Metal Ion-Responsive Self-Propelled Motion of Compound A on Aqueous Surfaces

Megan Santamore
Electrical and Computer Engineering
Princeton University
Princeton, NJ, USA
ms9923@alumni.princeton.edu

Atsuro Takai
Molecular Design and Function Group
National Institute for Materials Science
Tsukuba, Japan
takai.atsuro@nims.go.jp

Lara Rae Holstein
Molecular Design and Function Group
National Institute for Materials Science
Tsukuba, Japan

Masayuki Takeuchi
Molecular Design and Function Group
National Institute for Materials Science
Tsukuba, Japan
takeuchi.masayuki@nims.go.jp

Abstract—**Certain chemical compounds are known to demonstrate self-propelled motion on the surface of aqueous solutions due to Marangoni flow, or movement due to differences in surface tension across the surface of the object in question. Previous work in this field has shown that introducing reducing agents or other reactive species in solution impacts the surface tension across that compound, leading to new patterns of motion for the self-propelled movement of such compounds. One of these compounds, known as compound A (as this work is not yet published, the identity of the molecule being studied is not revealed in this report), is known to act as an ionophore, forming a complex around metal cations. This work demonstrates how this complex formation reaction shortens the time these compounds spend in self-propelled motion on the surface of water, as well as limits the spatial range of motion of compound A crystals on the surface of water. As further shown in this work, this is likely due to the marked decrease in surface tension on the surface of an aqueous solution when the metal ion and compound A complex is formed. Ultimately, a better understanding of how complex formation impacts the motion of such compounds will allow for water-purification systems to be designed using compound A's ionophore properties.**

I. INTRODUCTION

In nature, living matter exhibits a range of dynamic, autonomous motions. Scallops that exhibit reciprocal motion when they open, sucking in water from their surroundings and propelling forward, and close, releasing water back into their surroundings, thereby propelling them backwards, will not achieve a net displacement in a highly viscous fluid. Additionally, flagella exhibit propeller-like motion due to their motor and filament structure. Similarly, cilia exhibit side-to-side beating motions that allow the cell to coordinate back-and-forth motion. Outside purely biological systems, certain compounds exhibit dynamic, autonomous functions. One of the most common examples of such autonomous motion of chemicals is when differences in interfacial tension drive the motion of a compound; this is known as Marangoni flow.

Previous work in this field has been conducted with camphor, whose structure is shown in Figure 1, a compound that exhibits autonomous, self-propelled motion on the surface of water. When a crystal or compound of camphor is placed on the surface of water, it will begin to dissolve into the solution in all directions. Subsequently, the surface tension force acting on the camphor compound will be equal in all directions, resulting in no net movement of the compound. However, if there is any perturbation in the solution, such that the concentration of camphor in one direction decreases significantly, then the surface tension force will pull the camphor in the direction of the lower concentration of camphor in the solution. This interplay results in the self-propelled movement of camphor on the surface of an aqueous solution. This motion will occur until the camphor crystal is fully dissolved in the solution.

Fig. 1. Molecular structure of camphor.

Compound A is another compound known to demonstrate such autonomous motion on the surface of water, behaving similarly to camphor. Compound A's structure and identity will remain anonymous since this work is novel and currently unpublished. It is also known that compound A is an ionophore, meaning that when it is placed in a solution containing metal ions, compound A forms a complex with these ions. Moreover, compound A is a compound with interesting biological applications, as these complexes allow compound A to transport ions through membranes.

Knowing what the typical motion of compound A crystals' self-propelled movement on water looks like, this project investigates compound A crystals' self-propelled movement on water with metal ions in solution, which results in compound

A complex formation and may, thus, result in changes to the compound A's movement in water.

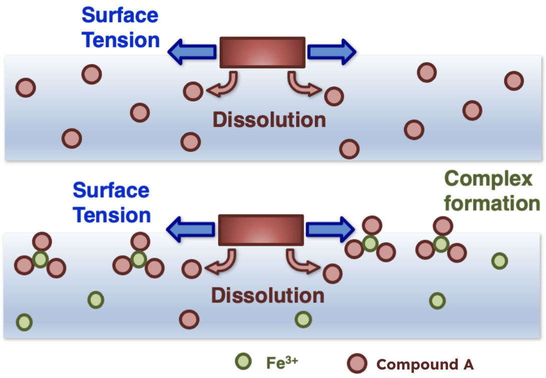

Fig. 2. Self-propelled motion of compound A on water in typical conditions and when there are metal ions in solution, in this case Fe^{3+}

II. METHODOLOGY AND RESEARCH SUMMARY

A. *Fe^{3+} and Compound A Complex Formation*

Research has shown that when metal ions are introduced into a solution containing compound A, the compound A and metal ion complex causes noticeable shifts in peaks on the solutions UV-Vis spectrum, which can be seen in Figure 3

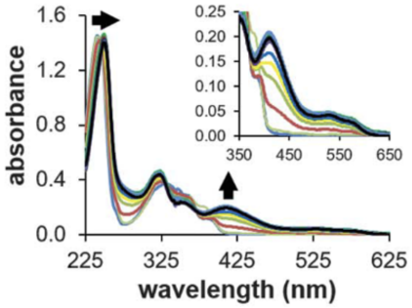

Fig. 3. When Fe^{3+} forms a complex with three of compound A, a rightward peak shift around 250 nm and an upward shift around 420 nm are known to occur [2].

