JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc

Demonstration

Gold at the End of the Rainbow: A Simple and Colorful Modification of the Golden Penny Demonstration

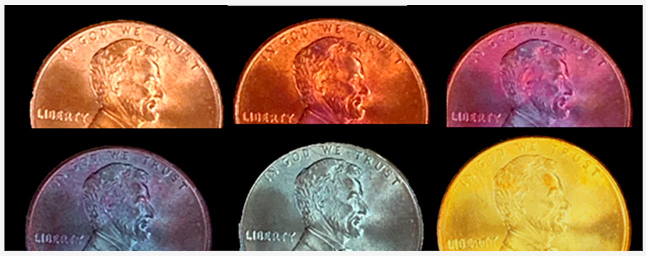
Thomas S. Kuntzleman* and Levi T. Hogan

Cite This: J. Chem. Educ. 2022, 99, 3083−3086

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: The “Golden Penny” demonstration is a popular experiment that involves treating copper coins with chemical reagents to form brass, an alloy of copper and zinc that has a golden color. Reported here is a very simple modification for forming golden color on copper coins that does not require the use of chemical reagents. Instead, golden colored surfaces can be generated by simply heating copper coins on a hot plate to form nanoscale films of copper oxide. In addition to gold, such oxide layers display a range of other colors including orange, magenta, violet, and silver.



KEYWORDS: *General Public, High School/Introductory Chemistry, First-Year Undergraduate/General, Demonstrations, Inquiry-Based/Discovery Learning, Oxidation/Reduction, Stoichiometry, Surface Science, Thermodynamics*

Downloaded via UNIV BOLOGNA on January 27, 2024 at 10:32:42 (UTC).
See https://pubs.acs.org/sharingguidelines for options on how to legitimately share published articles.

■ INTRODUCTION

Creating brass coatings on copper coins (such as U.S. pennies) to give the coin a golden colored plate is a classic chemistry demonstration that has been enjoyed by many.[1−4] To carry out this experiment, a copper coin is first placed on a pile of granular zinc that is immersed in a solution of either strong base or zinc ions. As a result, zinc is chemically deposited on the surface of the copper, which forms silver colored γ-brass.[2,5] Brass is an alloy of copper and zinc that exists in several different phases of different colors.[1,2,5] When such silvery coins are heated in the flame of a Bunsen burner, the γ-brass (∼65% zinc content)[2,5] is converted into α-brass (∼35% zinc content),[2,5] which is yellow in color. Overall, this experiment gives the illusion that the copper coin has first been changed into silver and then into gold upon heating, prompting some to dub this experiment “copper to silver to gold”.[1,4] When solutions of 1 M $ZnCl_2$ or 1 M $ZnSO_4$ are used in this experiment, the development of the layer of γ-brass includes oxidation of the granular zinc and concomitant reduction of zinc ions onto the copper coin:[2]

$$\mathrm{Zn(s,\ granular\ zinc)} \rightarrow \mathrm{Zn^{2+}(aq)} + 2e^- \quad (1)$$

$$\mathrm{Zn^{2+}(aq)} + 2e^- \rightarrow \mathrm{Zn(s,\ on\ coin\ surface)} \quad (2)$$

Alternatively, a solution of 3 M NaOH can be used.[1,3] In this case, the zincate ion is formed (eq 3), which provides the source of zinc metal in the γ-brass (eq 4).

$$\mathrm{Zn(s,\ granular\ zinc)} + 2\mathrm{OH^-(aq)} + 2\mathrm{H_2O(l)} \rightarrow \mathrm{[Zn(OH)_4]^{2-}(aq)} + \mathrm{H_2(g)} \quad (3)$$

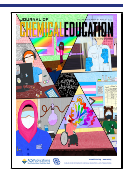
$$\mathrm{[Zn(OH)_4]^{2-}(aq)} + 2e^- \rightarrow \mathrm{Zn(s,\ on\ coin\ surface)} + 4\mathrm{OH^-(aq)} \quad (4)$$

The new demonstration reported here is a simplified method of producing a golden color, as well as several other colors, on copper coins. No chemical reagents or solutions are required to produce such colors. Instead, copper containing coins are heated on a hot plate in a controlled fashion. The heating process produces a thin film of Cu_2O on the surface of the coin that displays a variety of colors, including gold. In addition to greatly simplifying the process of producing a golden color on the surface of copper coins, this new procedure allows for inquiry-based investigations and discussions involving the topics of density, percent composition, and chemical thermodynamics.

