Synthesis and Characterization of Luminescent Lanthanide Nano-Rings

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In partial fulfillment of the requirements for graduation with the Dean's Scholars Honors Degree in Chemistry

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Synthesis and Characterization of Luminescent Lanthanide Nano-Rings

Department of Chemistry

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Abstract

It is not uncommon for inorganic chemistry classes to gloss over the chemistry of the lanthanides. Because most inorganic chemists work closely with the *d*-electrons of the transition metals, the shielded and inert *f*-electrons of the lanthanides may at first glance seem monotone or even boring. However, to truly appreciate the lanthanides and the complexes they produce, one must come to embrace their chemical simplicity and understand their much more interesting electronic properties that lead to extremely interesting luminescent and magnetic molecules. Furthermore, though the lanthanides generally only form 3+ ions, it is important to consider that their high coordination number can lead to some very large and unusual molecular structures.

Additionally, lanthanide complexes are known for their photophysical properties, specifically their sharp emission peaks. This, along with the fact that they don't photobleach and are relatively nontoxic, make them ideal for biological probes. If the ligand in the complex can be functionalized to couple with an antibody, the complex should then be able to follow the antibody wherever it goes, for example, to a cancerous tumor, and the probes would then aggregate in the area, causing localized luminescence, aiding in early detection of cancer.

This thesis reports the synthesis of a 42-nuclear lanthanide nano-ring: likely the highest nuclearity lanthanide complex ever produced. This complex, referred to as Ln_{42}, is produced by reacting an *ortho*-vanillin based ligand with lanthanide acetate, the suitable lanthanides being gadolinium, terbium, dysprosium, and holmium. The complex self-assembles, interestingly, first hydrolyzing the ligand such that the only portion that remains in the final complex is deprotonated *ortho*-vanillin. Acetate and hydroxyl groups also remain in the final complex, in addition to the lanthanide centers. The structure in the crystalline solid state was determined using single crystal X-ray diffraction.

As is typical for lanthanide complexes, Ln_{42} has interesting photophysical properties that warrant study. Complex Tb_{42} displays sharp emission peaks at the characteristic wavelengths for Tb^{3+}. Little or no peak was observed for Dy_{42}, which indicates that fluorescence should also not be observed for Ho_{42} or Gd_{42}. Because lanthanides are not excited directly but rather due to an energy transfer by the ligand, this shows that the excited state for the ligand is somewhat lower in energy than is optimal, but the fact that it is energetic enough to excite terbium is promising. Further characterization of that energy transfer can be determined by quantum yield and lifetime experiments, which are at this time still ongoing.

Future planned research includes completing the photophysics measurements as well as functionalizing the ligands with biologically active groups in order to assess Ln_{42}'s suitability as a bioprobe, as well as Small Angle X-ray Scattering (SAXS) studies both to help us understand the behavior of the structure in solution and to help the scientists who study SAXS to further the field by optimizing their methods on a completely unprecedented molecule. This highlights the most important goal of synthe-

sizing and characterizing Ln_{42}. In synthesizing Ln_{42}, we have discovered something entirely unique in the field of lanthanide chemistry, and its study has many far-reaching implications that we may not have even yet considered as a result of its novelty.

Background

"Lanthanum has only one important oxidation state in aqueous solution, the +3 state. With few exceptions, this tells the whole boring story about the other 14 lanthanides"
-G. C. Pimentel and R. D. Spratley[1]

At first glance, the chemistry of lanthanides (often referred to as "rare earths" despite their relative abundance) seems to be a rather simple matter. Found in the *f*-block, separated from the rest of the periodic table, the entire lanthanide series can exist as 3+ ions and very little else, with nearly all variation between them attributed to ionic radius rather than electronic structure.[2] Due to this ionic character, lanthanides generally do not form covalent bonds. Just because the *f*-shell electrons aren't participating in bonds, however, does not mean that they aren't doing anything. In fact, the ability to have 14 chemically similar elements with differing electronic structures is what makes the lanthanides so useful.

In general, when discussing lanthanides, the most common property to be considered is luminescence. Because the *f*-electrons don't participate in bonding, even when lanthanides are in molecules, the photophysical properties of their *f-f* transitions are reminiscent of atomic and ionic spectra. Specifically, the absorption and emission bands are very narrow and the shift between the absorption and the emission peaks (Stokes shift) is minimal.[3] Sharp emission peaks are a desirable quality for many applications that use wavelength-specific detection. As such, lanthanides are useful for a variety of applications. However, harnessing those emission peaks is a non-trivial task. Due to the symmetry of the orbitals (which is a topic that is mostly beyond the scope of this thesis), *f-f* transitions are classically forbidden by quantum mechanics. This means that the absorptivities of the lanthanides are extremely low, and as a result, luminescence via direct excitation is negligible using a standard-energy light source. Additionally, the lack of a Stokes shift would require the excitation light source to be nearly the same wavelength as the emission peak, making detection extremely difficult.[4] However, these problems can be circumvented by the use of ligands which can more readily absorb light and then transfer the energy directly to the lanthanide, which can then be used to excite its electrons (Figure 1). With the electrons forced into the excited state, they then are able to relax and emit light at their characteristic wavelength.[5]

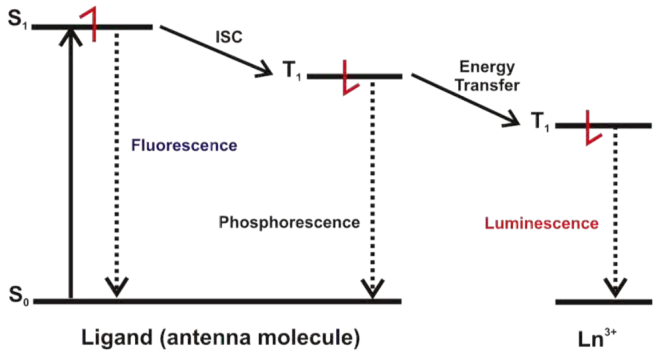

Figure 1: The antenna effect for a lanthanide. Note that the ligand's triplet state is higher in energy than the lanthanide's excited state. ISC = inter-system crossing

This process is known as the antenna effect, and it is easily the most useful property to consider when working with lanthanide luminescence. That being said, not all ligands are suitable for use as antennae for lanthanides. Firstly, because the goal of the antenna effect is to transfer energy, the ligand must have a high molar absorptivity coefficient. Secondly, because we want the energy to transfer to the lanthanide, the ligand should not emit strongly, which would cause the energy to be lost before it reaches the lanthanide. Finally, because the ligand needs to be able to provide enough energy to excite the electrons in the lanthanide, its triplet state must be slightly higher in energy than the excited state of the lanthanide.[6] If all three of those conditions are satisfied, the antenna effect may occur and thus the luminescent properties of the lanthanide can be harnessed.

