Electronic Supplementary Material for Chemical Communications

Signal Amplification and Transduction by Photo-Activated Catalysis

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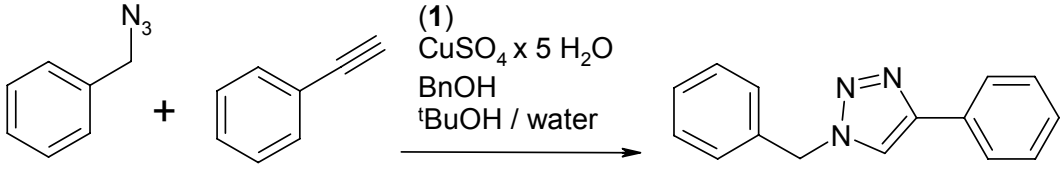
Supporting information

1) Light depending Cu(I)-catalyzed cycloaddition in water

The Cu(I)-catalyzed cycloaddition in aqueous solution is light-depending and proceeds only under continuous irradiation. Cu(I) is not stable in aqueous solution and disproportionates. To allow photoreduction of **1** benzyl alcohol was used as sacrificial electron donor.



Scheme S-1: Light- dependent cycloaddition using catalytic amounts of **1**) and a Cu(II)-salt.

To monitor the reaction's conversion the resonance shift of the benzylic CH_2-signal in the ^{1}H-NMR-spectrum is used. Whereas the CH_2-group of benzyl azide shows a singlet at 4.33 ppm the corresponding signal of the CH_2-group of the triazole-product appears at 5.55 ppm. Both peaks are unaffected by any signals of other components or by-products, neither at the beginning nor at the end of the reaction (Fig. 1, 2, 3). From peak areas the conversion of the reaction was determined.

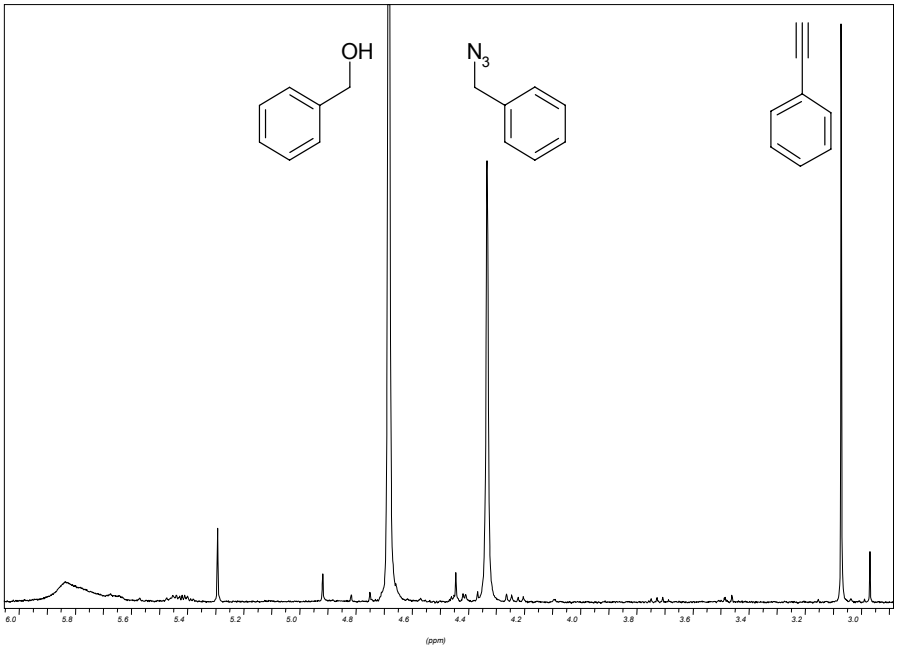


Figure S-1: ^{1}H-NMR-spectrum of the reaction mixture after 10 min of irradiation. Assignment of main resonance signals is shown.

