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Wavelength-Dependent Selectivity in [4 + 4]-Cycloaddition Reactions

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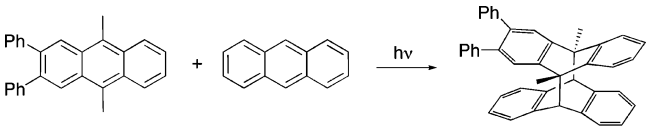

Selective excitation of a variety of anthracene derivatives in the presence of anthracene led to the formation of only the cross-cyclomer products, while irradiating these mixtures at wavelengths where anthracene also absorbs led to both dianthracene and the mixed cyclomers being formed. This method was shown to be general, so long as the chromophore was inert toward forming its homodimer and could be irradiated at wavelengths at which anthracene does not absorb.

The concept of complementarity is one of the cornerstones of modern organic chemistry, with reactions between acids and bases, donors and acceptors, dienes and dienophiles, or nucleophiles and electrophiles facilitating the efficient construction of a myriad of complex structures. Unfortunately, examples of complementary pairs of molecules are notably lacking in the context of [4 + 4]-photocycloaddition reactions. Thus, irradiating two anthracene derivatives, **X** and **Y**, generally yields both the **di-X** and **di-Y** photodimers in addition to the cross-cyclomer **XY**.[1] For this reason, while these bimolecular photochromic reactions provide unique opportunities for the construction of dynamic materials, their use has largely been restricted to the creation of relatively simple structures created via the homodimerization of identical chromophores.[2]

We therefore decided to explore the possibility of increasing the selectivity of anthracene photocycloaddition reactions by exciting only one component in a binary mixture of two chromophores, **X** and **Y**.[3] Because the dimer **di-Y** can only form from the excited state **Y***, this photoproduct should not be observed when the solution is irradiated at wavelengths where only **X** absorbs. We posited that the cross cyclomer **XY** could be obtained as the exclusive product if we could identify an anthracene derivative **X** that (i) could be selectively excited in the presence of **Y** and (ii) was limited by steric constraints from forming its homodimer **di-X**, yet was still able to form **XY**.

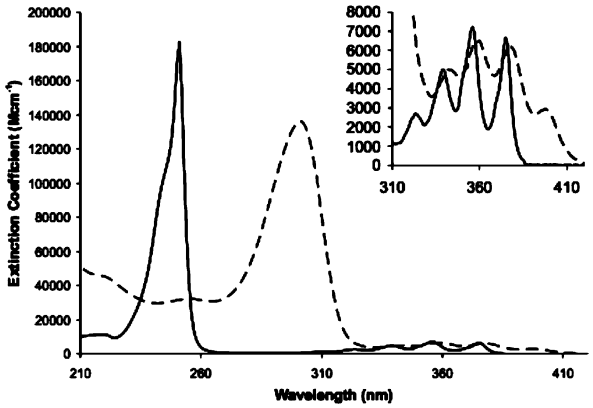

FIGURE 1. UV−vis absorption spectra of anthracene (solid line) and **TPA** (dashed line) in acetonitile at 25 °C. Inset: enlarged view of these spectra in the range 310−420 nm.

It has previously been reported that 2,3,6,7-tetraphenylanthracene (**TPA**) is not converted into its homodimer (**di-TPA**) even after prolonged irradiation in a Rayonet with 300 nm light, yet does form cross-cyclomers with derivatives that lack bulky substituents on the outer rings of the anthracene.[3a] As such, this molecule satisfies our second criteria for selectivity. The UV−vis absorption spectrum of this compound is shown in Figure 1, along with that of anthracene (**A**). **TPA** exhibits characteristic anthracene-like absorption bands between 325 and 400 nm; these are red-shifted by approximately 25 nm relative to those of anthracene (Figure 1, inset). This compound also possesses a strong absorption band at shorter wavelengths ($\lambda_{max} = 301$ nm) where the absorption of anthracene is negligible. The presence of two ranges of wavelengths at which **TPA** absorbs while anthracene does not, coupled with the reluctance of **TPA** to form homodimers, suggested that **TPA** and anthracene could constitute a complementary pair under conditions where **TPA** is selectively excited.

Our initial photochemical experiments on these compounds were carried out in a Rayonet using either 300 or 350 nm lamps. When a 1:1 mixture of **TPA** and **A** was irradiated with light centered at 300 nm, two photoproducts were formed in an approximately 1:9 ratio. These products were identified as dianthracene (**di-A**) and the cross-cyclomer **TPA-A**, respectively.