Lanthanide luminescence is a fairly well-studied and well-understood field, so much of the current research being done on lanthanides tends to focus more on optimizing lanthanide complexes for specific applications. Since there are 14 chemically similar lanthanides, many of the same complexes can be made with different lanthanides to the same chemical effect, meaning that lanthanide complexes can theoretically be tuned to as many wavelengths as the electronic configurations allow.[7] In practice, however, since the lanthanides decrease in ionic radius across the series, most complexes are only able to adopt a certain structure for a particular range of atomic radii. As such it is more common that a certain complex will form with four or five lanthanides than all 14.[2] Even so, this tunability makes lanthanides a good candidate for use in light-emitting diodes,[8,9] lasers,[10,11] and biological probes,[12–14] among other applications.

The bioprobe application is particularly interesting because the structure of the complex determines not only the luminescence but also the functionality of the complex in a biological environment. A bioprobe, as it is discussed in this thesis, is quite simply a luminescent molecule or nanoparticle that can be selectively attached to a biological medium which is then tracked spectroscopically.[15] Traditionally, fluorescent organic molecules known as fluorophores were the most heavily studied potential bioprobes.[16–19] Organic fluorophores are convenient as they can be designed easily and synthesized from relatively inexpensive starting materials. Additionally, there is a near-endless array of possible organic fluorophores. However, they

photobleach quickly, have very broad peaks due to vibrational relaxation, and tend to have relatively small Stokes shifts compared to other methods.[20] Additionally, because they are generally fluorescent rather than phosphorescent, the lifetime of the excited state is extremely short, making time-resolved detection difficult. This is a problem because time-resolved detection is important for background removal.[14] As such, it is increasingly clear that organic fluorophores are an imperfect solution, and other avenues must be explored.

The problems associated with organic fluorophores led to the development of various inorganic bioprobes. One such type of inorganic bioprobe uses quantum dots as the luminescent species.[20–23] Quantum dots are semiconducting nanoparticles that emit a certain wavelength of light based on their size.[24] Quantum dots have narrower emission bands and larger Stokes shifts than fluorophores, of which both attributes are beneficial to bioprobe applications.[20] Additionally, because their emission wavelengths can be tuned directly, they can be designed to contrast with their surroundings.[23] However, quantum dots are commonly cadmium-based nanocrystals, and as such there are questions as to whether the cadmium in the probe would cause it to be toxic.[25–27] Additionally, though their wavelengths can be tuned within a certain range, they can be difficult to tune to near-infrared wavelengths, which are often used in deeper tissue spectroscopy, and they are also flushed out of the body relatively quickly, which can make long-term tracking difficult.[12] As such, though generally more ideal spectroscopically than fluorophores, their chemical properties make for a number of complications which indicate the need for research in other areas.

Because of the concerns with the spectroscopic properties of fluorophores and the chemical properties of quantum dots, the next logical step is to consider yet another source of luminescence: lanthanides.[3,12,14,28–31] As discussed previously, lanthanides have very narrow emission bands, which is important for selective detection.[28] Not only that, but because the lanthanides are in many cases chemically interchangeable, the luminescence can theoretically be tuned to the UV range (Gd), various wavelengths in the visible range (Sm, Eu, Tb, Dy, and Tm), and various wavelengths in the near-infrared region (Nd, Ho, Er, Yb).[14] As such, though lanthanide luminescence cannot be fine-tuned as quantum dots can, there is a wide variety of wavelengths to choose from, notably several in the near-infrared range. Additionally, although the Stokes shift for free lanthanide ions is extremely small, lanthanide complexes display very large pseudo-Stokes shifts as a consequence of the antenna effect.[28] This reduces the spectral interference from the source, and is therefore an important property to consider.[3] Finally, lanthanide ions are known to be relatively non-toxic.[32] As such, lanthanide complexes are extremely promising for use as bioprobes.

There are several factors that need to be considered when designing a complex that is to be used as a biological probe.[12] Firstly, the human body is a chemical-rich environment, so the complex must be able to

exist in those conditions without falling apart. Secondly, although lanthanides are generally not particularly toxic, so too must the ligands be of low toxicity. And, of course, it must also meet all of the criteria for luminescence via the antenna effect, as discussed previously. Finally, the complex must be designed such that it can couple with the biological material that is to be tracked (often an antibody).[33] Often times that means that the complex will have a group such as isothiocyanate (Figure 2), sulfonyl chloride (Figure 3), N-hydroxysuccinimide (Figure 4), or maleimide (Figure 5).[34] These groups can all allow the complex to bind to various biological molecules that can track biological events.

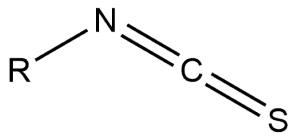

Figure 2: Isothiocyanate group

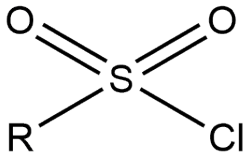

Figure 3: Sulfonyl chloride group

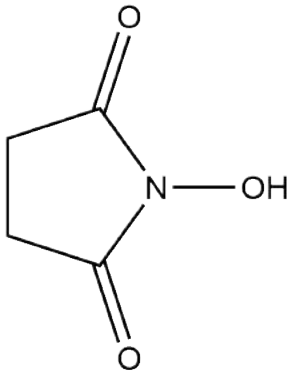

Figure 4: N-hydroxysuccinimide group

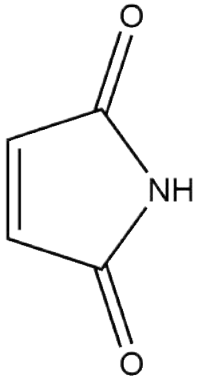

Figure 5: Maleimide group

When designing complexes, instead of beginning with those biologically active groups, it may instead be beneficial to first design a complex with a space where these groups might be able to be added after the synthesis has proven successful and has been optimized, as added sterics can be difficult to work with in an initial synthesis. To that end, we have previously synthesized a number of interesting lanthanide complexes with Schiff-base ligands, all of which have open aryl carbons that could eventually be functionalized with bio-active groups. One such compound is a "sandwich" structure (Figure 6), which was made with an N,N'-bis(5-bromo-3-methoxysalicylidene)phenylene-1,2-diamine ligand (H_2LBr, figure 7).[35] Another such compound is a "drum" structure (Figures 8 and 9), which was made with a similar Schiff-base ligand that has a flexible C-C backbone (H_2L^n, figure 10).[36] It should be noted, however, that the "drum" structure contains both lanthanide and cadmium ions. Though structurally interesting, the presence of toxic cadmium ions likely rules out the use of those structures for *in-vivo* biological studies.