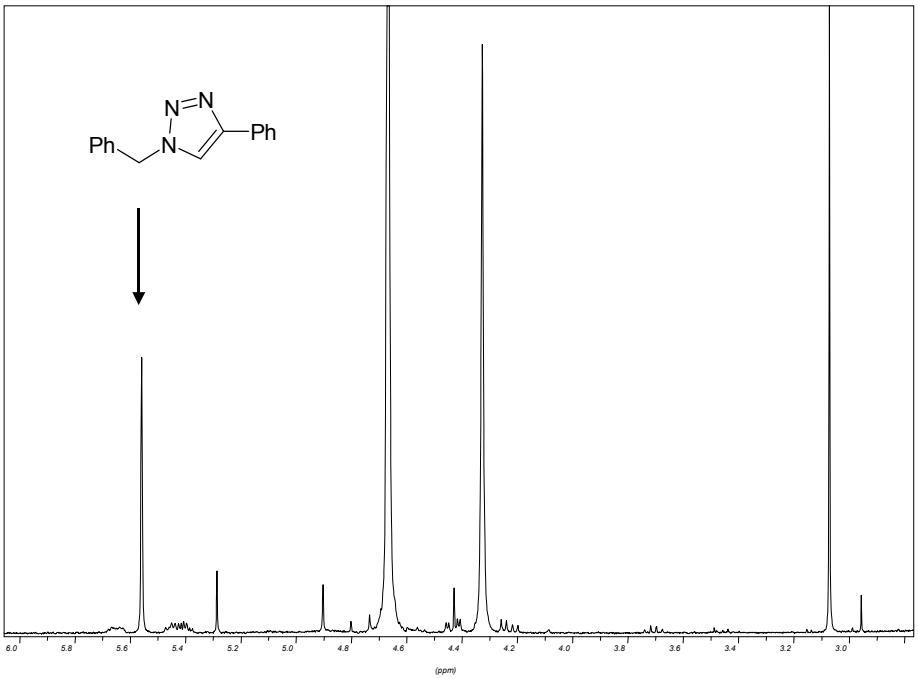


Figure S-2: ^{1}H-NMR-spektrum of the reaction mixture after 280 min of irradiation. The arrow marks the growing resonance signal of the triazole-CH_2-group.

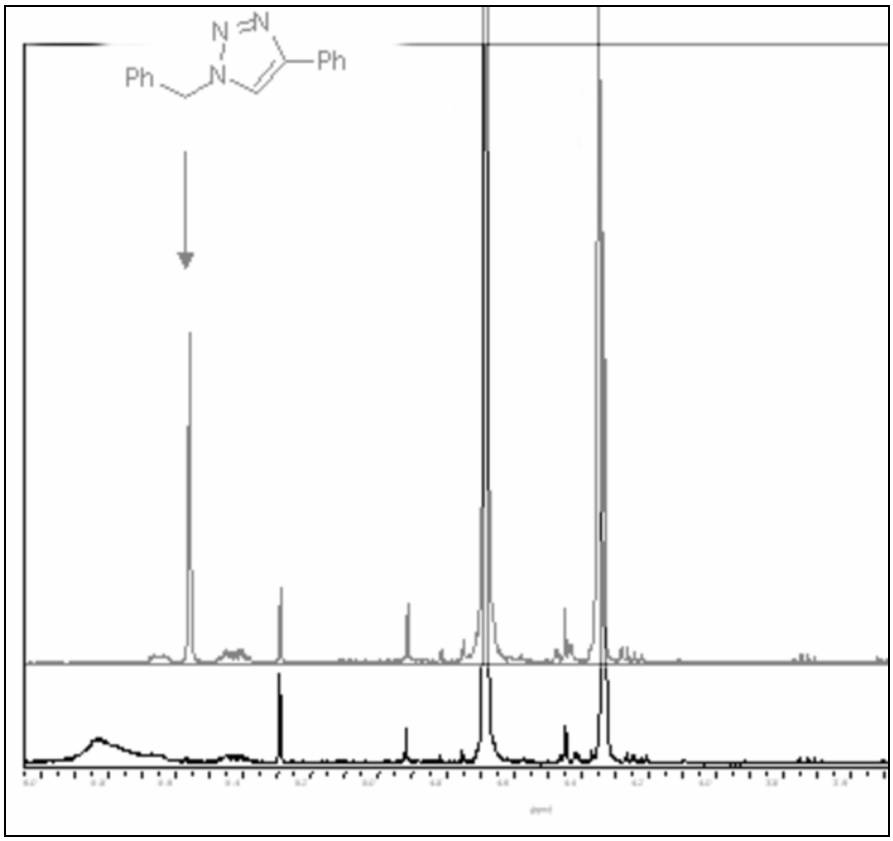


Figure S-3: Figures S-1 and S-2 in overlaid fashion.

