First Triazole-Bridged Unsymmetrical Porphyrin Dyad via Click Chemistry

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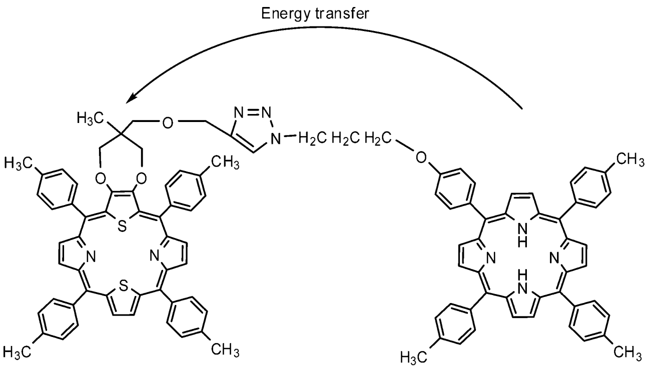

Click chemistry has been successfully applied in the synthesis of the first example of a triazole-bridged porphyrin dyad containing N_2S_2 porphyrin and N_4 or ZnN_4 porphyrin subunits, and fluorescence study indicated a possibility of singlet−singlet energy transfer from the N_4 or ZnN_4 porphyrin subunit to the N_2S_2 porphyrin subunit.

"Click" chemistry represents a modular approach toward synthesis that uses only the most practical transformations to make connections with excellent fidelity.[1] The Cu(I)-catalyzed Huisgen 1,3-dipolar cycloaddition of alkynes and azides to give 1,4-disubstituted 1,2,3-triazoles has emerged as a powerful linking reaction and found widespread applications ranging from combinatorial drug research,[2] material science,[3] to bioconjugate chemistry.[4] Interestingly, the reports on application of this versatile Cu(I)-catalyzed 1,3-diploar cycloaddition protocol to porphyrin chemistry are very scarce.[5]

Photoinduced electron and energy transfer are two important processes involved in natural photosynthesis. Several covalently linked porphyrin dyads have been prepared to study these processes.[6] Recently, we developed methods to synthesize the functionalized heteroporphyrin building blocks and used them for the synthesis of several covalently linked ethyne-, phenylethyne-, and diphenylethyne-bridged unsymmetrical porphyrin dyads containing two dissimilar porphyrin subunits such as N_4−N_3S, N_4−N_3O, N_3O−N_3S, N_3S−N_2S_2, etc.[7] The excited-state properties of these porphyrin dyads were studied to identify the suitable porphyrin dyad in which maximum unidirectional singlet−singlet energy transfer occurs for molecular electronic applications. In continuation of our efforts toward the synthesis of heteroporphyrin-based porphyrin assemblies, we describe our attempts toward the synthesis of the first triazole-bridged porphyrin dyad containing N_2S_2 porphyrin and N_4/ZnN_4 porphyrin subunits using click chemistry. The preliminary photophysical study supported an efficient energy transfer from N_4/ZnN_4 porphyrin subunit to N_2S_2 porphyrin subunit on selective excitation of N_4/ZnN_4 porphyrin subunit.

The N_2S_2 porphyrin containing alkyne functional group and the N_4 porphyrin building block containing azide functional group were synthesized over a sequence of steps as shown in Schemes 1 and 2, respectively. The required thiophene, 3,4-(2-methyl-2-hydroxymethylpropane-1,3-diyldioxy)thiophene **1** was synthesized in four steps starting from thiophene by slight modifications of a reported procedure.[8] The thiophene diol **2** was synthesized by treating 1 equiv of a 2,5-dilithiated derivative of thiophene **1** with 2.5 equiv of *p*-tolualdehyde in *n*-hexane. The TLC analysis showed the formation of the desired diol with some amount of thiophene mono-ol. The required diol **2** was separated by column chromatography and afforded pure diol **2** as a colorless solid in 62% yield. The diol **2** was characaterized by ^{1}H and ^{13}C NMR, IR, mass, and elemental analysis.

