

Directional Motion of Gallium-Based Liquid Metal Induced by Asymmetric Chemical Surrounding

Bingxing Wang^{1,*}, Qi Wang¹, Yanwei Zhang¹, Yongcai Zhang², Yuanchao Li¹, Donglin Zhao³

¹College of Chemistry and Chemical Engineering, Henan Institute of Science and Technology, Xinxiang 453003, China

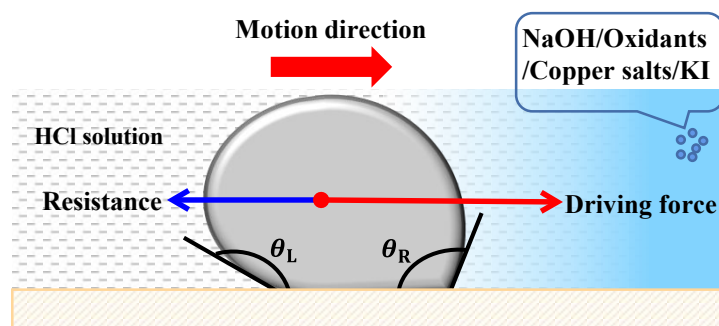
²Department of Chemistry and Chemical Engineering, Yangzhou University, Yangzhou 225009, China

³Division of Chemical and Energy Engineering, School of Engineering, London South Bank University, London SE1 0AA, UK

ABSTRACT

Interfacial, or surface, tension is a significant topic in chemical education. This paper describes the directional motion of gallium-based liquid metal drops resulting from a difference of interfacial tension across the drop. This demonstration can engage students in discovering the underlying chemical principles. A mechanism for the drop's directional motion is proposed to provide insight into this intriguing phenomenon. It appears that unbalanced chemical environments cause different physical or chemical processes to occur on each hemisphere of the drop such as a pH difference, redox reactions, galvanic replacement, or adsorption. As a result, a difference in interfacial tension across the drop is generated, providing the driving force that acts on the drop. This demonstration can be used to introduce the fundamental principles in chemical reactions such as redox activity, electrical double layer formation, and interfacial tension.

GRAPHICAL ABSTRACT



KEYWORDS

First-Year Undergraduate/General, Upper-Division Undergraduate, Interfacial/Surface Tension, Electrochemistry, Electrical Double Layer, Surface Science

INTRODUCTION

Interfacial tension refers to the attractive forces between molecules that exist at the interface between solid-liquid, solid-gas, liquid-liquid or liquid-gas phases. Specifically, the tension that arises at the interface of a liquid and air is known as surface tension. In natural contexts, numerous fascinating phenomena emerge that are related to the surface or interfacial tensions. For instance, water striders effortlessly move across the surface of water. A ring of clear liquid, known as the “tears of wine”, can be observed near the top inner rim of a glass of wine from which droplets form and fall back into the wine. Additionally, objects such as paper clips, coins, needles, and razor blades possess the ability to float on the surface of water. Water droplets and bubbles possess a spherical shape. All of these remarkable occurrences are attributed to the presence of surface or interfacial tension.

Surface tension has been a significant topic in chemical education as evidenced by the inclusion of this concept in physical chemistry textbooks¹ and a multitude of papers²⁻⁶ published in this Journal. For instance, some studies have introduced simple apparatuses to demonstrate the effects of surface tension on liquids,⁷ while others have developed various methods to accurately measure surface tension.⁸⁻¹⁰ Additionally, the floatation of glass coverslips on water has been used to explore the self-assembly of molecular monolayers.¹¹ The motion of solids and liquids has been studied as an educational demonstration of surface tension. Researchers have observed the self-motion of sodium benzoate flakes on a water surface¹² and designed a boat that runs on liquids as “fuel”.¹³ Another study showed how the self-propulsion of sodium oleate tablets can be driven by interfacial tension imbalance induced by inhomogeneous adsorption of oleate/oleic acid molecules.¹⁴ These findings demonstrate the vast array of techniques and experiments that have been developed to better understand the concepts of surface or interfacial tension.

