Inorganic Chemistry
Article
pubs.acs.org/IC

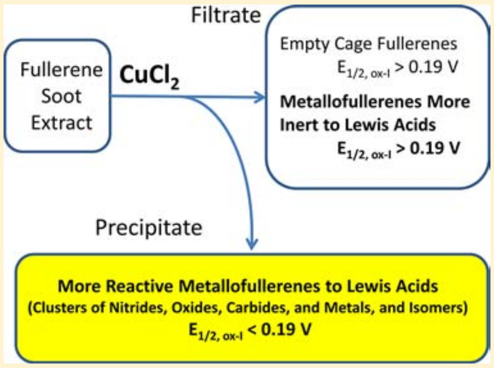
$CuCl_2$ for the Isolation of a Broad Array of Endohedral Fullerenes Containing Metallic, Metallic Carbide, Metallic Nitride, and Metallic Oxide Clusters, and Separation of Their Structural Isomers

Steven Stevenson* and Khristina A. Rottinger

Chemistry Department, Indiana-Purdue University at Fort Wayne (IPFW), 2101 E. Coliseum Blvd, Fort Wayne, Indiana 46805, United States

Ⓢ *Supporting Information*

ABSTRACT: A typical arc-synthesis generates many types of fullerenes and endohedrals. Resulting soot extracts contain a complex mixture of >50 types of fullerenes, metallofullerenes, and their structural isomers. Prior to application development, novel separation methods are required to fractionate this rich array of metallic, metallic carbide, metallic nitride, and metallic oxide endohedrals, all of which can be present in a single, soot extract. Herein, we report the discovery of $CuCl_2$ as a Lewis acid that will selectively precipitate only the more reactive members of each of these endohedral families. The more reactive $Sc_4O_2@I_h\text{-}C_{80}$, $Sc_3C_2@I_h\text{-}C_{80}$, and $Sc_3N@D_{3h}\text{-}C_{78}$ endohedrals are quickly removed from extracts to greatly decrease the number of endohedrals present in a sample. Experiments indicate that enrichment factors of several orders of magnitude can be achieved within minutes of reaction time. $CuCl_2$ also has sufficient selectivity to resolve and separate structural isomers, as demonstrated with $Er_2@C_{82}$ (isomer I, $C_s(6)\text{-}C_{82}$ versus isomer III). The selective complexation of $CuCl_2$ with fullerenes can be correlated to their first oxidation potential. We estimate a significantly lower threshold of precipitation for $CuCl_2$ (<0.19 V) compared to stronger Lewis acids. Fullerenes and metallofullerenes having first oxidation potentials above 0.19 V tend to remain unreacted in solution. In contrast, species with first oxidation potentials below 0.19 V (vs Fc/Fc^+) precipitate via complexation, and are easily decomplexed. $CuCl_2$ is compared to Lewis acids having higher precipitation thresholds (e.g., $FeCl_3$) in our goal to predict a priori which endohedrals would remain in solution versus which endohedral species would complex and precipitate. The ability to predict endohedral precipitation a priori is beneficial to the design of purification strategies for metallofullerenes.



■ INTRODUCTION

Metallofullerene[1−5] extracts can become complex when several families of endohedrals are simultaneously produced. The introduction of nitrogen and oxygen (e.g., N_2, air, and nitrates) into an electric-arc reactor creates a diverse family of endohedral clusters entrapped within an array of fullerene cages, many of which possess structural isomers.

Soot extracts that are generated under mild CAPTEAR[6] conditions contain metallic[1] (e.g., $Er_2@C_{82}$), metallic carbide[4,7] (e.g., $Sc_3C_2@C_{80}$, $Sc_4C_2@C_{80}$), metallic nitride[5,8,9] (e.g, $Sc_3N@C_{78}$), and metallic oxide[10−13] (e.g., $Sc_4O_2@C_{80}$) families of endohedral species. The sum of these metallofullerenes typically represents only 1−10% of the extract. The remaining 90−99% of the sample often consists of lower-mass, empty-cage fullerenes, such as C_{60}, C_{70}, which can be removed by selective complexation and precipitation with a Lewis acid (e.g., $AlCl_3$[14] or $TiCl_4$[15,16]) or via their immobilization onto solid supports containing reactive aminosilica[17,18] or cyclopentadiene.[17,19] Earlier work on the purification of C_{60} from other empty-cage fullerenes has been achieved using $AlCl_3$.[20] Selective chemical oxidation methods have also shown success for isomeric separation of $Sc_3N@D_{5h}\text{-}C_{80}$.[21]

Simplification of these endohedral-containing extracts prior to HPLC fraction collection is highly desired. Their direct injection into HPLC is problematic because of (1) the presence of >50 different fullerenes and metallofullerenes, along with their structural isomers, (2) the need for multiple columns of proprietary, stationary phases necessary to resolve the coelution of fullerenes, (3) the large expense of HPLC instrumentation, specialty columns, solvents, solvent waste, and time, and (4) the low solubility and poor abundance of targeted metallofullerenes, each of which can be present in only trace amounts (e.g., <0.1%) of the injected extract.

The goal of this research is to discover a new Lewis acid with a lower precipitation threshold such that separation between individual metallofullerenes could be achieved. Results indicate a remarkable selectivity of $CuCl_2$ for those endohedrals possessing low first oxidation potentials (<0.19 V). The majority of endohedrals (0.19 V to 0.70 V) possess first oxidation potentials above the precipitation threshold of $CuCl_2$ (∼0.13 V to 0.18 V), and these more inert metallofullerenes

Received: May 28, 2013
Published: July 26, 2013

tend to remain in solution. Shown in Table 1, lower mass, empty-cage fullerenes (e.g., $C_{60}-C_{88}$) also have much higher first oxidation potentials (0.72 V to 1.21 V) and are largely not precipitated upon addition of $CuCl_2$.

