

1,2,3-Triazoles as Conjugative π -Linkers in Push–Pull Chromophores: Importance of Substituent Positioning on Intramolecular Charge-Transfer

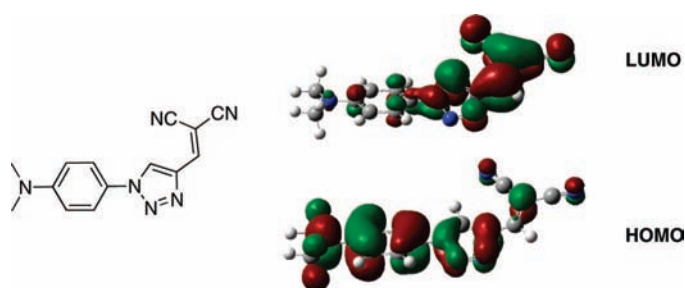
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ABSTRACT



Isomeric charge-transfer chromophores using 1,2,3-triazol-diyl as linker have been studied experimentally and computationally. The instability of the polarized reactants precluded the use of the Huisgen reaction and alternative synthetic methodologies were employed. Charge-transfer absorptions between an *N,N*-dimethylanilino and a dicyanovinyl group are modest to strong, with maxima from $\lambda_{\text{max}} = 400$ to 453 nm depending on substituent positioning. TD-B3LYP/6-31G(d) calculations are within 0.6 eV of experiment and assign these bands as HOMO–LUMO transitions.

The independent discoveries of the Cu(I)-catalyzed Huisgen's 1,3-dipolar cycloaddition¹ by Sharpless^{2a} and Meldal^{2b} in 2002 have led to thousands of new examples of this reaction subclass. The excellent regioselectivity for the 1,4-isomer of the 1,2,3-triazole and the enhanced reactivity of the Cu(I)-catalyzed process, along with the versatility of reaction conditions (and other factors) have made it the flagship reaction of the Sharpless "click" chemistry.³ As such, it has been widely applied of late, particularly in bioconjugation and drug discovery, and also in advanced material sciences toward dendrimers and surface modification.⁴

While 1,2,3-triazole chemistry is historically related to the manufacture of dyes and to photographic imaging,⁵ advancements based on the "click" methodology have resulted in only a few examples of photophysical interest. In general, the recent examples favor the use of the 1,2,3-triazol-1,4-diyl moiety as a structural linkage between two components and are not concerned with mediating their electronic communication. This is related to the stability and ease of synthesis of alkyl azides, which are by far the most often used; the resultant 1,2,3-triazole adducts are photophysically

(1) Huisgen, R.; Szeimies, G.; Moebius, L. *Chem. Ber.* **1967**, *100*, 2494.
(2) (a) Rostovtsev, V.; Green, L. G.; Fokin, V. V.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2002**, *41*, 2596. (b) Tornøe, C. W.; Christensen, C.; Meldal, M. *J. Org. Chem.* **2002**, *67*, 3057.
(3) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, *40*, 2004.

(4) (a) Moses, J. E.; Moorhouse, A. D. *Chem. Soc. Rev.* **2007**, *36*, 1249. (b) Nandivada, H.; Jiang, X.; Lahann, J. *Adv. Mater.* **2007**, *19*, 2197. (c) Ou, T.-M.; Lu, Y.-J.; Tan, J.-H.; Huang, Z.-S.; Wong, K.-Y.; Gu, L.-Q. *Chem. Med. Chem.* **2008**, *3*, 690.

(5) (a) Wamhoff, H. In *Comprehensive Heterocyclic Chemistry*; Katritzky, A. R., Rees, C. W., Eds.; Pergamon: Oxford, 1984; Vol. 5, Part 4A, p 669. (b) Fan, W.-Q.; Katritzky, A. R. In *Comprehensive Heterocyclic Chemistry II*; Katritzky, A. R., Rees, C. W., Scriven, E. F. V., Eds.; Elsevier: Oxford, 1996; Vol. 4, p 1.

dark to through-bond interaction of the unified components. Examples are only now appearing that suggest movement in the direction of extended π -chromophores that incorporate the 1,2,3-triazole moiety into the conjugation path.⁶

