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Copper Ligand and Anion Effects: Controlling the Kinetics of the Photoinitiated Copper(I) Catalyzed Azide—Alkyne Cycloaddition Polymerization

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Abstract

The kinetics of photoinduced copper(I) catalyzed azide-alkyne cycloaddition (CuAAC) polymerizations were assessed as a function of copper(II) amine-based ligands. Copper(II) bromide ligated with 1,1,4,7,10,10-hexamethylenetetramine (HMTETA) exhibited the fastest kinetics in both Norrish type(I) and type(II) photoinitiating systems. A characteristic induction period is observed with these polymerizations and is manipulated by adding an external tertiary amine in Norrish Type(II) photoinitiating systems or by changing the anion of the copper(II) salt. Halides, specifically bromide and chloride, exhibit the fastest kinetics with the smallest induction period in comparison with organic anions, such as bistriflimide and triflate. The temporal control of the photo-CuAAC polymerization is affected by pre-ligation of the copper catalyst, by the presence of certain anions such as acetate, and by specific ligands such as tetramethylethylenediamine (TMEDA).

1 Introduction

Since its discovery in 2002, the copper(I) catalyzed azide—alkyne cycloaddition (CuAAC) reaction¹ has been one of the most influential ‘click’ reactions. Click reactions are energetically favorable, proceed under mild conditions, are highly selective, are high yielding with a wide scope of starting materials, and produce a product that is easily extracted and isolated.² Indeed, the CuAAC reaction (Scheme 1a) provides a facile synthetic route for the production of 1,4 disubstituted 1,2,3-triazole adducts. The reaction has been used in a range of fields, such as materials science and polymers,³ protein chemistry,⁴ bioconjugation reactions,⁵ and drug discovery.⁶

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Conflicts of interest

There are no conflicts to declare.

In CuAAC chemistries, the copper(I) source is usually introduced directly by adding a copper(I) salt or by adding a copper(II) salt in conjunction with a reducing agent, such as sodium ascorbate.[–] In an effort to afford this reaction with spatiotemporal control, several researchers have photoinitiated the CuAAC reaction through the use of an external photosensitizing or photoinitiating agent capable of reducing copper(II) to copper(I) (Scheme 1b).[–] The overall ability to dictate when and where a chemical reaction takes places using light is critical to multiple applications in materials science, such as photo-lithography, dental materials,[·] and stereolithographic 3D-printing. Due to the highly orthogonal and efficient nature of CuAAC as a ‘click’ reaction and the added control and simplicity that photochemistries provide, the use of photo-CuAAC chemistries in material science has allowed for the preparation of complex architectures, well-defined structures, and efficient post-modification of materials.^{·–}

For a CuAAC reaction to be kinetically favorable and rapid, the need to stabilize the copper(I) catalyst state and protect it from oxidation or disproportionation is especially significant. Nitrogen-based ligands serve to stabilize the copper(I) oxidation state, preventing copper disproportionation effects, and enhancing solubility in neat reactions. The use of these amine ligands is common in atomic transfer radical polymerization (ATRP), where the ability to control the copper oxidation state is critical for the selectivity and kinetics of the reaction.[·] While copper ligands and copper catalyst performance have been studied in both ATRP and CuAAC chemistries that are not light activated,[–] efforts to understand copper(II) catalyst performance and ligand effects in photo-mediated CuAAC polymerizations are notably absent.

Herein, the reaction kinetics of photo-CuAAC polymerizations are assessed as a function of copper(II) species complexed with different polydentate amine ligands in both Norrish type(I) and type(II) photopolymerization schemes. The effects of the ligands and counter ions on the temporal control of the photo-CuAAC polymerization are assessed by evaluating the long-term stability of these copper complexes in the presence and absence of photoinitiators and light. Finally, the robustness of the photo-CuAAC polymerization is demonstrated to be heavily dictated by the copper(II) source and ligand species present.

