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Adaptive nanostructures Through Dynamic Molecular Systems

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RESEARCH FOUNDATION OF THE CITY UNIVERSITY OF NEW YORK

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14. ABSTRACT

It was the overall aim of this research program to develop a new class of transient functional nanostructures based on self-assembling peptides. These materials mimic the ability of living systems to rapidly adapt and respond to new situations by changing their structure and optical properties. While they are conceptually inspired by biology, the systems that were developed are much simpler in composition, and combine biological and synthetic components, giving rise to structures and functions, including adaptive fluorescence emission, that are not accessible using biological or synthetic approaches alone. The main outcomes were: development of dynamic peptide libraries for discovery of self-assembling peptides (Nature Nanotechnology, 2016), discovery of customizable polymeric peptide pigments with sequence tunable properties (Science, 2017) and the demonstration of amino acid encoded transient assemblies, showing transient electroconductance (Nature Chemistry, 2018).

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AFoSR FINAL REPORT

AFoSR 15-1-0192: Adaptive Nanostructures through Dynamic Molecular Systems

August 2015-July 2018
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Program: Natural Materials and Systems

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Summary
It was the overall aim of this research program to develop a new class of *transient* functional nanostructures based on self-assembling peptides. These materials mimic the ability of living systems to rapidly adapt and respond to new situations by changing their structure and optical properties. While they are conceptually inspired by biology, the systems that were developed are much simpler in composition, and combine biological and synthetic components, giving rise to structures and functions, including adaptive fluorescence emission, that are not accessible using biological or synthetic approaches alone.

In the first year, we demonstrated a range of new peptide nanostructures with morphologies that were dictated by the peptide sequence. These were discovered through *dynamic peptide libraries (DPLs)*, a screening methodology that was developed in my lab, which allows for the peptide sequence space to be searched for self-assembling structures. In this approach, unprotected homo- and hetero-dipeptides (including aromatic, aliphatic, polar and charged amino acids) were subjected to continuous enzymatic condensation, hydrolysis and sequence exchange to create a dynamic combinatorial peptide library. By changing the environmental conditions during the selection process, different sequences and consequent nanoscale morphologies are selected (as published in *Nature Nanotechnology*). During the **second year** of the program we demonstrated further insights in sequence/structure relationships in tripeptide self-assembly (which formed the basis for a publication in *Science*). Furthermore, we demonstrated the ability to program transient and adaptive self-assembly of peptide-based structures and investigated the ability to utilize covalent and non-covalent (including ionic, pi-stacking and H-bonding) interactions to influence transient assembly behavior. This concept was demonstrated by producing dynamically unstable conducting wires, in collaboration with AFoSR Natural Materials-funded researcher Dr Allon Hochbaum, UCI. In a continuation of our quest to explore the short peptide sequence space for self-assembly propensity, we demonstrated that, firstly, tripeptide sequence isomers enabled for the systematic regulation of molecular order/disorder in peptide nanostructures. In an opportunistic new direction, we demonstrated that a range of tyrosine containing tripeptides were suitable substrates for the formation of mimics of the biological pigment melanin. Specifically, by simply varying peptide sequence we could produce melanin like materials with unprecedented control of shape and optical properties, as published in *Science*. In the **third and final year**, the concepts of amino acid-encoded assembly were further developed and published (*Nature Chemistry*, 2018). The concept of amino acid encoded assembly was also combined

with enzymatic oxidation to enable further control of the optical properties of peptide-based polymeric pigments. Although using a different approach from that originally envisaged for the project (we had anticipated that synthetic chromophores would be essential, in our new approach new chromophores are formed spontaneously from amino acid components), this approach gave rise formation of melanin-like microparticles with remarkable control over emission, which could be adaptively modified by changing amino acid feed (objective 3). This work is in preparation for submission to a leading journal, and summarized below. We also finalized other papers in year 3. *Overall, we have achieved the objectives of the proposal and have made very significant contributions to the nascent field of adaptive nanotechnology.*

Brief descriptions of key outputs.

1: Dynamic Peptide Libraries.