Liquid metals exist as either an alloy or an elemental metal and remain in liquid form at room temperature. They possess both fluid and metallic properties thus making an interesting topic for study. Traditionally, mercury has been the most recognized liquid metal. The mercury beating heart

demonstration has been popularized for electrochemistry education.¹⁵⁻¹⁸ This demonstration shows the oscillations that occur due to the periodic changes in surface tension of mercury droplets caused by redox reactions. Unfortunately, the high toxicity of mercury has limited its use as a classroom demonstration. Gallium-based metal alloys provide an alternative to mercury as they not only have fluidity at room temperature but also have low vapor pressure, and are non-toxic. This means these metals can serve as safer demonstrations.¹⁹⁻²² In a previous demonstration, gallium and its alloys formed a beating heart that occurred in a uniform solution where oscillations were induced by the periodic change of surface tension. Self-propulsion or deformation of the liquid metals resulted from a surface tension gradient²³⁻²⁴ that was derived from ionic imbalance,²⁵ redox reaction,²⁶⁻²⁸ or electric field.²⁹⁻³⁰

In the previous Gallium-based liquid metal beating heart demonstrations, the position of the iron nails or the electrodes in contact with the liquid metal droplets required careful adjustment to trigger a “heartbeat” or oscillation. Here, we present a straightforward and visually striking demonstration to introduce some fundamental principles in chemical reactions, including redox, electrical double layer, and interfacial tension. Adding chemical substances far from one side of the droplets in a uniform aqueous solution can produce directional movement of Ga-based liquid metal. To reduce the necessary amount of chemicals, a small device is employed. This demonstration, simple and visually stimulating, can effectively motivate undergraduate students to explore the underlying principles and provide them with hands-on laboratory experience. Ultimately, we propose a mechanism of droplet movement to interpret these intriguing phenomena.

MATERIALS AND EQUIPMENT

The experimental setup consisted of several reagents and materials, including Galinstan - a Ga-based liquid metal composed of 68.5% gallium, 21.5% indium, and 10% tin, 1 mol/L hydrochloric acid, aqueous hydrogen peroxide at 35% concentration, potassium dichromate, copper sulfate, copper (II) chloride, potassium iodide, and deionized water. The experiment was carried out in a homemade polymethylmethacrylate (PMMA) channel with the dimensions of 4 mm width, 4 mm depth, and 40 mm length, along with a 3-mm radius cylindrical chamber at each end (Figure 1). The PMMA substrate

1
2
3 can be purchased from local stores or on line, then fabricated by a numerical controlled machine.
4
5 Alternatively, polytetrafluoroethylene (PTFE) is another choice for the substrate. The channel can also
6
7 be fabricated on a glass slide using polydimethylsiloxane (PDMS) through molding technique, or
8
9 80 printed by a 3D printer with polylactic acid (PLA). The reagents were applied to the channel and
10
11 chambers using a spatula or dropper.

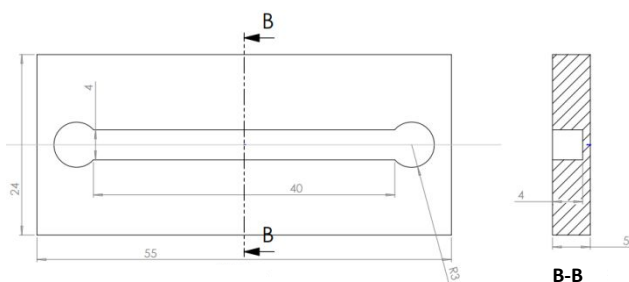


Figure 1. Machine drawing of the channel used in this demonstration (unit: mm).

EXPERIMENTAL PROCEDURE

25
26
27 85 To perform this experiment, the PMMA channel is first filled with 1 mol/L HCl solution. With the aid of
28
29 a pipette, a drop of Galinstan with a volume of approximately 20 μL is added near the center of the
30
31 channel. Observing and recording what is happening to the drop begins at this point. To create an
32
33 unsymmetric solution, one chemical chosen from sodium hydroxide, potassium dichromate, copper
34
35 sulfate, copper (II) chloride, potassium iodide, and aqueous H_2O_2 (35%) is then added to the right
36
37 90 chamber. Different unsymmetric solutions are produced by adding respective chemicals to fresh HCl
38
39 solution with fresh Galinstan drop. An instructor performs the demonstration, and students observe
40
41 and make note with further discussions. A USB camera is employed to capture the Galinstan drop's
42
43 directional motion under different conditions. Students are encouraged to carry out this experiment
44
45 independently or in groups under supervision. Demonstration interaction with questions and
46
47 95 discussions, takes place before and during the demonstration to facilitate students' understanding of
48
49 interfacial tension and redox reaction concepts. The accompanying Supporting Information includes
50
51 videos of the experiment, learning objectives, and guidelines of demonstration interaction.
52
53
54
55
56
57
58