■ BACKGROUND

The formation of thin metal oxide layers on metal surfaces is known to produce colors that span the full spectrum of the rainbow.[6−13] Such films can be created by thermal or electrochemical treatment. Heating copper in the presence of oxygen gas causes nanothin layers of copper(I) oxide to form on the copper surface:[6−8,10]

Received: June 1, 2022
Revised: July 13, 2022
Published: July 26, 2022



ACS Publications

© 2022 American Chemical Society and Division of Chemical Education, Inc.

https://doi.org/10.1021/acs.jchemed.2c00545
J. Chem. Educ. 2022, 99, 3083−3086

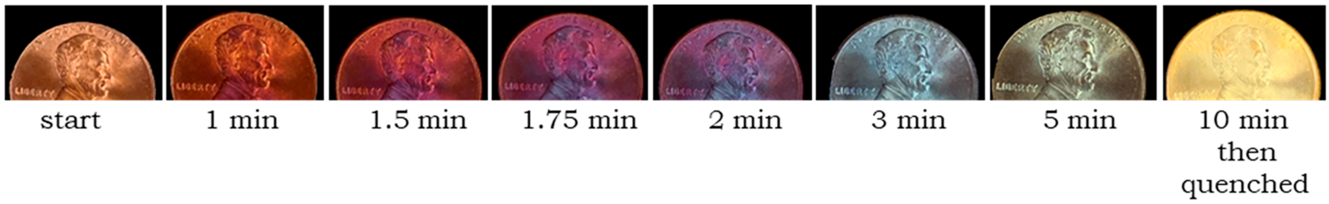


Figure 1. Colors observed on a U.S. penny heated on a hot plate and treated as described in the text. For appropriate comparison, backgrounds have been blacked out. The picture of the coin at 10 min was taken with the coin on a lab bench, and all others were taken while the coins were on a hot plate. All pictures were taken under room lights.

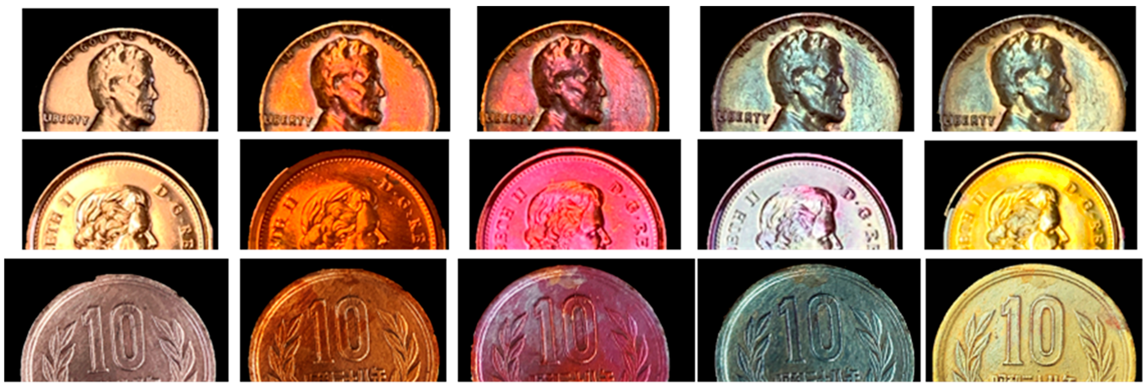


Figure 2. Color progression observed upon heating (top row) a 1968 U.S. penny at 220 °C, (middle row) a 2012 Canadian steel penny at 240 °C, and (bottom row) a Japanese 10-yen coin at 230 °C. The Canadian penny was not buffed with steel wool prior to heating. Increased time heated is from left to right. For appropriate comparison, backgrounds have been blacked out. Pictures of all coins in the last row were taken after quenching in water and placing coins on a lab bench. All other pictures were taken while coins were on a hot plate. All pictures were taken under room lights.

