Formation of Porphyrin Nanowires via β-Cyclodextrin-Adamantane Host-Guest Binding

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Introduction

Since their initial synthesis in 1935 by Paul Rothemund, porphyrins have been studied in several different scientific contexts from photodynamic therapy to organic geochemistry to toxicology. Due to the macrocyclic conjugated system characteristic of porphyrins, they possess advantageous reactive and fluorescence properties.[1-3]

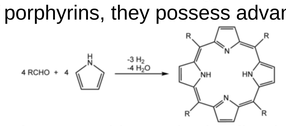


Fig. 1: To the left is the original synthesis of functionalized porphyrin developed by Paul Rothemund in 1935 using four pyrrole and four modified aldehyde units.[2]

Our interest with porphyrins lies in using their reactive abilities to form a nanostructure by sequencing monomers into a wire by applying host-guest chemistry to modified β-cyclodextrin and adamantane functional groups. Current issues with porphyrin dimer nanowires that will be combated include preventing aromatic stacking through π-π interactions while maintaining solubility in water.[4] In addition, further attention is present in manipulating the fluorescent and chelation properties of the nanostructures to allow for success in fields and applications such as therapeutics and drug delivery.[5]

Further Theory

Naturally occurring cyclodextrins, α-, β-, and γ-, contain six, seven, and eight glucose units, respectively, and form a toroidal shape featuring a lipophilic cavity in water. Owing to this unique structure of cyclodextrin molecules, host-guest inclusion complexes can be formed with other hydrophobic molecules under specific conditions.[6]

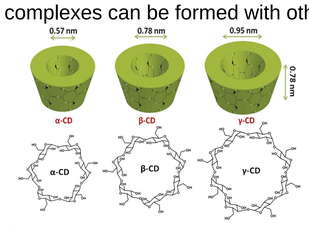


Fig. 2: To the left is a visual of the three natural types of cyclodextrin and a comparison of their respective cavity sizes.[7]

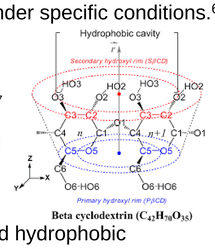


Fig. 3: To the right is a detailed representation of the toroidal structure and lipophilic cavity of β-cyclodextrin.[8]

Supramolecular chemical interactions between cyclodextrin and hydrophobic adamantane have been studied for years and have proven to be effective in synthesizing self-assembling molecular systems, specifically with β-cyclodextrin.[6] Coupling these favorable binding interactions with porphyrins' large macrocyclic structure as a backbone for both functional groups suggests that an intermolecular nanowire material could be self-assembled in solution.

Reaction Methods

Functionalization of the tetraphenylporphyrin began with the addition of propargyl bromide to a dihydroxylbenzaldehyde precursor followed by a click reaction between the alkyne arm and azidoadamantane. These click reactions between alkyne and azide functional groups are known for being high-yielding and efficient. A second alkyne group is added to the benzaldeyde derivative followed by the addition of pyrrole, producing the tetraphenylporphyrin flanked with alkyne and adamantane arms present in **Fig. 6**.

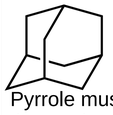


Fig. 4: To the left is the structure of adamantane whose hydrophobic nature allows for inclusion complexes to be formed with cyclodextrin.[6]

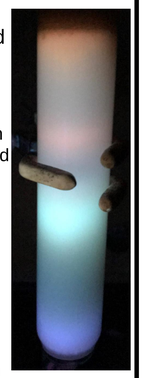


Fig. 5: To the right is a column separation of the functionalized benzaldehyde from the first step of the synthesis.

Pyrrole must be purified by distillation prior to its utilization in the synthesis. Chelation of zinc to the central pocket of the porphyrin steadies the π electrons in the aromatic system and improves stability in strong acids and bases without damaging advantageous fluorescence properties.[9] Characterization of synthetic intermediates was accomplished using ESI and MALDI-TOF mass spectrometric and NMR spectroscopic methods. Most reaction steps must be either charged with or completed under argon. Separations and purifications were completed after each step using either thin-layer and column chromatography or liquid-liquid extraction using a separatory funnel.