Experimental procedure:

Under an atmosphere of argon 1 g of benzyl azide (7.5 mmol), 766 mg of phenyl acetylene (7.5 mmol), 1620 mg of benzyl alcohol (1545 µl, 15.0 mmol, 2 eq) and 15 ml of *tert*-butanol were added into a Schlenk-flask. Then a solution of 187 mg of $CuSO_4$ x 5 H_2O (0.75 mmol, 10 mol%) in 7 ml of water was added. The mixture was degassed and saturated with argon three times. After warming to 25 °C 163 mg of **1** (0.3 mmol, 4 mol%) were added and the mixture was stirred well. To keep the reaction temperature constant at 25 °C the Schlenk-flask was placed into a thermostated water-bath. The mixture was irradiated for 90 min, then stirred in the dark for 130 min, irradiated again for 70 min and finally stirred in the dark for 130 min. Following of the reaction for a longer time or an additional period of irradiation was not possible as the triazole product begins to precipitate from the solution when a conversion of approx. 40 % is reached. Reaction conversion was monitored by aliquots of 40 µl taken every 10 minutes from the mixture and diluted with 0.8 ml $CDCl_3$. After phase separation a NMR-spectrum was recorded.

For irradiation a commercial available Osram® daylight lamp (200 W, 220 V) was used. To exclude irradiation with UV-light a LOT-Oriel filter was used. To compensate fluctuations in

electricity and therefore in the intensity of emitted light, experiments were repeated twice and each day at the same time.

Figure S-4 gives the reaction conversion versus time. An induction period of approx. 50 min, a significant increase in the reaction rate upon irradiation and ceasing of the reaction in the dark is clearly shown. The reaction does not stop immediately, as the formed Cu(I) is catalytically active until it disproportionates due to its instability in aqueous solution.

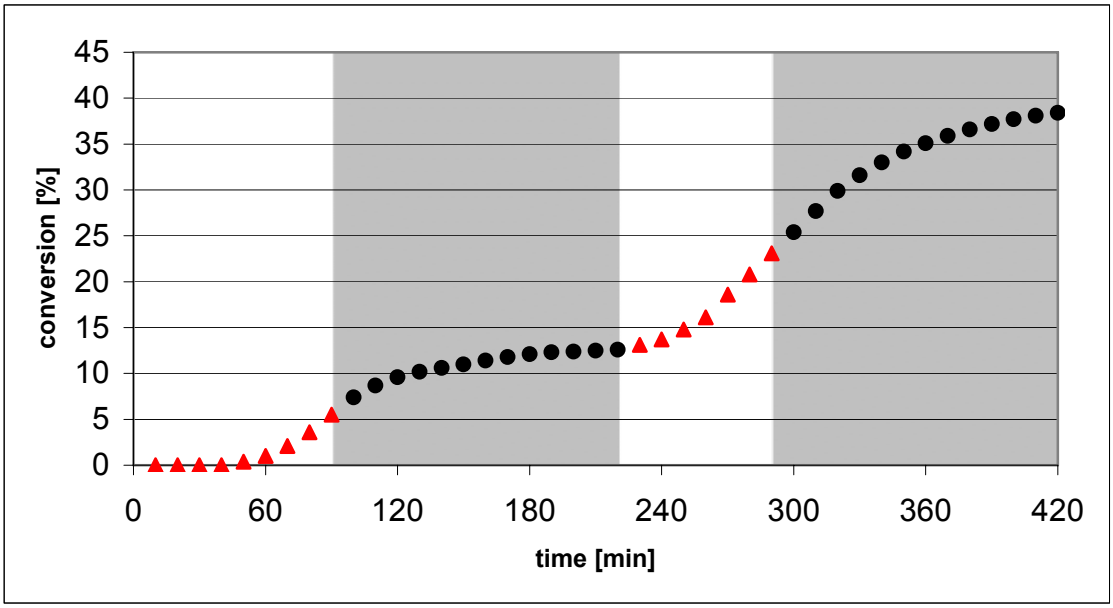


Figure S-4: Progress of reaction conversion during periods of irradiation (red dots, white background) and dark periods (black dots, grey background).

In order to explain the lag time until the reation starts, a possible coordination of Cu^{2+} to the flavine was investigated. This was done by observing changes in the UV/Vis and fluorescence spectrum of **1**, during addition of $CuCl_2$. Results revealed that neither the absorption nor the emission behaviour of **1** in buffered aqueous solution changed when $CuCl_2$ was added. For titration-experiments a stock solution of $CuCl_2$ (c = 10 mM) was added to solution of **1** (c = 50 µM) in phosphate buffer (pH = 6, c = 100 mM). Further results of these experiments showed a dependence of the photophysical properties of **1** on the pH-value of the solution which corresponds to the behaviour of similar systems.[1]

[1] J.T. Simpson, A. Krantz, F.D. Lewis, B. Kokel, *J. Am. Chem. Soc.* **1982**, *104*, 7155; F. Kavanagh, R.H. Goodwin, *Archiv. Biochem.* **1948**, *20*, 315.

Results of light-depending cycloadditions (scheme 1) revealed a dependence of the lag time on the pH-value of the solution. At acidic conditions the lag time becomes longer, while it shortens at basic conditions.