2. Materials and Methods

2.1 Materials

Copper(II) chloride (CuCl₂), copper(II) bromide (CuBr₂), copper(II) acetate [Cu(OAc)₂], *N,N,N',N',N'*-pentamethyldiethylenetriamine (PMDETA), tetramethylethylenediamine (TMEDA), 2,2'-bipyridine (BPY), di-(2-picoly)amine (DPA) and 1,1,4,7,10,10-hexamethylenetetramine (HMTETA), 4,*N,N*-trimethylaniline, and 1-dodecyne were used as received from Sigma Aldrich. Copper(II) acetylacetonate [Cu(AcAc)₂] was used as received from Chem-Impex. Copper(II)

2.2 Copper Ligand Synthesis

Synthesis of CuBr₂-TMEDA: In a round-bottom flask, 1.28 g (~5.75 mmol) of CuBr₂ was dissolved in approximately 30 mL of methanol. A solution of 0.67 g (~5.75 mmol) of

TMEDA in 10 mL of methanol was added to the CuBr_2 /methanol solution dropwise. The reaction proceeded for 3 hours. The resulting green liquid was heated under reduced pressure to evaporate the solvent. The dark green powder was further dried under vacuum. The product was obtained in 89% yield (1.74 g). Elemental Analysis, Calculated (%): C, 21.22; H, 4.75; N, 8.25; Measured (%): C, 21.28; H, 4.65; N, 8.38

Synthesis of CuBr_2 -BPY: In a round-bottom flask, 1.12 g (~5.0 mmol) of CuBr_2 was dissolved in approximately 40 mL of anhydrous ethanol. A solution of 0.78 g (~5.0 mmol) of BPY in 10 mL of anhydrous ethanol was added to the CuBr_2 /EtOH mixture dropwise. The reaction proceeded for 18 hours. The resulting light brown solution was heated under reduced pressure to remove the solvent. The remaining light brown solid was further dried under vacuum. The product was obtained in 43% yield (0.82 g). Elemental Analysis, Calculated (%): C, 31.65; H, 2.12; N, 7.38; Measured (%): C, 32.58; H, 2.21; N, 7.80

Synthesis of CuBr_2 -DPA: In a round-bottom flask, 0.224 g (~1.00 mmol) of CuBr_2 was dissolved in approximately 15 mL of anhydrous ethanol. A solution of 0.20 g (~1.00 mmol) of DPA in 10 mL of anhydrous ethanol was added to the CuBr_2 /EtOH mixture dropwise. The reaction proceeded for 3 hours. The resulting blue precipitate was filtered from the solution. The remaining blue solid was further dried under vacuum. The product was obtained in 71% yield (0.30 g). Elemental Analysis, Calculated (%): C, 34.10; H, 3.10; N, 9.94; Measured (%): C, 34.34; H, 3.01; N, 10.02

Synthesis of CuBr_2 -Me₆TREN: In a round-bottom flask, 0.097 g (~0.43 mmol) of CuBr_2 was dissolved in approximately 15 mL of anhydrous ethanol. A solution of 0.10 g (~0.43 mmol) of Me₆TREN in 10 mL of anhydrous ethanol was added slowly to the CuBr_2 /EtOH mixture. The reaction proceeded for 3 hours, resulting in a green solution. The solution was heated under reduced pressure to evaporate the solvent. The remaining green solid was further dried under vacuum. The product was obtained in 87% yield (0.17 g). Elemental Analysis, Calculated (%): C, 31.76; H, 6.66; N, 12.35; Measured (%): C, 31.47; H, 6.69; N, 12.32

Synthesis of CuBr_2 -HMTETA: In a round-bottom flask, 0.20 g (~0.87 mmol) of CuBr_2 was dissolved in 25 mL of anhydrous ethanol. A solution of 0.20 g HMTETA in 7.5 mL of ethanol was added to the reaction mixture dropwise. The reaction proceeded for 3 hours, was heated under reduced pressure, and kept to dry for 24 hours under vacuum to give a green solid. The product was obtained in 99% yield (0.39 g). Elemental Analysis, Calculated (%): C, 31.76; H, 6.66; N, 12.35; Measured (%): C, 32.39; H, 6.59; N, 12.59

