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Reactivity of Long Conjugated Systems: Selectivity of Diels–Alder Cycloaddition in Oligofurans

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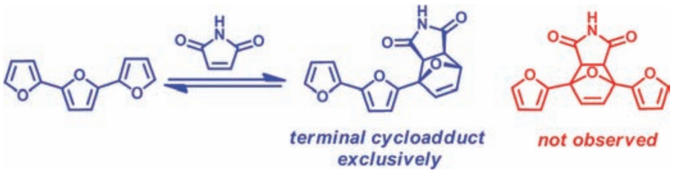
ABSTRACT



Taking advantage of the synthetic availability and solubility of long oligofurans, their reactivity toward dienophiles was studied as a model for the rarely investigated reactivity of long conjugated systems. Unlike oligoacenes, the reactivity of oligofurans decreases or remains constant with increasing chain length. Terminal ring cycloadducts of oligofurans are kinetically and thermodynamically favored, whereas central ring cycloadducts are preferred in oligoacenes, because of the different driving forces in the two reactions: π-conjugation in oligofurans and aromatization/dearomatization in oligoacenes.

π-Conjugated systems, such as oligothiophenes and oligoacenes, are the most important building blocks for organic electronic materials.[1] Despite recent interest in these materials,[2] very little is known about their reactivity. The reactivity of these electron-rich compounds toward dienophiles is of particular interest because it holds the key to both their stability and their diverse chemistry. Acenes become more reactive with increasing length: while benzene is a very weak diene, pentacene undergoes Diels–Alder (DA) cycloaddition readily.[3] The poor stability of higher acenes is a major impediment to the application of acene-based compounds in electronic devices.

Although π-conjugated oligomers and polymers have been known for a long time, studies of the reactivity of long conjugated systems are rare.[1,3b,4] The site selectivity problem associated with oligoenes was studied over 60 years ago by Alder and Schumacher, who proposed that the addition of maleic anhydride proceeds to the central double bonds of an oligoene system.[5] In the study of DA addition of maleic anhydride to conjugated tetraene systems it was found that the addition is selective to the terminal bonds.[6] The initial growth of carbon nanotube fragments by DA cycloaddition was also studied.[7] Gaining understanding and control of the reactivity of long conjugated systems is required for the future progress of the whole field of organic electronic materials and will be an important step toward understanding the reactivity of conducting polymers.

The reaction of furan with maleimide is a classical textbook reaction that was studied by Diels and Alder

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more than 80 years ago[8] and led to applications in many fields, such as medicinal chemistry, dendrimer formation,[9] self-healing polymers,[10] etc. Recently, we prepared a series of α-oligofurans consisting of up to 9 rings.[11] Long oligofurans have several advantages over the extensively studied oligothiophenes, such as higher rigidity, better solubility, better packing, and higher fluorescence. In addition, we showed that oligofurans have mobilities in Field Effect Transistors (FETs) that are similar to those of the corresponding oligothiophenes.[12−15]

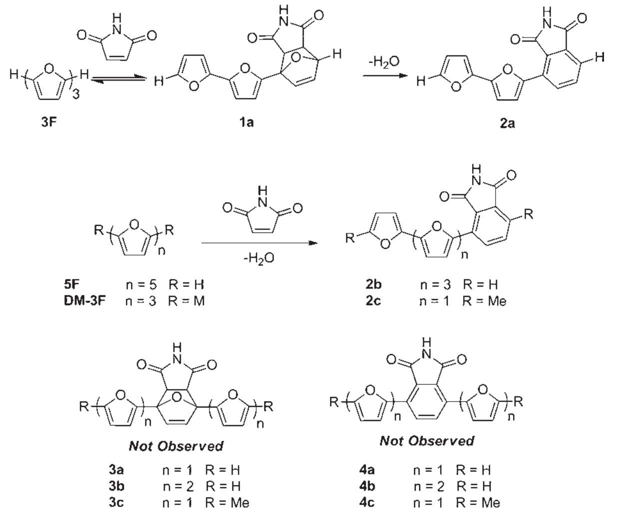
One of the greatest advantages of molecular semiconductors is the potential for solution processing, which is expected to reduce the cost of device fabrication considerably. In this regard, several solution processable pentacene precursors have been synthesized, where the soluble unit can be thermally removed by retro DA reaction after casting of the film.[16] In order to apply similar processes to long oligofurans, their DA reactivity should be investigated. Here, we report a combined experimental and computational study of the DA reactivity of conjugated oligofurans, which importantly serves as a case study for the reactivity and selectivity of long conjugated systems in general.

