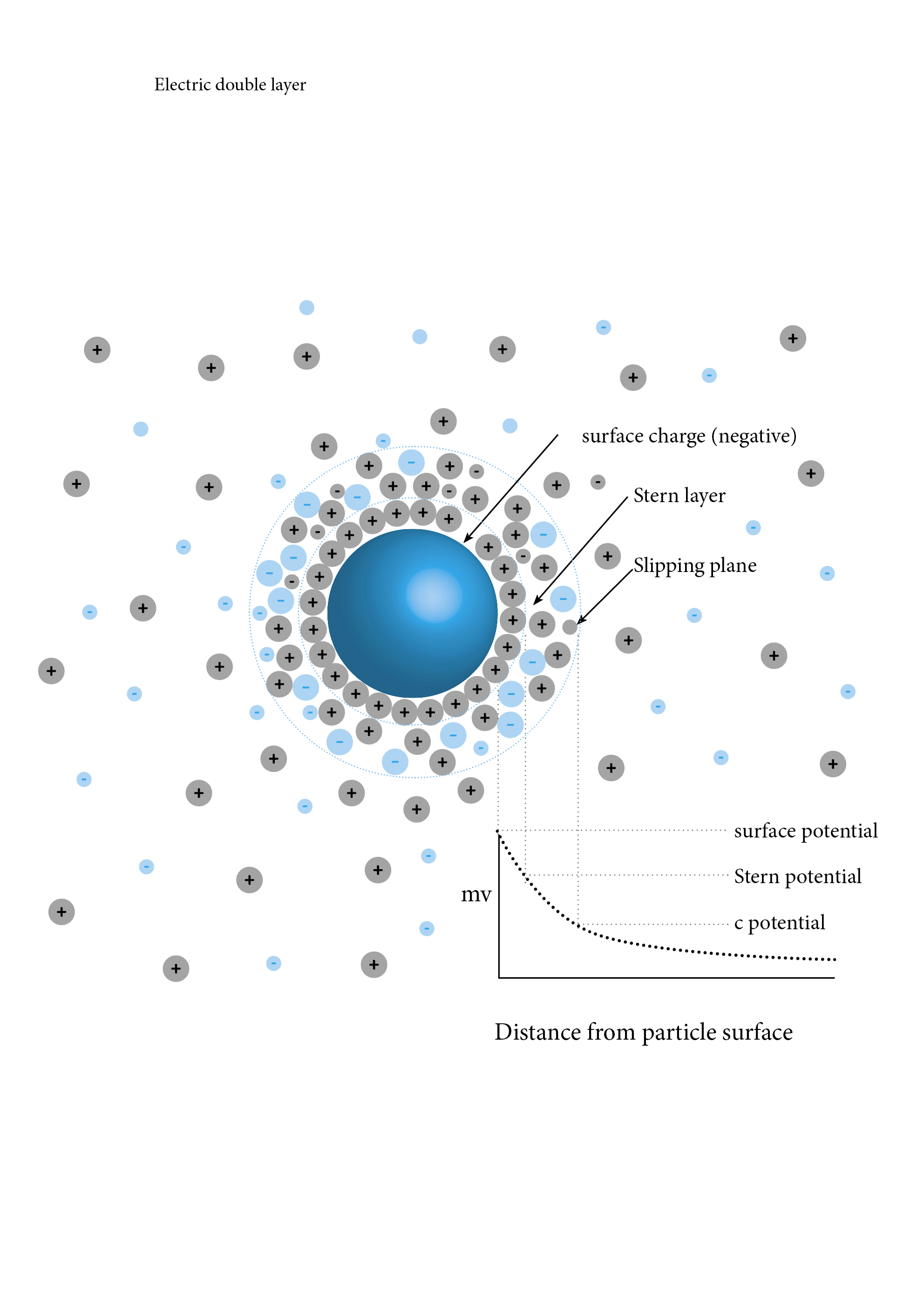


Figure 1. Schematic illustration of electric double layer structure of negatively charged nanoparticle in colloidal suspension.