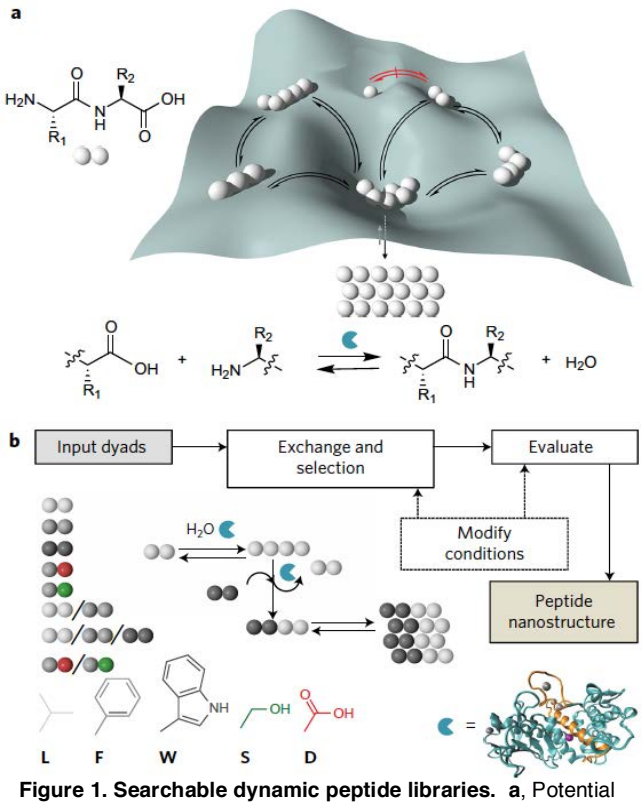

Figure 1. Searchable dynamic peptide libraries. **a**, Potential energy surface showing the formation of peptide oligomers (strings of beads). The depth of the wells represents the relative stability of the self-assembling peptides formed. **b**, Schematic representation of DPL, which involves (mixtures of) dipeptides as chemical inputs, dynamic exchange and selection through enzymatic condensation, hydrolysis and transacylation. The conditions may be modified to influence the supramolecular interactions and thermodynamic selection (*Nature Nanotechnology*, 2016).

The design and selection of self-assembling peptide sequences is challenging because of the vast combinatorial space available and the still very limited insights and lack of fundamental guiding principles for peptide assembly in water. We developed a methodology that allows the peptide sequence space to be searched for self-assembling structures by creating libraries with dynamically exchanging components. In this approach, unprotected homo- and hetero-dipeptides (these form the input 'dyads', which dictate the chemical space which is searched, including aromatic, aliphatic, polar and charged amino acids, Figure 1) are subjected to continuous enzymatic condensation, hydrolysis and sequence exchange to create a dynamic combinatorial peptide library. The free-energy change associated with the assembly process itself gives rise to selective amplification of self-assembling candidates. By changing the environmental conditions during the selection process, different sequences and consequent nanoscale morphologies are selected, which led to the discovery of a number of new peptide sequences, including those that assembly under non-aqueous and high-salt conditions.

2: Amino Acid-Encoded Biocatalytic Self-Assembly Enables the Formation of Transient Conducting Nanostructures.

In this work, we demonstrated the *active selection* of target structures from a multitude of possible options, which was achieved by adding amino acids as 'encoding' moieties. We demonstrated this concept by using a range of amino acid amides to actively decorate a self-assembling core molecule *in situ*, thereby controlling their amphiphilicity and consequent mode of assembly.

The core molecule is the organic semiconductor naphthalene diimide, functionalized with D- and L- tyrosine methyl esters as competing reactive sites. In the presence of α -chymotrypsin and a selected encoding amino acid, kinetic competition between ester hydrolysis and amidation results in covalent or non-covalent amino acid incorporation, and variable supramolecular self-assembly pathways. Taking advantage of the semi-conducting nature of the naphthalene diimide core, electronic wires could be formed and subsequently degraded, giving rise to temporally regulated electro-conductivity (Figure 2) when using glutamic acid amide to regulate the process. The work is significant because it shows that addition of single amino acids can have a very dramatic impact on the formation of supramolecular structures, and more importantly that these structures can be *actively and transiently* accessed.