$$2Cu(s) + \frac{1}{2}O_2(g) \rightarrow Cu_2O(s) \qquad (5)$$

Light interacting with thin film surfaces is known to produce a variety of colors,[6−15] such as the rainbow of colors observed on bubble surfaces.[15] Generally, such films are on the order of tens to hundreds of nanometers thick. Light incident on nanoscale surfaces interferes constructively or destructively such that specific wavelengths of light are either amplified or attenuated.[6−14] The wavelength (and therefore color) of amplified light depends upon factors such as the refractive index and thickness of the film.[6,10−14] This phenomenon contributes to a variety of beautiful effects including the intense coloration of blue *Morpho* butterfly wings[14] and the wide range of colors observed by metal oxide films on metal surfaces.[6−13] In fact, a previous report in this *Journal* described how thermal treatment could be used to generate oxide coatings on metal objects (including coins) to produce a variety of colors.[12] However, this report did not focus on generating specific, uniform coloration on the surface of coins but instead described nonuniform coloration that occurred when different metal objects were heated to very high temperatures. It is well-established that uniform colors can be produced on copper surfaces by the formation of 20−100 nm thick layers of Cu_2O on the metal.[6−11] The specific color displayed depends largely upon the thickness of the Cu_2O film.[6−11] In this demonstration, a simple heat treatment is used to form nanolayers of Cu_2O on copper surfaces to generate a wide range of colors. The method may be used to generate a golden color on copper coins, eliminating the need for chemical reagents in the golden penny demonstration.

■ HAZARDS

Hot plates set to high temperatures can cause burns. Coins heated on hot plates should be cooled in water or left to sit undisturbed for at least 5 min prior to handling.

■ MATERIALS AND METHODS

Unless otherwise noted, results on United States pennies minted after 1982 are described. These pennies contain a zinc core with a copper plate.[3,16,17] A uniform color is best achieved on newer coins with bright, shiny surfaces. For best results, pennies should be buffed with steel wool to expose the bare copper surface. Once this has been done, a cotton swab is used to clean the newly exposed surface. Gloves may be worn when handling the pennies to avoid transferring oils to the penny surface. Alternatively, near-mint-condition coins are used. Once prepared, pennies are placed on a hot plate (we used Thermo Scientific model SP88857100 or Fisher Scientific catalog 11-510-49SH) with a surface temperature that reads 220−250 °C when measured with a noncontact infrared thermometer. The hot plate should be allowed to warm up for at least 10 min prior to experimentation. Color progression develops more quickly at higher temperatures, but color tends to develop more evenly over the coin surface at lower temperature.

■ RESULTS AND DISCUSSION

A U.S. penny dated after 1982 and prepared as described in the Materials and Methods section is placed on a hot plate at 225 °C. Within 45 s, the surface of the coin is observed to darken, and by 1 min the coin takes on an orange color (Figure 1). With continued heating, the surface color continues to change to deep orange, red-orange, magenta, violet, silver-red, silver, and yellow-silver, and then to a faint yellow at 3.5 min (see