The reaction of terfuran (**3F**) and maleimide in ethyl acetate proceeds at rt to yield the cycloadduct **1a**, which in turn aromatizes to the thermodynamic product **2a** (Scheme 1). Compound **1a** was confirmed by X-ray crystallography as the *exo* cycloadduct (Figure 1).[17] The cycloaddition of **3F** with maleimide to produce **1a** is reversible[18] at rt: when the isolated cycloadduct **1a** is redissolved in acetone-d_6, the reverse reaction yields **3F** and maleimide after several days (see Supporting Information (SI)). Importantly, the products of cycloaddition to the central ring (**3a** and **4a**) were not observed. The same trend was observed for longer oligofurans as well: the reaction of **5F** with maleimide in dichlorobenzene at 150 °C proceeds selectively to the terminal ring to yield **2b** (Scheme 1; see also SI). High temperature is required in order to fully dissolve **5F**. The terminal selectivity of oligofurans is in sharp contrast to the selectivity of oligoacenes but similar to that of oligoenes (the selectivity of oligoenes was studied for relatively short systems, which have only four conjugated double bonds).[6]

In order to verify that the exclusive site selectivity in DA cycloaddition is a result of electronic and not steric factors, methyl groups were introduced at the terminal positions of **3F**, yielding dimethyl-terfuran (**DM-3F**) (Scheme 1; for preparation of **DM-3F**, see SI). **DM-3F** was reacted with maleimide in the same manner as described above for **3F**. The only observed product is **2c**, which is the terminal cycloadduct after aromatization. Thus, steric factors can be ruled out in the selective terminal addition of dienophiles to oligofurans.

When **3F** was reacted with 1 equiv of dimethylacetylene dicarboxylate (DMAD) in ethyl acetate at rt overnight, cycloadduct **5** was observed along with the aromatization product **6** (Scheme 2). Again, cycloaddition occurs exclusively

Scheme 1. Reactions of **3F**, **DM-3F**, and **5F** with Maleimide



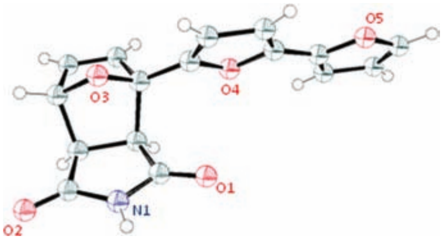


Figure 1. ORTEP representation (50% elipsoid probability) of **1a** (gray, carbon; red, oxygen; blue, nitrogen).

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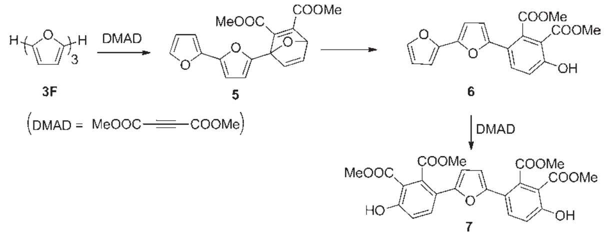
Scheme 2. Reaction of **3F** with DMAD



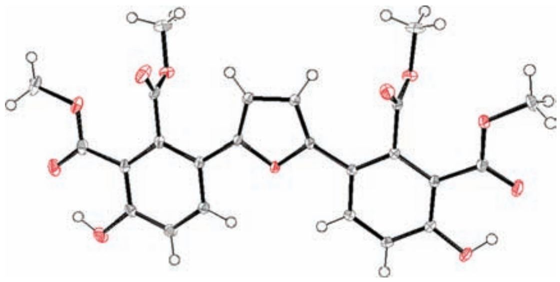


Figure 2. ORTEP representation (50% elipsoid probability) of **7** (gray, carbon; red, oxygen).

in a terminal position. The use of 2 equiv of DMAD (either in a one-pot reaction or via stepwise addition of 1 equiv followed by a second equivalent) resulted in a doubly aromatized compound **7** where both additions proceeded at the terminal rings. The crystal structure of **7** reveals a completely planar structure with a conjugated backbone (Figure 2). This reaction should be useful for the introduction of various substituted phenyl groups to furan oligomers or for the synthesis of multisubstituted benzenes.[19]

Regioselectivity and reactivity as a function of chain length in the reaction of oligofurans with maleimide were studied using DFT calculations at the M06-2X/6-31G(d) and B3LYP/6-31G(d) levels (Table 1 and Figures 3 and 4; for benchmark calculations using different basis sets and high level *ab initio* methods, see SI).[20,21] For comparison, similar computational studies were performed for oligoacenes and oligothiophenes. Since benchmark studies are falling between M06-2X and B3LYP methods, and since the differences between these two methods are large, we provide the values for both methods. We believe that the most accurate values should be somewhere in between the values obtained at the M06-2X and B3LYP methods.