HAZARDS AND WASTE DISPOSAL

Unless exposed at a very high concentration, Galinstan is nontoxic.³¹ The disposal of Galinstan does not pose a significant environmental threat although its potential to adhere to most surfaces can pose a problem. If a surface contains aluminum components, adsorption of the alloys is very problematic and so such surfaces should be avoided. In contrast, chemicals such as sodium hydroxide, hydrochloric acid, hydrogen peroxide, and potassium dichromate are corrosive and can cause significant harm if mishandled. When using potassium dichromate, a highly toxic substance, caution must be taken. However, less toxic strong oxidants can also be tested as alternatives to trigger the directional motion of the galinstan drop. Copper salts and potassium iodide can also cause skin and eye irritation. Given these hazards, the students must be made aware of the potential risks as well as the precautions that need to be taken before handling these chemicals. They should refer to the material safety data sheet (MSDS)³² for each chemical to fully understand associated hazards. To prevent accidents, the students are required to follow standard lab safety protocols at all times and proper personal protective equipment, such as goggles, gloves, and lab coats, should be worn during the experiments. Finally, any solutions used in an experiment should be disposed of in appropriate waste containers.

RESULTS AND DISCUSSION

Video images were recorded to demonstrate the directional motion of the Galinstan drop in the following. Upon the addition of NaOH to the right chamber of a channel filled with HCl solution, the Galinstan drop quickly migrated towards the right side (Figure 2). This suggests that the Galinstan drop prefers migrating towards the higher pH region. These observations are consistent with Zavabeti et al.'s findings that the self-propulsion of liquid metal drops occurs due to a pH imbalance resulting in a difference in interfacial tension on opposing hemispheres of the drop.²⁵ Higher surface tension on the HCl side propels the drops towards the NaOH side with lower surface tension. The difference in interfacial tension was confirmed by Handschuh-Wang et al.'s research on Galinstan, which showed a higher interfacial tension in an HCl solution than that in a NaOH solution.²⁹

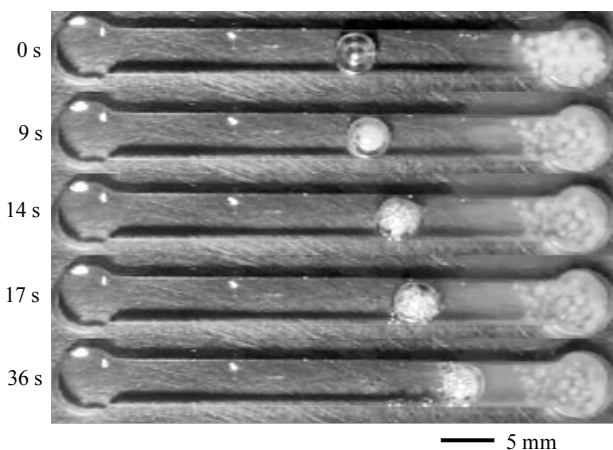
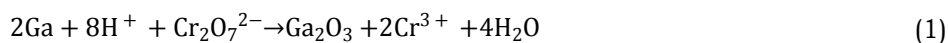


Figure 2. Video images of the directional motion of Galinstan drop in 1 mol/L HCl solution with the addition of NaOH to the right chamber.

When using oxidants, the Galinstan drop was observed to move towards the oxidants. Figure 3 illustrates the displacement of the drop in an HCl solution with the addition of potassium dichromate in the right chamber. Initially, the potassium dichromate dissolves, diffuses, and eventually reaches the liquid metal drop. Following this, the drop begins to elongate and after 203 seconds, it quickly moves to the right side. Similarly, a comparable behavior was displayed by mercury.²⁷ This motion of the mercury drop was ascribed to the asymmetry of the interfacial tension on the two sides of the drop, which resulted from the formation of a concentration gradient of dichromate ions. Gallium, the main component in Galinstan, has a lower standard reduction potential (Ga^{3+}/Ga : -0.529 V vs. SHE) than the other two components (In^{3+}/In : -0.340 V; Sn^{2+}/Sn : -0.138 V). Thus, upon contact with oxidants exhibiting a higher standard reduction potential than gallium, the predominant oxidation reaction involves gallium. The surface of the Galinstan drop can be oxidized by the dichromate ion to form a Ga_2O_3 film. The redox reaction is described as follows:



The higher concentration of potassium dichromate on the right side of the Galinstan drop resulted in the formation of a thicker oxide film on the right side than that on the left side. Although the Ga_2O_3 film formed on the Galinstan surface can be dissolved by an acidic solution, when the formation rate of the oxide film exceeds the rate of dissolution, more oxide film remains on the right side than on the left side. The presence of an oxide film on the liquid metal surface can significantly reduce the interfacial tension,^{24, 33} which leads to a higher tension on the left side than the right and ultimately

caused the displacement of the drop towards the right. The presence of hydrogen peroxide solution in the right chamber induces similar redox reactions, resulting in the drop moving to the right side in an acidic electrolyte, as demonstrated in Figure 4. This motion can be again attributed to the difference in interfacial tension caused by the difference in oxide film thickness on the two sides of the drop. The reaction between Ga and H_2O_2 can be represented by the following equation:

