

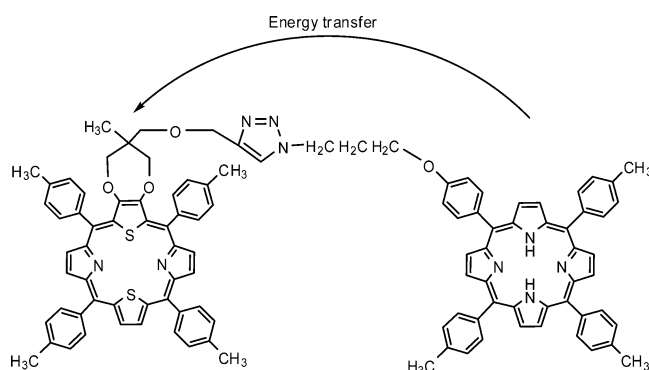
First Triazole-Bridged Unsymmetrical Porphyrin Dyad via Click Chemistry

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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-dipolar 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-diylidioxy)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 characterized by ¹H and ¹³C NMR, IR, mass, and elemental analysis.

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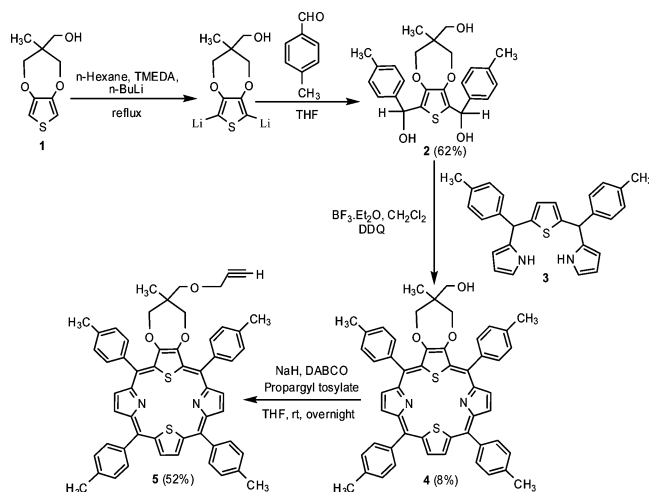
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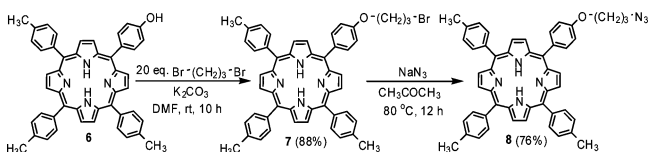
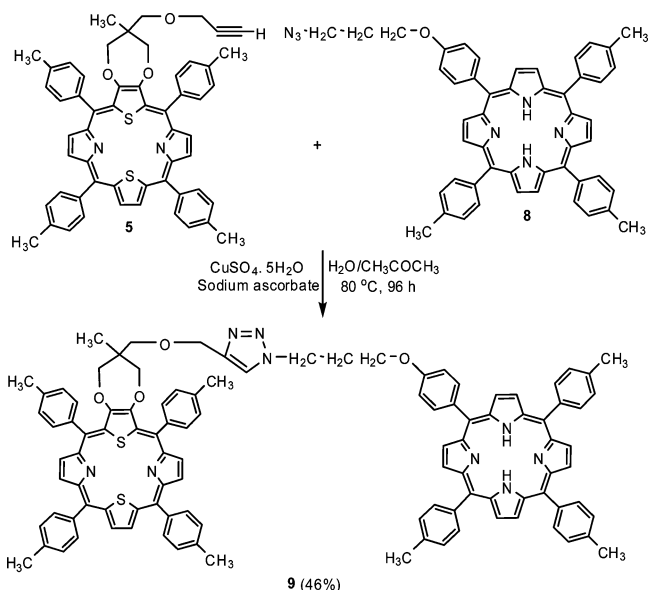
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SCHEME 1. Synthesis of N₂S₂ Porphyrin Containing Ethynyl Functional Group 5


The diol **2** was condensed with known 16-thiatripyrrane⁹ **3** in dichloromethane in the presence of a catalytic amount of BF₃–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-thiaporphyrin¹⁰ (S₂TPP) due to the presence of the propylene dioxy methanol substituent at the β -thiophene ring of porphyrin **4**. The N₂S₂ 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**.

The other required porphyrin building block, N₄ 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 K₂CO₃ 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 (H₂TPP). The azido porphyrin **8** was prepared by reacting bromoporphyrin **7** with NaN₃ in acetone