Synthesis of $\text{Cu}(\text{TFSI})_2$ -PMDETA: In a round-bottom flask, 0.194 g (~0.16 mmol) of $\text{Cu}(\text{TFSI})_2$ was dissolved in approximately 15 mL of anhydrous ethanol. After stirring, 0.028 g (~0.16 mmol) of PMDETA was added to the solution. The reaction proceeded for 3 hours, resulting in a blue solution. The solution was heated under reduced pressure to evaporate the solvent. The remaining blue solid was further dried under vacuum. The product was obtained in 63% yield (0.08 g). Elemental Analysis, Calculated (%): C, 19.59; H, 2.91; N, 8.79; S, 16.09; Measured (%): C, 18.51; H, 3.18; N, 8.40; S, 16.418

Synthesis of Cu(OTf)₂-PMDETA: In a round bottom flask, 0.10 g (~0.28 mmol) of Cu(OTf)₂ was dissolved in 20 mL of acetonitrile. After stirring, 0.048 g (~0.28 mmol) of PMDETA was added dropwise to the solution. The reaction proceeded for 6 hours, resulting in a dark blue solution. The solution was heated under reduced pressure to evaporate the solvent. The dark blue solid was dried under vacuum overnight. The product was obtained in 80% yield (0.118 g). Elemental Analysis, Calculated (%): C, 24.70; H, 4.33; N, 7.85; S, 11.99; Measured (%): C, 23.74; H, 4.47; N, 7.33; S, 11.15

The synthesis of CuBr₂ and CuCl₂ with PMDETA followed the procedure by Margaf et al.

Elemental Analysis CuBr₂ PMDETA, Calculated (%): C, 27.75; H, 5.84; N, 10.59; Measured (%): C, 28.19; H, 5.94; N, 11.16 Elemental Analysis CuCl₂ PMDETA, Calculated (%): C, 35.12; H, 7.53; N, 13.65; Measured (%): C, 33.99; H, 7.69; N, 13.41

2.3 Monomer Synthesis

AZD and YNE were synthesized based on previous literature procedures and confirmed via NMR spectroscopy (see supporting information for characterization). Their structures are shown in Scheme 2.

2.4 Polymerization Kinetics

An equimolar ratio of azide and alkyne functional groups from AZD and YNE was used in all polymer samples. The copper(II) catalyst was then added to the resin formulation. Initial copper(II) concentrations were kept constant in all kinetic studies at 1.15 mol% (relative to the azide mol functionality). Methanol was added to assist with solubility of the copper(II) ligand in the polymer sample, but was later removed under reduced pressure such that the total amount of residual methanol was less than 1 wt%. A 0.2 gram aliquot of the monomer/copper mixture was taken out and 1 wt% of camphorquinone was added to the reaction mixture. A DAC 150.1 FVZ-K Flacktek Speed Mixer was utilized to mix the components under high speed. All resins samples were placed between glass slides separated by 0.11 mm plastic shims and secured with binder clips.

The reaction kinetics were measured via real-time Fourier Transform Infrared (FTIR) spectroscopy using an IS-50 spectrometer (Thermofisher). The alkyne overtone (C-H stretch next to triple bond) between 6430 and 6570 cm⁻¹ was monitored as a function of time once light was irradiated onto the sample, starting the reaction. The sample was irradiated using an OmniCure Series 2000 lamp, that was filtered using either a 405 or 470 nm band pass interference filter, equipped with a 200 Watt mercury arc bulb (Lumen Dynamics). The decrease in the alkyne peak area was converted to overall alkyne conversion in the system using a Beer's law analysis.

3. Results and Discussion

The copper(I) catalyzed azide-alkyne cycloaddition polymerization is a step growth polymerization taking place between a multifunctional azide and multifunctional alkyne in the presence of copper(I) as shown in Scheme 3a. Photoreduction of copper(II) to copper(I) in CuAAC polymerizations occurs using either Norrish Type(I) or Type(II) photoinitiating

reactions (Scheme 3b). The Norrish Type(I) reaction, also known as an α -cleavage reaction, is the direct photolytic cleavage of a species into two radicals. In the presence of a copper(II) source, these radicals may be able to directly reduce the copper(II) source to copper(I). Many Type(I) photoinitiators absorb in the UV-region. Since azides can decompose under UV-irradiation, Norrish Type(II) reactions have been employed in photoinitiating the CuAAC reaction using camphorquinone and a co-initiator such as a tertiary amine. Mechanistically, the Norrish Type(II) reaction is an electron transfer reaction and typically abstracts a hydrogen intermolecularly in the presence of a co-initiator. In the presence of a copper(II) species, these radicals can reduce copper(II) to copper(I). In the absence of an external amine, this hydrogen can be extracted from another source, such as the amine-based ligand used in the CuAAC reaction.

