[6+2] Photocycloadditions

Investigation of Routes to New Substituted Cyclooctatetraenes

Bachelor thesis in Chemistry
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Abstract

This report describes [6+2] photocycloadditions between dimethyl acetylene dicarboxylate and several different aromatic compounds. The aromatic compounds were benzene, toluene, aniline, para-xylene, anisole, trifluoromethylbenzene, triethylsilylbenzene, ortho-xylene and benzonitrile. The compounds were irradiated for 24 or 48 hours before being analyzed with $^1$H NMR spectroscopy, and purified with column chromatography or recrystallization. Benzene, toluene, trifluoromethylbenzene and fluorobenzene yielded the cycloadduct we expected, i.e. methyl-, fluoro- and trifluoromethylsubstituted dimethyl cyclooctatetraene-1,2-dicarboxylate. Further analyses were made with GC-MS and $^{13}$C NMR on the successful reactions.
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Abbreviations and symbols

COT  Cyclooctatetraene
DMAD  Dimethyl acetylenedicarboxylate
EDG  Electron-donating group
EWG  Electron-withdrawing group
GC-MS  Gas chromatography-Mass spectrometry
HOMO  Highest occupied molecular orbital
LUMO  Lowest unoccupied molecular orbital
MO  Molecular orbital
NMR  Nuclear Magnetic Resonance
o  Ortho
p  Para
SOMO  Singly occupied molecular orbital
TLC  Thin Layer Chromatography
## Contents

1 Introduction  
   1.1 Aromaticity and antiaromaticity ........................................ 1  
   1.2 Baird’s rule ......................................................................... 2  
   1.3 Cycloadditions ..................................................................... 4  
   1.4 Photocycloadditions of aromatic compounds ......................... 5  
   1.5 Aim .................................................................................... 7

2 Experimental methods and materials ........................................... 8  
   2.1 Materials ........................................................................... 8  
      2.1.1 Apparatus ..................................................................... 8  
      2.1.2 Chemicals .................................................................... 8  
      2.1.3 Analysis ....................................................................... 8  
      2.1.4 Software ...................................................................... 9  
   2.2 Methods ............................................................................... 9  
      2.2.1 Procedure ..................................................................... 9

3 Results ..................................................................................... 10  
   3.1 Successful reactions ............................................................ 10  
   3.2 Attempted reactions ............................................................ 13  
   3.3 UV-Vis absorption spectroscopy ........................................... 15

4 Discussions and Conclusion ....................................................... 16

A Spectra and chromatograms .................................................... 19  
   A.1 NMR ............................................................................... 19  
   A.2 GC-MS ............................................................................ 31  
   A.3 UV-Vis ............................................................................. 45
1 Introduction

In the extensive world of organic chemistry, there are still many unexplored paths that may lead to new molecules or quicker and more effective routes to already existing compounds. As organic chemistry is a gigantic research field, a lot of research is done on this every year. A new compound can be part of a new medicine or a quicker and more effective route can lower costs of existing molecules. Examples of discoveries that have made this possible are different kinds of metal catalysis [1]. An unexplored approach for finding new routes is photo-induced antiaromaticity, discovered by Colin Baird in 1972 [2]. Exciting an S\(_0\) state aromatic compound, to its S\(_1\) or T\(_1\) state makes it antiaromatic and therefore more reactive. Opposite to this, exciting an S\(_0\) state antiaromatic compound to its first S\(_1\) or T\(_1\) state makes it aromatic. This is a key to unlock faster paths to compounds or for creating completely new ones.

1.1 Aromaticity and antiaromaticity

Aromacity is a concept in chemistry that adheres to the unusually high stability in cyclic organic molecules. The most famous molecule representing aromaticity is benzene, C\(_6\)H\(_6\). The structure of benzene was debated a lot during the 19th century, but in 1865 August Kekulé proposed that the structure was 1,3,5-cyclohexatriene with alternating double bonds. But this was not good enough of an explanation as benzene does not react as other alkenes, thus it was concluded it had something contributing to stability that other alkenes did not have. With the discovery of the phenomena of quantum mechanics, the German physicist Erich Hückel solved the so-called benzene problem with molecular orbital (MO) theory and showed that the stability of aromatic compounds are due to electron delocalization of \(\pi\)-orbitals in a closed circuit. The Hückel’s rule for aromaticity explained that the molecule should be cyclic, planar and have 4\(n\)+2 \(\pi\)-electrons conjugated in the ring [3, 4]. It is this extra stability that makes aromatic compounds unique and nonreactive. Benzene needs a suitable catalyst to undergo reactions that normal alkenes efficiently

![Figure 1: \(\pi\)-orbital delocalization and resonance structures of benzene](image-url)
undergo and the reactions are mostly substitutions instead of additions. Aromatic rings can also be heterocycles and contain for example nitrogen, oxygen, and other heteroatoms, as long as they contain the right number of $\pi$-electrons. Aromatic compounds have a diamagnetic ring current, which gives them a region of their own in nuclear magnetic resonance spectroscopy [5].