Among the various nanomaterials, metal nanoparticles are of great importance, due to their remarkable physical and chemical properties. They distinguish from other nanomaterials by their bright colors arises from their optical properties. When metal nanoparticles (especially silver and gold nanoparticles) are irradiated using electromagnetic radiation, the wavelength of light becomes much longer than the nanoparticle size, causing the conduction electrons to oscillate when interacting with the light. This oscillation around the surface of the nanoparticle causes a dipole oscillation towards the electric field of light. The amplitude of the oscillation reaches its maximum at a certain frequency and is therefore known as localized surface plasmon resonance (LSPR). LSPR causes strong absorption of light, which can be measured using ultraviolet visible (UV-Vis) spectrophotometry. This phenomenon is responsible for the unique and unusual colors of various metal nanoparticles. The size of the nanoparticles plays a crucial role in LSPR phenomenon, for example, increasing the size of silver nanoparticles leads to a wider absorption peak in UV-Vis spectrometry and appears by different color.21-22

The synthesis of metal nanoparticles by the reduction method have often been discussed in articles in this journal. 8,23 These methods are based on the reduction of metal ions, in particular gold and silver ions, to produce solutions of metal nanoparticles. Most applications of metallic nanoparticles require preparing them in the form of aqueous colloidal suspensions called hydrosols.

Colloidal suspensions are differentiated from other types of solutions due to Brownian motion and Tyndall effect phenomena.Brownian motion is a random movement or zigzag-like motion of nanoparticles in colloidal suspensions that results from collisions between the nanoparticles and the molecules of the dispersion medium. The Tyndall effect is an optical property that arises from passing a beam of light through colloidal suspensions. When a light beam passes through a colloidal suspension, the light collides with the nanoparticles inside, and this results in light scattering in all directions. This phenomenon is represented by seeing a beam of light inside the solution. The light scattering is attributed to the size of particles in the solution. In comparison, true solutions of ions or molecules have solute particles with sizes below 1 nm. This size is too small to lead to light scattering, and therefore no beam of light is detected.

The present study describes a simple laboratory activity composed of three successive experiments in which the students explore the reduction preparation method of silver nanoparticles and its electrostatic stabilization. This series of experiments constitutes a new twist on ways to integrate the topics of nanomaterials with one of the basic subjects taught in chemistry; namely, reduction and oxidation reactions. Two well-known oxidation reduction reactions are presented to the students and then tested in the lab to introduce them to synthesis of metal nanoparticles by reduction method, electrostatic stabilization of metal nanoparticles, zeta potential, Tyndall effect and surface plasmon resonance. The uniqueness of the proposed lab activity is that it based on visual and attractive color changes. The lab activity was taught a second-year college students majoring in chemistry as part of a chemistry laboratory course.

Experimental Overview

The lab activity consists of three parts, firstly, the students explore the known reduction of silver ions by copper metal, the formation of grey-black precipitate of silver atoms and turning the color of the solution from transparent to blue which is typical to copper ions (Cu2+). Secondly, synthesis of silver nanoparticles using a well-known method reported in the literature 24. This method is based on reduction of silver ions by tri-sodium citrate that acts both as reducing agent and electrostatic stabilizer, it adsorbs to the surface of silver nanoparticles produced and give them negative electrostatic charge. Thirdly, the blue color solution of Cu2+ that obtained in part 1, is used to induce aggregation of silver nanoparticles by naturalizing the negative charges of it. All the appealing visual color changes that are attributed to the lab activity were analyzed by UV-Visible spectrophotometer, a Malvern Zetasizer Nano by the well-known Dynamic Light Scattering (DLS) technique to determine the size of silver nanoparticles and the value of zeta potential, and a laser beam in order to observe Tyndall effect.

Experimental section

Reduction of Silver Ions by Copper Disks

A solution of silver nitrate (1M) was prepared by dissolving 42.5 g of silver nitrate (AgNO3, 99%, Sigma-Aldrich) in 250 mL of double-distilled water. 10 copper disks (the mass of each disk is 1.5 g) were then added to the solution. Gradually, a grey colored precipitate appeared accompanied with turning the color of the solution from transparent to blue. After 30 minutes, the blue colored solution was separated from the silver precipitate by filtration and set aside.

