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Laboratory Experiment

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Synthesis and Characterization of Metal Complexes with Schiff Base Ligands

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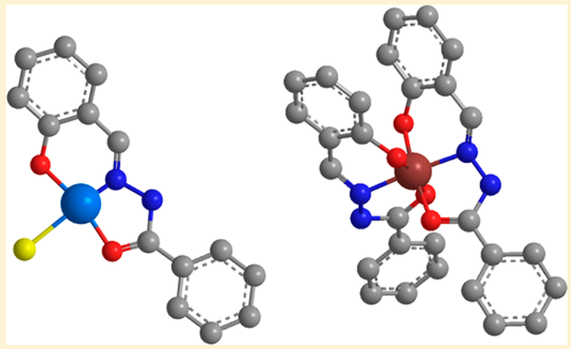
Supporting Information

ABSTRACT: In order for undergraduate laboratory experiments to reflect modern research practice, it is essential that they include a range of elements, and that synthetic tasks are accompanied by characterization and analysis. This intermediate general chemistry laboratory exercise runs over 2 weeks, and involves the preparation of a Schiff base ligand and its metal (Fe^{3+} or Cu^{2+}) complex. Students are then able to determine the metal—ligand stoichiometry of one metal—ligand pair. This experiment demonstrates that varying the transition metal can give rise to different structures, and hence different properties.



KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Interdisciplinary/Multidisciplinary, Inquiry-Based/Discovery Learning, Coordination Compounds, UV-Vis Spectroscopy*

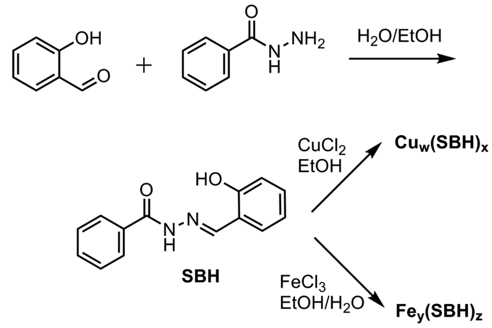
INTRODUCTION

As a result of historical divisions of chemistry schools into distinct areas of chemistry, such as "organic", "inorganic", "analytical", etc., many laboratory programs still tend to teach and assess these aspects of chemistry in isolation. However, this is inconsistent with modern research practice in which the majority of research programs incorporate techniques across various disciplines. To develop students into modern scientists, it is essential that laboratory teaching model research practice,[1] necessitating the development of integrated laboratory exercises.[2] Herein, a laboratory experiment is described for intermediate general chemistry students that teaches a wide range of laboratory skills.

The preparation and characterization of metal complexes and metal—ligand interactions has historically played a foundational role in many branches of chemistry and beyond,[3] and continues to be key in diverse research areas from bioinorganic chemistry[4] to molecular framework materials[5] to small molecule catalysis.[6] Key to all these applications is the dependence of complex composition and structure on the metal ion, and its oxidation state. Schiff bases, or imines, have long been known to be useful metal ligands,[7] with key roles in biology as intermediates of many enzymatic reactions,[8] and applications in chemistry, such as in asymmetric catalysis.[9] They are readily prepared by reaction of amines with aldehydes or ketones to form a hemiaminal, which is then dehydrated to form an imine. Due to the relatively simple yet robust synthetic procedure, Schiff base formation and complexation have formed the basis of a number of elegant reported undergraduate experiments that explore various aspects of Schiff base chemistry, from the formation of organometallic complexes,[10] to combinatorial synthesis,[11] to spectral analysis.[12] In this experiment, Schiff base ligands are used to demonstrate the effect of metal ion on metal—ligand stoichiometry.

In this experiment, students synthesize salicylaldehyde benzoyl hydrazone (SBH) (Scheme 1), a Schiff base-type ligand; prepare a Cu^{2+} or Fe^{3+} metal—SBH complex; and investigate the properties of this complex, most notably the binding stoichiometry. By providing students with different metal starting materials and requiring them to share their results at the end of semester, students are able to engage in enquiry-driven learning,[13] with community-based enquiry, strengthening their critical thinking skills.[14]

Scheme 1. Synthesis of Salicylaldehyde Benzoyl Hydrazone (SBH) and Its Copper and Iron Complexes