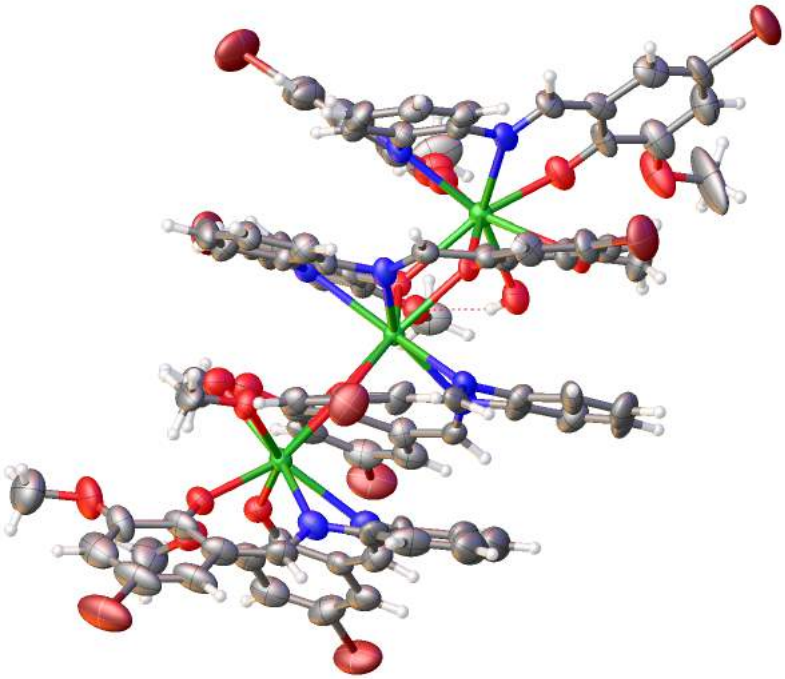

Figure 6: "Sandwich" structure, figure adapted from Yang and Jones 2005[35]

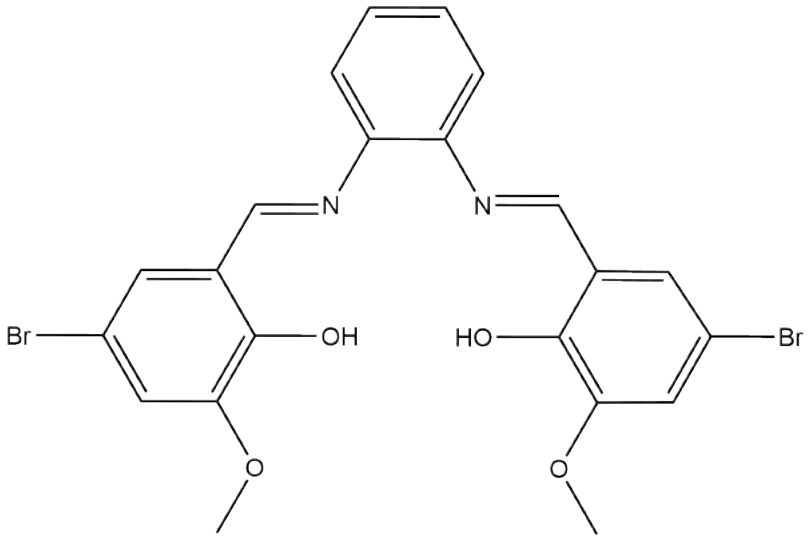

Figure 7: H_2L ligand used in "sandwich" structure, figure adapted from Yang and Jones 2005[35]

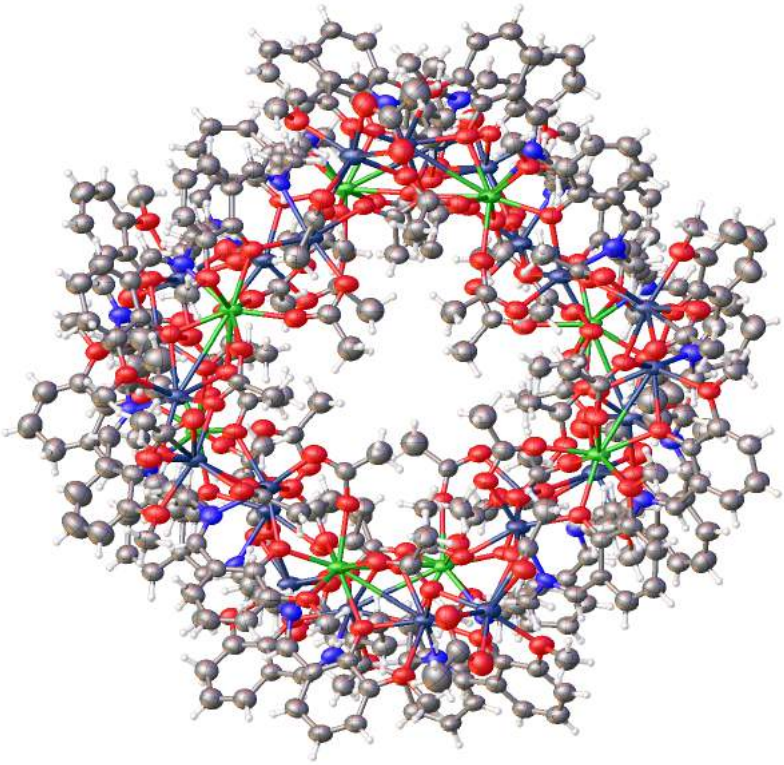

Figure 8: "Drum" structure, top view, figure adapted from Yang et al. 2013[36]
Dark blue = Cd, Green = Nd, Gd, Er, Yb

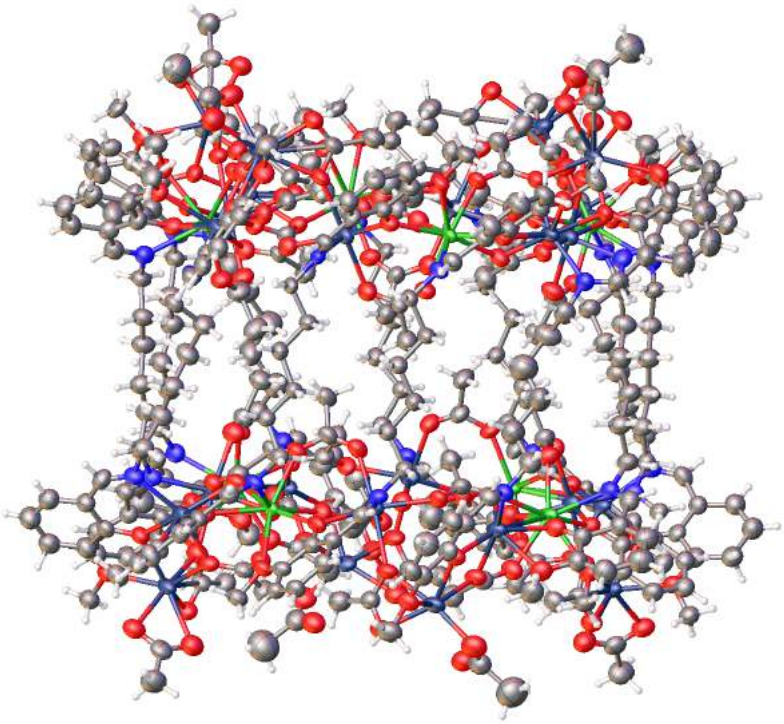

Figure 9: "Drum" structure, side view, figure adapted from Yang et al. 2013[36]
Dark blue = Cd, Green = Nd, Gd, Er, Yb