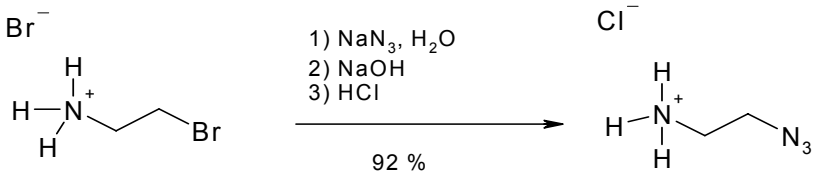
2) Light initiated Cu(I)-catalyzed cycloaddition in acetonitrile

Synthesis:

Safety. Sodium azide is toxic and can generate the extremely hazardous hydrazoic acid (volatile, toxic, explosive) if it is in contact with acids. Organic azides with a saturated carbon:azide ratio of < 6 (such as azidoethylamine or azidopropylamine) may be heat and shock sensitive and should be handled carefully. Phenylacetylene is suspected to cause cancer.

Dansyl chloride, 2-bromoethylamine hydrobromide, 3-bromopropylamine hydrobromide, propargylamine and dabsyl chloride were obtained from Fluka Chemicals. Benzyl azide was synthesized from benzyl bromide and sodium azide.

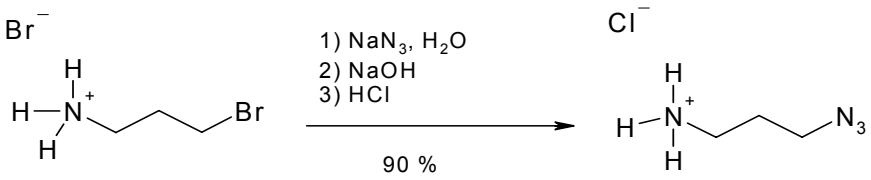
Abbreviations: DCM = methylene chloride**;** DMSO = dimethyl sulfoxide**;** EE = ethyl acetate**;** PE = petrol ether**;** Dabsyl = dimethylaminobenzenesulfonyl**;** Dansyl = dimethylaminonaphthalenesulfonyl; TLC = thin layer chromatography on silica gel



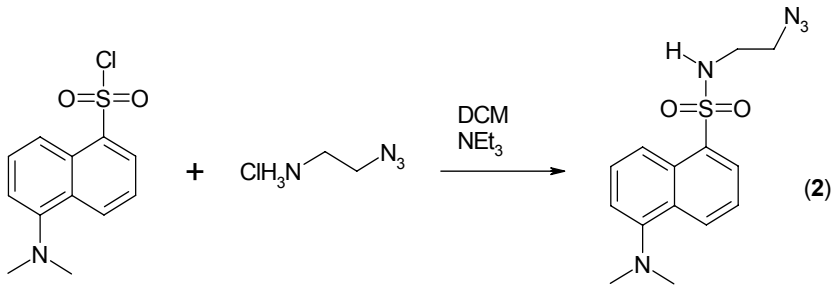
The hydrobromide (2 g, 9.8 mmol) was dissolved in a saturated aqueous solution of NaN_3 (2.56 g, 39.4 mmol, 4 eq) and heated to 90 °C for 16 h. **CAUTION!** as the solution is acidic this causes the formation of volatile and toxic HN_3! After cooling the solution to room temperature NaOH was added to make the solution basic (pH > 10). This produces the free amine which was separated from all inorganic compounds by distillation under reduced pressure (100 mbar, bp: 50 – 60 °C). The distillate was an aqueous solution of the amine which was afterwards acidified with 6 N hydrochloric acid. Lyophilisation of this solution gave the desired 2-azidoethylamine hydrochloride as a colourless, hygroscopic solid (1.1 g; 92 %).

^{1}H-NMR (300 MHz, MeOD): δ = 3.12 (t, ^{3}J = 5.6 Hz, 2 H), 3.75 (t, ^{3}J = 5.6 Hz, 2 H); ^{13}C-NMR (75.5 MHz, MeOD): δ = 40.06 (–, 1 C), 49.49 (–, 1 C); MS (ESI, H_2O/MeCN): m/z (%)= 87.0 [K^+] (100), 127.9 [K^++MeCN] (17); IR (KBr): $\bar{\nu}$ [cm^{-1}] = 3530, 2988, 2145, 1605, 1498, 1276, 1148; MF: $C_2H_7N_4Cl$; MW = 122.56 g/mol;

This method can also be used to synthesize 3-azido-propylamine hydrochloride as a colourless, hygroscopic solid in a comparable yield of 90 %:



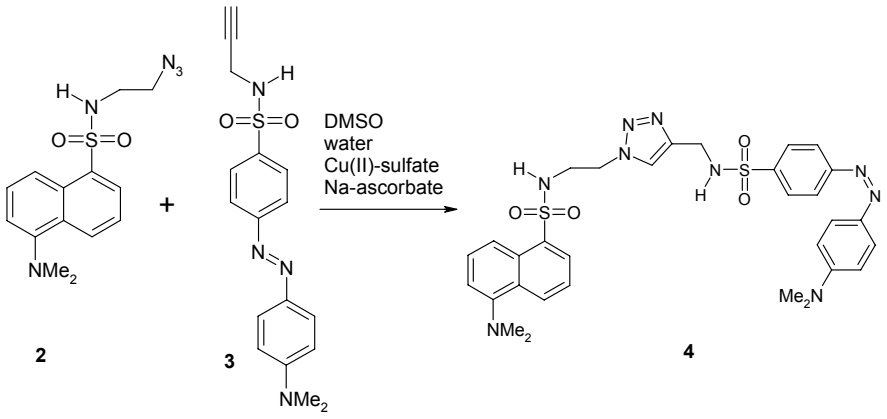
^{1}H-NMR (300 MHz, MeOD): δ = 1.97 (tt, ^{3}J = 6.6 Hz, ^{3}J = 7.4 Hz, 2 H), 3.01 – 3.06 (m, 2 H), 3.52 (t, ^{3}J = 6.6 Hz, 2 H); ^{13}C-NMR (75.5 MHz, MeOD): δ = 27.96 (–, 1 C), 38.54 (–, 1 C), 49.61 (–, 1 C); MS (ESI, H_2O/MeCN): m/z (%)= 101.0 [K^+] (100), 142.0 [K^++MeCN] (13); IR (KBr): $\bar{\nu}$ [cm^{-1}] = 3532, 2987, 2147, 1604, 1497, 1278, 1149; MF: $C_3H_9N_4Cl$; MW = 136.58 g/mol;



Dansyl chloride (864 mg, 3.2 mmol) was dissolved in 10 ml DCM. To this solution 1.78 ml NEt_3 (1296 mg, 12.8 mmol, 4 eq) and 785 mg 2-azido-ethylamine hydrochloride (6.4 mmol, 2 eq) were added. The mixture was stirred 1 h at room temperature and diluted with 40 ml DCM as TLC showed almost 100 % conversion. The solution was washed once with 50 ml of saturated aqueous solution of $NaHCO_3$, dried over Na_2SO_4, filtered and concentrated under reduced pressure. The crude product was purified by column chromatography over a short silica column, eluting with EE:PE = 7:3. This gave the dansyl derivative as light yellow oil, which crystallized after drying in vacuum (972 mg, 95 %).

^{1}H-NMR (300 MHz, $CDCl_3$): δ = 2.88 (s, 6 H, 2 CH_3), 3.05 (dt, ^{3}J = 5.8 Hz, ^{3}J = 6.3 Hz, 2 H, CH_2), 3.28 (t, ^{3}J = 5.8 Hz, 2 H, CH_2), 5.43 (t, ^{3}J = 6.3 Hz, 1 H, NH), 7.18 (dd, ^{3}J = 7.7 Hz, ^{4}J = 1.0 Hz, 1H), 7.48 – 7.58 (m, 2 H), 8.24 (dd, ^{3}J = 7.3 Hz, ^{4}J = 1.3 Hz, 1 H), 8.29 (d, ^{3}J = 8.8 Hz, 1H), 8.55 (dt, ^{3}J = 8.5 Hz, ^{4}J = 1.1 Hz, 1H); ^{13}C-NMR (75.5 MHz, $CDCl_3$): δ = 41.3 (–), 44.4 (+), 49.8 (–), 114.3 (+), 117.5 (+), 122.1 (+), 127.6 (+), 128.4 (C_{quat}), 128.5 (+), 128.8 (C_{quat}), 129.7 (+), 133.5 (C_{quat}), 150.9 (C_{quat}); UV (MeOH) λ_{max} (log ε) = 336 nm (3.684); MS (ESI, DCM/MeOH): m/z (%)= 320.2 [MH^+] (100), 639.4 [$2M+H^+$] (20); elemental analysis (%) calcd for $C_{14}H_{17}N_5SO_2$: C 52.65 H 5.37 N 21.93; found: C 52.71 H 5.44 N 21.79; MF: $C_{14}H_{17}N_5SO_2$; MW = 319.38 g/mol;

Dabsyl alkyne (**3**) and the cycloaddition product (**4**) were synthesized as previously described.[2]



In a 500 mL round-bottomed flask compounds **2** (192 mg, 0.60 mmol) and **3** (206 mg, 0.60 mmol) were dissolved in 60 mL DMSO. Water (30 mL) was added, followed by aqueous sodium ascorbate (0.2 mL of 1 M stock solution) and aqueous copper sulfate (0.6 mL of 100 mM stock solution). The reaction was followed by TLC, eluting with 1:1 PE:EE. After stirring overnight, the reaction was found to be complete, and 150 mL water was added to precipitate the product. After standing open to air for several hours, the orange solid was filtered and washed with water. The product was dried to give 314 mg of triazole **4** (79 %). The orange solid is recrystallized from acetonitrile to give red crystals.