SCHEME 2. Synthesis of N₄ Porphyrin Containing Azide Functional Group 8

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


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 CuSO₄ 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 porphyrin 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 N₄ 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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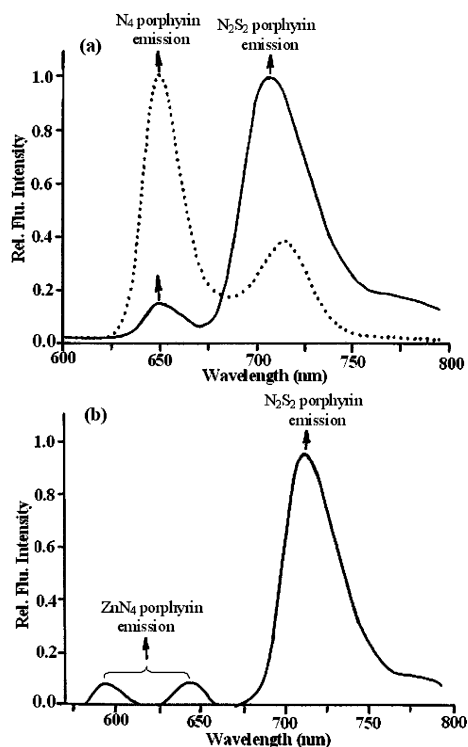


FIGURE 1. (a) Comparison of steady-state emission spectra of dyad **9** (—) and a 1:1 mixture of **5** and **8** (···). The excitation wavelength used was 420 nm. (b) Steady-state emission spectrum of dyad **Zn9** recorded in toluene at the excitation wavelength 550 nm.

recorded in toluene at room temperature (Figure 1) indicated a possibility of energy transfer from the N₄/ZnN₄ porphyrin subunit to the N₂S₂ porphyrin subunit in dyad **9**.

When dyad **9** was excited at 420 nm where the N₄ porphyrin subunit absorbs strongly, the emission of the N₄ porphyrin was quenched by 97% and a strong emission from the N₂S₂ 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 N₄ porphyrin subunit (Figure 1a). These observations support the energy transfer from the N₄ porphyrin subunit to the N₂S₂ porphyrin subunit in the triazole-bridged porphyrin dyad **9**. We compared the photophysical properties observed for the triazole-bridged N₄–N₂S₂ porphyrin dyad **9** with those of our previously reported^{6f} diphenylethyne-bridged N₄–N₂S₂ porphyrin dyad **10**, and the comparison of steady-state emission spectra of **9** and **10** recorded at 420 nm where the N₄ porphyrin subunit absorbs strongly is shown in Figure 2. In **10**, on excitation at 420 nm where the N₄ porphyrin subunit absorbs strongly, the emission was noted from both N₄ and N₂S₂ porphyrin subunits unlike in **9** in which the major emission was noted from the N₂S₂ 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 N₄ porphyrin subunit to the N₂S₂ porphyrin subunit is increased. Similarly, the fluorescence spectrum of **Zn9** was recorded at 550 nm where the ZnN₄ porphyrin subunit absorbs strongly, the ZnN₄ porphyrin emission was quenched to 98%, and a strong emission from the N₂S₂ porphyrin subunit was observed (Figure 1b) supporting an energy transfer from the ZnN₄ porphyrin subunit to the N₂S₂ porphyrin subunit in dyad

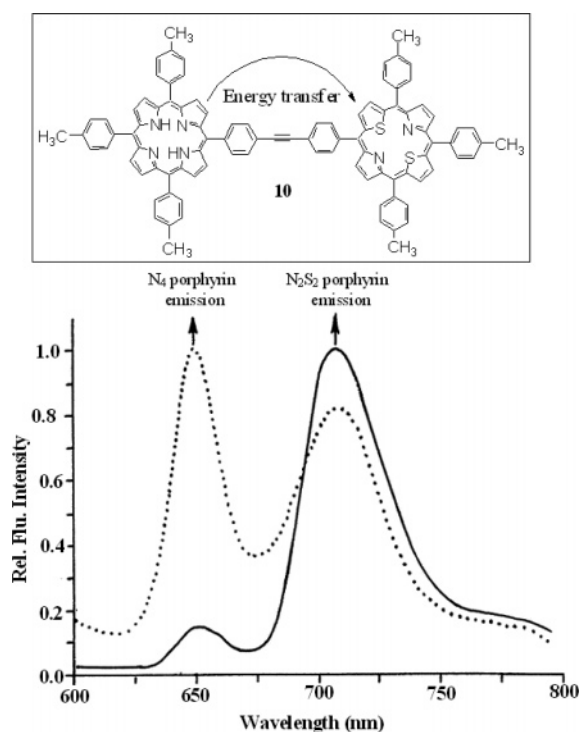


FIGURE 2. Comparison of steady-state emission spectra of dyad triazole bridged N₄–N₂S₂ porphyrin dyad **9** (—) and diphenylethyne bridged N₄–N₂S₂ porphyrin dyad **10** (···) in toluene, using $\lambda_{\text{ex}} = 420$ nm.

Zn9. More studies are required for the complete understanding of the excited-state dynamics of dyads reported here.

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, ¹H 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 N₄ or the ZnN₄ porphyrin subunit to the N₂S₂ 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 N₄–N₂S₂ 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 CuSO₄ (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}. ¹H NMR (400 MHz, CDCl₃, 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. Found: C, 78.79; H, 5.47; N, 7.85; S, 4.01. UV-vis (in toluene, λ_{max}/nm , $\epsilon/mol^{-1} dm^3 cm^{-1}$): 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). 1H 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, $J = 12.2$ 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 , $\epsilon/mol^{-1} dm^3 cm^{-1}$): 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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