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■ EXPERIMENT

The timespan of this experiment is two, 4 h sessions, with a prelab quiz administered at the beginning of each session. The experiment is carried out individually. In the first session, students prepare solutions of benzhydrazide (7.3 mmol) in water and salicylaldehyde (15.1 mmol) in ethanol. The solution of salicylaldehyde is added with stirring to the solution of benzhydrazide over 10 min. SBH is collected as a solid, washed with ethanol, and recrystallized from ethanol. The yield, appearance of the ligand, and melting point are recorded. Each student is assigned either Cu^{2+} or Fe^{3+} ion from which to prepare a metal–SBH complex. SBH (2.9 mmol) is dissolved in ethanol on a steam bath, and immediately a solution of the relevant metal salt (3–6 mmol) is added. The metal–SBH complex precipitates and the solid is collected. The yield and appearance of the complex are recorded. In the second session, students record the full UV–visible absorption spectra for solutions of the ligand, metal salt and metal complex. The wavelength of maximum absorbance, intensity at this wavelength, and solution color are recorded for each solution. Students perform the method of continuous variation to generate a Job's plot at a wavelength for the metal–ligand pair to determine the stoichiometry of metal:ligand binding. Eleven different solutions are prepared containing varying amounts of ligand and metal solution, but a constant total concentration of ligand and metal; absorbance values are collected for each solution. A plot of the absorbance against mole fraction of ligand is prepared, and the stoichiometry is obtained from the point at which the slope changes from positive to negative. Students collate results so that they can comment on the differences between the iron and copper complexes. A detailed description of the experimental procedure is in the Supporting Information.

■ HAZARDS

Students must wear safety glasses and laboratory coats at all times. The synthetic steps should be performed in a fumehood. Salicylaldehyde, SBH, and the iron and copper complexes are irritating to eyes and skin. Benzhydrazide is toxic if swallowed and irritating to eyes and skin. The copper(II) and iron(III) chloride salts are harmful if swallowed and by inhalation. Ethanol and methanol are both highly flammable and toxic, the latter being particularly toxic when absorbed through the skin. Students are provided with access to the material safety data sheets for all chemicals, and are asked questions on safety aspects of the experiment as part of their prelab work.

■ RESULTS AND DISCUSSION

This experiment has been performed in an intermediate general chemistry laboratory course with 250 enrolled students. Students in this course had completed first-year general chemistry, comprising introductory organic, inorganic, physical and theoretical chemistries. This experiment is part of a rotation of five mutually exclusive experiments comprising the laboratory component of the unit of study. Each rotation consists of 60 students divided into five groups. One group of students (12 in total) completes the experiment on each lab day, carrying out the experiments individually. As previously stated, this experiment is split up into two separate sessions: the first being the synthesis of SBH and a metal–SBH complex; the second being a UV–visible spectroscopic analysis exercise, consisting of obtaining the UV–visible spectrum of SBH and the metal–SBH complex, as well as establishing the metal:SBH stoichiometry via a Job's Plot.

All students reported the appearance of SBH as off-white crystals, with 89% (of the 250 students) obtaining crystals following recrystallization, and the remaining 11% collecting a powder (or very small crystals), even after purification, likely due to insufficient solubilization or too rapid cooling during recrystallization. Yields ranged from 13 to 97%, with an average of 65%. The greatest sources of yield loss arose from insufficient rinsing of crude product into the Büchner funnel, and use of excess solvent in the recrystallization step. A melting point of SBH within 1% of the literature value of 182 °C[15] was reported by 71% of students. For the remainder of students, for the vast majority (>96%), reported melting points were lower than literature values, indicating impurities. The copper complex was collected as dark green crystals or powder (yields 30–89%, average 56%) and the iron complex as very dark brown crystals or powder (yields 39–95%, average 62%).

Absorption spectra of methanolic solutions of SBH and the two metal complexes (Figure 1) were collected so that students could relate major absorption peaks to the colors of the three solutions (pale yellow for SBH, dark yellow-brown for the Fe complex, yellow-green for the Cu complex).

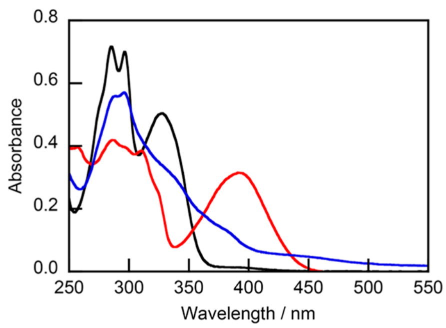

Figure 1. Representative student data of UV–visible absorption spectra for SBH (black), Fe–SBH complex (blue), and Cu–SBH complex (red). All solutions were 33 μM in methanol.