Antiaromacity is the opposite to aromaticity as the cyclic delocalization destabilizes the molecule relative to its open-chain analogue. An antiaromatic compound has $4n\pi$-electrons conjugated in the system. This concept was established by Ronald Breslow in 1967 [6]. For antiaromatic compounds, the $\pi$-electron energy is higher than that of a reference compound that does not have a cyclic delocalization of its molecules, for example cyclobutadiene and 1,3-butadiene. This lowers the thermodynamic stability of the product. Unlike an aromatic compound, where there is a high degree of symmetry and the $\pi$-electrons are delocalized, antiaromatic compounds have localized $\pi$-electrons and can have distorted structures. Another thing that can be seen is that the ring current of antiaromatic compounds is paramagnetic. Cyclooctatetraene has 8 $\pi$-electrons but distorts into a tub shape to avoid being planar and antiaromatic.[7]

Figure 2: COT in its tub conformation

1.2 Baird’s rule

Colin Baird is a Canadian theoretical chemist who in 1972 published what was later named as Baird’s rule. In his discovery, he extended the concepts of aromaticity and antiaromacity to the lowest $3\pi^*\pi^*$ state with the help of perturbation MO theory. He compared the energies of triplet cyclic molecules and energies of triplet polyene molecules. To describe the orbital interaction in triplets he used the terms “Type I” and “Type II” effect. If we denote two radical units as X and Y, where the radical units are what we would get if we split the molecule into two halves with an odd number of carbon atoms, type I effects are the interactions between the two SOMOs of X and Y, while type II effects are the interactions between the SOMO of X (or Y) with the vacant and doubly occupied MO’s of Y (or X). The type I effect is either zero or destabilizing. If the MOs of X and Y are either both asymmet-
Figure 3: Type I interaction of non-bonding MOs of radicals X and Y in triplet XY for (a) 4\(n\) + 2 rings and (b) 4\(n\) rings.

Figure 3: Type I interaction of non-bonding MOs of radicals X and Y in triplet XY for (a) 4\(n\) + 2 rings and (b) 4\(n\) rings.

...
Figure 4: Type II interaction in (a) 4n ring triplets and (b) 4n+2 ring triplets.

been expanded to the first excited singlet state. Sung and coworkers recently used a pair of expanded porphyrins to confirm the rule [8]. Even though it is a discovery with big potential for organic synthesis and photochemistry it has not been utilized to its full potential, but that is now changing. Excited state (anti)aromaticicity is a growing field with applications in many areas of chemistry [9]. Benzene has even been called the molecular Dr. Jekyll and Mr. Hyde, as a stable molecule in the ground state, Dr. Jekyll, and as a reactive molecule in the excited states, Mr. Hyde. [10]

1.3 Cycloadditions

Cycloadditions are pericyclic reactions. Pericyclic reactions have transition states that include a cyclic arrangement of atoms, and together with that, a cyclic arrangement of interacting orbitals. Pericyclic reactions are also concerted, which means that they proceed in a single step without intermediates. Cycloadditions are reactions when two or more molecules react to create a ring system, mostly π-bonds are broken to create new σ-bonds. Cycloadditions are categorized by an [i+j+] nomenclature, where i, j and other letters represent how many electrons are partaking in the transformation from reactant to product from each starting material molecule. For example, one [2+2] cycloaddition is the reaction between two ethene molecules to create cyclobutane, two electrons from each ethene are participating. One [4+2] well-known cycloaddition is the reaction between 1,3-butadiene and ethene to create cyclohexene, the Diels-Alder reaction. For such cycloadditions, one can group the reactants into the electron-rich diene and the electron-poor dienophile. This is a basis for the Diels-Alder reaction, which is a [4+2] cycloaddition between a conjugated diene and a substituted alkene. The most simple Diels-Alder reaction
is the reaction shown below (Figure 5). The diene and dienophile can each have an electron-withdrawing group or electron-donating group. A reaction is the most favourable if the diene and the dienophile do not have the same kind of group, for example diene having an EDG and the dienophile an EWG. This allows them to match up better and be more stable, as the EDG “satisfies” the EWG with electrons. In a cycloaddition the LUMO of the dienophile and the HOMO of the diene mix to create new bonds and merge into a ring, and there is also a conservation of orbital symmetry. This means that the orbital symmetries of the starting material are the same as in the product. The conservation of orbital symmetry can pose a problem for certain reactions. For example if we take the [2+2] cycloadditions in figure 5, the ground state of two ethene molecules corresponds to the doubly excited state of cyclobutane. Because this is very unfavourable, such reactions are termed “forbidden”. But for the [4+2] reaction above we do not have the same problem and it does not form an excited state product. These reactions are termed “allowed”. It should be noted that “forbidden” reactions are not unable to occur, they are just unfavourable. A forbidden reaction can be made allowed by changing the geometry. Cycloadditions are called thermal if the reactants are in the ground state and photocycloadditions if at least one reactant is in an excited state [11].

1.4 Photocycloadditions of aromatic compounds

Due to photocycloaddition occurring in the excited state, it is a good opportunity to apply Baird’s rule by doing photocycloaddition with aromatic compounds. As aromatic compounds are very unreactive in the ground state, they barely undergo thermal cycloadditions as the aromaticity will be broken. However when they are in an excited state, lots of photocycloadditions occur [12]. Many reactions that are forbidden are allowed in the excited state, and many reactions allowed in the ground state are forbidden in the excited state. [2+2] Photocycloadditions are common while [4+2] are rare, common [2+2] photocycloadditions are when making cyclobutanes or four membered heterocycles. Benzene derivatives can react with alkenes in meta [3+2], ortho [2+2] and para [4+2] cycloadditions. The meta photocycloaddition is more well documented than the ortho and para, because those are more rare and usually do not have as high yields as meta reactions. But all these reactions can be used to create complicated products in a few steps. Some ortho and para
cycloadditions have yielded various cyclooctenes [13]. Alkynes react with benzene and benzene derivatives as well, in an ortho addition, to create COT derivatives, which have more uses than the cyclooctenes created from reactions with alkenes, for example in molecular electronics. Commercially, COT derivatives are mostly synthesized with from metal catalysis. For example unsubstituted COT is synthesized from acetylene with a nickel catalyst in several steps. Tetrasubstituted COT have also been synthesized with monosubstituted acetylenes, also with a nickel catalyst. These reactions have higher yields than the photocycloadditions, but need several steps and catalysts to work [14].