These experiments were replicated, and similar peak shifts were seen at the Fe^{3+} and compound A complex concentrations at which unusual self-propelled motion was also known to be observed. These complex formation confirmation peaks can be seen in Figure 4. The UV-Vis spectroscopy peaks on this graph shift in a manner indicative of complex formation, as indicated by the literature. Using the saturation curve derived from this data, as seen in Figure 5, we can confirm that a compound A and metal ion complex is indeed forming.

B. *The Self-Propelled Motion of compound A is Dependent on the Concentration of Fe^{3+} in Solution*

The concentration of the compound A and metal ion complex impacts the self-propelled motion of compound A on water, such that as the complex concentration increases, compound A spends less time in motion, and compound A's movement is confined spatially. This can be seen in Figure 6. With any amount of metal cations in solution, the motion of compound A halts much faster than it would otherwise without metal ions in solution. Additionally, with higher concentrations of metal ions, the space over which compound A moves appears to decrease markedly.

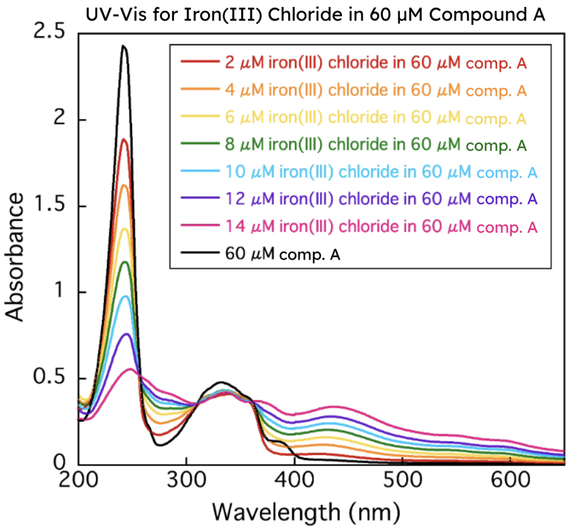

Fig. 4. When Fe^{3+} forms a complex with three of compound A, a rightward peak shift around 250 nm and an upward shift around 420 nm are shown to occur, as expected for this chemical system.

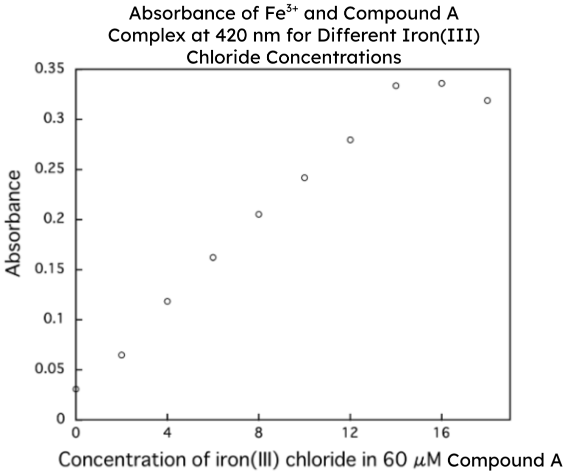

Fig. 5. The absorbance across different concentrations of the Fe^{3+} and compound A complex at 420 nm is plotted to confirm complex formation.

C. *The surface tension of the compound A and Fe^{3+} complex is significantly less than Fe^{3+} or compound A alone*

There is a marked decrease in surface tension for compound A and metal ion complexes when just compound A or metal ions alone at that concentration do not show such a decrease. This can be seen in Figure 7.