https://doi.org/10.1021/acs.jchemed.2c00545
J. Chem. Educ. 2022, 99, 3083−3086

Figure 1 for some representative colors). The color progression tends to stop at yellow, but the yellow color continues to deepen with additional heating. After 10 min, the penny is removed from the hot plate and quenched in water, causing further development of the golden color (Figure 1, image on far right). The observed colors persist for a few months but begin to slowly fade thereafter. The colors observed are consistent with the colors that develop on copper surfaces on which nanolayers of Cu_2O form via electrochemical and thermal treatments.[6−11] The shift in color observed is likely due to growth in the thickness of the layer as more Cu_2O forms, in agreement with the effect of metal oxide film thickness on the surface of metals.[6−13] Interestingly, colors other than yellow are also observed to persist if coins are removed from the hot plate (and allowed to cool at room temperature) once the desired color is observed. When coins that have developed any color are immersed in a mixture of 5% NaCl in vinegar, the color formed on the surface dramatically fades within a few seconds, and the original copper color is restored. This effect of acid on metal oxide nanolayers has been observed previously.[11] The dissolution of the nanolayer of Cu_2O formed on the pennies can be explained by its reaction with protons:

$$Cu_2O(s) + 2H^+(aq) \rightarrow 2Cu^+(aq) + H_2O(l) \quad (6)$$

It is observed that pennies that have had their nanolayer removed by acid treatment can have their color restored. To do so, such pennies are first rinsed with water and dried. Next, the coin is prepared and reheated again as described in the Materials and Methods section.

A similar advancement of color is observed on older U.S. coins and coins from other countries that contain copper or copper plating (Figure 2). U.S. pennies minted prior to 1982, which are composed of an alloy of 95% copper and 5% zinc,[1] tend to develop colors that are not as vibrant (Figure 2, top row) as those observed on the newer U.S. pennies. On the other hand, beautiful and vibrant colors routinely develop on near-mint-condition Canadian steel pennies (Figure 2, middle row), which contain a core of 94% steel/1.5% nickel and are plated with 4.5% copper.[18] Two-color iridescence is routinely observed in these near-mint-condition coins as they transition from one color to another. Also, a Japanese 10 yen coin (an alloy of 95% copper and 5% zinc/tin)[19] is observed to follow a similar advancement of color upon heating (Figure 2, bottom row), forming a nice golden hue after quenching in water.

■ CONNECTIONS TO THE CURRICULUM

This demonstration connects to the chemistry curriculum in several ways, a few of which are mentioned here. First, a variety of introductory chemical principles including dimensional analysis, density, and stoichiometric relationships can be used to explain the observation that no significant change in mass is observed on coins before and after the development of color as measured on a balance with a tolerance of ± 0.1 mg. This might at first blush seem to be inconsistent with the incorporation of oxygen atoms into the coin to form the oxide layer on its surface. However, it can be shown that the formation of an oxide layer 100 nm thick encasing the entire coin would cause an increase in mass too small to register on the balance. This is shown using the radius of a U.S. penny (0.95 cm),[20] the thickness of a U.S. penny (0.15 cm),[20] and the density of Cu_2O (6.0 g cm^{-3}).[21] The volume of an oxide coating encasing the outside of the coin, V_o, would be

$$V_o = V_{oc} - V_c \quad (7)$$

where V_{oc} is the total volume of the oxidized coin and V_c is the original volume of the coin. Expanding eq 7, we have

$$V_o = \pi r'^2 h' - \pi r^2 h \quad (8)$$

where r is the radius of the original penny, h is the thickness of the original penny, r' is the radius of the oxidized penny ($r' = r + 100$ nm), and h' is the thickness of the oxidized penny ($h' = h + 200$ nm). Note that because the 100 nm thick oxide film would form on both the top and bottom of the penny, $h' = h + 200$ nm. Using these definitions and parameters, the volume of a layer of Cu_2O encasing the entire penny would be 6.6×10^{-5} cm^3. Multiplying this volume by the density of Cu_2O yields a mass of 4.0×10^{-4} g. Noting that it is only the oxygen atoms in the Cu_2O that would be responsible for any increase in mass and the fact that Cu_2O is 11.2% oxygen by mass, such a layer would correspond to a mass increase of only 4.4×10^{-5} g, which is below the tolerance of the balance (see Supporting Information for more detail).