One active direction in organic materials chemistry involves the development of charge-transfer (CT) chromophores as nonlinear optical (NLO) components in photonics applications.⁷ A CT chromophore is composed of a strongly electron donating moiety conjugated through a π -linker to a strongly electron-accepting one. To our knowledge, this basic motif has not been attempted with 1,2,3-triazol-diyls as the active π -linker. For a first systematic study of such systems, the strong electron donor *N,N*-dimethylanilino (DMA) and the strong electron acceptor dicyanovinyl (DCV) were chosen as substituents.⁸ The 1,2,3-triazole ring has four unique points of attachment, two on the heteroatoms N-1 and N-2 and two on carbons C-4 and C-5. Seven constitutional isomers are possible, compounds 1–7 (Figure 1).

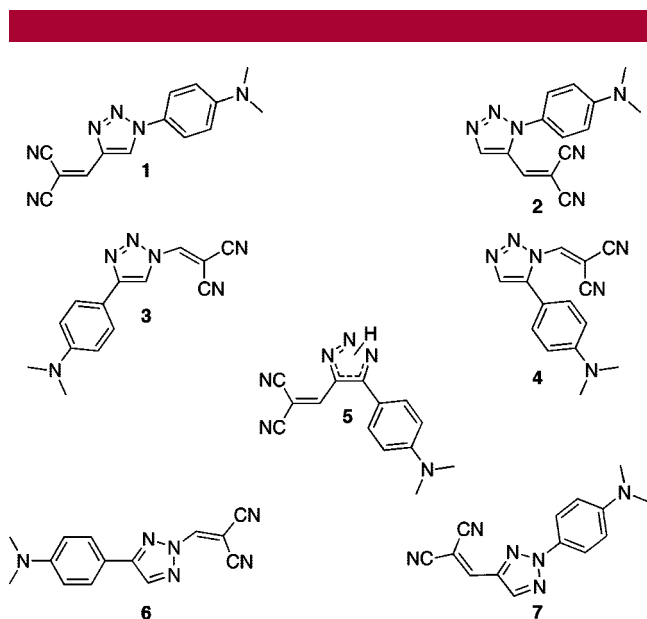


Figure 1. Isomeric donor–acceptor-substituted 1,2,3-triazoles 1–7.

Of the isomers presented in Figure 1, only 1, 2, 5 and 6 could so far be prepared. Moreover, the use of “click” chemistry as the key and final step of their synthesis was severely limited by the instability of the requisite polarized reactants. Thus, these isomers were prepared by alternative synthetic methods in order to establish the feasibility of constructing CT chromophores with 1,2,3-triazol-diyl as the

(6) (a) Schweinfurth, D.; Hardcastle, K. I.; Bunz, U. H. F. *Chem. Commun.* **2008**, 2171. (b) Meudtner, R. M.; Ostermeier, M.; Goddard, R.; Limberg, C.; Hecht, S. *Chem. Eur. J.* **2007**, *13*, 9834. (c) Parent, M.; Mongin, O.; Kamada, K.; Katan, C.; Blanchard-Desce, M. *Chem. Commun.* **2005**, 2029.

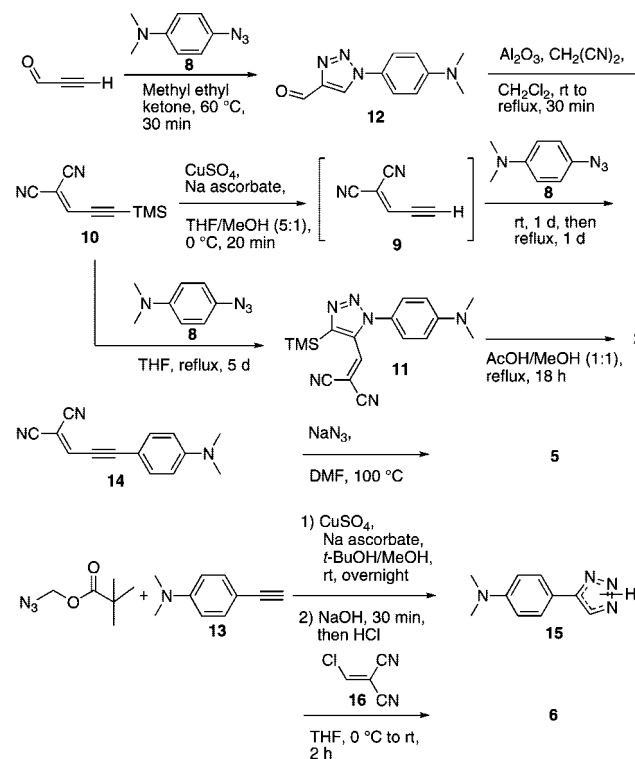
(7) (a) May, J. C.; Biaggio, I.; Bures, F.; Diederich, F. *Appl. Phys. Lett.* **2007**, *90*, 251106/1. (b) Forest, S. R.; Thomson, M. E., Eds. *Organic Electrooptics and Optoelectronics*, Special Issue of *Chem. Rev.* **2007**, *107*, 923.