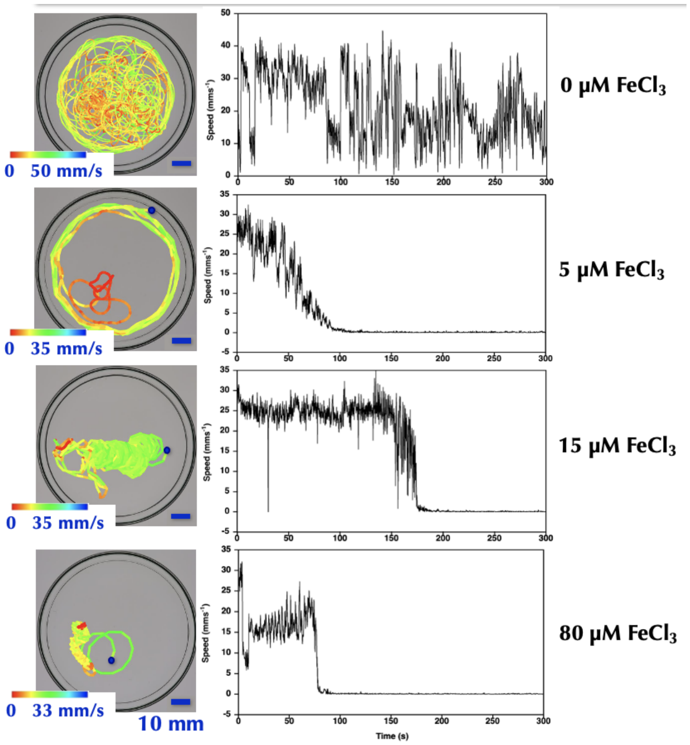

Fig. 6. The leftmost images in each row show the top view of the motion of the compound A crystal in aqueous solutions with varying concentrations of iron(III) chloride. The speed at which the particle is moving is indicated by the color. The rightmost images show the speed profile of the compound A crystal over time, showing that when metal cations are present in solution, the motion of the compound A crystal halts faster than it would otherwise without those metal cations.

III. CONCLUSIONS AND FUTURE WORK

In conclusion, this work demonstrates how the complex formation known to occur between compound A and iron(III) chloride both shortens the time that compound A spends in self-propelled motion on the surface of water and limits the spatial range of motion of compound A crystals on the surface of water. This work shows that this change in the self-propelled motion of compound A is likely due to the marked decrease in surface tension on the surface of an aqueous solution when the metal ion and compound A complex is formed.

Chemotaxis is the movement of an organism or cell in response to chemical stimuli. Typically, cells detect chemical gradients through receptors on their surface, which trigger the movement of the cell in response to its environment based on that gradient. Going forward, this responsiveness to metal ion concentration could be used for controlled movement of compound A by maintaining a set metal ion concentration gradient.

ACKNOWLEDGMENT

I would like to thank my PIs, Dr. Masayuki Takeuchi and Dr. Atsuro Takai. Also, I would like to thank Lara Rae Holstein for her guidance in the laboratory. I would also like to thank Dr. Lynn Rathbun and all the other CNF iREU program staff for their administrative support and for providing all of us with this amazing research opportunity. I would also like to thank the National Science Foundation for supporting this research (NSF Grant Number 2246252). Lastly, but certainly not least, I would like to thank the nine other students in this program for the shared meals, laughs, and adventures this summer. All of you made this summer a once-in-a-lifetime experience that I will treasure for a long, long time.

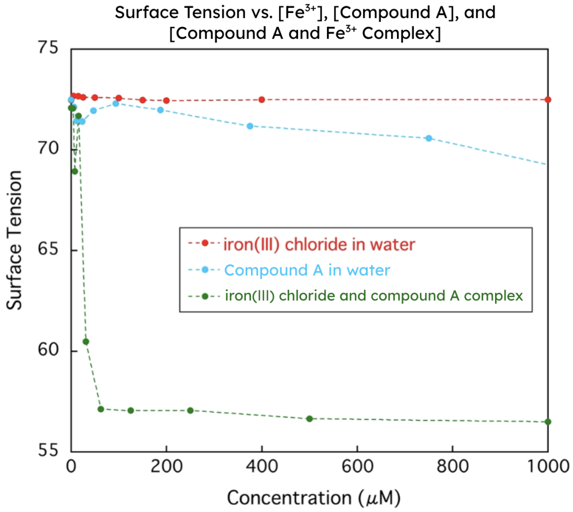

Fig. 7. Plot showing the measured surface tension of aqueous solutions containing a varying concentration of iron(III) chloride in water, compound A in water, and the compound A and iron(III) chloride complex in water.

REFERENCES

[1] A. S. Grillo et al., "Restored iron transport by a small molecule promotes absorption and hemoglobinization in animals," Science, vol. 356, no. 6338, pp. 608–616, May 2017. doi:10.1126/science.aah3862

[2] X. Ju et al., "Technology roadmap of Micro/Nanorobots," ACS Nano, vol. 19, no. 27, pp. 24174–24334, Jun. 2025. doi:10.1021/acsnano.5c03911

[3] J. Kim et al., "Advanced Materials for Micro/nanorobotics," Chemical Society Reviews, vol. 53, no. 18, pp. 9190–9253, 2024. doi:10.1039/d3cs00777d