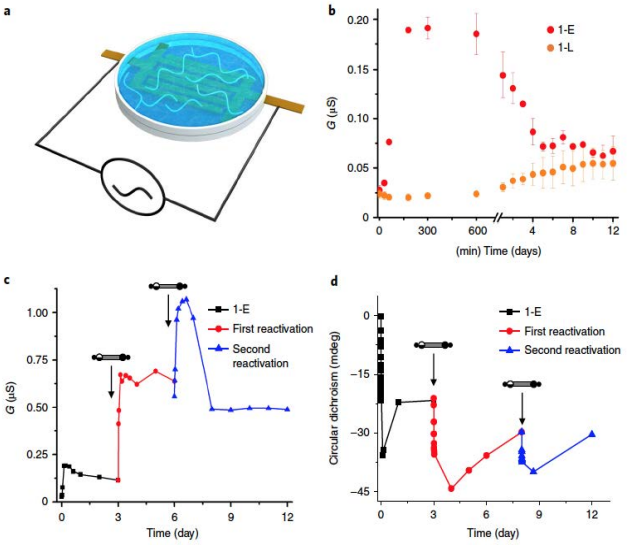

Figure 2: Transient supramolecular conductance in aqueous media. **a**, Schematic of the electrochemical transport characterization device in which electrical conductivity was measured. **b,** Background subtracted time-dependent conductance (G) of 1–E (red curve), showing transient conductance, and 1–L (orange curve), displaying a continuous increase, in line with their respective structural dynamics (the data presented for each trace are an average of two independent samples). **c,d,** Multiple reactivation of 1–E transient conducting nanostructures as seen by time-dependent variation in the sample conductance (c) and the circular dichroism signal upon the addition of compound 1 (d) after three and six days of the reaction.

3: Polymeric Peptide Pigments with Sequence-Encoded Properties

The biosynthesis of functional materials typically involves spatial and temporal control of chemical reactions and the use of template-like interfaces, which contrast the way in which most synthetic materials, including melanins, enamel, bone, *etc.* are produced. It occurred to us that the dramatic sequence dependent assembly of tyrosine-tripeptides discovered during this project could potentially serve as tunable template-like precursors for the formation of melanin-like materials. In these structures, tyrosine phenols are presented in a (supra-)molecular context dictated by the peptide sequence by repositioning amino acids. We demonstrated that enzymatic oxidative polymerization can be tuned in a sequence dependent manner resulting in peptide sequence-encoded

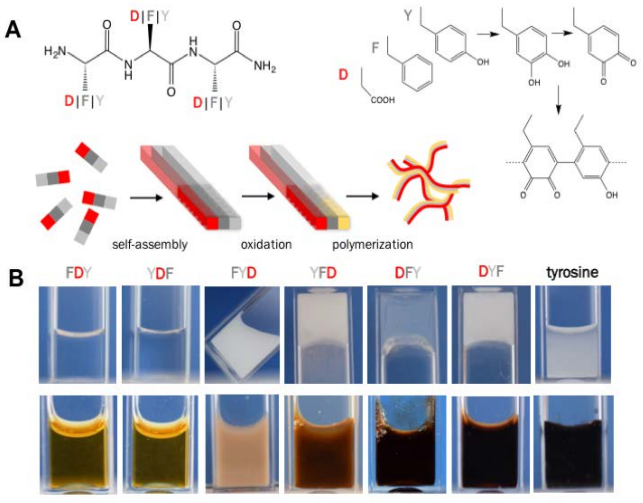

Fig. 3. Sequence-dependent polymeric peptide pigments. (**A**) Schematic representation of the selected tripeptide sequences, and the controlled formation of polymeric peptide pigments by enzymatic oxidation and further polymerization of pre-organized tripeptides. (**B**) Macroscopic images of the materials formed by the self-assembly of the tripeptides (20 mM in phosphate buffer at pH 8) (upper panel), following 24 h (lower panel) of enzymatic oxidation (0.2 $\mu g/\mu$), including oxidation of tyrosine as a control.

properties such as UV absorbance, morphology, coloration and electrochemical properties over a considerable range. This approach provides substantial improvements compared to conventional melanin synthesis and provides fundamental insights into how sequence dependent peptide templates may be suitable precursors for bio-inspired materials synthesis (Figure 3).

4: Adaptive Emission through Reactive Incorporation of Chemical Feeds

(This work is unpublished, so a more detailed description is provided).