Synthesis of Silver Nanoparticles by Reduction Method

The preparation of silver nanoparticles was based on the well-known method based on reduction of silver ions by tri-sodium citrate 24. An aqueous solution of silver nitrate (AgNO3, 99%, Sigma-Aldrich) was prepared by dissolving 0.0425g silver nitrate in 250 mL double-distilled water. The solution was placed on stirring hot plate and heated to boiling. An aqueous solution of 1% w/w tri-sodium citrate dihydrate (HOC(COONa)(CH2COONa)2 · 2H2O, Sigma-Aldrich) was prepared by dissolving 0.2 g in 20 mL double-distilled water. 5mL of the solution of tri-sodium citrate was added drop by drop to the boiled solution of silver nitrate with vigorous stirring. Gradually, the mixed turned from transparent to yellow-green color indicating the formation of stable colloidal suspension of silver nanoparticles. The colloidal suspension was removed from the hot plate and allowed to cool.

Aggregation and Precipitation of Silver Nanoparticles by Cu+2 Ions- Converting the Yellow-Green Solution to Blue Colored Solution

Four different mixed solutions were prepared by combining in different volume proportions the blue filtered solution of Cu2+ ions obtained in part1 with the yellow-green solution of silver nanoparticles obtained in part 2, as described in Table 1.

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| --- | --- | --- | --- |
| Table 1. Description of the volume proportions of five different solutions prepared. | | |  |
| *Number of Solution* | *Volume of silver nitrate solution (mL)* | *Volume of filtrated Cu2+*  Solution (mL) | *Total Volume of Solution (mL)* |
| 1 | 60 | 0 | 60 |
| 2 | 40 | 20 | 60 |
| 3 | 30 | 30 | 60 |
| 4 | 20 | 40 | 60 |

The students observed visible color changes and analyzed the mixed solutions with a UV-Visible spectrophotometer (UV-Visible spectrophotometer Ultraspec 2100 pro-Amersham Bioscienece), a Malvern Zetasizer Nano ZS (Malvern Instruments Ltd., GB) by the well-known Dynamic Light Scattering (DLS) technique to determine the size of silver nanoparticles and the value of zeta potential.

HAzards

Silver nitrate (AgNO3) can burn the eyes and skin. The eyes should be flushed with plenty of water for at least 15 minutes if exposed. Tri-sodium citrate causes eye irritations; if exposed, immediately flush the eyes with water for at least 15 minutes. All the other materials are non-toxic. During the lab work students must wear protective glasses and lab coats. Never look directly into a laser or shine it at another person.

experimental results and disscussion

During the first experiment, the students review the well-known reduction oxidation reaction between silver ions (Ag+) and copper disks. Based on the values of Standard Reduction Potentials (E0) of copper and silver ions 25, the students could roughly estimate that Cu(s) could spontaneously reduce silver ions in aqueous solution. (see Table 2).

|  |
| --- |
| Table 2. Values of Standard Reduction Potentials of Ag+ and Cu+2. |
| *Half-Reaction* | | *Standard Reduction Potential (V)* |
| Cu2+(aq) + 2e- Cu(s) | | +0.34 |
| Ag+(aq) + e- Ag(s) | | +0.80 |
| E0 for the reaction: | |  |
| 2Ag+(aq) + Cu (s) 2Ag(s) + Cu2+(aq) | | (+0.8)-(+0.34)= 0.46>0 |

The solution of silver nitrate is initially colorless. After immersing the copper disks, the transparent color of the solution turns gradually to blue accompanied by the appearance of a grey-black color precipitate (Figure 2).

תמונה שמכילה זכוכית

התיאור נוצר באופן אוטומטי

Figure 2. (A) An aqueous solution of silver nitrate with copper disks inside the beaker. (B) 30 min later (c) After filtration and separation of the gray- black precipitate from the blue solution.