There have been many photoreactions leading to COT. For example photorearrangement of tricyclo[3.3.0.0^{2,6}]octa-3,7-diene with semibullvalene as a side product, decarboxylation of bicyclo[4.2.1]nona-2,4,7-trien-9-one, and photolysis of tetracyclo[4.2.0.0^{2,4}.0^{3,5}]-octane. [12] Aromatic rings with attached long alkyne chains have been seen to undergo intramolecular alkyne-arene photocycloaddition and create cyclopentane-annulated cyclooctatetraenes. A heterocyclic five-membered ring is made when there are oxygens in the chain containing the alkyne [15]. Having an EWG on the acetylene chain is good for making a COT from a benzene derivative. In 1961, Grovenstein and Rao performed a photoreaction between benzene and DMAD and they proposed the structure to be a dimethyl cyclooctatetraene-1,2-dicarboxylate due to its similar properties to cyclooctatetraene-carboxylate. This was done by irradiating a DMAD and benzene solution, with benzene in excess, for 47 hours with ultraviolet light. They proposed the mechanism to be as in Scheme 1 which means it is a [6+2] photocycloaddition. Even though it is similar to a [2+2] cycloaddition, because all the six $\pi$-electrons in the benzene ring participates in the reaction, it is classified as [6+2]. They reported a yield of 15% [16]. The product and mechanism was later confirmed and extended by Bryce-Smith and Lodge [17]. Grovenstein later did another reaction between molten naphtalene and benzene which gave a complicated mixture with a yield of 11%. But only 6% of the product was what we would expect by following the same reaction mechanism as for the benzene reaction, a dimethyl benzocyclooctene-7,8-dicarboxylate. The other products were other bicyclic and tricyclic molecules [18]. An alternative way to create a nonsubstituted COT is a simple photoaddition between acetylene and benzene, but it is made in

\[
\begin{align*}
\text{hv} & \quad \text{CO}_2\text{Me} \\
\text{CO}_2\text{Me} & \quad \text{CO}_2\text{Me} \\
\text{CO}_2\text{Me} & \quad \text{CO}_2\text{Me}
\end{align*}
\]

\text{Scheme 1: Reaction mechanism of the cycloaddition}
very small amounts with a quantum yield below 0.001. When they tried the reaction with benzene-d$_6$, a COT with six deuterium substituents was found, so the reaction is not a tetramerization of acetylene. This is another confirmation of the reaction mechanism of Grovenstein and Rao’s experiment [19]. What can be expanded is to use mono- or disubstituted benzene rings to create substituted COT. The benzene rings should have EDG to complement the electron-withdrawing carboxylate groups. The reactions should yield three isomers (substituents at place 3/8, 4/7 and 5/6) due to the symmetry of dimethyl cyclooctatetraene-1,2-dicarboxylate.

Scheme 2: Reaction scheme for the project

1.5 Aim

The aim of this project is to explore if the [6+2] photocycloaddition that Grovenstein and Rao reported [16] is possible for substituted benzene rings. We will explore the effects of various EWG and EDG and their effect on the reactivity, and how they favour or disfavour the mechanism. If a reaction occurs with a substituted benzene ring, the product shall be purified and analyzed.
2 Experimental methods and materials

2.1 Materials

2.1.1 Apparatus

A RPR-100 Rayonet Photochemical Chamber Reactor was used, equipped with low pressure Hg lamps emitting light at 254 nm. Three kinds of quartz tubes were used, 1 mL, 15 mL and 70 mL. The 1 mL quartz tube and the 15 mL tube were used for the preliminary small-scale experiments and the 70 mL tube for large-scale experiments.

2.1.2 Chemicals

All the chemicals used in the reaction were analytical grade (>98%). The chemicals were supplied by Sigma Aldrich. Solvents were either purchased as anhydrous or had been dried according to standard procedure. The drying process involved utilization of fresh and oven-dried 4 Å molecular sieves which was dried overnight.

2.1.3 Analysis

Analysis was made with TLC, NMR, GC-MS and UV-Visible spectroscopy. TLC was used to check for products or for monitoring reactions. Solvents used for TLC were n-pentane, diethyl ether and ethyl acetate. The TLC plates had silicone oxide as adsorbant. $^1$H NMR spectroscopy (400 MHz) was used after the reaction finished to check if a reaction succeeded and also for the pure product. $^{13}$C NMR (100 MHz) was used for the pure product. The NMR apparatus was a JEOL Eclipse operating at 400 MHz. CDCl$_3$ was used as a solvent for all NMR samples, except for reaction 10 where C$_6$D$_6$ was used. Column chromatography was used for separating compounds when needed. GC-MS was used to check for the number and identities of isomers. GC-MS were performed using an Agilent 5975C inert MSD system equipped with a Triple-Axis Detector. Samples were introduced using split-injection (2μL injection volume; Split Ratio: 100:1; 250 °C inlet temperature; Flow Rate: 120 mL/min). The starting temperature of the column oven was 70 °C (0.5 min equilibration time) and the ending temperature was 320 °C. The temperature rate was set to 20 °C/min resulting in a 12.5 min total run time. Helium was used as a carrier gas at a flow rate of 1.2 mL/min. The column used was an Agilent 19091S-433: 325 °C: 30 m x 250 μm x 0.25 μm (front SS-inlet: He; out: vacuum). Mass spectrometer: Source temperature: 250 °C, Quad-temperature 150 °C. The UV-Visible spectroscopy was used to record electronic absorption spectra of the reactants between 200-800 nm, the UV-Visible spectroscopy apparatus was a
a Varian Cary 50 UV-vis spectrometer.