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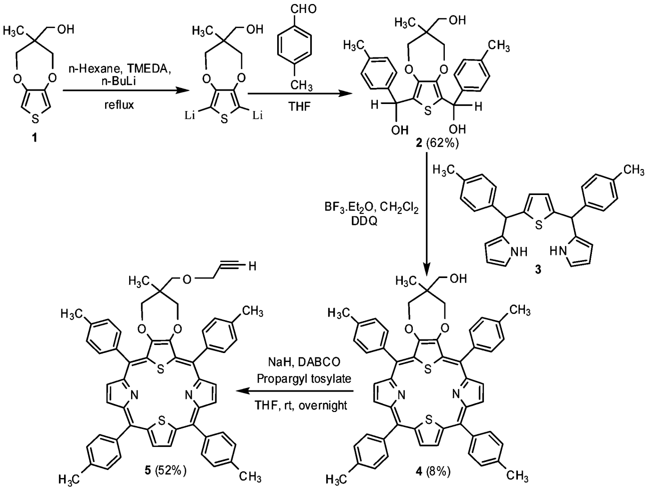
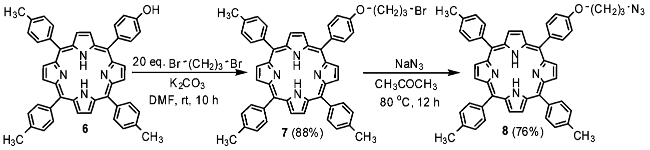
SCHEME 1. Synthesis of N_2S_2 Porphyrin Containing Ethynyl Functional Group 5

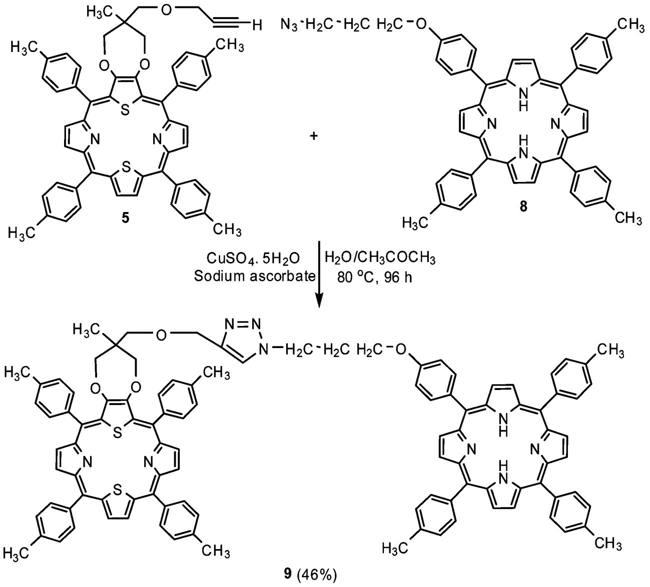


The diol **2** was condensed with known 16-thiatripyrrane[9] **3** in dichloromethane in the presence of a catalytic amount of BF_3−etherate followed by oxidation with DDQ. TLC analysis of the reaction mixture indicated the formation of porphyrin **4** as the sole porphyrin product. Column chromatography on silica gave the desired porphyrin **4** as a purple solid in 8% yield. The molecular ion peak at 821 in the ES-MS spectrum confirmed porphyrin **4**. In the ^1H NMR spectrum, the two β-thiophene protons appeared as a singlet at 9.64 ppm and the four β-pyrrole protons appeared as two sets of doublets corresponding to two protons each at 8.46 and 8.59 ppm. The absorption spectrum of **4** showed four Q-bands and one Soret band which were red-shifted as compared to 5,10,15,20-tetraphenyl-21,23-thiaporphyrin[10] (S_2TPP) due to the presence of the propylene dioxy methanol substituent at the β-thiophene ring of porphyrin **4**. The N_2S_2 porphyrin containing alkyne functional group **5** was prepared by reacting **4** with propargyl tosylate in the presence of NaH/DABCO in THF at room temperature overnight. The crude porphyrin was purified by silica gel column chromatography, using petroleum ether/dichloromethane (50:50), and afforded the pure porphyrin **5** in 52% yield. The molecular ion peak at 859 in the ES-MS spectrum and the ethyne CH proton signal as a singlet at 4.18 ppm in the ^1H NMR spectrum confirmed the porphyrin **5**. The absorption spectrum of **5** showed four Q-bands and one Soret band with peak positions matching those of porphyrin **4**.