When the **TPA**/anthracene mixture was irradiated with 350 nm light, both dianthracene and **TPA-A** were again formed,

(1) (a) Bouas-Laurent, H.; Castellan, A.; Desvergne, J. P.; Lapouyade, R. *Chem. Soc. Rev.* **2001**, *30*, 43 and references therein. (b) Bouas-Laurent, H.; Castellan, A.; Desvergne, J. P.; Lapouyade, R. *Chem. Soc. Rev.* **2000**, *29*, 43−55.

(2) (a) Ihara, T.; Fujii, T.; Mukae, M.; Kitamura, Y.; Jyo, A. *J. Am. Chem. Soc.* **2004**, *126*, 8880. (b) de Schryver, F. C.; Anand, L.; Smets, G.; Switten, J. *Polym. Lett.* **1971**, *9*, 777. (c) Jones, J. R.; Liotta, C. L.; Collard, D. M.; Schiraldi, D. A. *Macromolecules* **2000**, *33*, 1640. (d) Mitsuishi, M.; Tanuma, T.; Matsui, J.; Chen, J.; Miyashita, T. *Langmuir* **2001**, *17*, 7449. (e) McSkimming, G.; Tucker, J. H. R.; Bouas-Laurent, H.; Desvergne, J. P.; Coles, S. J.; Hursthouse, M. B.; Light, M. E. *Chem.−Eur. J.* **2002**, *8*, 3331. (f) Nakatsuji, S.; Ojima, T.; Akutsu, H.; Yamada, J. *J. Org. Chem.* **2002**, *67*, 916. (g) Ojima, T.; Akutsu, H.; Yamada, J.; Nakatsuji, S. *Polyhedron* **2001**, *20*, 1335. (h) Takaguchi, Y.; Tajima, T.; Yanagimoto, Y.; Tsuboi, S.; Ohta, K.; Motoyoshiya, J.; Aoyama, H. *Org. Lett.* **2003**, *5*, 10, 1677. (i) Molard, Y.; Bassani, D. M.; Desvergne, J. P.; Horton, P. H.; Hursthouse, M. B.; Tucker, J. H. R. *Angew. Chem., Int. Ed.* **2005**, *44*, 1072.

(3) For other examples of approaches to improving the selectivity of these reactions, see: (a) Bailey, D.; Williams, V. E. *Chem. Commun.* **2005**, 2569. (b) Bouas-Laurent, H.; Lapouyade, R. *Chem. Commun.* **1969**, 817. (c) Lapouyade, R.; Castellan, A.; Bouas-Laurent, H. *C. R. Acad. Sc. Paris* **1969**, *268*, 217.

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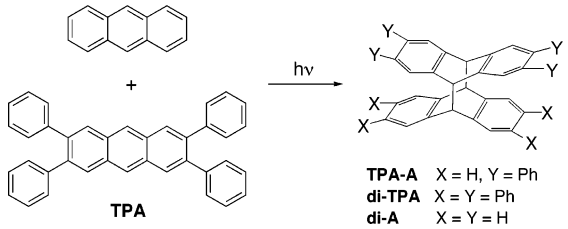
SCHEME 1



but in a 1:3 ratio rather than the 1:9 ratio observed at 300 nm. After long irradiation periods (>140 min) at this wavelength, trace quantities (~3%) of a third photoproduct also started to appear. This minor product was identified as **di-TPA**, the homodimer of **TPA**, a compound that had not previously been observed. The formation of this dimer is quite slow; irradiation of a benzene solution of **TPA** at 350 nm for 2 h led to only 25% of the starting material being converted into this product. Under the same conditions, anthracene was quantitatively converted to dianthracene in under 2 h. It is unclear at this time why this product is not observed when 300 nm light is employed, although photofragmentation of the dimer at shorter wavelengths may be a contributing factor.