Nature's pigments, including melanins, are remarkable materials that serve critical protective and communication functions across life forms and have exciting potential opportunities as functional materials. While they are made from chemically simple building blocks, their biosynthesis and assembly relies on tightly regulated processes that are both temporally and spatially controlled, and further fine-tuned by incorporation of locally available metabolites. Spatiotemporal control of structure formation is increasingly incorporated in laboratory-based biomimetic synthesis strategies through considerations of assembly pathways and kinetics, controlled order/disorder, confinement, hierarchy, *in situ* chemical activation and reaction-diffusion gradients. *Yet, customizable pigment materials that respond to and incorporate chemical signals have not been achieved to date.* Here, we show formation of melanin-like particles from self-assembling peptide and amino acid precursors with customizable properties that mimic, but go far beyond those observed in natural melanins. The particles provide customizable coloration and intense and dramatically tunable fluorescence emission from blue to far-red which can be fine-tuned by chemical feed of (*combinations of*) amino acids to the reactive pigment particles.

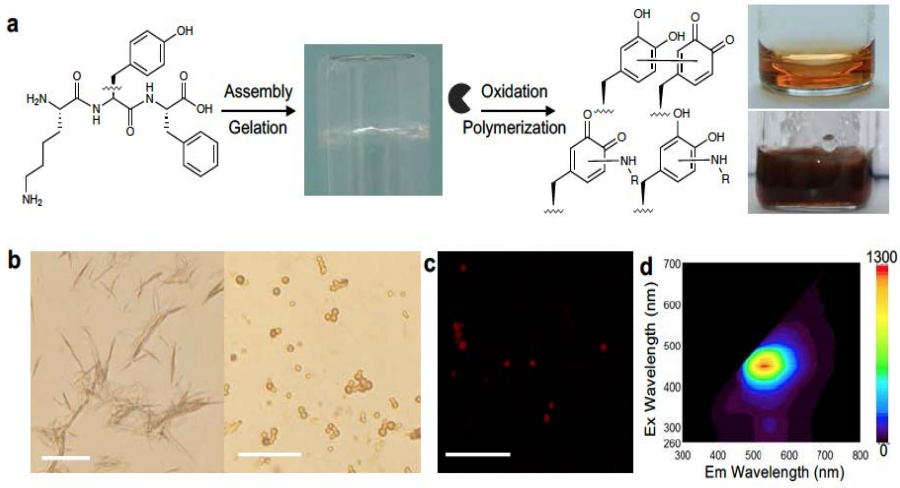

Fig. 4. KYFox peptide pigment. a. The tripeptide KYF (chemical structure presented) self-assembles into a translucent hydrogel containing nanofibrils (30 mM, pH 7.5) to pre-organize tyrosine residues for enzymatic oxidation (tyrosinase, 0.2 mg/ml), resulting in KYFox polymeric spheres. R represents the peptide KYF. Macroscopic images of hydrogel before and after 24 h of oxidation are presented. **b.** Time dependent optical microscopy analysis show transition from peptide fibrils to polymeric peptide spheres over the course of 24 h of oxidation. Scale bars=20 μm. **c.** Confocal microscopy images at low magnification using excitation wavelength 561 nm (bottom). **d.** 2D fluorescence heat map of KYFox (suspension) after 24 h of oxidation.

Melanin formation-resulting in patterned coloration in animals-requires tight regulation of chemical processing, through a multistep oxidative polymerization process that is both spatially and temporally confined, with the properties of the melanins formed dictated by the availability and incorporation of specific metabolites. When tyrosine alone is present, the brown-black pigment eumelanin is formed, while the presence of cysteine gives rise to its incorporation to form pheomelanin associated with yellow and red coloration. In addition to coloration, melanins play an important role in sun protection, through the broadband absorption in the ultra-violet (UV) and visible spectra as a result of the pigments' chemical heterogeneity and (supramolecular) disorder, which is also responsible for the materials' (weak) excitation-dependent fluorescence. Here, we demonstrate that the chemical space of melanin-like pigments

and their UV absorption and fluorescence properties can be dramatically expanded and tuned, much beyond what has been observed in biological systems, achieved by simply varying the chemical feed of (combinations) of amino acids that become incorporated during the melanin formation process.