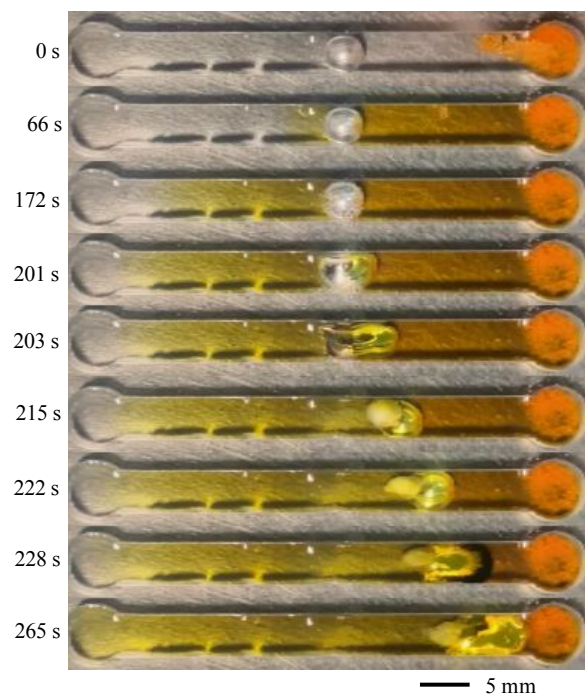


Figure 3. Directional motion of a Galinstan drop in 1 mol/L HCl solution with the addition of $\text{K}_2\text{Cr}_2\text{O}_7$.

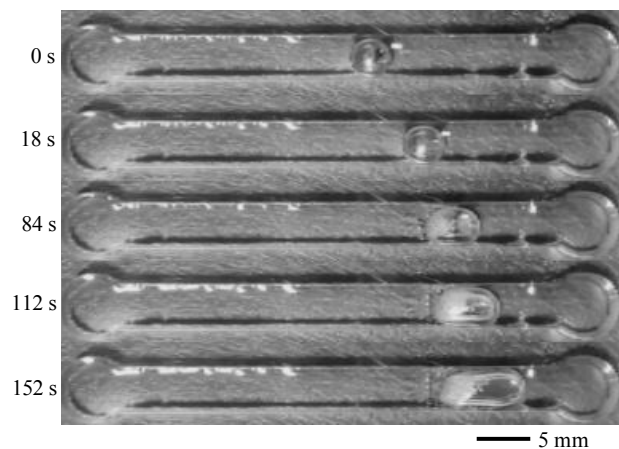
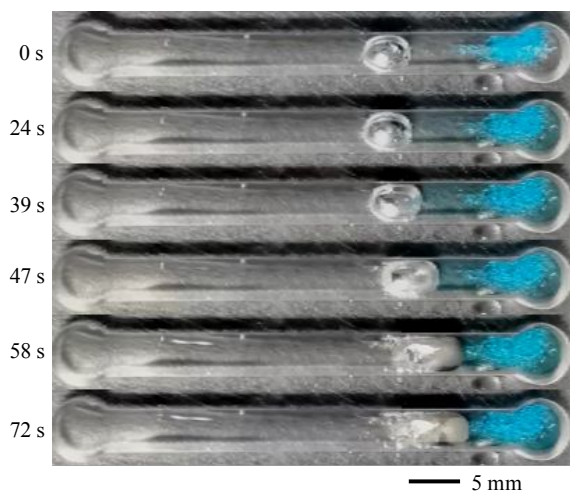


Figure 4. Directional motion of a Galinstan drop in 1 mol/L HCl solution with the addition of aqueous H_2O_2 (35%).