While the use of polypyridine based complexes is extremely common in photoinduced redox chemistry, previous studies on copper(I) amine ligands used in non-photoinduced CuAAC reactions, showed pyridine-based ligands to be ineffective in catalyzing the CuAAC reaction when compared to aliphatic ligands. The sluggish kinetics were attributed to several factors, including the basicity and the electron donating properties of aliphatic amines as compared with pyridine based amines that may facilitate the formation of the copper(I)-acetylide complex. The aromatic pyridine based copper(II) ligands (BPY, DPA; scheme 2) showed a similar effect in which low conversion (<15%) was observed over two hours (Figure S2) when using a Norrish Type(II) photosensitizer, camphorquinone. Moreover, these copper(II) species showed poor solubility in the CuAAC resin.

The aliphatic amines (HMTETA, PMDETA, and Me₆TREN) displayed enhanced kinetics. Copper(II) bromide ligated to HMTETA exhibits the most rapid conversion of alkyne functional groups, where the average initial rate of polymerization was twice as fast with HMTETA as compared with PMDETA and Me₆TREN (Figure 1a). Previous studies on non-photoinitiated CuAAC showed that tridentate ligands performed better in catalyzing CuAAC reactions over tetradentate amines. It was speculated that this behavior owed to tetradentate ligands coordinatively saturating the copper(I) source and disfavoring copper(I)-alkyne coordination; however, the opposite trend is observed here in photo-CuAAC polymerizations. One potential explanation for this discrepancy owes to the photo-CuAAC initiation mechanism in the absence of an accelerating amine (Figure 1d). Since the ligand is the only source of abstractable *N*- α -carbon hydrogens, a tetradentate ligand (HMTETA) is expected to exhibit faster kinetics than a tridentate ligand (PMDETA) due to the increase in availability of these abstractable hydrogens. While also a tetradentate ligand, Me₆TREN is not as fast as HMTETA potentially due to steric hindrances caused by branching.

Cyclic voltammetry studies were performed in water to assess the complexes' redox potential (Figure S3). Qui et al. showed that the redox potential in copper/amine based species is directly correlated to the *N*-ligand structure. They found that the reducing power increases as the number of *N*-atoms increases. Unsurprisingly, the same trends were obtained with the copper(II) ligands by which HMTETA showed a higher reducing potential (−0.045 V) compared to PMDETA and Me₆TREN (−0.089 and −0.073 V, respectively). Since the reducing power measured can be related to the ease of hydrogen abstraction by the photoinitiator, the higher reducing power of copper(II)/HMTETA is a viable explanation to

why it exhibits the fastest kinetics. Thus, when a type(I) photoinitiator, such as phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide (Irgacure 819) which does not require hydrogen abstraction to reduce copper(II) is used and was initiated under 30 mW/cm of 405 nm light, copper/HMTETA displays the fastest kinetics (Figure 1b). Regardless of the type of photoinitiator used, HMTETA performs better kinetically than other polydentate ligands in photo-CuAAC polymerizations. This result highlights the significance copper(II) to copper(I) reduction has in determining overall reactivity in photo-CuAAC polymerizations.