First, we developed a method to produce melanin-like micro-particles. Similar to the results describe under '3', we use as a precursor tyrosine-containing self-assembling tripeptide which forms supramolecular structures, thus providing ordering of tyrosine residues within supramolecular substrates, which template and spatially confine the enzymatic oxidation to catecholes and quinones (Fig. 4a) and subsequent polymerization process. Based on the observation that lysines are featured in rapidly polymerizing mussel adhesives and are involved in cation-π interactions, we used Lys-Tyr-Phe (KYF), which is known to form nanofibrous gels. At physiological pH in aqueous buffer, the peptide self-assembles into a translucent hydrogel (Fig. 1a) composed of a physically entangled network of nanofibrils (Fig. 4b). Next, we used mushroom tyrosinase to oxidize the pre-organized tyrosine residues. Upon oxidation, a reddish-brown color appears, representing the oxidized and polymerizing KYF (KYF_{ox}), which turns into a suspension with a colloidal film forming on the surface after 24 h (not shown). Optical (Fig. 4b) and transmission electron microscopy (TEM) analyses reveal the formation of micron-sized spheres, maturing to ~2 μm in diameter, during the enzymatic oxidation process. Confocal microscopy analysis of KYF_{ox} shows that the spheres fluoresce upon excitation at 561 nm (Fig. 4c). 2D excitation/emission analysis shows a strong excitation maximum at 460 nm and a weak maximum at 300 nm, with emission maximum at 536 nm (Fig. 4d). By contrast, oxidized Y (Y_{ox}), which lacks the supramolecular structure provided by the tripeptide, or synthetic melanin have much weaker and broader emission, demonstrating that it is the controlled supramolecular interactions that guide the oxidation and polymerization process in the KYF system (Fig. 4a) that gives rise to the dramatically enhanced fluorescence intensity.

Inspired by animal melanin biosynthesis, where coloration is regulated by cysteine/tyrosine ratios, we sought to customize the properties of KYF_{ox} pigment by using reaction diffusion of cysteine (C) as a chemical feed, introduced after 3 h of oxidation. At this time point the micron-sized spheres have already formed, but the catecholes and quinones are still reactive and accessible to react with the amino acid nucleophile by its diffusion. C addition results in a color change of the reaction from reddish-brown of KYF_{ox} to yellow (Fig. 5a). Next, we examined whether C incorporation changes the pigment fluorescence. 2D fluorescence analysis shows significantly broader and blue shifted excitation of the yellow pigment compared to that of KYF_{ox} (Fig. 5c). Following metabolic feed with C, the amino acid is incorporated to the oxidized tripeptide *via* a similar mechanism to that of pheomelanin synthesis. First, the sulfur group is conjugated to the peptide catechol or quinone groups, followed by cyclization through the conjugation of the cysteine amine to the catechol/quinone, thus forming a new conjugated chromophore (Fig. 5b), which is responsible for the color and emission change observed.

We then hypothesized that the photonic properties could be further customized by inclusion of additional amino acid metabolites with different chemical properties that could potentially form new chromophores or influence supramolecular order through non-covalent contributions. Thus, we explored metabolic feed using amino acids with different side chain properties: basic (histidine, H), aromatic (phenylalanine, F), and aliphatic (isoleucine, I). Remarkably, the incorporation of amino acids by diffusion into the reactive particles resulted in readily observed, dramatic color changes from the reddish-light brown observed for KYF_{ox} to red for H, more intense red for F, and a darker shade of brown for I (Fig. 5a). UV-Vis analysis shows that the H-

pigment absorbs at 280 and 350 nm, the F-pigment in addition strongly absorbs at 500 nm, and the I-pigment uniquely absorbs at 620 nm.

Significant changes to the fluorescence spectra of KYF_{ox} occur following the amino acid feed with the most dramatic change observed by the red F-pigment, including narrowing of both excitation and emission spectra, and a remarkable emergence of near infrared (IR) fluorescence observed for the aliphatic I-pigment (Fig. 5c). Emission spectra were obtained on both the suspension and solution fractions. At excitation 460 nm, a ~3-fold increase in fluorescence intensity was observed for the F-pigment (Fig. 5d) and 27 nm and 38 nm redshifts observed for the red H and F-pigments, respectively, compared to KYF_{ox}. These strong shifts and intense yellow emission are likely related to a combination of changes in supramolecular order/disorder, as no change in fluorescence was observed for the free Y_{ox} following a metabolic feed with F, in addition to the changes in chemical connectivity and conjugation upon covalent incorporation.