In addition, the chemical reaction responsible for producing the Cu_2O nanolayer (eq 5) can be analyzed thermodynamically. For example, $\Delta H°$ for the reaction is calculated to be −169 kJ mol^{-1} using standard enthalpies of formation (Table 1), and $\Delta S°$ is found to be −76 J mol^{-1} K^{-1} using standard entropies (Table 1). Thus, the reaction is enthalpically favored but entropically disfavored. According to the equation $\Delta G° = \Delta H° - T\Delta S°$, the reaction is predicted to be spontaneous ($\Delta G° = -130$ kJ mol^{-1}) at $T = 240$ °C, consistent with the results of the experiment. Further, using the equation $T \approx \Delta H°/\Delta S°$, the temperature at which the reaction becomes nonspontaneous is estimated to be over 2200 K, well above the temperatures employed in this experiment, and well above the melting temperatures of both copper and zinc (see Supporting Information for more detail).

Table 1. Thermodynamic Values of Substances in Equation 5.[21,22]

substance	$\Delta H_f°$/kJ mol^{-1}	$S°$/J mol^{-1} K^{-1}
Cu(s)	0	33.1
Cu_2O(s)	−169	93.0
O_2(g)	0	205

Finally, the simplicity of this procedure coupled with the wide range of potentially manipulated conditions make this experiment a strong candidate for inquiry-based explorations. How do various pretreatments (acid wash, acetone wash, buffing vs no buffing) affect the coloration achieved? How does the speed of color progression vary with temperature? Can a difference in color development be observed in magnetic (Canadian steel pennies) as compared to nonmagnetic coins? Do the colors develop more quickly in an oxygen rich as compared to an oxygen-depleted atmosphere? Our students have been motivated to spend time in the lab, exploring these and other questions.

■ CONCLUSION

The procedure described here outlines a simple and novel method for carrying out the "copper to silver to gold" demonstration in a manner that is fascinating and unique. In fact, several colors other than silver and gold (Figures 1 and 2) are routinely observed during the demonstration. In contrast to

https://doi.org/10.1021/acs.jchemed.2c00545
J. Chem. Educ. 2022, 99, 3083−3086

the original demonstration, the color changes are not due to the formation of a metal alloy but rather of a nanothin layer of Cu_2O. This new protocol only requires controlled heating of the coins, eliminating the need for chemical reagents. Because it is easy to set up and carry out, this experiment has great potential to allow a wider audience of teachers and their students to conduct it. Indeed, we have presented this demonstration to elementary-aged students, students in nonmajors science courses, and students in General Chemistry courses. The demonstration connects to several topics in the General Chemistry curriculum and is quite amenable for students to carry out on their own in laboratory experiments and inquiry-based explorations.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00545.

Tips on carrying out the demonstration, links to videos illustrating the demonstration, and further detail on calculations (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Author

Thomas S. Kuntzleman − *Department of Chemistry, Spring Arbor University, Spring Arbor, Michigan 49283, United States;* orcid.org/0000-0002-2691-288X; Email: Tom.Kuntzleman@arbor.edu

Author

Levi T. Hogan − *Department of Chemistry, University of Wisconsin—Madison, Madison, Wisconsin 53706, United States;* orcid.org/0000-0001-5349-8656

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.2c00545

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We wish to thank Bruce W. Baldwin and Gary Richardson for helpful discussion, and the reviewers for helpful comments and suggestions for further explorations.

■ REFERENCES

(1) Shakhashiri, B. Z. *Chemical Demonstrations: A Handbook for Teachers of Chemistry*; University of Wisconsin Press: Madison, 1983; Vol. *4*, pp 263−268.

(2) Szczepankiewicz, S. H.; Bieron, J. F.; Kozik, M. The "Golden Penny" Demonstration: An Explanation of the Old Experiment and the Rational Design of the New and Simpler Demonstration. *J. Chem. Educ.* **1995**, *72* (5), 386−388.

(3) Dominic, S. Gold Pennies. *J. Chem. Educ.* **1995**, *72* (5), 389−390.