Table 1. First Oxidation Potentials for Selected Fullerenes and Metallofullerenes

fullerene	cluster type	$E_{1/2}$, ox-I (V, Fc/Fc$^+$)	ref.
C_{60}-I_h (1)	empty	+1.21	39
C_{70}-D_{5h} (1)	empty	+1.19	39
C_{76}	empty	+0.81	39
C_{82}-C_2 (3)	empty	+0.72	39
$Sc_3N@I_h$-C_{80}	nitride	+0.62	40
$Sc_2O@C_s$-C_{82}	oxide	+0.35	41
$Sc_3N@D_{5h}$-C_{80}	nitride	+0.34	38
$Sc_3N@D_3$-C_{68}	nitride	+0.33	42
$Er_2@C_{82}$ (Isomer III)	metal	+0.19^a	43
$Sc_3N@D_{3h}$-C_{78}	nitride	+0.12	44
$Sc_4O_2@I_h$-C_{80}	oxide	0.00	45,46
$Sc_3C_2@I_h$-C_{80}	carbide	−0.03	47

^{a}SWV, pyridine.

Results indicate the threshold of precipitation for endohedrals with $CuCl_2$ is much lower than that for presently used Lewis acids (e.g., $AlCl_3$,[14,15] $FeCl_3$,[14,15] $AlBr_3$,[14,15] and $TiCl_4$[15,16]). Hence, we propose a first Lewis acid step using a "weak" Lewis acid, such as $CuCl_2$, with its low precipitation threshold to obtain a fraction containing predominantly the more reactive endohedrals. A second Lewis acid precipitation step with a "stronger" Lewis acid, such as those described above, with a higher precipitation threshold, would be performed to obtain a second endohedral, enriched fraction, containing the more inert metallofullerenes.

The advantage of discovering a Lewis acid with a lower precipitation threshold (i.e., $CuCl_2$) is the ability to fractionate within endohedral family members. Splitting metallofullerenes into two fractions is beneficial to those wanting "pre-cleanup" steps for obtaining multiple samples of enriched endohedrals prior to HPLC fraction collection.

The experimental results show an enrichment of low-abundant endohedrals by 2−3 orders of magnitude after selective precipitation with $CuCl_2$. The time to selectively precipitate endohedrals with lower oxidation potentials is only 10 to 60 min, depending on which metallofullerene is targeted.

We also demonstrate the versatility of the $CuCl_2$ approach for endohedrals with various types of clusters. For example, the $CuCl_2$ approach selectively precipitates a variety of cluster types, including metals, metal carbides, metal nitrides, and metal oxide endohedrals. We also show the $CuCl_2$ approach can distinguish and separate structural isomers (e.g., $Er_2@C_{82}$, isomers I and III).

An overview of our $CuCl_2$ method for fractionating the reactive endohedrals (i.e., lower first oxidation potentials) away from the more inert metallofullerenes (i.e., higher first oxidation potentials) and lower mass empty-cage fullerenes (also with higher first oxidation potentials) is shown in Figure 1.

■ EXPERIMENTAL SECTION

Endohedral metallofullerene extracts were prepared as previously described[6,22] in our electric-arc reactor. Er- or Sc-based extracts containing fullerenes and metallofullerenes were obtained by packing either Er_2O_3 or Sc_2O_3 powder along with either copper[22] or copper nitrate hydrate[6] into cored-graphite rods. Vaporization of these packed rods was performed under a dynamic flow of He, with air introduced into the arc-reactor at 1−6 Torr/min.

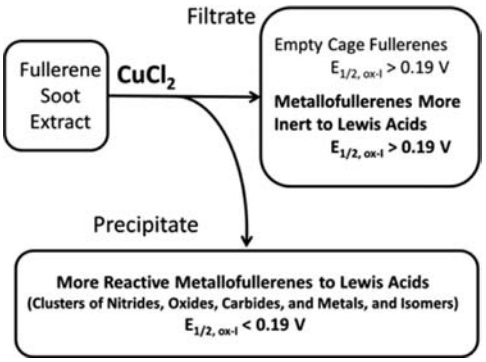


Figure 1. Overview of the $CuCl_2$ approach for fractionating more reactive endohedrals away from the less reactive metallofullerenes and lower mass empty-cage fullerenes.

CAPTEAR conditions[6] were used in the generation of extracts containing Sc- or Er-based endohedrals (e.g., $Sc_4O_2@I_h$-C_{80}, $Sc_3N@D_{3h}$-C_{78}, $Er_3N@I_h$-C_{80}, and $Er_2@C_{82}$ isomers). For the synthesis of scandium carbide endohedrals (e.g., $Sc_4C_2@I_h$-C_{80}), an atmosphere deficient in air was used. For scandium carbide soot extracts, cored graphite rods were packed with Sc_2O_3 or recycled[23,24] Sc_2O_3 and Cu and vaporized under an inert atmosphere (e.g., He).

SAFA[17,18] experiments to isolate either $Er_3N@C_{80}$ or $Sc_3N@C_{80}$ used vacuum-dried, diaminosilica gel. Washes of the spent aminosilica with carbon disulfide provided the fullerene samples used in Figures 3a, 4a, and 5a.

HPLC analysis is performed on a PYE column (SES Research) using toluene as a mobile phase at 0.75 mL/min with UV detection at 360 nm. A discussion and description of our Lewis acid separations and decomplexation of precipitated endohedrals is previously described.[14]

Mass spectral analysis is performed on a Bruker Microflex LT mass spectrometer. Samples are spotted on a stainless steel plate without using a matrix. The analysis is performed in the positive-ion mode.

■ RESULTS AND DISCUSSION

Metallic Carbide Endohedrals. To demonstrate the feasibility of $CuCl_2$ to selectively precipitate metallic carbide endohedrals (e.g., $Sc_3C_2@I_h$-C_{80}), a fullerene extract was prepared (see Experimental Section). For this Lewis acid experiment, 100.3 mg of Sc-fullerene extract is dissolved in 110 mL of carbon disulfide. The corresponding HPLC chromatogram of this soot extract is shown in Figure 2a. While stirring under ambient conditions, 103 mg of anhydrous $CuCl_2$ is added. The reaction is allowed to proceed for 15 min. The precipitated endohedrals are released from the complex as previously described.[14] The HPLC chromatogram for the recovered metallofullerenes is shown in Figure 2b, with the metal carbide, $Sc_3C_2@I_h$-C_{80}, being the dominant endohedral species.