Synthetic Sequence

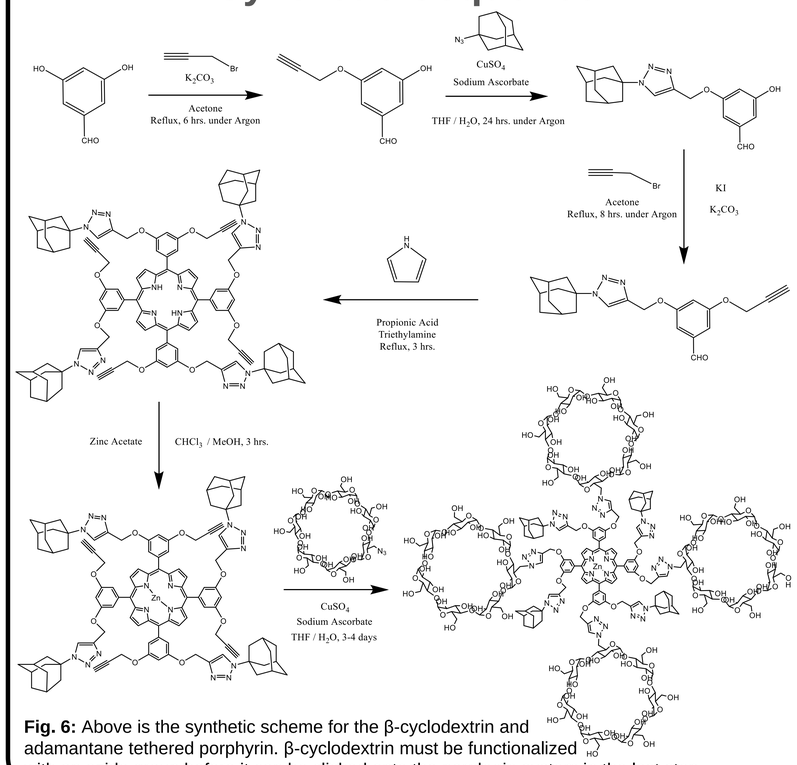


Fig. 6: Above is the synthetic scheme for the β-cyclodextrin and adamantane tethered porphyrin. β-cyclodextrin must be functionalized with an azide group before it can be clicked onto the porphyrin system in the last step.

Nanowire Design and Assembly

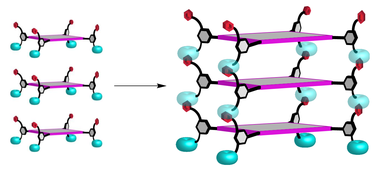


Fig. 7: Above is a schematic illustration of the hypothesized multilayer assembly of the nanowire.

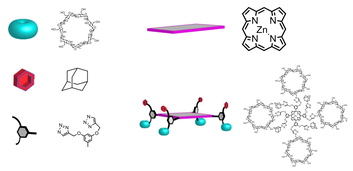


Fig. 8: Above is a structure key for the illustration on the left.

Characterization Results

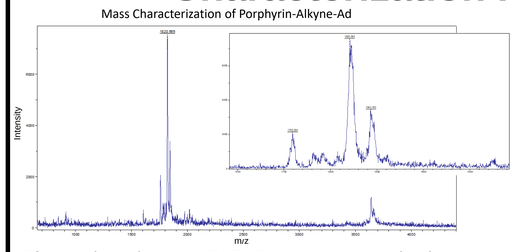
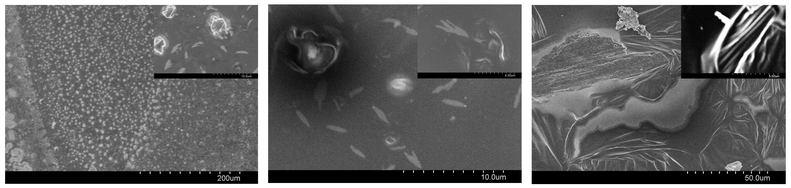


Fig. 9: Above is a MALDI-TOF mass spectrum for the porphyrin molecule flanked with adamantane and alkyne arms. This product precedes the β-cyclodextrin reaction.

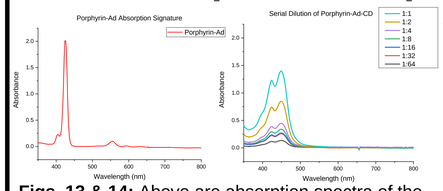
All intermediate products were determined to be pure using the techniques described in **Reaction Methods**. Due to failures in purification and characterization of the final porphyrin product in **Fig. 6**, the reaction was completed three times. Conclusive characterization of the expected product could not be completed using the methods described above. Because visible chemical changes occurred across the reactions, other instrumental methods such as SEM imaging and UV-Vis spectroscopy were employed to investigate the chemical interactions.

Microscopy Imaging



Figs. 10, 11, & 12: Above are SEM images of the porphyrin before and after the β-cyclodextrin reaction. From left to right, the images represent the precursor porphyrin, the final porphyrin at low concentration, and the final porphyrin at high concentration. Also, zoomed inlet images are present. Microscopy images of the porphyrin systems suggest structural differences and formations of aggregate complexes occurred. In addition, there appears to be a dependence on increased concentration for the nanoscale networks to be formed.

Spectroscopic Analysis



Absorptions characteristic of porphyrins are often influenced upon formation of complexes or aggregates in solution. One substantial feature of aggregated porphyrins due to aromatic stacking is the broadening of spectral bands, which diminishes the fluorescence properties and reduces the efficacy of porphyrins in most applications.[10-11] The differences between the spectra of the porphyrin precursor and the final product in methanol further suggest that structural alterations are occurring.

Figs. 13 & 14: Above are absorption spectra of the porphyrin systems before and after the final reaction.

Conclusions and Future Directions

While the theorized nanowire structure present in **Nanowire Design and Assembly** was unable to be characterized, SEM imaging and absorption spectroscopic analysis of the final porphyrin product suggests that a complex structure has formed. TLC and ESI analyses of the final product also suggest that several different complexes formed, creating a nanoscale network rather than uniform wires. The interesting data could have resulted from partial clicking of β-cyclodextrin, porphyrin overlapping during wire formation, aromatic stacking in solution, or an amalgamation of all three. Further purification of the product and refinement of the synthetic sequence is necessary. Minimizing π-π stacking aggregates and improving solubility in water will facilitate the formation of the ideal uniform nanostructures. Binding studies via SPR offer an avenue to investigate the extent of the formation of the inclusion complexes between two porphyrins rather than a network of porphyrins. Upon successful formation of nanowires in the future, immediate and plausible group directions and applications include using monomer and dimer porphyrin nanowires for photonic or electronic materials.

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