2.1.4 Software
The NMR-spectra were processed with Delta and analyzed with MestReNova 9.0.1. Molecular formulas were drawn in ChemDraw std 11.0.

2.2 Methods
2.2.1 Procedure
The experiments were split into two parts, a preliminary to see if a reaction occurred with a certain aromatic compound, and if the reaction worked then a large-scale experiment was conducted to allow purification of the products. In a pre-dried apparatus, an inert atmosphere (argon) was made inside the tube. This was made, by under vacuum, heating the tube for 2 minutes, then letting it cool to room temperature and afterwards saturating the tube with argon. The chemicals were added to the tube, first the aromatic compound and then the DMAD was added dropwise. The tube was shaken a bit and then left under argon for ca. 20 minutes. The equivalents of the chemicals are 1:75 between DMAD and the aromatic compound. Afterwards the mixture was degassed by bubbling with argon gas to remove dissolved oxygen. It was then placed in the Rayonet photoreactor for a certain amount of time (24 or 48 hours). The lamps had a wavelength of 254 nm. After the solution of reaction mixture was irradiated, the reaction mixture was first checked with TLC, then the leftover aromatic compound and solvent was evaporated with a rotary evaporator or by distillation. The crude product was then analyzed by NMR to see if the reaction had succeeded.

If there was only one product, the crude product was purified with recrystallization. If there was more than one product, the mixture was purified by column chromatography. Finally, the pure product was analyzed by both $^1$H and $^{13}$C NMR.

![Figure 6: Substituted benzenes used in the project: Toluene (1), aniline (2), p-xylene (3), anisole (4), fluorobenzene (5), trifluoromethylbenzene (6), triethylsilylbenzene (7), o-xylene (8), and benzonitrile (9).]
3 Results

The $^1$H NMR peaks for COT are found in the alkene region between 5-8 ppm, and were used as our main tool for deducing if a reaction had created our cycloadduct.

3.1 Successful reactions

Reaction classifications
A: Small scale experiment (Benzene and toluene).
B: Large scale experiment (Benzene and toluene).
C: Test reaction for a 1:5 ratio of reagents

1. Benzene A: Small-scale preparative experiment. A solution of benzene (6 mL, 67.5 mmol, 75 eq) and DMAD (0.11 mL, 0.90 mmol, 1 eq) was made. The solution was split into three tubes, two medium sized tubes (X and Y) and a small quartz tube (Z). Tube X was irradiated for 24 hours, Y was irradiated for 48 hours, Z was placed in an external lamp and irradiated for 24 hours. All had turned into yellowish-brown liquids after being irradiated. Tubes X and Z were combined and TLC analysis (70/30 pentane/diethylether) showed a spot that was different from the starting materials. An $^1$H NMR spectrum was recorded and it showed peaks of a cycloadduct. The spectrum can be seen in the appendix in Figure 11. Tube Y had a similar TLC to tube X+Z and had a similar $^1$H NMR spectrum recorded that was similar to the spectra of X+Z.

Tube X: 24 hour irradiation time
Tube Y: 48 hour irradiation time
Tube Z: 24 hour irradiation in an external lamp

2. Benzene B: Large-scale reaction. A solution of benzene (30 mL, 337.5 mmol, 75 eq) and DMAD (0.55 mL, 4.5 mmol, 1 eq) was degassed by bubbling with argon for 20 minutes. It was irradiated for 48 hours, with a TLC analysis (70/30 pentane/diethylether) being made after 24 hours that showed similar results to experiment 1. After 48 hours the solution turned into a yellowish-brown liquid, after evaporating unreacted benzene it had turned into a yellowish-brown mixture of crystals and liquid. The crude isolated yield of this crystal mixture was 68%. The crystals were recrystallized from methanol. After the recrystallization, the isolated yield was 12%. Both $^1$H and $^{13}$C NMR were recorded on these crystals. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.19 (d, J = 5.6 Hz 2H, COT), 6.06 (d, J = 4.0 Hz, 1H, COT), 6.03 (d, J = 2.4 Hz, 1H, COT), 5.95 (s, 1H, COT), 5.92 (s, 1H, COT), 3.73 (s, 6H, OMe). $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 165.88 (Carbonyl), 143.0 (COT), 132.6 (COT), 131.9 (COT), 130.0 (COT), 52.0 (Ester carbon). The spectra can be seen...
3. **Toluene A**: Small-scale preparative experiment. A solution of toluene (7 mL, 67.5 mmol, 75 eq) and DMAD (0.11 mL, 0.90 mmol, 1 eq) was degassed by bubbling with argon for 20 minutes. It was irradiated for 24 hours, after evaporating unreacted toluene it turned more brown and viscous. A TLC analysis (70/30 pentane/diethylether) showed a spot that was different from the starting materials. An $^1$H NMR spectrum was recorded. $^1$H NMR showed results of a cycloadduct compound and different isomers. The spectrum can be seen in the appendix in Figure 14.