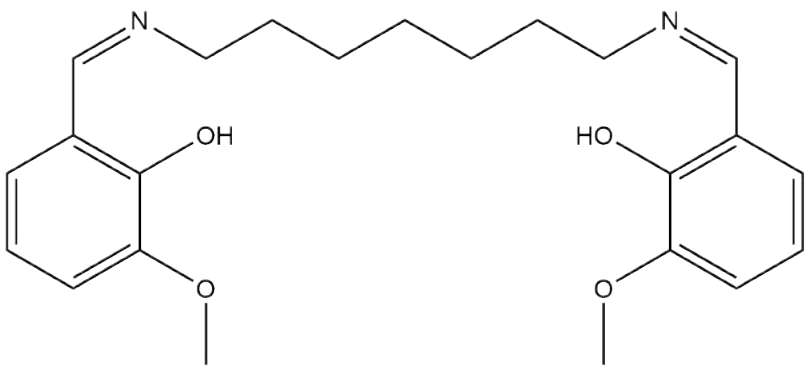

Figure 10: H_2L^7 ligand used in "drum" structure, figure adapted from Yang et al. 2013[36]

The focus of this thesis is the synthesis of interesting new structures that could potentially have applications as bioprobes. Because the "drum" is structurally interesting but not a suitable bioprobe, there is interest in finding similar structures that do not contain cadmium. One reason the "drums" may be better bioprobe candidates than the "sandwiches" is their size. Larger complexes with more lanthanide centers have more photoemissive atoms, which allows for more durability, in that damage to one center may not kill the luminescence of the entire complex.[36] Finally, Schiff bases are easily hydrolyzed. Since a bioprobe would necessarily be in an aqueous environment, there is reason to believe that a ligand that lacks a Schiff base could make a more successful bioprobe.

Experimental methods

Synthesis of Ligand

Although the ligand in the final complex is simply deprotonated *o*-vanillin, in order to react correctly, it must be prepared with a sacrificial Schiff base. As such, *o*-vanillin was reacted with *tert*-butylamine in a 1:1.1 molar ratio in ethanol (Figure 11). This reaction mixture was heated under reflux for an hour and the solvent was then removed. Due to the low melting point of this species, referred to as HL^{tBu}, an oil formed, so the mixture was held at -20°C overnight. This caused a yellow solid to separate from the oil. This solid was stored over a desiccant to mitigate hydrolysis but is otherwise shelf-stable.

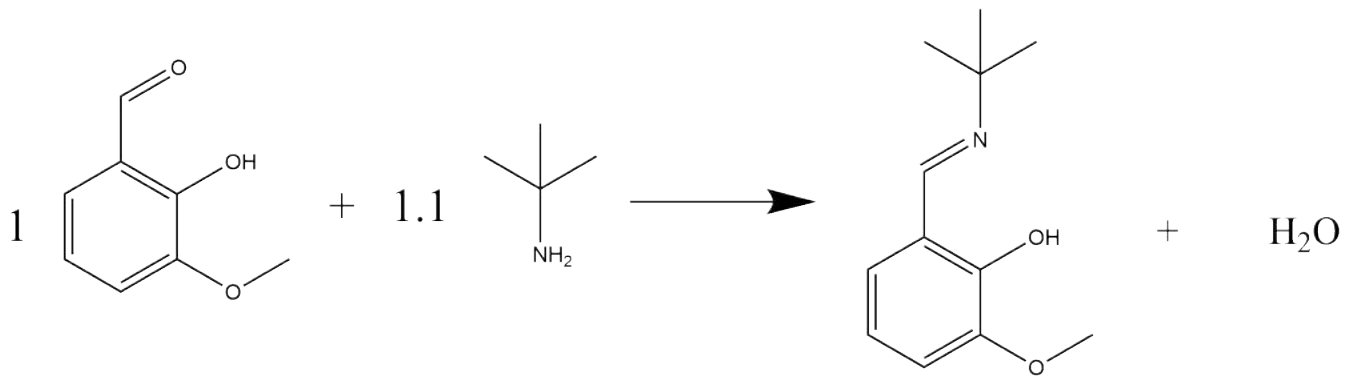

Figure 11: Synthesis of HL^{tBu}

Synthesis of Ln_{42} Complex

To form the complex, $Ln(OAc)_3 \bullet nH_2O$ (Ln = Gd, Tb, Dy, Ho) was reacted in the presence of NEt_3 with HL^{tBu} in a 1:2 molar ratio (Figure 12) in a 50/50 mixture of ethanol and toluene, using ethanol that was as dry as practical (no additional drying should be needed for properly stored 100% ethanol). The reaction mixture was then heated under reflux for an hour. The complex can be collected either by crystallization or solvent removal and precipitation.

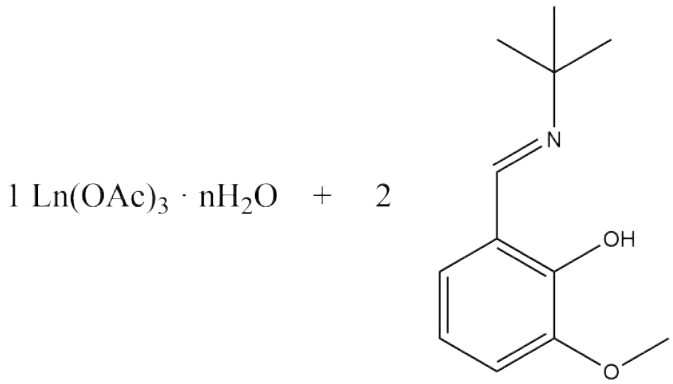

Figure 12: Synthesis of Ln_{42} complex where Ln = Gd, Tb, Dy, Ho

Crystallization of Ln_{42} Complex

To grow crystals, both for the purposes of crystallography and the collection of a very pure product, the original reaction mixture was first cooled to just above room temperature and then filtered directly into test tubes. To avoid cross-contamination, the filtration was used using as little glassware as possible, with any glassware that must be used cleaned thoroughly. These test tubes were then set up for slow vapor diffusion in a tightly sealed jar with diethyl ether. Crystals only formed well in jars that were filled nearly to the top of the test tubes with ether. This is likely due to the fact that the remaining space contains humid air

which interferes with the crystallization process, so as much air as possible should be displaced by ether. Crystals generally form within a week and must remain under solvent to avoid loss of crystallinity.

Quick Collection of Ln_{42} Complex

When an exceptionally pure and/or crystalline product is not required, it is quicker and higher in yield to directly remove the solvent and precipitate the complex. To do this, the reaction mixture was placed on a rotovap and the solvent removed as much as possible. This produced a bright yellow oil which sometimes contains small, pale yellow crystals, depending on the strength of the vacuum. Diethyl ether was added to the sludge, which immediately formed a pale yellow film on the sides of the flask in a bright yellow solution. The pale yellow solid was collected via vacuum filtration and washed with diethyl ether. To further purify the product, the solid was soaked for two days in diethyl ether.