1
2
3 155 The low standard reduction potential of gallium results in galvanic replacement reactions
4
5 occurring when gallium-based metal alloys encounter many metal salt solutions at the liquid metal-
6
7 solution interface.³⁴⁻³⁵ In this study, we demonstrate the directional motion of a Galinstan drop in an
8
9 HCl solution by adding copper sulfate (Figure 5) and copper (II) chloride (Figure 6). As observed, the
10
11 liquid metal drop rapidly moves towards the right side when the blue (from CuSO₄) or green (from
12
13 160 CuCl₂) color reaches the drop. Dark gray or reddish-orange typically appears with time at the interface
14
15 of the liquid metal and copper salt solutions, with both colors confirmed as presence of copper.^{26, 35}
16
17 Equation (3) describes the galvanic replacement reaction that occurs with the addition of copper salt.
18
19 The locomotion of liquid metal is initiated by the surface tension difference associated with the
20
21 unbalanced interfacial tension, as copper generated in galvanic replacement form a galvanic cell with
22
23 165 gallium, leading to the reduction of interfacial tension at the right hemisphere.²⁶ Therefore, the
24
25 unbalanced interfacial tension on the Galinstan drop causes the motion of the drop towards the right
26
27 side. In the case of CuCl₂, the speed of the liquid metal drop is faster than that in CuSO₄. After 41
28
29 seconds, the drop arrives at the right chamber and then quickly migrates towards the left side. In
30
31 Figure 6, we note that the Galinstan drop always moves towards the areas where the electrolyte is
32
33 170 green or dark green, reflecting the direction with concentrated CuCl₂ solution. When the drop occupies
34
35 the right chamber, the original CuCl₂ solution with high concentration is pushed into the left side of
36
37 the drop. The Galinstan drop continuously pursues the concentrated CuCl₂ solution, as copper is left
38
39 behind and new galvanic replacement takes place. Thus, the mechanism for this case is likely similar
40
41 to that of CuSO₄ addition, as copper generated from galvanic replacement on one hemisphere drive the
42
43 175 directional motion of the drop by causing the unbalanced interfacial tension on the drop surface.





18
19 **Figure 5.** Movement of a Galinstan drop in 1 mol/L HCl solution with the addition of CuSO_4 .



46 180 **Figure 6.** Snapshots of the motion of a Galinstan drop in 1 mol/L HCl solution with the addition of CuCl_2 .

47
48 If potassium iodide was added to the right chamber, the Galinstan drop also moves to the right
49 side, as shown in Figure 7. Handschuh-Wang et al. observed that the interfacial tension of Galinstan
50 can be greatly reduced by acidified KI solution, where I^- is a surface-active anion.²⁹ When potassium
51 iodide dissolves, diffuses, and gets in touch with the right hemisphere of the Galinstan drop, the iodide
52 anion will be adsorbed on the right hemisphere, increasing the surface charge density of the electrical
53
54
55
56 185
57
58

double layer and thereby lowering the interfacial tension. This interfacial tension gradient across the Galinstan drop generates a force that propels the drop towards the right side.

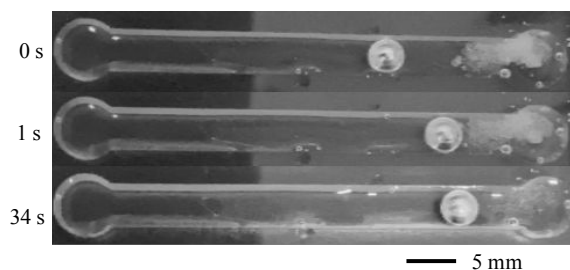


Figure 7. Directional motion of a Galinstan drop in 1 mol/L HCl solution with the addition of KI.

When immersed in an acidic electrolyte, the Galinstan drop undergoes a chemical reaction with the acid solution. The dominant and more active metal, gallium, reacts to generate Ga^{3+} ions, positively charging the drop surface. Adsorbed Ga^{3+} cations cause an accumulation of anions in the surrounding electrolyte, leading to an evenly distributed surface charge across the liquid metal-electrolyte interface, forming an electrical double layer (EDL). The interfacial tension (γ) on the liquid metal drop can be expressed by integrated Lippmann equation³⁶:

$$\gamma = \gamma_0 - \frac{1}{2}cV^2 \quad (4)$$

where γ_0 denotes the maximum surface tension when $V = 0$, c is the EDL capacitance per unit area, and V is the potential difference across the EDL.

Interfacial tension could be adjusted by directly modifying the EDL by altering the electrolyte surrounding.²⁵ The impact of the surrounding chemical environment on interfacial tension has been demonstrated for mercury³⁷ and liquid gallium³⁸. The maximum surface tension is a function of electrolyte type. When additional chemicals are introduced far from the one side of a Galinstan drop, they dissolve and diffuse to the drop. This results in two distinct hemispheres of the drop with differing chemical environments. The interfacial tension of the hemisphere exposed to the additional chemicals is altered by the factors such as changes in pH, redox reaction, galvanic replacement, and adsorption. This leads to a difference in interfacial tension across the drop.