^{1}H-NMR (300 MHz, DMSO-d_6): δ = 2.79 (s, 6 H, 2 CH_3), 3.06 (s, 6 H, 2 CH_3), 3.22 (t, ^{3}J = 6.0 Hz, 2 H, CH_2), 4.00 (s, 2 H, CH_2), 4.32 (t, ^{3}J = 6.0 Hz, 2 H, CH_2), 6.83 (d, ^{3}J = 9.3 Hz, 2 H), 7.21 (d, ^{3}J = 7.4 Hz, 1 H), 7.54 – 7.62 (m, 2 H), 7.76 (s, 1 H), 7.83 (d, ^{3}J = 9.1 Hz, 2 H),

[2] W.G. Lewis, F.G. Magallon, V.V. Fokin, M.G. Finn, *J. Am Chem. Soc.* **2004**, *126*, 9152 - 9153.

7.88 – 7.95 (m, 4 H), 8.08 (dd, ^{3}J = 7.3 Hz, ^{4}J = 1.0 Hz, 1H), 8.21 – 8.24 (m, 3 H), 8.44 (d, ^{3}J = 8.5 Hz, 1 H); ^{13}C-NMR (75.5 MHz, DMSO-d_6): δ = 37.9 (–), 39.7 (+), 42.25 (–), 44.9 (+), 48.9 (–), 111.5 (+), 115.0 (+), 118.85 (+), 122.0 (+), 123.4 (+), 123.51 (+), 125.3 (+), 127.8 (+), 128.3 (+), 128.8 (C_{quat}), 128.9 (C_{quat}), 129.5 (+), 135.2 (C_{quat}), 140.0 (C_{quat}), 142.5 (C_{quat}), 142.9 (C_{quat}), 151.2 (C_{quat}), 153.0 (C_{quat}), 154.4 (C_{quat}); UV (acetonitrile) λ_{max} (log ε) = 337 nm (3.679), 443 nm (4.478); MS (ESI, DCM/MeOH): m/z (%)= 662.3 [MH^+] (100); elemental analysis (%) calcd for $C_{31}H_{35}N_9S_2O_4$: C 56.26 H 5.33 N 19.05; found: C 56.34 H 5.38 N 19.19; MF: $C_{31}H_{35}N_9S_2O_4$; MW = 661.80 g/mol;

Absorption spectra and experimental procedure:

To prevent loss of light intensity required for the photoreduction process the alkyne compound is added after irradiation. Compound **3** shows strong absorption in the blue-light region (λ_{max} (log ε) = 442 nm (4.496), in acetonitrile solution) and therefore competes with **1** absorbing between 400 and 500 nm (λ_{max} (log ε) = 449 nm (3.953), in aqueous solution).

The azide compound shows no absorbance in the relevant region above 400 nm.

Emission spectroscopy:

Fluorescence measurements were carried out at 25 °C in 1 cm quartz cuvettes. The excitation wavelength was 337 nm for all measurements and the internal photomultiplier voltage was adjusted to 700 V. The intensity of fluorescence of (**2**) was measured in a range of 420 nm to 650 nm. Concentration of (**2**)/(**3**) was 4 µmol/L or lower to avoid intermolecular quenching of fluorescence, which was observed at concentrations higher than 20 µmol/L. To determine the conversion of the reaction the decrease of intensity of the maximum fluorescence at 524 nm was observed.

Figure S-5 shows the reaction rate depending on the concentration of Cu(I). Results clearly show a linear dependence for the experimental conditions employed (acetonitrile as solvent; triethylamine as additive; low concentration of 10^{-4} to 10^{-3} mol/L). The reaction rate is first order in Cu(I). For catalytic reactions in aqueous solution and concentrations > 10^{-2} mol/L a binuclear Cu(I)-complex was previously proposed.[3]

[3] V.O. Rodionov, V.V. Fokin, M.G. Finn, *Angew. Chem. Int. Ed.* **2005**, *44*, 2210 - 2215.

