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Synthetic Methods

High-Yield Formation of Substituted Tetracyanobutadienes from Reaction of Ynamides with Tetracyanoethylene

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Abstract: A high-yielding sequence of [2+2] cycloaddition–retroelectrocyclization of ynamides with tetracyanoethylene (TCNE) is described. The reaction provided tetracyanobutadiene (TCBD) species, which were characterized by various techniques. DFT and TD-DFT calculations were also performed to complement experimental findings.

The sequence of [2+2] cycloaddition–retroelectrocyclization (CA–RE) between tetracyanoethylene (TCNE) and alkynyl-transition metal complexes has been known for several decades[1] and has extensively been studied.[2] However, to the best of our knowledge, this reactivity with purely organic alkynes has been discovered only in 1999 with α-substituted thienylalkynes.[3] Since then, other alkynes substituted by electron-donating groups (EDG) have been shown to react the same way (Figure 1).[4] This reaction has mostly been popularized by Diederich and co-workers for the last decade.[5] Aniline-,[6] azulene-[7] and heteroazulene-substituted[8] alkynes represent the best examples of this reaction by providing yields over 90%, by simply mixing the two reactants together in a solvent at room temperature. However, the reactivity of TCNE with alkynes directly substituted by an electron-donating heteroatom has never been described so far.

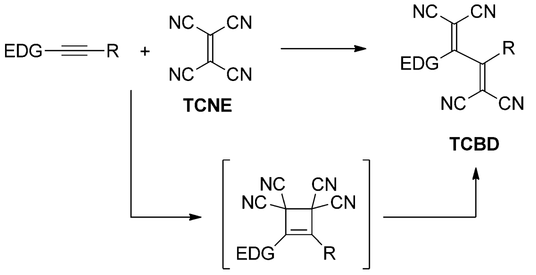

Figure 1. Previous work on [2+2] cycloaddition of TCNE with electron-rich alkynes.

As examples of such compounds, ynamides have received considerable attention during the last decade.[9] This interest can be explained by the new efficient synthetic methodologies recently developed.[10] The ynamide C–C triple bond is activated by the donating ability of the nitrogen atom (Figure 2). However, unlike ynamines, these compounds are stabilized by an electron-withdrawing group (EWG) on the nitrogen, which makes them air-stable and thus easy to handle. [2+2] Cycloadditions of ynamides are known and usually require a catalyst[11] or a Lewis acid,[12] except for their reaction with the ketene.[13]

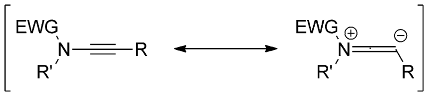

Figure 2. Ynamide mesomeric forms highlighting the electron richness of the C–C triple bond.

In this communication, we report on the reactivity of a variety of ynamides with TCNE to achieve tetracyanobutadiene (TCBD) species in moderate to excellent yields (57% to quantitative) at room temperature and without the need for any activating agent. In addition to their potential interesting optoelectronic properties, these new TCBDs may be easily functionalized in various positions thanks to the nature of their ynamide precursors.

At first, three different ynamides, which differ from each other by the nature of the electron-withdrawing group, were synthesized. Ynamides **1** and **2** (Scheme 1) were prepared according to literature procedures[14] whereas the synthesis of **3** has been inspired by a recent article from the Hsung group (see the Supporting Information for details).[15] Compounds **1**–**3** in dichloromethane were reacted with an equimolar amount of TCNE at room temperature overnight. The same reactivity was observed and TCBD adducts **4**, **5** and **6** were obtained in 92, 98 and 93% yield, respectively.[16] This reaction is supposed to proceed according to a sequence of [2+2] CA–RE as described in Figure 1.

Secondly, the scope of the reaction was investigated using the tosylate group. This EWG was preferred over the carbamate and the phosphonate due to its ease of preparation and higher degree of crystallinity.