To unravel the mechanism underlying the drop movement, the force analysis is depicted in Figure 8. The direction of the drop movement towards the right side is defined as positive. The driving force

(dF) imposed on the drop, induced by the unbalanced Young's force, can be given by the following equations:

$$F_R = (\gamma_{sa(R)} - \gamma_{sl(R)})dx = \gamma_{la(R)}\cos\theta_R dx \quad (5)$$

$$F_L = -(\gamma_{sa(L)} - \gamma_{sl(L)}) dx = -\gamma_{la(L)}\cos\theta_L dx \quad (6)$$

$$dF = F_R + F_L = \gamma_{la(R)}\cos\theta_R dx - \gamma_{la(L)}\cos\theta_L dx \quad (7)$$

where γ_{sa} , γ_{sl} , and γ_{la} denote the interfacial tensions on the solid/aqueous, solid/liquid metal and liquid metal/aqueous interfaces, respectively. The contact angle between the liquid metal droplet and the PMMA surface is represented by θ , while R and L indicate the right and left sides of the droplet. The thickness of the section of the drop is represented by dx . In a uniform acidic electrolyte, EDL is formed on the interface between the drop and the electrolyte. The absence of the attraction between the drop and the PMMA surface, along with the high interfacial tension γ_{la} between the drop and the electrolyte, leads to $\gamma_{la(R)} = \gamma_{la(L)}$ and $\theta_R = \theta_L > 90^\circ$, as shown in Figure 8A. Thus, dF is equal to 0 and no movement of the drop occurs. If the interfacial tension is reduced on the right hemisphere of the drop due to the addition of chemicals and remains constant on the left hemisphere, i.e. $\gamma_{la(R)} < \gamma_{la(L)}$, the right hemisphere of the drop will spread further towards the right side, causing $\theta_R < \theta_L$. As $\cos\theta_L < 0$ and $\theta_L > \theta_R$, dF always is positive, and the drop tends to move to the right side. The balance between the driving and resistance forces determines the forces acting on the droplet. When the driving force is greater than the resistance force, the drop moves towards the right side (Figure 8B).

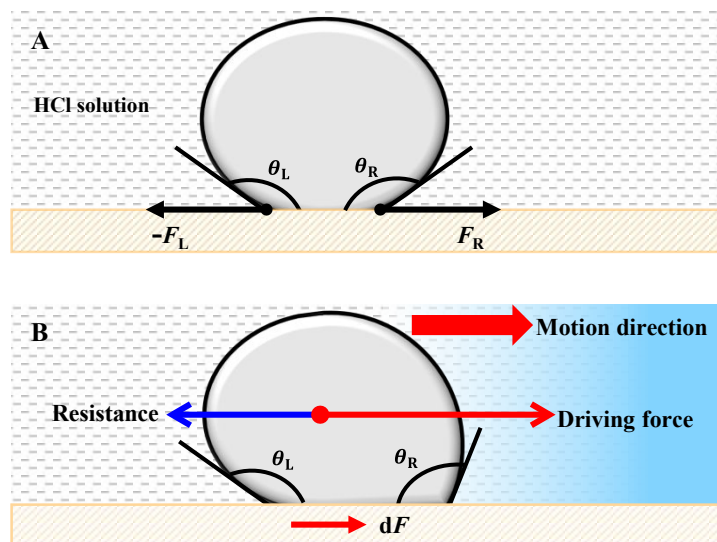


Figure 8. Mechanism of directional motion of a Galinstan drop towards the right side without (A) and with (B) the addition of different chemicals.

CONCLUSION

A classroom demonstration featuring directional motions of gallium-based liquid metal drops is presented as an effective tool to introduce fundamental principles in chemical reactions. These principles include redox reactions, the electrical double layer, and interfacial tension. This simple, visually observable experiment requires minimal chemicals and can effectively stimulate students' interest to explore the underlying chemical principles. The proposed mechanism of the drop's directional motions sheds light on these intriguing phenomena. When chemicals are added to only one side of the originally uniform electrolyte, the two hemispheres of the drop encounter different chemical surroundings, resulting in the difference in interfacial tension. The force acting on the drop is then analyzed in terms of the interfacial tension. When the difference becomes significant enough, the driving force will exceed the resistance force and propel the drop to move.

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.

Learning objectives, guidelines of demonstration interaction (PDF, DOCX)

Video S1: Adding sodium hydroxide to the right chamber filled with HCl solution (MP4)

Video S2: Adding potassium dichromate in HCl solution (MP4)

Video S3: Adding H₂O₂ (35%) in HCl solution (MP4)

Video S4: Adding CuSO₄ in HCl solution (MP4)

Video S5: Adding CuCl₂ in HCl solution (MP4)

Video S6: Adding KI in HCl solution (MP4)

AUTHOR INFORMATION

Corresponding Author

*E-mail: wangbxucl@outlook.com

ORCID

Bingxing Wang: 0000-0002-4406-6736

Yongcai Zhang: 0000-0003-1551-754X

Donglin Zhao: 0000-0002-2291-6672

Note

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the Key Scientific and Technological Project of Henan Province (222102230079), the Key Scientific Research Projects of Colleges and Universities in Henan Province of China (22A150039), Postgraduate Education Reform and Quality Improvement Project of Henan Province (YJS2022JC24), and Research and Practice Project of High Education Reform of Henan Institute of Science and Technology (2021XJGLX07).