5. **Toluene B**: Large scale reaction. A solution of toluene (35 mL, 337.5 mmol, 75 eq) and DMAD (0.55 mL, 4.5 mmol, 1 eq) was degassed by bubbling with argon for 20 minutes. It was irradiated for 48 hours and after the reaction it had an orange-brown colour. The unreacted toluene was evaporated and a TLC analysis (70/30 pentane/diethylether) was made, the spots looked similar to the small-scale experiment. The crude product was purified with column chromatography using SiO$_2$ and a 70/30 pentane/diethyleter mixture as eluent. According to TLC analysis, fractions 4-9 contained product and were put in a flask and evaporated. After this it had a weight of 0.3781 gram (36% isolated yield); isomer ratio 2:4:3:8:2 by GC yields. $^1$H and $^{13}$C NMR spectra were recorded on the product. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.74, 7.73, 7.71, 7.55, 7.54, 7.53, 7.38, 7.35, 7.30, 7.29, 7.19, 7.18, 7.17, 7.14, 6.88, 6.61, 6.57, 6.15, 6.14, 6.08, 6.07, 6.04, 6.00, 5.99, 5.97, 5.96, 5.88, 5.85, 5.79, 5.79, 5.78, 5.78, 5.66, 3.91, 3.83, 3.73, 3.72, 3.71, 3.66, 3.64, 2.16 (s, Methyl), 1.87 (s, Methyl), 1.81 (s, Methyl).

$^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ Carbonyl (171.5, 171.0, 168.0, 167.7, 166.1, 166.0, 165.9), COT (145.6, 143.8, 142.7, 142.0, 141.4, 140.8, 139.4, 138.6, 136.2, 135.7, 135.3, 134.8, 133.3, 132.4, 131.9, 131.6, 131.0, 130.8, 130.1, 129.9, 128.9, 128.8, 128.5, 128.4, 128.2, 128.0, 127.9, 127.2, 126.2, 125.8, 124.9), Ester carbon (52.5, 52.2, 52.0, 51.9, 51.6), Methyl (23.6, 22.5, 20.9). The spectra can be seen in Figures 16 and 17. GC-MS were also recorded on the product after separation. GC retention time (min)/(m/z)([M$^+$]): 6.876/234; 7.002/234; 7.180/234; 7.237/234; 7.391/234. The spectra and chromatograms can be seen in Figures 34-40.

7. **p-Xylene**: A solution of p-xylene (8.2 mL, 67.5 mmol, 75 eq) and DMAD (0.11 mL, 0.90 mmol, 1 eq) was degassed by bubbling with argon for 20 minutes. It was irradiated for 24 hours and had unreacted p-xylene evaporated. An $^1$H NMR spectrum was recorded. The $^1$H NMR spectrum showed traces of products resembling the cycloadduct. The spectrum can be seen in the appendix in Figure 20.
9. Trifluoromethylbenzene: A solution of trifluoromethylbenzene (6.5 mL, 52.5 mmol, 50 eq) and DMAD (0.13 mL, 1.05 mmol, 1 eq) in 5 mL n-heptane was degassed by bubbling with argon for 20 minutes. After 24 hours in the photoreactor the reaction mixture was yellow. Unreacted solvent was evaporated. A TLC analysis with 50/50 pentane/ethyl acetate was made, it showed spots different from the starting materials. $^1$H NMR was recorded on the crude product. The spectrum can be seen in the appendix in Figure 22. It showed peaks that resembles the cycloadduct. The crude product was purified with column chromatography using SiO$_2$ and a 50/50 pentane/ethyl acetate mixture as eluent. Fractions 3-5 contained product according to TLC analysis. Fractions 3-5 had the eluent evaporated. The weight of the compound after this was 0.1179 gram (yield 51%); ratio of isomers 1:2 by GC yields. GC-MS was run on the product. GC Retention time (min)/$\text{m/z}$(\([\text{M}^+])$: 6.241/288; 6.281/288. The spectra and chromatogram can be seen in Figures 41-43. $^1$H and $^{13}$C NMR was recorded. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.86, 6.61, 6.52, 6.34, 6.33, 6.31, 6.30, 6.25, 6.00, 5.97, 3.81, 3.79, 3.75, 3.67. $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ Carbonyl (171.1, 165.2), COT (141.9, 141.6, 139.2, 134.5, 133.3, 129.9, 129.7, 126.4), Ester carbon (52.3, 52.3, 52.1, 51.7). The spectra can be seen in Figures 23 and 24.