The yellow green colored solution of silver nanoparticles is shown in Figure 3A. As described previously, its characteristic color is due to localized surface plasmon resonance (LSPR) phenomenon. The UV-Visible spectrum for the as prepared silver colloidal suspension is presented in Figure 3B. The plasmon resonance produces a peak near 400 nm that is typical to silver nanoparticles. The size measurements obtained by dynamic light scattering technique showed a bimodal particle size distribution, which suggests the presence of two populations of silver particles, one have a size of 67 nm and the other with 5.5 nm (Figure 3C). A stable colloidal suspension can be controlled by maximizing the repulsive forces between the nanoparticles in order to keep each one discrete and prevent them from adhering to each other and aggregate. Electrostatic repulsion plays an important role in stabilizing colloidal suspensions. In our case, tri-sodium citrate has two functions as a reducer and stabilizer. In addition to the reduction of silver ions, it adsorbs onto the surface of the silver nanoparticles produced to cause anionic repulsion between them. The anionic charge of silver nanoparticles was determined by zeta potential measurements and yielded high negative value of -38.7 mV that indicates the adsorption of tri-sodium citrate ions onto the surface of silver nanoparticles, and moreover, it indicates the high stability of the silver colloidal suspension. Figure 4 presents a schematic representation of the silver nanoparticles capped by tri-sodium citrate and the result of zeta potential measurement.

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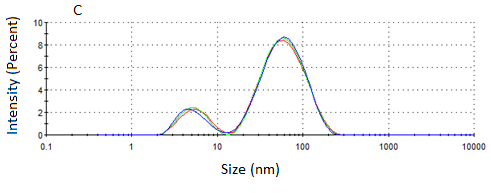


Figure 3. (A) Yellow green colloid solution of silver nanoparticles (B) UV-Vis absorption spectrum for the as prepared silver colloid (C) size distribution of as prepared silver nanoparticles.

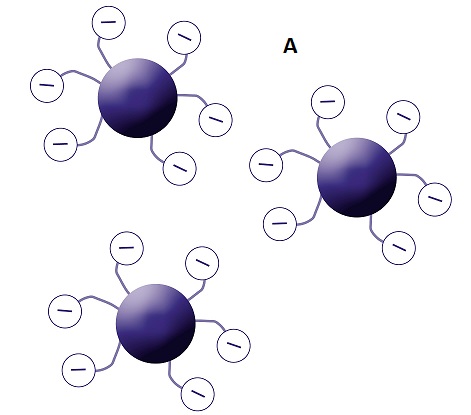
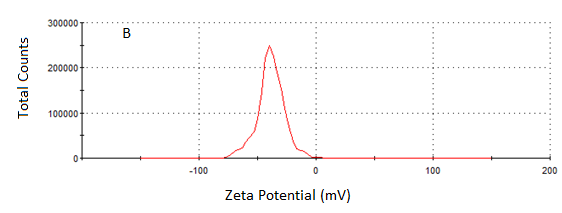


Figure 4. (A) Schematic illustration of silver nanoparticles stabilized by tri-sodium citrate (B) zeta potential measurement of the as prepared silver colloid.

During the first and second part of the lab activity, the students experienced two different reactions for the reduction of silver ions. In the first reaction, they produced macroscale silver precipitate, whereas, in the second reaction they produce colloidal suspension of silver nanoparticles. The students could visually observe the different results, especially the role of tri-sodium citrate as stabilizer.

The blue filtered solution of Cu2+ ions that obtained in the first part of the lab activity, was used to induce the aggregation of silver nanoparticles. According to the second part of the lab activity, silver nanoparticles are stabilized by the negative charge of the adsorbed tri-sodium citrate. By adding the solution of Cu2+, it naturalizes the negative charge of silver nanoparticles and then induces aggregation of it.

As a first step, the students analyzed the different mixed solutions prepared, as shown in Table 1. These solutions consist of different volume proportions between the silver colloidal suspension and the solution of Cu2+. Similarly, when adding the solution of Cu2+ to the colloidal suspension of silver nanoparticles, its color turns from yellow green to dark blue. The solutions were analyzed by their plasmon absorption using UV-Visible spectrophotometry. The UV-Visible spectra are presented in Figure 5, obviously, it shows that increasing the volume proportion of Cu2+ solution resulted in decreasing the absorption intensity and the absorption bands broadened. This indicates the aggregation of silver nanoparticles, due to the spontaneous attraction between negative and positive charges, the added positively charged copper ions will be attracted directly to the surface of the silver nanoparticles, causing the reduction of its negative charge. This process enhances the attraction between the silver nanoparticles, resulting in the immediately disappearance of the yellow green color of the solution and the appearance of dark blue color. The broad and weak absorption band appeared after adding Cu2+ corresponding to the possible formation of Cu(H2O)6+2 complex 26.