Another salient feature observed in photo-CuAAC reactions is a characteristic induction period, where no conversion takes place after the light is commenced. The induction period in photo-CuAAC reactions has been attributed, mainly, to oxygen inhibition via oxidation of copper(I) to copper(II) at the early stages of the reaction. Though, when oxygen was removed from DMF using a freeze pump thaw cycle in a model photo-CuAAC reaction, the conversion profile, including the inhibition period, did not change compared with an identical sample that did not undergo oxygen removal. This result indicates that role of oxygen inhibition is minor. Another potential explanation owes to the copper(II) inhibition of the photoinitiator triplet state, which depends on the quantum yield and absorbency of the photoinitiator. Since the HMTETA system can abstract hydrogen faster than the other tested ligands, it would follow that its induction period is lower. Indeed, in addition to exhibiting the fastest kinetics, copper(II)/HMTETA also had the smallest induction period out of the three aliphatic ligands tested, suggesting that HMTETA is the best at protecting the copper(I) oxidation state in the neat polymerizations and that copper(I) is less effective at the quenching of the photoinitiator as compared with copper(II). In other words, the faster the copper(II) reduction to copper(I), the smaller the inhibition period in the photopolymerization. Finally, with the addition of 4,*N,N*-trimethylaniline, an accelerating amine, the inhibition period of all these reactions was reduced to less than one minute (Figure 1c), indicating an increased rate of the camphorquinone triplet state reacting with the tertiary amine over quenching by the copper(II) ligand.

The counter ion of the copper(II) ligand species plays a significant role in photo-CuAAC polymerization kinetics. Figure 2 shows the effect of bromide, chloride, TFSI, and OTf on the kinetics of the photo-CuAAC polymerization with AZD/YNE, using PMDETA as the ligand and camphorquinone as the photoinitiator. Copper(II) bromide and chloride complexes exhibit faster kinetics than OTf and TFSI (Figure 2) despite the low basicity of the four anions. These kinetic trends were also seen when Me₆Tren was the ligating amine, when a different multifunctional alkyne was used and when Irgacure 819 was used as a photoinitiator (Figures S4–S6). Bertrand showed that basic anions can act as ligands promoting the alkynyl hydrogen abstraction and subsequent metalation (structure **2** to **3**, Scheme 1b), while disfavoring the formation of the bis(copper) acetylide complex (structure **3**, Scheme 1b). Since halides (chloride and bromide) are typically thought to inhibit the reaction rate of CuAAC reactions, their ability to assist with the CuAAC polymerization as compared with organic anions (TFSI and OTf) suggests that other factors are playing a role in the kinetics of neat photo-CuAAC polymerizations, such as copper(II) to copper(I) redox potentials, solubility of the copper species in the resin formulation, and the relative size of the counter anion. While halides are effective in increasing the rate of the photo-CuAAC

reaction in neat polymerizations, this may not apply in organic media. For example, the bromide anion can have a strong inhibitory effect in organic media due to bromide's affinity to bind to copper(I) centers. As an aside, copper(II) acetate ligands initiated a reaction between AZD and YNE in the presence of methanol and in the absence of light and a photoinitiator. This reaction was also observed with copper(II) acetylacetonate ligated to PMDETA. The non-photoinitiated CuAAC polymerization in the presence of $\text{Cu}(\text{OAc})_2$ and $\text{Cu}(\text{AcAc})_2$ ligands indicates a loss of temporal control over the reaction. As previously noted by Kuang et al., copper(II) acetate can be used as a CuAAC catalyst in the presence of auxiliary nitrogen donor ligands and in the absence of light.

The primary kinetic factors affecting the rate of polymerization of the photo-CuAAC reaction in relation to the copper(II) source can be categorized into two parts. The first part is related to the ability of copper(II) to be reduced to catalytic copper(I). Effects of ligands on reduction potentials, copper(II) interactions with photoinitiators, and solubility in the resin formulation would fall into this category. The second part is related to the ligand and anion effects on copper(I) catalysis within the CuAAC mechanism.

Pre-ligation of the copper(II) salt with the amine before addition to the resin formulation is critical to maintaining temporal control over this reaction. When copper(II) chloride was pre-ligated to PMDETA, no reaction was observed over 10 hours in the absence of a photoinitiator and an external source of light (Figure 3). When copper(II) chloride and the PMDETA were added separately in the reaction mixture, however, polymerization began in the absence of an external light source or a photoinitiator in the system. This result suggests that copper(I) is formed despite the fact that there is no initial source of copper(I) in this system. While copper(II) reduction to copper(I) has been observed with copper(II) bromide TMEDA through Glaser-Hay coupling using excess TMEDA as a base, this mechanism is unlikely to be occurring in the system since the near-IR alkyne peak at 6509 cm^{-1} remained unchanged in a solution of YNE and copper(II) bromide and PMDETA added separately, in the absence of a multifunctional azide (Table S1, entry 9). In any case, these results demonstrate the importance of pre-ligation of the amine with the copper(II) salt in photo-CuAAC polymerizations to maintain the latency of initiation in the absence of light.