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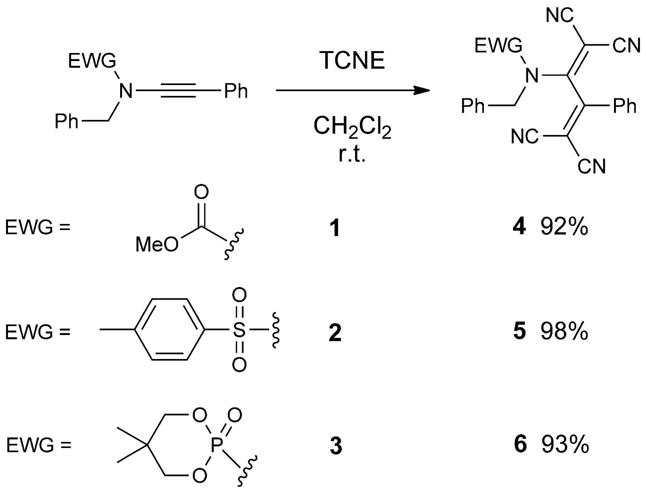
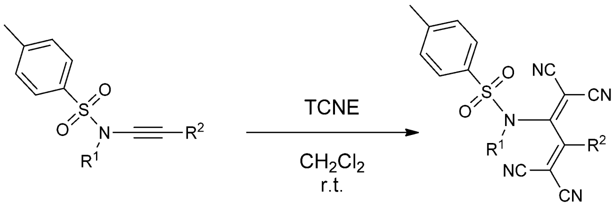


Scheme 1. Reactivity of ynamides **1**–**3** with TCNE giving the corresponding TCBD adducts **4**–**6** in excellent yields.

Table 1. Scope of the [2+2] CA–RE of ynamides and TCNE.



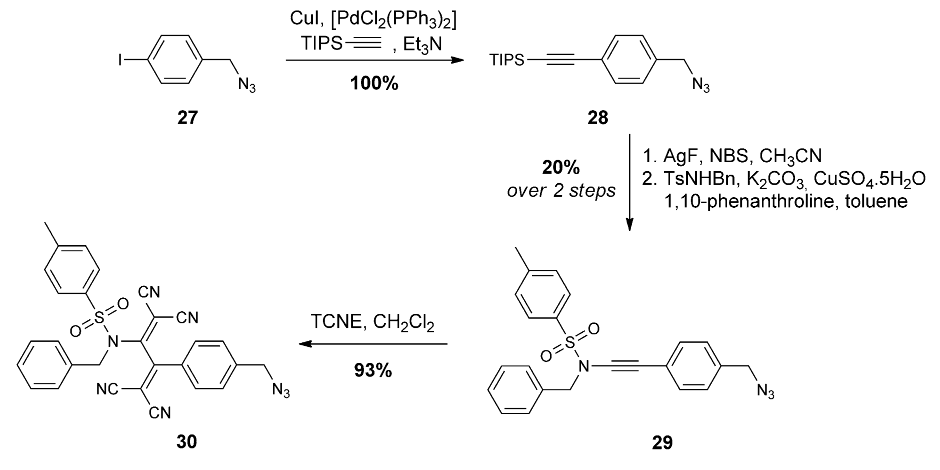
Entry	Ynamide		TCBD	Yield [%]
1	**7**	$R^1 = CH_3$, $R^2 = Ph$	**17**	100
2	**8**	$R^1 = CH_2CH_2Ph$, $R^2 = Ph$	**18**	95
3	**9**	$R^1 = CH_2Ph$, $R^2 = p\text{-Cl-}C_6H_4$	**19**	90
4	**10**	$R^1 = CH_2Ph$, $R^2 = p\text{-OMe-}C_6H_4$	**20**	100
5	**11**	$R^1 = CH_2Ph$, $R^2 = p\text{-CN-}C_6H_4$	**21**	57
6	**12**	$R^1 = CH_2Ph$, $R^2 = p\text{-NPh}_2\text{-}C_6H_4$	**22**	92
7	**13**	$R^1 = CH_2Ph$, $R^2 = H$	**23**	100
8	**14**	$R^1 = CH_2Ph$, $R^2 = n$-hexyl	**24**	100
9	**15**	$R^1 = CH_2Ph$, $R^2 =$ pyridin-3-yl	**25**	58
10	**16**	$R^1 = CH_2Ph$, $R^2 =$ thiophen-2-yl	**26**	87

Ynamides **7**–**16** were synthesized according to Evano's[10c,17] or Hsung's[14a] procedures. The influence of the second group linked to the nitrogen (R^1 in Table 1) was first evaluated by turning it into a methyl or a homobenzylic group (entries 1 and 2). No dramatic change was observed, the yield of the reaction remaining excellent (95% to quantitative). The influence of the group linked to the C–C triple bond was also evaluated. Electron-rich phenyl groups (*p*-methoxyphenyl and *p*-diphenylaniline, entries 4 and 6) did not change the yield (quantitative and 92% respectively). However, electron-poor phenyl groups (*p*-chlorophenyl and *p*-cyanophenyl, entries 3 and 5) slightly to moderately decreased the reactivity (90% and 57% respectively). Nevertheless, particularly noteworthy is the significant increase of the yield with *p*-cyanophenyl group when using 2 equivalents of TCNE instead of 1 (from 57% to 79%). The *n*-hexyl group or a hydrogen in lieu of a phenyl one provided TCBD in quantitative yields (entries 7 and 8). Heteroaromatic substituents were also studied: Whereas a thiophen-2-yl group did not really affect the yield of the reaction (87%, entry 10), a pyridin-3-yl group significantly decreased the yield to 58%, even using two equivalents of TCNE. Indeed, three equivalents of TCNE and a longer reaction time of 64 h were necessary to give **25** in 75% yield. In every instance, when the yield was not over 90%, the conversion was not complete. It was never due to decomposition during the purification process. No other product was formed.