Job's plot analysis of copper binding (Figure 2) revealed a turning point at a ligand mole fraction (χ_L) of 0.5, corresponding to formation of a 1:1 complex. Ninety-four percent of students measured a turning point of between 0.45 and 0.55, therefore concluding the 1:1 complexation (average χ_L = 0.50, st. dev. = 0.03, n = 80). In a prework exercise, students identified the ligand mole fractions corresponding to binding stoichiometries of ML, ML_2, M_2L, M_2L_3 and ML_3.

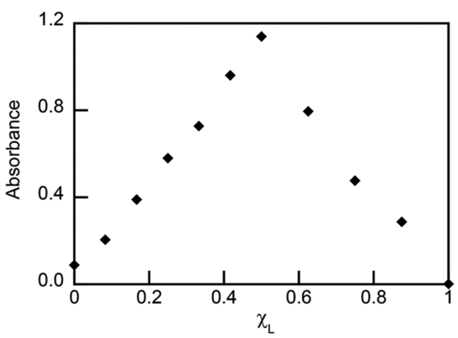

Figure 2. Representative student data for Job's plot of Cu^{2+} with SBH. λ_{abs} = 400 nm, [Cu^{2+} + SBH] = 0.42 mM in methanol.

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They then compared their measured turning point with these values. Students additionally performed regression analysis of the two segments of the plot, and solved simultaneous equations to determine the turning point (see Supporting Information). The obtained value of 1:1 binding is consistent with stoichiometries reported in the literature determined by Job's plot,[16] as well as by conductivity studies.[17]

In contrast, a Job's plot for iron and SBH (Figure 3) exhibits maximum absorption at a ligand mole fraction of 0.67,

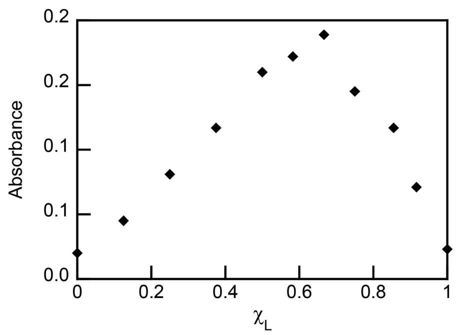

Figure 3. Representative student data for Job's plot of Fe^{3+} with SBH. λ_{abs} = 550 nm, [Fe^{3+} + SBH] = 0.40 mM in methanol.

corresponding to formation of the ML_2 complex, in agreement with Job's analysis reported in the literature.[18] Eighty-six percent of students measured a turning point of between 0.62 and 0.71, therefore concluding the 1:2 complexation (average χ_L = 0.65, st. dev. = 0.04, n = 70). Elemental analysis[19] and infrared spectroscopy[20] further confirmed this stoichiometry.

The experiment has the following key learning outcomes:

- Improve synthetic skills (dropwise addition of reagents, recrystallization, vacuum filtration, preparation of metal complexes), assessed by yield and appearance of ligand and complex;
- Exposure to a range of analytical techniques (UV−visible spectroscopy, use of a micropipette, volumetric glassware, and melting point apparatus), assessed by reported spectra, graphs and melting points;
- Improve data analysis (use of Excel for plotting data and linear regression analysis), assessed by Job's plot and determined stoichiometry; and
- Improve understanding (for example, of relationship of absorption spectrum to color, complexes of varying ligand numbers), assessed through preparation of the experimental report.

This experiment was not related to any lecture content, but students were able to observe that the identity of the metal ion affected the composition of the complex. Furthermore, as the use of structure-drawing software was a generic learning outcome for this laboratory course, students drew reasonable structures for the resulting metal complexes (see Supporting Information). Furthermore, students were required to compare measured melting points to literature values, which gave them the experience of searching the literature for such information.

While this experiment studies only Cu^{2+} and Fe^{3+} binding to SBH, SBH complexes of other transition metals have been reported and characterized.[21,22] Here, we chose to focus on Cu^{2+} and Fe^{3+} based on the robust results they gave in a screen of first row transition metals, but this experiment could readily be expanded to include other transition metals.

A current and ongoing challenge in undergraduate laboratories is to give students a sense of the applicability of each experiment. SBH complexes have wide-ranging reported applications, with Cu complexes used in surface coatings with antibacterial and flame retardant properties,[23] as well as having reported anticancer activity. Fe complexes of SBH, on the other hand, had been proposed for use as magnetic resonance imaging (MRI) contrast agents[24] or sulfide oxidation catalysts.[25]

SUMMARY

This laboratory experiment was appropriate for an intermediate, general or inorganic chemistry course. The experiment used simple, inexpensive starting materials, and demonstrated a number of important principles related to modern chemistry research.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00555.

Instructor notes and student handouts (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

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