By comparison between the curves, the students observe that increasing the volume proportion of Cu2+ solution, the intensity of absorption decrease, that is mean, increasing the number of Cu2+ ions leads to more aggregated silver nanoparticles.

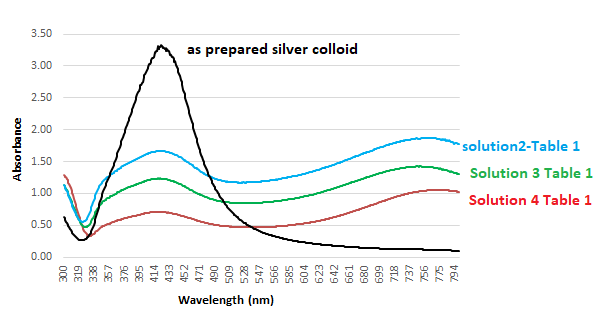


Figure 5. UV-Visible absorption spectra of the different solutions as shown in Table 1.

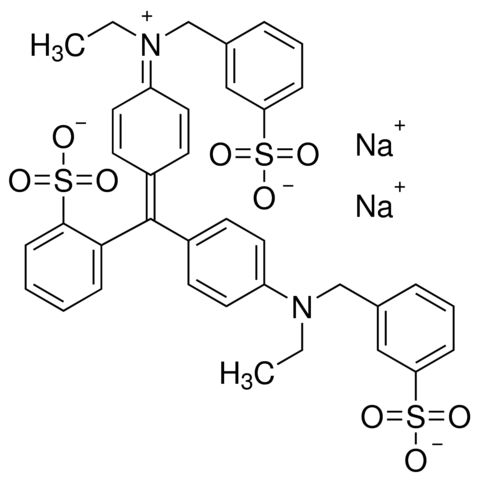
For the continuous analyzation of the aggregation process of silver nanoparticles, the mixed solution of 40 mL silver colloid and 20 mL Cu2+ (solution 2 in Table 1) was analyzed with time. The students monitored the visually and attractive color changes for 2 hours and analyzed it by following the UV-Visible absorption spectra, particle size and zeta potential. They found that the yellow green solution of silver nanoparticles vanished and turned into a blue solution with a grey-black precipitate, just like the solution obtained in part 1 of the experiment, (Figure 6).

תמונה שמכילה בקבוק, קטן, שולחן, יין

התיאור נוצר באופן אוטומטי

Figure 6. (a) Filtrate of the blue solution obtained in experiment 1 (B) Orange-green solution obtained in experiment 2 (c) Immediately after the addition of solution a to solution b (d) 2 hours after the addition of solution a to solution b, (lower image) Solution d after filtration.

To make the experiment more interesting, the students compared the color changes when mixing the yellow green solution of silver nanoparticles with an aqueous solution of blue food coloring, which yielded a light green yellow solution (Figure 7). By examining the chemical structure of blue food dye (Scheme 1), it is a negatively charged molecules just like the tri-sodium citrate, consequently it increases the magnitude of negatively charge of silver nanoparticles and the colloidal suspension remains stable. The students were asked to explain the appearance of light green yellow color in terms of color blending arises by mixing two colors together.



Scheme 1. Chemical structure of blue food dye.

תמונה שמכילה גביע, שולחן, שתייה, קפה

התיאור נוצר באופן אוטומטי

Figure 7. (a) Solution of blue food color (b) Orange-green solution obtained in experiment 2 (c) Solution obtained after the addition of solution a to solution b.