From these figures, we can draw the conclusion that only electron-poor groups might significantly decrease the yield of the reaction in some particular cases but remain very well tolerated.

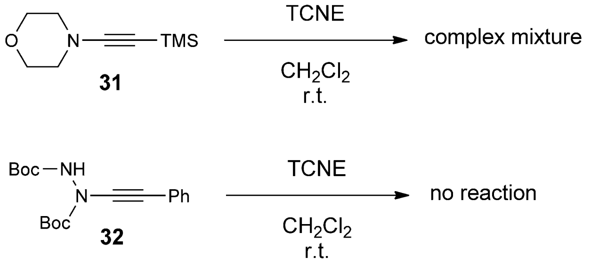
In addition, ynamide **29**, bearing an azide functional group, was synthesized in 19% yield over 3 steps starting from the known azide **27** (Scheme 2).[18] A Sonogashira coupling using (tri-isopropylsilyl)acetylene gave the protected alkyne **28** in quantitative yield and the latter was then reacted with silver fluoride and *N*-bromosuccinimide.[19] The bromide derivative formed was unstable, and was further reacted under Hsung's reaction condition to afford ynamide **29**. Reaction with one equivalent of TCNE gave TCBD **30** in an excellent 93% yield. This azide-functionalized TCBD **30** allows us to envisage further incorporation of new functional groups by copper-catalyzed azide–alkyne cycloaddition (CuAAC) reaction[20] for instance, as it was performed in the past with other related TCBDs.[21]

This reactivity does not seem to be a general property of N-substituted alkynes but a particularity of ynamides. Indeed, when reacting the commercially available ynamine **31** with TCNE using the same procedure as described above, a complex



Scheme 2. Synthesis of ynamide **29** and further reactivity to form TCBD **30**.

mixture of inseparable colored products was obtained, probably resulting from the over reaction of this very reactive species, as it has already been described in the literature with other related compounds.[22] By contrast, when ynehydrazide **32**[23] was reacted with TCNE, no reaction occurred (Scheme 3). In each case, no TCBD could be isolated. These observations led us to conclude that the right balance was found with ynamides for the reaction with TCNE to yield TCBDs in high yields.



Scheme 3. Reactivity of an ynamine and an ynehydrazide with TCNE.

Products **4**–**6** and **17**–**26** were characterized by ^{1}H and ^{13}C NMR spectroscopy, mass spectrometry, UV/Vis spectroscopy and electrochemistry. Additionally, compounds **4**, **5**, **17**, **19**–**22** and **25** were also characterized by X-ray diffraction, confirming unambiguously the structure of the adducts synthesized (Figure 3 and S1–S10 in the Supporting Information). X-ray structures of compounds **4**–**5**, **17**, **19**–**22** and **25** reveal highly distorted TCBD groups with significant twist between the two dicyanovinyl planes (Figure 3). Indeed, the torsion angle between these groups ranges between 56 and 68°, except for compound **17** the torsion angle of which is 110°. The s-*cis* conformation in the solid state is consistent with that reported for TCBD analogs.[4a,24] DFT optimized geometries both in vacuum and in solvents, suggest that the s-*cis* conformation is preferred in solution even though the difference with the s-*trans* conformation stays within a few hundreds of eV (Table S2 in the Supporting Information). Both experiment and calculations evidence clearly a single-bond character of the central C–C bond of the TCBD group (Table S1 in the Supporting Information).