Comparison of the amount of $Sc_3C_2@I_h$-C_{80} before (0.2%) and after (30%) the $CuCl_2$ reaction indicates an enrichment by greater than 2 orders of magnitude. For the isolation of $Sc_3C_2@I_h$-C_{80}, subsequent fraction collection from an enriched sample (Figure 2b) is clearly favored over direct HPLC fraction collection from the soot extract (Figure 2a). Analysis of the MALDI mass spectrum (Figure 2c) of the decomplexed precipitate indicates the presence of other endohedrals present in minor amounts relative to $Sc_3C_2@I_h$-C_{80}. If purified $Sc_3C_2@$

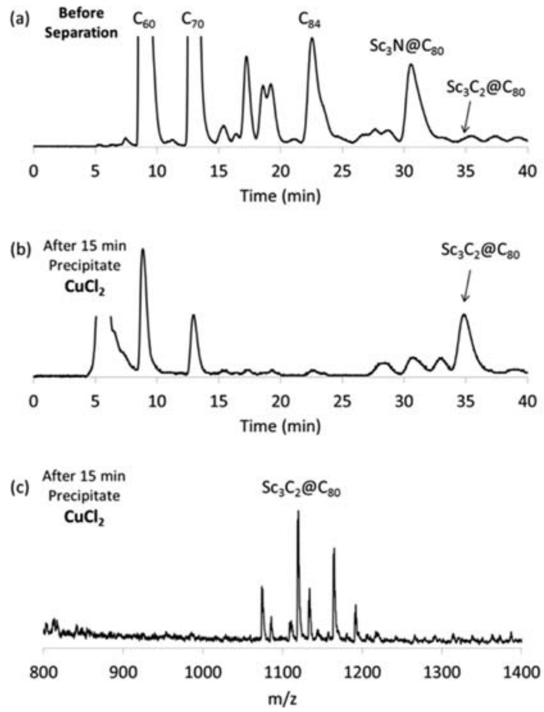


Figure 2. (a) HPLC chromatogram of soot extract before reaction with $CuCl_2$, (b) HPLC chromatogram of the decomplexed precipitate obtained after 15 min of reaction time, and (c) corresponding MALDI mass spectrum of the recovered precipitate.

I_h-C_{80} is desired, only a single pass on a PYE column with toluene as an eluent is necessary.

Metallic Nitride Endohedrals. The family of metallic nitride clusters in fullerene cages has shown recent success in medical applications[25−33] (e.g., MRI and X-ray contrast agents) and nonmedical applications[34] (e.g., photovoltaic devices). The most readily abundant metallic nitride endohedrals are the Sc-based family of metallofullerenes, which are used in this study as representative members of the class of metallic nitride metallofullerenes.

To produce a simpler extract (i.e., to minimize the synthesis of metallic and metallic carbide endohedrals), the CAPTEAR[6] electric-arc synthesis was used to create an oxidizing atmosphere in the reactor. With C_{60} and C_{70} being the dominant fullerenes, $Sc_3N@I_h$-C_{80} is the third most dominant species. In comparison to $Sc_3N@I_h$-C_{80}, $Sc_3N@D_{3h}$-C_{78} is often the fourth most dominant species.

While recent literature describes several methods to obtain purified $Sc_3N@I_h$-C_{80},[17−19,21,35] there is a paucity of literature on novel isolation approaches for the less abundant $Sc_3N@D_{3h}$-C_{78} species. Rather, the literature describes the HPLC fraction collection of $Sc_3N@D_{3h}$-C_{78} directly from soot extract as the method for its purification.[36]

In our pursuit to manipulate reactivity differences between $Sc_3N@D_{3h}$-C_{78} and $Sc_3N@I_h$-C_{80} as a basis for a chemically based separation method, we needed a sample containing both species. A carbon disulfide wash (see Experimental Section) of the spent diaminosilica gel used in the isolation of $Sc_3N@I_h$-C_{80} permitted a sample containing low mass, empty cage fullerenes (e.g., C_{60}, C_{70}), a trace of metallic oxide endohedrals, and the more abundant metallic nitride endohedrals (e.g., $Sc_3N@D_3$-C_{68}, $Sc_3N@D_{3h}$-C_{78}, and $Sc_3N@I_h$-C_{80}).

To demonstrate the effectiveness of $CuCl_2$ as a selective precipitation agent for $Sc_3N@D_{3h}$-C_{78}, 50 mg of this Sc-based fullerene mixture (Figure 3a) was dissolved in 50 mL of carbon disulfide. While stirring, 51.1 mg of anhydrous $CuCl_2$ was added. This reaction mixture was allowed to proceed for 60 min. After filtration, the recovered endohedrals from the precipitate were analyzed by HPLC (Figure 3b) and MALDI (Figure 3c).

Comparison of the amount of $Sc_3N@D_{3h}$-C_{78} present in the sample before (Figure 3a, 0.40%) versus after reaction (Figure 3b, 30%) indicates a factor of 75 times increase in $Sc_3N@D_{3h}$-C_{78} when using the $CuCl_2$ approach. Results show that $Sc_3N@D_{3h}$-C_{78} is the dominant fullerene in both the HPLC chromatogram (Figure 3b) and MALDI mass spectrum (Figure 3c), which further confirms $Sc_3N@D_{3h}$-C_{78} as the most abundant species.