REFERENCES

- (1) Atkins, P.; Paula, J. D. *Atkins' Physical Chemistry*. 10th ed.; Oxford University Press: Oxford, 2014; pp 683-688.
- (2) Gencer, S.; Ekici, F. Preservice Chemistry Teachers' Understanding of Surface Tension through Guided-Inquiry. *J. Chem. Educ.* **2022**, *99* (12), 3946-3953.
- (3) Gesser, H. D.; Paul, K. A Demonstration of Surface Tension and Contact Angle. *J. Chem. Educ.* **2000**, *77* (1), 58-59.
- (4) Park, C.; Lee, C. Y.; Hong, H.-G. Undergraduate Students' Understanding of Surface Tension Considering Molecular Area. *J. Chem. Educ.* **2020**, *97* (11), 3937-3947.
- (5) Gugliotti, M.; Todd, S. Tears of Wine. *J. Chem. Educ.* **2004**, *81* (1), 67-68.

- (6) Crowe, C. D.; Hendrickson-Stives, A. K.; Kuhn, S. L.; Jackson, J. B.; Keating, C. D. Designing and 3D Printing an Improved Method of Measuring Contact Angle in the Middle School Classroom. *J. Chem. Educ.* **2021**, *98* (6), 1997-2004.
- (7) Rosenthal, A. J. Demonstration of Surface Tension. *J. Chem. Educ.* **2001**, *78* (3), 332-333.
- (8) Huck-Iriart, C.; De-Candia, A.; Rodriguez, J.; Rinaldi, C. Determination of Surface Tension of Surfactant Solutions through Capillary Rise Measurements: An Image-Processing Undergraduate Laboratory Experiment. *J. Chem. Educ.* **2016**, *93* (9), 1647-1651.
- (9) Gascon, K. N.; Weinstein, S. J.; Antoniadis, M. G. Use of Simplified Surface Tension Measurements To Determine Surface Excess: An Undergraduate Experiment. *J. Chem. Educ.* **2019**, *96* (2), 342-347.
- (10) Bai, Y. S.; Li, G. L.; Li, L.; Wang, K. W.; Li, S. R.; Liu, H. H. Optimized and Refined Apparatus for Measuring Surface Tension with the Bubble-Pressure Method. *J. Chem. Educ.* **2021**, *98* (3), 1052-1056.
- (11) Chan, C. J.; Salaita, K. The Molecular Boat: A Hands-On Experiment To Demonstrate the Forces Applied to Self-Assembled Monolayers at Interfaces. *J. Chem. Educ.* **2012**, *89* (12), 1547-1550.
- (12) Darvesh, K. V.; Martin, E. Self-Motion of Sodium Benzoate Flakes on a Water Surface: A Demonstration. *J. Chem. Educ.* **2017**, *94* (2), 226-229.
- (13) Renney, C.; Brewer, A.; Mooibroek, T. J. Easy Demonstration of the Marangoni Effect by Prolonged and Directional Motion: "Soap Boat 2.0". *J. Chem. Educ.* **2013**, *90* (10), 1353-1357.
- (14) Watahiki, Y.; Nomoto, T.; Chiari, L.; Toyota, T.; Fujinami, M. Experimental Investigation of the Self-Propelled Motion of a Sodium Oleate Tablet and Boat at an Oil-Water Interface. *Langmuir* **2018**, *34* (19), 5487-5494.
- (15) Stribling, D.; Brewer, C. R.; Goldsby, K. A. Resuscitating the Mercury Beating Heart: An Improvement on the Classic Demo. *J. Chem. Educ.* **2021**, *98* (2), 662-664.
- (16) Demiri, S.; Najdoski, M.; Mirceski, V.; Petruševski, V. M.; Daniel, R. Mercury Beating Heart: Modifications to the Classical Demonstration. *J. Chem. Educ.* **2007**, *84* (8), 1292-1295.
- (17) Keizer, J.; Rock, P. A.; Lin, S.-W. Analysis of the Oscillations in "Beating Mercury Heart" Systems. *J. Am. Chem. Soc.* **1979**, *101* (19), 5637-5649.
- (18) Castillo-Rojas, S.; Burillo, G.; Vicente, L. Complex Oscillatory Behavior of the Mercury Beating Heart System. *Chem. Educator* **2002**, *7* (3), 159-165.
- (19) Yi, L. T.; Wang, Q.; Liu, J. Self-Powered Gallium-Based Liquid-Metal Beating Heart. *J. Phys. Chem. A* **2019**, *123* (43), 9268-9273.
- (20) Ealy, J. L. Gallium beating heart. *J. Chem. Educ.* **1993**, *70* (6), 491-492.
- (21) Wang, B.; Wang, Q.; Jiang, X.; Zhang, Y.; Zhang, Y.; Zhang, Y. Direct Current (DC) Electric Field-Enabled Beating Heart of Ga-Based Liquid Metal. *J. Chem. Educ.* **2022**, *99* (9), 3337-3341.
- (22) Wang, B.; Jiang, X.; Zhang, Y.; Yu, L.; Zhang, Y. A Safer Alternative for the Mercury Beating Heart Demonstration. *J. Chem. Educ.* **2022**, *99* (2), 1095-1099.