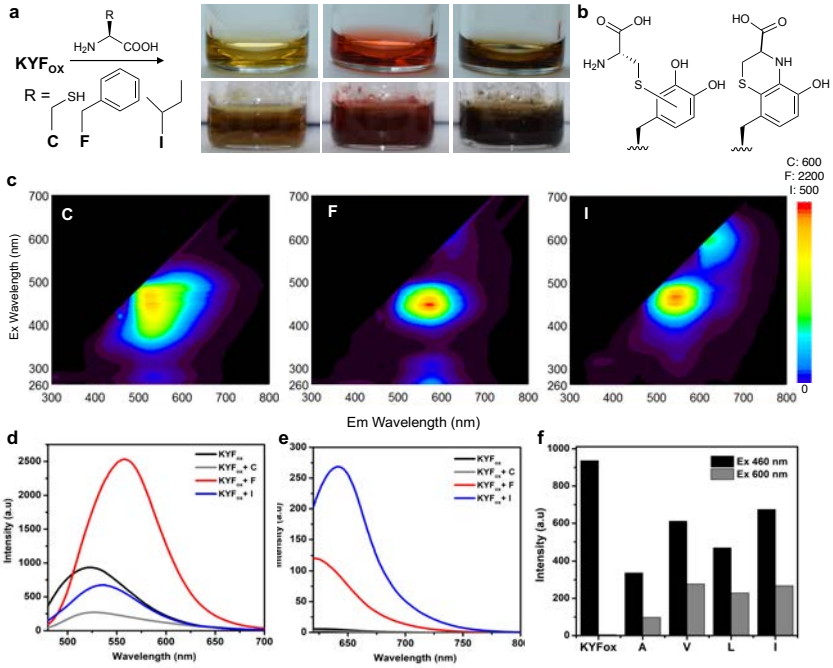

Fig. 5. Peptide pigments formation by amino acid metabolic feed. a. KYF_{ox} is used as a template to form a range of pigments directed by amino acid metabolic input. Chemical structures of cysteine (C) phenylalanine (F) and isoleucine (I) side chains and macroscopic images of the peptide pigments solution fractions (top) and suspensions (bottom) taken after 24 h of oxidation are presented. **b**. Chemical structures of KYF_{ox} side chains formed following C incorporation. **c**. 2D fluorescence heat maps of C-, F- and I-pigments. **d**. Emission spectra of the pigments at excitation 460 nm (**d**) and 600 nm (**e**). **f**. Emission intensity at excitation 600 nm of KYF_{ox} and pigments formed by aliphatic amino acids feed.

To study whether the observed near IR fluorescence of the aliphatic I-pigment (Fig. 5e) originates from changes in the local polarity upon incorporation of the alkyl side chain, we expanded the metabolic feed to include additional aliphatic amino acids: alanine (A), valine (V) and leucine (L). All aliphatic pigments absorb at 620 nm. Emission intensity (Fig. 5f) and shifts in the near IR fluorescence compared to KYF_{ox} were found to correlate with amino acid hydrophobicity. These results suggest that incorporation of aliphatic amino acids reduce the local polarity for the oxidized tyrosine chromophore and demonstrate that emission can be rationally tuned.

Next, we analyzed the changes in fluorescence of individual microspheres upon metabolic feed using confocal microscopy. We reasoned that fine-tuning of the particles' fluorescence could be achieved by providing combinations of amino acids as the chemical feed. We observed that spheres formed by F-feed have the strongest yellow-red fluorescence, with ~5-fold increase in intensity compared to spheres forming by I-feed, which have the strongest far-red fluorescence (Fig. 6a-b). Combining F and I resulted in a dark red color (Fig. 6e), increased yellow-red

fluorescence compared to that of the I-pigment (Fig. 6c), and increased far-red fluorescence (Fig. 6d) compared to that of the F-pigment, as observed for individual particles (Fig. 6a-b), the solution phase (Fig. 6c-d) and the overall suspension. Combining C with either F or I results in orange/yellow-brown color of the reactions (Fig. 5e). These spheres (C+F and C+I) show increased green fluorescence (Fig. 6a-b), suggesting that C is predominantly incorporated. Thus, the microspheres' fluorescence can be tuned across the green, yellow and far-red regions of the spectra, with C promoting green fluorescence, F yellow fluorescence and I infrared fluorescence.