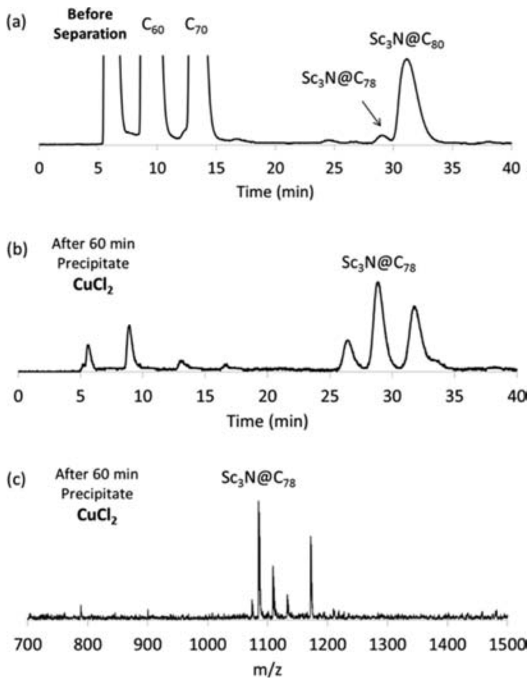


Figure 3. (a) HPLC chromatogram before reaction with $CuCl_2$, (b) HPLC chromatogram of the decomplexed precipitate obtained after 60 min of reaction time, and (c) corresponding MALDI mass spectrum of the recovered precipitate.

Clearly the enriched $Sc_3N@D_{3h}$-C_{78} sample in Figure 3b is preferred in lieu of the sample in Figure 3a for subsequent HPLC fraction collection. If purified $Sc_3N@D_{3h}$-C_{78} is desired, it is readily isolated via a single injection onto a PYE column with toluene as the mobile phase (see Supporting Information). The significance of this accomplishment will be the increased availability of purified $Sc_3N@D_{3h}$-C_{78} because of its ease of isolation.

Metallic Oxide Endohedrals. The discovery[10−12] of metallic oxide clusters entrapped within fullerenes is recent. This new family of compounds has the most atoms encapsulated in a fullerene (i.e., seven entrapped atoms, $Sc_4O_3@I_h$-C_{80})[11] and other interesting features, such as mixed oxidation states[10] (e.g., two Sc^{2+} and two Sc^{3+} ions in $Sc_4O_2@I_h$-C_{80}). However, their yield is often low, as metallic oxide endohedrals consist of <1% in typical soot extracts.

The motivation to develop a new method to overcome their low abundance is the impetus for exploring the use of $CuCl_2$. To demonstrate the use of $CuCl_2$ as a tool for selectively reacting with a metallic oxide endohedral, 50.3 mg of Sc-based fullerenes (see Experimental Section) is dissolved in 50 mL of carbon disulfide (Figure 4a). While stirring, 50.1 mg of anhydrous $CuCl_2$ was added. The reaction mixture is stopped after 20 min.

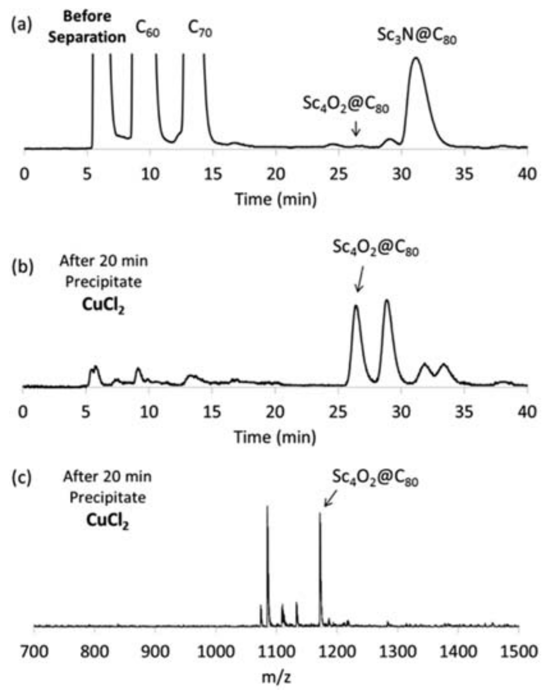


Figure 4. (a) HPLC chromatogram of before reaction with $CuCl_2$, (b) HPLC chromatogram of the decomplexed precipitate obtained after 20 min of reaction time, and (c) corresponding MALDI mass spectrum of the recovered precipitate.

HPLC and MALDI analysis of endohedrals recovered from the decomplexed precipitate is provided in Figures 4b and 4c, respectively. A comparison of the percent abundance of $Sc_4O_2@I_h$-C_{80} in the sample before (0.21%) versus after reaction (33%) clearly demonstrates the selectivity of $CuCl_2$ for $Sc_4O_2@I_h$-C_{80}. An enrichment factor of greater than 2 orders of magnitude is achieved. HPLC fraction collection from the sample in Figure 4b permits isolated $Sc_4O_2@I_h$-C_{80} (Supporting Information).

$Sc_4O_2@I_h$-C_{80} is the most abundant of the metallic oxide endohedrals in extracts produced via the CAPTEAR[6] synthetic process, and is now the easiest metallic oxide fullerene to isolate with the $CuCl_2$ separation method. This will be impactful given the high demand for purified samples of $Sc_4O_2@I_h$-C_{80}.

Metal Endohedrals (Structural Isomers). The next experiment was evaluating $CuCl_2$ to determine whether this Lewis acid could selectively precipitate structural isomers of metallofullerenes. We switched from Sc-based to Er-based endohedrals because of confirmed structures (via X-ray crystallographic analysis) of noncarbide clusters, (i.e., $Er_2@C_{82}$, isomers I, $C_s(6)$-C_{82} versus III). We also wanted to demonstrate that our $CuCl_2$ method would be successful for non-Sc endohedral metallofullerenes.

To prepare a sample enriched in $Er_2@C_{82}$ (isomer I, $C_s(6)$-C_{82} and isomer III), we generated an Er-based sample using CAPTEAR conditions (see Experimental Section). Removal of $Er_3N@I_h$-C_{80} was accomplished via our SAFA[17,18] process. To evaluate $CuCl_2$, 18 mg of Er-based fullerene sample (see Experimental Section) containing $Er_2@C_{82}$ isomers was dissolved in 25 mL of carbon disulfide (Figure 5a). While stirring 12.8 mg of anhydrous $CuCl_2$ was added, and the reaction was allowed to proceed for 44 min.