UV/Vis absorption spectra are shown in Figure 4 and S11–S16 (see the Supporting Information). Except for the donor-substituted compounds, they reveal two broad absorption bands in the UV range at approximately 340 and 260 nm with little solvatochromism indicative of non-polar ground states. TD-DFT calculations and tentative deconvolution of these optical spectra show that several electronic transitions contribute to each band (Figure S15 and Table S5 in the Supporting Information). Moreover, neither the HOMO nor the HOMO-1 (Table S3) are involved in these transitions leading to the absence of absorption in the visible spectrum. Indeed, natural transition orbital[25] plots reveal the electronic redistributions upon excitation that mainly involve the dicyanovinyl moiety connected to the phenyl ring for the first band and the other dicyanovinyl group for the second one (Table S5). Significant

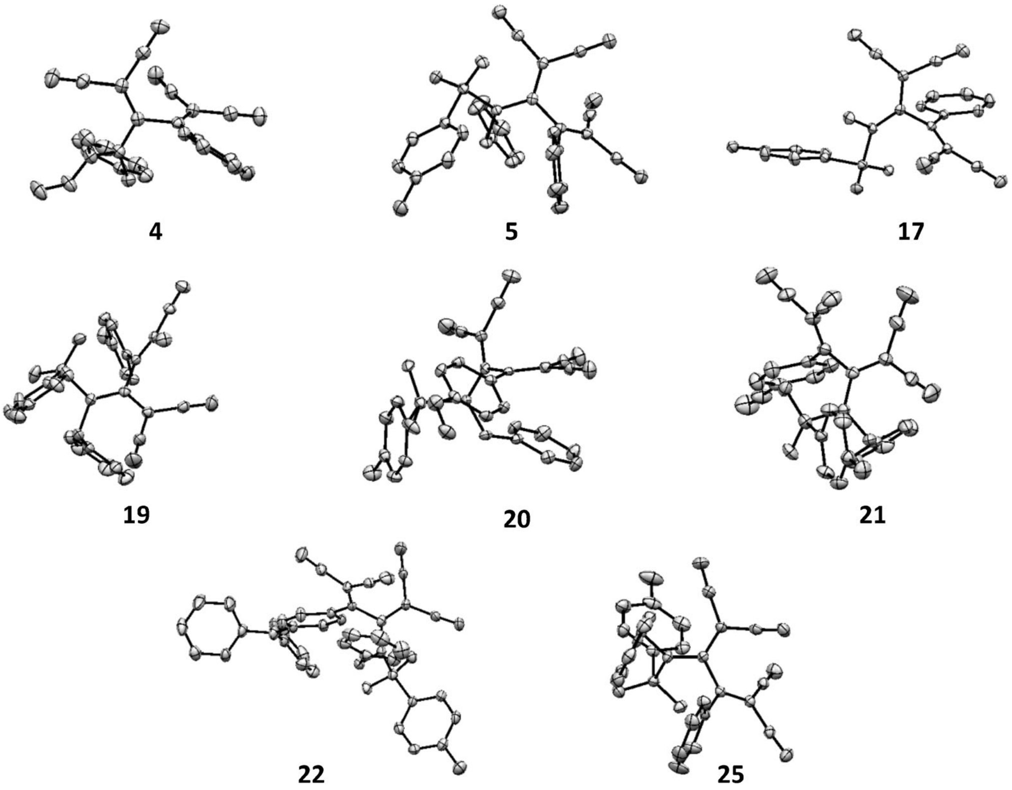


Figure 3. X-ray structures of compounds **4**, **5**, **17**, **19**–**22** and **25**. Solvent and hydrogen atoms are omitted for clarity.

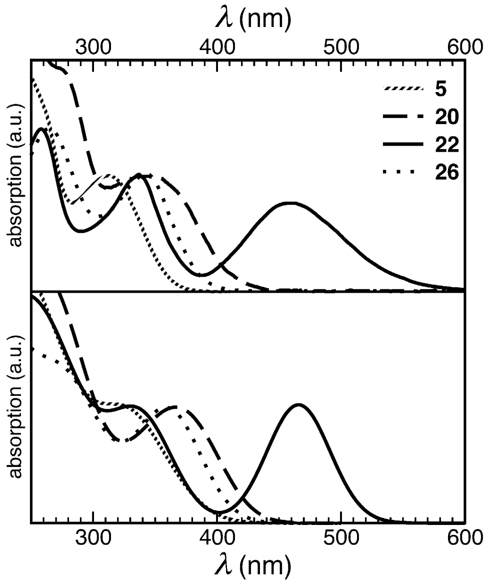


Figure 4. Experimental (top) and calculated (bottom) normalized UV/Vis absorption spectra of compounds **5**, **20**, **22** and **26** in CH_2Cl_2. To ensure easy comparison, calculated data have been shifted by an overall offset of 0.36 eV.

red shift occurs upon donor substitution with appearance of a clear isolated band in the visible range for the strongest donor (compound **22**) (Figure 4). Comparison of molecular (Table S4) and transition (Table S6) orbitals of compound **22** reveal the HOMO→LUMO nature of this band, while higher-lying bright states show good correspondence with those discussed for compounds lacking donor substitution. Compounds **20** and **26** show an intermediary behavior due to smaller splittings between the first two excited states (Table S6 in the Supporting Information).