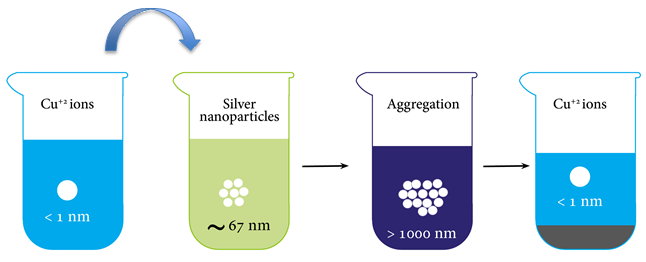
A laser beam was used as a simple way to distinguish between the different colored solutions. The students could not detect anything in the solution of copper ions, whereas a red line could be seen in the solution of silver nanoparticles when the laser beam was passed through it. In addition, the students were asked to monitor the changes that occurred when the two solutions were mixed. In this case, the red line was visible at the beginning but gradually disappeared. Conversely, the red line in the solution of silver nanoparticles was not affected by the addition of the blue food coloring solution (Figures 8, and 9 respectively).

Tyndall effect is a property of colloidal suspensions that distinguish them from true solutions. This phenomenon is related to the particles` size in solutions. When light is shined through a true solution just like the solution of Cu2+ ions, the light passes cleanly through it. The size of ions or molecules in true solutions is bellow 1 nm. However, the size of dispersed nanoparticles in colloidal suspensions is greater than 1 nm, when the light is passed through it, the nanoparticles scatter the light in all directions, making it readily seen. Scheme 2 illustrates schematically the changes in solute particles size during the aggregation process, which explains the observations shown in Figure 8.

תמונה שמכילה אדם, מקורה, אחזקה, יד

התיאור נוצר באופן אוטומטי

Figure 8. Laser beam passing through: (a) Filtrate of the blue solution obtained in experiment 1 (b) yellow green solution obtained in experiment 2 (c) immediately after addition solution a to b, (d) solution c after 3 hours.



Scheme 2. Schematic illustration of the inside solutions through the aggregation process.

תמונה שמכילה מקורה, מדף, שולחן, ישיבה

התיאור נוצר באופן אוטומטי

Figure 9. Laser beam passing through: (a) a solution of blue food coloring (b) the yellow green solution obtained in experiment 2 (c) the solution after adding solution a to b.

The students analyzed the visually colored aggregation process with time, by monitoring the changes in silver particles size, the value of zeta potential and UV-Vis absorption. As mentioned in the introduction section, zeta potential exhibits the electrical potential at the slipping plane of the electric double layer around each nanoparticle and provide indications on colloid stability. The average value of zeta potential for the as prepared silver colloidal suspension is-38.7 mV, this value indicates a stable colloidal suspension. Upon adding the Cu2+ solution, zeta potential value decreases significantly to -7.4 mV, that mean, the negative electric charge of silver nanoparticles decreases. When Cu2+ solution was added to the silver colloid, the Cu2+ ions were attracted by the negative charged citrate anions adsorbed to the surface of silver nanoparticles, and the ions tended to eliminate the repulsive electrostatic force. Therefore, silver nanoparticles aggregated, leads to increase particle size. Figure 10 presents the results of silver particle size measurements with time upon adding Cu2+.

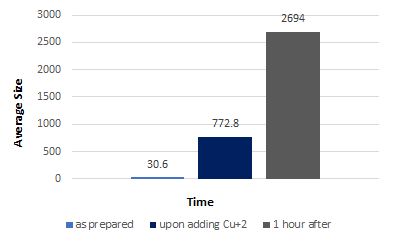


Figure 10. Average size of silver nanoparticles with time.

The aggregation process of silver nanoparticles was also monitored by UV-Visible absorption measurements for the as prepared silver colloid (A), immediately after adding Cu2+ solutions (B) , 1 hour after adding Cu2+ solution (C), and after complete precipitation and turning the yellow green silver solution to blue colored solution with grey-black precipitate (D). The results clearly show that upon time, the intensity of absorption decreases, and absorption bands became more broadened, (Figure 11). For comparison, the students conduct the UV-Visible absorption measurements for the mixed solution of silver nanoparticles with the blue food color solution. The resulted curve (Figure 11E) confirms that the silver nanoparticles did not affected upon adding the blue food color. This result was confirmed by measuring the value of zeta potential and the size of silver nanoparticles, the higher negative charge value of zeta potential was kept (-33.5 mV), and the average particle size is 46.44 nm.