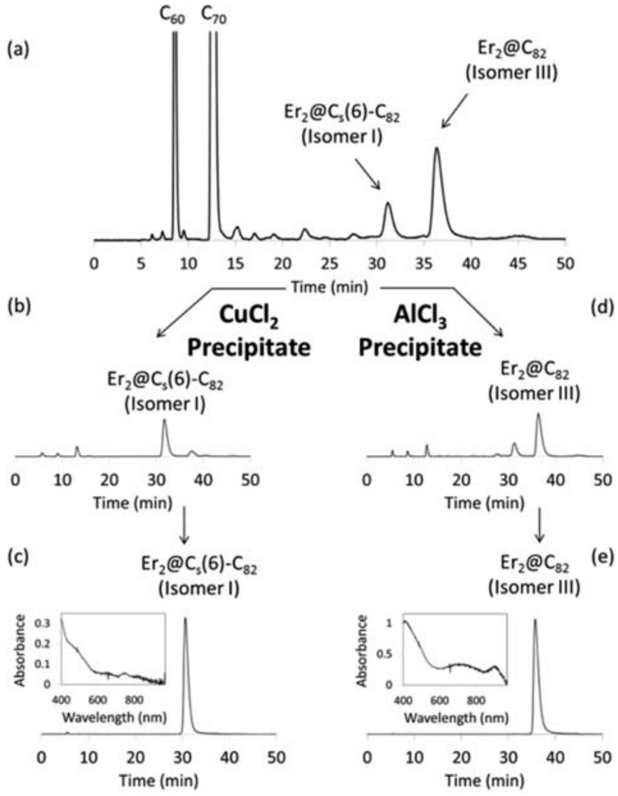


Figure 5. (a) HPLC chromatogram before reaction with $CuCl_2$ or $AlCl_3$, (b,d) HPLC chromatograms of the decomplexed precipitates obtained after 44 min of reaction time when using (b) $CuCl_2$ or (d) $AlCl_3$, (c,e) HPLC chromatograms for isomerically purified $Er_2@C_{82}$, isomers I and III. UV−vis spectra are obtained in CS_2.

Decomplexation of the precipitate resulted in a sample containing ∼90% $Er_2@C_{82}$ (Figure 5b), of which isomer I, $Er_2@C_s(6)$-C_{82} is the dominant endohedral metallofullerene in the sample. A single pass on a PYE column with toluene as the eluent leads to facile purification of $Er_2@C_s(6)$-C_{82} (isomer I) as shown in Figure 5c.

To compare the effect of using $AlCl_3$ as the Lewis acid, 18 mg of the identical sample containing $Er_2@C_{82}$ (Figure 5a) was dissolved in 25 mL of carbon disulfide. To this stirring solution, 12 mg of $AlCl_3$ was added. HPLC analysis (Figure 5d) of the precipitate obtained after 44 min of reaction reveals, in sharp contrast, the presence of $Er_2@C_{82}$ (isomer III) as the dominant metallofullerene (Figure 5d). Based on the similar ratios of isomers III/I in Figures 5a and 5d, $AlCl_3$ precipitated both isomers I and III of $Er_2@C_{82}$. In contrast, the weaker $CuCl_2$ selectively precipitated $Er_2@C_s(6)$-C_{82}, isomer I. Purified $Er_2@C_{82}$ (isomer III) is shown in Figure 5e. Obtained in carbon disulfide, the UV−vis data for the two purified $Er_2@C_{82}$ isomers are shown in Figures 5c and 5e. The cage isomer for $Er_2@C_{82}$, isomer I is assigned via crystallographic analysis to be

$Er_2@C_s(6)$-C_{82}.[37] $Er_2@C_{82}$, isomer III is awaiting crystallographic analysis to determine its cage symmetry.

Precipitation Threshold Comparison. Based on these results from $CuCl_2$ experiments, the next step was to investigate why $CuCl_2$ precipitated much fewer endohedrals in comparison with the more reactive $AlCl_3$, $AlBr_3$, $FeCl_3$ and $TiCl_4$ Lewis acids,[14−16] which successfully separated empty-cage fullerenes from metallofullerenes. The drawback to using these stronger Lewis acids is their precipitation of the entirety of the metallofullerenes (i.e., with metallic, metallic carbide, metallic nitride, and metallic oxide clusters). While it was beneficial to have an enriched sample of endohedrals with empty-cage fullerenes removed, there remained a plethora of different families of endohedrals that still needed separation.

Recently Shinohara et al.[15,16] have correlated the ability of a Lewis acid to precipitate a metallofullerene based on the endohedral's first oxidation potential. It was determined that $TiCl_4$ could precipitate metallofullerenes with first oxidation potentials <0.62 V−0.72 V.[16] They noted that smaller, empty-cage fullerenes (e.g., C_{60}-C_{88}) have oxidation potentials greater than this threshold to explain their unreactive behavior when exposed to $TiCl_4$. The first oxidation potentials of C_{60}−C_{86} range from 0.72 V−1.21 V. For comparison, $Sc_3N@I_h$-C_{80}, a more inert metallofullerene, has a first oxidation potential of +0.62 V (versus Fc/Fc^+).[38]

Reactions using other Lewis acids such as $FeCl_3$ and $AlCl_3$ with soot extracts have also demonstrated an ability to separate metallofullerenes (precipitated) from these unreactive C_{60}-C_{88} empty-cage fullerenes (filtrate).[14,15] Hence their threshold of precipitation appears to be comparable with $TiCl_4$. We sought to estimate the threshold of precipitation for $CuCl_2$ reactions for different types of fullerenes. We suspected the threshold for $CuCl_2$ to be lower than these stronger Lewis acids based on our results described herein.