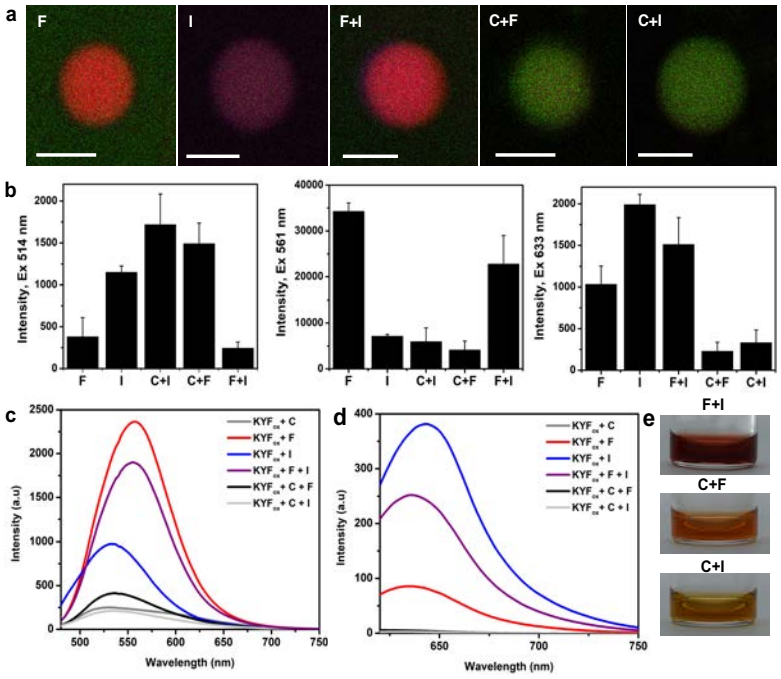

Fig. 6. **Pigment particles with tunable fluorescence formed by varying chemical feed. a.** Confocal microcopy images of pigment spheres formed by metabolic feed with indicated amino acids or amino acids combinations. Images showing merged fluorescence at excitation wavelengths: 514 nm, 561 nm, and 633 nm. Scale bar=2 μm. **b**. Fluorescence intensity obtained by confocal microscopy analysis at excitation wavelengths 514 nm, 561 nm, and 633 nm. Values represent average of 5 spheres; error bars represent SD. **c-d**. Emission spectra of pigments (solution fraction) formed by amino acids or amino acids combinations at excitations 460 nm (**c**) and 600 nm (**d**). C- F- and I-pigments are presented in **c-d** for comparison purposes.

Our approach holds promise for the design of synthetic materials which mimic nature's protective and aesthetic properties. Moreover, the process involves the spontaneous, *in situ*, formation of new chromophores and may be relevant to the origins of coloration in biology. The simplicity of the process and chemistry involved suggests applications, for example in sensing of metabolites or in the adaptive enhancement of photoprotection or coloration properties.

Collaborations/ interactions/ transitions

Dr Elisa Riedo (CUNY ASRC): Combining thermochemical nanolithography and biocatalytic self-assembly to create transient nanopatterns.
Dr Jack Szostak (Harvard): Co-assembly of RNA and peptides to influence replication as relevant to origin-of-life challenges.
Dr Oleg Gang (Columbia University and BNL): transient nanopatterns for multiscale fabrication.
Dr Dan Heller (Memorial Sloan Kettering Cancer Center): peptide nanostructures as smart delivery vehicles.
Dr Chris Bettinger (Carnegie Mellon): characterization of materials properties on synthetic melanin templated by peptide self-assembly.

Collaborations within AFoSR program:

Dr Allon Hochbaum: Dr Ulijn visited UC Irvine during the spring of 2016. Proof of concept work was performed on measurement of transient conductance of naphthalene based nanostructures produced by biocatalyic self-assembly.
Dr Raymond Tu: Joint project on the interfacial assembly of tripeptides to create stabilized bubbles for medical imaging.

Publications:
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Papers published acknowledging AFoSR support.