SCHEME 2. Synthesis of N_4 Porphyrin Containing Azide Functional Group 8



SCHEME 3. Synthesis of Triazole-Bridged Porphyrin Dyad 9 under "Click" Reaction Conditions



The other required porphyrin building block, N_4 porphyrin azide **8** was synthesized from hydroxyl porphyrin **6** as shown in Scheme 2. The porphyrin **6** was converted to bromo porphyrin **7** by treating **6** with 20 equiv of 1,3-dibromopropane in DMF in the presence of K_2CO_3 overnight at room temperature followed by column chromatographic purification. The molecular ion peak at 795 in the ES-MS spectrum and a clean ^1H NMR spectrum confirmed porphyrin **7** (Supporting Information). The absorption spectrum showed four Q-bands and one Soret band and the peak positions matched those of 5,10,15,20-tetraphenylporphyrin (H_2TPP). The azido porphyrin **8** was prepared by reacting bromoporphyrin **7** with NaN_3 in acetone at 80 °C overnight followed by column chromatographic purification. Compound **8** was confirmed by spectroscopic techniques.

The triazole-bridged porphyrin dyad **9** was prepared under click reaction conditions by reacting **5** and **8** in the presence of sodium ascorbate and $CuSO_4$ in a water−acetone mixture at room temperature for 4 days (Scheme 3).[1] After standard workup, the crude compound was subjected to silica gel column chromatographic purification and pure pophyrin dyad **9** was obtained as a purple solid in 46% yield. The dyad **9** was confirmed by molecular ion peak at 1615 in the ES-MS spectrum and the ^1H NMR spectrum in which the signals correspond to both porphyrinic subunits and bridging methylene and triazole groups were present (Supporting Information). The Zn(II) derivative of **9** (**Zn9**) was prepared by treating **9** in dichloromethane with methanolic $Zn(OAc)_2$ at refluxing temperature for 1 h and purified by silica gel column chromatography. The Zn(II) ion forms a complex only with the N_4 porphyrin subunit of dyad **9**.

The absorption spectrum of dyads **9** and **Zn9** is essentially a linear combination of absorption spectra of both the porphyrin subunits indicating no ground state interaction between the two porphyrin subunits. The redox potentials of dyads **9** and **Zn9** and monomers were measured (Supporting Information) by cyclic voltammetry, and differential pulse voltammetric measurements at a glassy carbon electrode in dichloromethane containing 0.1 M TBAP showed that the redox potentials are in the same range as those of their corresponding monomeric analogues indicating the absence of electronic interaction between two porphyrin subunits in dyads **9** and **Zn9**. However, the steady-state fluorescence spectrum of dyad **9** and **Zn9**

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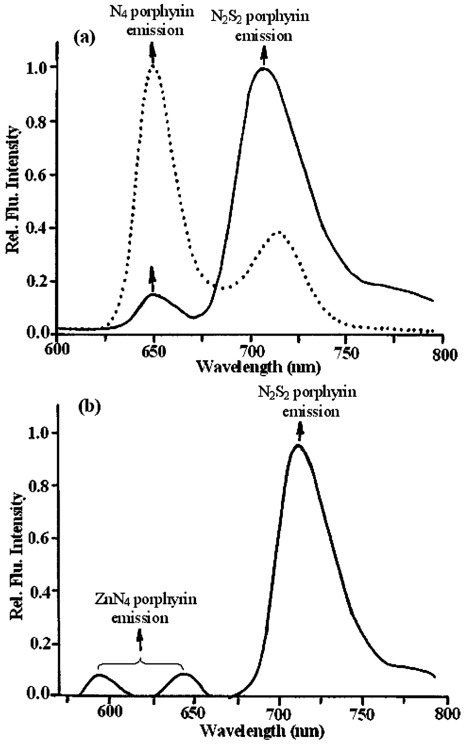

FIGURE 1. (a) Comparison of steady-state emission spectra of dyad **9** (—) and a 1:1 mixture of **5** and **8** (···). The excitation wavelength used was 420 nm. (b) Steady-state emission spectrum of dyad **Zn9** recorded in toluene at the excitation wavelength 550 nm.

recorded in toluene at room temperature (Figure 1) indicated a possibility of energy transfer from the N_4/ZnN_4 porphyrin subunit to the N_2S_2 porphyrin subunit in dyad **9**.