Single Crystal X-ray Diffraction

Crystal structures were collected by Joe Espinoza and Dr. Vincent Lynch using an Agilent SuperNova machine with an AtlasS2 CCD detector and an Oxford Cryostream 700 low temperature device. The structures were solved by Dr. Lauren DePue and Dr. Vincent Lynch on OLEX2[37] using the ShelXT[38] structure solution program using Direct Methods and refined with the ShelXL[39] package using Least Squares minimization.

Photophysics

An absorbance spectrum was taken with an OceanOptics Red Tide UV-Vis spectrophotometer from 220-920 nm. Excitation and emission spectra were taken using a Fluorolog 3 fluorimeter. The emission spectrum was taken from 339 to 650 nm with an excitation wavelength of 324 nm, and the emission spectrum was taken from 200 to 600 nm with the detector set at 540 nm.

Results

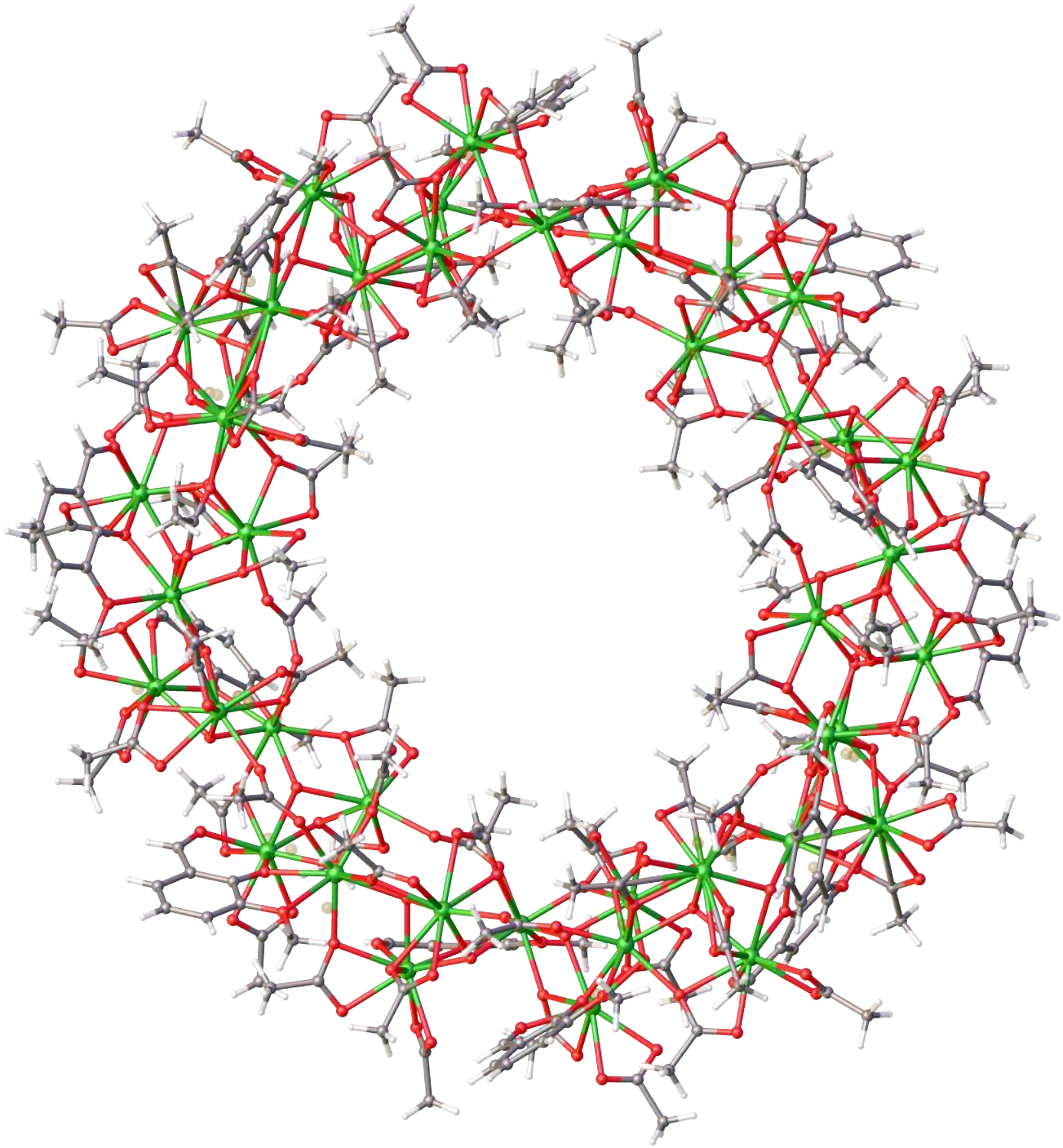

Figure 13: Crystal structure of Dy_{42}.
$C_{280}H_{350}Dy_{42}O_{238}$: M = 14348.62 Da, monoclinic, space group $P2_{1/c}$ (no. 14)

Green = Dy, Red = O, Grey = C.

Note: Gd_{42}, Tb_{42}, and Ho_{42} are isostructural to Dy_{42}.

Additional crystal data can be found in supporting information section.