Table 1. Calculated, at M06-2X/6-31G(d) (M06) and B3LYP/6-31G(d) (B3L) Levels (in kcal/mol), Activation Energies ($\Delta E^{\ddagger}$) and Reaction Energies (ΔE) for the Cycloaddition of Maleimide to Oligofurans (**nF**), Oligoacenes (**nA**), and Oligothiophenes (**nT**) as well as to Dimethyl-terfuran, **DM-3F** (**M**) in Terminal (ter.) and Central (cent.) Rings

oligofurans (**nF**)

	$\Delta E^{\ddagger}$				ΔE			
	ter.		cent.		ter.		cent.	
n	M06	B3L	M06	B3L	M06	B3L	M06	B3L
1	11.8	20.1	-	-	-17.0	-5.0	-	-
2	12.1	20.8	-	-	-13.0	2.2	-	-
3	12.3	20.6	14.8	27.4	-12.4	2.7	-8.1	10.3
4	12.5	20.6	14.9	27.8	-12.5	2.8	-7.7	11.0
5	12.9	20.6	15.5	28.2	-12.5	2.9	-7.4	11.7
M	11.9	22.5	14.5	27.1	-12.6	4.3	-7.8	10.4

oligoacenes (**nA**)

	$\Delta E^{\ddagger}$				ΔE			
	ter.		cent.		ter.		cent.	
n	M06	B3L	M06	B3L	M06	B3L	M06	B3L
1	25.1	36.6	-	-	-3.3	13.5	-	-
2	18.2	29.5	-	-	-16.7	0.5	-	-
3	16.0	27.1	8.6	21.7	-21.7	-4.0	-34.5	-15.6
4	14.9	26.2	5.8	18.8	-24.0	-5.9	-41.3	-21.5
5	14.4	25.7	2.9	15.9	-25.1	-6.8	-48.7	-27.9

oligothiophenes (**nT**)

	$\Delta E^{\ddagger}$				ΔE			
	ter.		cent.		ter.		cent.	
n	M06	B3L	M06	B3L	M06	B3L	M06	B3L
1	21.1	30.3	-	-	-15.4	-1.3	-	-
2	20.1	29.1	-	-	-11.4	6.0	-	-
3	20.1	28.7	21.5	35.3	-10.8	6.5	-6.9	14.2
4	20.0	28.6	21.5	35.6	-10.8	5.8	-6.4	14.9
5	20.1	28.6	22.1	35.9	-10.7	6.6	-5.7	15.5

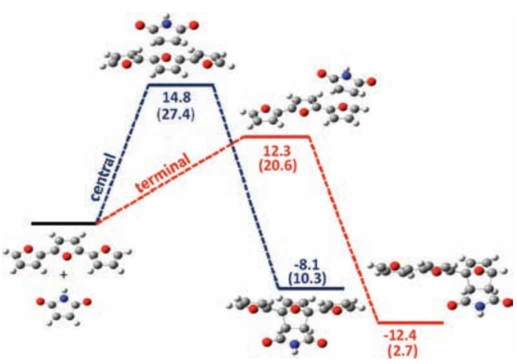


Figure 3. Calculated (at M06-2X/6-31G(d), in kcal/mol; values at B3LYP/6-31G(d) are given in parentheses) pathway for the reaction of **3F** and maleimide.

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(20) All calculations were performed using Gaussian 09 software. Frisch, M. J.; et al. *Gaussian 09*, revision A.02; Gaussian, Inc.: Wallingford, CT, 2009. See Supporting Information for full reference.

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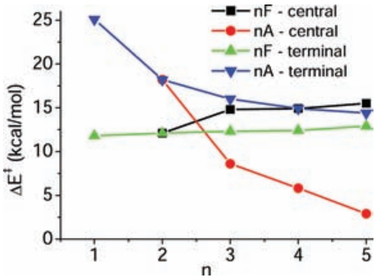

Figure 4. Activation energies (at B3LYP/6-31G(d)) of Diels–Alder reactions between oligofurans (**nF**) or oligacenes (**nA**) and maleimide at terminal and central rings.