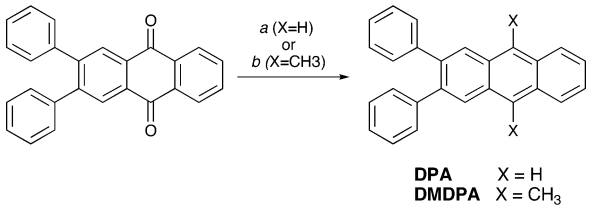
The greater selectivity for the cyclomer **TPA-A** over **di-A** when light centered at 300 nm was employed is likely due to the preferential excitation of **TPA** at these wavelengths. However, because the light sources employed in these initial experiments deliver light over a relatively broad spectral range, it is difficult to exclusively excite only one chromophore of a binary mixture. To explore the effects of selective excitation, we decided to repeat the experiments described above using a fluorimeter as the light source, hence enabling irradiation over a much narrower range of wavelengths.[4] Three solutions of 10 mM **TPA** and 10 mM anthracene in 1 mL of $CDCl_3$ were prepared; these solutions were irradiated at 301, 376, or 399 nm. The sample irradiated at 301 nm exhibited slow formation of a single photoproduct, which was identified as the cross-cyclomer **TPA-A** by ^{1}H NMR. Similar results were observed with the sample irradiated at 399 nm; again, no **di-A** formation was observed. This is consistent with our expectations, since at these wavelengths only **TPA** should be excited. In contrast, irradiation of the third mixture with 376 nm light, a wavelength where both chromophores absorb, causes the formation of both **di-A** and **TPA-A** in approximately a 1:4 ratio. Trace amounts of **di-TPA** were detected in the samples excited at 376 and 399 nm, while no homodimer was formed when the sample was irradiated at 301 nm (Scheme 1).

These results suggest that the phenyl groups attached to the anthracene core provide enough of a perturbation to the absorption spectrum to allow for selective excitation. We were interested in determining whether the same strategy could be carried out using analogues that contained fewer pendant phenyl substituents. Two such derivatives, 2,3-diphenylanthracene (**DPA**) and 9,10-dimethyl-2,3-diphenylanthracene (**DMDPA**) were therefore prepared from 2,3-diphenyl-9,10-anthraquinone (Scheme 2).[5]

(4) It should be noted that while the use of a fluorimeter necessarily limited the scale of the reactions studied herein, it offered the advantage of allowing us to easily change the wavelength of excitation. In principle, selective irradiation can be accomplished at larger scales using higher intensity light sources (e.g., Rayonets or immersion well systems) fitted with appropriate cutoff filters.

(5) Bailey, D.; Williams, V. E. *Tetrahedron Lett.* **2004**, *45*, 2511−2513.

SCHEME 2[a]



[a] Reagents and conditions: (a) (i) $LiAlH_4$, $AlCl_3$, THF, reflux 22 h; (ii) 10% Pd/C, xylenes, reflux, 5 days (82% yield/two steps); (b) (i) MeLi, Et_2O; (ii) $SnCl_2$, aqueous HCl (23% yield/two steps).

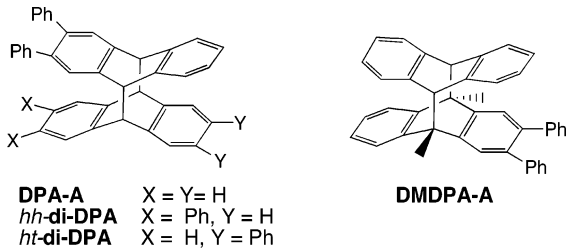


FIGURE 2. Structure of photocyclomers **DPA-A**, **di-DPA**, and **DMDPA**.

While four peripheral phenyl substituents greatly inhibit homodimer formation, two of these groups appear to be much less effective at blocking this reaction. **DPA** was found to undergo facile homodimer formation when illuminated in a Rayonet; after 130 min of irradiation at 300 nm, a 5 mM acetonitrile solution of this compound was converted to a single photoproduct in 50% yield. This product was identified as one of the two possible photodimers, **(*ht*)-di-DPA** or **(*hh*)-di-DPA**. Although the available information does not allow us to distinguish between these two photoproducts, steric considerations suggest that the head-to-tail product **(*ht*)-di-DPA** is likely to be favored. **DMDPA**, like 9,10-dimethylanthracene,[3b] fails to undergo any observable photodimer formation under the same conditions, presumably due to the presence of the methyl groups at the 9- and 10-positions.

The UV−vis spectra of **DPA** and **DMDPA** are similar to that of **TPA**. Both compounds absorb strongly between 270 and 300 nm and exhibit a 10−30 nm red-shift in their S0→S1 absorption bands relative to those of anthracene. Selective irradiation experiments on mixtures of **DMDPA** and anthracene yield similar results to those carried out with **TPA**. Irradiation at 290 nm, where only **DMDPA** absorbs, led to the exclusive formation of the cross-cyclomer **DMDPA-A**, whereas excitation with 372 nm light yields dianthracene and the cross-coupled product in a 2:9 ratio. The outcome was somewhat more complex when **DPA** and anthracene mixtures were illuminated, because **DPA** is capable of forming its homodimer. Selectively exciting **DPA** with 281 nm light afforded both **di-DPA** and **DPA-A** in a 1:2 ratio, while excitation of both chromophores at 372 nm led to the formation of all three possible photoproducts (Figure 2).