In order to investigate the electronic properties of these new TCBD compounds, cyclic voltammetries were recorded in acetonitrile (Figure S17). Two distinct reversible one-electron reduction waves can be observed at approximately −0.5 and −1.0 V vs Fc^+/Fc (Table 2) that may be assigned to the subsequent reduction of the two dicyanovinyl groups. Moreover, these TCBD species are among the easiest ones to reduce out of such adducts according to the literature,[4a,24] making them potential super-acceptors. From these values were deduced the two electronic affinities (Table 2) for each compound (see the Supporting Information for details).[26] In addition, no oxidation could be observed (except for compound **22**), in major contrast with other examples of adducts from reaction of TCNE with electron-rich alkynes.[6a,7a,8]

Table 2. Measured half-wave potentials ($E_{1/2}$) and electronic affinities (EA) of compounds **4–6**, **20**, **22** and **26** calculated on the basis of cyclic voltammetry. Acetonitrile solution of 0.1 mol L^{-1} of $n\text{Bu}_4\text{NPF}_6$ and 10^{-3} mol L^{-1} of TCBD at $100\ \text{mV s}^{-1}$. DFT calculated values ($EA^{i,cal}$) obtained at B3LYP/6-31+G* level in acetonitrile are also reported.

Compounds	**4**	**5**	**6**	**20**	**22**	**26**
$E_{1/2}{}^1$(V vs Fc^+/Fc)	−0.52	−0.54	−0.62	−0.58	−0.60	−0.52
$E_{1/2}{}^2$(V vs Fc^+/Fc)	−1.06	−1.00	−1.04	−1.02	−1.01	−0.93
EA^1[ev]	4.32	4.29	4.21	4.26	4.24	4.31
$EA^{1,cal}$[ev]	4.54	4.50	4.37	4.44	4.28[a]	4.46
EA^2 [ev]	3.77	3.83	3.78	3.81	3.81	3.90
$EA^{2,cal}$[ev]	3.69	3.71	3.85	3.70	3.71[a]	3.82

[a] Values derived from total electronic energies instead of Gibbs free energies

From a theoretical point of view, calculated adiabatic electron affinities correlate nicely with the experimental values given in Table 2. Electron affinities are only slightly affected by the substitutions implemented in this work, the lowest value being observed with the strongest donor group (compound **22**). Optimized geometries of anions evidence sizeable diminution of both the dihedral angle and the C–C bond length between the two dicyanovinyl groups consistently with the orbital structure of the LUMO (Tables S3 and S4). This is even more pronounced for di-anions and indicates electron removal from orbitals delocalized over the whole TCBD unit. Moreover, except for **22**, calculated adiabatic ionization energies in acetonitrile amount to approximately 7 eV (Tables S7 and S9 in the Supporting Information), reaching almost that of benzene. For the unsubstituted compounds, this is consistent with a HOMO mainly localized on the benzyl ring (Table S3) leading to an increased bond length alternation in their cationic forms (Table S8). Such high oxidation potentials explain that no oxidation could be observed by cyclic voltammetry in these conditions.

To conclude, an original reactivity between fourteen different ynamides and TCNE has been described. It allows for the formation of new TCBD species in good to quantitative yields by simply mixing equimolar quantities of ynamides and TCNE in dichloromethane at room temperature. These new compounds were characterized by various techniques and their properties were explained by TD–DFT calculations. In this communication, the nature of all the different functional groups of the ynamides has been investigated, bringing us to the conclusion that only a strong electron-withdrawing group linked to the C–C triple bond can affect the yield of the reaction. Moreover, this reactivity paves the way to the construction of more sophisticated systems that could exhibit interesting properties for new materials in opto-electronic devices.

CCDC 905007 (**3**), CCDC 881967 (**4**), CCDC 884433 (**5**), CCDC 960613 (**17**), CCDC 962305 (**19**), CCDC 962971 (**20**), CCDC 962979 (**21**), CCDC 966740 (**22**) and CCDC 976260 (**25**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif

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Keywords: [2+2] cycloaddition · tetracyanobutadienes · tetracyanoethylene · ynamides

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[16] Typical experimental procedure for the formation of TCBD compounds: A solution of ynamide (1.0 equiv) and tetracyanoethylene (1.0 equiv) in CH_2Cl_2 (0.1 M) was stirred at room temperature overnight. The solvent was evaporated, and if needed the residue was subjected to chromatography on silica gel, to afford TCBD moieties.

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