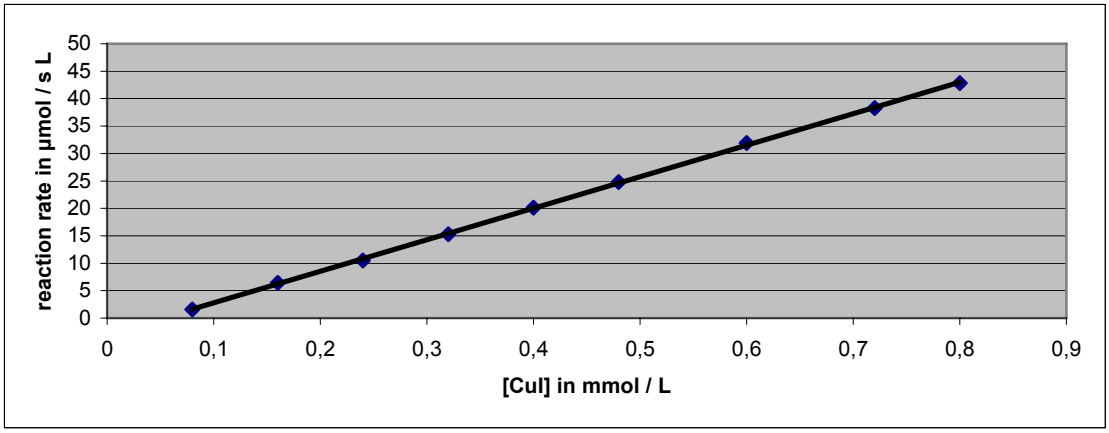


Figure S-5: Dependence of the cycloaddition reaction rate on the Cu(I)-concentration.

Experimental procedure for kinetic measurements:

Azide **2** (63.9 mg, 0.2 mmol) was dissolved in a Schlenk tube in different amounts of acetonitrile (approx. 2.0 – 2.9 ml, depending on the volume of CuI solution which is added later). Alkyne **3** (68.5 mg, 0.2 mmol) was dissolved in a Schlenk flask in 7.0 ml acetonitrile. Both solutions were degassed and saturated with argon. Then, 27.7 µl NEt_3 (20.2 mg, 0.2 mmol) and various amounts (approx. 100µL to 1000 µL) of a stock solution of 38.1 mg CuI (0.2 mmol) in 20 ml degassed acetonitrile were added to the azide solution to ensure a constant overall volume. Finally, the alkyne solution was added. The mixture was stirred well and aliquots of 20 µl were taken every minute. The samples were added to a solution of 20 µl of 30 % aqueous H_2O_2 in 2000 µl acetonitrile to stop the reaction. Samples of 60 µl of this solution were diluted with 3000 µl of acetonitrile to determine the emission spectra.[2]

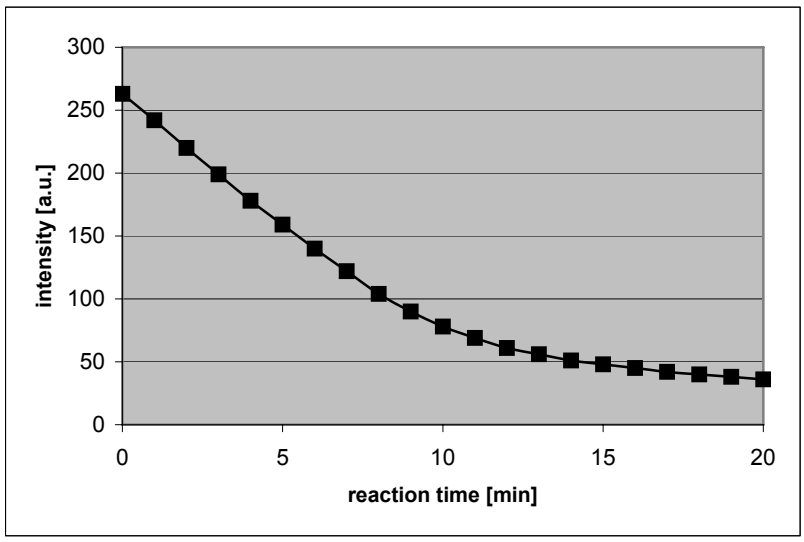


Figure S-6: Decrease of emission intensity over 20 min of reaction time exemplary for one reaction in acetonitrile.