(8) Hansch, C.; Leo, A.; Taft, R. W. *Chem. Rev.* **1991**, *91*, 165.

π -linker leaving the synthetic challenge of producing such materials by direct “click” chemistry for future work. Charge-transfer between these groups is documented herein both experimentally, when possible, and computationally⁹ for all seven isomers.

Isomers 1–4, with substituents at N-1, C-4, and C-5, formally result from the Huisgen cycloaddition under thermal or Cu(I)-catalyzed “click” conditions. The reaction of 4-azido-*N,N*-dimethylaniline (**8**)¹⁰ with dicyanoenyne (**9**) formed the basis of the synthetic approach toward isomers 1 and 2 (Scheme 1), but with limited success.

Scheme 1. Synthesis of Isomeric 1,2,3-Triazoles 1, 2, 5 and 6.



TMS = trimethylsilyl.

Intermediate 9 is not isolable and must be generated in situ by desilylation of the corresponding trimethylsilyl-protected enyne (**10**)¹¹ with MeOH.^{12a} Unfortunately, this synthesis of 1 was hampered by the apparent instability of 9, which went on to subsequently react with 8 through a low-yielding process (ca. 5%) after 2 or more days of reaction time. Alternatively, isomer 1 could be prepared efficiently by reaction of 8 and propynal to give triazole 12 (67%), followed by Knoevenagel condensation (99%). Isomer 2, which is also not available through the Cu(I)-catalyzed process, was prepared instead by the thermal 1,3-dipolar cycloaddition of 8 and 10 to give 11

(9) Frisch, M. J. et al. *Gaussian*, Revision C.02, Gaussian, Inc., Wallingford CT, 2004. A full reference may be found in the Supporting Information.

(10) Ugi, I.; Perlinger, H.; Behringer, L. *Chem. Ber.* **1958**, *91*, 2330.

(11) (a) Sorg, A.; Siegel, K.; Brückner, R. *Chem. Eur. J.* **2005**, *11*, 1610.

(b) Hopf, H.; Kreutzer, M. *Angew. Chem., Int. Ed.* **1990**, *29*, 393.

with the TMS group at C-4 (19%), followed by desilylation. Conveniently, the bulky TMS group controls the regiochemistry of the reaction, which is highly selective (although low yielding) for the 1,5-donor–acceptor-substituted 1,2,3-triazole product.¹³ Protodesilylation was accomplished under acidic conditions to give **2** in high yield (78%). The regiochemistries of **1** and **2** are confirmed by the characteristic ¹H NMR shifts for positions C-4 and C-5¹⁴ as well as by the X-ray crystal structures of the precursors **11** (Figure 2) and **12** (see Supporting Information).

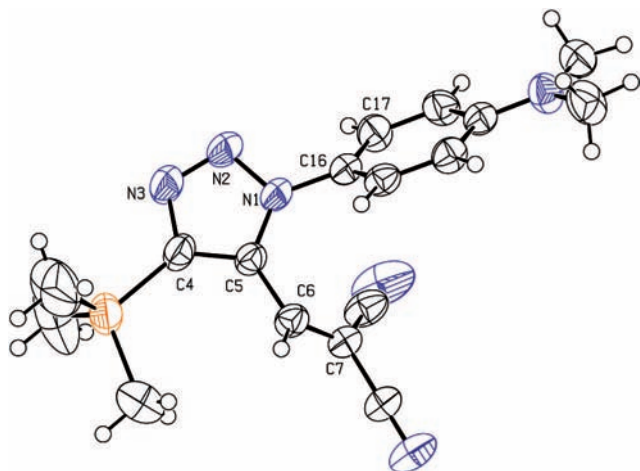


Figure 2. ORTEP plot of crystal structure of **11** at 220 K, arbitrary numbering. Atomic displacement parameters are drawn at the 50% probability level.