When comparing the first oxidation potentials (Table 1) for a variety of fullerenes and metallofullerenes with our experimental data, it is clear that the precipitation and reactivity order to $CuCl_2$ is $Sc_4O_2@I_h$-C_{80} > $Sc_3N@C_{78}$ > $Sc_3N@C_{68}$ > $Sc_3N@I_h$-C_{80} > C_{60}-C_{88}. This order of complexation is in agreement with the trend of increasing first order oxidation potentials of 0.00 V, +0.12 V, +0.33 V, +0.62 V, and 0.72−1.21, respectively. Because $Sc_3N@C_{68}$ remained unreacted (i.e., in the filtrate) upon exposure to $CuCl_2$, the threshold for precipitation was initially in the range of +0.12 V and +0.33 V.

To more accurately determine the threshold of precipitation for $CuCl_2$, an endohedral with a first oxidation potential between +0.12 V and +0.33 V was sought. The published oxidation potential for $Er_2@C_{82}$ (isomer III), obtained in pyridine, is +0.19 V.[43] This $Er_2@C_{82}$ isomer was not readily precipitated with $CuCl_2$ (Figure 5b). Thus, the threshold of precipitation for $CuCl_2$ can be estimated between +0.12 V and +0.19 V.

The significance of the lower threshold of precipitation for $CuCl_2$ is the ability to divide the total metallofullerene content into two samples, such as a first fraction containing the reactive endohedrals versus a second fraction containing the more inert metallofullerenes instead of obtaining just one sample containing all the endohedrals. With $CuCl_2$ separations, endohedrals with first oxidation potentials lower than +0.19 V would be easily precipitated. Endohedrals with first oxidation potentials greater than 0.19 V (e.g., 0.19 V-0.70 V, the range for the more inert metallofullerenes) would tend to remain unreacted when $CuCl_2$ is used as the precipitating agent.

Recovery and Extent of Separation. Fullerenes and endohedral metallofullerenes can be complexed to Lewis acids and subsequently decomplexed via addition of ice and water. Upon addition of carbon disulfide in a separatory funnel,[14] the recovered metallofullerenes in the CS_2 layer can be analyzed via HPLC and MALDI mass spectrometry. The percent recovery for decomplexed endohedrals, as previously reported,[14] is 83%, 86%, and 83% for $AlBr_3$, $FeCl_3$, and $AlCl_3$, respectively. In this study, the percent recovery for decomplexed metallofullerenes from $CuCl_2$ is comparable.

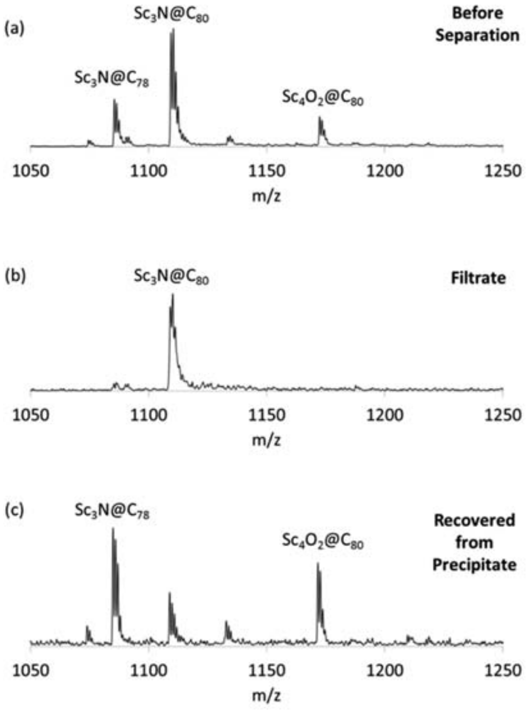


Figure 6. Mass spectral analysis of fullerenes in the (a) starting extract, (b) filtrate, and (c) endohedrals decomplexed from the precipitate.

To demonstrate the ability to remove $Sc_3N@C_{78}$ and $Sc_4O_2@C_{80}$, 50 mg of Sc-based fullerene mixture (Figure 6a) was dissolved in 50 mL of carbon disulfide. While stirring, 51.1 mg of anhydrous $CuCl_2$ was added. Upon reaction for 60 min, the mixture was filtered. The MALDI mass spectrum of endohedrals left unreacted (i.e., remaining in solution, filtrate) is shown in Figure 6b.

Mass spectral analysis of decomplexed endohedrals recovered from the precipitate (Figure 6c) clearly demonstrates the high selectivity of $CuCl_2$ for those endohedral metallofullerenes possessing very low first oxidation potentials (e.g., $Sc_4O_2@I_h$-C_{80} and $Sc_3N@D_{3h}$-C_{78}). The results in Figure 6 indicate that all the $Sc_4O_2@I_h$-C_{80} and virtually all of the $Sc_3N@D_{3h}$-C_{78} has complexed with $CuCl_2$ and precipitated (i.e., removed from solution) during the 60 min of reaction time.

■ CONCLUSION

The discovery of $CuCl_2$ as a new Lewis acid for selectively precipitating endohedral metallofullerenes is demonstrated. The use of $CuCl_2$ successfully separates a broad array of endohedral clusters (e.g., only metals, metal carbides, metal nitrides, and metal oxides). $CuCl_2$ has also been shown to be effective in separating structural isomers of endohedrals, such as $Er_2@C_s(6)$-C_{82} (isomer I) and $Er_2@C_{82}$ (isomer III). The threshold of precipitation for $CuCl_2$ is estimated to be in the range of 0.12 V to 0.19 V. This much lower threshold of precipitation, relative to currently used stronger Lewis acids, has the advantage of selective complexation with fewer endohedrals because many metallofullerenes possess first oxidation potentials above +0.19 V.

A logical experimental design for future endohedral separations would be a first Lewis acid precipitation stage with $CuCl_2$ to obtain the more reactive endohedrals to Lewis acids, followed by a second Lewis acid stage with a stronger Lewis acid (e.g., $TiCl_4$, $AlCl_3$, $FeCl_3$) for precipitation of metallofullerenes more resistant to complexation. The endohedral enriched samples would then be subject to automated HPLC fraction collection for isolating purified metallofullerenes.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

HPLC chromatograms of purified endohedral metallofullerene samples. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: stevenss@ipfw.edu.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. All authors contributed to the work described herein (e.g., separation science, reactivity of endohedrals with $CuCl_2$, characterization by HPLC and MALDI, and conclusions).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

S.S. thanks the National Science Foundation for RUI Grant 1151668 for financial support.