Using selective irradiation to restrict the outcome of these reactions to the creation of cross-cyclomers is not limited to phenyl-substituted anthracenes such as **TPA** and **DMDPA**. The UV−vis absorption spectrum of 9,10-dimethylanthracene (**DMA**) is similar to that of anthracene, but with peaks that are red-shifted by approximately 20 nm relative to those of the latter. It should therefore be possible to selectively excite **DMA** in

the presence of anthracene. Indeed, irradiation of a mixture of **DMA** and anthracene at 398 nm led to the formation a single observed photoproduct that was identified as **DMA-A**.[6] When this mixture was irradiated at 376 nm, both dianthracene and the mixed cyclomer were formed, as expected. The same outcome is observed over a range of concentrations, although, as expected, the reaction is much slower in dilute solution than in more concentrated samples. For example, when both chromophores were present at initial concentrations of 4 mM, only about 30% of the **DMA** was consumed after 2 h, while approximately 80% of this starting material had reacted after the same period from a solution containing 10 mM of each reagent.

In the examples described above, the initial concentrations of both chromophores were equal. To determine whether the same selectivity would be observed if one of the two chromophores was present in large excess, we irradiated a chloroform solution containing 4 mM **DMA** and 11 mM anthracene with 398 nm light. During the initial stages of this experiment, the cross-cyclomer was formed as the exclusive product. Despite the low concentration of **DMA**, its conversion to **DMA-A** was complete in under 2 h, presumably due to the large excess of anthracene available for it to react with. Only after **DMA** had been completely consumed was dianthracene observed to slowly form in trace quantities.

This strategy can also be extended to other substituted derivatives, such as 9,10-dimethoxyanthracene, which does not homodimerize, yet is known to form cross-cyclomers with anthracene.[7] Selective excitation of this chromophore with 400 nm light in the presence of anthracene led to the formation of the cross-cyclomer; again, no dianthracene product was observed.

In conclusion, we have demonstrated the viability of a new strategy for enforcing formation of the cross-cyclomers in the [4 + 4]-photocycloaddition reaction of anthracene derivatives by exciting only one component of a binary mixture. This selectivity rests on two key features of the molecule being excited: (a) it must absorb in a range where the other chromophore does not, and (b) it must be relatively inert toward homodimer formation. These studies indicate that this strategy is fairly general, and works either when the excitation wavelength is blue- or red-shifted relative to S0→S1 absorption bands of anthracene. This approach is much less restrictive than previous examples of selective cross-cycloadditions, which either suffered from poor product stabilities[3a,b] or required that both chromophores be unreactive toward homodimerization.[3a,c] This added flexibility should facilitate the design of modular reversible materials whose structures can be altered using light.

Experimental Section

Nonselective irradiation experiments were performed under a nitrogen atmosphere in glass Schlenk tubes. These experiments were carried out in a Rayonet fitted with ten 300 or 350 nm lamps, as specified. In a typical experiment, a 2.5 mL benzene solution containing 4 mM of each chromophore was subjected to three freeze−pump−thaw cycles in order to ensure the exclusion of oxygen from the reaction mixtures. After irradiation for 2 h, the solvent was removed in vacuo and the ratio of the products was determined by ^{1}H NMR.

Samples of the photocyclomers prepared for the purposes of characterization were obtained by irradiating deoxygenated mixtures of the appropriate monomers with 350 nm lamps. Reagent ratios and irradiation times for these preparative experiments were optimized to maximize the formation of the desired products. Details of these experiments and the characterization of the photoproducts can be found in the Supporting Information.

Selective irradiation experiments were carried out in deoxygenated $CDCl_3$ solutions in quartz NMR tubes and using a spectroflourimeter as the light source (slit width = 5 nm). These experiments were typically carried out using 1 mL solutions containing 10 mM of each chromophore and were monitored by ^{1}H NMR.