When dyad **9** was excited at 420 nm where the N_4 porphyrin subunit absorbs strongly, the emission of the N_4 porphyrin was quenched by 97% and a strong emission from the N_2S_2 porphyrin subunit was observed (Figure 1a). Furthermore, when a 1:1 mixture of porphyrin **5** and **8** was excited at 420 nm, the emission was noted mainly from the N_4 porphyrin subunit (Figure 1a). These observations support the energy transfer from the N_4 porphyrin subunit to the N_2S_2 porphyrin subunit in the triazole-bridged porphyrin dyad **9**. We compared the photophysical properties observed for the triazole-bridged $N_4{-}N_2S_2$ porphyrin dyad **9** with those of our previously reported[6f] diphenylethyne-bridged $N_4{-}N_2S_2$ porphyrin dyad **10**, and the comparison of steady-state emission spectra of **9** and **10** recorded at 420 nm where the N_4 porphyrin subunit absorbs strongly is shown in Figure 2. In **10**, on excitation at 420 nm where the N_4 porphyrin subunit absorbs strongly, the emission was noted from both N_4 and N_2S_2 porphyrin subunits unlike in **9** in which the major emission was noted from the N_2S_2 porphyrin subunit (Figure 1a). Thus, it is clear from the study that on changing the rigid diphenylethyne bridged porphyrin dyad **10** to a flexible triazole-bridged porphyrin dyad **9**, the energy transfer efficiency from the N_4 porphyrin subunit to the N_2S_2 porphyrin subunit is increased. Similarly, the fluorescence spectrum of **Zn9** was recorded at 550 nm where the ZnN_4 porphyrin subunit absorbs strongly, the ZnN_4 porphyrin emission was quenched to 98%, and a strong emission from the N_2S_2 porphyrin subunit was observed (Figure 1b) supporting an energy transfer from the ZnN_4 porphyrin subunit to the N_2S_2 porphyrin subunit in dyad **Zn9**. More studies are required for the complete understanding of the excited-state dynamics of dyads reported here.

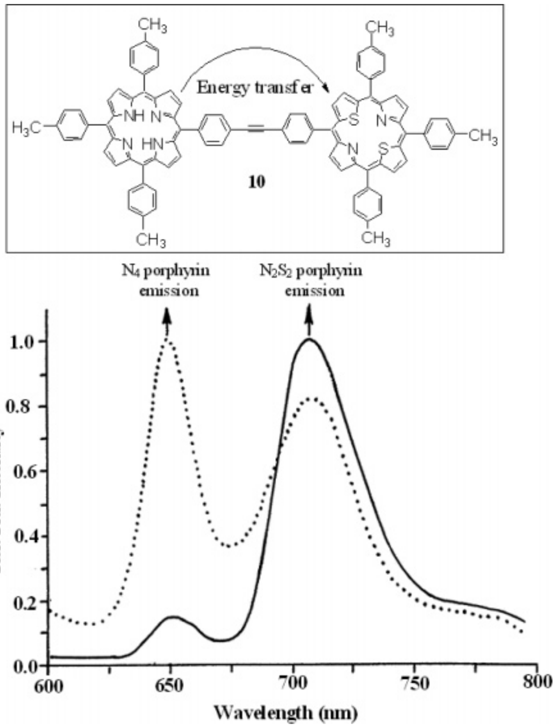

FIGURE 2. Comparison of steady-state emission spectra of dyad triazole bridged $N_4{-}N_2S_2$ porphyrin dyad **9** (—) and diphenyl ethyne bridged $N_4{-}N_2S_2$ porphyrin dyad **10** (···) in toluene, using $\lambda_{ex} = 420$ nm.

In summary, we synthesized the appropriate ethyne and azide porphyrin building blocks and used them for the synthesis of the first triazole-bridged porphyrin dyad containing two different porphyrin subunits under click reaction conditions. Collectively, ^{1}H NMR, UV−vis, and redox potential data indicate that there is no specific interaction between the two porphyrin subunits in triazole-bridged dyads. However, the preliminary fluorescence studies indicated a possibility of energy transfer from N_4 or the ZnN_4 porphyrin subunit to the N_2S_2 porphyrin subunit in these porphyrin dyads. The synthetic strategy reported here can be extended to synthesize various other triazole-bridged porphyrin dyads and other novel constructs to study their excited-state dynamics, and such synthetic efforts are underway in our laboratory.