The two isomers **3** and **4** were ultimately unobtainable through the “click” or the thermal Huisgen cycloaddition methodology. The most obvious approach involving reaction of 4-ethynyl-*N,N*-dimethylaniline¹⁵ (**13**) with (azidomethylidene)propanedinitrile¹⁶ in the presence (or absence) of Cu(I) did not afford the expected target compounds **3** or **4**, even after the conditions were varied extensively.

Isomer **5** was obtained from alkyne **14**¹⁷ by reaction with NaN₃ in DMF (61%) (Scheme 1). The tautomeric form with hydrogen at N-2 is most stable according to calculations at the B3LYP/6-31G(d) level of theory. Isomer **6** was obtained

(12) (a) Moonen, N. N. P.; Pomerantz, W. C.; Gist, R.; Boudon, C.; Gisselbrecht, J.-P.; Kawai, T.; Kishioka, A.; Gross, M.; Irie, M.; Diederich, F. *Chem. Eur. J.* **2005**, *11*, 3325. (b) Bures, F.; Schweizer, W. B.; May, J. C.; Boudon, C.; Gisselbrecht, J.-P.; Gross, M.; Biaggio, I.; Diederich, F. *Chem. Eur. J.* **2007**, *13*, 5378. (c) Meier, H.; Jürgen, G.; Kolshorn, H.; Mühlhng, B. *Chem. Eur. J.* **2004**, *10*, 360. (d) Spittler, E. L.; Monson, J. M.; Haley, M. M. *J. Org. Chem.* **2008**, *73*, 2211.

(13) Zanirato, P. *J. Chem. Soc., Perkin Trans. 1* **1991**, 2789.

(14) (a) Alonso, G.; Garcia-Lopez, M. T.; Garcia-Munor, G.; Madronera, R.; Rico, M. *J. Heterocycl. Chem.* **1970**, *7*, 1270. (b) Tsy-pin, G. I.; Timofecva, G. N.; Mel'nikov, V. V.; Gidasov, B. V. *Zh. Org. Khim.* **1975**, *11*, 1395.

(15) Leonard, K. A.; Nelen, M. I.; Anderson, L. T.; Gibson, S. L.; Hilf, R.; Detty, M. R. *J. Med. Chem.* **1999**, *42*, 3942.

(16) Josey, A. D.; Dickinson, C. L.; Dewhirst, K. C.; McKusick, B. C. *J. Org. Chem.* **1967**, *32*, 1941.

(17) (a) May, J. C.; Lim, J. H.; Biaggio, I.; Moonen, N. N. P.; Michinobu, T.; Diederich, F. *Opt. Lett.* **2005**, *30*, 3057. (b) Michinobu, T.; May, J. C.; Lim, J. H.; Boudon, C.; Gisselbrecht, J.-P.; Seiler, P.; Gross, M.; Biaggio, I.; Diederich, F. *Chem. Commun.* **2005**, 737.

by the addition/elimination reaction of DMA-substituted 1,2,3-triazole (**15**) with (chloromethylidene)propanedinitrile (**16**) (63%). The predominance of the *2H* tautomer of the 1,2,3-triazole reactant¹⁸ and the corresponding stability of **6** over **3** and **4** according to calculations may explain this high regioselectivity. The synthesis of isomer **7** was not attempted.

The UV/Vis spectra in CH₂Cl₂ of **1**, **2**, **5**, **6** and **11** are given in Figure 3.