(4) Bejan, D.; Hastie, J.; Bunce, N. J. New Observations on the Copper-to-Silver-to-Gold Demonstration. *J. Chem. Educ.* **2008**, *85* (10), 1381.

(5) Mellor, J. W. A Comprehensive Treatise on Inorganic Chemistry; Longmans, Green, and Company: London, 1923; Vol. *4*, p 673.

(6) Kim, S. J.; Kim, S.; Lee, J.; Jo, Y.; Seo, Y.-S.; Lee, M.; Lee, Y.; Cho, C. R.; Kim, J.-p.; Cheon, M.; Hwang, J.; Kim, Y. I.; Kim, Y.-H.; Kim, Y.-M.; Soon, A.; Choi, M.; Choi, W. S.; Jeong, S.-Y.; Lee, Y. H. Color of Copper/Copper Oxide. *Adv. Mater.* **2021**, *33*, 2007345.

(7) Constable, H. The Cause of the Colours Shown during the Oxidation of Metallic Copper. *Proc. R. Soc. A* **1927**, *115* (772), 570−588.

(8) Miley, H. A. Copper Oxide Films. *J. Am. Chem. Soc.* **1937**, *59* (12), 2626−2629.

(9) Campbell, W. E.; Thomas, U. B. Tarnish Studies. The Electrolytic Reduction Method for the Analysis of Films on Metal Surfaces. *Trans. Electrochem. Soc.* **1939**, *76*, 303−328.

(10) Doi, Y. On the Mechanism of Colouring of Oxidized Copper, *J. Phys. Soc, Jpn.* **1949**, *4*, 118−119.

(11) Fredj, N.; Burleigh, T. D. Transpassive Dissolution of Copper and Rapid Formation of Brilliant Colored Copper Oxide Films. *J. Electrochem. Soc.* **2011**, *158* (4), C104−C110.

(12) Campbell, D. J.; Baliss, M. S.; Hinman, J. J.; Ziegenhorn, J. W.; Andrews, M. J.; Stevenson, K. J. Simple Methods for Production of Nanoscale Metal Oxide Films from Household Sources. *J. Chem. Educ.* **2013**, *90* (5), 629−632.

(13) Gaul, E. Coloring Titanium and Related Metals by Electrochemical Oxidation. *J. Chem. Educ.* **1993**, *70* (3), 176−178.

(14) Bober, B. A.; Ogata, J. K.; Martinez, V. E.; Hallinan, J. E.; Leach, T. A.; Negru, B. Investigating Nanoscopic Structures on a Butterfly Wing to Explore Solvation and Coloration. *J. Chem. Educ.* **2018**, *95* (6), 1004−1011.

(15) Brill, T. B. Why Colors Appear as They Do. *J. Chem. Educ.* **1980**, *57* (4), 259−263.

(16) Vanselow, C. H.; Forrester, S. R. Shell Thickness of the Copper-Clad Cent. *J. Chem. Educ.* **1993**, *70* (12), 1023−1024.

(17) Thomas, N. C.; Faulk, S. A Simple Penny Analysis. *J. Chem. Educ.* **2008**, *85* (6), 817−818.

(18) Chande, D.; Fisher, T. C. G. Have a Penny? Need a Penny? Eliminating the One-Cent Coin from Circulation. *Canadian Public Policy* **2003**, *29* (4), 511−517.

(19) *Japan Mint Circulating Coin Designs.* https://www.mint.go.jp/eng/kids-eng/eng_kids_circulating_c.html (accessed 2022−04−15).

(20) *United States Mint, Coin Specifications.* https://www.usmint.gov/learn/coin-and-medal-programs/coin-specifications (accessed 2022−04−15).

(21) Dean, J. A. *Lange's Handbook of Chemistry*, 13th ed.; McGraw-Hill: New York, 1985.

(22) Tudela, D. Silver (II) Oxide or Silver (I,III) Oxide? *J. Chem. Educ.* **2008**, *85* (6), 863−865.