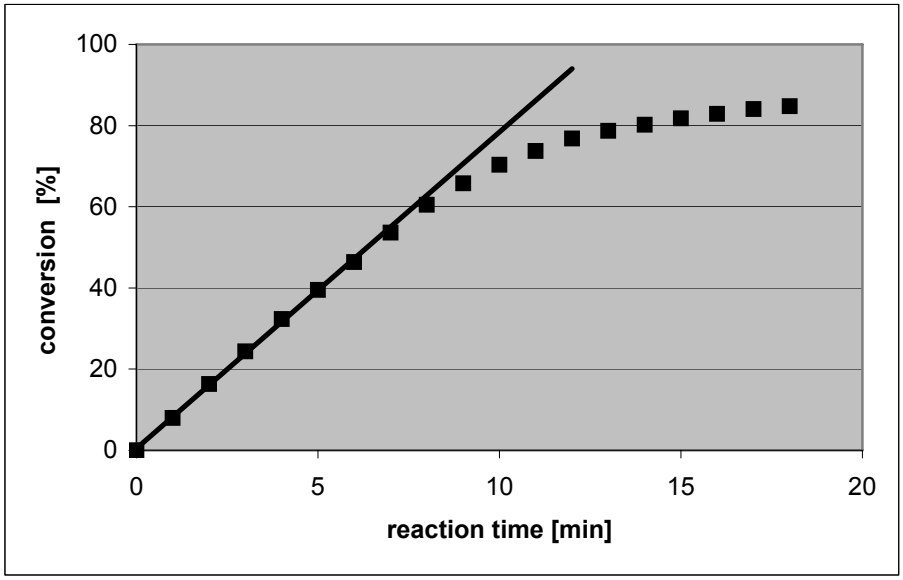


Figure S-7: Reaction conversion *vs* time exemplary for one reaction in acetonitrile.

Figure S-7 shows the conversion calculated from emission data in acetonitrile. This linear region (up to 40% conversion) is used to calculate the reaction rate which is shown in Figure S-5.

Reaction rates for irradiated reactions were calculated likewise. Using figure S-5 the concentration of Cu^+ generated by light is determined.

Cyclovoltammetry

Measurements were carried out under an inert atmosphere of argon in degassed and dry MeCN. The electrodes used were platinum (counter electrode), glassy carbon (working electrode) and Ag/AgCl (reference). Scan rate: 20 mV/s; electrolyte: tetrabutylammonium hexafluorophosphate (c = 0.2 mol/L). Concentrations of **1** and Cu(II) amine complexes were 2.5 mmol/L. E_0 values were determined versus Fc/Fc^+ as internal reference ($[E_0] = ([E_a]+[E_c])/2$).

Fluorescence titration experiments of 1 with $CuCl_2$ in MeCN

For titration-experiments aliquots of 20 µl of a stock solution of $CuCl_2$ (c = 10 mM) and NEt_3 (c = 100 nM) were added to a solution of **1** (c = 50 µM) in acetonitrile. The decrease of the emission maximum of **1** at approx. 520 nm (λ_{ex} = 441 nm) was followed (fig. S-8).

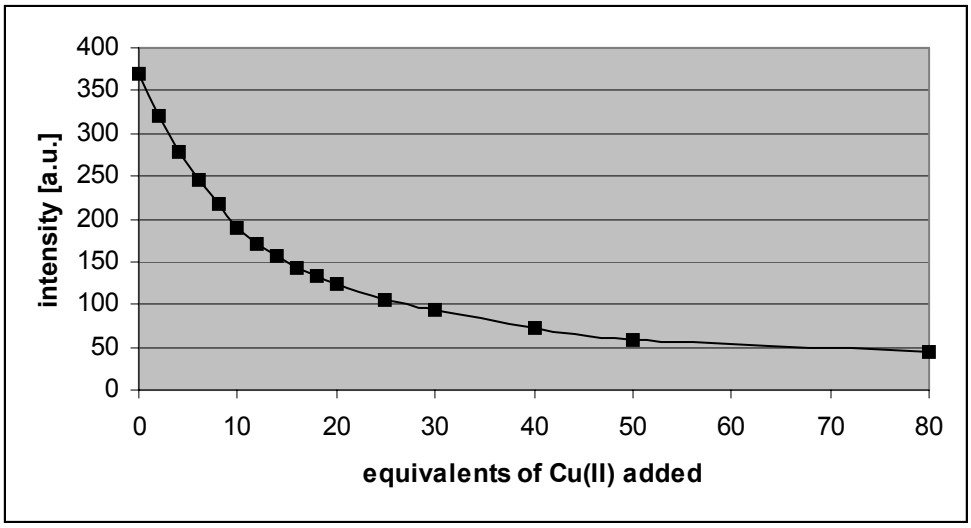


Figure S-8: Decrease of fluorescence of **1** (c = 50 μM) in MeCN after addition of $CuCl_2$.