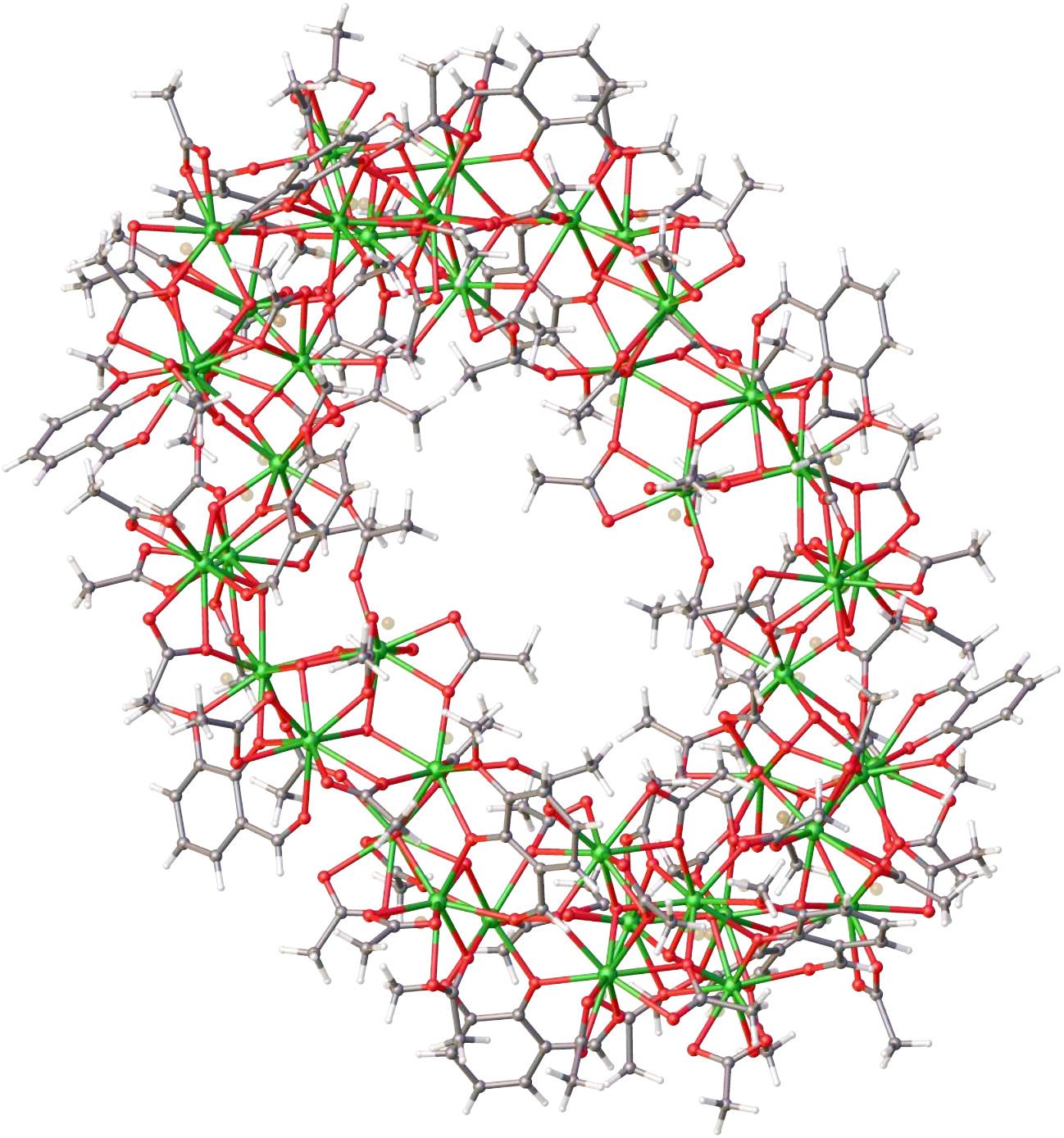

Figure 14: Angled view of Figure 13. Note the exposed phenyl rings which could be potential sites for bio-active groups.

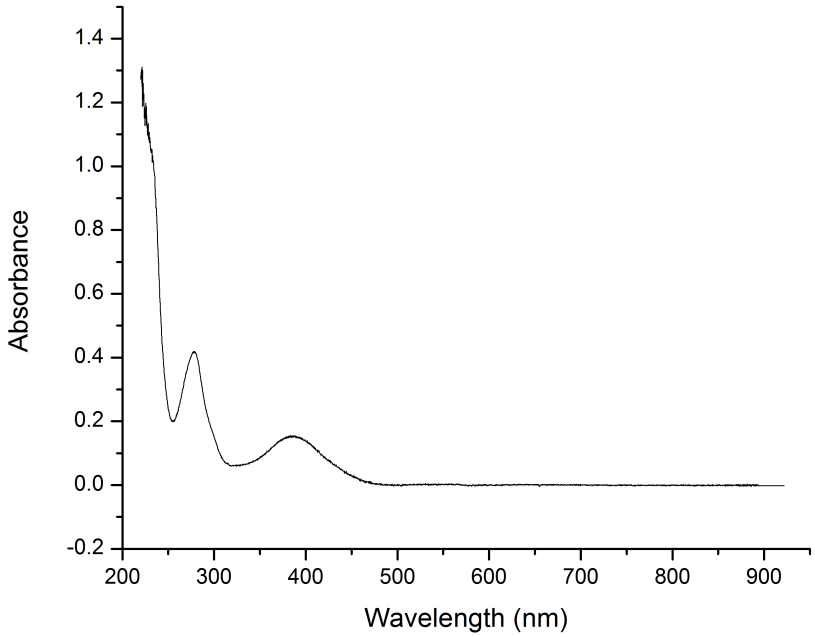

Figure 15: UV-Vis absorbance spectrum for Tb_{42}. Absorbance peaks at 279 nm and 387 nm.

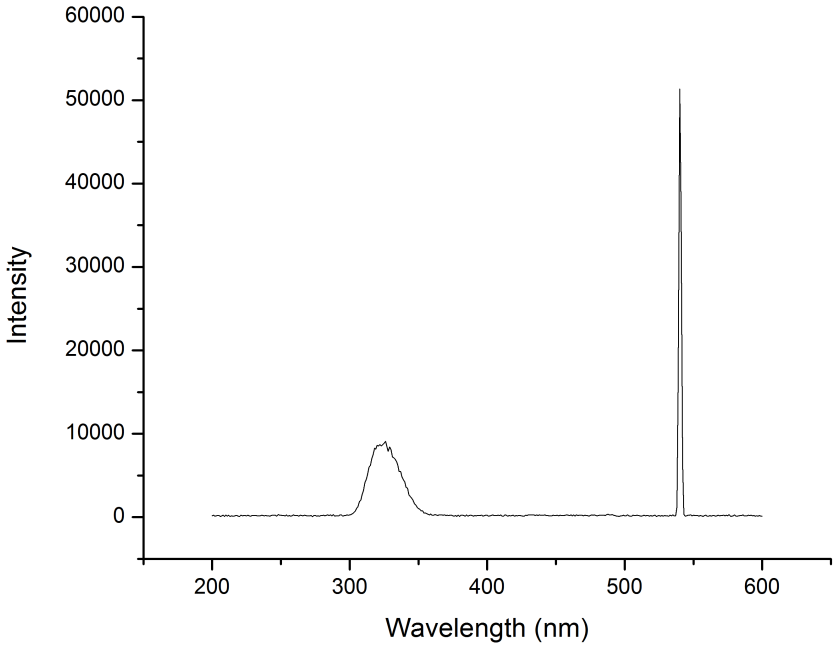

Figure 16: Excitation spectrum for Tb_{42} measured at 540 nm. Excitation peak at 324 nm. Sharp peak at 540 nm is due to Rayleigh scattering from the light source.

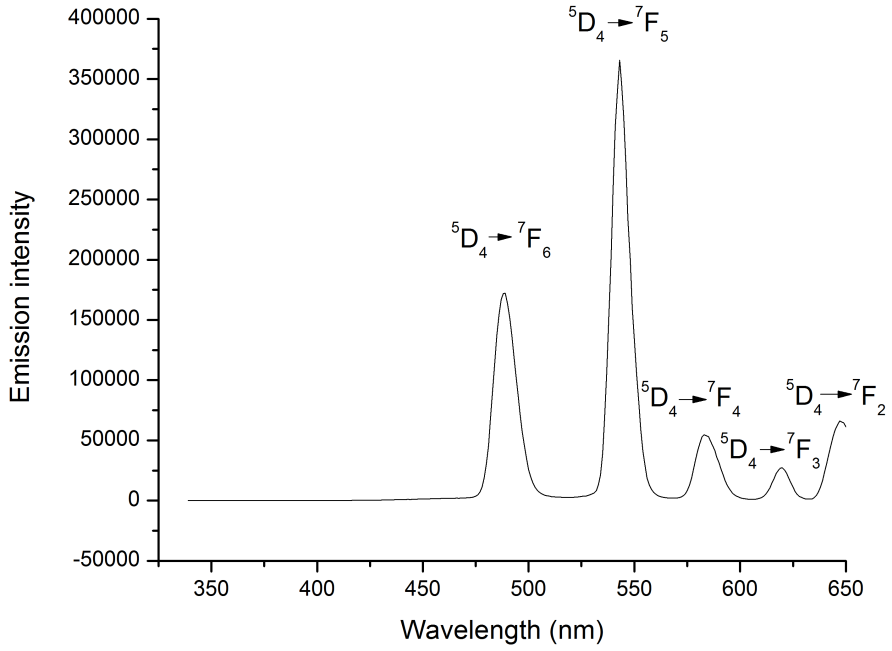

Figure 17: Emission spectrum for Tb_{42} with a 324 nm excitation wavelength. Emission peaks at 489 nm, 543 nm, 583 nm, 619 nm, and 648 nm.[40]