- (23) Duan, M. H.; Zhu, X. Y.; Shan, X. H.; Wang, H. Z.; Chen, S.; Liu, J. Responsive Liquid Metal Droplets: From Bulk to Nano. *Nanomaterials* **2022**, *12* (8), 1289.
- (24) Fu, J. H.; Liu, T. Y.; Cui, Y. T.; Liu, J. Interfacial Engineering of Room Temperature Liquid Metals. *Adv. Mater. Interfaces* **2021**, *8*, 2001936.
- (25) Zavabeti, A.; Daeneke, T.; Chrimes, A. F.; O'Mullane, A. P.; Zhen Ou, J.; Mitchell, A.; Khoshmanesh, K.; Kalantar-zadeh, K. Ionic Imbalance Induced Self-Propulsion of Liquid Metals. *Nat. Commun.* **2016**, *7*, 12402.
- (26) Chen, S.; Yang, X. H.; Cui, Y. T.; Liu, J. Self-Growing and Serpentine Locomotion of Liquid Metal Induced by Copper Ions. *ACS Appl. Mater. Interfaces* **2018**, *10* (27), 22889-22895.
- (27) Nakata, S.; Komoto, H.; Hayashi, K.; Menzinger, M. Mercury Drop "Attacks" an Oxidant Crystal. *J. Phys. Chem. B* **2000**, *104* (15), 3589-3593.
- (28) Chen, S.; Liu, J. Spontaneous Dispersion and Large-Scale Deformation of Gallium-Based Liquid Metal Induced by Ferric Ions. *J. Phys. Chem. B* **2019**, *123* (10), 2439-2447.
- (29) Handschuh-Wang, S.; Chen, Y. Z.; Zhu, L. F.; Gan, T. S.; Zhou, X. C. Electric Actuation of Liquid Metal Droplets in Acidified Aqueous Electrolyte. *Langmuir* **2019**, *35* (2), 372-381.
- (30) Hu, L.; Wang, L.; Ding, Y. J.; Zhan, S. H.; Liu, J. Manipulation of Liquid Metals on a Graphite Surface. *Adv. Mater.* **2016**, *28* (41), 9210-9217.
- (31) Dickey, M. D. Liquid Metals at Room Temperature. *Physics Today* **2021**, *74* (4), 30-36.
- (32) MSDS-Query and Download in Multiple Languages; ChemicalBook Inc. <https://msds.chemicalbook.com/IndexEN> (accessed March 2023).
- (33) Khan, M. R.; Eaker, C. B.; Bowden, E. F.; Dickey, M. D. Giant and Switchable Surface Activity of Liquid Metal via Surface Oxidation. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111* (39), 14047-14051.
- (34) Hoshyargar, F.; Crawford, J.; O'Mullane, A. P. Galvanic Replacement of the Liquid Metal Galinstan. *J. Am. Chem. Soc.* **2017**, *139* (4), 1464-1471.
- (35) Oloye, O.; Fernando, J. F. S.; Waclawik, E. R.; Golberg, D.; O'Mullane, A. P. Galvanic Replacement of Liquid Metal Galinstan with Copper for the Formation of Photocatalytically Active Nanomaterials. *New J. Chem.* **2020**, *44* (35), 14979-14988.
- (36) Darhuber, A. A.; Troian, S. M. Principles of Microfluidic Actuation by Modulation of Surface Stresses. *Annu. Rev. Fluid Mech.* **2005**, *37* (1), 425-455.
- (37) Grahame, D. C. The Electrical Double Layer and the Theory of Electrocapillarity. *Chem. Rev.* **1947**, *41* (3), 441-501.
- (38) Frumkin, A.; Polianovskaya, N.; Grigoryev, N.; Bagotskaya, I. Electrocapillary Phenomena on Gallium. *Electrochim. Acta* **1965**, *10* (8), 793-802.