■ ABBREVIATIONS

SAFA, Stir and Filter Approach; CAPTEAR, Chemically Adjusting Pressure, Temperature and Reactivity; HPLC, High Performance Liquid Chromatography; MALDI, Matrix Assisted Laser Desorption Ionization

■ REFERENCES

(1) Shinohara, H. *Rep. Prog. Phys.* **2000**, *63*, 843.

(2) Lu, X.; Feng, L.; Akasaka, T.; Nagase, S. *Chem. Soc. Rev.* **2012**, *41*, 7723.

(3) Popov, A. A.; Yang, S.; Dunsch, L. *Chem. Rev.* **2013**, DOI: 10.1021/cr300297r .

(4) Lu, X.; Akasaka, T.; Nagase, S. *Acc. Chem. Res.* **2013**, *46* (1), 1627.

(5) Zhang, J.; Stevenson, S.; Dorn, H. C. *Acc. Chem. Res.* **2013**, *46* (7), 1548.

(6) Stevenson, S.; Thompson, M. C.; Coumbe, H. L.; Mackey, M. A.; Coumbe, C. E.; Phillips, J. P. *J. Am. Chem. Soc.* **2007**, *129*, 16257.

(7) Wang, C. R.; Kai, T.; Tomiyama, T.; Yoshida, T.; Kobayashi, Y.; Nishibori, E.; Takata, M.; Sakata, M.; Shinohara, H. *Angew. Chem., Int. Ed.* **2001**, *40*, 397.

(8) Dunsch, L.; Georgi, P.; Krause, M.; Wang, C. R. *Synth. Met.* **2003**, *135*, 761.

(9) Stevenson, S.; Rice, G.; Glass, T.; Harich, K.; Cromer, F.; Jordan, M. R.; Craft, J.; Hadju, E.; Bible, R.; Olmstead, M. M.; Maitra, K.; Fisher, A. J.; Balch, A. L.; Dorn, H. C. *Nature* **1999**, *401*, 55.

(10) Stevenson, S.; Mackey, M. A.; Stuart, M. A.; Phillips, J. P.; Easterling, M. L.; Chancellor, C. J.; Olmstead, M. M.; Balch, A. L. *J. Am. Chem. Soc.* **2008**, *130*, 11844.

(11) Mercado, B. Q.; Olmstead, M. M.; Beavers, C. M.; Easterling, M. L.; Stevenson, S.; Mackey, M. A.; Coumbe, C. E.; Phillips, J. D.; Phillips, J. P.; Poblet, J. M.; Balch, A. L. *Chem. Commun.* **2010**, *46*, 279.

(12) Mercado, B. Q.; Stuart, M. A.; Mackey, M. A.; Pickens, J. E.; Confait, B. S.; Stevenson, S.; Easterling, M. L.; Valencia, R.; Rodriguez-Fortea, A.; Poblet, J. M.; Olmstead, M. M.; Balch, A. L. *J. Am. Chem. Soc.* **2010**, *132*, 12098.

(13) Stevenson, S. In *Handbook of Carbon Nano Materials*; D'Souza, F. D., Kadish, K. M., Eds.; World Scientific: Singapore, 2011; Vol. *1*, p 185.

(14) Stevenson, S.; Mackey, M. A.; Pickens, J. E.; Stuart, M. A.; Confait, B. S.; Phillips, J. P. *Inorg. Chem.* **2009**, *48*, 11685.

(15) Akiyama, K.; Hamano, T.; Nakanishi, Y.; Takeuchi, E.; Noda, S.; Wang, Z. Y.; Kubuki, S.; Shinohara, H. *J. Am. Chem. Soc.* **2012**, *134*, 9762.

(16) Wang, Z. Y.; Nakanishi, Y.; Noda, S.; Akiyama, K.; Shinohara, H. *J. Phys. Chem. C* **2012**, *116*, 25563.

(17) Stevenson, S.; Harich, K.; Yu, H.; Stephen, R. R.; Heaps, D.; Coumbe, C.; Phillips, J. P. *J. Am. Chem. Soc.* **2006**, *128*, 8829.

(18) Stevenson, S.; Mackey, M. A.; Coumbe, C. E.; Phillips, J. P.; Elliott, B.; Echegoyen, L. *J. Am. Chem. Soc.* **2007**, *129*, 6072.

(19) Ge, Z. X.; Duchamp, J. C.; Cai, T.; Gibson, H. W.; Dorn, H. C. *J. Am. Chem. Soc.* **2005**, *127*, 16292.

(20) Bucsi, I.; Aniszfeld, R.; Shamma, T.; Prakash, G. K. S.; Olah, G. A. *Proc. Natl. Acad. Sci. U.S.A.* **1994**, *91*, 9019.

(21) Elliott, B.; Yu, L.; Echegoyen, L. *J. Am. Chem. Soc.* **2005**, *127*, 10885.

(22) Stevenson, S.; Mackey, M. A.; Thompson, M. C.; Coumbe, H. L.; Madasu, P. K.; Coumbe, C. E.; Phillips, J. P. *Chem. Commun.* **2007**, 4263.

(23) Stevenson, S.; Coumbe, C. E.; Thompson, M. C.; Coumbe, H. L.; Phillips, J. P.; Buckley, J. L.; Wynne, J. H. *Ind. Eng. Chem. Res.* **2008**, *47*, 2096.

(24) Wynne, J. H.; Buckley, J. L.; Coumbe, C. E.; Phillips, J. P.; Stevenson, S. *J. Environ. Sci. Health, Part A: Environ. Sci. Eng. Toxic Hazard. Subst. Control* **2008**, *43*, 357.

(25) Wilson, J. D.; Broaddus, W. C.; Dorn, H. C.; Fatouros, P. P.; Chalfant, C. E.; Shultz, M. D. *Bioconjugate Chem.* **2012**, *23*, 1873.