Discussion

Although it is not uncommon for lanthanide complexes to adopt intricate structures, these rings (henceforth referred to as Ln_{42}) are unprecedented in that, to my knowledge, they are the highest nuclearity lanthanide complex ever synthesized. Additionally, many high-nuclearity lanthanide complexes contain other metal centers such as cadmium.[36] Ln_{42} contains only lanthanide metal ions, which eliminates the concerns regarding the toxicity of cadmium if the complexes are to be used in a biological setting. To gain some insight into why these complexes are able to form, one may closely examine the structure and notice that it consists very nearly of 14 $Ln_3L(OAc)_6(OH)_2$ units ($L = o$ -Vanillin). This suggests an aspect of a likely very complicated mechanism that involves the synthesis of these "monomer" units, which later self-assemble into the familiar ring structure. This is particularly intriguing given the relative simplicity of the synthetic methods that are used to produce this complex.

Although perhaps the most interesting aspect of Ln_{42} is the structure itself, it is important to consider its potential both as a bioprobe and as a guide for designing future bioprobes. At the present time, Ln_{42} is not thought to be suitable in its own right as a bioprobe as it appears to degrade in water. That being said, it shows some progress in the way of lanthanide complexes as the synthesis can be carried out

in the often quite humid environment of Austin, Texas, and synthesis has been successful with a solvent system containing up to 10% water. In fact, some amount of water actually participates in the reaction, as evidenced by the hydroxyl groups present in the complex. As such, an in-depth study of the mechanism of this reaction may provide clues that lead to the development of a similar complex that is completely water-stable.

It is also worth noting that although HL^{tBu} as seen in figure 11 is a Schiff-base ligand, the Ln_{42} complex contains no nitrogen atoms or *tert*-butyl groups, which indicates that the ligand hydrolyzed back to *o*-vanillin and *tert*-butylamine, and only the *o*-vanillin was incorporated into the complex. Knowing this, we attempted the synthesis of Ln_{42} with *o*-vanillin rather than the Schiff-base ligand, but to our surprise, the synthesis was not successful. This is likely due to the fact that, along with the hydroxyl groups in the complex, the hydrolysis of the Schiff base pulls water out of the solvent, which accounts for our ability to synthesize Ln_{42} easily in humid atmospheric conditions.

The photophysical properties of Ln_{42} are important both to its future as a bioprobe and to the general understanding of the energy transfer between the ligand and the lanthanide. Studies to date on Tb_{42} and Dy_{42} have shown that the energy transfer does occur for Tb_{42} (as evidenced by the presence of emission peaks), but occurs either imperceptibly or not at all for Dy_{42}. Tb_{42} shows a strong sharp peak at 543 nm, as well as three smaller peaks, of decreasing intensity, at 488 nm, 648 nm, 583 nm, and 620 nm (Figure 17). Not only are the peaks morphologically indicative of lanthanide ions due to their sharpness, the energies of the observed peaks closely match the literature values for terbium.[41] This shows beyond the shadow of a doubt that energy transfer is occurring to a significant extent for terbium. While it is somewhat disappointing that luminescence is not observed for Dy_{42}, it makes sense that Tb_{42} would be a more efficient emitter, as the most favorable electronic transition for dysprosium is approximately 1000 cm^{-1} higher in energy than that of terbium.[41] Because holmium's most favorable transition is even higher in energy than that of dysprosium, and gadolinium's is an order of magnitude higher than that,

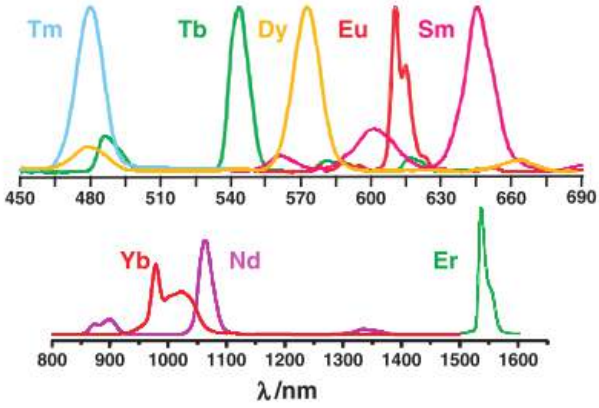

Figure 18: Emission spectra for β-diketonate lanthanide complexes. Figure adapted from Bunzli 2009.[14]

we should not expect for them to luminesce. However, the excitation and emission spectra of gadolinium may nonetheless be useful, because the transition is so energetic that there is no chance of any luminescence from the gadolinium, and as such, it provides us with the spectrum for the ligand in complex, which may be slightly different from the free ligand. Because the same ligand in the same structure is used each complex, this provides a useful background and it gives us insight into what happens to the energy that is not transferred to the lanthanide.

The vast majority of time spent thus far on Ln_{42} research has been on the optimization of the synthetic methods, and as such, there is still much characterization to be done. This includes but is not limited to completing the photophysics experiments with quantum yield and lifetime measurements, the former of which would provide insight into the efficiency of the energy transfer from the ligand, and the latter of which would give us information on the speed of the whole process. Additionally, experiments regarding the electrochemistry of the complex have been proposed. While most lanthanides do not normally form ions other than 3+, the unprecedented nuclearity of Ln_{42} could potentially delocalize electrons and stabilize charge, so as such, it would be interesting to perform a cyclic voltammogram to determine whether any lanthanides in the complex are redox-active at a useful potential. In essence, because no similar molecules have ever been observed, we want to thoroughly measure any property we can so as to learn more about the behavior of lanthanides in extremely large systems.

While understanding the behavior of lanthanides in large systems is extremely important, we also recognize that the physical structure of the molecule is very unusual and certainly worth studying in more detail. To that end, we have recently begun a collaboration with the Dmitri Svergun group at the European Molecular Biology Laboratory in Hamburg. Specifically, we will be working with them to investigate Ln_{42} using Small Angle X-ray Scattering (SAXS). While this is nominally interesting in regard to the characterization of Ln_{42} as it can give us insight into the behavior of the complex in solution, the true value of the collaboration lies in method development for SAXS.