11. Fluorobenzene: A solution of fluorobenzene (5.0 mL, 52.5 mmol, 50 eq) and DMAD (0.13 mL, 1.05 mmol, 1 eq) in 5 mL n-heptane was degassed by bubbling with argon for 20 minutes. After being irradiated 24 hours, the reaction mixture was yellow. Unreacted solvent was evaporated. An $^1$H NMR was recorded on the crude product. The spectrum can be seen in the appendix in Figure 27. It showed peaks that resembles the cycloadduct. The crude product was purified with column chromatography using SiO$_2$ and a 70/30 pentane/ethyl acetate mixture as eluent. Fraction 1, fractions 2-3 and fractions 4-9 showed a product according to TLC. GC-MS was recorded on the crude product and all the fractions. For the crude product: GC Retention time (min)/$\text{m/z}$(\([\text{M}^+])$: 6.333/238; 6.550/238; 6.659/238; 6.933/238. For the purified product: GC Retention time (min)/(m/z)(\([\text{M}^+])$: 6.556/238; 6.659/238; 6.934/238. The spectra and chromatograms can be seen in Figures 46-56. The fractions had the eluent evaporated. After this it weighed 0.0948 gram (yield 38%); ratio of isomers 1:2:1. $^1$H and $^{13}$C NMR was recorded on fraction 1. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.23, 7.22, 7.21, 7.09, 7.08, 7.06, 6.96, 6.85, 6.29, 6.28, 6.27, 6.26, 6.25, 6.07, 6.06, 6.04, 6.03, 5.96, 5.96, 5.94, 5.93, 5.84, 5.81, 5.79, 5.78, 5.75, 5.74, 3.83, 3.80, 3.78, 3.75, 3.73, 3.72, 3.72, 3.63, 3.61. $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ Carbonyl (165.5, 158.1, 155.6, 154.0, 152.1), COT (141.8, 140.9, 140.0, 139.9, 136.7, 134.5, 134.4, 133.9, 133.3, 133.3, 133.0, 131.5, 131.0, 129.7, 129.4, 128.8, 125.9, 125.6, 124.9, 124.6, 120.1, 115.2, 111.1, 110.9, 108.6,
Ester carbon (53.4, 52.4, 52.2, 52.2, 52.1, 52.1, 51.9). The spectra can be seen in the appendix in Figures 28 and 31. Only $^1$H NMR was recorded on the other fractions. The spectra can be seen in the appendix in Figures 29 and 30. Polymers stuck on the sides of the quartz tube and precipitated in acetone. They were isolated and dried. These polymers can be seen in Figure 7.

![Image](image_url)

**Figure 7:** The polymers from reaction 9 with fluorobenzene

14. **o-Xylene:** A solution of o-xylene (6.4 mL, 52.5 mmol, 50 eq) and DMAD (0.13 mL, 1.05 mmol, 1 eq) in 5 mL $n$-heptane was degassed by bubbling with argon for 20 minutes. After being irradiated for 24 hours the colour of the solution was yellow. A TLC analysis (70/30 pentane/diethylether) showed small traces of a product. A $^1$H NMR spectrum was recorded. The $^1$H NMR showed small traces of products resembling the cycloadduct. The spectrum can be seen in the appendix in Figure 33.

### 3.2 Attempted reactions

4. **Aniline:** A solution of aniline (6.2 mL, 67.5 mmol, 75 eq) and DMAD (0.11 mL, 0.90 mmol, 1 eq) was degassed by bubbling with argon for 20 minutes. After being irradiated for 24 hours it was dark brown. Distillation was used to evaporate unreacted aniline. NMR showed no peaks of a product resembling the cycloadduct, starting material was recovered. See Figure 15 in appendix for the $^1$H NMR spectrum.

6. **Benzene C:** A solution of benzene (0.47 ml, 5.28 mmol, 5 eq) and DMAD (0.13 ml, 1.05 mmol, 1 eq) in 10 mL $n$-heptane was degassed by bubbling with ar-
argon for 20 minutes. After 24 hours of irradiation a precipitate had formed at the bottom, but $^1$H NMR showed no peaks of the cycloadduct. The $^1$H NMR spectra can be seen in the appendix in Figure 18. For the rest of the reaction mixture, the heptane was evaporated and an $^1$H NMR sample was made of what was left. It did not show any product, starting material was recovered. The $^1$H NMR spectrum can be seen in the appendix in Figure 19.

8. Anisole: A solution of anisole (5.7 mL, 52.5 mmol, 50 eq) and DMAD (0.13 mL, 1.05 mmol, 1 eq) in 5 mL $n$-heptane was degassed by bubbling with argon for 20 minutes. After 24 hours of irradiation the solution was dark brown. The unreacted anisole was evaporated. An $^1$H NMR spectrum was recorded but it showed no peaks resembling the cycloadduct. The $^1$H NMR spectrum can be seen in the appendix in Figure 21.

10. Triethylsilylbenzene[20]: Small scale experiment. A solution of triethylsilylbenzene (0.13 g, 0.67 mmol, 10 eq) and of DMAD (9 μL, 0.07 mmol, 1 eq) in 1 mL $n$-heptane was degassed, but that caused a spill and $\frac{2}{3}$ of the solution was lost. It was irradiated for 24 hours. $^1$H NMR and GC-MS showed no trace of a cycloadduct. $^1$H NMR spectra can be seen in the appendix in Figures 25 and 26. Gas chromatograms can be seen in Figures 44 and 45.

12. Benzonitrile: A solution of benzonitrile (5.4 mL, 52.5 mmol, 50 eq) and DMAD (0.13 mL, 1.05 mmol, 1 eq) in 5 mL $n$-heptane was degassed by bubbling with argon for 20 minutes. After 24 hours of irradiation the colour was dark red-brown. TLC analysis (70/30 pentane/diethylether) was identical to the starting materials, no significant reaction seems to have occurred.