Experimental Section

Triazole-Bridged $N_4{-}N_2S_2$ Porphyrin Dyad 9. Compound **5** (30 mg, 3.49 mmol) dissolved in acetone (3 mL) was placed in a 100-mL round-bottom flask fitted with a reflux condenser. Compound **8** (26 mg, 3.49 mmol) dissolved in acetone (2 mL) was added to the solution followed by the addition of sodium ascorbate (13.8 mg, 0.70 mmol) and $CuSO_4$ (8.7 mg, 0.35 mmol) dissolved in water (1 mL), then the mixture was stirred until a clear solution was obtained. The reaction mixture was stirred at 80 °C for 96 h. After standard workup with dichloromethane, the crude reaction mixture was purified by silica gel column chromatography, using dichloromethane as eluent, and the desired porphyrin dyad **9** was collected as a purple solid in 46% yield (4.2 mg). Mp >300 °C. IR (KBr film): ν 3068, 2927, 2850, 1577, 1042, 980, 790, 580 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ −2.79 (s, 2 H), 1.28 (s, 3 H), 2.50 (t, $J = 12.0$ Hz, 6.1 Hz, 2 H), 2.75 (s, 21 H), 3.76−3.85 (m, 4 H), 4.01 (d, J = 12.2 Hz, 2 H), 4.11 (d, J = 12.0 Hz, 2 H), 4.38−4.44 (m, 4 H), 7.30 (s, 1 H), 7.46−7.64 (m, 12 H), 7.91 (d, J = 7.8 Hz, 2 H), 8.00 (d, J = 7.8 Hz, 2 H), 8.08−8.18 (m, 16 H), 8.44 (d, J = 4.0 Hz, 2 H), 8.60 (d, J = 4.0 Hz, 2 H), 8.84−8.86 (m, 8 H), 9.62 (s, 2 H) ppm. ES-MS: $C_{106}H_{87}N_9O_4S_2$, calcd av mass 1614.9, obsd m/z 1615.0 (M^+,100%). Anal. Calcd: C, 78.83; H, 5.43; N, 7.81; S, 3.97. Foumd: C, 78.79; H, 5.47; N, 7.85; S, 4.01. UV−vis (in toluene, λ_{max}/nm, ϵ/mol^{-1} dm^3 cm^{-1}): 417 (403 158), 439 (188 651), 521 (21 034), 536 (28 272), 578 (sh), 646 (3363), 704 (6810).

Triazole-Bridged $ZnN_4-N_2S_2$ Porphyrin Dyad Zn9. A solution of **9** (3.1 mg, 0.18 mmol) and $Zn(OAc)_2$ (10 mg, 9.29 mmol) in dichloromethane/methanol (3:1, 20 mL) was stirred at room temperature for 2 h. The crude compound was purified by silica gel column chromatography, using dichloromethane as eluent, and the desired porphyrin **Zn9** was collected as a violet solid in 76% yield (1.9 mg). ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ 1.28 (s, 3 H), 2.52 (t, J = 12.0 Hz, 6.1 Hz, 2 H), 2.76 (s, 21 H), 3.77−3.85 (m, 4 H), 4.02 (d, = 12.2 Hz, 2 H), 4.11 (d, J = 12.0 Hz, 2 H), 4.38−4.45 (m, 4 H), 7.31 (s, 1 H), 7.46−7.65 (m, 12 H), 7.92 (d, J = 7.8 Hz, 2 H), 8.02 (d, J = 7.8 Hz, 2 H), 8.09−8.19 (m, 16 H), 8.45 (d, J = 4.0 Hz, 2 H), 8.60 (d, J = 4.0 Hz, 2 H), 8.84−8.86 (m, 8 H), 9.62 (s, 2 H) ppm. ES-MS: $C_{106}H_{85}N_9O_4S_2Zn$, calcd av mass 1678.3, obsd m/z 1679.1 (M^+ + H, 35%). Anal. Calcd: C, 75.85; H, 5.10; N, 7.51; S, 3.82. Found: C, 75.81; H, 5.12; N, 7.55; S, 3.78. UV−vis (in toluene, λ_{max}/nm, ϵ/mol^{-1} dm^3 cm^{-1}): 422 (345 690), 440 (263 401), 521 (20 781), 546 (13 692), 582 (sh), 636 (2045), 704 (6731).

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Supporting Information Available: Experimental procedures and full spectroscopic data for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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