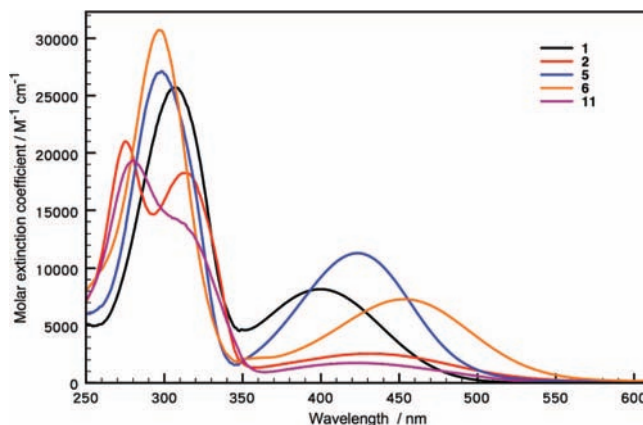


Figure 3. UV/Vis spectra of **1** (black), **2** (red), **5** (blue), **6** (orange), and **11** (purple) in CH₂Cl₂ at *c* = 5 × 10⁻⁵ M.

As solids, isomers **1**, **2** and **6** are red-orange in color, while **5** is brown. The spectra of all four isomers feature broad CT absorptions of modest to strong intensity with maxima between $\lambda_{\text{max}} = 400$ and 453 nm. Isomer **1** has its longest wavelength CT absorption at $\lambda_{\text{max}} = 400$ nm (3.10 eV, $\epsilon = 8.1 \times 10^3 \text{ M}^{-1} \text{ cm}^{-1}$), while **2** absorbs at $\lambda_{\text{max}} = 433$ nm (2.86 eV, $\epsilon = 2.5 \times 10^3 \text{ M}^{-1} \text{ cm}^{-1}$). Silylated **11** has a longest wavelength absorption at $\lambda_{\text{max}} = 421$ nm (2.94 eV, $\epsilon = 1.7 \times 10^3 \text{ M}^{-1} \text{ cm}^{-1}$), about 10 nm hypsochromatically shifted compared to the desilylated analogue **2**. Isomer **2** has a B3LYP/6-31G(d)-optimized geometry where the DCV moiety is nearly coplanar with the 1,2,3-triazole ring.¹⁹ The gas-phase calculated and X-ray crystal structures of **11** compare well and are both nonplanar due to strong repelling close contacts between the DCV and TMS groups. The X-ray structure of Figure 2 shows the large out-of-plane twisting of the DCV moiety with a torsion angle C4–C5–C6–C7 of 128°. (DMA torsion angle N2–N1–C16–C17 = –57°). Despite these geometric effects, the intramolecular CT is not much affected. The conjugation pathway for isomer **5**, which avoids conjugation through the N-1 position, shows the strongest CT band at $\lambda_{\text{max}} = 423$ nm (2.93 eV, $\epsilon = 11.3 \times 10^3 \text{ M}^{-1} \text{ cm}^{-1}$). Isomer **6**, with the acceptor attached to N-2, presents the longest-wavelength absorption of this series at $\lambda_{\text{max}} = 453$ nm (2.74 eV, $\epsilon = 7.3 \times 10^3 \text{ M}^{-1} \text{ cm}^{-1}$). In all

(18) Oziminski, W. P.; Dobrowolski, J. C.; Mazurek, A. P. *J. Mol. Struct.* **2003**, *651–653*, 697.

(19) For an X-ray crystal structure of a planar 1,5-substituted triazole, see: Brunner, M.; Maas, G.; Klärner, F.-G. *Helv. Chim. Acta* **2005**, *88*, 1813.

cases, the CT nature of these absorptions is confirmed by quenching with trifluoroacetic acid and reconstitution of the absorption upon addition of triethylamine.

The calculated transition energies of **1–7** and **11** at the TD B3LYP/6-31G(d) level compare well with the set of experimental values (see Supporting Information for full details). There is a standard deviation (SD) of only 0.6 eV between experimental and calculated values. The calculated oscillator strengths (f) correlate well with the measured molar extinction coefficients except for **6**, which is predicted to be more intense than as measured. All longest wavelength absorption are composed of only HOMO to LUMO transitions with a clear shift of electron density from the donor to the acceptor according to molecular orbital analysis. Both the HOMO and LUMO have considerable density on the 1,2,3-triazole ring as well (see images in abstract and Supporting Information). Within the series of seven possible isomers, **3** is predicted to have the lowest energy absorption at 560 nm (2.21 eV, $f = 0.16$), while substantially bathochromically shifted CT bands are also expected for **4** and **7**, with predicted absorptions at 468 nm (2.65 eV, $f = 0.11$) and 481 nm (2.58 eV, $f = 0.39$), respectively.