It should be noted that a pre-ligated copper-amine catalyst, $\text{CuBr}_2/\text{TMEDA}$, promoted the polymerization of AZD and YNE in the absence of light and photoinitiator. In an effort to understand this reaction, a model system, containing 100 mM of 1-dodecyne in methanol and 10 mM of $\text{CuBr}_2/\text{TMEDA}$ was studied using UV-Vis spectroscopy and NMR in methanol. The UV-Vis spectra showed a steady decrease in the copper(II) concentration over 1000 minutes (Figure 4a), which was not observed for either the PMDETA or Me_6TREN , as shown in Figure 4b and 4c. Furthermore, no decrease in the copper(II) peak was observed in the absence of an alkyne (Supporting Information, Figure S7). Additionally, ^1H NMR analysis of the identical systems in deuterated methanol, showed a decrease in the $\text{H}\equiv\text{C}$ bond (2.15 ppm) and the emergence of new peak at 2.63 ppm when $\text{CuBr}_2/\text{TMEDA}$ was used (Figure 4d) in less than 12 hours, indicating a potential reaction between the alkynyl -H and the copper ligand. ^{13}C NMR analysis showed a complete disappearance of both alkynyl carbons ($\text{C}\equiv\text{C}$, at 69 and 85 ppm), while no change in the NMR spectra of $\text{CuBr}_2/\text{PMDETA}$ and Me_6TREN was observed (Figures S8, S9).

A potential copper(I) source for these copper(II)/TMEDA catalyzed reactions could be the reduction of copper(II) in alcoholic solvents. This phenomenon has been documented in literature through a hypothesized oxidative homocoupling of methanol into formaldehyde or an alcoholic reduction of copper(II) mechanism. Since a small amount of methanol is initially added to the resin formulation to help solubilize the copper(II) catalyst in, it was thought that methanol could be playing a role in copper(II) reduction. However, the ^{13}C NMR spectra shows no evidence of an aldehyde peak emergence at 200 ppm. Additionally, a similar decrease in the copper(II) UV-vis peak was observed using chloroform as the solvent indicating that this behavior is not limited to alcoholic solvents (supporting information, Figures S10, S11).

An alternative cause of the reaction in the presence of TMEDA copper(II) ligands, could be ligand to metal or halide to metal charge transfer in which photoreduction of copper(II) to copper(I) can occur under UV-irradiation. While no external light source was used, it is possible that ambient light conditions could be sufficient for copper(II) to copper(I) reduction over long periods of time due to halide to metal or ligand to metal charge transfer.

While the exact mechanism of copper(II) reduction with copper(II) TMEDA species in the presence of alkynes is under current investigation, it is clear that using a copper(II) TMEDA catalyst in photo-CuAAC polymerizations prevents temporal control over the reaction. Nevertheless, the use of copper(II) TMEDA ligands could be implemented as an efficient catalyst for the CuAAC reaction in organic media.

4. Conclusions

The use of different copper(II) catalysts in photo-CuAAC polymerizations can have an immense effect on the kinetic and chemical behavior of these systems. Pyridine-based copper(II) ligands show little reaction in photo-CuAAC, whereas aliphatic amines show enhanced kinetic performance. Most notably, however, the CuAAC reaction can lose its temporal control under certain conditions, such as the absence of pre-ligation, the use of certain amine-based polydentate ligands like TMEDA, or the use of different anions such as acetate and acetylacetonate. While the photo-CuAAC reaction is considered an extremely robust and effective reaction, our results show that more consideration must be paid to the copper(II) source to fully optimize and manipulate the kinetics and behavior of this photoinduced polymerization, specifically relating to its spatial and temporal control characteristics.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

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Figure 1.