9,10-Dimethyl-2,3-diphenylanthracene (DMDPA). In oven-dried glassware, 2,3-diphenylanthraquinone (0.30 g, 0.83 mmol) was dissolved in 30 mL dry diethyl ether and cooled to 0 °C, at which point 1.4 M MeLi (2.65 mL 3.7 mmol) was slowly added. After addition, the solution was warmed to room temperature. After 90 min, 30 mL of 10% HCl solution saturated with $SnCl_2$ was added and allowed to stir for a further 60 min. This solution was then diluted with water (75 mL) and extracted with diethyl ether (3 × 75 mL). After the ethereal layer was dried with magnesium sulfate, the solution was concentrated in vacuo. This crude product was then directly applied to a silica column and eluted with a mixture of hexanes and toluene (1:1) to afford 0.07 g (20 mmol, 23%) of the desired product as a yellow solid: mp 204−205 °C; ^{1}H NMR (400 MHz, $CDCl_3$) 8.36 s (2H), 8.34 dd (2H, J = 3.3 Hz, J = 6.9 Hz), 7.53 dd (2H, J = 3.3 Hz, J = 6.9 Hz), 7.33−7.25 m (10H), 3.14 s (6H); ^{13}C NMR (125 MHz, $CDCl_3$) 142.1, 138.2, 130.5, 130.3, 129.5, 128.7, 128.1, 127.3, 126.8, 125.6, 125.1, 14.4; FT-IR: (cm^{-1}) 3077, 3050, 3017, 2920, 1598, 1490, 1443, 1386, 1021, 876, 766, 742, 699, 638, 595, 544; EI-MS 358.2 (M^+ 100), Anal. Calcd for $C_{28}H_{22}$: C, 93.81; H, 6.19. Found: C, 93.57; H, 6.30.

2,3-Diphenylanthracene (DPA). In an oven-dried round-bottom flask, 2,3-diphenylanthraquinone (0.200 g, 0.56 mmol) was dissolved in 30 mL of dry THF; to this was carefully added 210 mg (5.6 mmol) of $LiAlH_4$ and 0.37 g (2.8 mmol) of $AlCl_3$. The resulting mixture was refluxed for 22 h, cooled, poured over diethyl ether (50 mL), and carefully quenched with water (50 mL). This mixture was extracted with diethyl ether (3 × 50 mL). The combined organic extracts were dried ($MgSO_4$) and concentrated in vacuo. The crude product was dissolved in 20 mL of xylenes, and 0.20 g of Pd/C was added to the solution, which was then refluxed for 5 days. The product was purified by column chromatography (silica gel, eluent: gradient 100% hexanes to 1:1 hexanes/toluene) to afford 0.150 g (82%) of the desired product as a yellow solid: mp 98−100 °C; ^{1}H NMR (500 MHz, $CDCl_3$) 8.47 s (2H), 8.06 s (2H), 8.02 dd (2H, J = 3.3 Hz, J = 6.4 Hz), 7.48 dd (2H, J = 3.2 Hz, J = 6.5 Hz), 7.28−7.23 m (10H); ^{13}C NMR (100 MHz, $CDCl_3$) 141.5, 139.0, 132.1, 130.0, 129.6, 128.3, 127.9, 126.6, 126.2, 125.5; FT-IR (cm^{-1}) 3054, 3017, 2916, 1598, 1490, 1427, 1068, 1020, 957, 903, 772, 739, 699, 564, 467; EI-MS 330.1 (M^+, 100). Anal. Calcd for $C_{26}H_{18}$: C, 94.51; H, 5.49. Found: C, 94.17; H, 5.65.

Supporting Information Available: ^{1}H and ^{13}C NMR spectra of all compounds; UV−vis absorption spectra of compounds DMDPA, DMA, and DPA. Synthetic and analytical details for the preparation of the photocyclomers. This material is available free of charge via the Internet at http://pubs.acs.org.

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(6) Although no other photoproducts were observed from this reaction, we did find that more **DMA** was consumed than anthracene, suggesting that the former decomposes via an additional, unidentified pathway. This observation may be associated with the pronounced tendency of **DMA** to form a 9,10-endoperoxide when irradiated in the presence of even trace quantities of oxygen. A similar observation was made for experiments involving 9,10-dimethoxyanthracene. See: Schmidt, R.; Schaffner, K.;. Trost, W.; Brauer, H.-D. *J. Phys. Chem.* **1984**, *88*, 956.

(7) Bouas-Laurent, H.; Lapouyade, R. *C. R. Acad. Sci., Ser. C* **1967**, *12*, 1061.