13. 3-Hexyne: A solution of benzene (90 μL, 1 mmol, 1 eq) and 3-hexyne (5.7 mL, 50 mmol, 50 eq) was degassed by bubbling with argon for 20 minutes. After 24 hours of irradiation, the reaction mixture had a yellow colour. Excess solvent was evaporated and an $^1$H NMR was recorded. The $^1$H NMR spectrum can be seen in the appendix in Figure 32. $^1$H NMR showed no peaks resembling a cycloadduct. The GC-MS showed that the reaction had caused dimerization of 3-hexyne, due to the molar mass of 3-hexyne being 82 g/mol. GC Retention time (min)/(m/z)([M$^+$]): 3.523/162; 3.552/162; 3.575/162; 3.615/162. The chromatogram and spectra can be seen in Figures 57-61.
3.3 UV-Vis absorption spectroscopy

A series of 5.1 mmol solutions of benzene, toluene, trifluoromethylbenzene, fluorobenzene, 3-hexyne and DMAD in \( n \)-heptane were measured by UV-Vis spectroscopy. This was performed to see if DMAD’s absorption at 254 nm was significant compared to the other compounds. The spectrum can be seen in Figure 62. Since the aromatic compound was in 50 or 75 times excess, a spectrum was calculated to compare a 50:1 benzene:DMAD solution. The spectrum can be seen in Figure 63.
4 Discussions and Conclusion

<table>
<thead>
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<th>Reagent</th>
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<tr>
<td>Benzene</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>o-xylene</td>
<td>Trace amounts</td>
</tr>
</tbody>
</table>

Table 1: Summarization of the results

The yields and the crystal characteristics of reaction 2 were similar to those that Grovenstein and Rao reported. The NMR spectrum was also good as there only was one product, so the peaks could be classified. We have obtained products from reactions 5, 9 and 11. Due to the products being isomers, they were hard to separate and we got mixtures as results. Because of this the NMR spectra are messy, but we can see COT peaks. Together with GC-MS we can see that we have five products for reaction 5, two for reaction 9 and three for reaction 11. We are sure of this due to all of their molecular ions having the weight of the respective compounds. For reaction 5, the separation was less effective and we got more products, those could be a4 and a5 as they are intermediate steps in the reaction, they were in lower quantity than the COT products. The major product is a3 as this positioning farthest away from the ester groups gives less steric interaction and a more stable product. The same can be said for the other reactions, with b2 and c3 being the major product. In reaction 11, we got three products each with the molecular weight of the associated cycloadducts, so we believe these substituted COT are what we have obtained. For reaction 9, we only got two GC peaks with the correct molecular weight, this can be due to the trifluoromethyl group being too sterically congestive for it to place itself at the position closest to the ester groups. For reactions 5, 9 and 11, the calculated isolated yields are higher than reaction 2, but there were solvents left when the compounds were weighed. This is especially true for reaction 9 where there is a large pentane peak in the NMR. To get a more correct yield, the products need
better purification. The products can be seen in Figures 8, 9 and 10.

Figure 8: Products from reaction 5 with Toluene

Figure 9: Products from reaction 9 with Trifluoromethylbenzene

For this reaction to occur, it was crucial for the substituents to be compatible with the mechanism. That was why reactions 4, 8, and 12 did not work, as amino and nitrile groups are π-EWG. The methoxy group is π-EDG. Being π-withdrawing or -donating creates resonance structures that disturbs the antiaromaticity by polarizing the molecule. By polarizing the molecule we will no longer have a conjugated π-system and it will no longer be antiaromatic in the excited state, an escape π-way will be made. This makes the reaction much less favourable. The xylenes had only traces of our cycloadduct, this could be do due to the steric hindrance that the extra methyl group causes, especially for p-xylene. Longer reaction times could be used to see if these reactions work, but just at a slower rate. Reaction 6 might not have worked because the reactants were too diluted. For reaction 13, dimerization of 3-hexyne seems to be more favourable than the reaction to create 1,2-diethylcyclooctatetraene, this might be due to the lack of EWG and EDG interactions between 3-hexyne and benzene. Toluene, trifluoromethylbenzene and
fluorobenzene worked as the substituents are \(\sigma\)-electron donating or -withdrawing and do not disturb the antiaromaticity of the benzene ring.

What can be done to continue this project is to try with longer reaction times for ortho- and para-xylene, and also try a reaction with meta-xylene. By trying with larger scale reactions for toluene, fluorobenzene and trifluoromethylbenzene, we can get more product and separate them more efficiently with high performance liquid chromatography. This would also allow to do better classifications of these compounds as they are completely new, what we have now is not good enough proof for the existence of these molecules. We can also try more substituted benzene rings with \(\sigma\)-electron donating or -withdrawing groups. The project can also be expanded to use other alkynes, for example methylacetylene carboxylate. Six-membered heterocycles can also be used to try to create eight-membered heterocycles, five-membered rings can also be used as reactants to create seven-membered rings.

The conclusions that can be drawn from this project is that these reactions show us a new way to create substituted COTs. It is important for the substituent to be \(\sigma\)-donating or -withdrawing to not disturb the antiaromaticity. Being EDG and EWG does not seem to matter as long as \(\pi\)-electrons are not donated or withdrawn. Longer reaction times than 24 hours might be necessary to obtain a significant amount of product.
A Spectra and chromatograms

A.1 NMR

In this section, NMR spectra are shown.

Figure 11: $^1$H NMR spectrum of reaction 1. Benzene A (CDCl$_3$, 400 MHz)
Figure 12: $^1$H NMR spectrum of reaction 2. Benzene B (CDCl$_3$, 400 MHz)

Figure 13: $^{13}$C NMR spectrum of reaction 2. Benzene B (CDCl$_3$, 101 MHz)
Figure 14: $^1$H NMR spectrum of reaction 3. Toluene A (CDCl₃, 400 MHz)

Figure 15: $^1$H NMR spectrum after reaction 4. Aniline (CDCl₃, 400 MHz)
**Figure 16:** $^1$H NMR spectrum of reaction 5. Toluene B (CDCl$_3$, 400 MHz)