Conversion profile of a 1:1 stoichiometric mixture of AZD and YNE monomers in the presence of 1.5 wt% copper(II) bromide pre-ligated to a polydentate amine, and under 470 nm light at 30 mW/cm², containing (A) 1 wt% camphorquinone, (B) 1 wt% Irgacure 819, and (C) 1 wt% camphorquinone and 1 wt% trimethylaniline. For all these samples, light was not irradiated until after 5 minutes after measurement started (indicated in the grey box) to show temporal control over the reaction. All sample thicknesses were kept constant at 0.11 mm. (D) Schematic of the Norrish Type (II) photoinitiation of CuAAC polymerizations with camphorquinone and a tertiary amine.

Figure 2.

Conversion profile between AZD and YNE using different equimolar amounts of copper(II) anion sources ligated to PMDETA in the presence of 1 wt% camphorquinone under 470 nm light at 30 mW/cm². The halides (bromide and chloride) exhibited the fastest reaction kinetics compared to triflate and bistriflimide ions. All sample thicknesses were kept constant at 0.11 mm.

Figure 3.

Conversion profile for the CuAAC polymerization using equimolar amount of AZD and YNE comparing a pre-ligated copper(II) chloride PMDETA ligand vs. a non-ligated copper(II) chloride catalyst where the PMDETA ligand was added separately. No reaction was observed in the pre-ligated copper(II) complex over 10 hours, whereas near full conversion was observed with the non-ligated copper(II) source within 2 hours. All sample thicknesses were kept constant at 0.11 mm.

Figure 4.

UV-Vis spectra over 1000 minutes at a constant pathlength of 1 cm of 100 mM 1-dodecyne and 10 mM of (A) CuBr₂/TMEDA, (B) CuBr₂/PMDETA, and (C) CuBr₂/Me₆TREN in methanol. A decrease in the peak between 600 and 800 nm was observed only for the copper(II) TMEDA ligand indicating copper(II) reduction in the presence of the alkyne. (D) Change in ¹H NMR spectra at time=0 (red) to time=18 hours (blue) for a solution of 100 mM 1-dodecyne and 10 mM copper(II) bromide TMEDA in deuterated methanol. The NMR shows a decrease in the peak at 2.15 ppm and an appearance of a peak at 2.63 ppm.

Scheme 1.

(A) Schematic of the copper(I) catalyzed azide—alkyne cycloaddition reaction. An alkyne moiety (blue) reacts with an azide functionality (red) in the presence of a copper(I) catalyst to yield a 1,4 disubstituted 1,2,3-triazole product. (B) Photo-CuAAC mechanistic cycle: Copper(II) reduces to copper(I) (1) in the presence of a photoinitiator (P.I.) and light, where the photoinitiator breaks into radicals (P.I.*) capable of reducing copper(II) to copper(I). The copper(I) species ligates to the alkyne, forming an intermediate (2). This ligation allows for the formation of a binuclear copper(I) acetylide (3). A nucleophilic attack of the azide on the

acetylide carbon creates the intermediate triazolide adduct with two ligated copper species (4) and the subsequent 1,2,3-triazole with a copper moiety on the C-5 position of the triazole intermediate (5). Finally, a 1,4-substituted 1,2,3-triazole is formed (6) and copper(I) is regenerated, completing the cycle.

Ligands:

TMEDA

PMDETA

HMTETA

Me₆TREN

BPY

DPA

Monomers:

AZD

YNE

Scheme 2.

Polydentate amine ligands and monomers used in this study.

Scheme 3.

(A) Schematic of the photo-CuAAC polymerization. An alkyne functional group (blue) reacts with an azide functionality (red) in the presence of copper(I), forming a step-growth network with triazole linkages (purple). (B) The photoinitiation of the reaction occurs by one of two routes: Norrish Type(I) and Norrish Type(II) photoinitiation. In Type(I) initiation, the photoinitiator (shown as RCOR') undergoes intersystem crossing to form an excited state which then dissociates into two radicals. One or more of these radicals can then reduce copper(II) to copper(I). In Type(II) initiation, the photoinitiator also undergoes intersystem

crossing, but then typically abstracts a hydrogen from a co-initiator (H-R''). The resulting co-initiator radical can then reduce copper(II) to copper(I).

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