As an example, the activation energy ($\Delta E^{\ddagger}$) and reaction energy (ΔE) for the reaction of **3F** with maleimide are shown in Figure 3. Terminal cycloaddition is both kinetically and thermodynamically preferred over cycloaddition to the central ring, with an activation energy difference of $\Delta\Delta E^{\ddagger} = 2.5$ kcal/mol and reaction energy difference of $\Delta\Delta E = 4.3$ kcal/mol at the M06-2X level. Terminal cycloaddition preference is significantly larger at the B3LYP level ($\Delta\Delta E^{\ddagger} = 6.8$ kcal/mol, $\Delta\Delta E = 7.6$ kcal/mol). Similar results are obtained for the reaction of **DM-3F** and maleimide, with $\Delta\Delta E^{\ddagger} = 2.6$ kcal/mol and $\Delta\Delta E = 4.8$ kcal/mol at M06-2X and $\Delta\Delta E^{\ddagger} = 4.5$ kcal/mol and $\Delta\Delta E = 6.1$ kcal/mol at B3LYP. The computational results support the selectivity observed in the experiments described above.

The reactivity trends (such as the chain length dependence of reactivity and cycloaddition position) of oligofurans differ significantly from those of oligoacenes (Table 1 and Figure 4) and are similar to those of oligothiophenes (although oligofurans generally have a higher reactivity toward DA cycloaddition than oligothiophenes).[22] While the activation energy for the cycloaddition of oligoacenes significantly decreases with increasing acene length (from 25.1 kcal/mol for benzene to 2.9 kcal/mol for cycloaddition to the central ring of pentacene at M06-2X; corresponding values at B3LYP are 36.6 and 15.9 kcal/mol), the activation energy for oligofuran cycloaddition slightly increases from **1F** to **2F** and practically does not change for longer oligomers. For oligoacenes, cycloaddition to the central ring is preferred significantly over terminal ring cycloaddition; for example, the difference between cycloaddition to the terminal and central ring of pentacene is 11.5 kcal/mol at M06-2X and 9.8 kcal/mol at B3LYP. The opposite trend is observed for oligofurans, with a difference of 2.6 kcal/mol at M06-2X (7.6 kcal/mol at B3LYP) in favor of terminal cycloaddition over central ring cycloaddition for **5F**. For oligothiophenes, such as quinquethiophene **5T**, terminal ring cycloaddition is preferred over central ring cycloaddition by 2.0 and 7.3 kcal/mol for M06-2X and B3LYP respectively, while the activation energy for terminal cycloaddition is 7.2 kcal/mol at M06-2X (8.0 kcal/mol at B3LYP) higher for **5T** compared to **5F** (Table 1).

In oligofurans, conjugation is the driving force of reactivity. Since addition to the central ring leads to the interruption of conjugation along the backbone it is disfavored. In oligoacenes, aromaticity is the driving force of reactivity and addition to the central ring leads to the formation of two aromatic subunits (e.g., addition to the central ring of pentacene leads to two naphthalene subunits). Importantly, since conjugation in oligofurans increases with chain length, long oligofurans are not more reactive than shorter ones, while the reactivity of oligoacenes increases strongly with chain length.

In summary, the reactivity of oligofurans toward dienophiles was studied (experimentally and computationally) as a test case of the reactivity of long conjugated systems. Terminal ring cycloadducts of oligofurans are kinetically and thermodynamically favored. We find that the reactivity of oligofurans decreases or remains constant with increasing chain length, which is the reverse of the trend known for oligoacenes. We have shown that the factors underlying this selectivity are electronic and not steric. These results are explained by the different reaction driving forces: aromatization/dearomatization in oligoacenes and π-conjugation in oligofurans. The fact that the reactivity of oligofurans remains constant with increasing chain length is related to their high conjugation and has important implications for understanding the chemical stability of long conjugated polymers.[1b,2a] We have shown that the reactivity of long conjugated systems occurs preferably at their terminals, and this should contribute in many cases to the increased stability of conjugated polymers compared to corresponding conjugated oligomers. According to the computational results, in reactions with dienophiles, oligothiophenes show similar selectivity to oligofurans, while they have significantly lower reactivity. The reaction of oligofurans with both maleimide and DMAD leads to subsequent aromatization and can be used as a method for the synthesis of multisubstituted benzenes, as well as oligofurans connected to substituted phenyl rings. This study, which is the first conducted on the Diels–Alder reactivity of long conjugated oligomers, can serve as a model system for the reactivity and stability of conjugated oligomers and polymers.

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Supporting Information Available. Experimental procedure, spectral data, X-ray structural data, CIF files, absolute energies and XYZ coordinates at different levels of theory for all calculated stationary points, and the coordinates of their optimized structures. This material is available free of charge via the Internet at http://pubs.acs.org.

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