**Figure 17:** $^{13}$C NMR spectrum of reaction 5. Toluene B (CDCl$_3$, 101 MHz)
Figure 18: $^1$H NMR spectrum of the precipitate dissolved in benzene from reaction 6. Benzene C (CDCl$_3$, 400 MHz)

Figure 19: $^1$H NMR spectrum of the solution of 6. Benzene C (CDCl$_3$, 400 MHz)
Figure 20: $^1$H NMR spectrum of reaction 7. Para-Xylene (CDCl$_3$, 400 MHz)

Figure 21: $^1$H NMR spectrum after reaction 8. Anisole (CDCl$_3$, 400 MHz)
Figure 22: $^1$H NMR spectrum of the crude product from reaction 9. Trifluoromethylbenzene (CDCl$_3$, 400 MHz)

Figure 23: $^1$H NMR spectrum of the purified product from reaction 9. Trifluoromethylbenzene (CDCl$_3$, 400 MHz)
Figure 24: $^{13}$C NMR spectrum of the purified product from reaction 9. Trifluoromethylbenzene (CDCl$_3$, 101 MHz)

Figure 25: $^1$H NMR spectrum of starting material of 10. Triethylsilanebenzene (C$_6$D$_6$, 400 MHz)
Figure 26: $^1$H NMR spectrum after reaction 10. Triethylsilanebenzene ($C_6D_6$, 400 MHz)

Figure 27: $^1$H NMR spectrum of crude product from reaction 11. Fluorobenzene ($CDCl_3$, 400 MHz)
Figure 28: $^1$H NMR spectrum of fraction 1 from reaction 11. Fluorobenzene (CDCl$_3$, 400 MHz)

Figure 29: $^1$H NMR spectrum of fraction 2-3 from reaction 11. Fluorobenzene (CDCl$_3$, 400 MHz)
Figure 30: $^1$H NMR spectrum of fraction 4-9 from reaction 11. Fluorobenzene (CDCl$_3$, 400 MHz)

Figure 31: $^{13}$H NMR spectrum of fraction 1 from reaction 11. Fluorobenzene (CDCl$_3$, 101 MHz)
Figure 32: $^1$H NMR spectrum after reaction 13. 3-Hexyne (CDCl$_3$, 400 MHz)

Figure 33: $^1$H NMR spectrum after reaction 14. o-xylene (CDCl$_3$, 400 MHz)
A.2 GC-MS

In this section, Gas chromatograms and mass spectra are shown.

Figure 34: Gas chromatogram of purified product from 5. Toluene B
**Figure 35:** Gas chromatogram of purified product from 5. Toluene B zoomed in on relevant peaks

**Figure 36:** Mass spectrum of product from 5. Toluene B at 6.876 min.
Figure 37: Mass spectrum of product from 5. Toluene B at 7.002 min.

Figure 38: Mass spectrum of product from 5. Toluene B at 7.180 min.
Figure 39: Mass spectrum of product from 5. Toluene B at 7.237 min.

Figure 40: Mass spectrum of product from 5. Toluene B at 7.391 min.
Figure 41: Gas chromatogram of purified product from 9. Trifluoromethylbenzene

Figure 42: Mass spectrum of purified product from 9. Trifluoromethylbenzene at 6.241 min.
Figure 43: Mass spectrum of purified product from 9. Trifluoromethylbenzene at 6.281 min.

Figure 44: Gas chromatogram of starting materials of 10. Triethylsilylbenzene.
Figure 45: Gas chromatogram of 10. Triethylsilylbenzene after 24 hours.

Figure 46: Gas chromatogram of crude product from 11. Fluorobenzene
Figure 47: Mass spectrum of crude product from 11. Fluorobenzene at 6.333 min

Figure 48: Mass spectrum of crude product from 11. Fluorobenzene at 6.550 min
Figure 49: Mass spectrum of crude product from 11. Fluorobenzene at 6.659 min

Figure 50: Mass spectrum of crude product from 11. Fluorobenzene at 6.933 min
Figure 51: Gas chromatogram of purified product from 11. Fluorobenzene.

Figure 52: MS spectrum of purified product from 11. Fluorobenzene at 6.556 min
Figure 53: Mass spectrum of purified product from 11. Fluorobenzene at 6.659 min

Figure 54: Mass spectrum of purified product from 11. Fluorobenzene at 6.934 min
Figure 55: Gas chromatogram of fraction 2 from 11. Fluorobenzene

Figure 56: Gas chromatogram of fraction 3 from 11. Fluorobenzene
Figure 57: Gas chromatogram of product from 3-Hexyne

Figure 58: Mass spectrum of product from 13. 3-Hexyne at 3.523 min
Figure 59: Mass spectrum of product from 13. 3-Hexyne at 3.552 min.

Figure 60: Mass spectrum of product from 13. 3-Hexyne at 3.575 min.
Figure 61: Mass spectrum of product from 13. 3-Hexyne at 3.615 min.

A.3 UV-Vis

In this section, UV-Vis spectra are shown.
Figure 62: Spectra comparing absorption of compounds

Figure 63: Spectra comparing absorption of a 50:1 Benzene:DMAD solution
References

References


[20] Raffaello Papadakis; Hu Li; Joakim Bergman; Anna Lundstedt; Kjell Jorner; Rabia Ayub; Soumyayjoti Haldar; Burkhard O. Jahn; Aleksandra Denisova; Roland Lindh; Biplab Sanyal; Helena Grennberg; Klaus Leifer; Henrik Ottosson. “Excited-State Antiaromaticity of the Benzene Ring Enabling Metal-Free Photochemical Silylations and Transfer Hydrogenation”. Submitted. 2016.