1. A. Lampel, Scott A. McPhee, H.-A. Park, G.G. Scott, S. Humagain, D.R. Hekstra, B. Yoo, P.W.J.M. Frederix, T.-D. Li, R.R. Abzalimov, S.G. Greenbaum, T.Tuttle, C. Hu, C.J. Bettinger and R.V. Ulijn, Polymeric Peptide Pigments with Sequence-encoded Properties, *Science*, **2017**, 356, 1064.
2. J.K. Sahoo, C.G. Pappas, I.R. Sasselli, Y.M. Abul-Haija and R.V. Ulijn, Biocatalytic Self-Assembly Cascades, *Angew. Chem. Int. Ed.*, **2017**, 56, 6828.
3. Y.M. Abul-Haija, G. Scott, J.K. Sahoo, T.Tuttle and R.V. Ulijn, Cooperative, Ion-sensitive Co-assembly of Tripeptide Hydrogels, *Chem. Comm*., **2017**, 53, 9562.
4. J.K. Sahoo, S. Roy, N. Javid, K.L. Duncan, L.A. Aitken, R.V. Ulijn Pathway-dependent Gold Nanoparticle Formation by Biocatalytic Self-assembly, *Nanoscale*, **2017**, 9, 12330.
5. M. Kumar, N.L. Ing, V. Narang, N. Wijerathne, A.I. Hochbaum and R.V. Ulijn, Amino Acid-Encoded Biocatalytic Self-Assembly Enables the Formation of Transient Conducting Nanostructures, *Nat. Chem*., **2018**, 10, 696-703.

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Abstract

In the third and final year, the concepts of amino acid-encoded, transient assembly were further developed and published (Nature Chemistry, 2018). This was the first demonstration of using amino acids as code to control dynamic assembly and dis-assembly behavior. By incorporating semiconducting elements, the approach enabled the first demonstration of conducting wires that could be formed and hydrolyzed in response to metabolites present. In a new direction, following from our discovery of polymeric pigments with tunable properties in year 2 (as published in Science, 2017), the concept of amino acid encoded assembly was also combined with enzymatic oxidation to enable further control of the optical properties of peptide-based polymeric pigments. This approach gave rise to the formation of peptide based microparticles with remarkable control over emission, which could be adaptively modified by changing amino acid feed. This work is in preparation for submission to a leading journal.

Distribution Statement

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AFoSR_final_project_report_2015-2018.pdf

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Archival Publications (published) during reporting period:

1. A. Lampel, Scott A. McPhee, H.-A. Park, G.G. Scott, S. Humagain, D.R. Hekstra, B. Yoo, P.W.J.M. Frederix, T.-D. Li, R.R. Abzalimov, S.G. Greenbaum, T.Tuttle, C. Hu, C.J. Bettinger and R.V. Ulijn, Polymeric Peptide Pigments with Sequence-encoded Properties, Science, 2017, 356, 1064.
2. J.K. Sahoo, C.G. Pappas, I.R. Sasselli, Y.M. Abul-Haija and R.V. Ulijn, Biocatalytic Self-Assembly Cascades, Angew. Chem. Int. Ed., 2017, 56, 6828.
3. Y.M. Abul-Haija, G. Scott, J.K. Sahoo, T.Tuttle and R.V. Ulijn, Cooperative, Ion-sensitive Co-assembly of Tripeptide Hydrogels, Chem. Comm., 2017, 53, 9562.
4. J.K. Sahoo, S. Roy, N. Javid, K.L. Duncan, L.A. Aitken, R.V. Ulijn Pathway-dependent Gold Nanoparticle Formation by Biocatalytic Self-assembly, Nanoscale, 2017, 9, 12330.
5. M. Kumar, N.L. Ing, V. Narang, N. Wijerathne, A.I. Hochbaum and R.V. Ulijn, Amino Acid-Encoded Biocatalytic Self-Assembly Enables the Formation of Transient Conducting Nanostructures, Nat. Chem., 2018, 10, 696-703.

New discoveries, inventions, or patent disclosures:
Do you have any discoveries, inventions, or patent disclosures to report for this period?

Yes

Please describe and include any notable dates

Patent Application US17/50953 submitted February 2017

Do you plan to pursue a claim for personal or organizational intellectual property?

Yes

Changes in research objectives (if any):

An additional objective was added, focused on the development of polymeric peptide pigments with tunable properties. This was an opportunistic new direction, which was discussed with AFoSR at every stage. It lead to a publication in Science. One area that received less emphasis than expected was the use of audible sound to achieve transient assemblies. While our previous work clearly demonstrated the ability to use ultrasound for this purpose, the effects of audible sound, while clearly present, were found to be difficult to reproduce.

Change in AFOSR Program Officer, if any:

The program was temporarily overseen by Dr Sofi Bin Salamon and then recently taken over by Dr J. Aura Gimm.

Extensions granted or milestones slipped, if any:

none

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Oct 18, 2018 19:15:25 Success: Email Sent to: rein.ulijn@asrc.cuny.edu