Traditional SAXS is often used to determine the structural properties of large molecules such as proteins[42–45] and nanoparticles.[46–50] However, the study of molecular nanoparticles using SAXS[51] has been extremely limited to date, and there is still much to learn in the process. Ln_{42} is an interesting molecule to study for those purposes due to its distinctive shape and its similarity in size to small proteins.[52] These same properties, as well as the fact that it contains 42 lanthanide centers, make it an even more interesting molecule to develop anomalous SAXS (ASAXS) methods. ASAXS can provide element-specific information about molecules by making measurements near the absorption edges of the elements of interest.[53] This is of

particular interest to biochemists who want to study proteins, but such measurements are made more difficult owing to the fact that there is a relatively narrow range of absorption edge energies that are amenable to ASAXS (typically about 7-20 keV), and neither carbon, nitrogen, oxygen, nor sulfur have absorption edges within that range.[54] However, certain metals that may be included in a protein such as zinc, cobalt, and iron do have absorption edges in that range, and proteins lacking those metals can also be tagged with elements that have ASAXS-favorable absorption edges, including lanthanides.[53] However, this technology is still fairly young and is in the early stages of development, and as such, it is not feasible at this time to study proteins and large molecules that have only a small number of ASAXS-active centers. Because Ln_{42} is similar in size to a small protein but contains 42 ASAXS-active centers, it could be used to refine ASAXS methods so that they can eventually be tuned to proteins with only one or two ASAXS-active centers.

While that concludes all of the experiments regarding Ln_{42} that are currently completed or planned, there is no doubt that it will find further use in the future. As with the SAXS studies, a molecule with properties as unique as Ln_{42} is of interest to researchers in a wide range of fields, spanning from the familiar synthetic inorganic chemistry to biochemistry to analytical and physical chemistry, and beyond. As a result, it has applications that far surpass what may be considered initially by a humble synthetic chemist. All this, having been synthesized at atmospheric conditions in a simple two-step reaction. The fact that that which was easily and reproducibly synthesized by a number of college sophomores in their first-ever research experience ended up being not only a typically luminescent lanthanide complex but also one of record-shattering proportions with a structure of interest to cutting edge researchers in a completely different field, all the way in Germany, is testament to the amazing possibilities in the field of lanthanide chemistry. While it does require a paradigm shift for those accustomed to the more commonly studied chemistry of transition metals to be truly appreciated, there is little doubt that the chemistry and study of lanthanide complexes is one of the best kept secrets of the chemistry world. With all due respect to Drs. Pimentel and Spratley, I sincerely hope that, if nothing else, this thesis has successfully been able to convince anybody who reads it that the lanthanides are anything but boring.

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Supplementary Information

Dy_{42} data

Table 1: Crystal data and structure refinement for Dy_{42}

Identification code	Dy42final
Empirical formula	$C_{280}H_{350}Dy_{42}O_{238}$
Formula weight	14342.57
Temperature/K	100.15
Crystal system	monoclinic
Space group	$P2_1/c$
a/Å	24.3748(4)
b/Å	38.7419(7)
c/Å	33.9057(6)
$\alpha/\circ$	90
$\beta/\circ$	109.4298(19)
$\gamma/\circ$	90
Volume/Å^3	30194.6(10)
Z	2
ρ_{calc}g/cm^3	1.578
μ/mm^{-1}	27.827
F(000)	13406.0
Crystal size/mm^3	0.219 x 0.161 x 0.122
Radiation	CuKα (λ = 1.54184)
2Θ range for data collection/$\circ$	4.534 to 149.068
Index ranges	$-30 \leq h \leq 30, -48 \leq k \leq 47, -42 \leq l \leq 41$
Reflections collected	290577
Independent reflections	60591 [R_{int} = 0.1085, R_{sigma} = 0.0846]
Data/restraints/parameters	60591/1680/2567
Goodness-of-fit on F^2	0.957
Final R indexes [I>=2σ (I)]	R_1 = 0.0525, wR_2 = 0.1195
Final R indexes [all data]	R_1 = 0.0935, wR_2 = 0.1385
Largest diff. peak/hole / e Å^{-3}	1.24/-1.27

Tb_{42} data

Table 2: Crystal data and structure refinement for Tb_{42}

Identification code	Tb42_Joe
Empirical formula	$C_{280}H_{350}Tb_{42}O_{238}$
Formula weight	14198.22
Temperature/K	100.00(10)
Crystal system	triclinic
Space group	P-1
a/Å	16.5744(9)
b/Å	32.0309(10)
c/Å	32.8458(9)
α / ∘	104.220(3)
β / ∘	103.587(4)
γ / ∘	99.951(4)
Volume/Å^3	15931.1(12)
Z	1
ρ_{calc}g/cm^3	1.48
μ/mm^{-3}	22.944
F(000)	6664
Crystal size/mm^3	0.331 x 0.164 x 0.052
Radiation	CuKα ($\lambda = 1.54184$)
2Θ range for data collection/ ∘	5.658 to 144.858
Index ranges	$-20 \leq h \leq 19, -39 \leq k \leq 32, -30 \leq l \leq 40$
Reflections collected	92711
Independent reflections	60135 [R_{int} = 0.0975, R_{sigma} = 0.1986]
Data/restraints/parameters	60135/1680/2563
Goodness-of-fit on F^2	0.91
Final R indexes [$I >= 2\sigma(I)$]	R_1 = 0.1018, wR_2 = 0.2354
Final R indexes [all data]	R_1 = 0.1954, wR_2 = 0.3167
Largest diff. peak/hole / e Å^{-3}	2.15/-2.35

Gd_{42} data

Table 3: Crystal data and structure refinement for Gd_{42}

Identification code	Gd42
Empirical formula	$C_{280}H_{350}Gd_{42}O_{238}$
Formula weight	14128.08
Temperature/K	153.15
Crystal system	triclinic
Space group	P-1
a/Å	16.7783(7)
b/Å	32.2020(11)
c/Å	33.0463(11)
α / ∘	104.060(2)
β / ∘	103.625(2)
γ / ∘	99.949(2)
Volume/Å^3	16323.8(11)
Z	2
ρ_{calc}g/cm^3	1.437
μ/mm^{-3}	4.262
F(000)	6622.0
Crystal size/mm^3	0.72 x 0.462 x 0.3
Radiation	MoKα ($\lambda = 0.71073$)
2Θ range for data collection/ ∘	2.152 to 55.202
Index ranges	$-21 \leq h \leq 21, -41 \leq k \leq 40, -42 \leq l \leq 42$
Reflections collected	410037
Independent reflections	65856 [R_{int} = 0.1162, R_{sigma} = 0.1605]
Data/restraints/parameters	65856/4110/2566
Goodness-of-fit on F^2	1.234
Final R indexes [$I >= 2\sigma(I)$]	R_1 = 0.0860, wR_2 = 0.1983
Final R indexes [all data]	R_1 = 0.1811, wR_2 = 0.2420
Largest diff. peak/hole / e Å^{-3}	2.80/-1.55

Ho_{42} data still being refined.

Additional crystal data (.cif files) available upon request.