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Figure 11. UV-Visible spectra of, (A), as prepared silver colloid, (B) immediately after adding Cu+2 solution, (C) 1 hour after adding Cu+2 ions, (D) after precipitation (E) silver colloid after adding blue food color solution.

pedagogical assessment

This lab activity was designed to introduce undergraduate students with fundamental concepts related to nanomaterials, synthesis, and properties. By conducting the experiments, students could compare properties of materials at the macro and nano scale. The students understand basic characteristics of nanomaterials, which are, electrostatic stabilization of colloid solutions, aggregation of nanoparticles, optical properties, and surface plasmon resonance of metal nanoparticles, electric double layer of electro statistically stabilized nanoparticles, and zeta potential.

The duration of the lab activity is 4 hours. The first hour is theoretical, a dialogue between the lecturer and the students about nanomaterials, basic concepts, and aspects. In the second hour, the students prepare the different solutions as reported in the experimental procedure, applied the reduction reaction of silver ions by copper metal to yield grey-black precipitate of silver, and reduction of silver ions by tri-sodium citrate and the formation of yellow green solution of silver nanoparticles. In the last two hours, the students analyzed the as prepared silver colloidal suspension by UV-Visible absorption, zeta potential and particle size measurements. Then they followed on the aggregation process of it and analyzed the process of visual colored aggregation of silver nanoparticles.

Student Learning Objectives

As a result of this lab activity, the students learn:

* Oxidation reduction reaction between silver ions and copper metal
* Synthesis of silver nanoparticles solution by reduction method
* Electrostatic stabilization of metal nanoparticles
* Localized surface plasmon resonance of metal nanoparticles
* Double electric layer of electrical charged nanoparticles and zeta potential
* Aggregation process of metal nanoparticles

After applying the successive experiments, the students will be able to understand the role of tri-sodium citrate as a colloidal stabilizer capable of preventing the aggregation of silver nanoparticles. The students will explore the visual color changes that are resulted from the addition of the blue solution prepared in the first part of the lab activity by UV-Visible absorption measurements, zeta potential and measuring the changes in silver particles size.

36 College freshmen from The Academic Arab College for Education in Haifa, Israel who are studying to be a chemistry teacher for high schools, participated in this lab activity as a part of the course “Chemistry in Lab”. Following the lab activity, the students were required to submit a laboratory report a week later in which they asked to answer scientific style questions that aimed to assist student`s understanding about the concepts, and characterization methods that are incorporated to the experiments. In addition, an optional question was provided through which students express their impression after completing the experiments.

Here are examples of student`s answers to this question:

Student 1: *“The experiments were amazing for me; I did not have any information about nanomaterials*

*before, during the lab activity, I learned new concepts that are related to materials at the*

*nanoscale. Converting the silver colloid solution obtained in the second experiment to blue*

*colored solution with grey black precipitate exactly likes the solution obtained in the first*

*experiment* *was the most important section for me, I understand very well the scientific*

*explanation of it.”*

Student 2: *“The most interesting section of the experiment it was when turning the silver colloid solution*

*to blue one. I learned new concepts that are related to nanomaterials.”*

Student 3: *“This is the first time that I learn about nanomaterials, I heard about it before, but I did not*

*know any knowledge about it. After the lab activity, the concepts of nanomaterials, and colloid*

*solution became much clearer.”*

Student 4: *“I liked the experiments very much, the precipitation of the “unseen” silver nanoparticles was*

*very interesting. In addition to the different analysis, the differentiation between the different*

*solutions by passing a beam of laser light was very interesting”.*

summary

This series of experiments constitutes a novel way to integrate an introduction to nanoscience into a basic lesson in chemistry. The lab activity is based on visual results for the students. The students found the lab activity very enjoyable especially when converting one solution to another accompanied by color changes. This made the students more curious about the different results and enables them to make the connection between different concepts in science. At the end of lab activity, the students learned new concepts of, colloid solution, capping agent, zeta potentials surface plasmon resonance, and aggregation.

Associated content

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.] Example brief descriptions with file formats indicated are shown below; customize for your material.

Instructor (DOCX)

Student (DOCX)

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Notes

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