For all isomers, except **5**, the 1,2,3-triazole makes a particularly intriguing linker where the CT path is “interrupted” by a tertiary amine center at N-1, which in the CT resonance structure will take on cationic character as a quaternary ammonium center. Despite this “interruption,” it is clear that CT can occur and may even be quite efficient depending on the substitution pattern. It has recently been noticed in our group and by others,¹² that for a series of donor-substituted cyanoethynylethenes, the longest-wavelength CT absorptions are found for systems with inefficient ground-state donor–acceptor conjugation. At weak conjugation, HOMO and LUMO energies remain close to those of the individual, undisturbed donor and acceptor components, respectively, as clearly revealed in electrochemical studies. Comparison of the energies of the calculated HOMO and LUMO levels at the B3LYP/6-31G(d) level of isomers **1–7** is not conclusive, as both the HOMO (SD = 0.2 eV) and LUMO (SD = 0.1 eV) energies vary significantly making it difficult to attribute the HOMO energies directly to the predicted HOMO–LUMO gap. However, **3**, which has the longest wavelength absorption according to calculation, also has the least negative HOMO energy at -5.4 eV (LUMO: -2.9 eV) while the HOMO energy of isomer **1**, with the shortest predicted wavelength absorption, is considerably more negative at -5.8 eV (LUMO: -2.6 eV).

Isomer **5** has a CT path that can avoid entirely the N-(1,2,3) positions, but nonetheless does not show superior CT in terms of the position of the absorption maximum compared to **2**, **6** and **11** and the calculated **3**, **4** and **7**, although it has by far the most intense absorption. The

analogous molecules with ethenediyl or ethynediyl as π -linkers have CT absorptions at $\lambda_{\text{max}} = 490$ nm (2.53 eV, $\epsilon = 4.6 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$)²⁰ and $\lambda_{\text{max}} = 477$ nm (2.60 eV, $\epsilon = 4.4 \times 10^4 \text{ M}^{-1} \text{ cm}^{-1}$), respectively.^{17b} That 1,2,3-triazole linkers only induce moderate shifts of the CT absorption relative to these conventional olefinic and acetylenic references is promising for their future applications.

In summary, except for **2**, donor–acceptor-substituted 1,2,3-triazoles were prepared by rather indirect routes instead of by using azide cycloaddition to an appropriate alkyne under thermal or “click” conditions. The production of CT chromophores, which must employ the requisite polarized reactants, pushes beyond the current limit of the “click” methodology. While, 4-aminophenylacetylenes and 4-aminophenylazides are fairly common reactants for “click” chemistry, strongly electron poor vinylic azides are rare and electron deficient enynes have been attempted only in this work. The complications that arise from the numerous side reactions available to these systems may explain their lack of use in “click” chemistry. The positioning of the donor and acceptor on the 1,2,3-triazole ring in **1–7** is ultimately responsible for about a 50 nm range (experimentally; computationally: 100 nm) of transition energies and also affects strongly the absorption intensity. To further motivate research toward formally “clicked” CT chromophores, electrochemical and NLO studies are currently underway on the isomers studied here and related systems. Both the synthetic approach and materials properties of 1,2,3-triazol-diyl linked donor–acceptor chromophores are being optimized. Exploration of their potency to form high-quality optical films by vapor-phase deposition is of particular interest.

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Supporting Information Available: Optimized geometries and TD parameters from B3LYP/6-31G(d) calculations, complete Gaussian 03 reference, depiction of HOMO and LUMO orbitals and energies, ORTEP plots of X-ray structures and CIF files, and experimental procedures and analytical characterization of all new compounds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(20) Staub, K.; Levina, G. A.; Barlow, S.; Kowalczyk, T. C.; Lackritz, H.; Barzoukas, M.; Fort, A.; Marder, S. R. *J. Mater. Chem.* **2003**, *13*, 825.