(26) Shultz, M. D.; Wilson, J. D.; Fuller, C. E.; Zhang, J. Y.; Dorn, H. C.; Fatouros, P. P. *Radiology* **2011**, *261*, 136.

(27) Fillmore, H. L.; Shultz, M. D.; Henderson, S. C.; Cooper, P.; Broaddus, W. C.; Chen, Z. J.; Shu, C. Y.; Zhang, J. F.; Ge, J. C.; Dorn, H. C.; Corwin, F.; Hirsch, J. I.; Wilson, J.; Fatouros, P. P. *Nanomedicine* **2011**, *6*, 449.

(28) Zhang, J. F.; Fatouros, P. P.; Shu, C. Y.; Reid, J.; Owens, L. S.; Cai, T.; Gibson, H. W.; Long, G. L.; Corwin, F. D.; Chen, Z. J.; Dorn, H. C. *Bioconjugate Chem.* **2010**, *21*, 610.

(29) Shultz, M. D.; Duchamp, J. C.; Wilson, J. D.; Shu, C. Y.; Ge, J. C.; Zhang, J. Y.; Gibson, H. W.; Fillmore, H. L.; Hirsch, J. I.; Dorn, H. C.; Fatouros, P. P. *J. Am. Chem. Soc.* **2010**, *132*, 4980.

(30) Dorn, H. C.; Fatouros, P. P. *Nanosci. Nanotechnol. Lett.* **2010**, *2*, 65.

(31) Shu, C. Y.; Corwin, F. D.; Zhang, J. F.; Chen, Z. J.; Reid, J. E.; Sun, M. H.; Xu, W.; Sim, J. H.; Wang, C. R.; Fatouros, P. P.; Esker, A. R.; Gibson, H. W.; Dorn, H. C. *Bioconjugate Chem.* **2009**, *20*, 1186.

(32) Shu, C. Y.; Ma, X. Y.; Zhang, J. F.; Corwin, F. D.; Sim, J. H.; Zhang, E. Y.; Dorn, H. C.; Gibson, H. W.; Fatouros, P. P.; Wang, C. R.; Fang, X. H. *Bioconjugate Chem.* **2008**, *19*, 651.

(33) Iezzi, E. B.; Duchamp, J. C.; Fletcher, K. R.; Glass, T. E.; Dorn, H. C. *Nano Lett.* **2002**, *2*, 1187.

(34) Ross, R. B.; Cardona, C. M.; Guldi, D. M.; Sankaranarayanan, S. G.; Reese, M. O.; Kopidakis, N.; Peet, J.; Walker, B.; Bazan, G. C.; Van Keuren, E.; Holloway, B. C.; Drees, M. *Nat. Mater.* **2009**, *8*, 208.

(35) Angeli, C. D.; Cai, T.; Duchamp, J. C.; Reid, J. E.; Singer, E. S.; Gibson, H. W.; Dorn, H. C. *Chem. Mater.* **2008**, *20*, 4993.

(36) Olmstead, M. H.; de Bettencourt-Dias, A.; Duchamp, J. C.; Stevenson, S.; Marciu, D.; Dorn, H. C.; Balch, A. L. *Angew. Chem., Int. Ed.* **2001**, *40*, 1223.

(37) Olmstead, M. M.; de Bettencourt-Dias, A.; Stevenson, S.; Dorn, H. C.; Balch, A. L. *J. Am. Chem. Soc.* **2002**, *124*, 4172.

(38) Cai, T.; Xu, L. S.; Anderson, M. R.; Ge, Z. X.; Zuo, T. M.; Wang, X. L.; Olmstead, M. M.; Balch, A. L.; Gibson, H. W.; Dorn, H. C. *J. Am. Chem. Soc.* **2006**, *128*, 8581.

(39) Suzuki, T.; Kikuchi, K.; Oguri, F.; Nakao, Y.; Suzuki, S.; Achiba, Y.; Yamamoto, K.; Funasaka, H.; Takahashi, T. *Tetrahedron* **1996**, *52*, 4973.

(40) Iiduka, Y.; Ikenaga, O.; Sakuraba, A.; Wakahara, T.; Tsuchiya, T.; Maeda, Y.; Nakahodo, T.; Akasaka, T.; Kako, M.; Mizorogi, N.; Nagase, S. *J. Am. Chem. Soc.* **2005**, *127*, 9956.

(41) Mercado, B. Q.; Chen, N.; Rodriguez-Fortea, A.; Mackey, M. A.; Stevenson, S.; Echegoyen, L.; Poblet, J. M.; Olmstead, M. M.; Balch, A. L. *J. Am. Chem. Soc.* **2011**, *133*, 6752.

(42) Yang, S. F.; Rapta, P.; Dunsch, L. *Chem. Commun.* **2007**, 189.

(43) Anderson, M. R.; Dorn, H. C.; Stevenson, S. A. *Carbon* **2000**, *38*, 1663.

(44) Cai, T.; Xu, L.; Shu, C.; Champion, H. A.; Reid, J. E.; Anklin, C.; Anderson, M. R.; Gibson, H. W.; Dorn, H. C. *J. Am. Chem. Soc.* **2008**, *130*, 2136.

(45) Rivera-Nazario, D. M.; Pinzon, J. R.; Stevenson, S.; Echegoyen, L. A. *J. Phys. Org. Chem.* **2013**, *26*, 194.

(46) Popov, A. A.; Chen, N.; Pinzon, J. R.; Stevenson, S.; Echegoyen, L. A.; Dunsch, L. *J. Am. Chem. Soc.* **2012**, *134*, 19607.

(47) Wakahara, T.; Sakuraba, A.; Iiduka, Y.; Okamura, M.; Tsuchiya, T.; Maeda, Y.; Akasaka, T.; Okubo, S.; Kato, T.; Kobayashi, K.; Nagase, S.; Kadish, K. M. *Chem. Phys. Lett.* **2004**, *398*, 553.